Development of Electron Cyclotron / Bernstein Wave Heating and Current Drive System and its Application to the QUEST Experiments

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Outline

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- **Antenna System Development**
  - **- Conceptual Design -**
  - **- Prototype Antenna – [ISTW 2007]**
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  - **- [4 x 4] CW Antenna –**
- **Ray Tracing Analysis [*OXB* scenario]**
  - **- Non-optimum Case -**
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- **Non-inductive Plasma Current Startup and Sustainment**
- **Future Plan (High Density Operation with High Power RF)**
- **(Preliminary) High Power Antenna Test**

O-X-B Ray tracing [Optimum Case]

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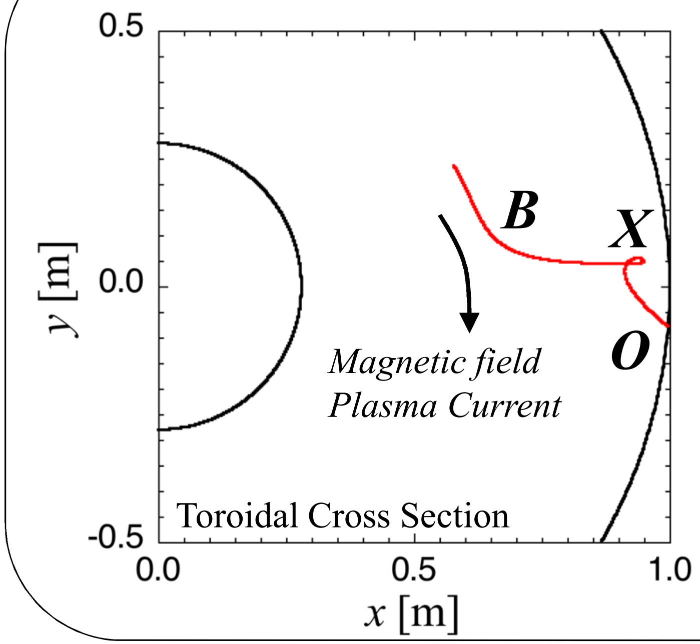
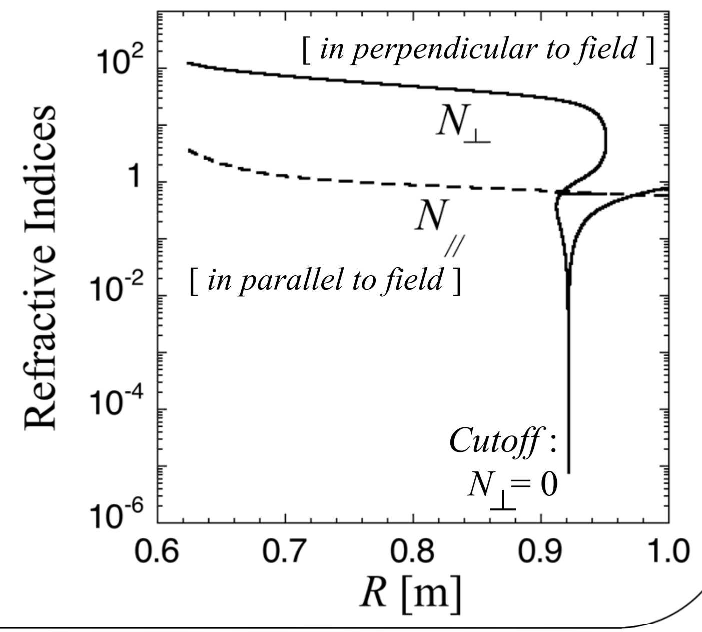
Electromagnetic waves
[O/X mode]

Electrostatic wave
[B mode]

n_{e0} = 2 x 10^{18} m^{-3}, T_{e0} =100eV, total current : 20kA





Conceptual Design [Phased-array Antenna System]

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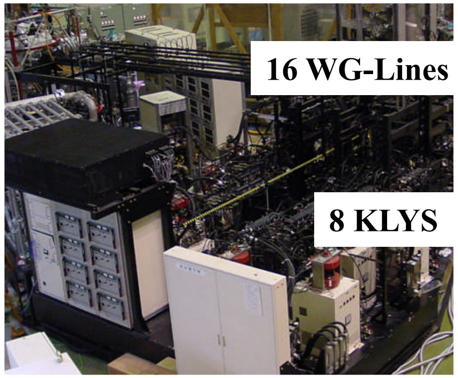
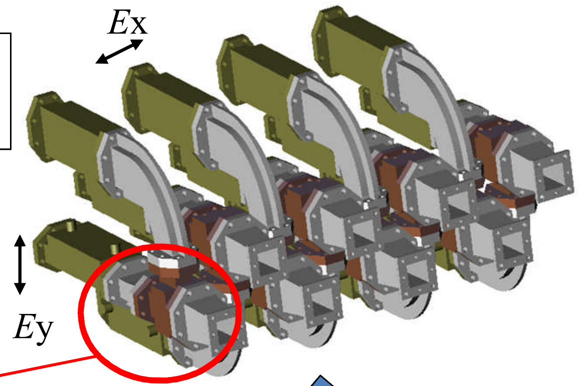
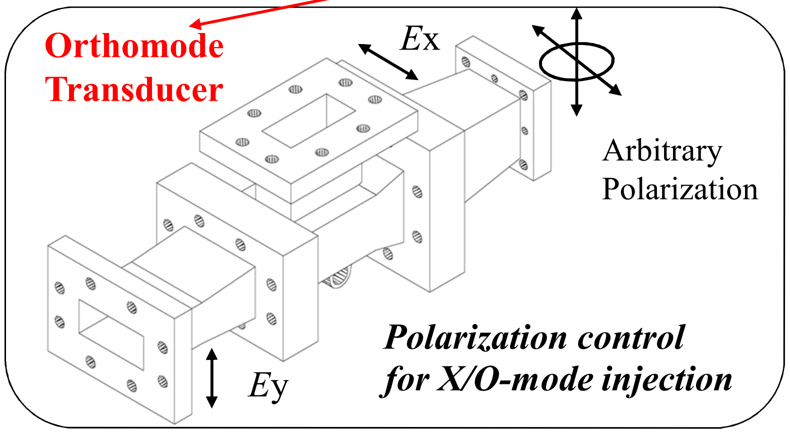
8.2GHz

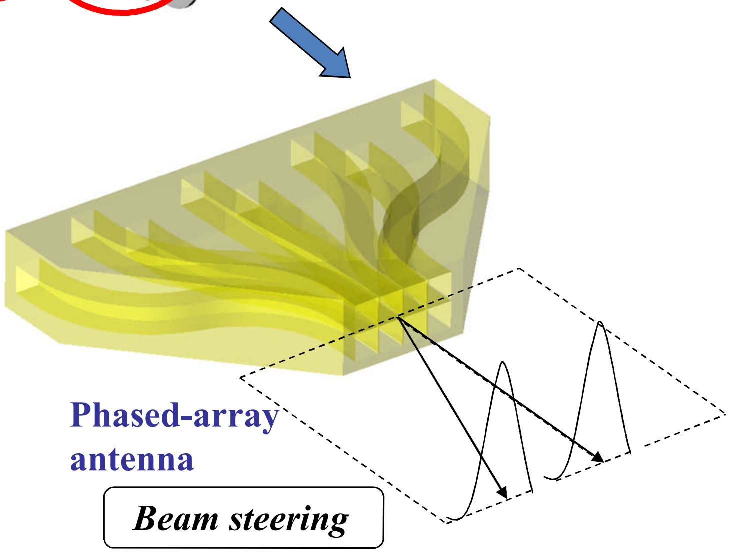


25kW x 8
= 200kW

16-WR137
inputs







Radiation Field Profiles from Prototype Antenna

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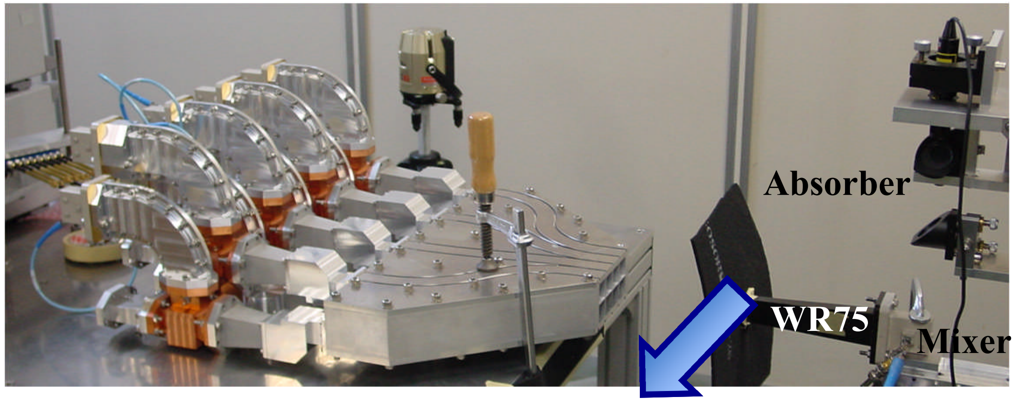

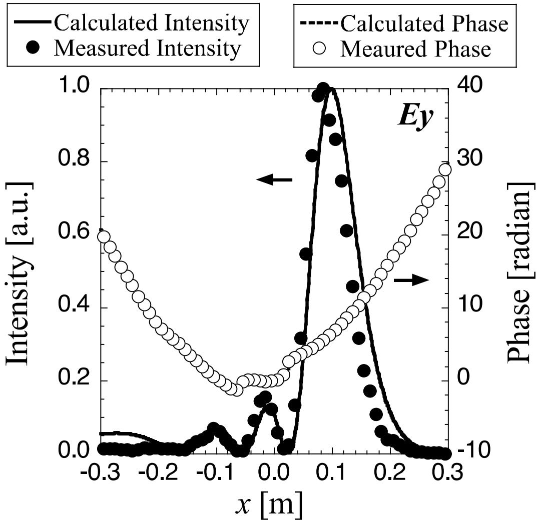

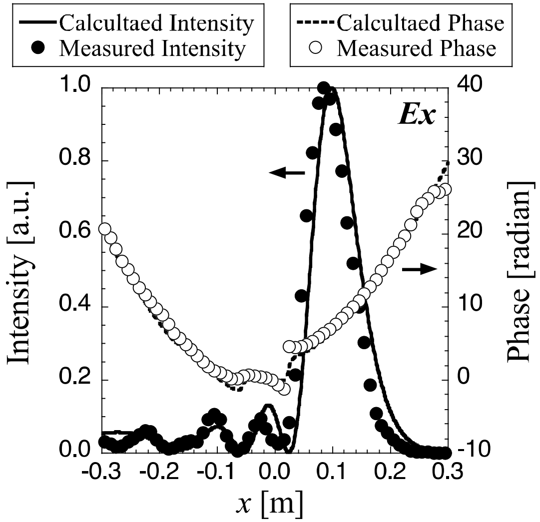

CW [4x2] Antenna Development

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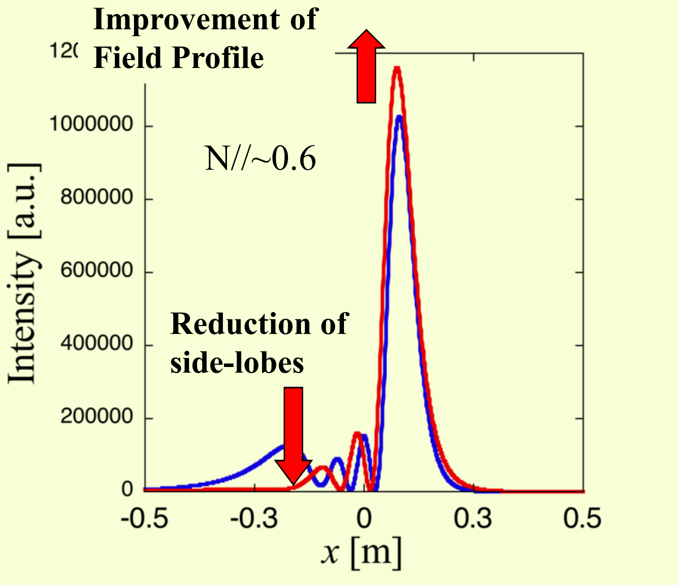
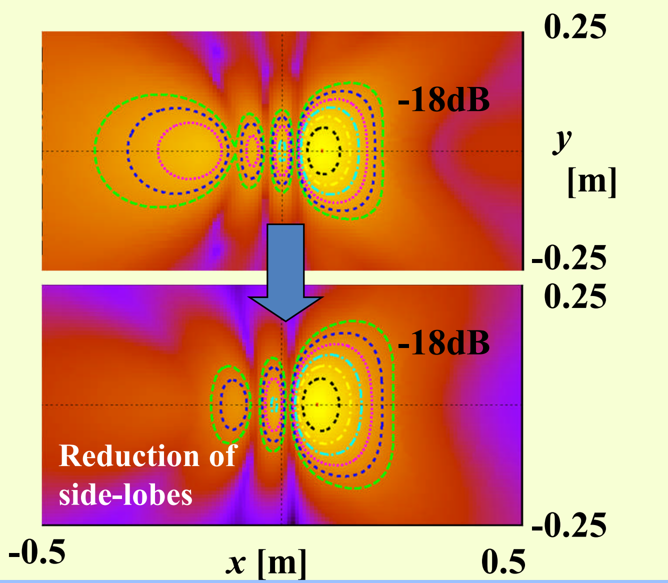
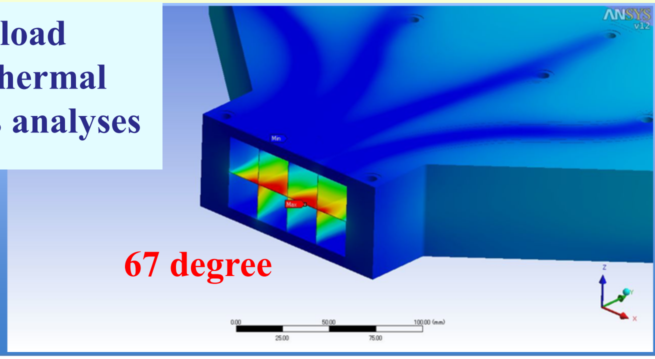




Heat load and thermal stress analyses



The heat load and thermal stress in CW 200 kW operation were analyzed with finite element codes.

The max. temperature was 67 degree C, and the thermal stress was analyzed to be moderate.

Radiation Field from CW [4x2] Antenna

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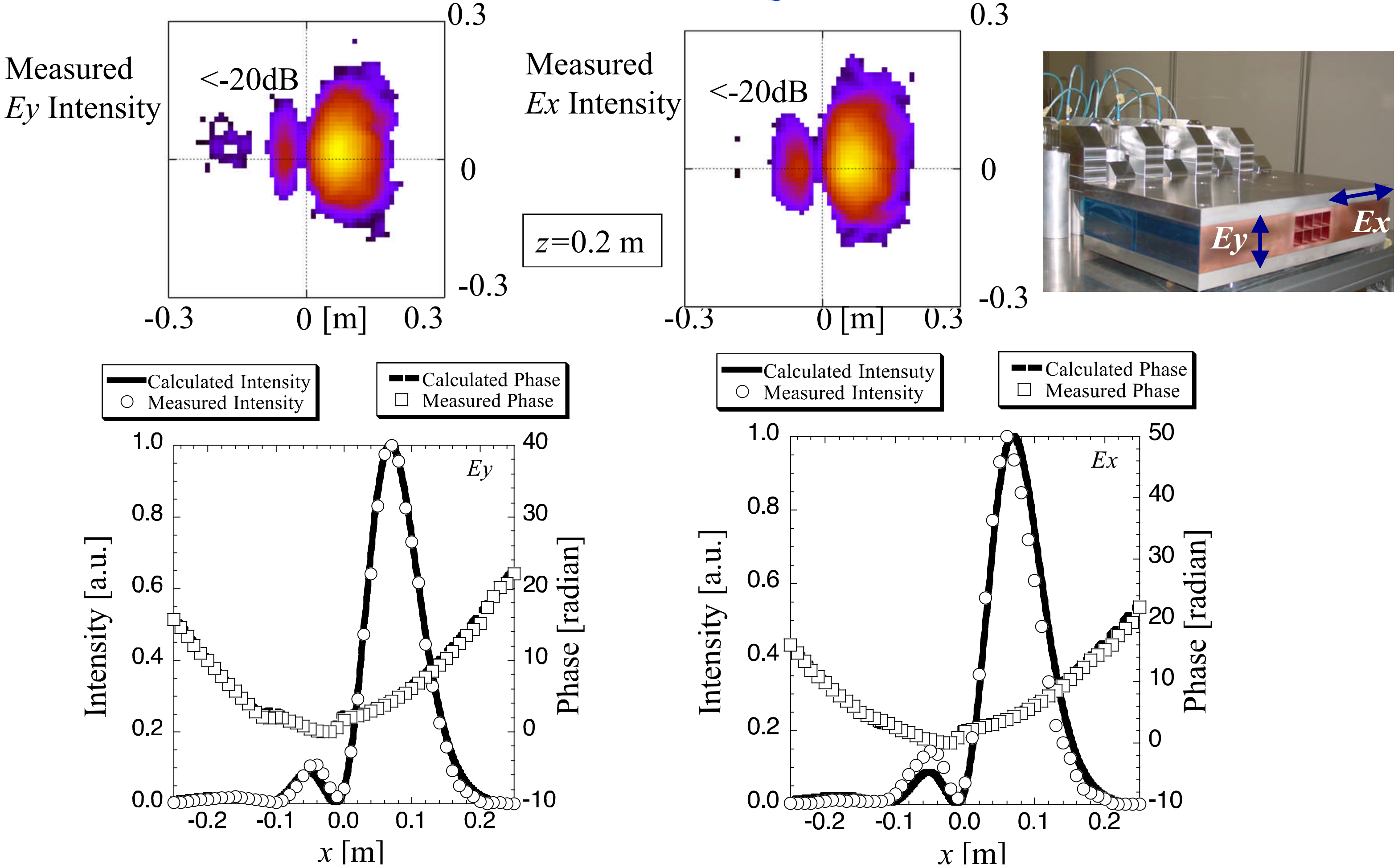
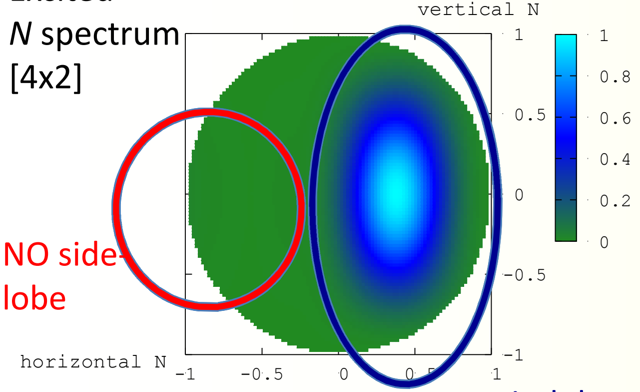


CW [4x4] Antenna Development

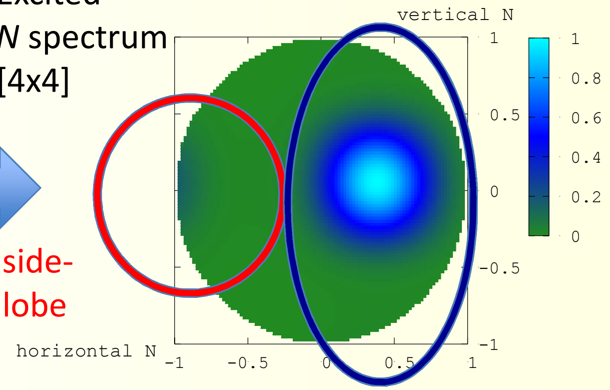
Excited
N spectrum
[4x2]



NO side-
lobe

main-lobe

Excited
N spectrum
[4x4]

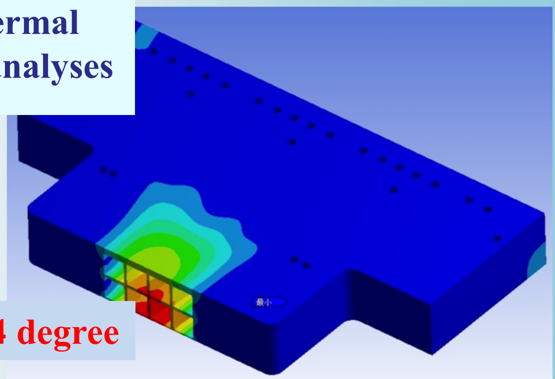


side-
lobe

main-lobe

High Mode
Conversion
to B-mode

Heat load and thermal stress analyses

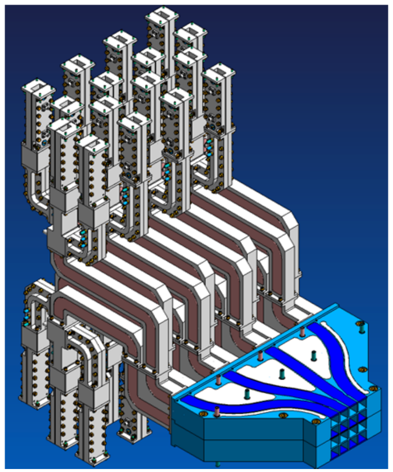


94 degree

half piece of [4x4] antenna

Directional
Coupler

OMT

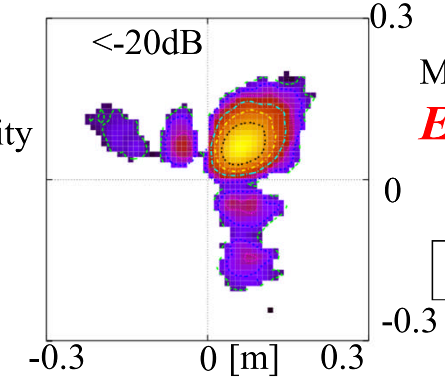


Conceptual Design of [4x4] Antenna

[4x4]
antenna

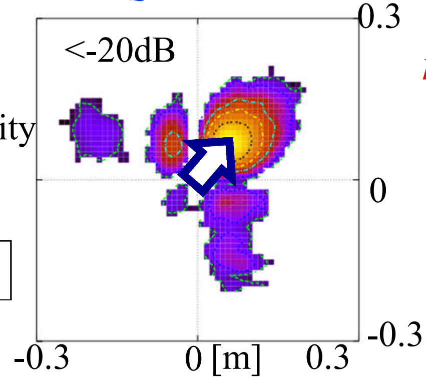
Radiation Field from CW [4x4] Antenna

Measured
Ey Intensity

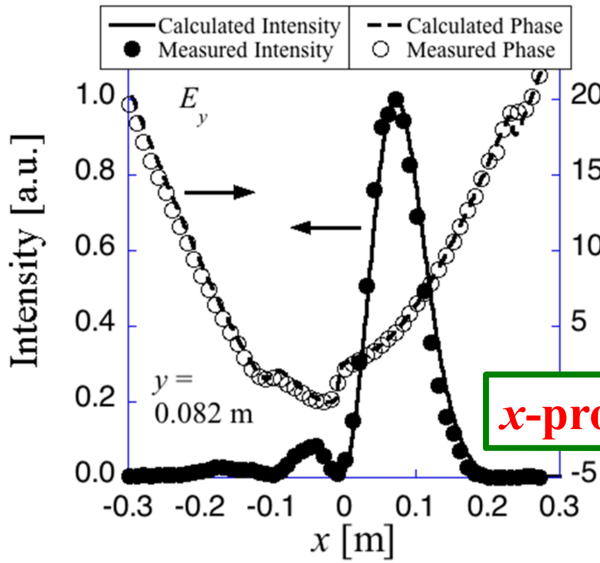


Measured
Ex Intensity

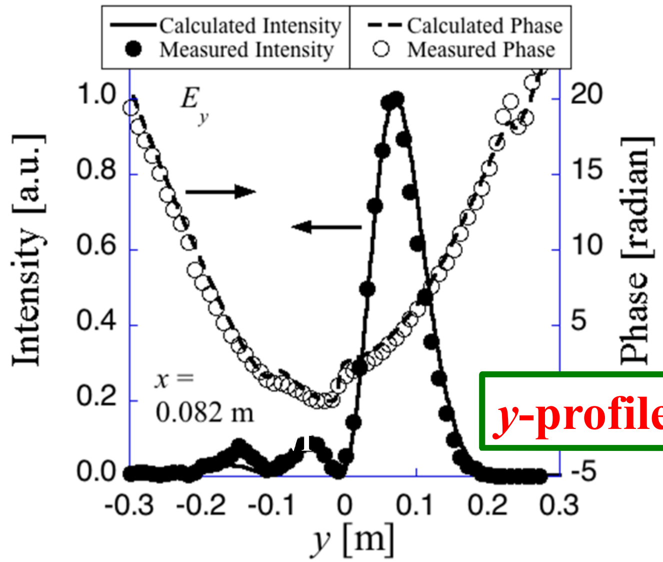
z=0.2 m



new [4x4] antenna



***x*-profile**



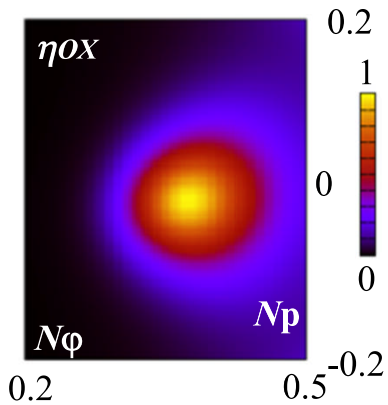
***y*-profile**

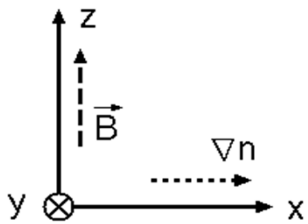
Multiple Ray Tracing Analysis including non-optimum cases

[with E. Kalinnikova]

-

O-X-B Mode Conversion in non-optimum case



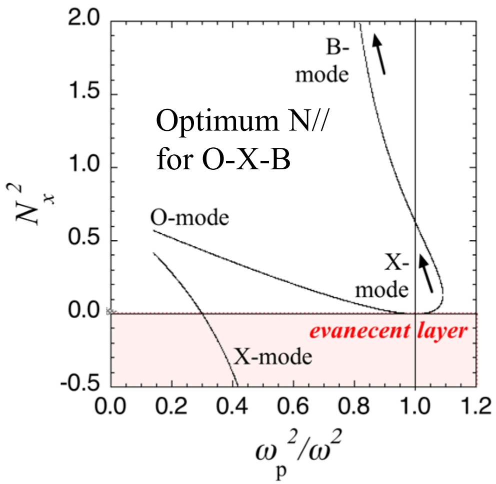


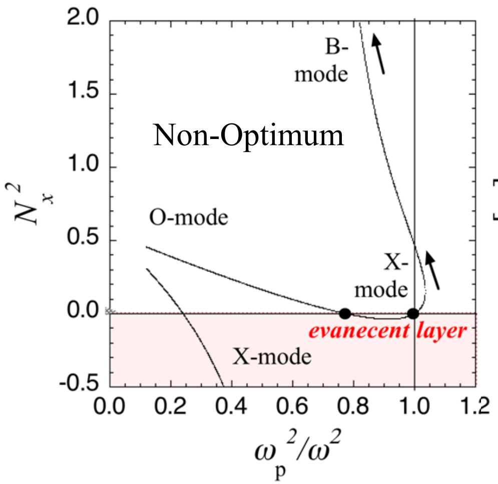
ω : wave angular frequency
Ω : electron cyclotron angular frequency
n_e : electron density at the plasma cutoff

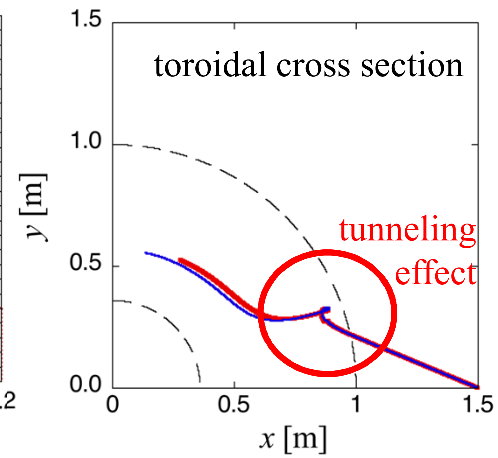
$Y = (\Omega/w)$,
$N_{zopt} = \{Y/(1+Y)\}^{1/2}$
$L_n = n_e/(dn_e/dx)$

$$\eta_{OX} = \exp\{-\pi k_0 L_n (Y/2)^{1/2} [2(1+Y)(N_z - N_{zopt})^2 + N_y^2]\}$$

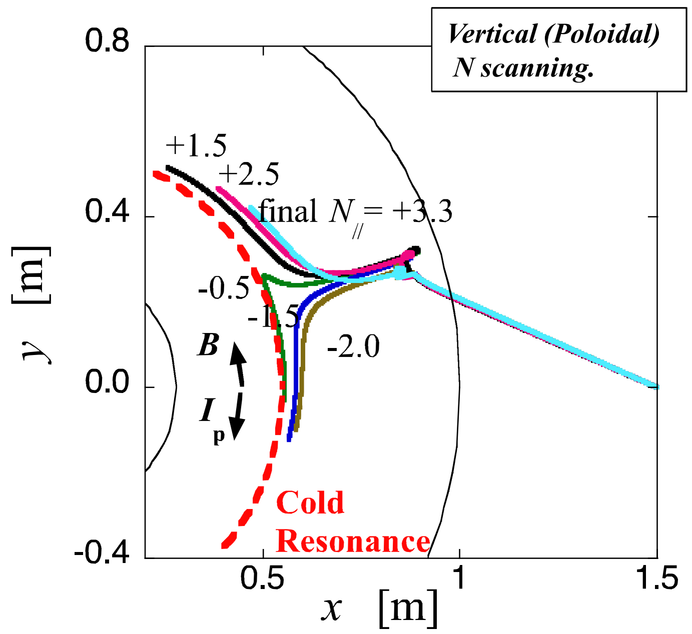
E. Mjolhus, J. Plasma Phys. **31** 7 (1984)

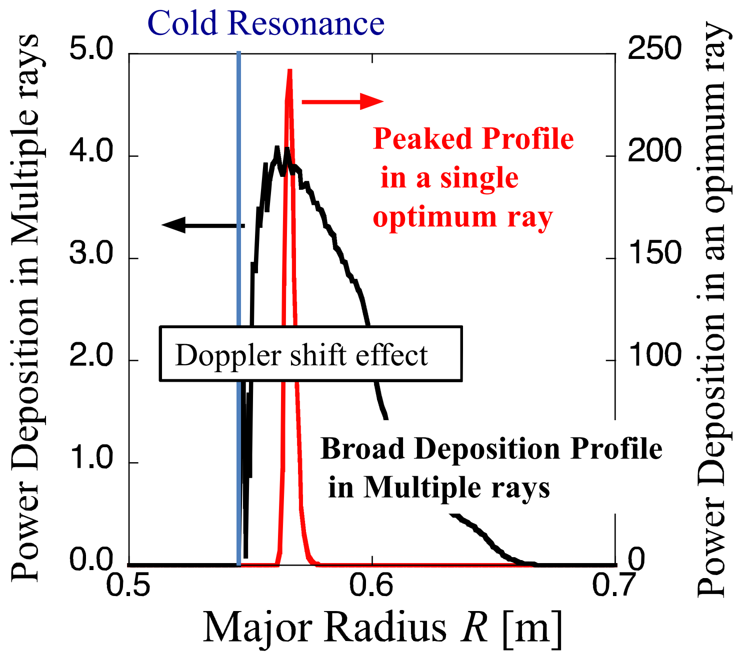






[4x2] Antenna Multiple Ray Tracing



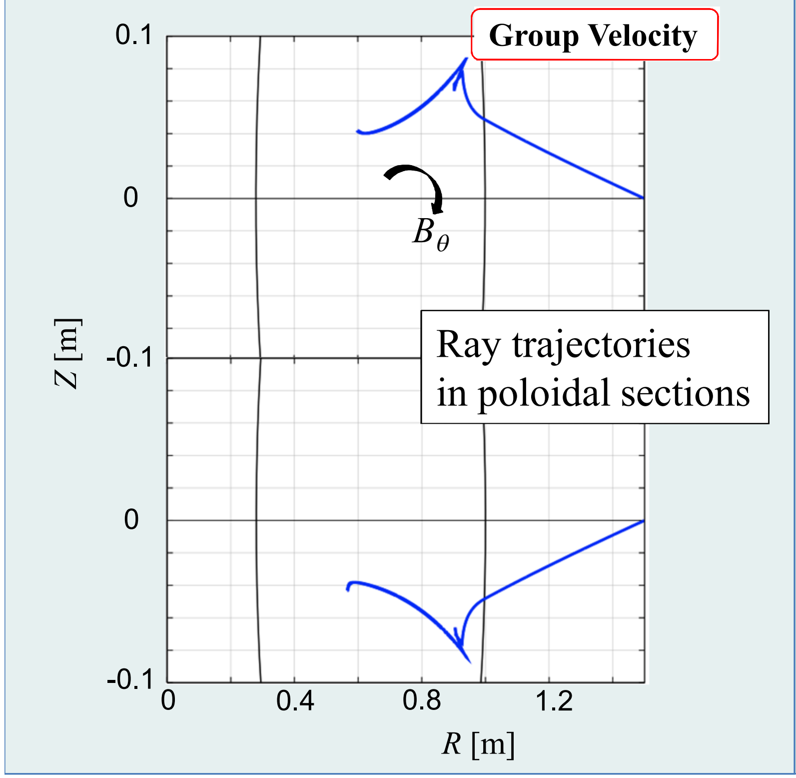


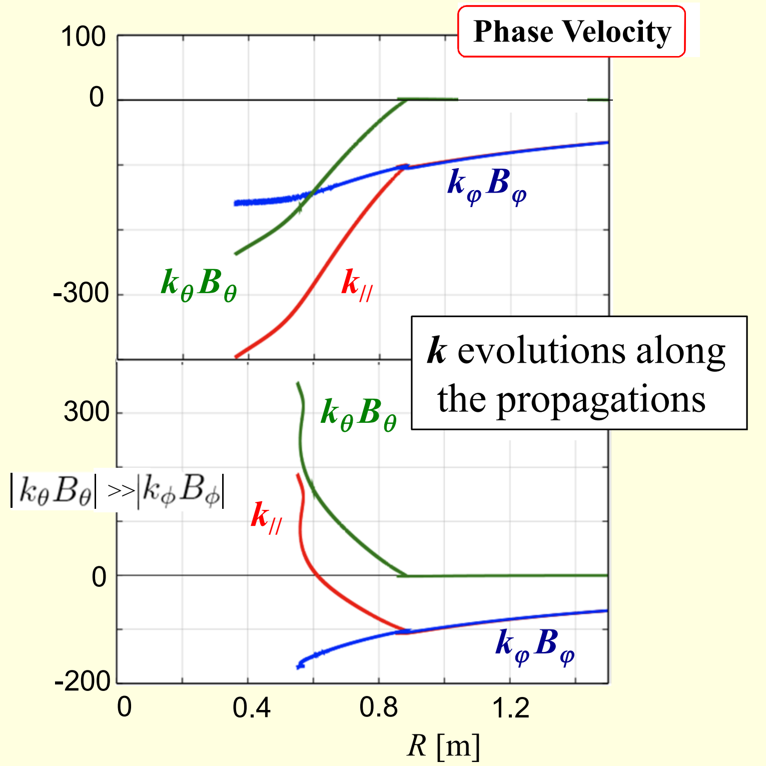
$N_{//}$ evolutions along the propagation

Broad power deposition

Low current drive efficiency by change of $N_{//}$ sign

Change of $N_{//}$ sign along propagation





$$k_{||} = \frac{k_\theta B_\theta + k_\phi B_\phi}{B}$$

In the electrostatic B-wave, N_θ or k_θ contribution was dominant in the $N//$ evolution not near the mid-plane of the torus.

Phase and Group Velocity Evolutions of EBW

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Poloidal N_θ near UHR

$$N_\theta = -\frac{Z}{r}\frac{Y^2}{R}\frac{1}{\sqrt{\left(X_0\frac{r}{a^2}+Y^2\frac{\cos\theta}{R}\right)^2+Y^4\frac{\sin^2\theta}{R^2}}}$$

$$X_0 = \frac{\omega_{\mathrm{p0}}^2}{\omega^2},\ \omega_{\mathrm{p}}^2 = \omega_{\mathrm{p0}}^2\left(1-\frac{r^2}{a^2}\right)$$

$$Y = \frac{\Omega}{\omega}$$

BWD Wave

T. Maekawa et al., Phy. Rev. Lett. ***86****, 3783 (2001).*

$$\frac{\partial D}{\partial \omega} = -\frac{4X}{\mu^4}\frac{1}{N^2N_{||}^2}\frac{1}{\omega}\left(\frac{N_{||}^2\mu^2}{2}-\frac{N^2N_{||}^2\mu^4}{4X}+1+F^{(1)}\right)$$

$$\frac{\partial D}{\partial k_r} = \frac{c}{\omega}\frac{2N_r}{N^2}\left(1+\frac{\mu^2N^2}{2Y^2}+\frac{X}{Y^2N_{||}\mu}G^{(0)}+\frac{X}{Y^2}\right)$$

Group Velocity $v_g = -\frac{\partial D/\partial \mathbf{k}}{\partial D/\partial \omega}$

in electrostatic approximation

[to be published, E. Kalinnikova]

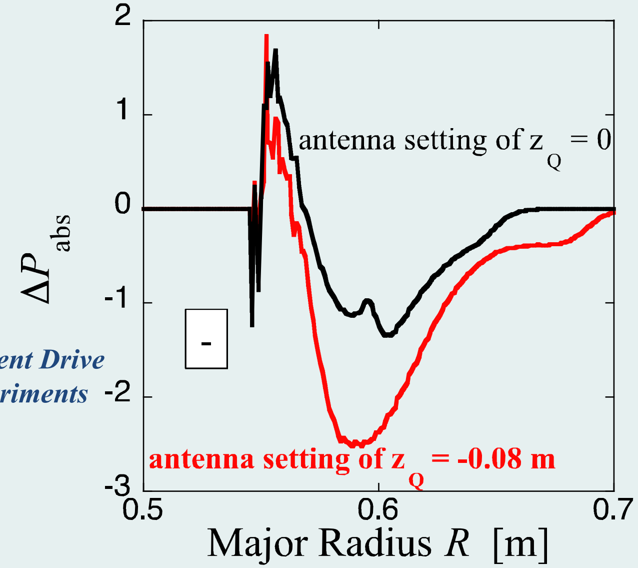
$$\frac{\partial D}{\partial k_\phi} = \frac{c}{\omega}\frac{2N_\phi}{N^2}+\frac{2X}{\mu^2}\frac{1}{N^2}\frac{c}{\omega}\left[\left(1+\frac{N^2\mu^2}{2X}\right)\left(\frac{B_\phi}{B}\frac{1}{N_{||}}+\frac{\mu^2}{2Y^2}R_{N\phi}\right)+\frac{B_\phi}{B}\frac{2}{\mu N_{||}^2}\left(F^{(2)}+K^{(1)}\right)+R_{N\phi}\frac{\mu}{2N_{||}Y^2}G^{(0)}\right]$$

$$\frac{\partial D}{\partial k_\theta} = \frac{c}{\omega}\frac{2N_\theta}{N^2}+\frac{2X}{\mu^2}\frac{1}{N^2}\frac{c}{\omega}\left[\left(1+\frac{N^2\mu^2}{2X}\right)\left(\frac{B_\theta}{B}\frac{1}{N_{||}}+\frac{\mu^2}{2Y^2}R_{N\theta}\right)+\frac{B_\theta}{B}\frac{2}{\mu N_{||}^2}\left(F^{(2)}+K^{(1)}\right)+R_{N\theta}\frac{\mu}{2N_{||}Y^2}G^{(0)}\right]$$

Antenna Z position

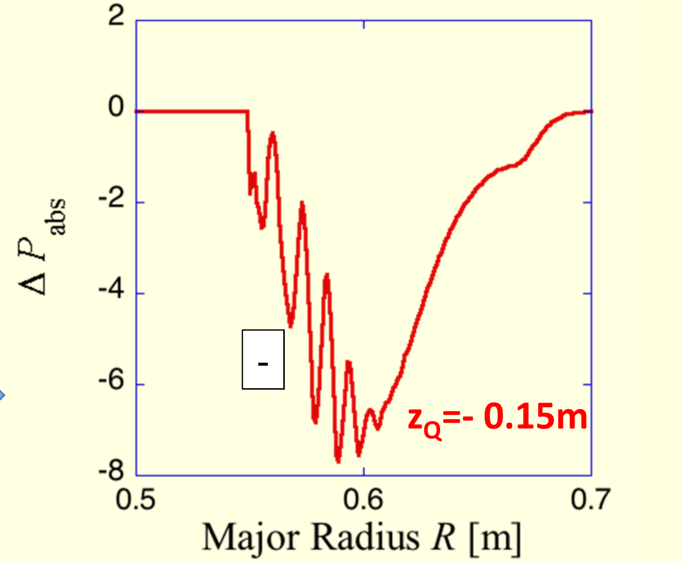
$$P_{\mathrm{abs}} = -2\,\mathrm{sgn}(\mathbf{I_p}\cdot\mathbf{B})\,\mathrm{sgn}(N_{//})\frac{\partial\,\mathrm{Im}\,D}{\partial s}$$

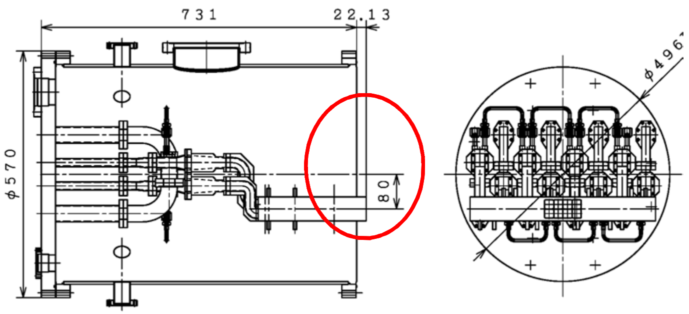
[4x2] Antenna

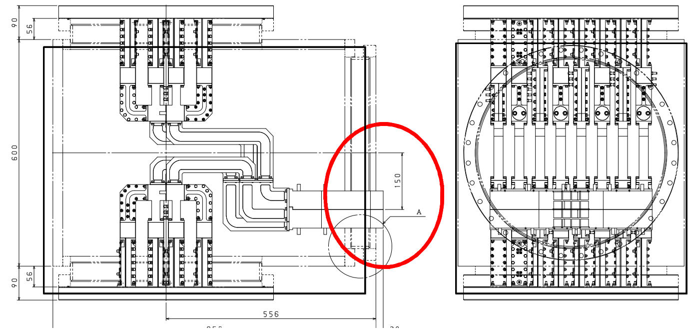


Current Drive Experiments

[4x4] Antenna







QUEST Experiments:

Non-inductive Plasma Current Startup and Sustainment

Non-inductive current startup and sustainment [I_p~12 kA]

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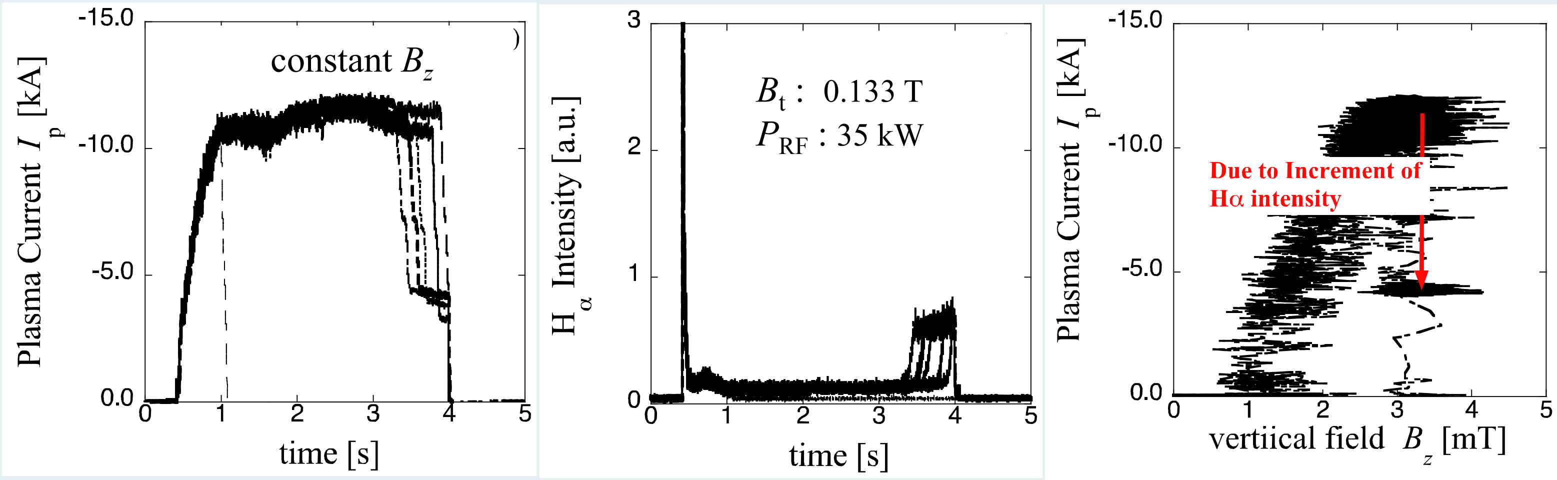
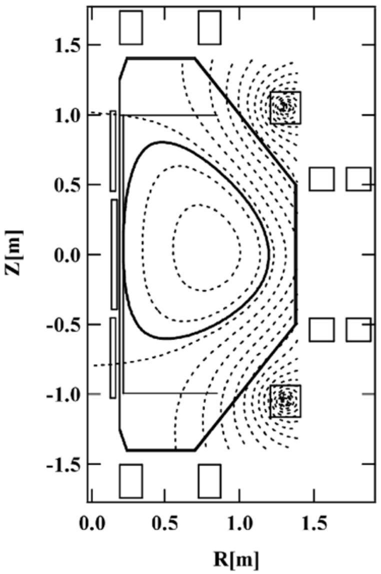
Typical time evolutions of plasma current I_p and the Ha intensity

I_p evolution in ramped–up B_z



- The vertical magnetic field B_z with two pairs of the poloidal magnetic coils (PFC1-7/2-6) was ramped up to about 3 mT.
- The plasma current was ramped up along the B_z evolution, but the discharge was terminated due to the recycling enhancement or the increment of the Ha intensity.

Reconstructed flux surfaces

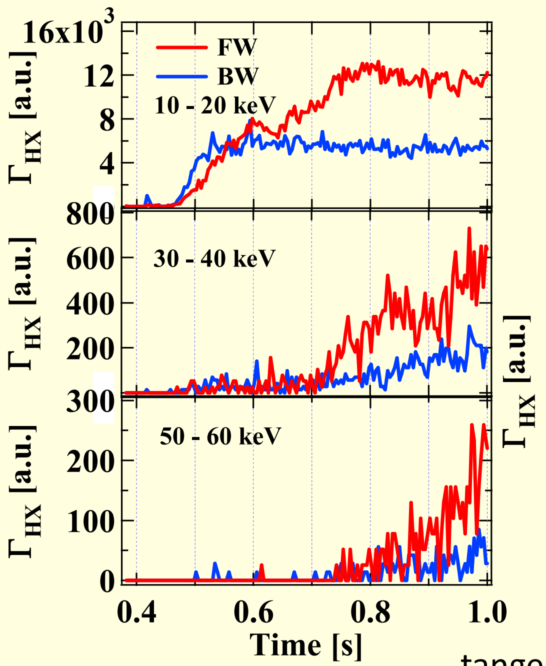


Limiter Configuration

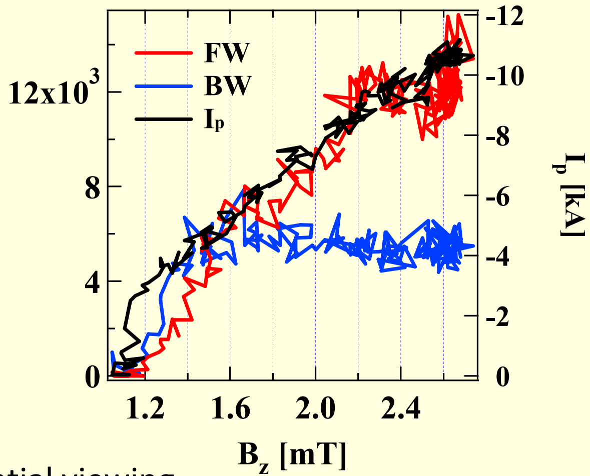
The ST plasma with a low aspect ratio of 1.5 was attained in the 12 kA discharges.

Typical time evolutions of HX intensities from forward and backward electrons

Low density case (< 3 x 10^{17} m^{-3})



I_p and HX intensity [10-20 keV] evolution in ramped–up B_z



tangential viewing

The hard X-ray intensity from current-carrying forward electrons accelerated by the RF injection was increased in the energy range of 10~20 keV, following the I_p ramped-up evolution.

Long pulse Divertor Configuration

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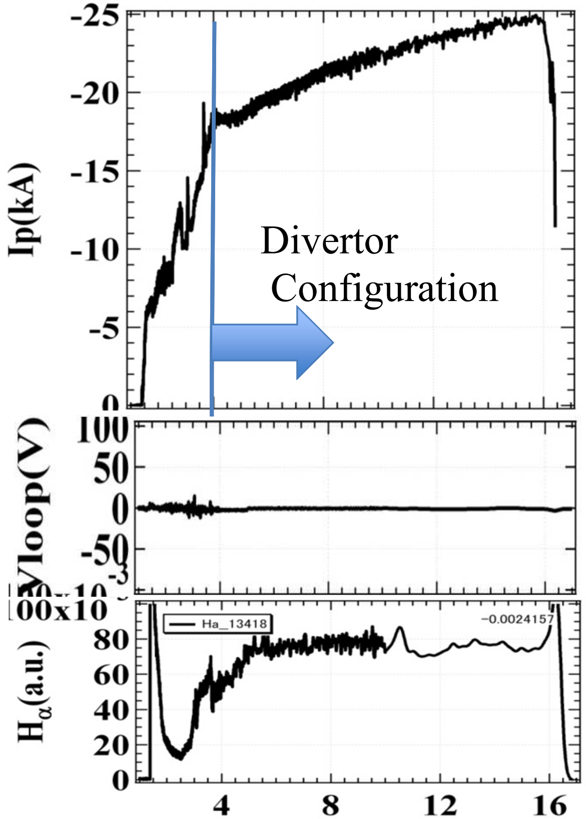

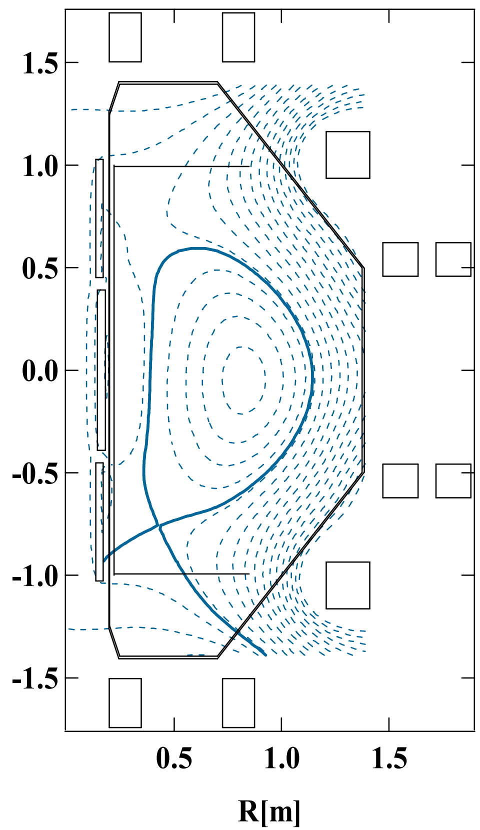

Current Drive Window in High Density Region

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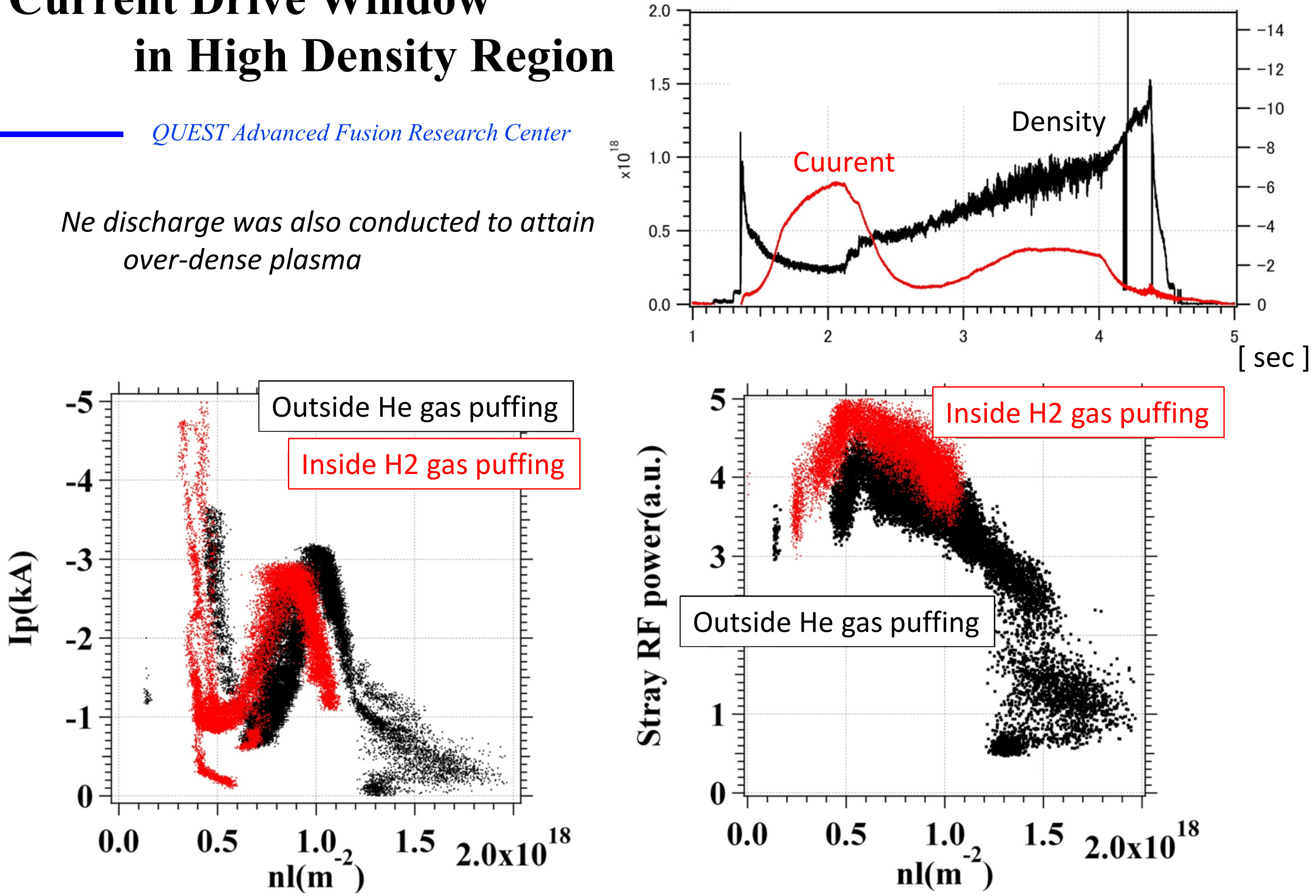
Ne discharge was also conducted to attain over-dense plasma



Future Plan [2012-]

High Density Operation with High Power RF

[2011] Future Plan for High Density Operation with High Power RF

8.56GHz ・ 250kW CW Klystron

VKX-7864B Typical Operating Parameters

Parameter	Value	Units
Center Frequency	8.560	GHz
Output Power	>250	kW
Gain, Saturated	>45	dB
Bandwidth (-1 dB)	>50	MHz
Efficiency	>41	%

Parameters:	Ef	If (Surge)	Eb	Ib	Pd	Po	Load VSWR	Iby
Units:	Vac	A	kV	Adc	W	kW	- - -	mA
Maximum:	13	18	53	12	8	300	1.05:1	30

FIGURE 2. RF OUTPUT POWER VERSUS FREQUENCY WITH BEAM VOLTAGE AS PARAMETER

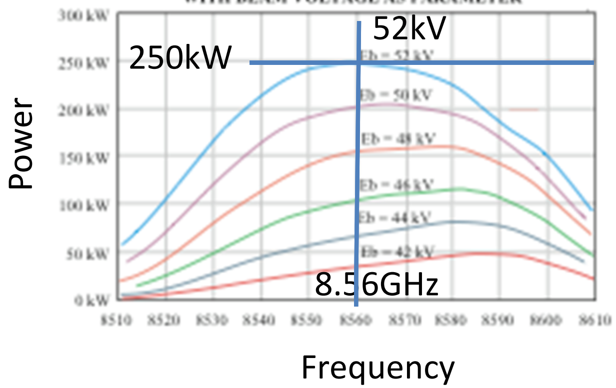


FIGURE 5. VKX-7864B

Front View

FIGURE 6. VKX-7864B

Rear View

HV Power Supply for 170 GHz Gyrotron in TRIAM-1M tokamak is available for the Klystron.
[70kV ・ 25A]

[2011-12] Future Plan for High Density Operation with High Frequency [28GHz]

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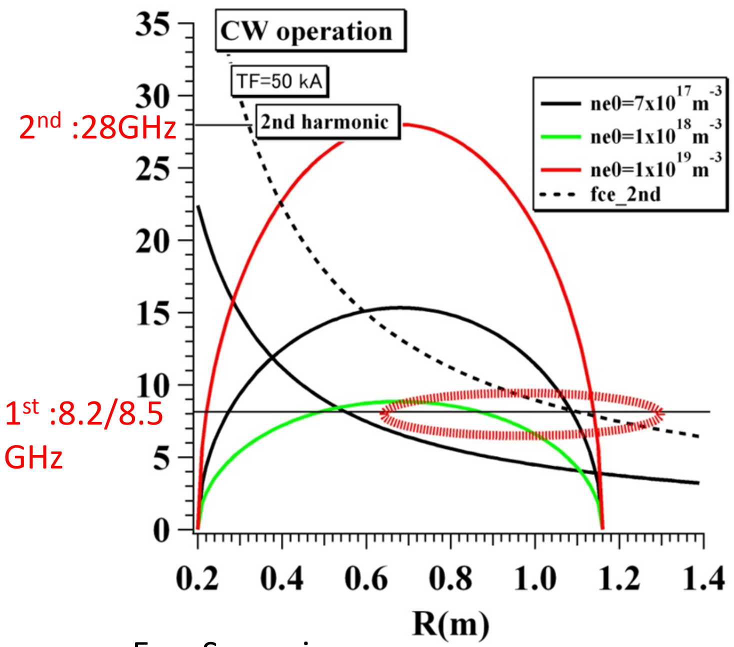
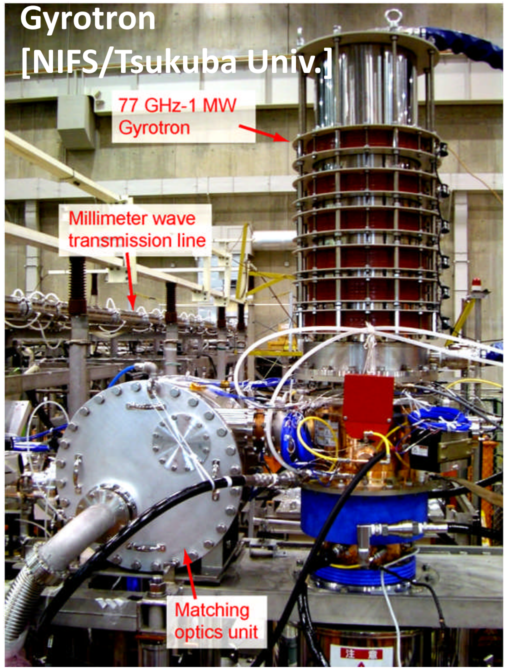


Exp. Scenario :

1) 1^{st} : 8.2/8.5GHz: production
2) 2^{nd} : 28 GHz : density ramp-up
3) 1^{st} : 8.2/8.5 GHz : EBWCD



Gyrtron, MOU, (Magnet) [from Tsukuba Univ.]
(Magnet), Mitre-bend [from NIFS]
G Tank, Power Supply, Transmission [Kyushu Univ.]

Installation of Antenna System to QUEST

High Power Test of Antenna Performance

High Power Fast-scanning Phase Shifter

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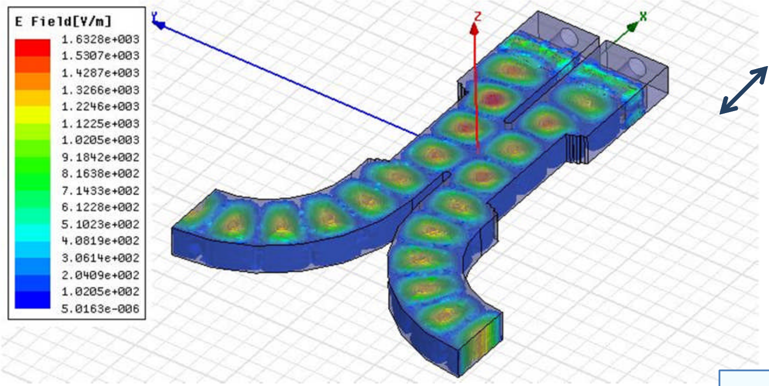


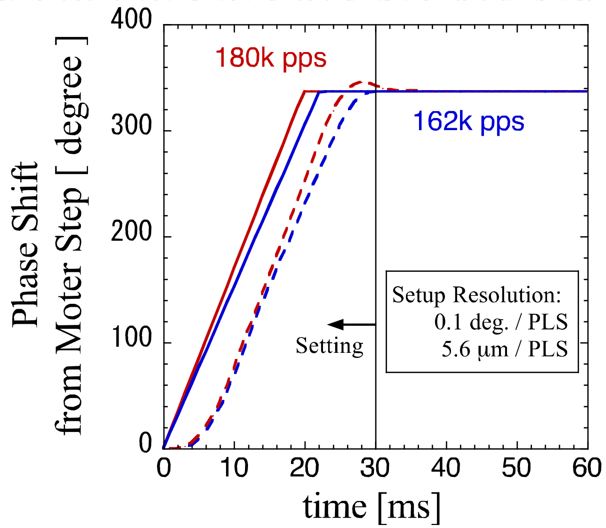
Feed-back Phase Control

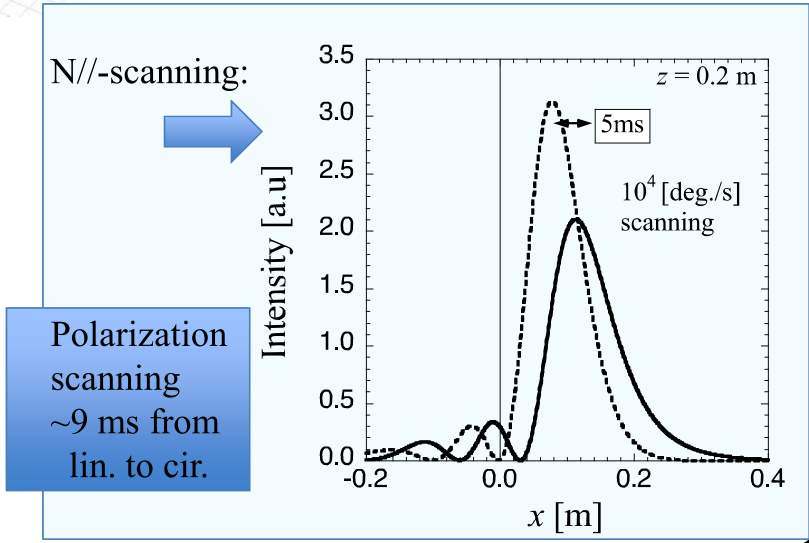
Incident Polarization ⟷ $I_p(t)$

Incident N// ⟷ $n_e(t)$

12.5kW CW

10^4 degree/s scanning





High Power Test of [4x2] CW Antenna

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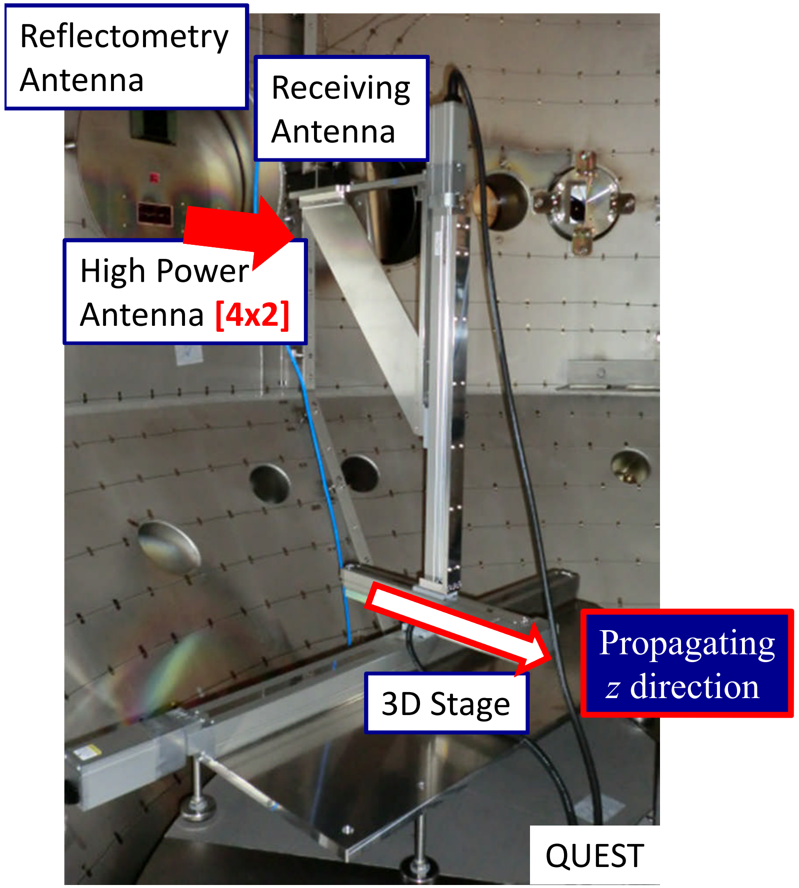
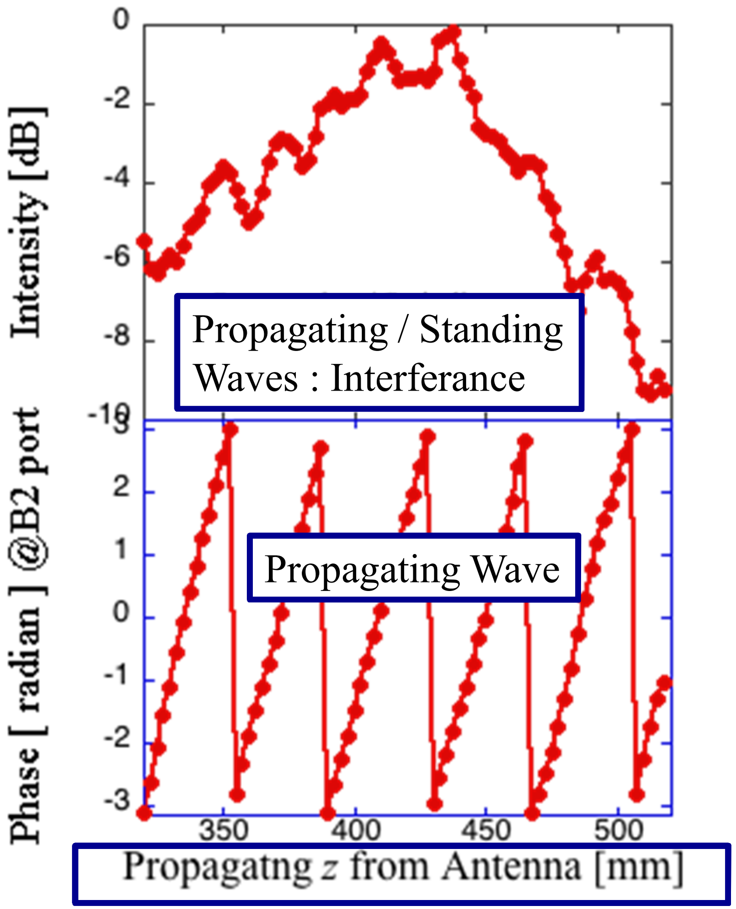
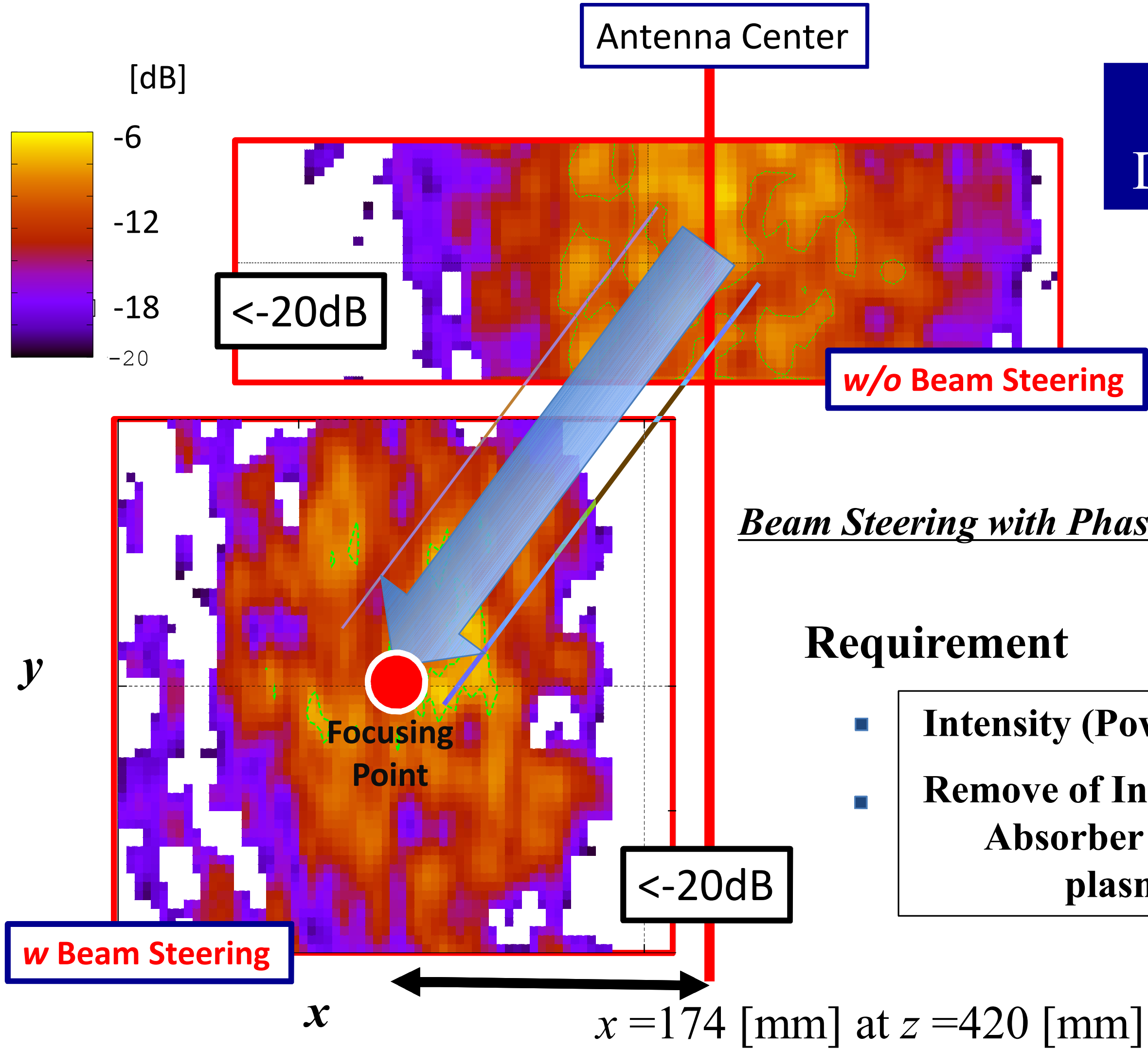




Intensity Distribution

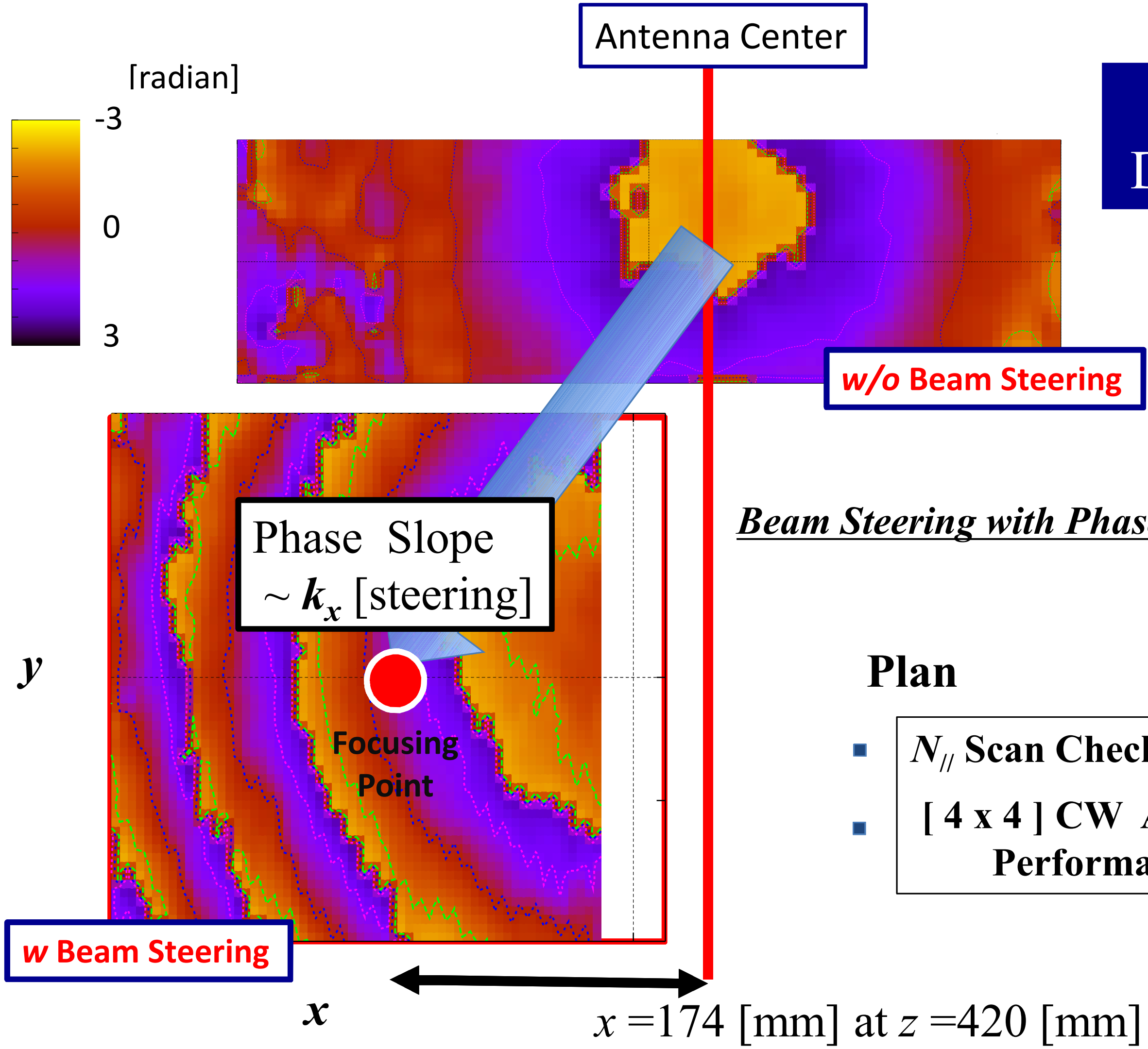


Beam Steering with Phase Array (Control)

Requirement

- Intensity (Power) Control
- Remove of Interferance
  Absorber to demonstrate plasma absorption

Phase Distribution



Beam Steering with Phase Array (Control)

Plan

- $N_{//}$ **Scan Check**
- **[4 x 4] CW Antenna Performance Check**

Sumary

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The phased-array antenna system for Electron Cyclotron/Bernstein Wave Heating and Current Drive experiments has been developed in the QUEST. The antenna was designed to excite a pure O-mode wave in the oblique injection for the O-X-B mode conversion experiments, and its good performances were confirmed at a low power level.

The plasma current (< ~15kA) with an aspect ratio of 1.5 was started up and sustained by only RF injection in the low-density operations. The long pulse discharge of 10 kA was also attained for 37 s.

The new density window to sustain the plasma current was observed in the high-density plasmas. The single-null divertor configuration with the high plasma current (<~25kA) was attained in the 17 s plasma sustainment.

The high power antenna test has been begun in the QUEST. The absorber system will be installed to demonstrate the plasma absorption in the high power test.