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Evaluation of Mode Purity of Ordinary and Extraordinary Modes by Fixed Elliptically Polarized Wave for ECH and ECCD

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Mode separation ratio from an arbitrary elliptically polarized electromagnetic wave to an ordinary and an extraordinary modes on a plasma surface for oblique launch is evaluated quantitatively for designing an electron cyclotron current drive (ECCD) antenna. An optimized elliptical polarization for the wide range of injection angles and magnetic fields is firstly investigated for ECCD and ECH experiments.

Keywords: Mode Separation Ratio, Elliptically Polarized, Ordinary Mode, Extraordinary Mode, Oblique Launch, ECCD, ECH

電子サイクロトロン共鳴加熱，及び電流駆動において楕円偏波によって励起される正常波，異常波の純度の評価

日本原子力研究所那珂研究所核融合工学部
三枝　幹雄

（1991年7月18日受理）

トカマク型核融合炉の定常化を目的とした電子サイクロトロン電流駆動実験において，プラズマへ入射される電磁波の偏波と励起される正常波，異常波の純度の評価を計算により行った。磁化プラズマ中に斜め伝搬する正常波又は異常波を励起させる為には，特定の楕円偏波を持つ電磁波が必要である。本論文では，DⅢ－Dのパラメータで外側入射の基本波の正常波と外側入射の2倍の高調波の異常波を用いた電流駆動実験で，任意の楕円偏波の電磁波がプラズマ表面で正常波と異常波に分離する割合の評価を行った。現在，電流駆動実験で使用している直線偏波では，2倍の高調波の異常波の方が基本波の正常波と比べ波の純度がかなり低下することが判った。また，楕円偏波を最適な形で固定することで，電流駆動実験に十分に広い入射角の範囲，トロイダル磁場の変化に対して常に80％以上の波の純度を保てることが確認された。

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Contents

目次

1. Introduction

Electron cyclotron current drive (ECCD) is one of the useful methods to drive a current and to control an current profile in order to improve energy confinement and suppress MHD instabilities [1]. There are three experimental regimes for electron cyclotron resonance heating (ECH) and ECCD, which use an inside launched extraordinary mode (X-mode), an outside launched ordinary mode (O-mode) and an outside launched second harmonic extraordinary mode. The outside launched regimes are suitable for a fusion reactor, because of easy access and assembly. Therefore, the calculations are performed for only outside launched experimental regimes.

Recently, waveguide modes which are used for ECH and ECCD systems have been mainly the HE_{11} mode in corrugated waveguides. The HE_{11} mode is a linearly polarized mode, which is best for purely exciting the O or X-mode in plasmas at perfectly perpendicular injection. The HE_{11} mode can produce a radiation pattern with very low sidelobes and cross-polarization [2]. In the next step, the suitable elliptical polarization for efficient ECCD will be used in future large tokamaks like International Thermonuclear Experimental Reactor (ITER) [3], a Japanese Fusion Engineering Reactor (FER) [4] etc., because the pure excitation of an O or X-mode at an oblique propagation in plasmas requires an appropriate elliptical polarization [5]. (The ordinary and extraordinary modes are usually defined at perfectly perpendicular propagation, but we call the oblique propagated waves the ordinary and extraordinary modes distinguished with the branches in this paper.) However, it is difficult for wide range of plasma parameters to make an optimized elliptical polarization for ECCD. Because, the optimum injection angle for ECCD depends on an electron temperature, density profile and a magnetic field. Furthermore, the optimum elliptical polarization depends on an injection angle, a magnetic field, a surface safety factor and an electron density at the plasma edge.

If mode purity is low, a fundamental X-mode is reflected at a right hand cut-off surface in the case of using a fundamental O-mode regime, and a second harmonic O-mode can be hardly absorbed in a resonance layer in the case of using a second harmonic X-mode regime. Therefore, an evaluation of mode purity of linear polarization or some fix elliptical polarization at various plasma parameters is important for selecting experimental regimes and an antenna design for ECCD.

In Section 2, the calculation model and used parameters of this paper are explained. Next, the mode purity on plasma surface using the linear and elliptical polarization are calculated for ECCD experiments in Section 3. We discuss the optimized elliptical polarization evaluated by scanning a magnetic field and an injection angle for ECCD and ECH experiments in Section 4.

2. Calculational Model

A simple cold dispersion relation is used to optimize the elliptical polarization which depends on plasma parameters and toroidal injection angles [6].

Figure 1 shows the coordinate for this calculation. The wave polarization can be calculated by the following equations.

$$\frac{E_y}{iE_z} = \frac{D\cdot(P - N^2\cdot\sin^2\theta)}{N^2\cdot\cos\theta\cdot\sin\theta\cdot(S - N^2)}, \tag{1}$$

$$\frac{E_x}{E_z} = \frac{(P - N^2\cdot\sin^2\theta)}{N^2\cdot\cos\theta\cdot\sin\theta}. \tag{2}$$

The refractive index of plasma waves is given by

$$N^2 = 1 + \frac{2(p-1)\cdot x + \sin^2\theta \pm \sqrt{\sin^2\theta + 4x\cdot(1-p)^2\cdot\cos^2\theta}}{2\{(1/p - 1)\cdot(x-1) - \sin^2\theta\}}, \tag{3}$$

+ ; Ordinary Mode (N_o),

- ; Extraordinary Mode (N_x),

where plasma parameters are defined as

$$S=1-\frac{p\cdot x}{x-1},$$

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where plasma parameters are defined as

$$S = 1 - \frac{p\cdot x}{x-1} ,$$

$$D=\frac{p\sqrt{x}}{1-x},$$

$$P=1-p,$$

$$p=\left(\frac{\omega_{pe}}{\omega}\right)^2,\ x=\left(\frac{\omega}{\omega_{ce}}\right)^2,\ y=\frac{1}{x}.$$

The stepwise shape of plasma density and no reflected power at the plasma edge are assumed. The power reflection at the plasma edge can be neglected except almost parallel injection, because the refractive index of a scrape-off layer is almost unity except a resonance layer. The boundary conditions can be decided, as the tangential components of electric and magnetic fields are continuous on the plasma surface.

Each electric field component in a vacuum region is written as

$$(E_{x1},\ E_{y1},\ E_{z1})=(-E_1\cos\theta_1,\ E_2,\ E_1\sin\theta_1)\ . \tag{4}$$

The relation between E_1 and E_2 is defined as

$$E_2=iRE_1, \tag{5}$$

R; modified polarization ratio. [7]

We neglect the tilt angle of polarization ellipse for briefness. **a**, **b**, **c** and **d** are defined by

$$a\equiv E_{yo}/i\ E_{zo},\quad b\equiv E_{yx}/i\ E_{zx},\quad c\equiv E_{xo}/E_{zo},\quad d\equiv E_{xx}/E_{zx}\ , \tag{6}$$

and can be calculated by using Eqs.(1), (2) and (3).

The boundary conditions are shown as

$$E_y=E_{yo}+E_{yx}=iaE_{zo}+ibE_{zx}=iRE_1\ ,$$
$$E_z=E_{zo}+E_{zx}=E_1\sin\theta_1\ . \tag{7}$$

The Eq.(7) can be modified to

$$\begin{pmatrix} E_{zo} \\ E_{zx} \end{pmatrix}=\frac{E_1}{a-b}\cdot\begin{pmatrix} R-b\cdot\sin\theta_1 \\ -R+a\cdot\sin\theta_1 \end{pmatrix}\ . \tag{8}$$

Each components of the pointing flux of O-mode (S_o) and X-mode (S_x) in plasmas are written as

$$S_{xo}=(e_o{}^2\ \sin\theta_o-c\ j_o)\ N_o\ E_{zo}{}^2,$$

$$S_{zo}=(e_o{}^2\ \cos\theta_o-j_o)\ N_o\ E_{zo}{}^2,$$

$$S_{xx}=(e_x{}^2\ \sin\theta_x\text{-}d\ j_x)\ N_x\ E_{zx}{}^2,$$
$$S_{zx}=(e_x{}^2\ \cos\theta_x\text{-}j_x)\ N_x\ E_{zx}{}^2, \qquad (9)$$

where e_o, j_o, e_x and j_x are defined as

$$e_o{}^2\equiv c^2+a^2+1,$$
$$j_o\equiv c\ \sin\theta_o+\cos\theta_o\ ,$$
$$e_x{}^2\equiv d^2+b^2+1,$$
$$j_x\equiv d\ \sin\theta_x+\cos\theta_x\ . \qquad (10)$$

θ_o, θ_x are decided from the Snell's law. But, those three angles (θ_1, θ_o, θ_x) are almost the same on the plasma surface.

The pointing flux of O and X-modes are written as

$$|S_o|^2=S_{xo}{}^2+S_{zo}{}^2, \qquad |S_x|^2=S_{xx}{}^2+S_{zx}{}^2, \qquad (11)$$

from Eqs.(3), (8), (9) and (10).

The mode purity is defined as So/(So+Sx) and Sx/(So+Sx) for the excitation of O and X-modes, respectively.

Used plasma parameters which are based on a DIII-D tokamak are shown in Table 1.

3. Calculational Results

The mode purity of the fundamental O-mode versus the toroidal injection angle at the various electron density by using the linearly polarized wave is shown in Fig.2 at a frequency of 60 GHz and a toroidal magnetic field of 1.53 T, where the toroidal injection angle is defined as $\pi/2-\theta_1$ in Fig.1. The region between two vertical broken lines ($\pi/2-\theta_1=20^\circ\sim30^\circ$) shows the suitable injection angle on the plasma surface. The suitable injection angle of fundamental O and X-modes in DIII-D for ECCD was predicted as $20^\circ\sim30^\circ$ by the ray tracing code [8,9] and the Fokker-Planck code. [10] The mode purity is not shown over 75°, because too large angle on a plasma surface has no meaning for ECCD. Furthermore, the plasma model is not accurate in the case of a large injection angle due to neglecting a reflection power on a plasma surface. The mode purity is about 70~80 % at the suitable toroidal injection angle for ECCD, and does not depend on the electron density except near the cut-off density.

The mode purity of the second harmonic X-mode by linearly polarized wave is shown in Fig.3 at a frequency of 110 GHz and a

$$S_{xx}=(e_x{}^2\ \sin\theta_x\text{-}d\ j_x)\ N_x\ E_{zx}{}^2,$$
$$S_{zx}=(e_x{}^2\ \cos\theta_x\text{-}j_x)\ N_x\ E_{zx}{}^2, \qquad (9)$$

where e_O, j_O, e_X and j_X are defined as

$$e_o{}^2 \equiv c^2+a^2+1,$$
$$j_o \equiv c\ \sin\theta_o+\cos\theta_o\ ,$$
$$e_x{}^2 \equiv d^2+b^2+1,$$
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The mode purity of the second harmonic X-mode by linearly polarized wave is shown in Fig.3 at a frequency of 110 GHz and a toroidal magnetic field of 1.4 T. This linear polarization is crossed to the linear polarization for the O-mode excitation. The mode purity is about 60~70 % at the suitable toroidal injection angle for ECCD.

The mode separation of linearly polarized wave depends on the magnetic field at the plasma edge significantly. Figures 4 (a) and (b) show the dependence of power separation ratio on a toroidal injection angle at various toroidal magnetic fields by using a fundamental O-mode (60GHz) and a second harmonic X-mode (110GHz), respectively. The mode purity increases with a magnetic field. This result indicates that the mode purity of a second harmonic X-mode is less than that of a fundamental O-mode in the case of using linear polarization for ECCD. In addition to the above, the mode purity of inside launched regime is higher than that of outside launched one.

The effect of the tilt angle between linearly polarized plane and the direction of magnetic field (E-B angle) on the power separation ratio is shown in Fig.5. This result can be calculated by using a pure imaginary modified polarization ratio in Eq.(5). The pure O-mode is changed to the pure X-mode during rotating from 0° to 90°. This result indicates that the power separation ratio of the linearly polarized wave depends on the surface safety factor (q-value), especially in low q discharges.

The dependence of power separation of the elliptically polarized wave on the toroidal injection angle at the various modified polarization ratio in the outside launched fundamental O-mode is shown in Fig.6. In this case, the optimized modified polarization ratio is 0.5 at the toroidal injection angle of 20°~30°. The positive modified polarization ratio indicates a left elliptic polarization.

The dependence of power separation on the magnetic field at the optimized elliptical polarization is shown in Fig.7. The mode purities of O-mode are over 95 % at the toroidal magnetic field of 1.0 to 2.0 T in the range of the toroidal injection angle of 20°~30°. This result indicates that if the range of optimum injection angle is decided for ECCD, the high mode purity can be obtained by selecting optimum elliptical polarization as long as almost the same safety factor discharge.

The same polarization is usually used in the wide range of toroidal injection angle, because the change of antenna is not easy without venting a vacuum vessel. Adjusting the polarization by rotating a pair of corrugated mirrors has been proposed by the ITER conceptual design activity [3]. However, the rotation of mirror with an appropriate curvature for focusing beams is very difficult, so that this system needs large space for many mirrors. We propose the optimized polarization in the wide range of toroidal injection angle and magnetic field. Figure 8 shows the mode purity with the optimized polarization in the wide range of toroidal injection angle in the case of outside launched fundamental O-mode (60GHz). The mode purities are over 85 % at the toroidal magnetic field of 1.0 to 2.0 T in the range of toroidal injection angle from -30° to 30°.

The dependence of mode purity on the toroidal injection angle at various modified polarization ratios in the outside launched second harmonic X-mode (110GHz) is shown in Fig.9. The optimized modified polarization ratio is -1.5 in the range of the toroidal injection angle of 20°~30°. The negative modified polarization ratio indicates a right elliptic polarization which is opposite rotation sense for the fundamental O-mode.

The dependence of mode purity on the toroidal magnetic field and the toroidal injection angle by using optimized polarization for ECCD is shown in Fig.10. The mode purities of X-mode are over 97 % at the toroidal magnetic field of 1.0 to 2.0 T in the range of the toroidal injection angle of 20°~30°. However, the mode purity at perpendicular injection is only 70 %. Figure 11 shows the mode purity of X-mode in the optimized polarization in the wide range of toroidal injection angle. The mode purities are over 80 % at the toroidal magnetic field of 1.0 to 2.0 T in the range of toroidal injection angle from -30° to 30°.

Figures 7 and 10 indicate the perfectly pure mode can be excited at a tilt angle of polarization ellipse of 0° as long as the safety factor is high. However, the tilted elliptical polarization must be required for a low safety factor discharge.

4. Conclusions

The mode separation ratio from an arbitrary polarized electromagnetic waves to an ordinary and an extraordinary modes on plasma surface is calculated for ECCD and ECH. The mode separation ratio depends on a magnetic field, a parallel refractive index, the safety factor on the plasma surface and a polarization of electromagnetic wave, but does not so depend on the electron density except near the cut-off density. The mode purity of second harmonic X-mode (60-70 %) is lower than that of fundamental O-mode (70-80 %) and the mode purity of inside launched regime can be predicted to be higher than that of outside launched one at the same toroidal injection angle in the case of linear polarization. The optimized elliptical polarization for the wide range of injection angles and magnetic fields is firstly investigated for ECCD and ECH experiments. The mode purity in the case of a outside launched fundamental O-mode is higher than 85 % and that in the case of a outside launched second harmonic X-mode is higher than 80 % in the range of toroidal injection angle from -30° to 30° and a toroidal magnetic field from 1.0 to 2.0 T.

Acknowledgements

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Table 1 Plasma Parameters used in the Calculations

Electron Density	**Sharp Edge Model $1\times10^{17} \sim 1\times10^{18}$ m^{-3}**
Magnetic Field	**1.0 ~ 3.0 T**
Toroidal Injection Angle	**0 ~ 75 degrees**
Frequency	**60 GHz for Outside Launched Fundamental O-mode** **110 GHz for Outside Launched Second harmonic X-mode**

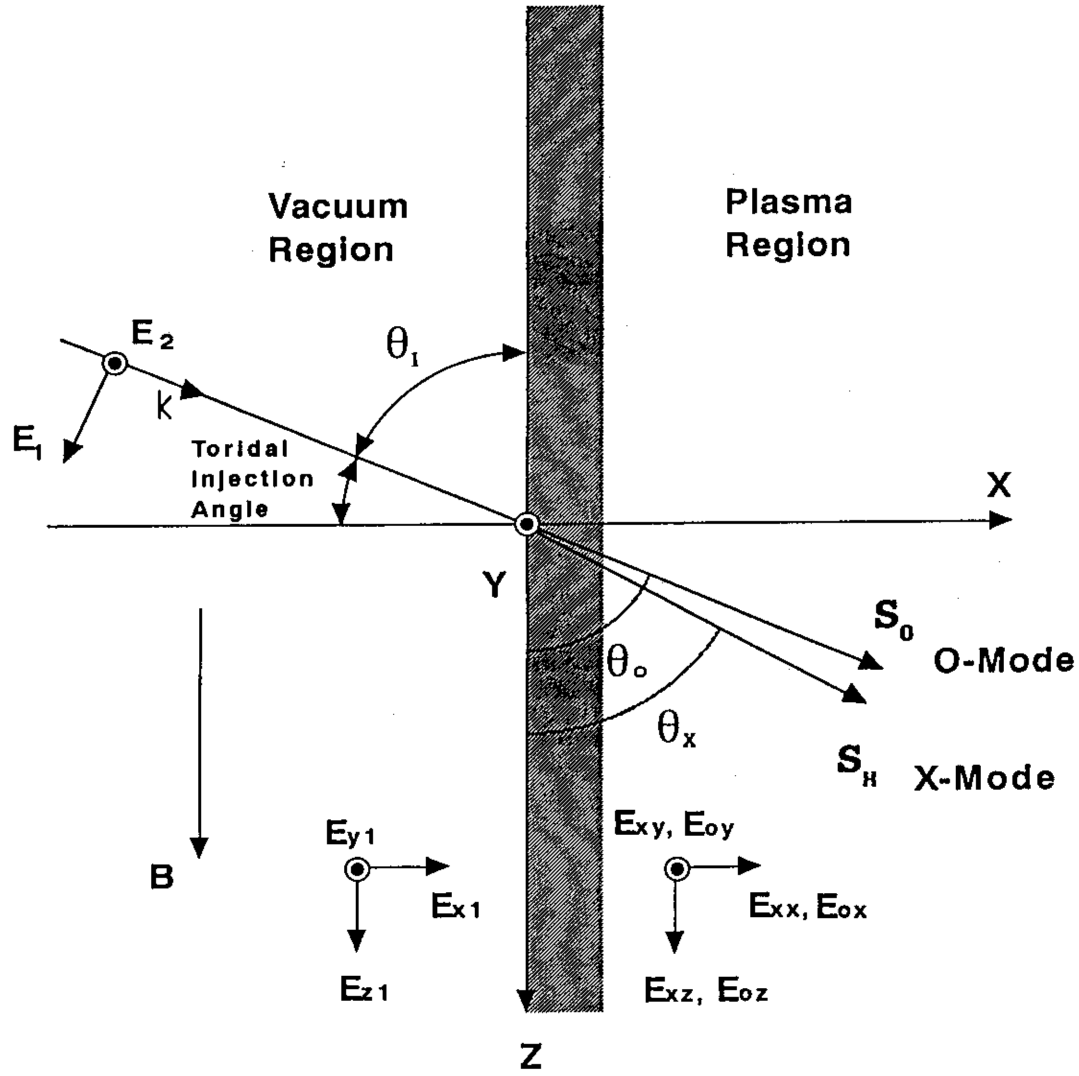


Fig. 1 The model and coordinate at the plasma boundary for calculation.

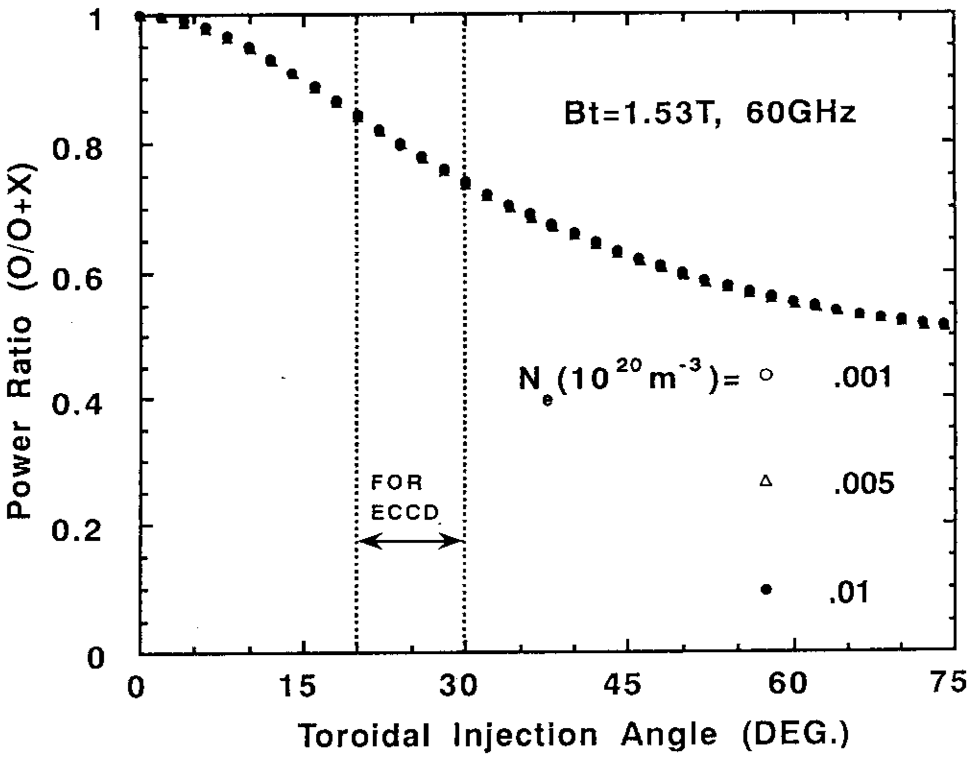


Fig. 2　The mode purity of fundamental ordinary mode versus the toroidal injection angle at various electron density by using the linearly polarized wave.

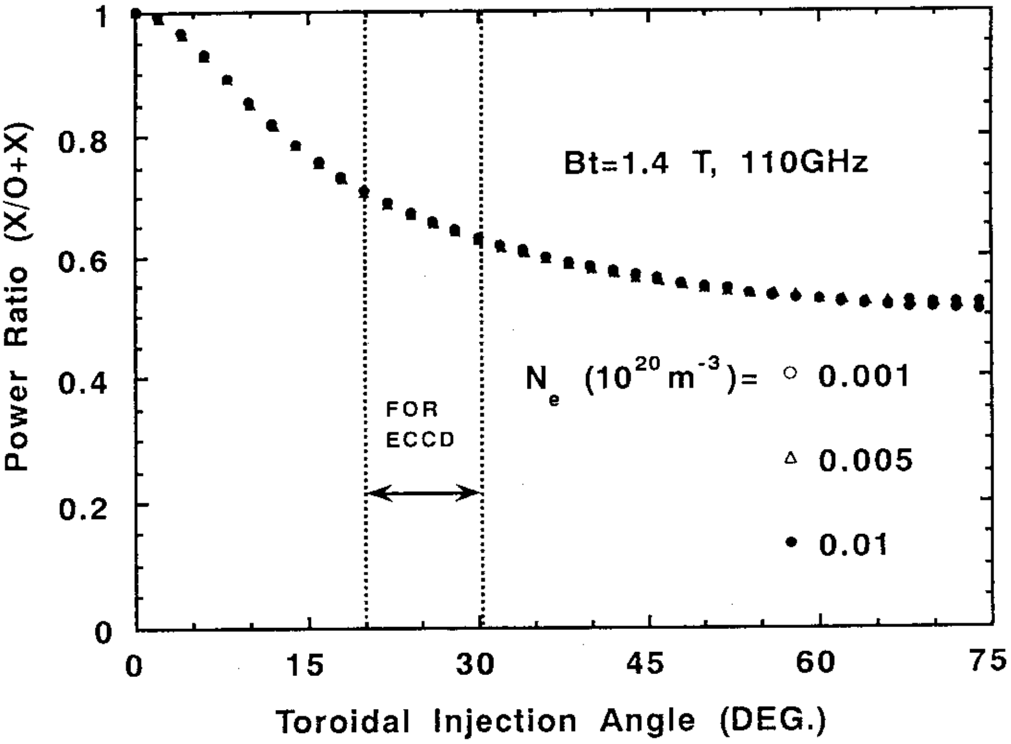
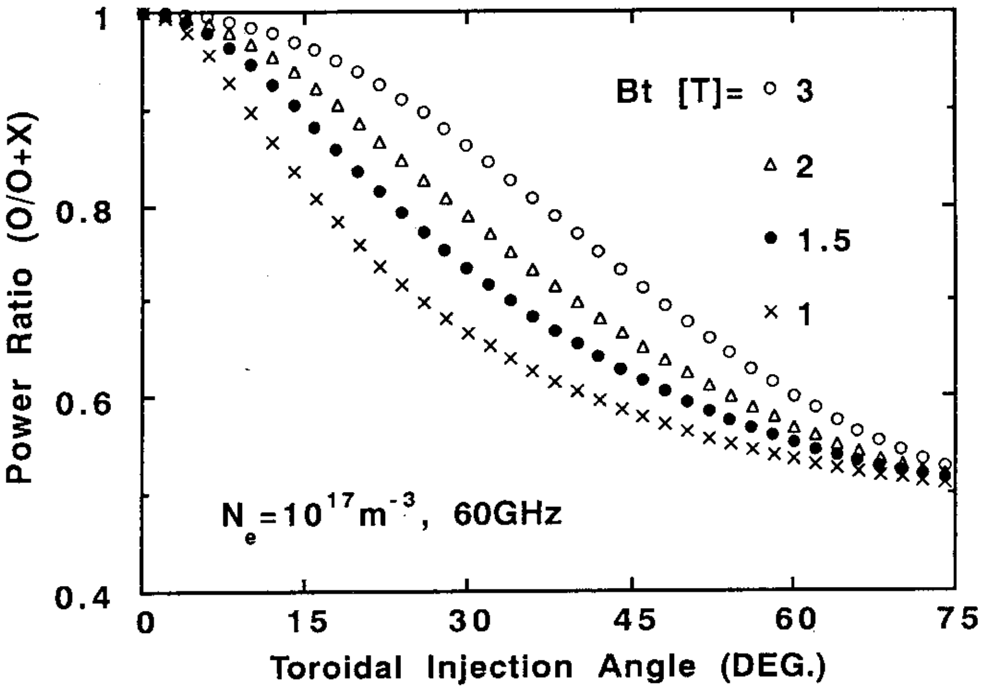
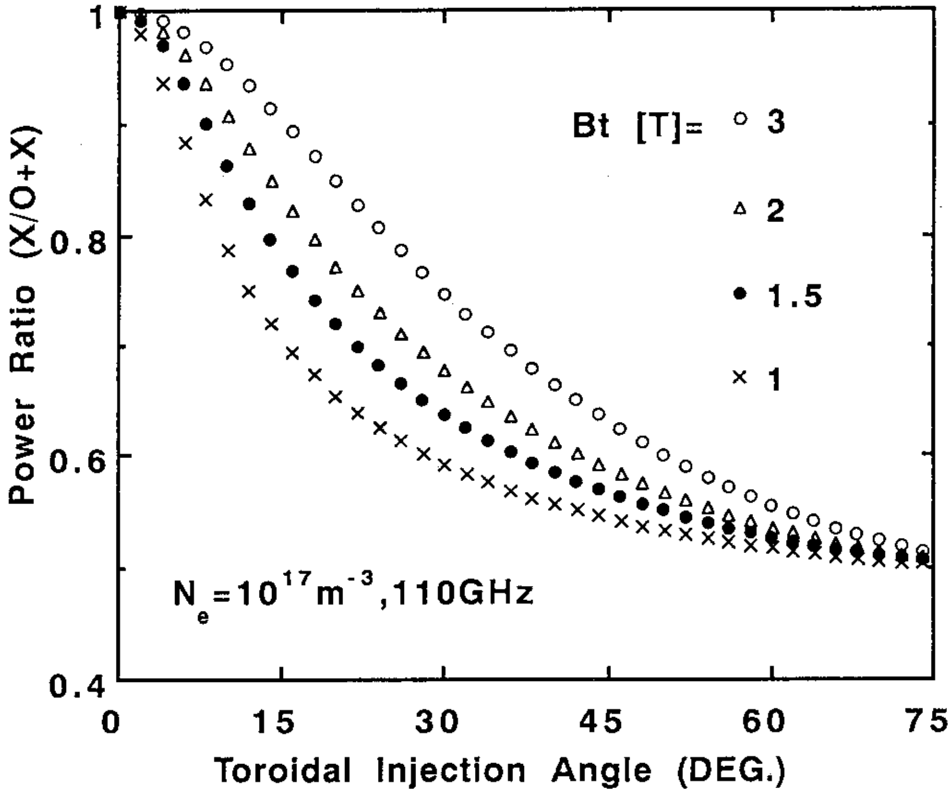


Fig. 3　The mode purity of second harmonic extraordinary mode versus the toroidal injection angle at various electron density by using the linearly polarized wave.



(a) Fundamental O-mode



(b) Second harmonic X-mode.

Fig. 4 Dependence of mode purity versus toroidal injection angle at the various magnetic fields.

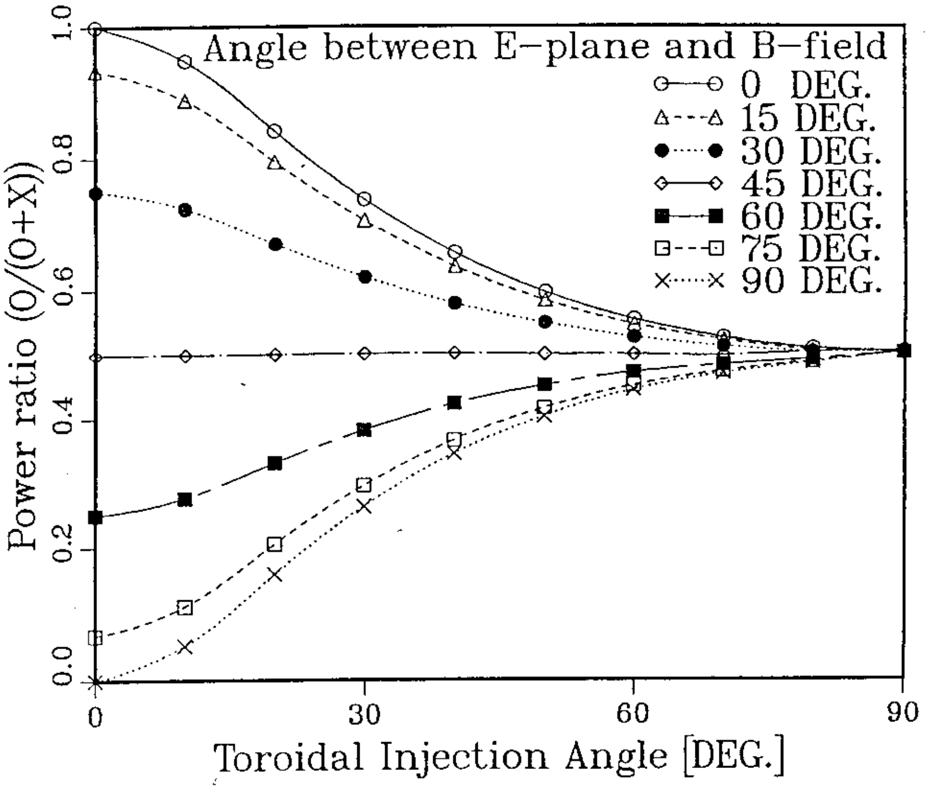


Fig. 5 Effect of the angle between linearly polarized plane and the direction of magnetic field on the power separation ratio.

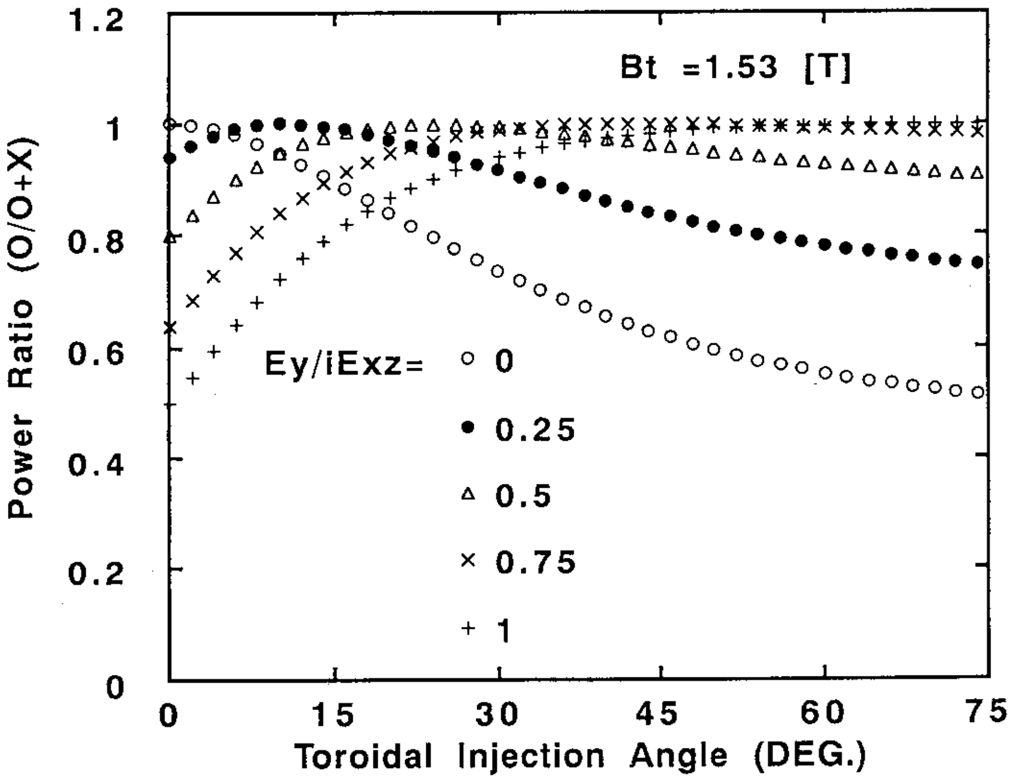


Fig. 6 Dependence of the mode purity on the toroidal injection angle at the various polarization ratio in the outside launched fundamental O-mode.

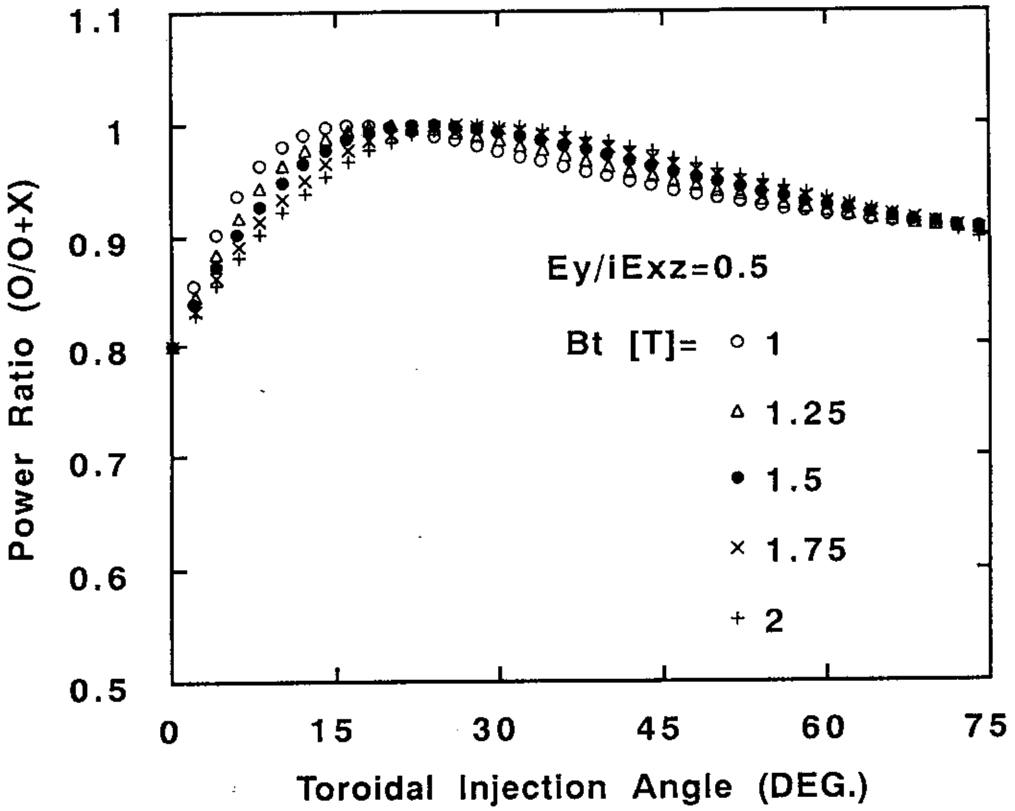


Fig. 7 Dependence of mode purity on the magnetic field at the optimized elliptical polarization for only ECCD ($Ey/iE_{xz} = 0.5$) in the outside launched fundamental O-mode.

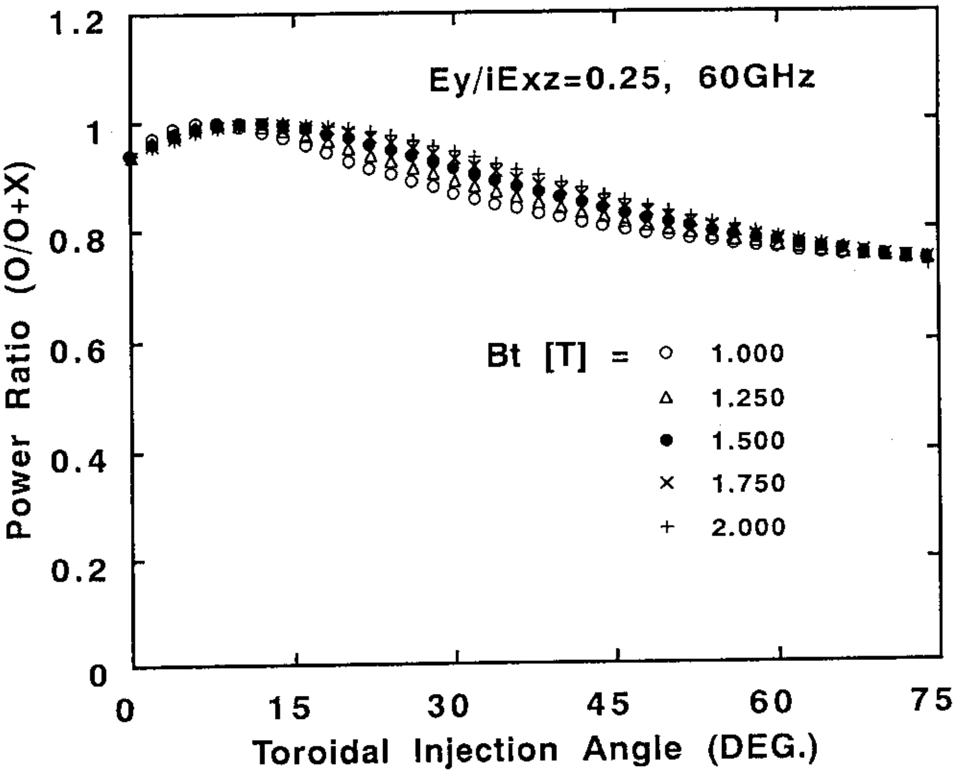


Fig. 8 Dependence of mode purity on the magnetic field at the optimized elliptical polarization for both of ECCD and ECH ($Ey/iE_{xz} = 0.25$) in the outside launched fundamental O-mode.

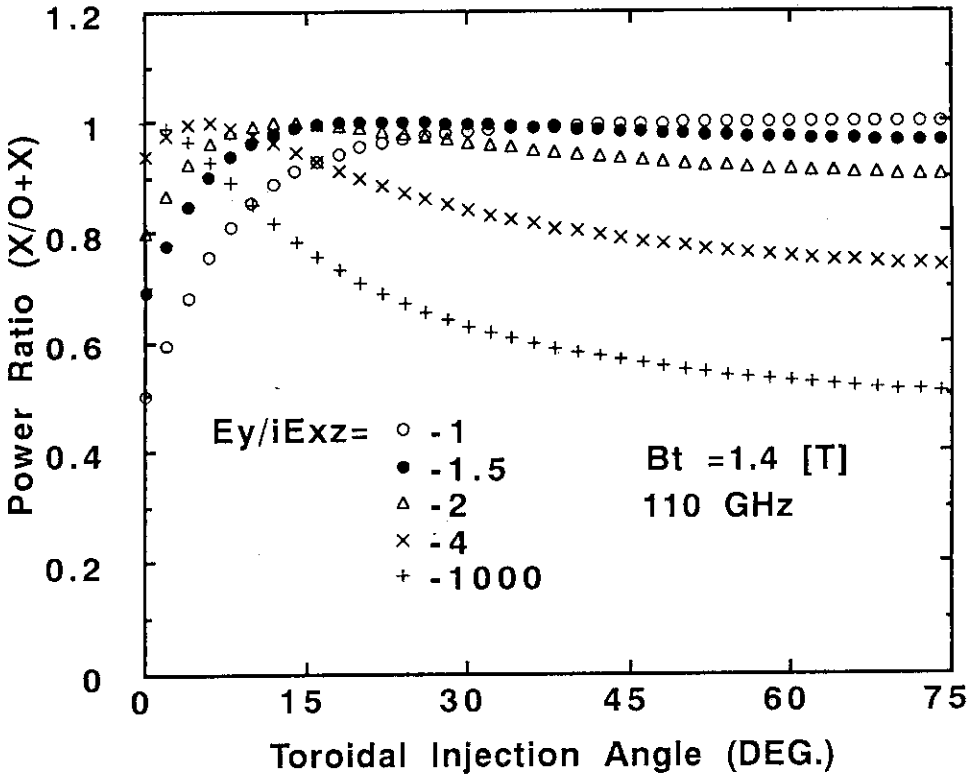


Fig. 9 Dependence of mode purity on the toroidal injection angle at the various polarization ratio in the outside launched second harmonic X-mode.

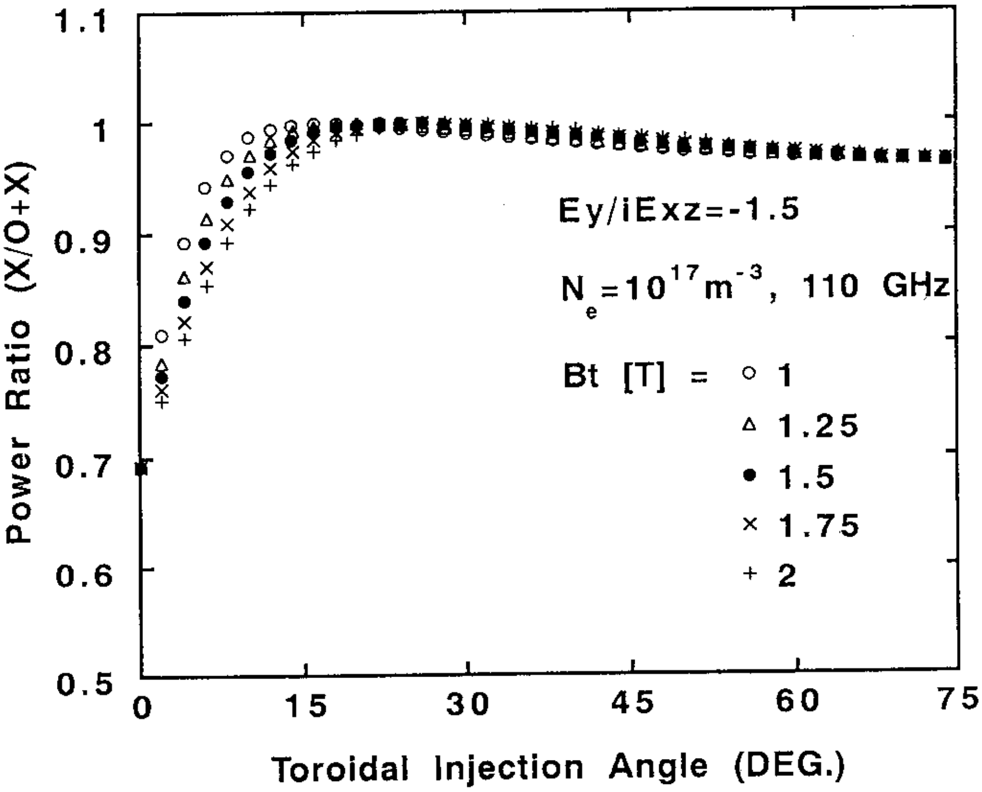


Fig. 10 Dependence of mode purity on the magnetic field at the optimized elliptical polarization for only ECCD ($Ey/iE_{xz}=-1.5$) in the outside launched second harmonic X-mode.

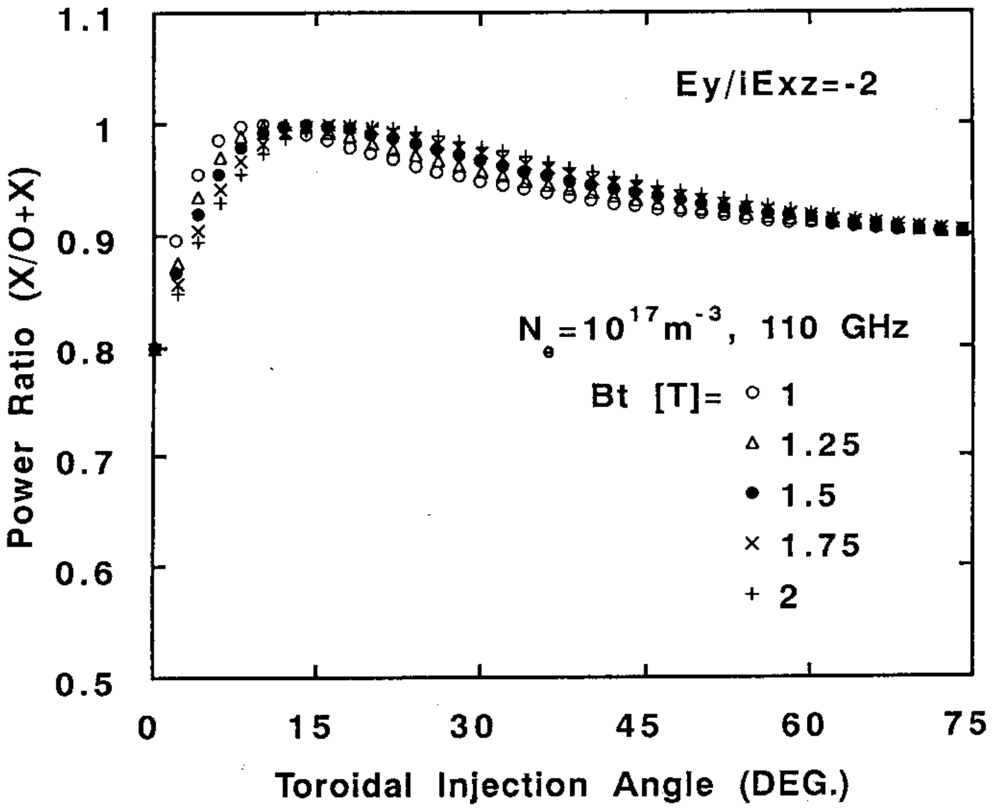


Fig. 11 Dependence of mode purity on the magnetic field at the optimized elliptical polarization for both of ECCD and ECH ($Ey/iE_{xz} = -2.0$) in the outside launched second harmonic X-mode.