Development of Phased-array Antenna System and Its Application to EBWH/CD Experiment in QUEST

H. Idei[1], M. Sakaguchi[2], E. Kalinnikova[2], K. Nagata[2], H. Zushi[1], H. Hanada[1], K. Nakamura[1], A. Fujisawa[1], O. Mitarai[3], K.N. Sato[1], M. Sakamoto[1], M. Hasegawa[1], Y. Higashizono[1], K. Ishiguro[2], H. Liu[2], S. Sharma[2], T. Ryokai[2], S. Tashima[2], Y.Hisano[2], N. Yoshida[1], H. Watanabe[1], T. Tokunaga[1], S. Kawasaki[1], H. Nakashima[1], A. Higashijima[1], T. Fujiwara[1], H. Igami[4], S. Kubo[4], M. Isobe[4], N. Nishino[5], Y. Nakashima[6], T. Maekawa[7], Y. Kishimoto[7], and Y. Takase[8]

[1]RIAM, Kyushu University, Fukuoka, Japan, [2]IGSES, Kyushu University, Fukuoka, Japan,
[3]Kyushu Tokai University, Kumamoto, Japan, [4] NIFS, Toki, Japan, [5]Hiroshima University, Japan,
[6]Plasma Research Center, University of Tsukuba, Japan,
[7]Graduate School of Energy Science, Kyoto University, Kyoto, Japan,
[8]Graduate School of Frontier Science, The University of Tokyo, Ibaragi, Japan

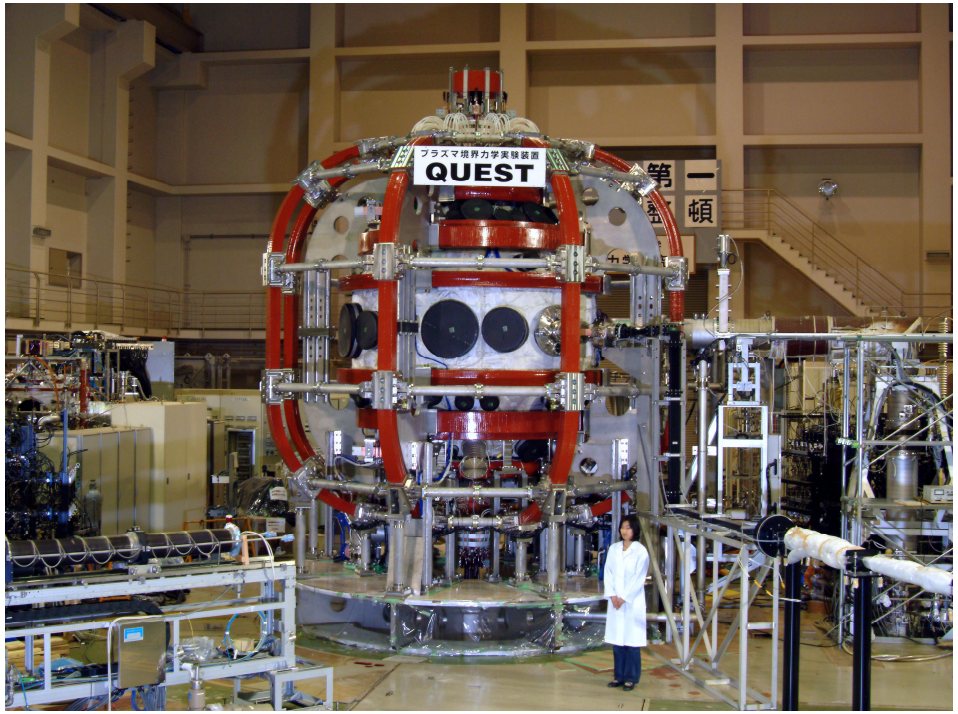
Outline

- **Introduction**
  - QUEST-
  - Conceptual Design of Phased-array Antenna-
  - Prototype Antenna-
- **Non-inductive Current Ramp-up and Sustainment using Prototype Antenna**
- **CW Antenna Development**
- **Phase-array Antenna for Plasma Diagnostics**
- **Summary**

Introduction [QUEST]

QUEST, Advanced Fusion Research Center

QUEST : Q-shu University Experiments with Steady State Spherical Tokamak)



The EBWH and EBWCD are one of attractive candidates of heating and current drive method to sustain the steady-state plasma in the spherical tokamak (ST) .

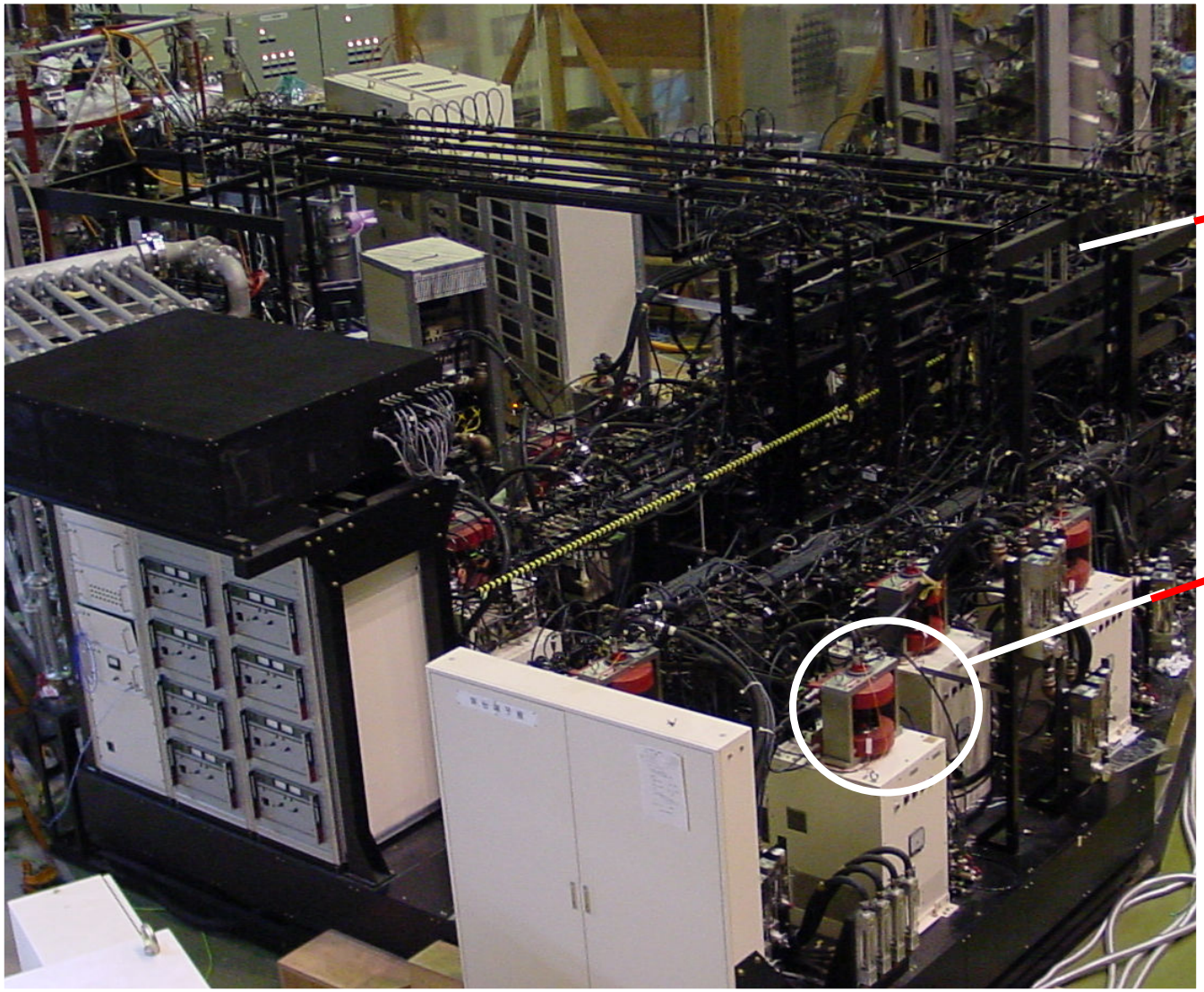
The establishment of steady-state current drive method is a key issue to study plasma-wall interaction phenomena in the steady-state QUEST plasma.

Major radius : 0.68m
Plasma minor radius : 0.40m
Magnetic field 0.25T(CW) -max. 0.5T

The 8.2 GHz LHCD system in the TRIAM tokamak will be used to the EBWH/CD in the QUEST tokamak

8.2GHz 200kW CW System

QUEST, Advanced Fusion Research Center



16-WR137 rectangular fundamental waveguide transmissions

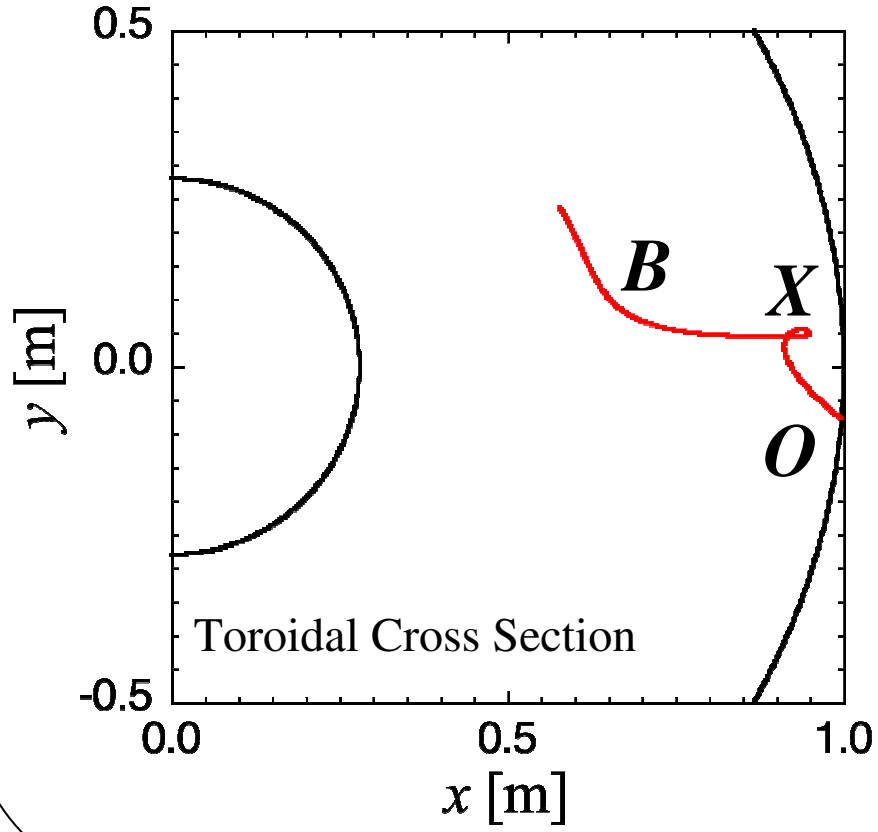
Klysitron (25kW) x 8 [200kW]

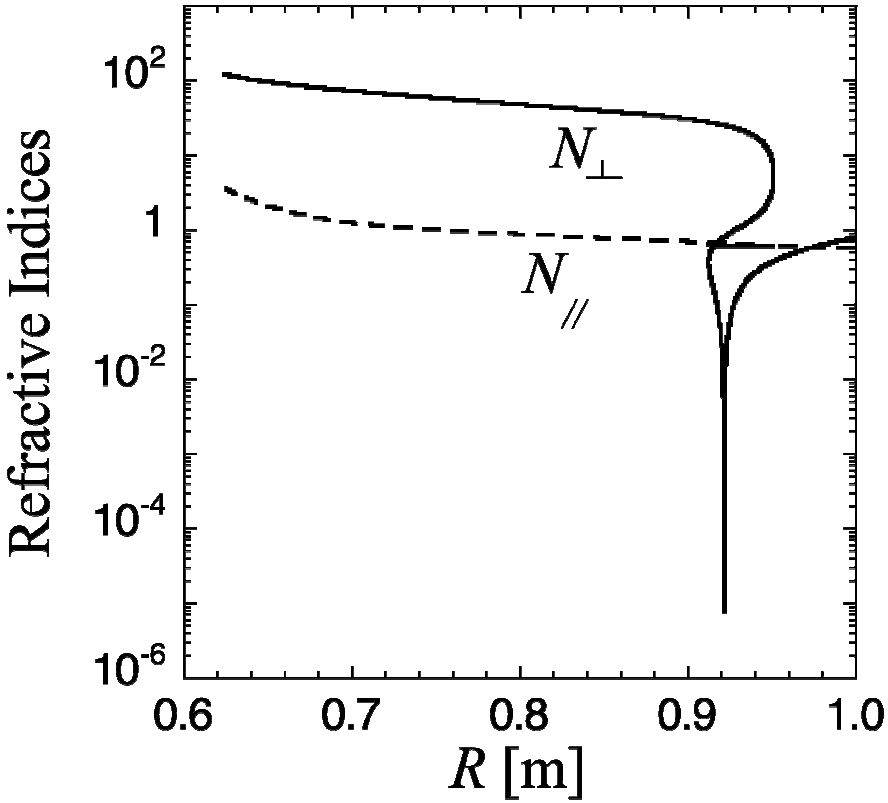
2 system: 200kW x 2
totally 400kW

O-X-B Ray tracing 【 O-X-B: Low density case 】

QUEST Advanced Fusion Research Center

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

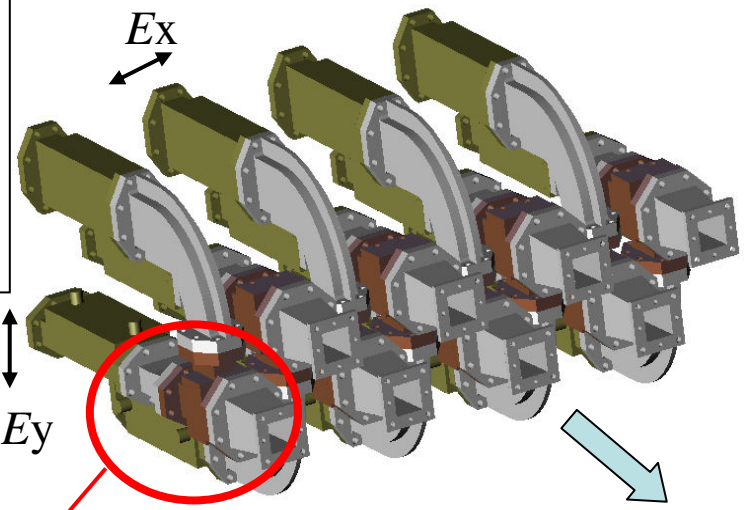


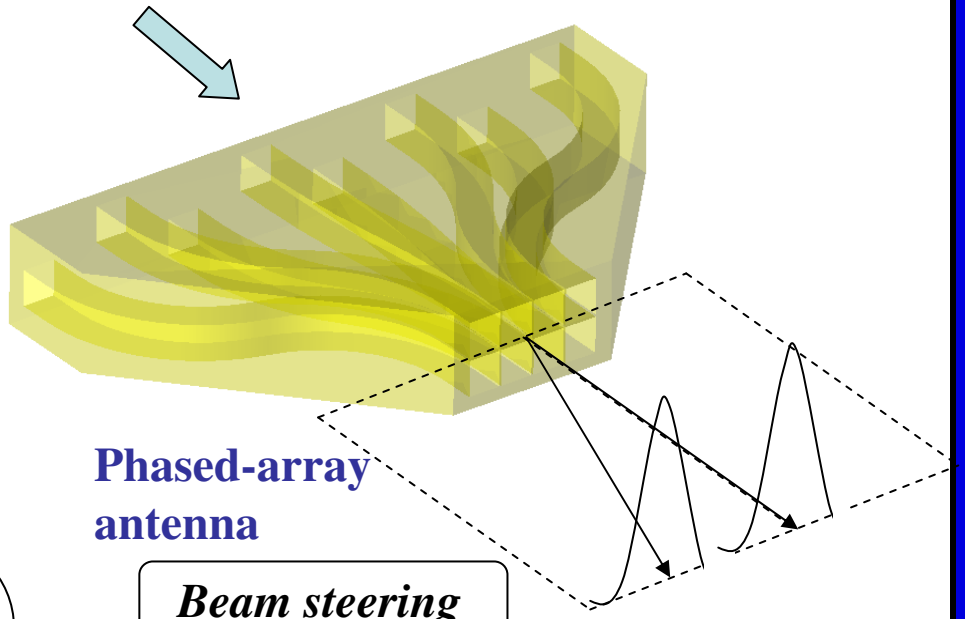


Conceptual Design

16-WR137 inputs with intensity and phase controls

8.2GHz

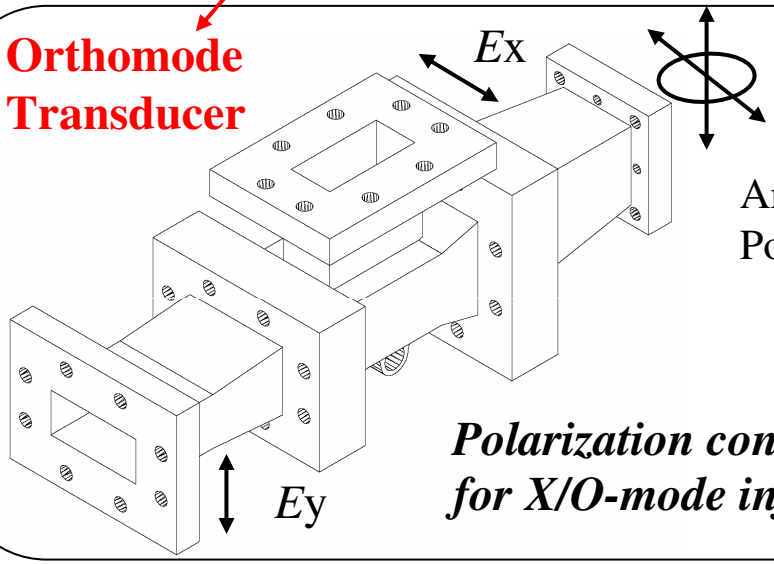




Phased-array antenna

Beam steering

Orthomode Transducer



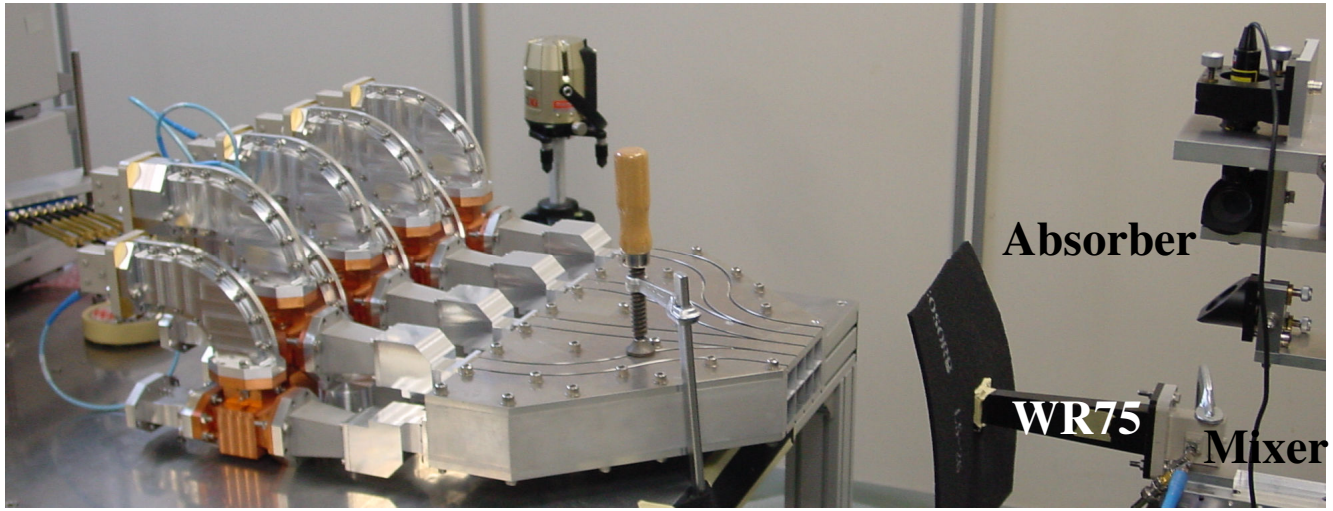
Arbitrary Polarization

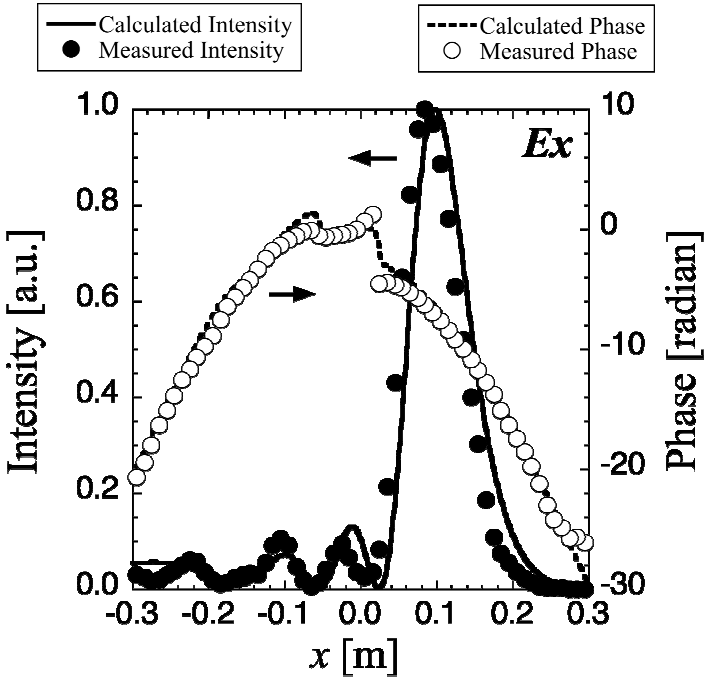
Polarization control for X/O-mode injection

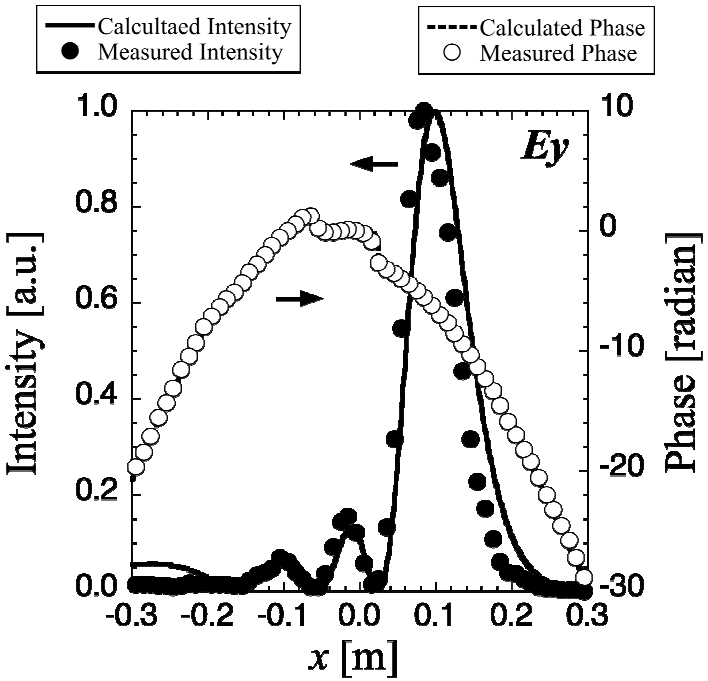
For the optimized O/X-mode injection,

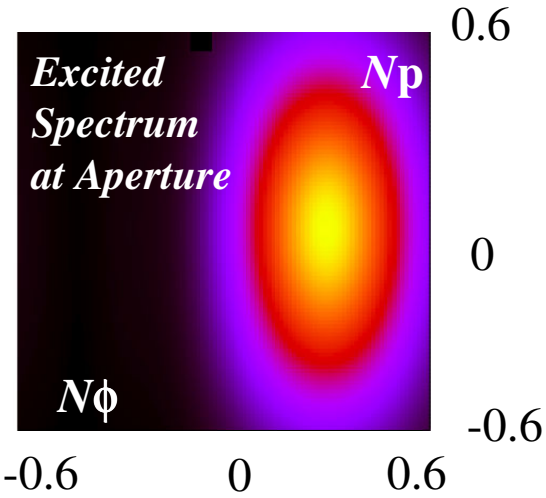
Perpendicular / Oblique Injection ⟺ *Linear / elliptical Polarization*

Radiation Field from Prototype Antenna



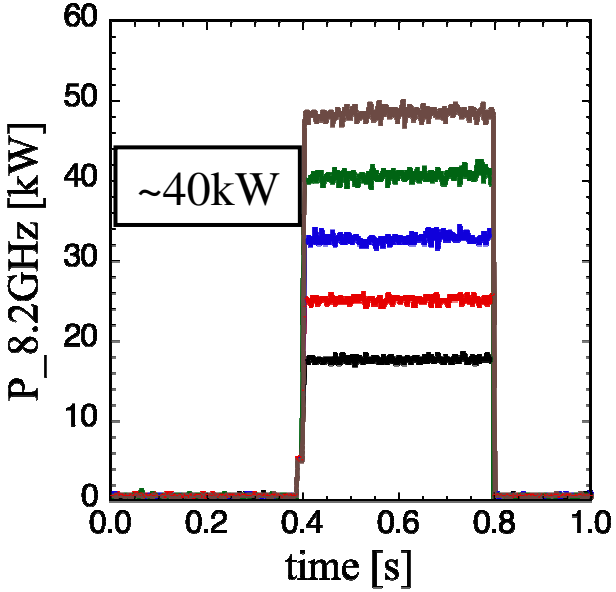


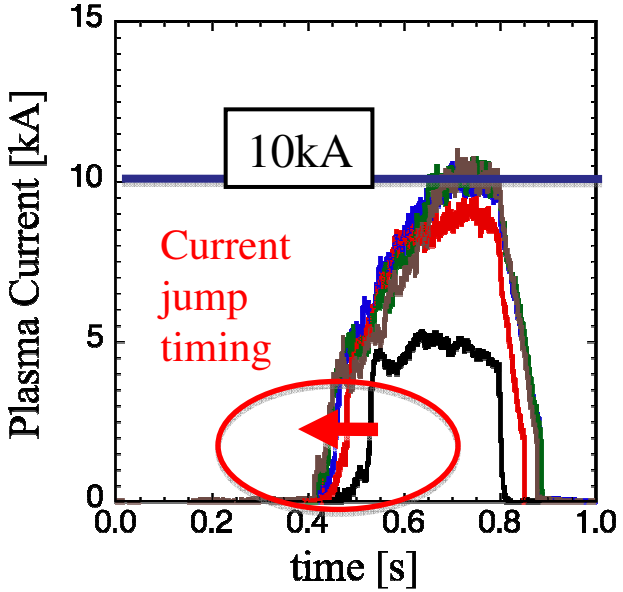


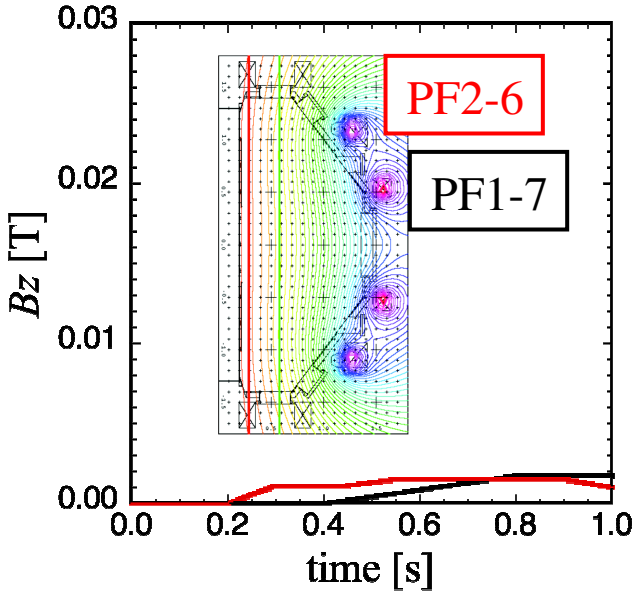


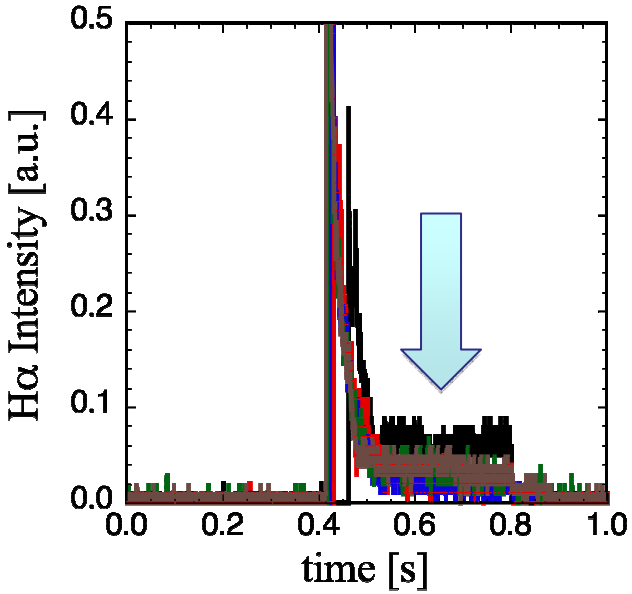
Non-inductive Current Ramp-up

QUEST Advanced Fusion Research Center





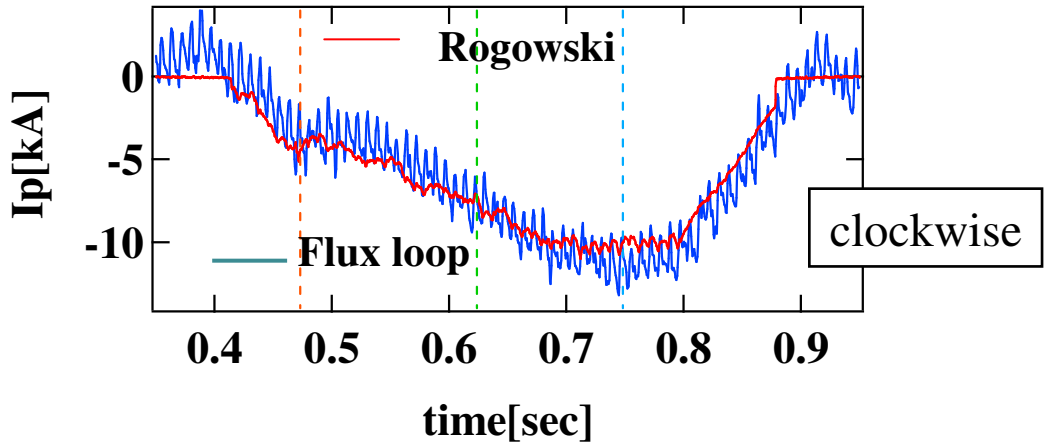




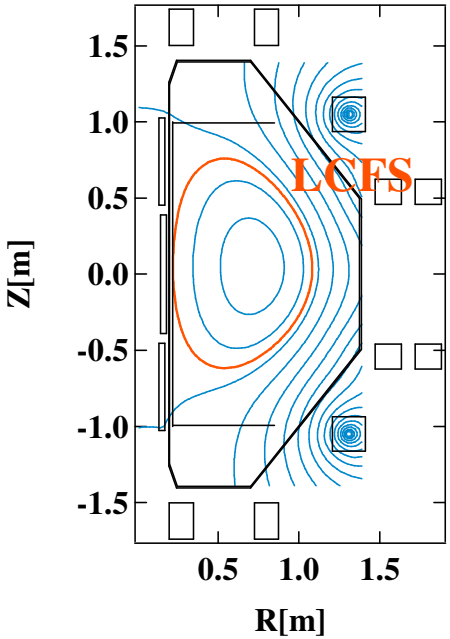
- **After wall-conditioning, the Ha and OII intensities were dramatically decreased even at the moderate RF power (P_{RF}) .**
- **The current jump was observed even at the lower P_{RF}=20kW.**
- **The 10kA plasma current was ramped up at P_{RF}~30kW with moderate B_z field for the equilibrium.**

Magnetic Flux Surface / Current Distribution and HX emission

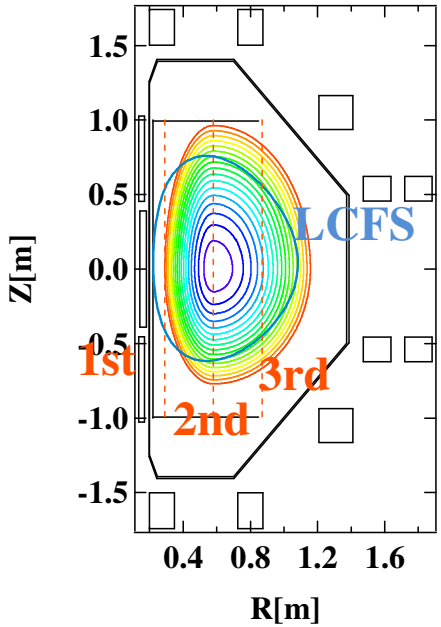
QUEST Advanced Fusion Research Center

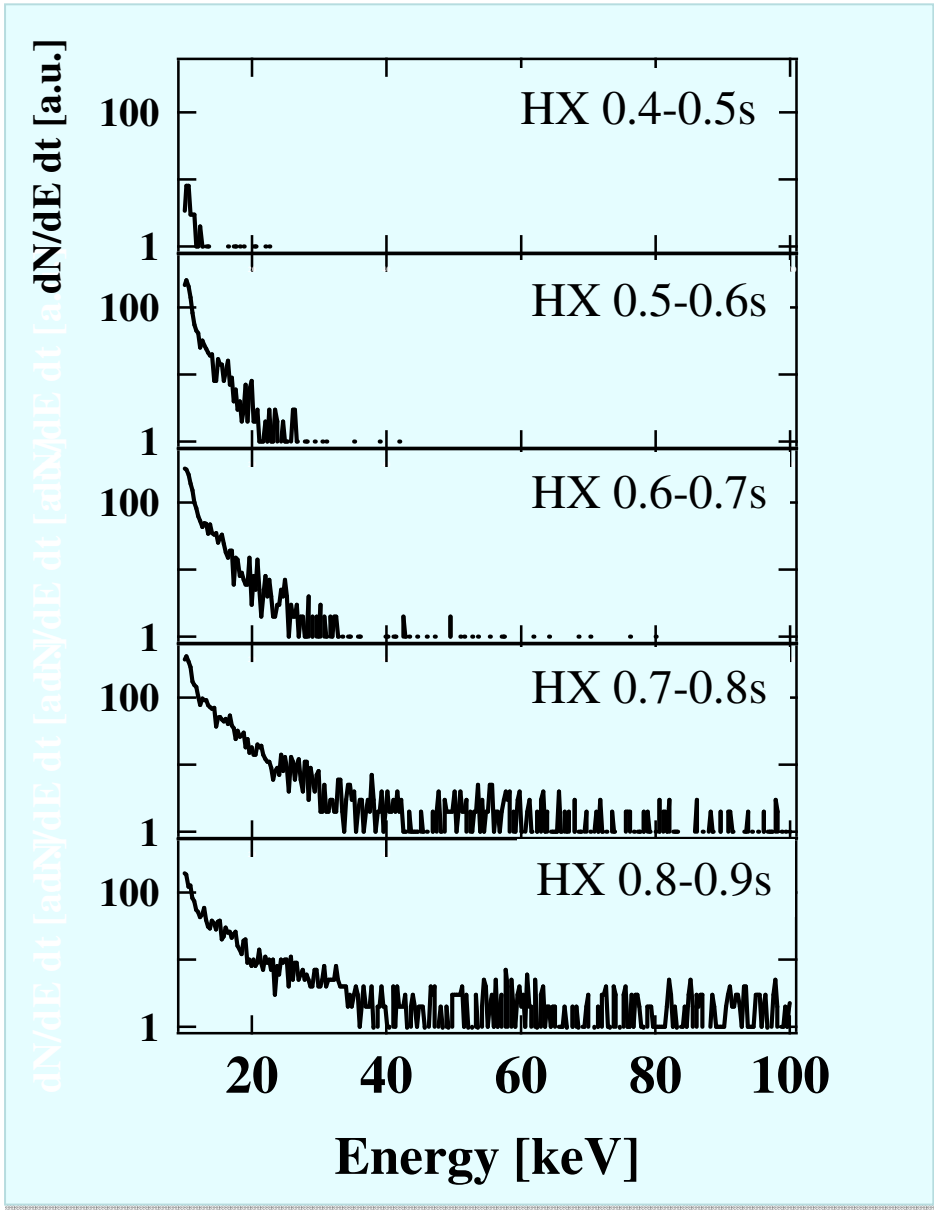


Magnetic flux surface (0.71sec-0.7935sec averaged)



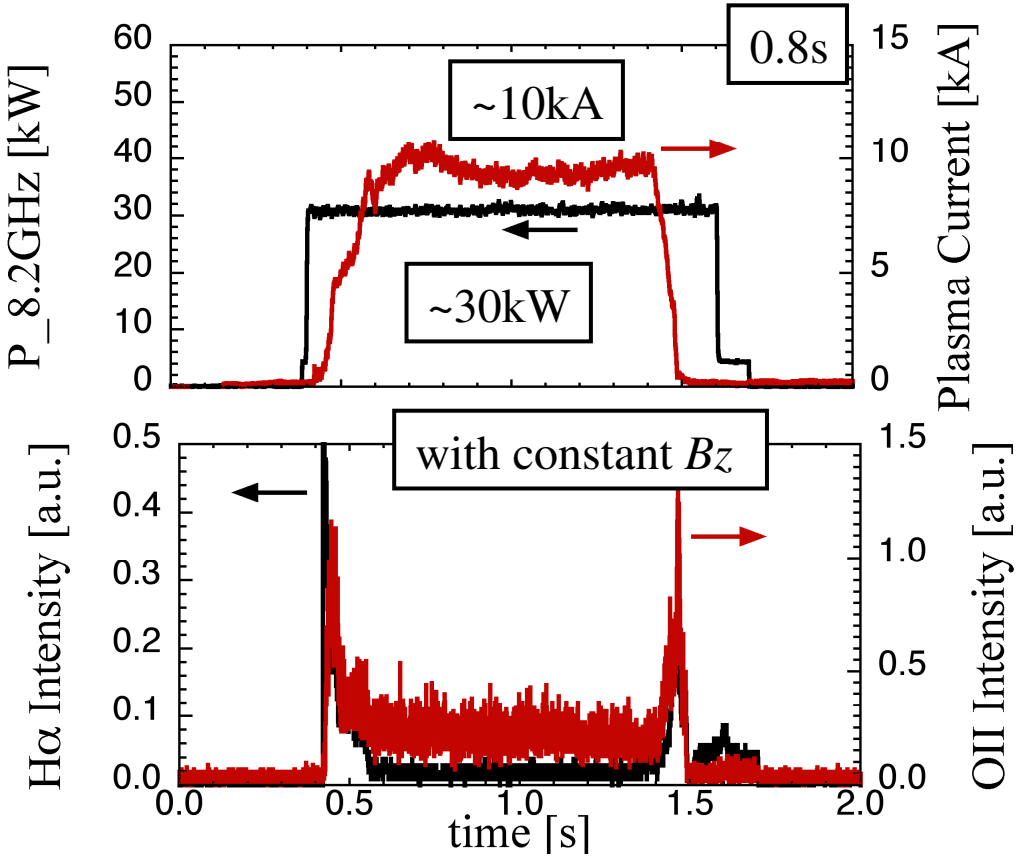
Current distribution





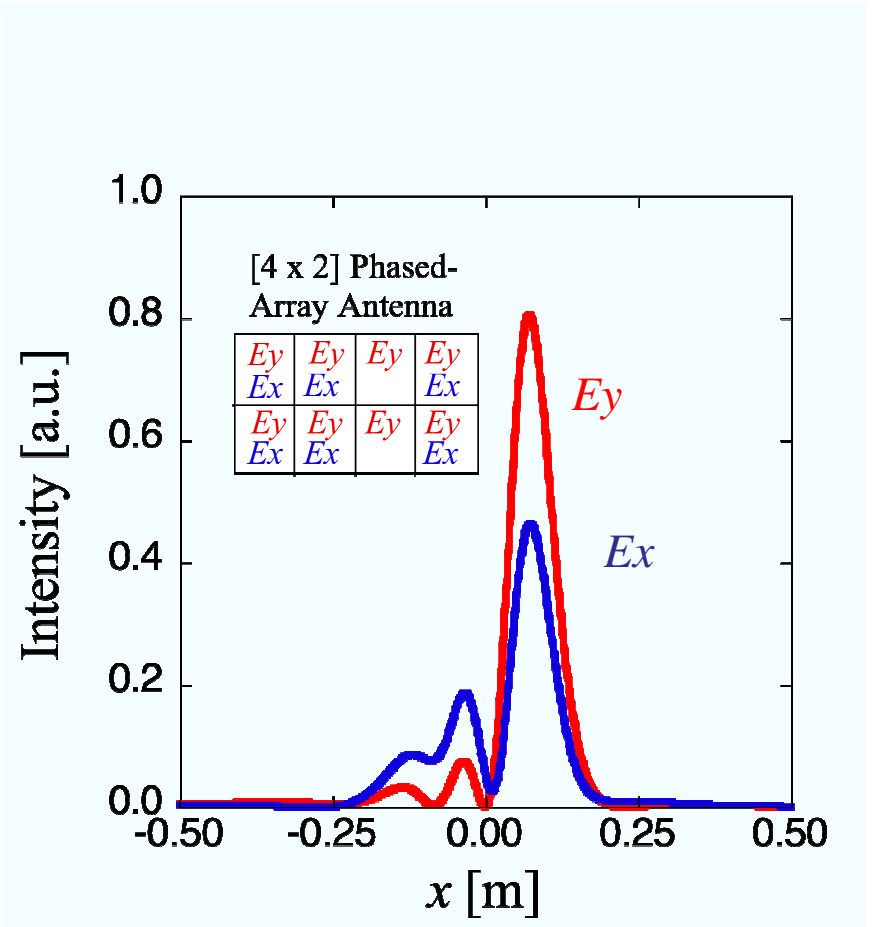
Non-inductive Current Sustainment (FY2009)

QUEST Advanced Fusion Research Center



The 10kA plasma current was sustained for 0.8 second, but terminated with increment of the Hα and OII intensity.

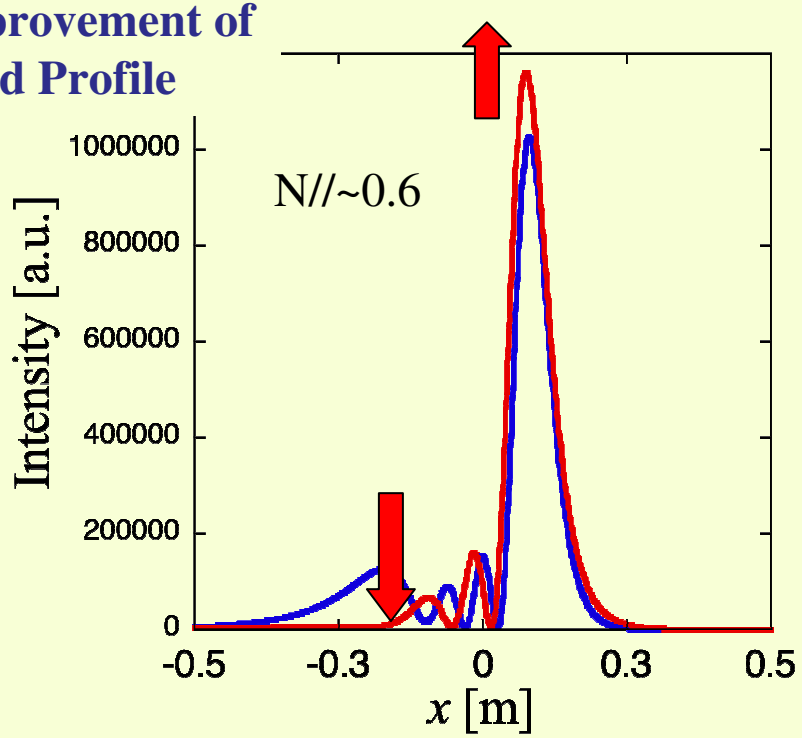
One broken klystron could not be operated. It should be repaired.

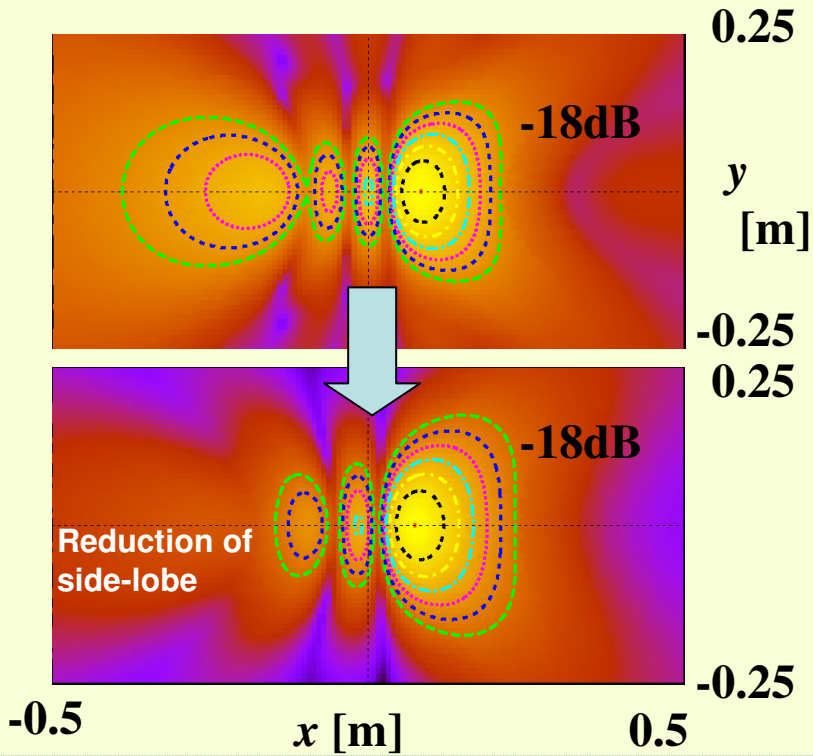


CW Antenna Development

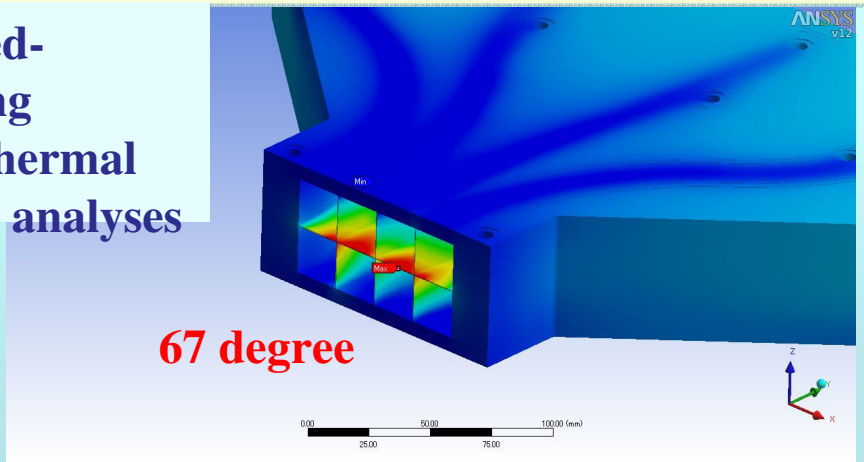
QUEST Advanced Fusion Research Center

Improvement of Field Profile





Forced-cooling and thermal stress analyses

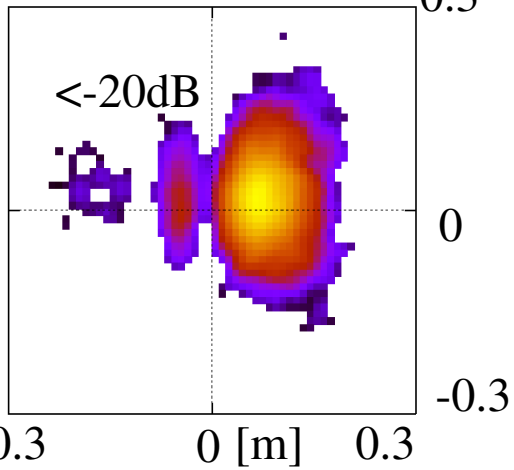


The heat load and thermal stress in CW 200 kW operation were analyzed with a finite element code.

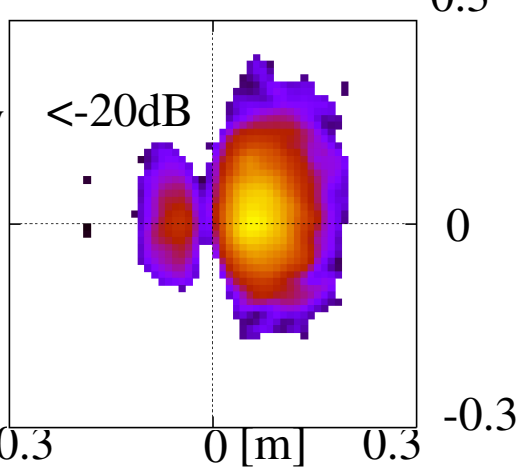
The max. temperature was 67 degree C, and the thermal stress was analyzed to be moderate.

Radiation Field from CW Antenna

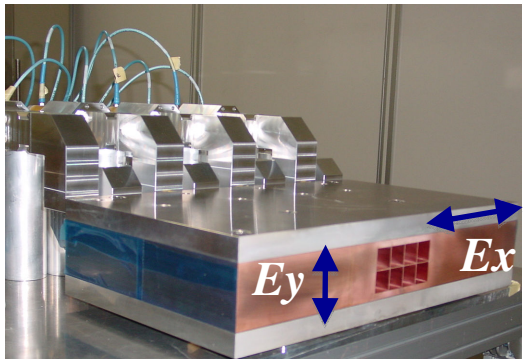
Measured
Ey Intensity

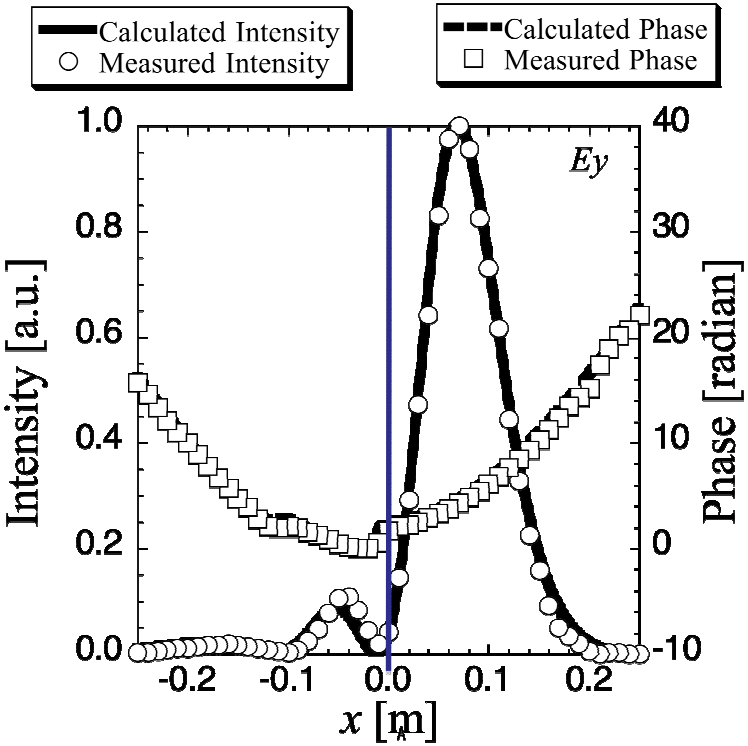


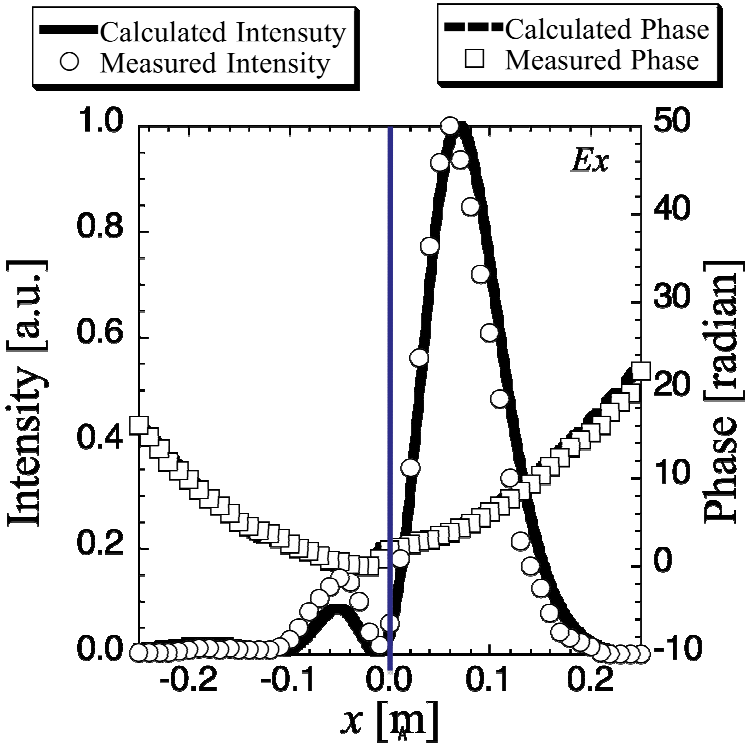
Measured
Ex Intensity

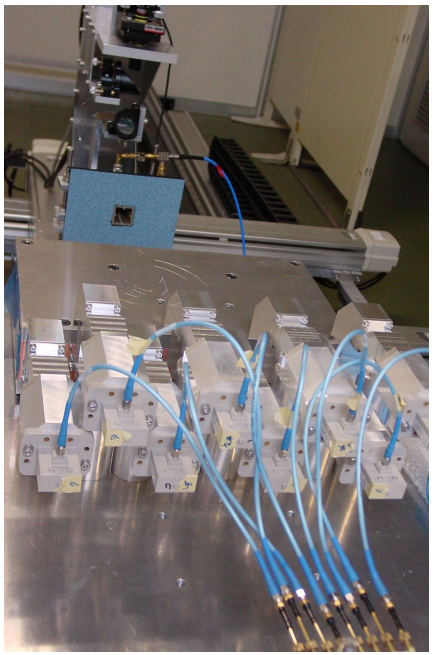


z=0.2 m

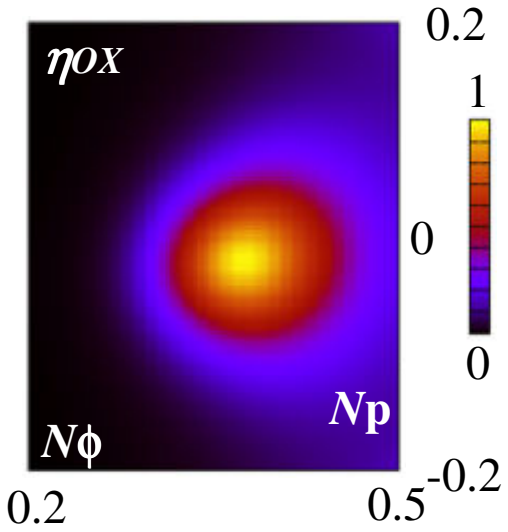


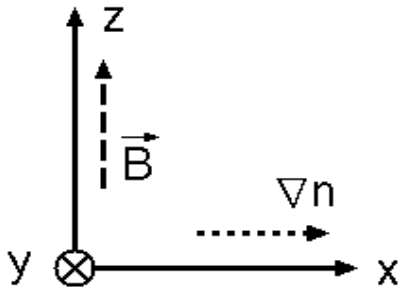






O-X-B Mode Conversion



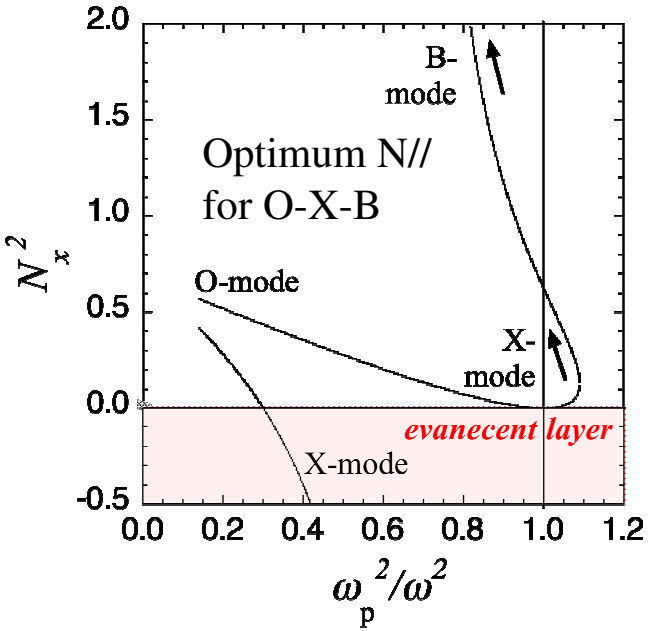


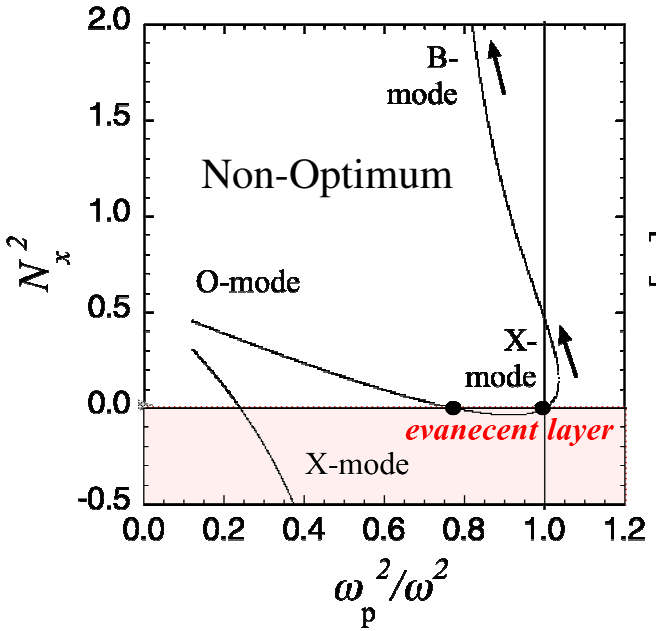
ω : wave angular frequency
Ω : electron cyclotron angular frequency
n_e : electron density at the plasma cutoff

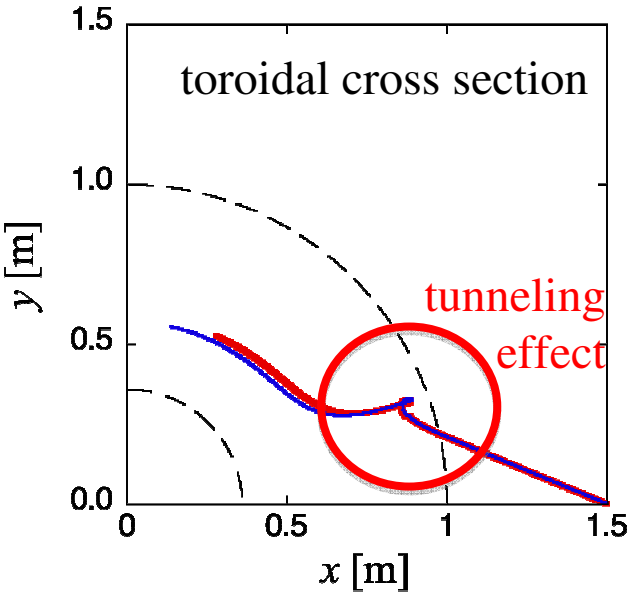
$Y = (\Omega/\omega)$,
$N_{zopt} = \{Y/(1+Y)\}^{1/2}$
$L_n = n_e/(dn_e/dx)$

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

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

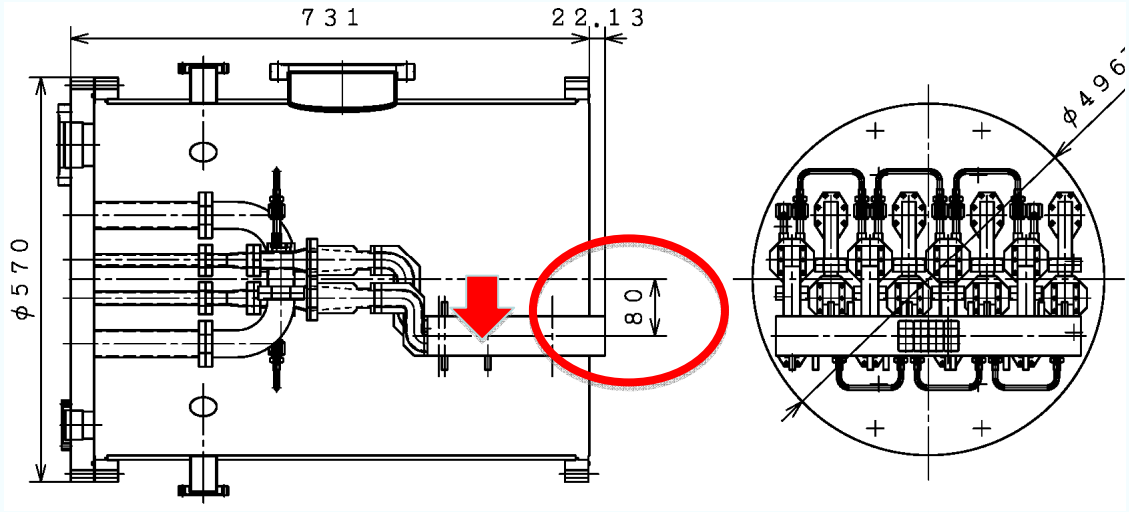


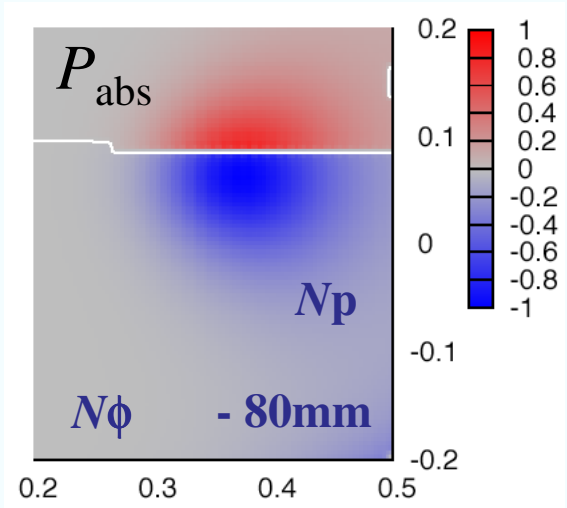


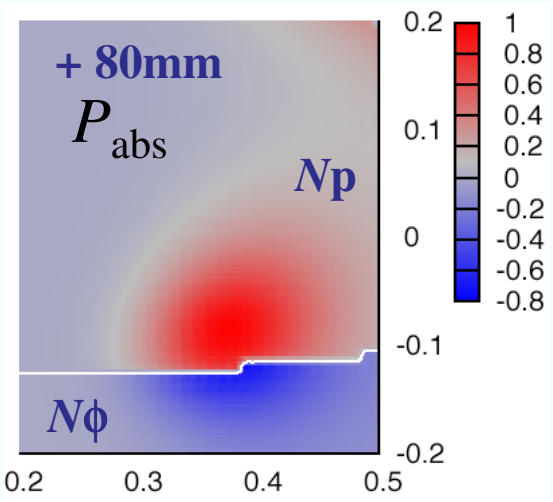


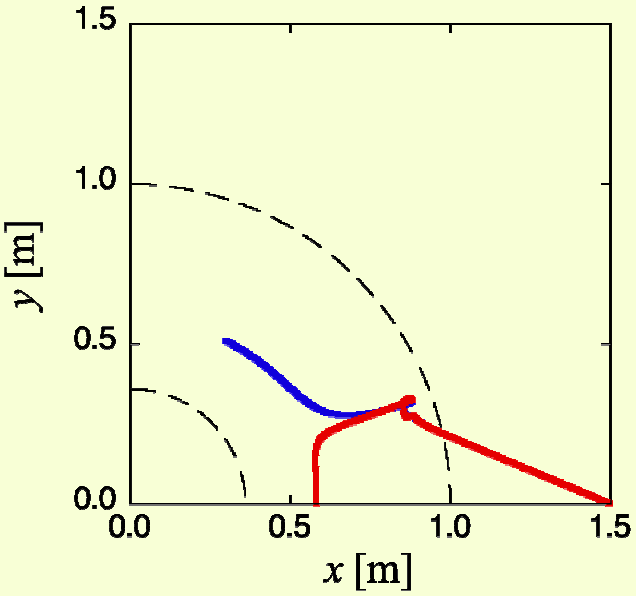
Antenna Set-up [Poster presented by E. Kalinnikova]

QUEST Advanced Fusion Research Center









The antenna set-up at lower side for equatorial plane is good for the EBWCD.

The vertical position of the plasma is controlled to make the large offset between the plasma (current) center and the antenna position.

Plasma Diagnostics using the Phased-array Antenna

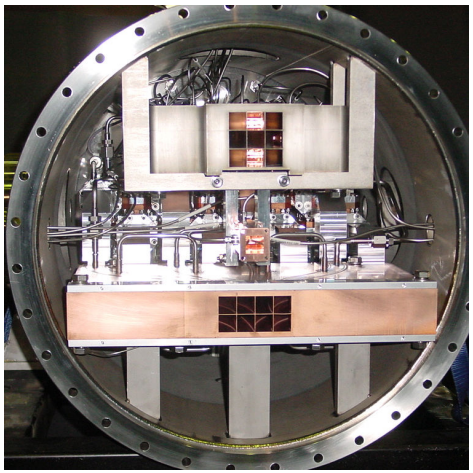
For Mode Conversion Study

EBW Emission Radiometry

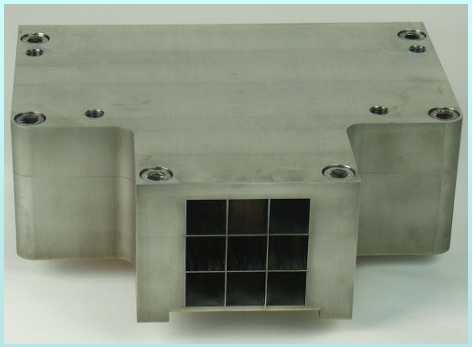
- MC eff. –
- T_e profile -

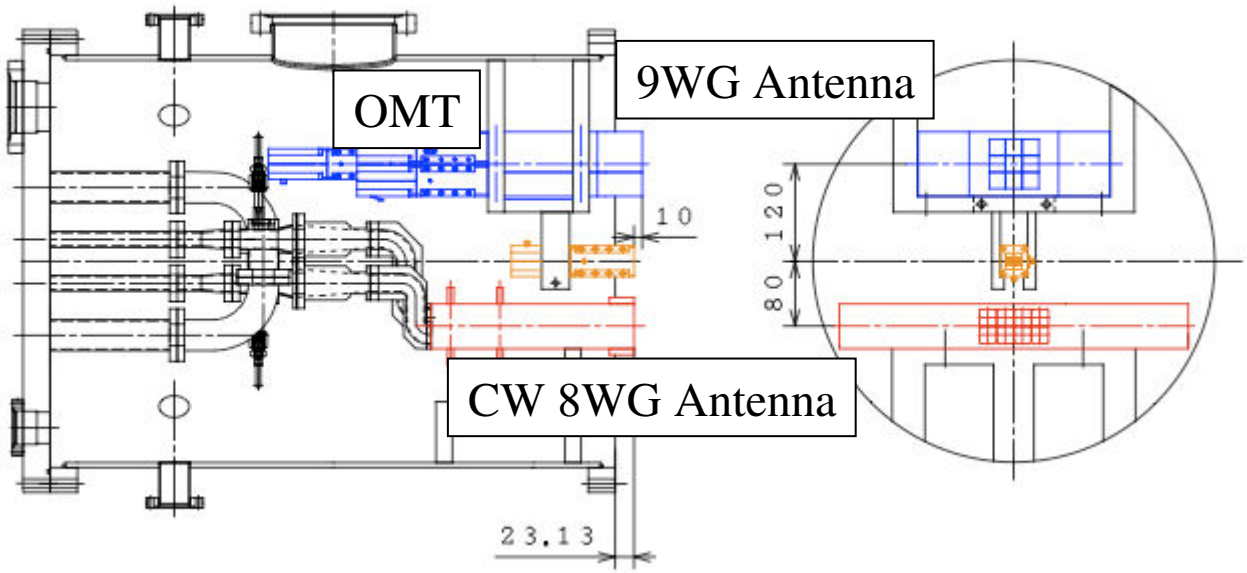
Reflectometry

- n_e profile -

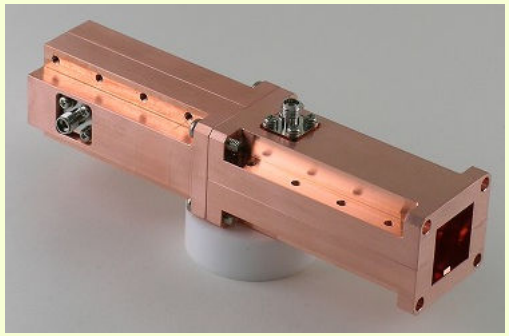


[3 x 3] Phased-array Antenna



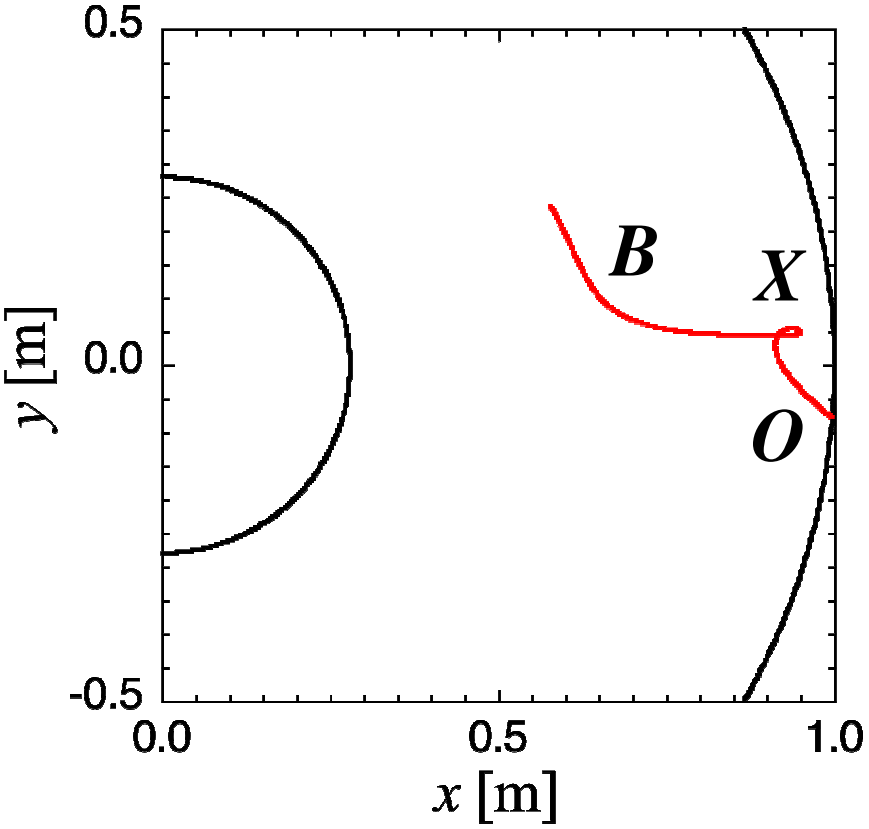


Broadband OMT [8-15GHz] for Plasma Diag.

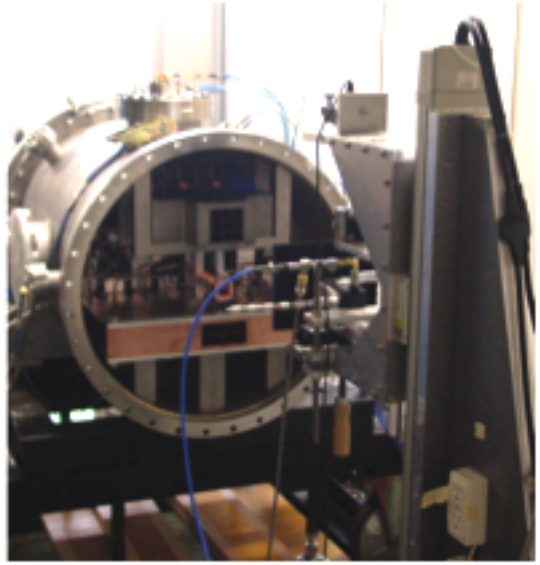


EBW Emission Diagnostics using the Phased-array Antenna

QUEST Advanced Fusion Research Center



Oblique viewing to detect the EBW emission after mode conversion.

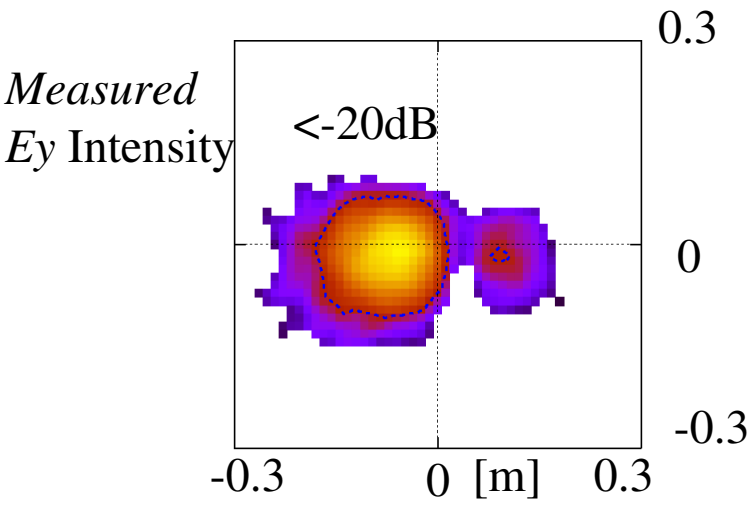


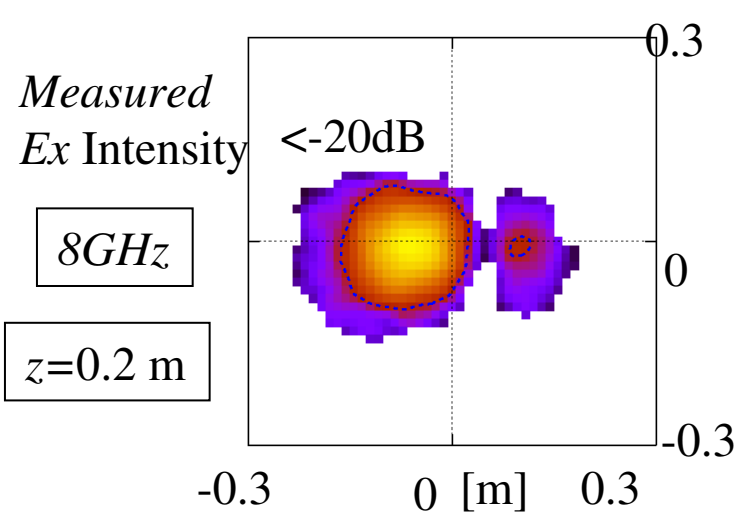
EBW Emission:
-- Inverse process for EBWH/CD --

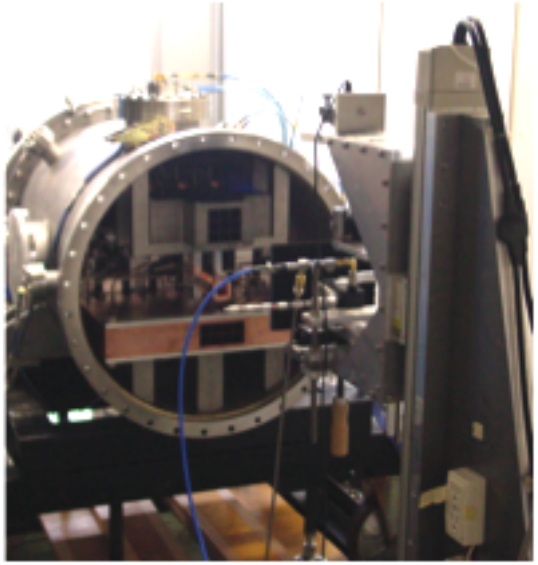
The PAA system will be used to investigate mode conversion phenomena into the Bernstein wave.

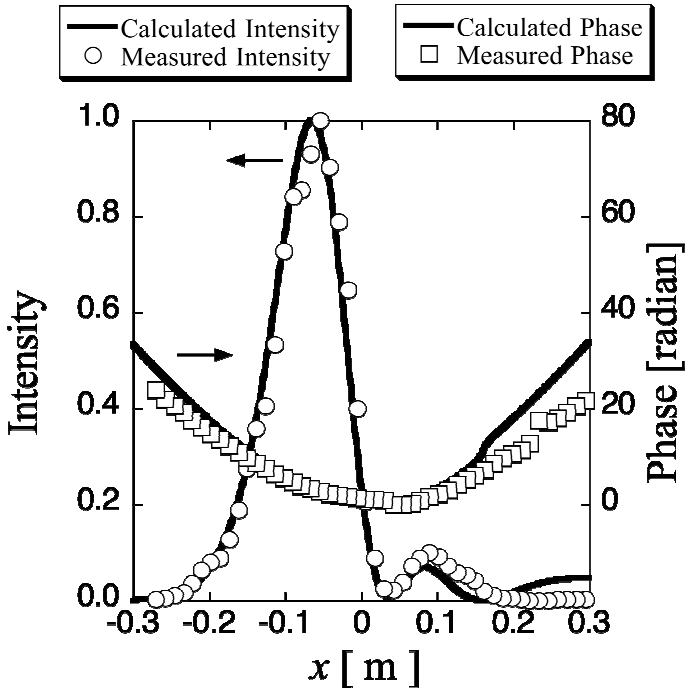
EBW Emission Diagnostics using the Phased-array Antenna

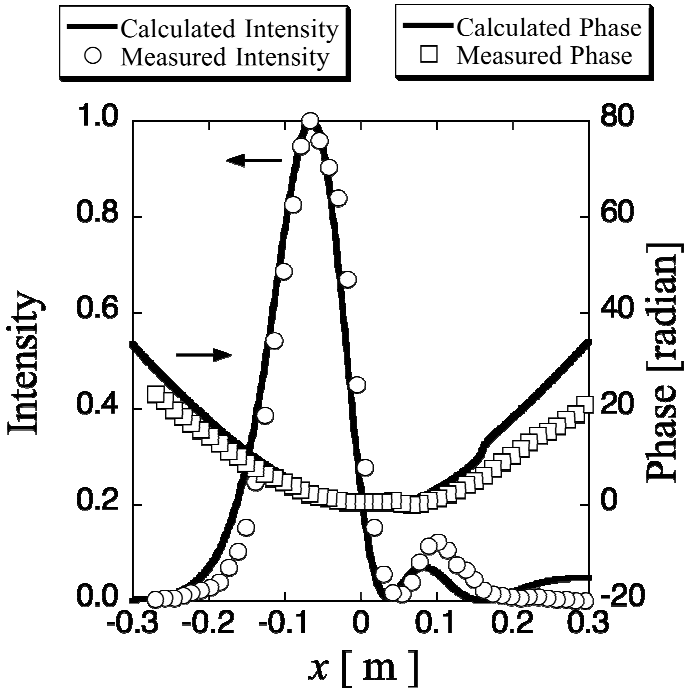
QUEST Advanced Fusion Research Center









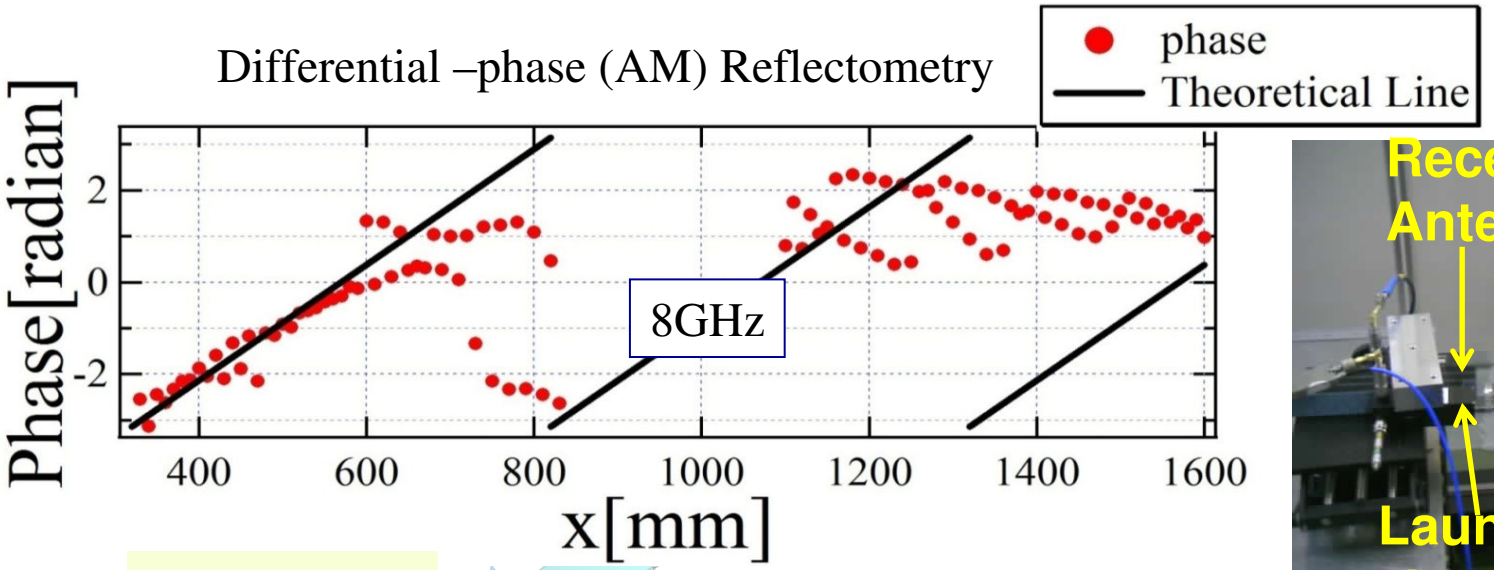


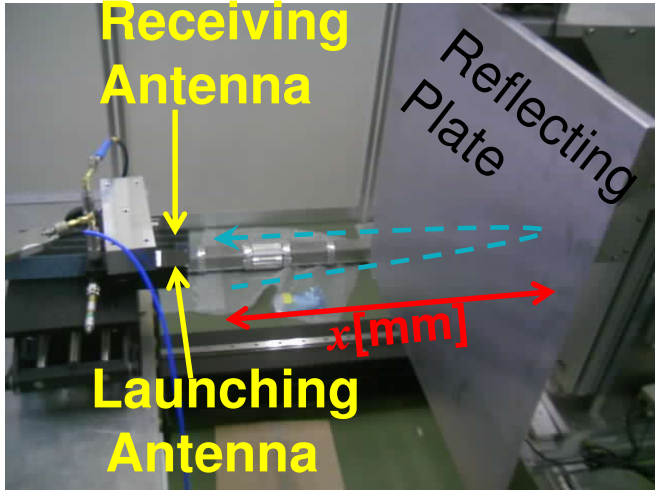
EBW Emission:
-- Inverse process for EBWH/CD --

The PAA system will be used to investigate mode conversion phenomena into the Bernstein wave.

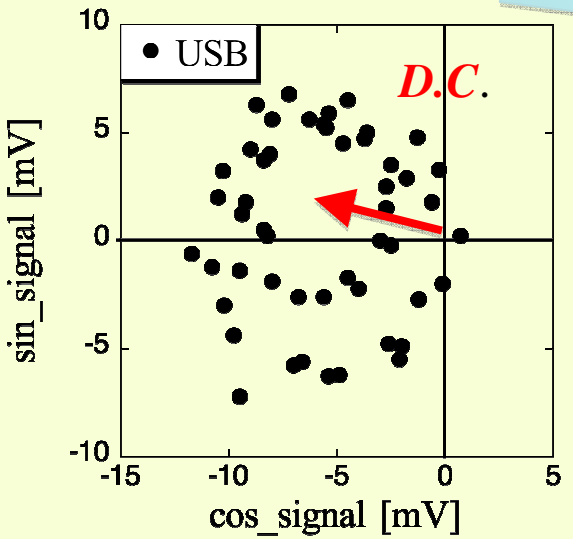
Differential-phase Reflectometry using Phased-array Antenna

QUEST Advanced Fusion Research Center

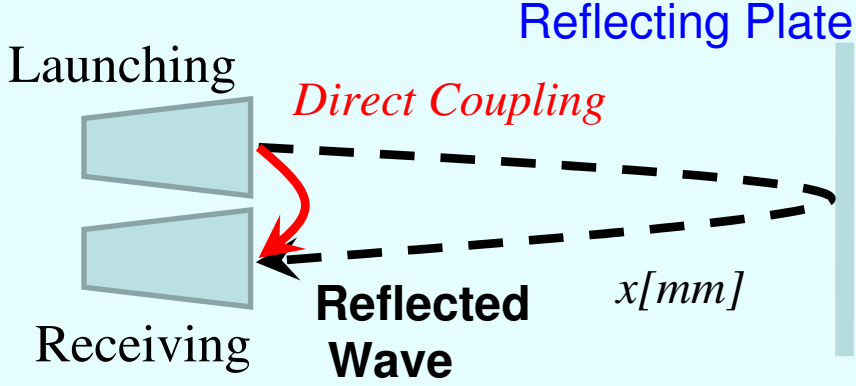




Lissajous Fig.



In ST, the operating frequency range is low…

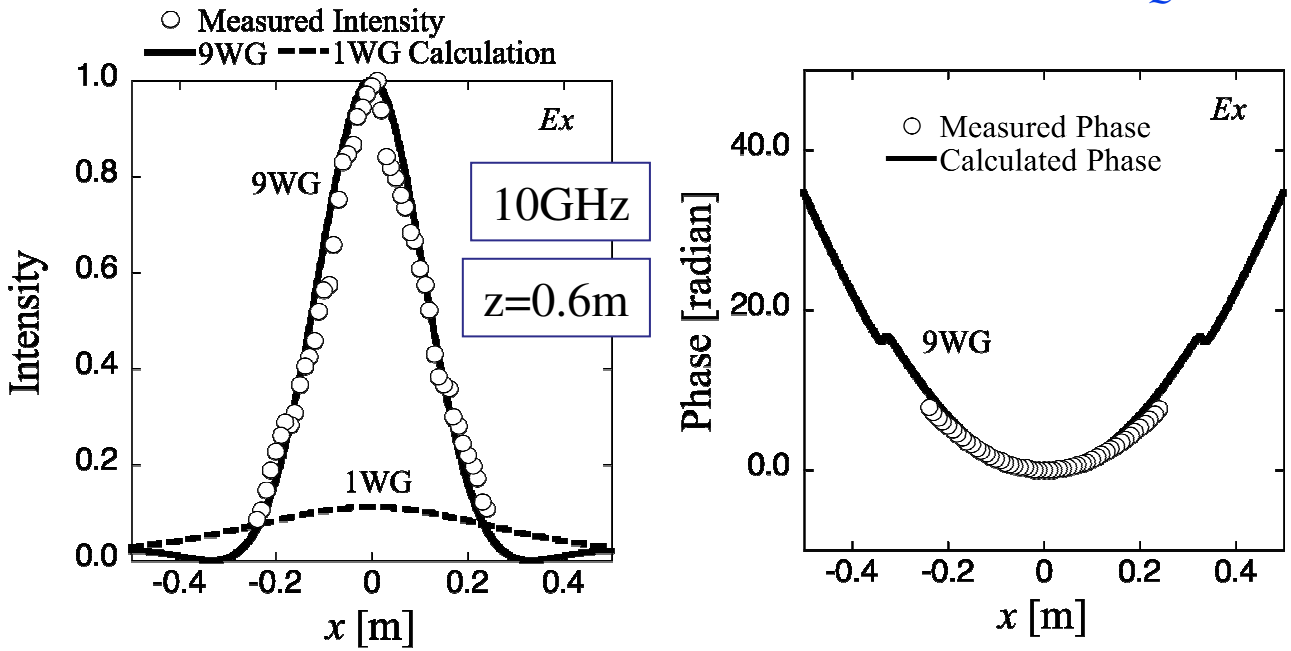


- Diffraction effect
- non-Focused Beam
  (bad Directivity)

Propagation Length ↑
Signal Level of Reflected Wave ↓

Differential-phase Reflectometry using Phased-array Antenna

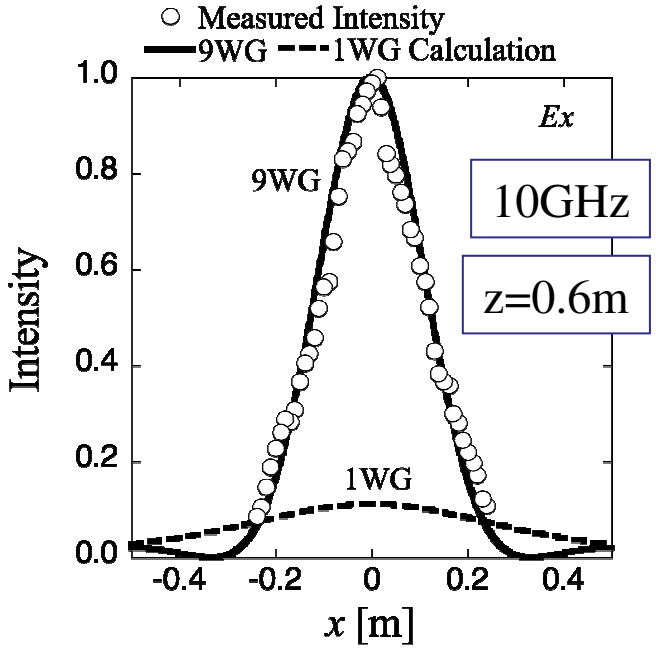
QUEST Advanced Fusion Research Center

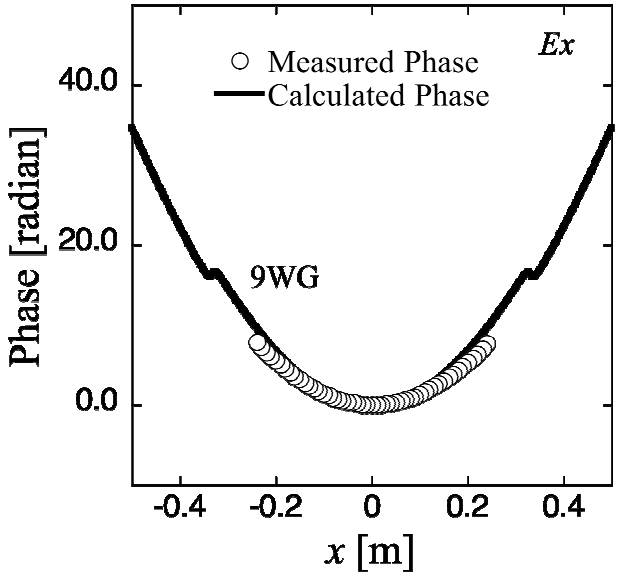


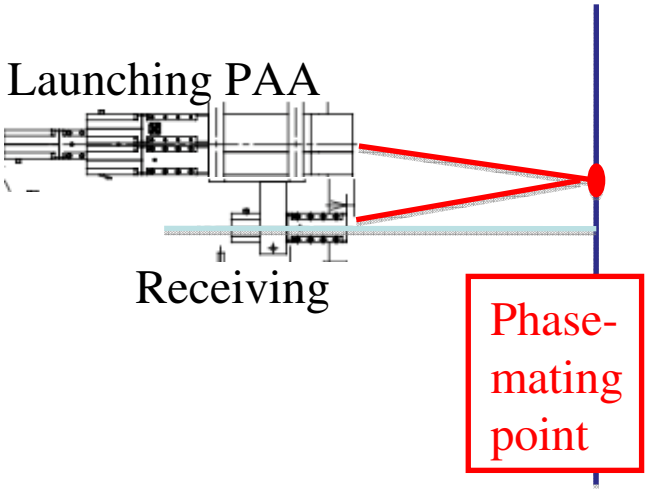
The PAA system focused the radiated field with good directivity even in the larger propagating length.

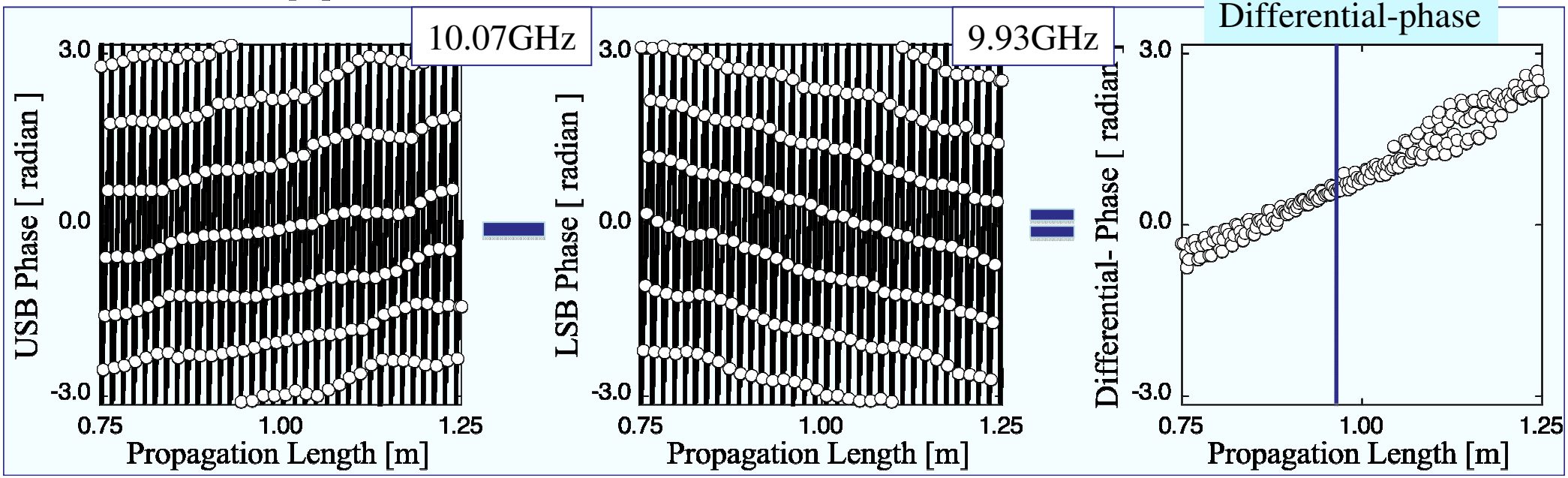
Differential-phase Reflectometry using Phased-array Antenna

QUEST Advanced Fusion Research Center









Summary

The EBWH/CD experiments using the 8.2GHz/200kW system has been conducted in QUEST.

The OMT and phased-array antenna system has been designed to control the polarization state and the launching angle.

The measured field profiles were in excellent agreement with the Kirchhoff integral evaluation.

The non-inductive current of 10kA was ramped-up and sustained for 0.8s at P_{RF}=30kW.

The CW antenna system has been designed and fabricated. The antenna is installing in the lower side for a equatorial plane in the QUEST.

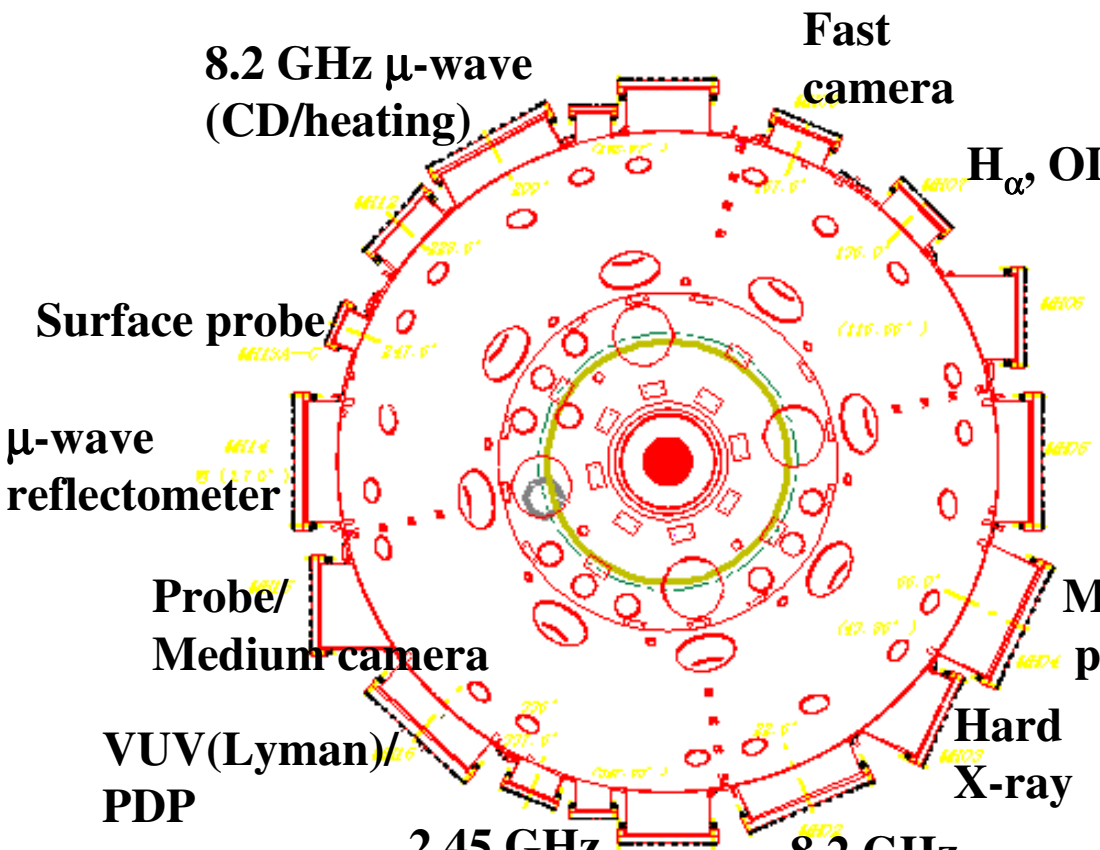
The phased-array antenna was also developed for the EBW radiometry and the reflectometry to study mode conversion phenomena It was confirmed to work correctly.

The EBWH/CD experiments using the CW antenna will start from a next week.

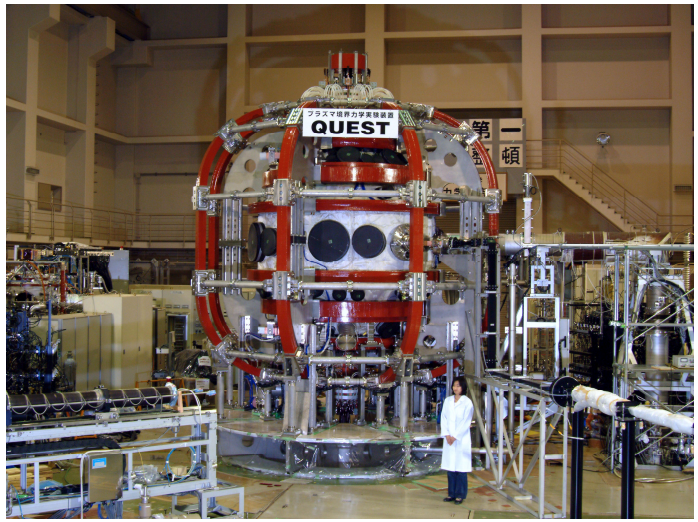
Backup slides

QUEST [Q-shu Univ. Exp. with Steady State Spherical Tokamak]

QUEST Advanced Fusion Research Center



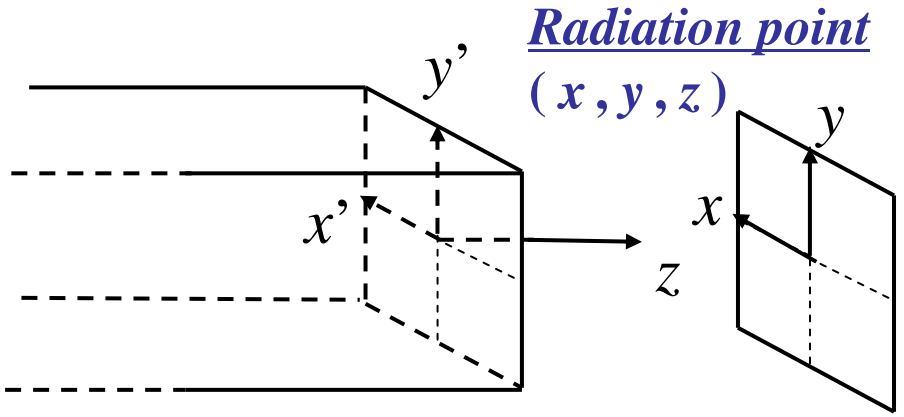
Major Radius :	0.68m
Minor Radius :	0.36m
*B*t:	0.25T[CW], 0.5T [Pulse]
Heating / CD:	8.2GHz 200kWx2 2.45GHz 50kW



Radiation Field of Phased Array Antenna
--Kirchhoff Integral and HFSS code --

QUEST Advanced Fusion Research Center

Kirchhoff Integral



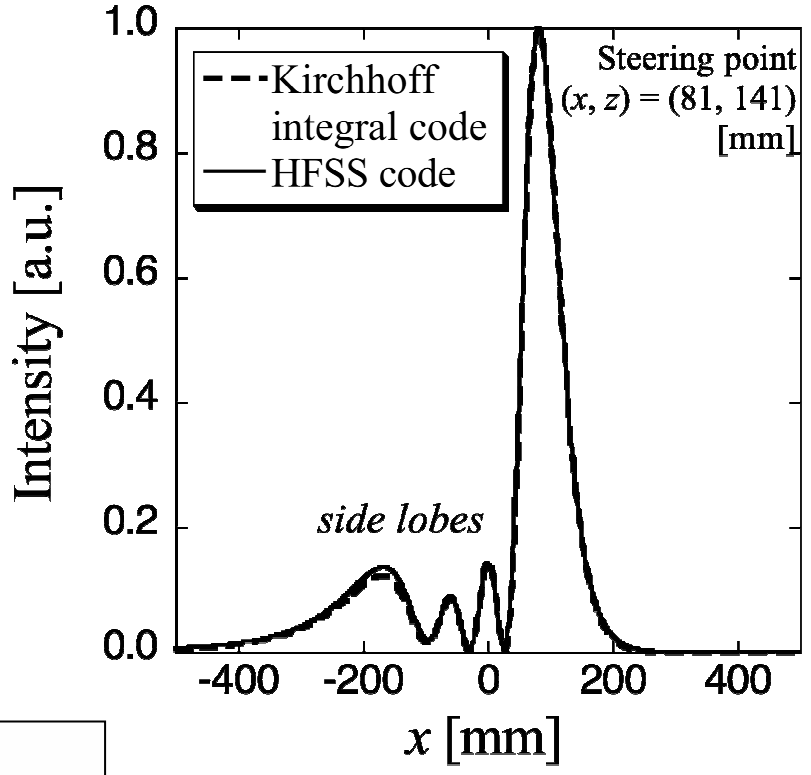
Output aperture

[Phased Square Waveguide array]

1 port

$$E_{x,y}(x,y,z) = \frac{ik}{2\pi z}\int_{-a/2}^{a/2}\int_{-a/2}^{a/2} E_{x,y}(x',y')[\exp(-ikr)/r]\mathrm{d}x'\mathrm{d}y',$$

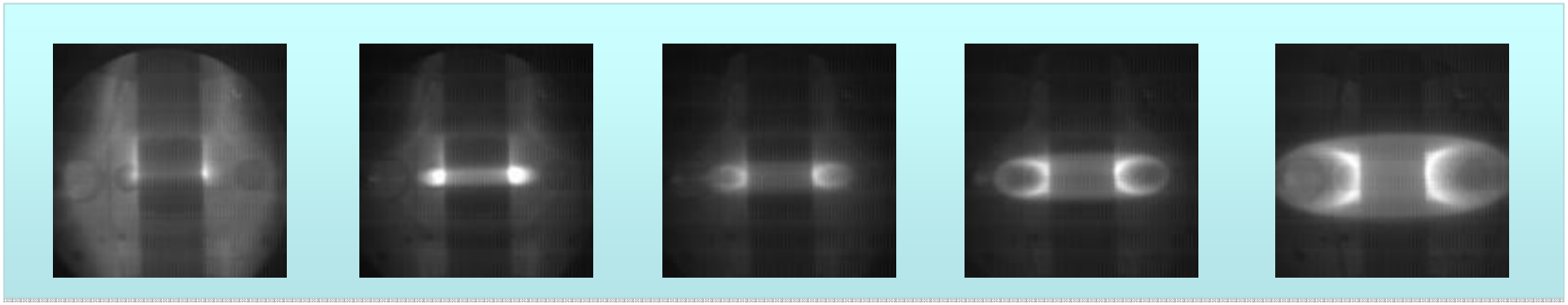
$$r = \sqrt{(x-x')^2+(y-y')^2+z^2},$$

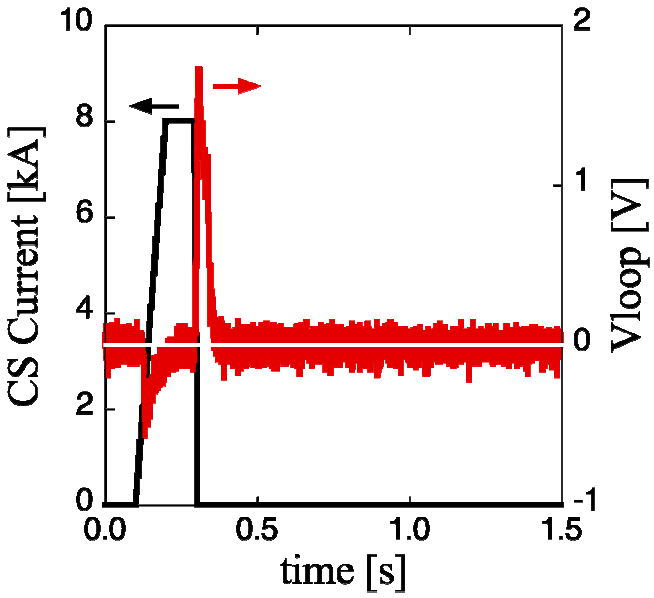


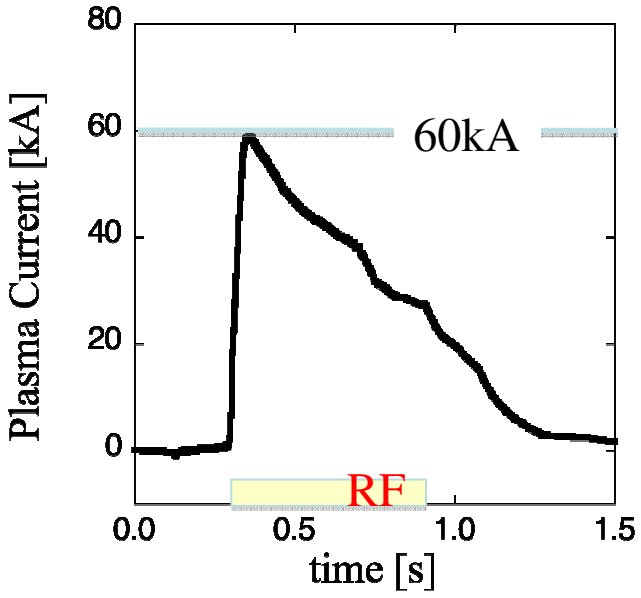
The Kirchhoff integral code has been developed for the optimization of incident conditions in the EBWH/ EBWCD experiments.

OH Discharge [< 60kA]

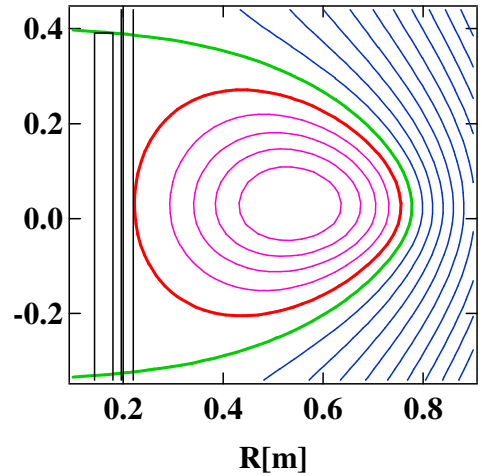
Fast Camera Diagnostics





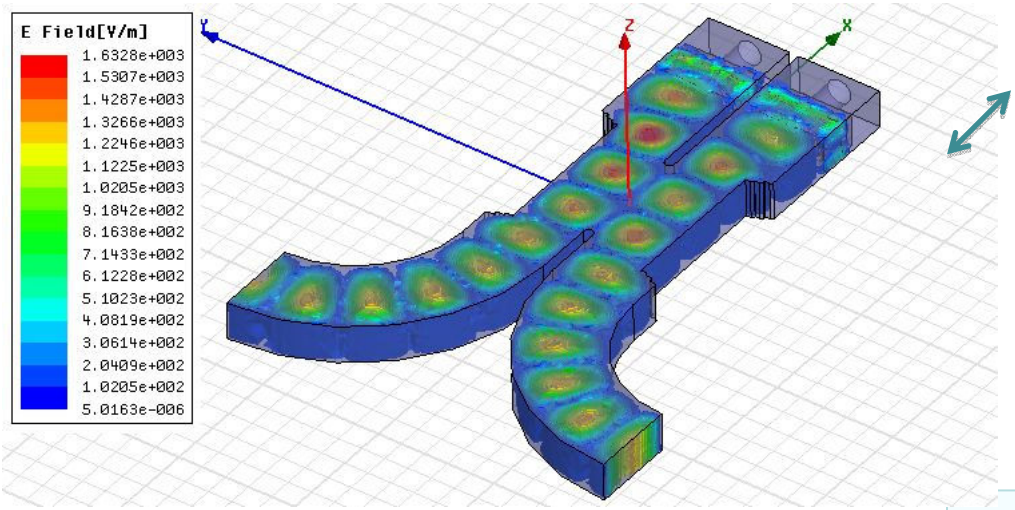


Magnetic flux surface



High Power Fast-scanning Phase Shifter

QUEST Advanced Fusion Research Center



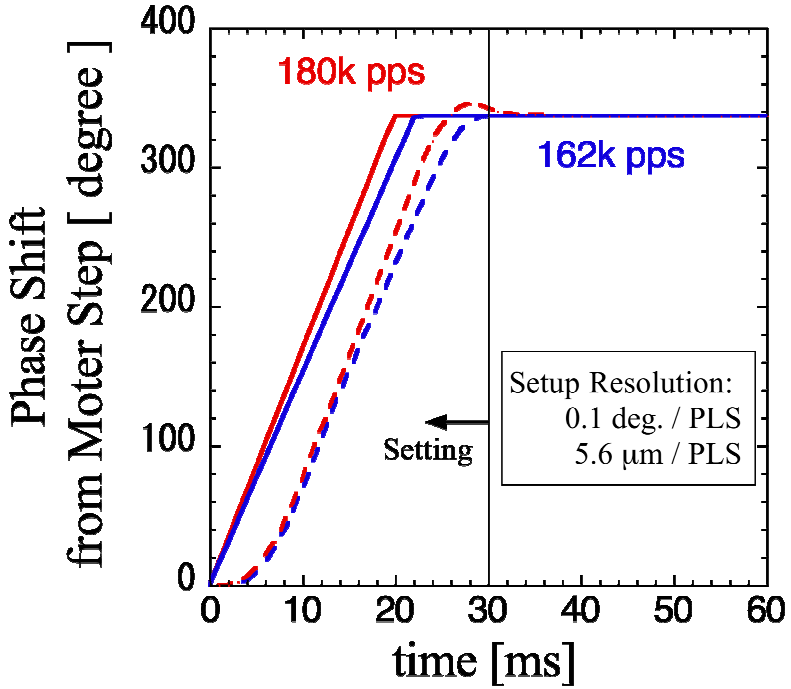
Feed-back Phase Control

Incident Polarization ⟷ $I_p(t)$

Incident N// ⟷ $n_e(t)$

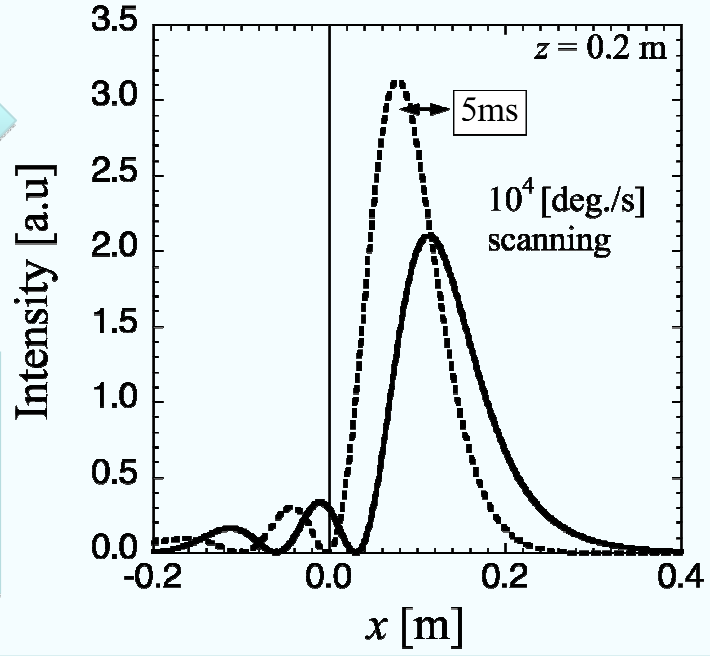
12.5kW CW

10^4 degree/s scanning



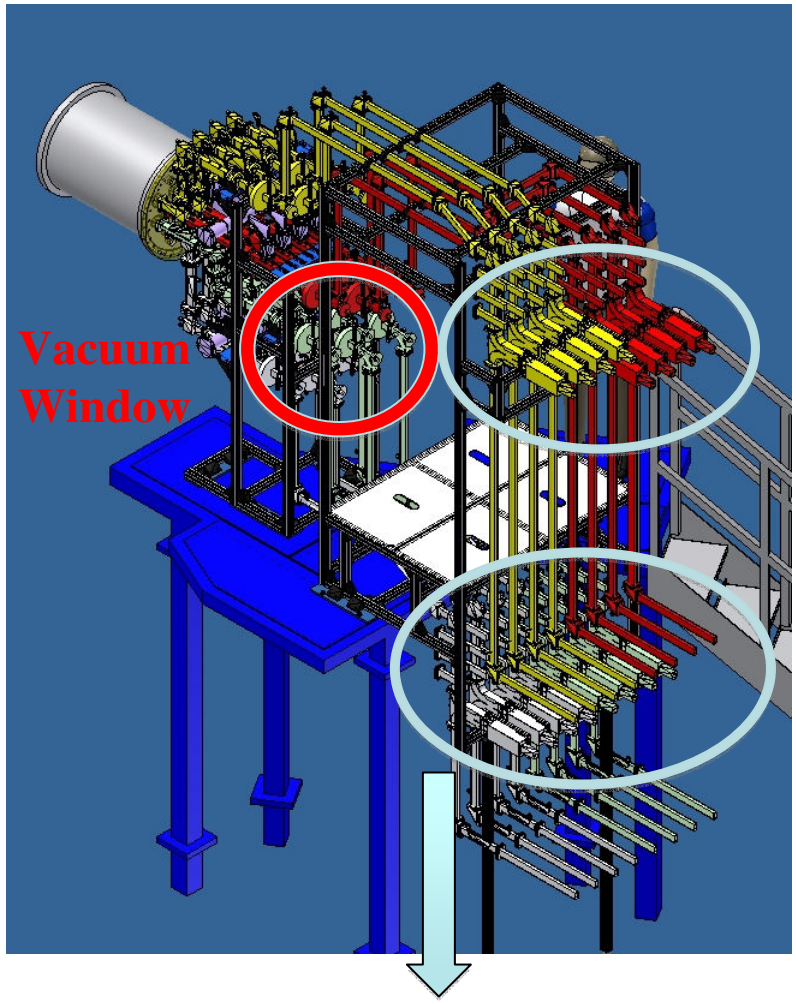
N//-scanning:

Polarization scanning ~9 ms from lin. to cir.

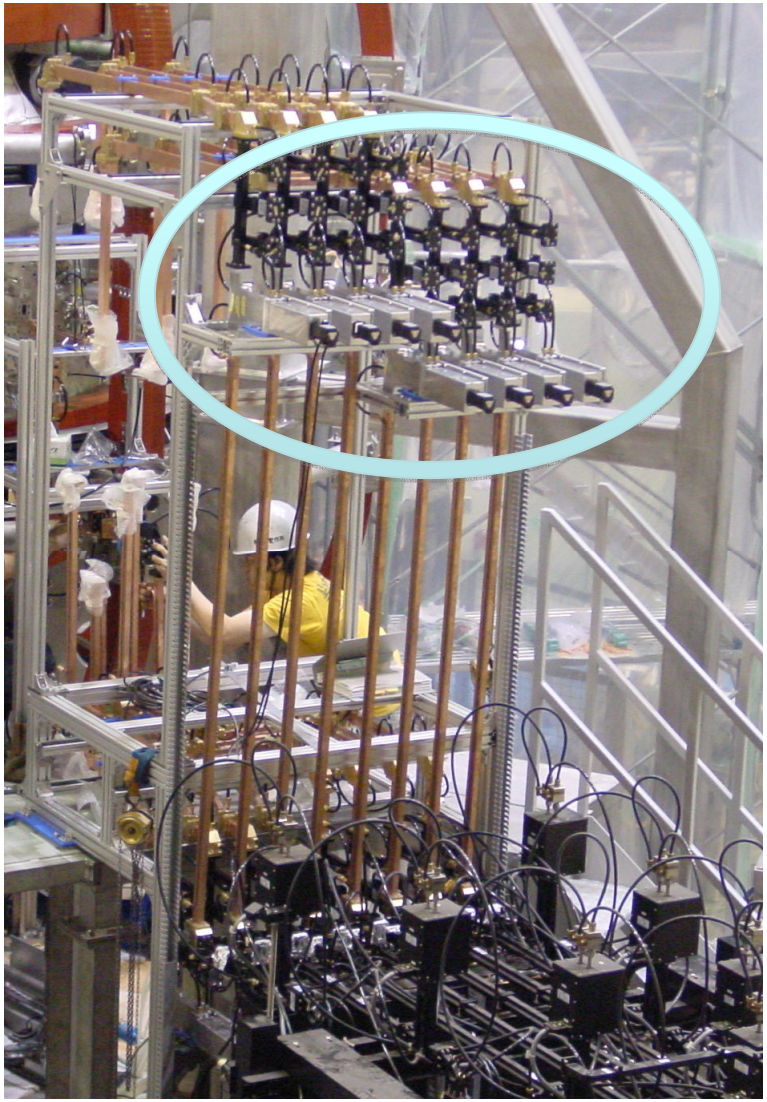


High Power CW Transmission Line

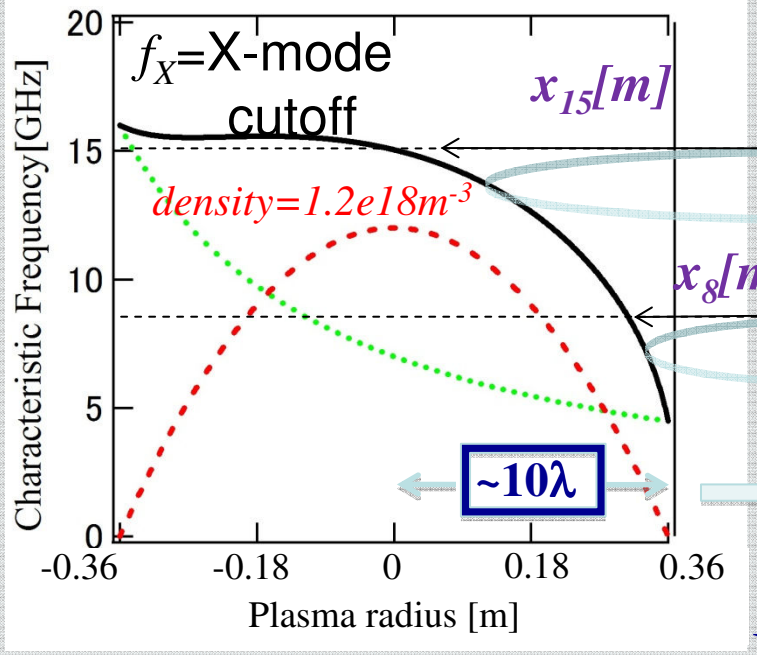
QUEST Advanced Fusion Research Center

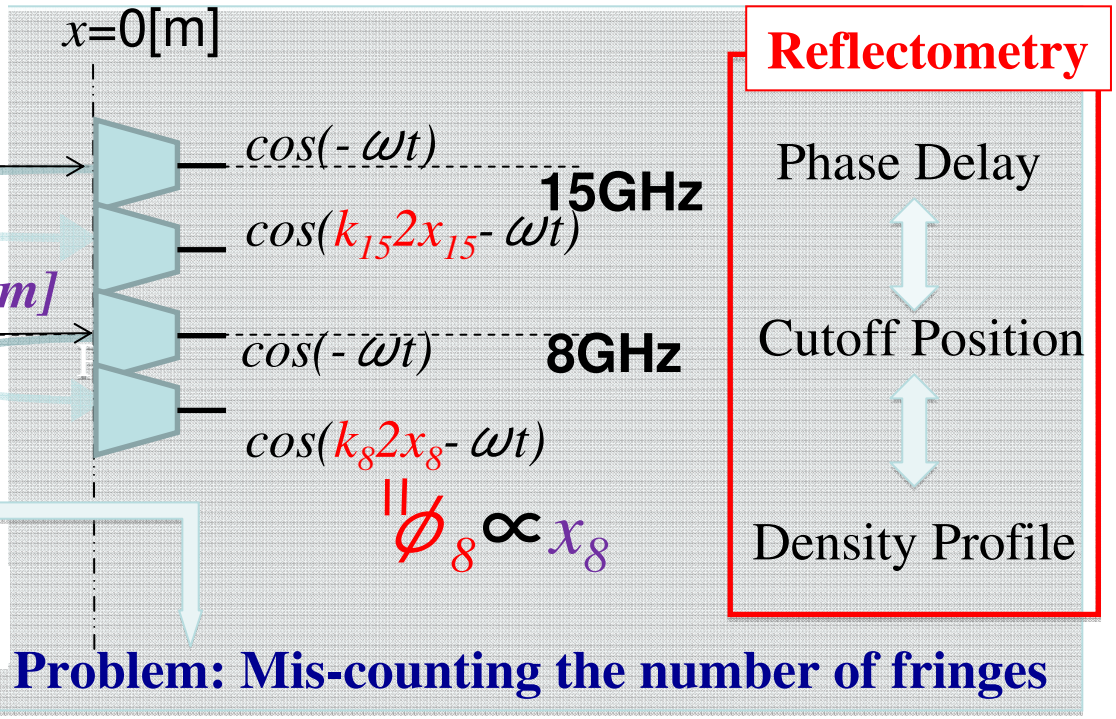


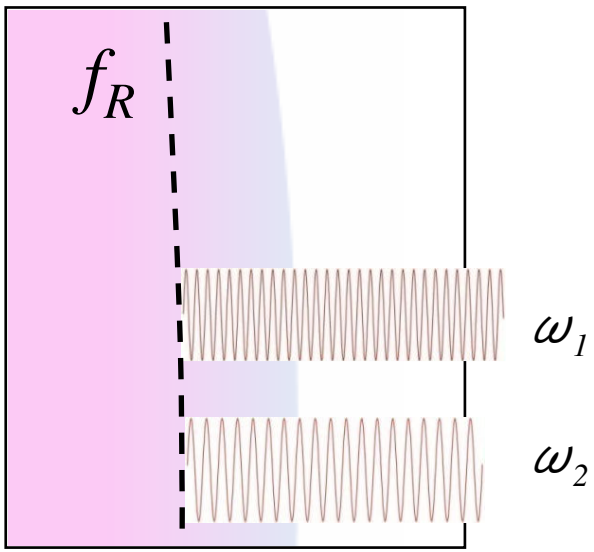
Fast-scanning Phase Shifter



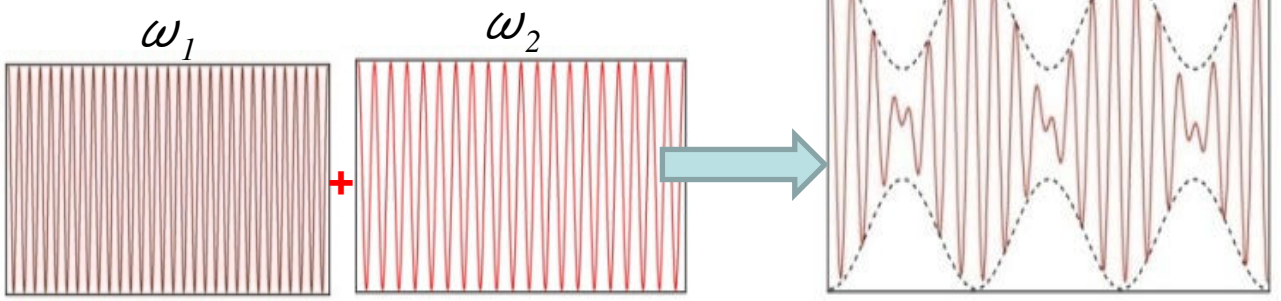
AM Reflectometry







Differential-phase [AM] reflectometry

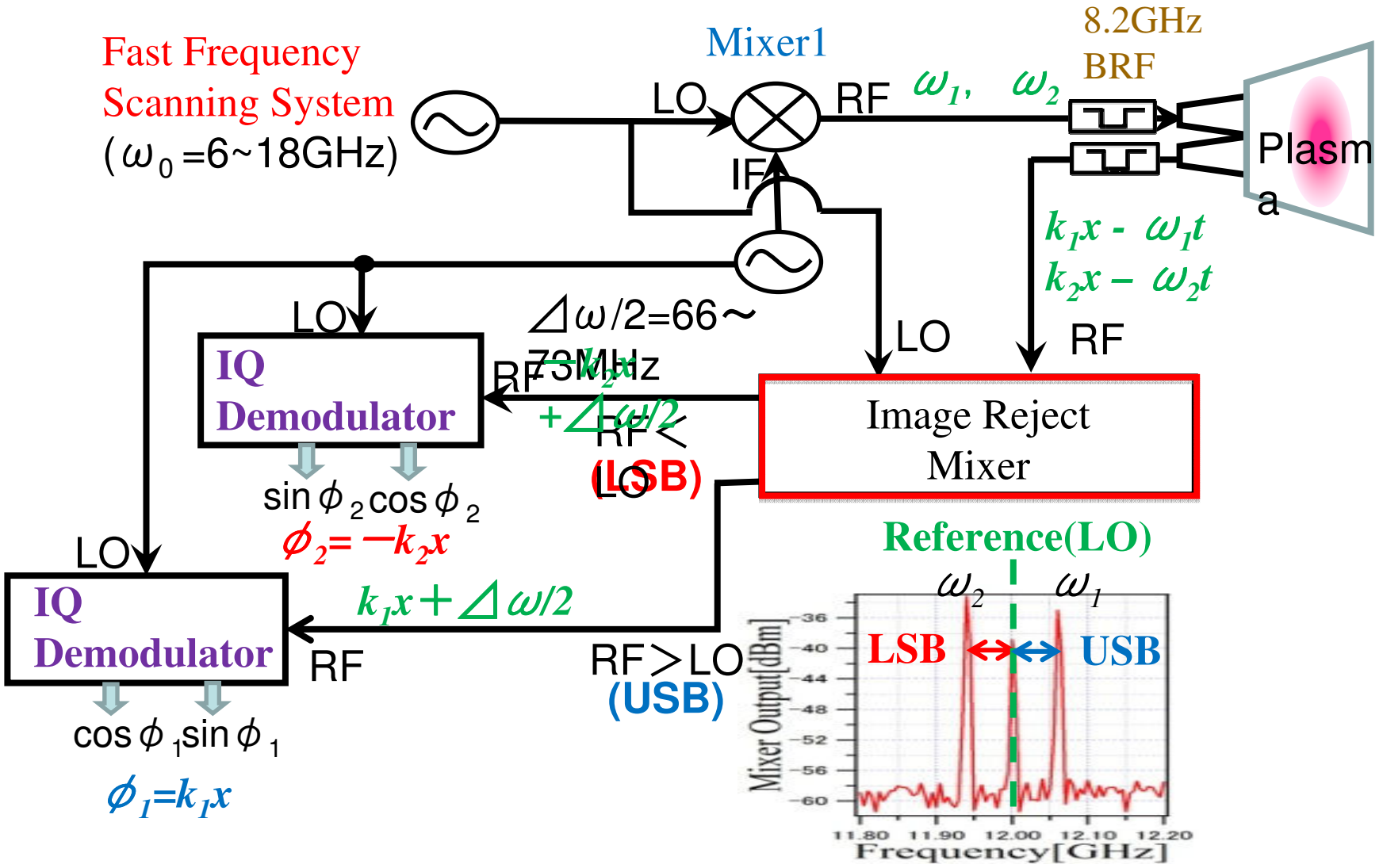


Δkx is measured to avoid the mis-counting.

Amplitude modulation ($\Delta\omega$)

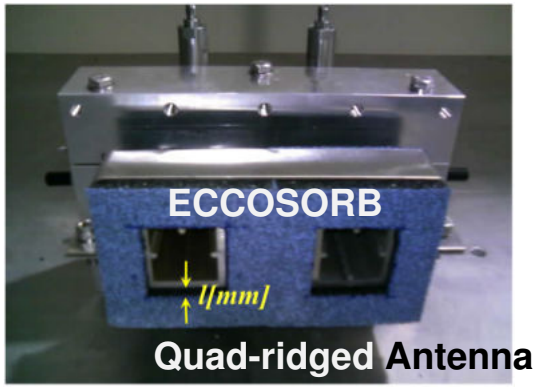
Single-Side-Band Heterodyne Differential-phase Reflectometry

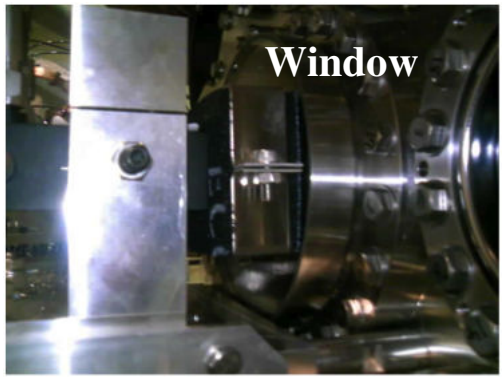
QUEST, Advanced Fusion Research Center



Experimental Setting and Results

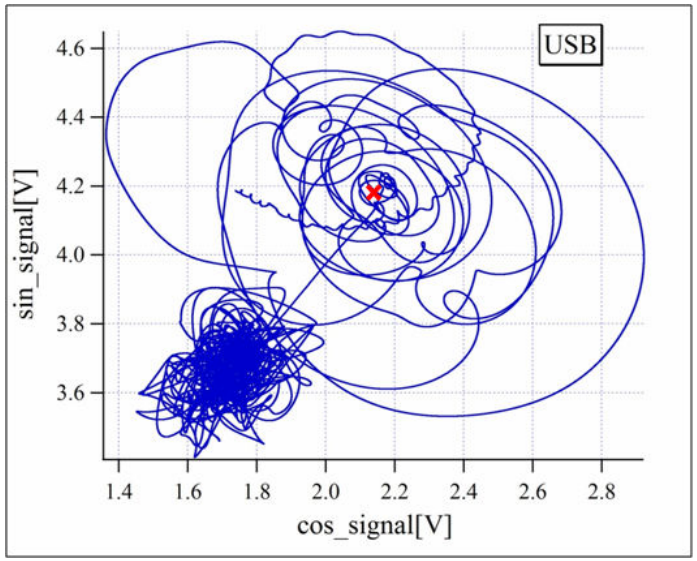
QUEST, Advanced Fusion Research Center

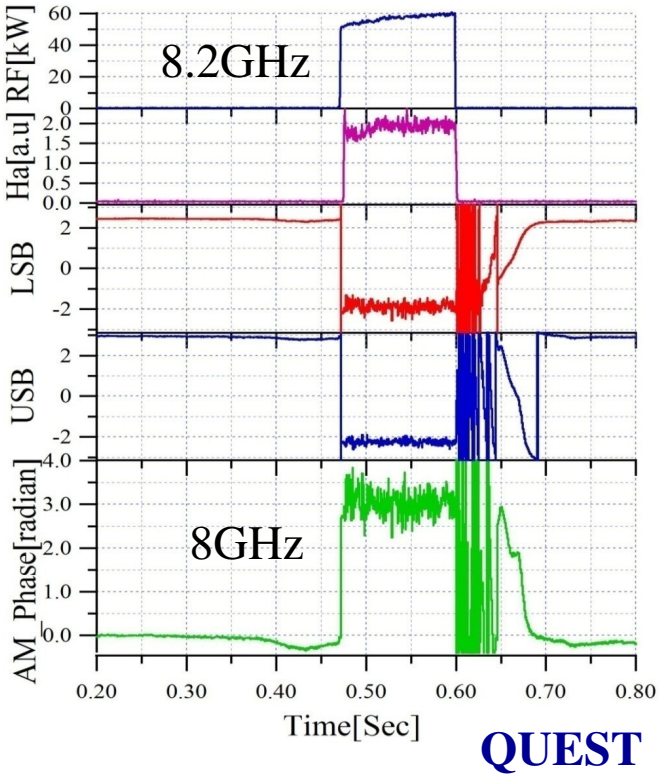




In the QUEST experiments,
two quad-ridged antennae were
set up in front of the vacuum window.

Reflected wave signal





QUEST