Fundamental X-mode Electron Cyclotron Current Drive using Remote-Steering Symmetric Direction Antenna at Larger Steering Angles

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Outline

1. Introduction
   Remote Steering Antenna relevant to ITER Application
   New Hardware on ECH/ECCD after the 19th IAEA in TRIAM-1M

2. Symmetric Direction Remote Steering Antenna with Larger Steering Angles
   Output Beam Pattern ---- Gaussian Content ----
   Output Steering Angle [based on Intensity & Phase Measurements]
   Transmission Efficiency

3. ECH / ECCD Experiments on the TRIAM-1M tokamak
   Mode Purity Control Experiment
   O-mode Experiment
   X-mode Experiment

4. Summary

Remote Steering Antenna with Symmetric- and Asymmetric- Angles

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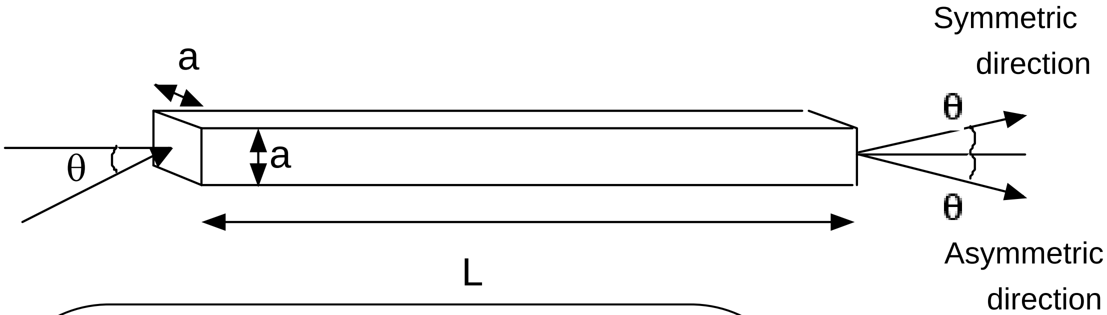
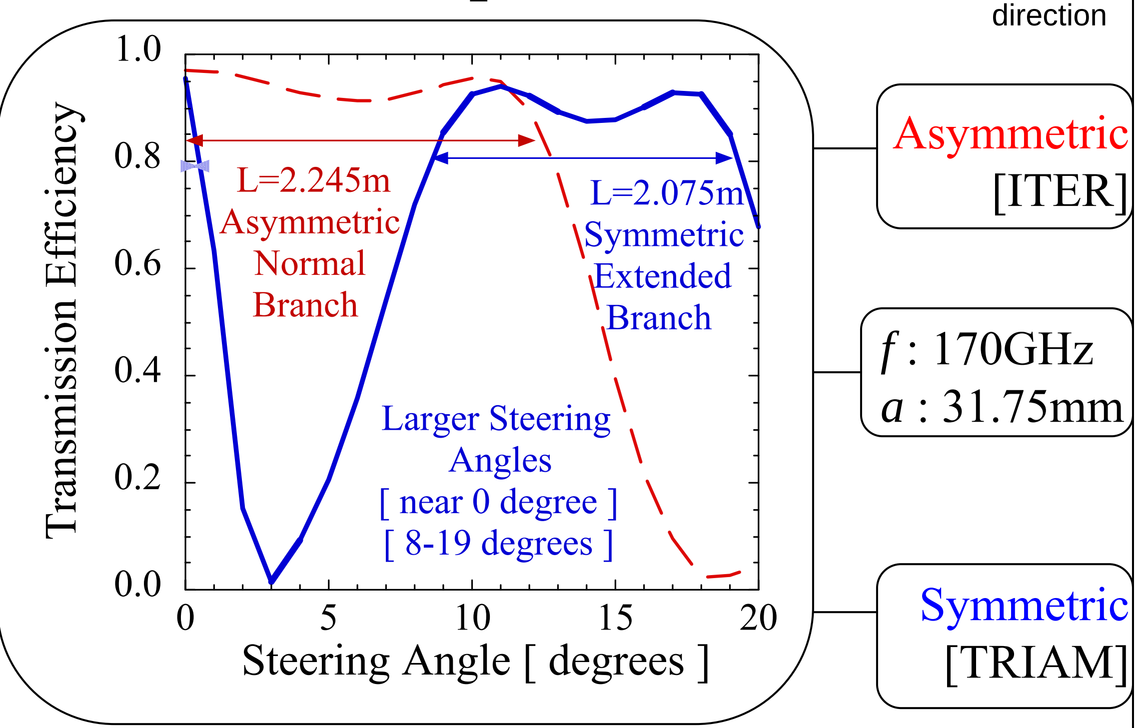
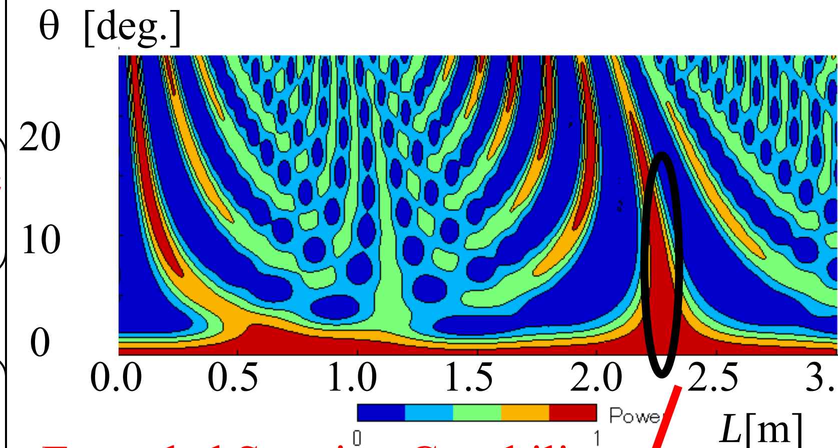


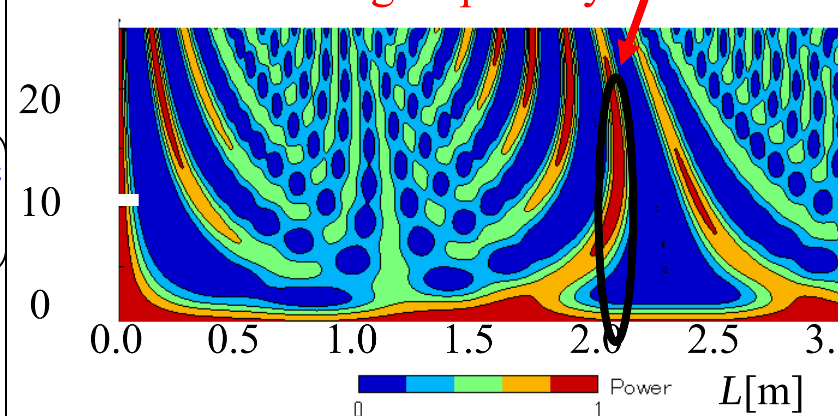


Dependence of Transmission Efficiency on θ and L

[imaging property in fundamental mode]



Extended Steering Capability



<u>$E_{\perp}$: perpendicular field to steering plane</u>

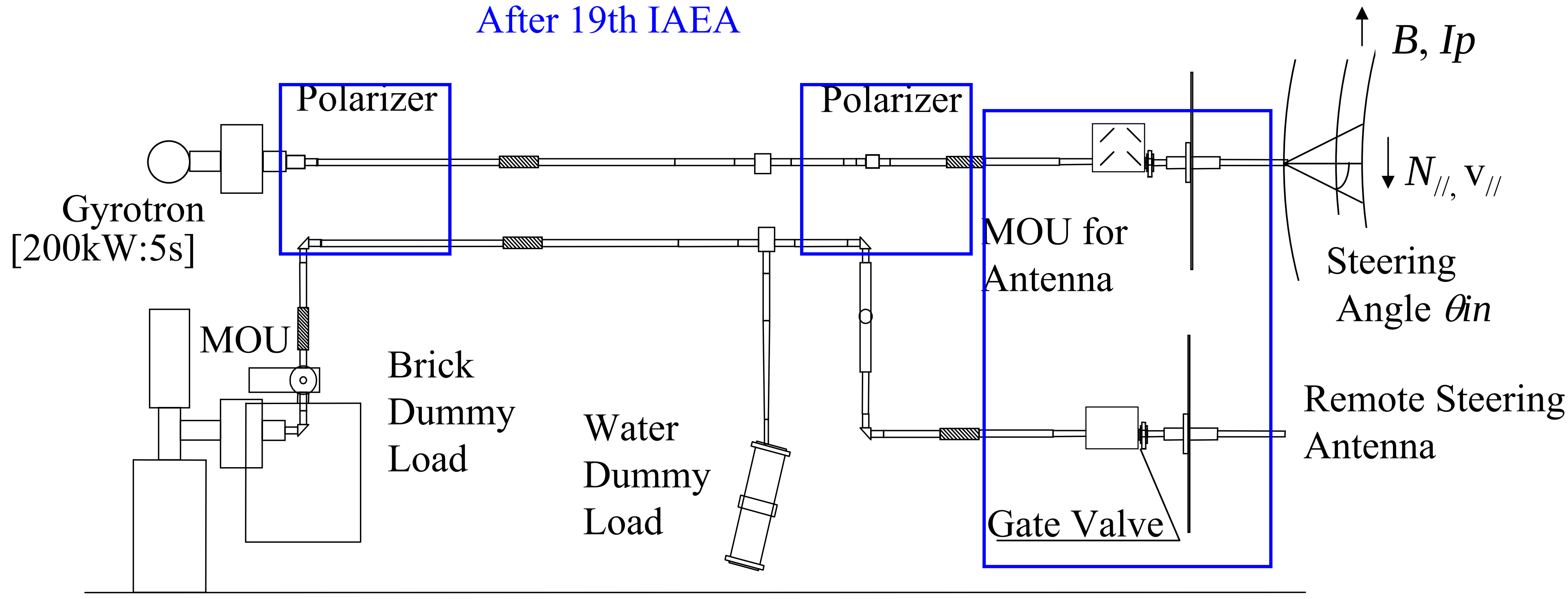
Transmission efficiency $= P_{out} / P_{in}$

ECH/ECCD System in TRIAM-1M tokamak

Operating Frequency : 170GHz : Magnetic Field ~ 6T.
Heating Scenario : Fundamental O/X-mode from Low Field side

ITER Condition

After 19th IAEA



Antenna System for the TRIAM-1M tokamak

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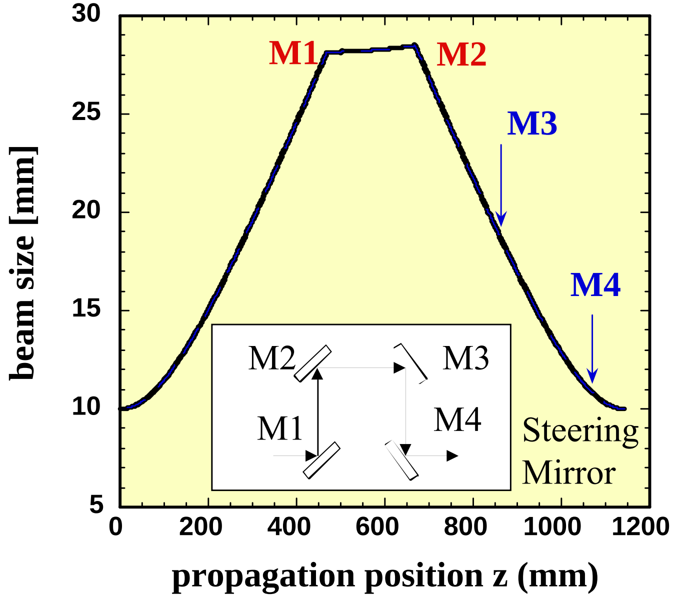
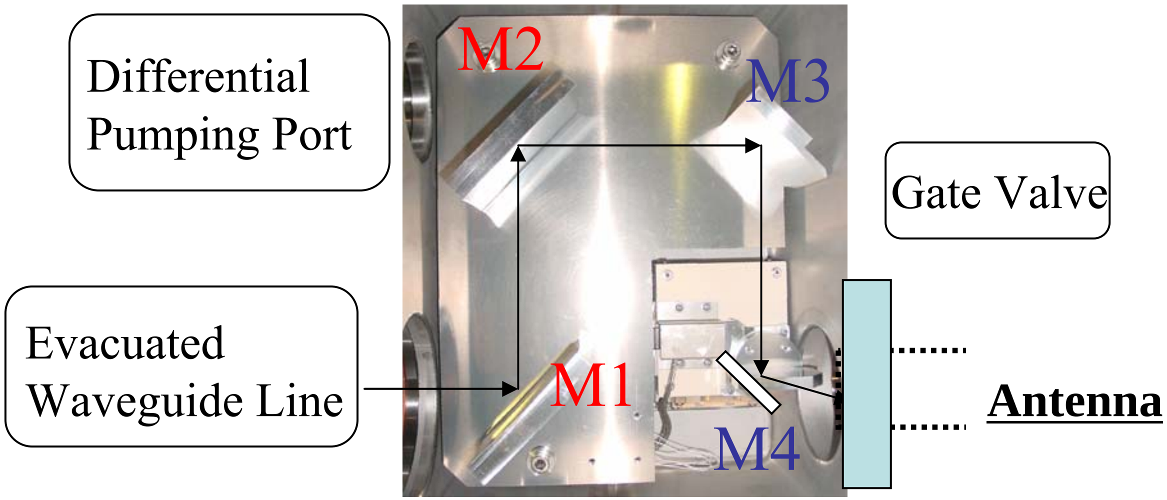
Matching Optics Unit for Antenna





Remote Steering Antenna

Square Corrugated Waveguide Antenna (Remote Steering Antenna)

Output Beam Analysis [Output pattern & Steering Angle]

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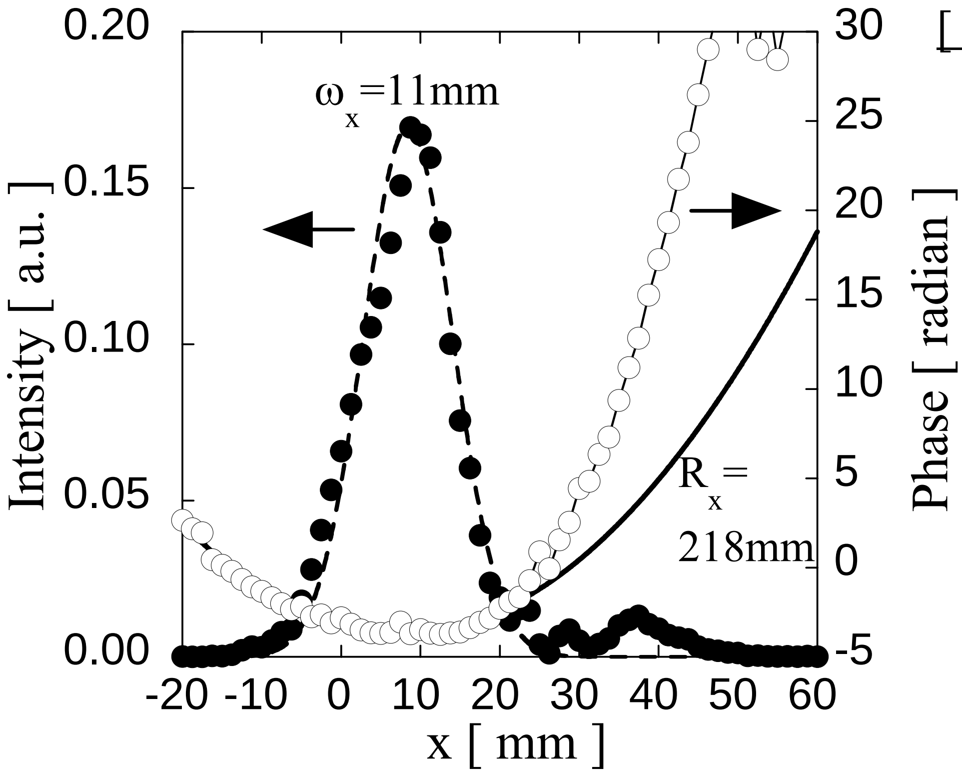
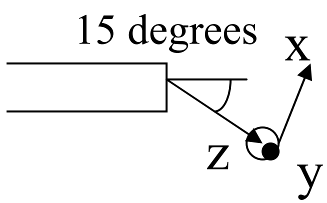


[*E*y Component: 15 degree steering case]



The phase profile is flat near the beam center. The beam propagates along the measuring z-axis.

The phase rapidly changes near the side lobe, therefore, the side lobe part is spread out from the main lobe along the propagation.

Output Beam is analyzed using Moment Method to evaluate the beam center offset and the steering angle, and using Matching Coefficient to evaluate Gaussian Content.

Analysis by Moment Method & Matching Coefficient

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The *n*-th moment in the *x* direction is defined with the amplitude distribution $A(x, y)$ as,

$$< x^n >= \int x^n A^2 \mathrm{d}x\mathrm{d}y \;/\; \int A^2 \mathrm{d}x\mathrm{d}y$$

The dependence of the beam center position on the propagating position z can be written as,

Beam Center

First moment $< x(z) >=< x(0) > -z \boxed{\dfrac{\int A^2(\partial\Phi/\partial x)\mathrm{d}x\mathrm{d}y}{k \int A^2 \mathrm{d}x\mathrm{d}y}}$ Propagating slope

$<x> = 8\mathrm{mm}$

Steering Accuracy :
-0.3 degree [in main lobe]

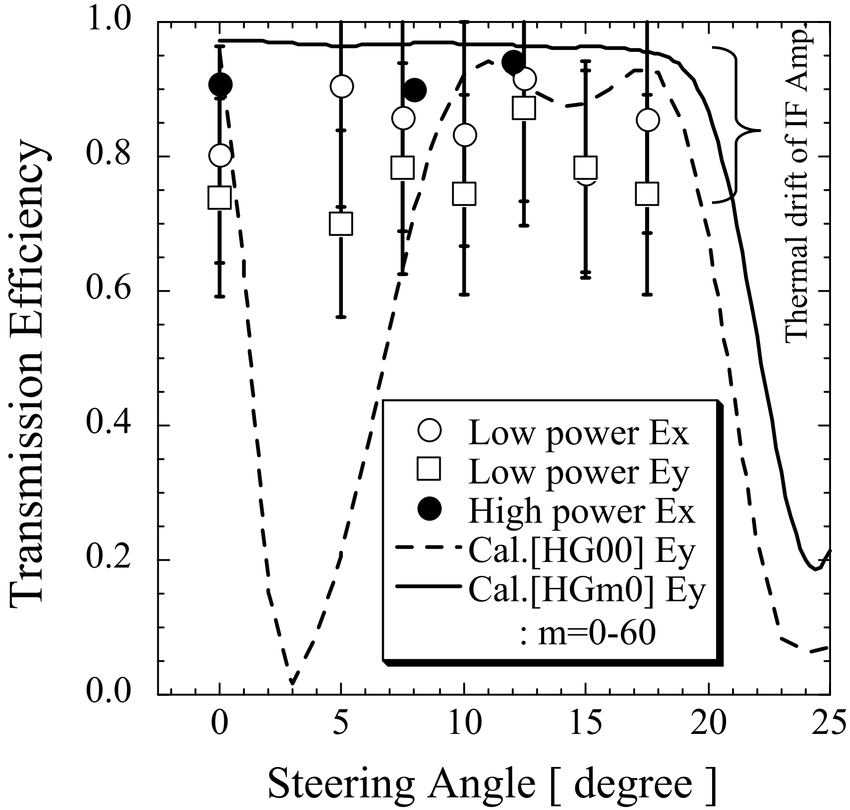
,where *k* and *Φ* are the wave number and the phase distribution.

$$\left|\int f g^* \mathrm{d}x\mathrm{d}y\right|^2 / \int |f|^2 \mathrm{d}x\mathrm{d}y / \int |g|^2 \mathrm{d}x\mathrm{d}y$$

f , g: Complex amplitude $Ae^{-\iota\Phi}$

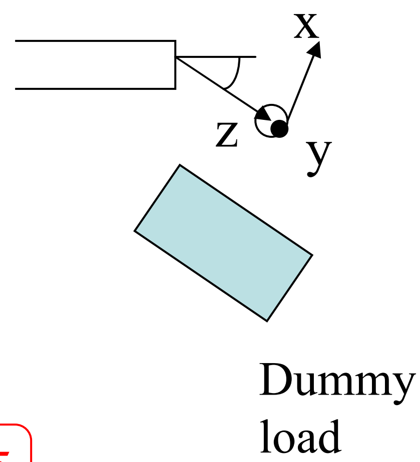
The complex amplitudes f , g are deduced from the intensity and phase distributions measured and calculated with the fitted w_x and R_x in Gaussian Optics.
The Gaussian content is evaluated as 0.85 for the output beam.

Transmission Efficiency



To evaluate the efficiency, the intensity patterns are integrated in the *x*-*y* plane at the low power test.

A dummy load is connected at the enterance and the end of the antenna at the high power test.



Trans. eff. : ~0.95

The efficiency in the imaging property calculation with the higher-order Hermite Gaussian modes [HG_{m0} modes (m=1-60)] is consistent with those in the measurement.

ECH / ECCD Experiments using Remote Steering Antenna on the TRIAM-1M tokamak

1. Mode Purity Control Experiment

----- *to optimize and confirm the incident polarization state*----

2. O-mode Experiment

3. X-mode Experiment

Mode Purity Control Experiment in Superposition to LHCD Plasma

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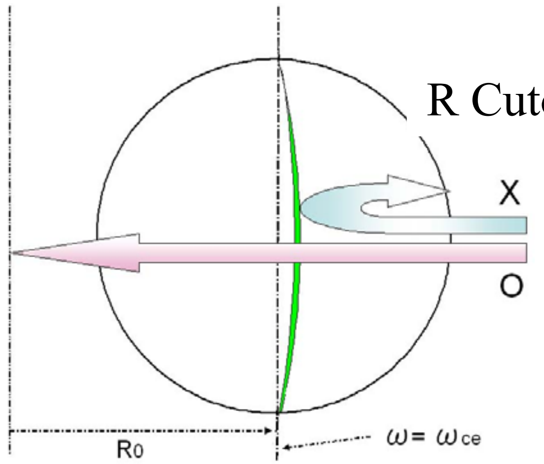
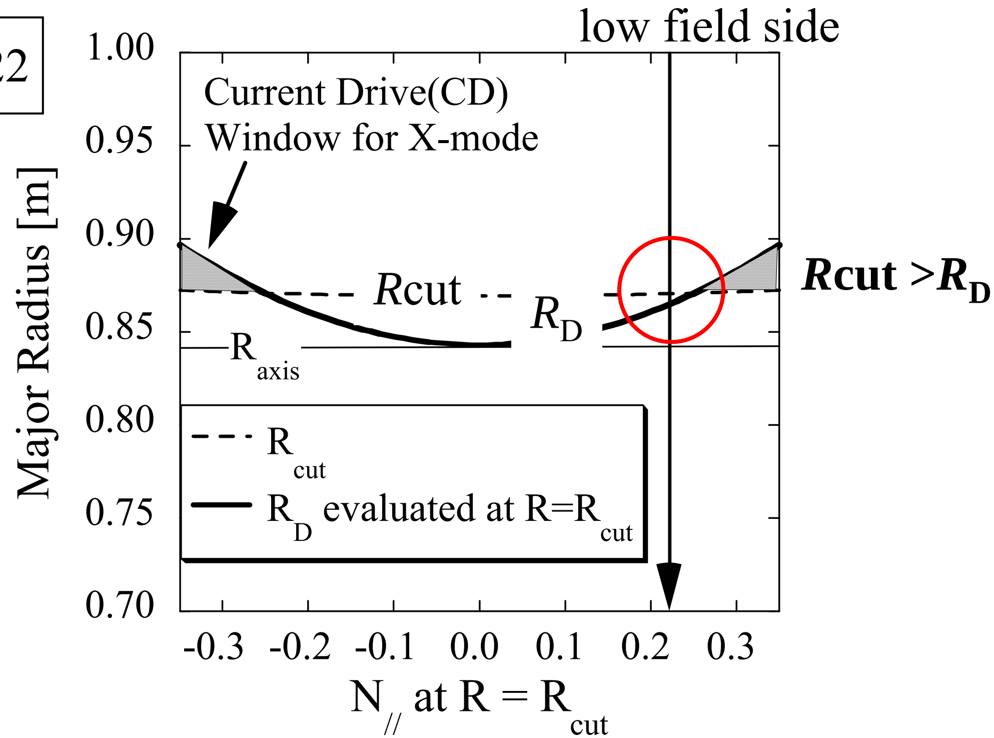
$n_e = 0.8 \times 10^{19}$ m^{-3}
in the target LHCD plasma

$N_{//}$~0.22





No coupling area for incident X-mode component

It is noted that it is ideal to confirm to the O-mode coupling for the incident beam.

- The R cutoff radius R_{cut} is 0.870m.
- The plasma center and the bulk resonance radii Raxis and Rres are 0.84m.
- The maximum resonance radius due to the Doppler shift effect R_D is 0.865m.

Mode Purity Control Experiment

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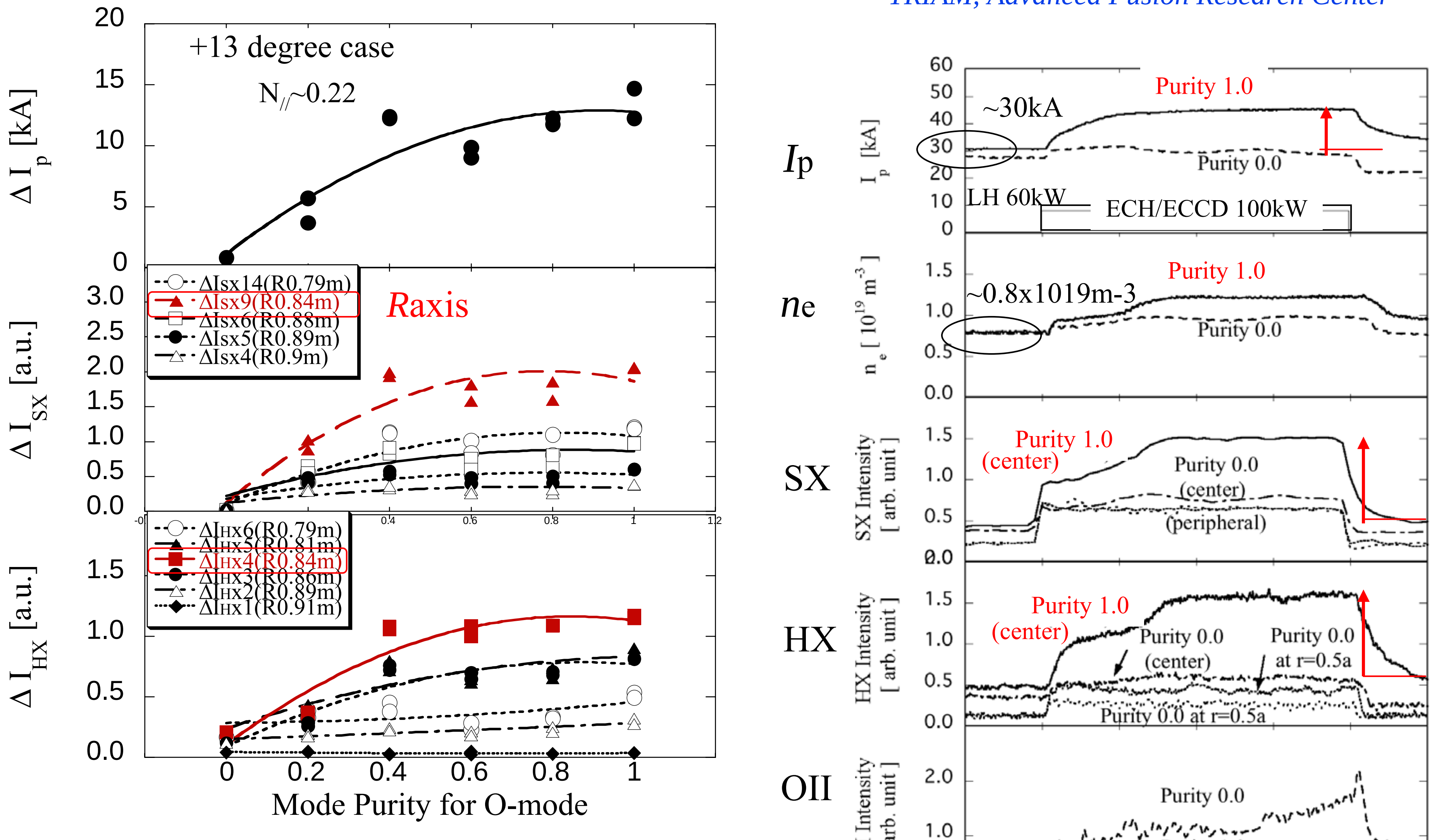

The increase of the current comes from a coupling of Electron Cyclotron Wave to the LHCD plasma.

Steering Angle Scan in the O-mode Experiment

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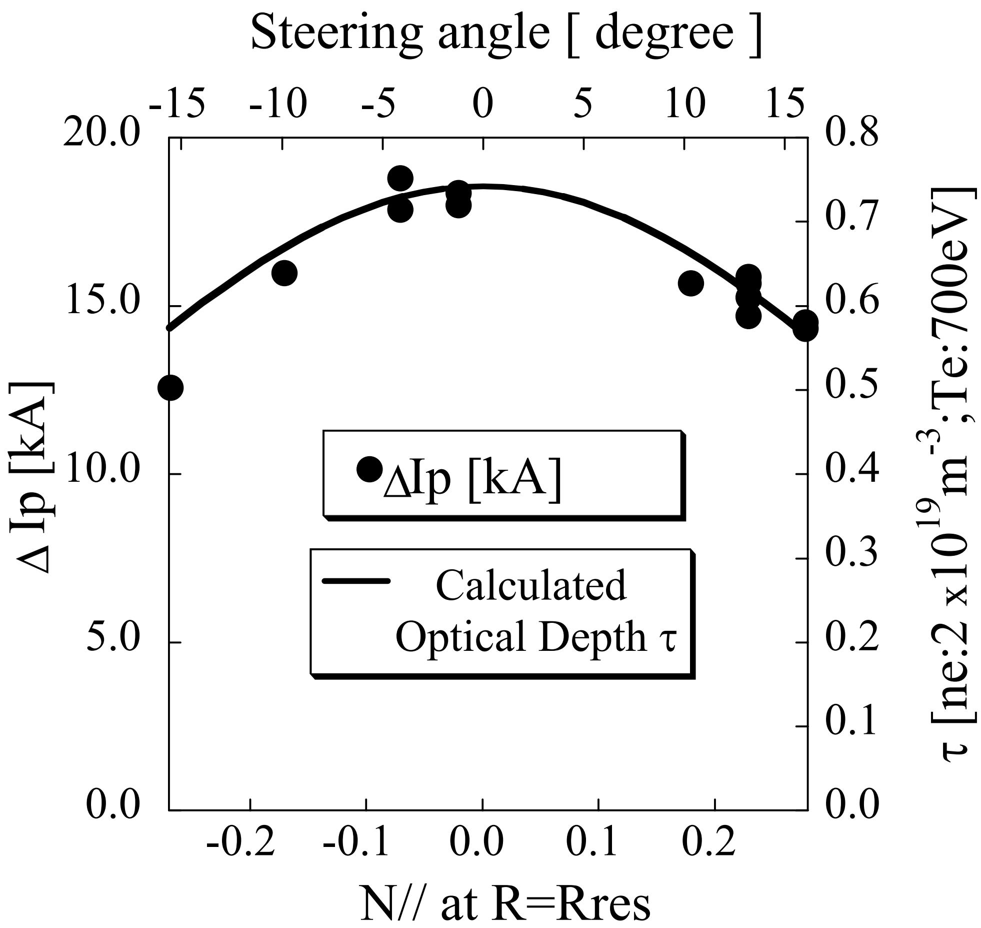


The increased current ΔI_p in the perpendicular injection is 18.3 kA.

The current drive efficiency

$\eta_{ECH\text{-}LH} = n_e I_p R/(P_{ECH\text{-}} P_{LH})$

in the superposition is evaluated as

0.325×10^{19} A/Wm^2.

That is comparable to

η_{LH} of 0.378×10^{19} A/Wm^2

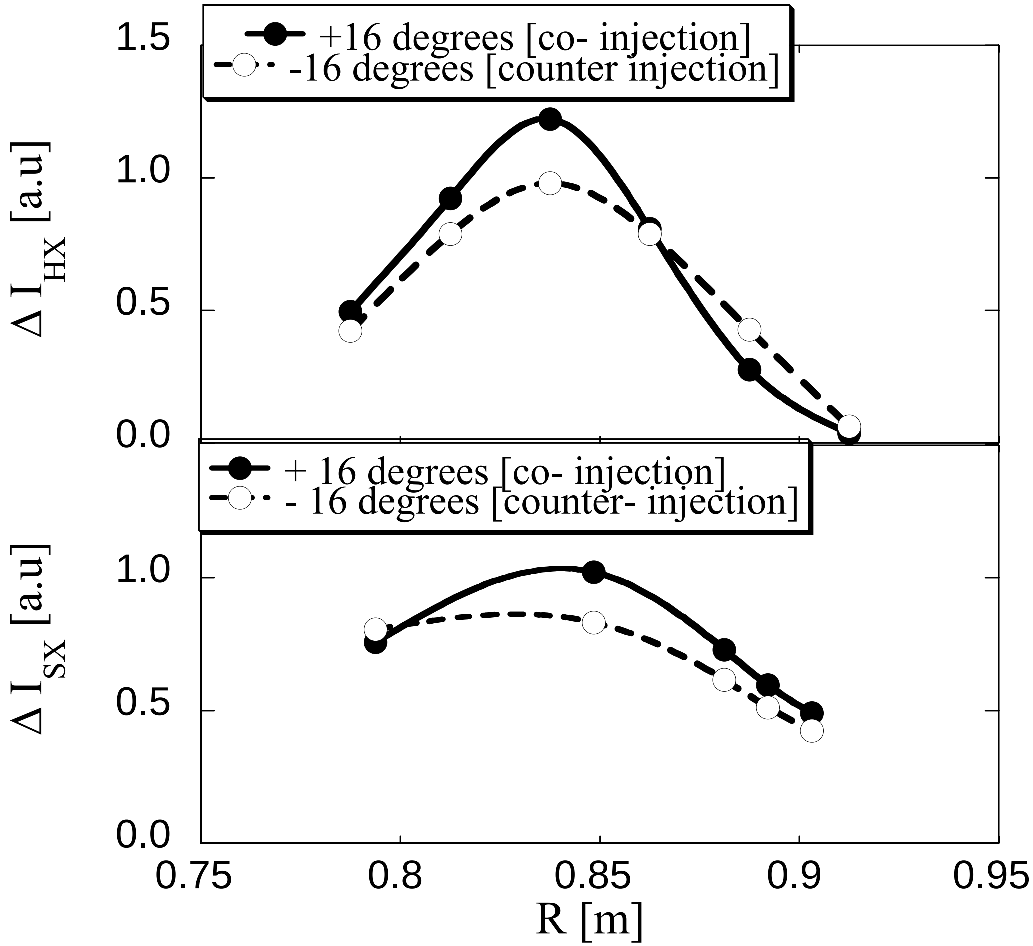
in the target LHCD plasma.

The heating effect in an improvement of the LHCD efficiency is dominant.

Peaked ΔI_{HX} Profile in the Co- Steering Case at the O-mode Injection

In the co- (+16 degrees) and counter- (-16 degrees) steering cases, the forward ($v_{//}>0$) and backward ($v_{//}<0$) fast electrons can be coupled with the incident wave between R_D and *R*res before the beam is absorbed by the bulk electrons.

The peaked ΔI_{HX} profile in the co- steering case suggests a direct coupling into the forward fast electrons at between $R = R_D$ and $R = R_{res}$.



X-mode Experiment in the Doppler-shifted ECCD in LHCD plasma

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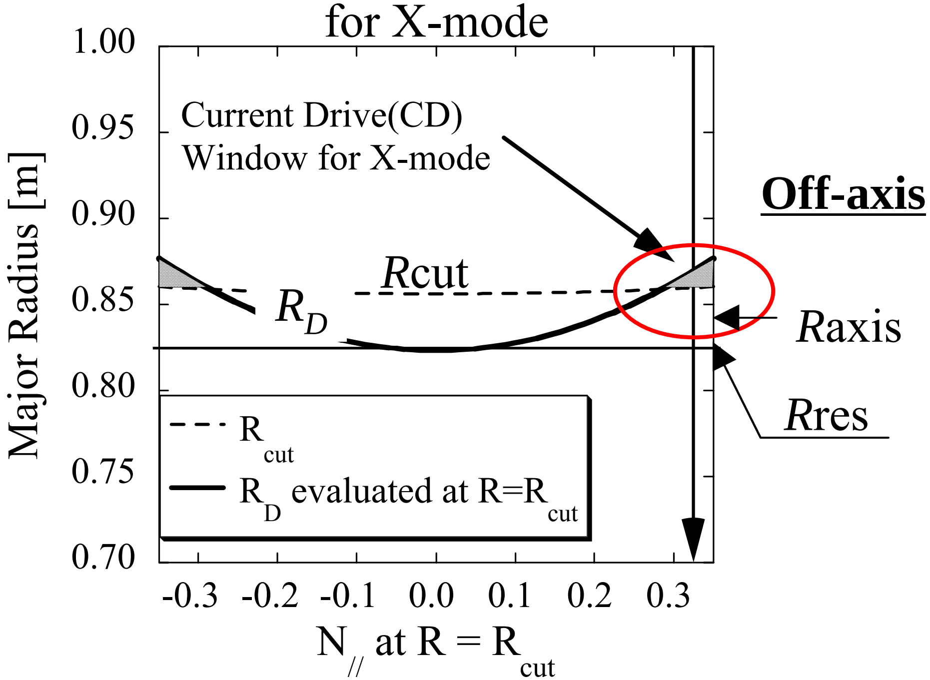
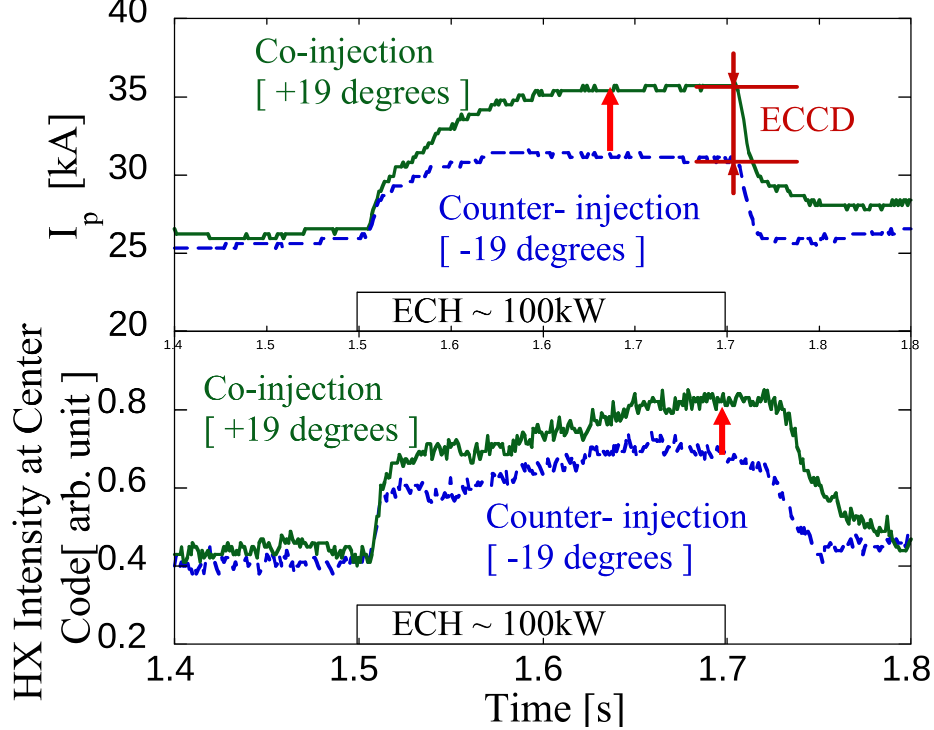
Doppler Up-shifted ECCD for X-mode



At same n_e=0.95 x 10^{19} m^{-3}



- **The parallel refractive index <u>$N_{//}$ is 0.32</u>**
- The Doppler resonance <u>R_D is 0.868m</u>.
- The R cutoff position <u>Rcut is 0.860m</u>.
- **There is a Current Drive (CD) window between R_D and R_{cut}, where the X mode can be absorbed.**

There are clear differences in the both steering cases in the increased current and the HXR intensity.

ECCD in X-mode Coupling to Fast Electrons in LHCD plasma

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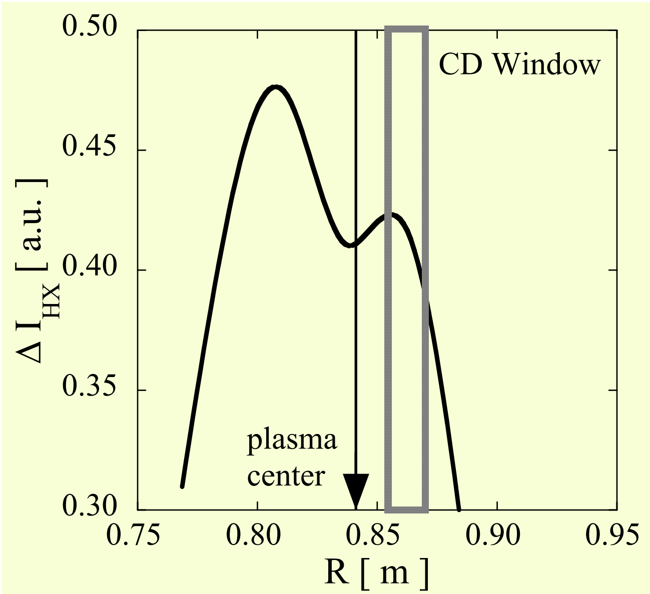
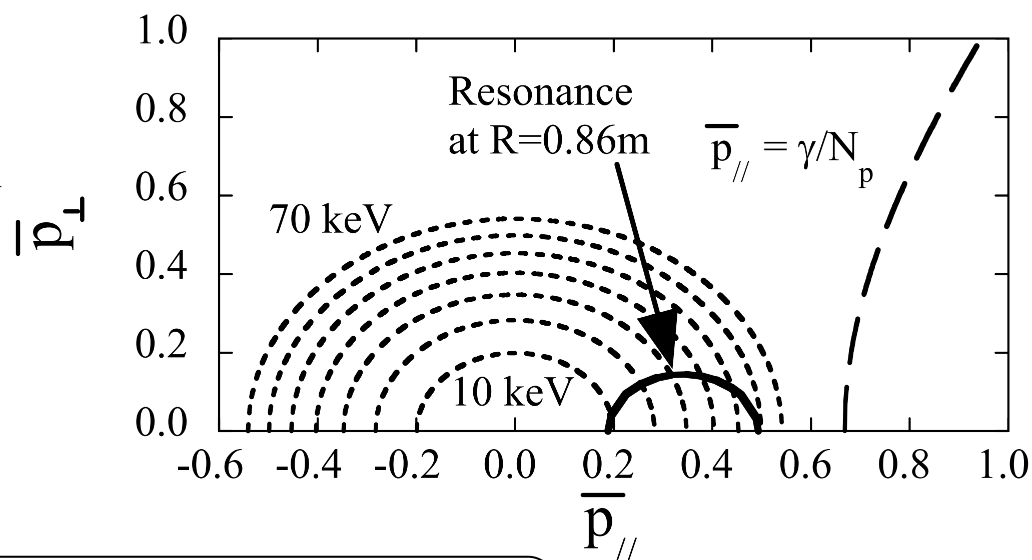


The hollow ΔI_{HX} profile is observed with a peak at the CD window. It indicates the incident X-mode wave is coupled around R=0.86m.

The possible energy range to be resonant with the incident X-mode at R=0.86m is evaluated as 10-60keV.
The resonant energy range for the EC wave is consistent with that of the forward fast electrons by the LH wave.



ΔI_p is due to the ECCD effect on a coupling for the forward fast electrons in the LHCD plasma.

Summary (I)

_The symmetric direction remote steering antenna with larger steering angle has been developed for the ECH/ECCD experiments on the TRIAM-1M tokamak.

_The steering angles of 8-19 degrees are available, in addition to that near 0 degree.

_The output beam from the antenna is the well-defined Gaussian beam with a correct steering angle.

_The Gaussian content and the steering angle accuracy are 0.85 and –0.3 degrees.

_The transmission efficiency is evaluated as 0.95 in the high power test.

_In the O-mode experiments, the dependence of the increased current on the steering angle is observed. However, the heating effect in an improvement of the LHCD efficiency, compared to the ECCD effect, is dominant.

Summary (II)

_In the X-mode experiment, there are clear differences in ΔI_p and ΔI_{HX} in the larger co- and counter- steering cases due to the ECCD effect on the coupling for the forward fast electrons in the energy range of 10-60keV at the medium density ($1 \times 10^{19} m^{-3}$).

_The hollow profile of the HXR intensity increased by ECH/ECCD is observed at the CD window.

_The resonant energy range is consistent with that of fast electron generated by the LH wave.

_The CD efficiency is roughly evaluated from the difference of the increased current (~ 5kA) between the co- and counter- steering cases as ten times smaller than that in LHCD.

The energy range of fast electrons coupled with EC wave is equivalent to that of resonant electrons for ECCD in high electron temperature plasmas at ITER.

This is a first application of the remote steering antenna to the ECH/ECCD experiment.