J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

Ray Trace and Fokker-Plank Analyses for Electron Bernstein Wave Heating and Current Drive in QUEST

H. Idei, N. Takeuchi[1)], S. Kubo[2)], A. Fukuyama[3)], H. Nuga[3)], M. Sakaguchi[4)], N. Nakamura, K. Hanada, H. Zushi, K. N. Sato, M. Sakamoto, M. Hasegawa, Y. Takase[5)], O. Mitarai[6)], T. Maekawa[7)] and Y. Kishimoto[7)]

Research Institute for Applied Mechanics, Kyushu University, Kasuga 816–8580, Japan
[1)] *Ariake National College of Technology, Ohmuta 836–8585, Japan*
[2)] *National Institute for Fusion Science, Toki 509–5292, Japan*
[3)] *Department of Nuclear Engineering, Kyoto University, Kyoto 606–8501, Japan*
[4)] *Communication Engineering Dept. Broad Wireless Corporation, Yokohama 220–0073, Japan*
[5)] *Department of Complexity Science and Engineering, University of Tokyo, Kashiwa 277–8561, Japan*
[6)] *Institute of Industrial Science and Technical Research, Tokai University, Kumamoto 862–8652, Japan*
[7)] *Graduate School of Energy Science, Kyoto University, Kyoto 606–8501, Japan*

(Received: 10 September 2008 / Accepted: 18 December 2008)

The Q-shu University Experiment with Steady State Spherical Tokamak (QUEST) was proposed at Kyushu University to study plasma-wall interaction phenomena in the steady-state plasma. The steady-state current drive experiments are planned with Electron Bernstein Wave Heating and Current Drive (EBWH/CD) in the QUEST. In order to evaluate the plasma current by the EBWH/CD, the power deposition was first evaluated using a ray tracing code TASK/WR. The local electric fields calculated in the ray trace were used to the Fokker Plank (TASK/FP) analysis. The driven-current was estimated from the WR and FP analyses in the *O-X-B* mode conversion scenario at rather low density ($\sim 0.2 \times 10^{19}\mathrm{m}^{-3}$) and temperature ($\sim$ 100eV).

Keywords: Electron Bernstein Wave, Ray Trace Analysis, Fokker-Plank Analysis, RF Heating, Current Drive

1. Introduction

Electron Bernstein wave heating and current dive (EBWH and EBWCD) is one of attractive candidates of heating and current drive method to sustain the steady-state plasma in the spherical tokamak (ST). The Q-shu University Experiment with Steady State Spherical Tokamak (QUEST) was proposed at Kyushu University, and the QUEST device has been constructed. The establishment of steady-state current drive method is a key issue to study plasma-wall interaction phenomena in the steady-state QUEST plasma. The steady-state current drive experiments were planned with the EBWH/CD in the QUEST.

In the ST devices, the plasma frequency may become larger than the electron cyclotron frequency in the operating density range due to the rather low magnetic field, and the electron cyclotron wave can not penetrate into the plasma due to the cutoff layers. In the EBWH/CD, some mode conversions from the electron cyclotron (electromagnetic) wave to the electron Bernstein (electrostatic) wave are required. In the X-B mode conversion scenario, a perpendicularly incident X-mode wave meets the R-cutoff, and converts to the B-mode wave by tunneling of the evanescent layer between the R-cutoff and the upper hybrid resonance (UHR). In the O-X-B mode conversion, an obliquely incident O-mode wave is converted into an X-mode wave at the O-cutoff, and propagates as X-mode wave. The X-mode wave reaches the UHR, and converts to the B-mode wave. In order to conduct the experiments, the launching mode, *i.e* the launching polarization, and the launching angle should be controlled to attain the high conversion efficiency. A phased-array antenna system, which enables us to control the launching polarization and angle, was proposed and under development for the EBWH/CD experiments in the QUEST. The prototype antenna system was designed[1] and tested at low and high power levels.

In order to study the wave propagation and absorption of the *B*-wave, the wave trajectory has been calculated, including the mode conversion processes, with some ray tracing codes[2]. The wave trajectory of the incident beam was calculated using the TASK/WR ray-tracing code[3] for the QUEST. The local wave electric fields were evaluated in the ray trace calculation, and used for the Fokker-Planck (TASK/FP)[3] analysis. The driven-current profile was estimated in the FP analysis.

This paper is organized as follows. Section 2 describes the experimental setup using the phased array-antenna in the QUEST. In Sections 3 and 4, the results of ray trace and FP analyses are shown, and the summary is finally given in Section 5.

author's e-mail: idei@triam.kyushu-u.ac.jp

2. Experimental Setup

The density gradient at the conversion into the B-mode wave is a key parameter to attain high conversion efficiency from the X/O-mode wave to the B-mode wave. Even mixture modes of the X/O-mode are required, depending the density gradient. In addition to the launching mode, the launching angle is also an essential parameter to achieve the high conversion efficiency. In the X-B mode conversion, the beam is injected in perpendicular to the magnetic field of the tokamak, while the beam is obliquely injected to the plasma with an optimum angle in the O-X-B mode conversion. The phased array antenna system should ensure the controllability of the launching polarization and angle for the EBWH/EBWCD experiments.

In order to control the launching polarization, an orthomode transducer was designed to mix two orthogonal electric-field components. The arbitrary polarized field was expressed using the two orthogonal components with a phase difference. The Lower Hybrid Current Drive (LHCD) system in the previous our TRIAM-1M tokamak will be used to the EBWH/CD in the QUEST. The operating frequency was 8.2GHz. In the system, the power of 200 kW was transmitted to the LHCD antenna using 16 rectangular-waveguide (WR-137) lines. The output polarization state at the orthomode transducer was controlled by the phase shifters and attenuators in the transmission lines. Figure 1(a) illustrates a conceptual design for the orthomode transducer part. Two field components with different intensity and phase at the rectangular waveguide input were mixed at the orthomode transducer, and were lead to the antenna with the arbitrary elliptical polarization state. The orthomode transducer was designed to be optimum at the operating frequency of 8.2GHz for the open-end operation. The VSWR at the open-end operation was less than 1.1 at the 8.2 GHz. The output waveguide of the orthomode transducer was square, not rectangular. The directional coupler measured the intensity and phase of the forward component, also did the component reflected from the antenna and the plasma. Figure 1(b) shows the designed phased-array antenna. The output aperture of the antenna was a 4×2 square-waveguide array. Using the phase differences among the 8 square-waveguides, the launching beam was steered to attain high conversion efficiency from the X/O-mode wave to the B-mode wave. In order to evaluate the radiation field pattern from the antenna, a simple Kirchhoff integral code has been developed. The Kirchhoff integral at the propagating z position was expressed as follows,

$$
\begin{aligned}
E_{x,z}(x,y,z) &= \frac{ik}{2\pi y}\int_{-a/2}^{a/2}\int_{-a/2}^{a/2} \mathrm{d}x'\mathrm{d}z' \\
&\quad \times E_{x,z}(x',z')[\exp(-ikr)/r], \\
r &= \sqrt{(x-x')^2+y^2+(z-z')^2},
\end{aligned} \tag{1}
$$

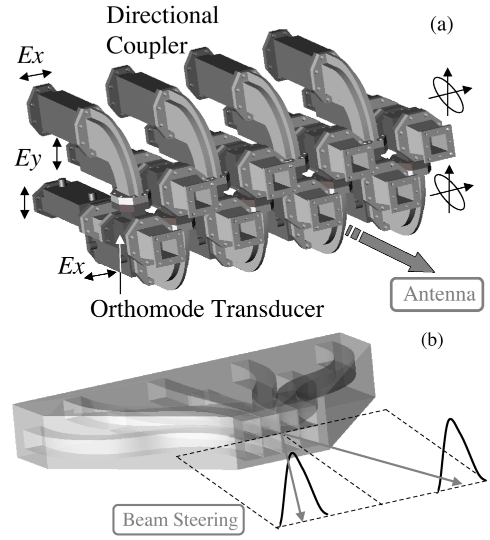

Fig. 1 Conceptual designs of (a): orthomode transducer part and (b): phased array antenna.

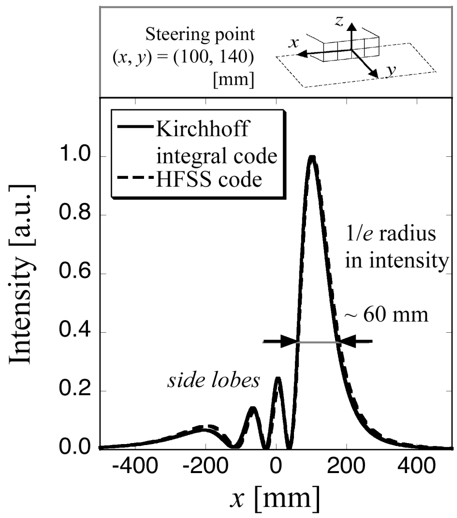

Fig. 2 Beam intensity profile evaluated using the Kirchhoff integral and HFSS codes. The steering point coordinates are illustrated.

where the coordinates of (x', z') and (x, z) were at the antenna aperture position(y=0) and at the radiated y position as shown in Fig.2, and a was a side of the square-waveguide, respectively. Figure 2 shows the beam intensity profiles from the antenna, which were evaluated using the Kirchhoff integral code and a 3D full-wave electromagnetic field simulation-code, HFSS[4]. The Kirchhoff integral code result coincided well with that of the HFSS code. The $1/e$-folding beam radius in the intensity profile was about 60 mm. The beam with the small beam radius was steered to the desired launching direction. There were three side-lobes, but the power levels of the side-lobes were $-6 \sim -11$ dB below the main lobe.

3. Ray Trace Analysis

At first the QUEST project will take the focus to study how to sustain the plasma current in steady state by the EBWH/CD. The steady-state current drive in the ST plasma is most important to study the plasma-wall interaction in the steady-state operation. In the first step, it was planned to sustain the rather low plasma current of 20kA in the lower density region, but in the steady state. In this scenario, the plasma current will start up by only the RF-wave without the induction electric field[5]. In the lower density and/or its lower gradient case, the *O*-*X*-*B* scenario was suitable for the EBWH/CD with a high conversion efficiency to the *B*-wave. The incident *O*-mode launched from the low -field/density side can be converted to the *X*-mode if the beam was injected with an appropriate angle oblique to the magnetic field. The optimum refractive index in parallel to the magnetic field $N_{//}^{\mathrm{opt}}$, at the *O*-cutoff layer, was given by

$$N_{//}^{\mathrm{opt}} = \sqrt{\frac{Y}{1+Y}}, \tag{2}$$

where Y was the raio of the electron cyclotron frequency ω_{ce} to the wave frequency ω. The wave propagation and absorption of the *B*-wave after the *O*-*X*-*B* mode conversion was evaluated using the TASK/WR ray tracing code. The wave trajectory was calculated from the following differential equations,

$$\frac{\mathrm{d}\boldsymbol{r}}{ds} = \frac{\partial D}{\partial \boldsymbol{k}}, \quad \frac{\mathrm{d}\boldsymbol{k}}{ds} = -\frac{\partial D}{\partial \boldsymbol{r}}, \quad \frac{\mathrm{d}t}{ds} = -\frac{\partial D}{\partial \omega}, \tag{3}$$

where $\boldsymbol{r}(s), \boldsymbol{k}(s)$ and $t(s)$ were the position/wave vectors and the time of the wave trajectory, respectively. The wave propagated to satisfy the local dispersion relation, $D(\omega, \boldsymbol{k}, \boldsymbol{r}) = 0$. The dispersion relations D for $O/X/B$-modes were described with non-relativistic hot plasma expressions without cold and electrostatic approximations. The geometrical coordinates were taken as a simple tokamak configuration with circular poloidal cross-sections. The major and minor radii were 0.64m and 0.36m in this study. The profiles of electron density and temperature, and plasma current were assumed to be parabolic. The central electron density and temperature were $n_{e0} = 0.2 \times 10^{19}$ m^{-3} and $T_{e0} = 100$eV, respectively. The total plasma current was 20kA. The *O*-cutoff was at the plasma radius r=0.28, and the corresponding $N_{//}^{\mathrm{opt}}$ was 0.605. Figure 3 shows the wave trajectory at the toroidal cross-section, indicating the *O*-*X*-*B* mode conversion processes. The evolutions of the refractive indices $N_{\perp}$ and $N_{//}$ in perpendicular and parallel to the magnetic field were shown in Fig.4 along the propagation. The incident *O*-mode with the optimum $N_{//}^{\mathrm{opt}}$ was converted to the *X*-mode at the *O*-cutoff layer. The *X*-mode was converted to *B*-mode at UHR again, and propagated to the high-density side (*i.e.* to the plasma center).

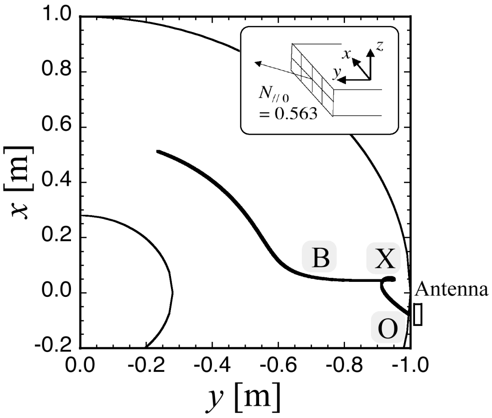

Fig. 3 Wave trajectory at the toroidal cross section (z=0) in the *O*-*X*-*B* conversion scenario. The (x, y, z) coordinates, and the parallel refractive index excited at the antenna, $N_{//0}$, are explained. The origin of the coordinates is a center of the QUEST device.

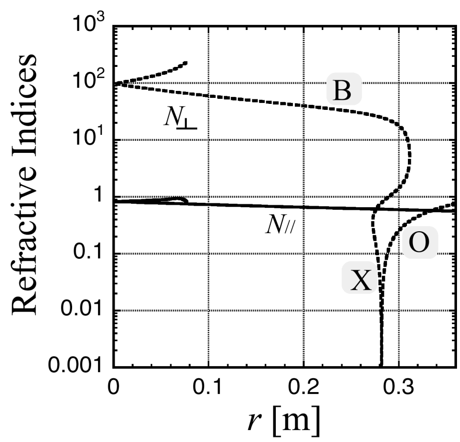

Fig. 4 Evolutions of refractive indices $N_{\perp}$ and $N_{//}$ in perpendicular and parallel to the magnetic field along the propagation in the *O*-*X*-*B* conversion scenario.

The absorption of the wave was evaluated from the optical thickness τ, which was obtained by integrating the partial derivative of the imaginary part of D along the propagation as follows,

$$\tau = 2 \int \frac{\partial\ [\mathrm{Im}(D)]}{\partial s} \mathrm{d}s. \tag{4}$$

Figure 5 shows the power deposition profile calculated from Eq.(4) in this *O*-*X*-*B* conversion scenario. The wave was perfectly absorbed before it reached to the cold resonance layer by the Doppler-shifted resonance condition of the *B*-wave.

4. Fokker-Planck Analysis

The local wave electric fields were calculated in the ray trace calculation, and used for the Fokker-Planck (TASK/FP) analysis. In the TASK/FP code, a quasi-linear RF operator in the velocity space

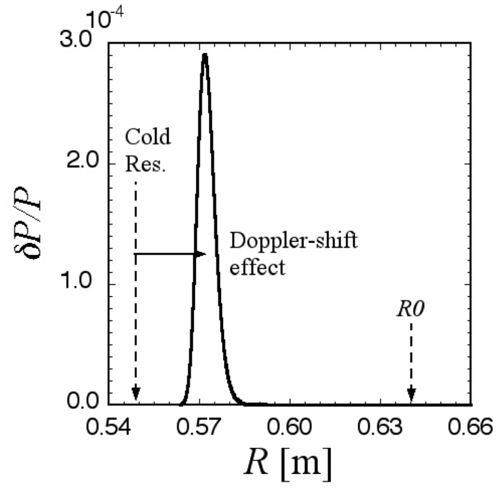

Fig. 5 Power deposition profile in the *O-X-B* conversion scenario at the QUEST.

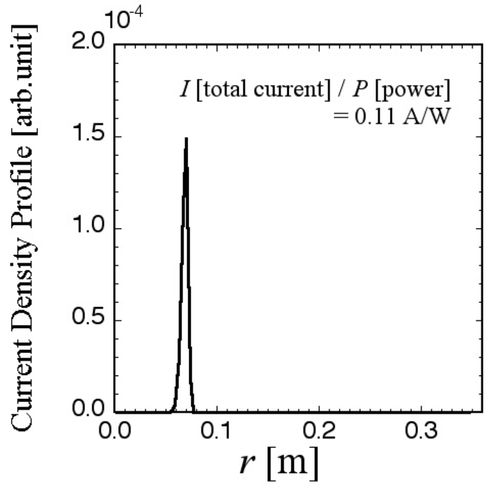

Fig. 6 Current profile driven in the *O-X-B* conversion scenario at the QUEST.

was evaluated from the wave field, and the bounce-averaged velocity distribution function was calculated to evaluate the plasma current driven by the EBWH/CD. The nonlinear collision operator was used with the trapped electron effect. Figure 6 shows the current density profile driven by the EBWH/CD in the *O-X-B* scenario. The ratio of the total driven-current $I_{\rm p}$ to the power $P_{\rm CD}$ was evaluated as $I_{\rm p}/P_{\rm CD}$ =0.11 A/W. The dimensionless current drive efficiency $\eta_{\rm\ EBCD}(\equiv 33\ n_{e,20}I_{\rm p}R/[P_{\rm CD}T_{\rm e,keV}])$ was 0.46. Here, $n_{e,20}$ and $T_{\rm e,keV}$ were the electron density and temperature in units of $[10^{20}{\rm m}^{-3}]$ and [keV], respectively. The obtained efficiency $\eta_{\rm\ EBCD}$ was comparable to the previous W-7AS result of 0.43[6].

In the first stage of the QUEST project, the total power of 400kW was available by 2 antenna systems at the 8.2GHz operating frequency. The plasma current of 20kA may be generated even in this *O-X-B* scenario at the lower density and temperature case, depending on the coupled power $P_{\rm CD}$ that was effective to drive the current. The window of the launching angle to attain the high conversion efficiency to the *B*-mode was narrow. The $N_{//}$ spectrum, which were excited at the antenna system, should be taken into account to evaluate the *O-X* mode conversion efficiency. The calculated driven-current profile was not consistent with the assumed profile at the ray trace analysis. In the plasma start-up phase, the high energy($\sim$5keV) component was observed at the Compact PWI Device experiment[7]. The energetic electrons played an important role on the formation of closed magnetic surfaces in the start-up phase[8]. The power deposition and driven-current profiles at the EBWH/CD became broader if there were energetic electrons. The more consistent ray trace and Fokker-Planck analyses were required in future, taking the mode conversion efficiency and the high-energy component into consideration.

5. Summay

The ray trace code TASK/WR and the Fokker Plank code TASK/FP were applied to evaluate the plasma current by the EBWH/CD in the QUEST. In the WR and FP analyses, the ratio of the total driven-current to the coupled power was 0.11A/W in the *O-X-B* mode conversion scenario at the lower density ($\sim 0.2\times10^{19}{\rm m}^{-3}$) and temperature($\sim$ 100eV). The dimensionless current drive efficiency $\eta_{\rm\ EBCD}$ was 0.46. If there were high energy components, the power deposition and driven-current profiles became broader. The effects of the high-energy component and the $N_{//}$ spectrum, which were excited at the antenna system, should be taken into account in the evaluation of the deposition and driven-current profiles.

6. Acknowledgment

This work was realized in the industry-academic collaboration between Kyushu University and Broad Wireless Corporation, and was done in part, in the NIFS bi-directional collaboration (NIFS06KUTR016/NIFS08KUTR033), and the RIAM Kyushu University collaboration programs (H18FP-11/H19FP-16).

[1] H. Idei *et al.,Proc. of 32nd Int. Conf. on Infrared and mm-Waves*, 789 (2007).
[2] T. Maekawa *et al.*, J. of the Phy. Soc. of Japan,**48** 247 (1980).
[3] A. Fukuyama, Fusion Eng. and Design,**53**, 71 (2001).
[4] http://www.ansoft.com/products/hf/hfss
[5] T. Maekawa *et al.*, Nuclear Fusion, **45** 1439 (2005).
[6] H. P. Laqua *et al.*, Phys. Rev. Lett.**90** 075003 (2003).
[7] T. Yoshinaga *et al.*, in preparation to be submitted.
[8] K. Ishiguro *et al.*, in this congress.