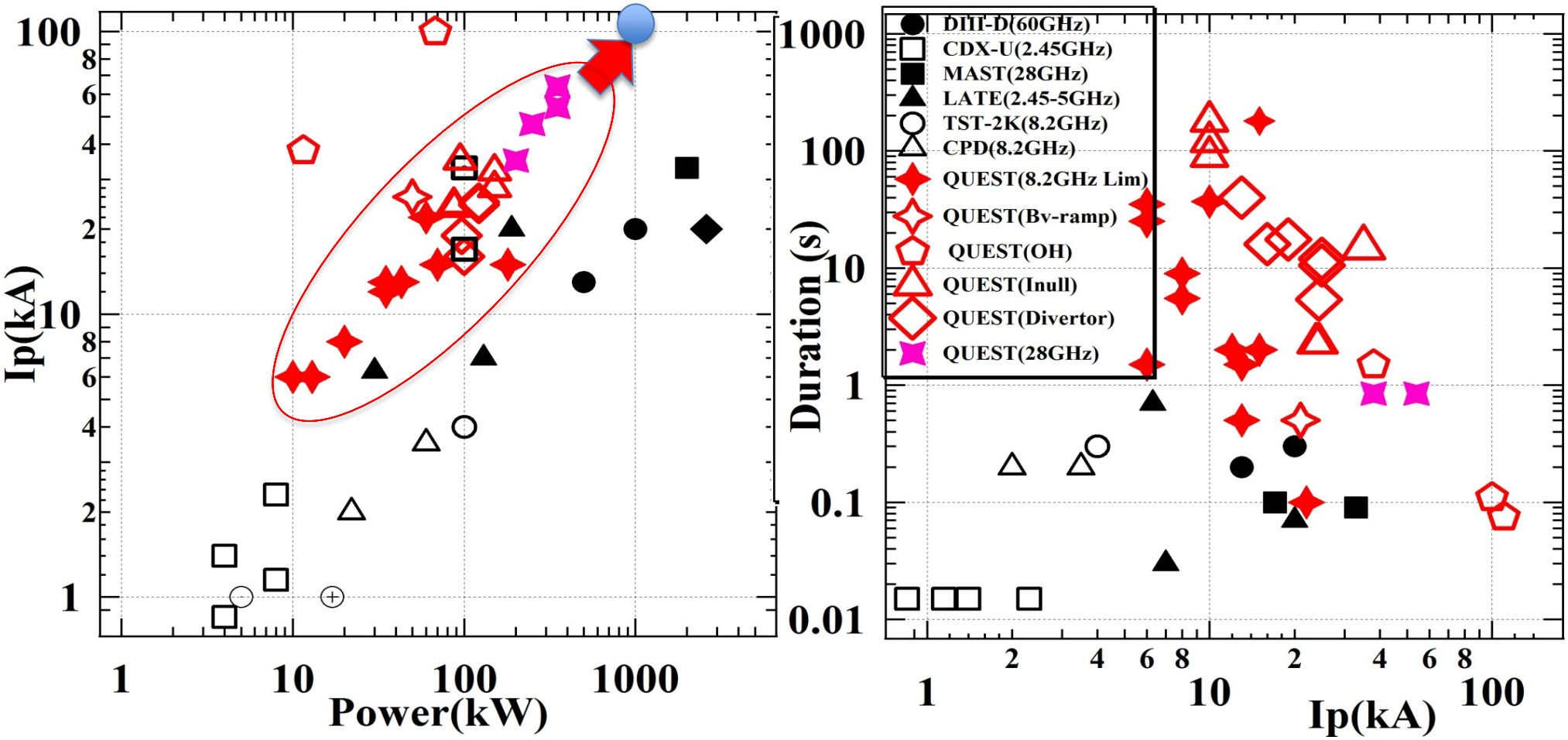
QUESTにおける高周波非誘導電流駆動実験について

ー２周波数(8.2 / 28 GHz) 電子サイクロトロン波加熱・電流駆動実験についてー

1. 新規 28 GHz システムについて
2. 28 GHz 第２高調波加熱・電流駆動効果（OH 放電への重畳）
3. 28 GHz 単独入射実験結果
4. 28 GHz プラズマへの8.2 GHz 重畳入射について
5. 【8.2 GHz + 28 GHz】2 周波数入射
   - 自発的密度ジャンプ現象
   - 高密度プラズマ放電
6. 8.5 GHz / 28 GHz 入射システムの検討

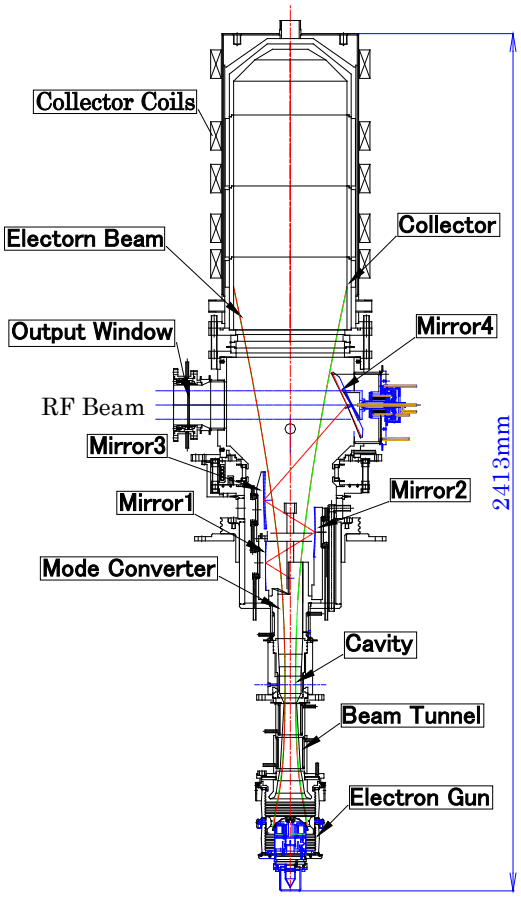
Non-inductive Operation in QUEST

100 kA @1MW



Gyrotron Development at Tsukuba University [28GHz]

QUEST Advanced Fusion Research Center



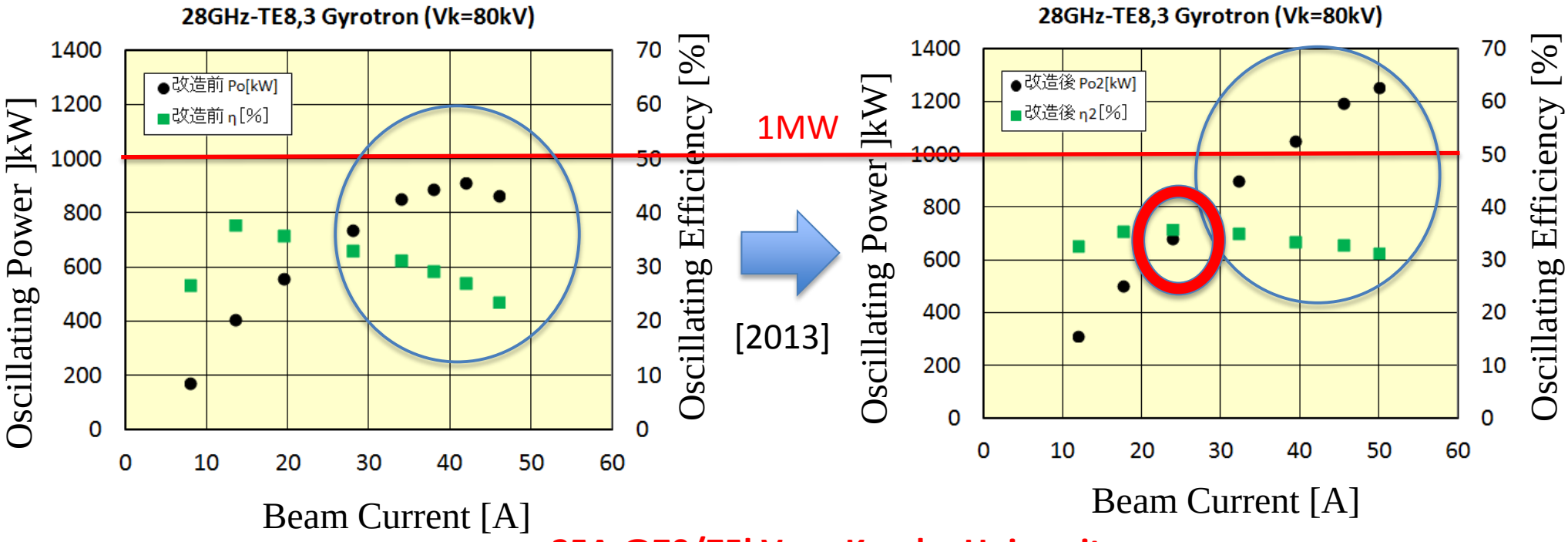
28 GHz gyrotron has been developed for Gamma-10/PDX projects at Tsukuba University.

Design Parameters From T. Kariya

28GHz 1MW 1s Gyrotorn for PRC(Tsukuba)	
Frequency	28GHz
Output Power	1MW
Pulse Width	1s
Output Efficiency	35% (W/O CPD)
Beam Voltage	80kV
Beam Current	40A
MIG	triode
Cavity Oscillation mode	$TE_{8,3}$
Built-in Mode Converter	with
Output mode	Gaussian like
Output Window	Sapphire Single Disk
	Aperture diameter 112mm
Collector	W/O CPD
	Sweeping coils

Gyotron Development at Tsukuba University [28GHz]

QUEST Advanced Fusion Research Center



25A @70/75kV ---- Kyushu University

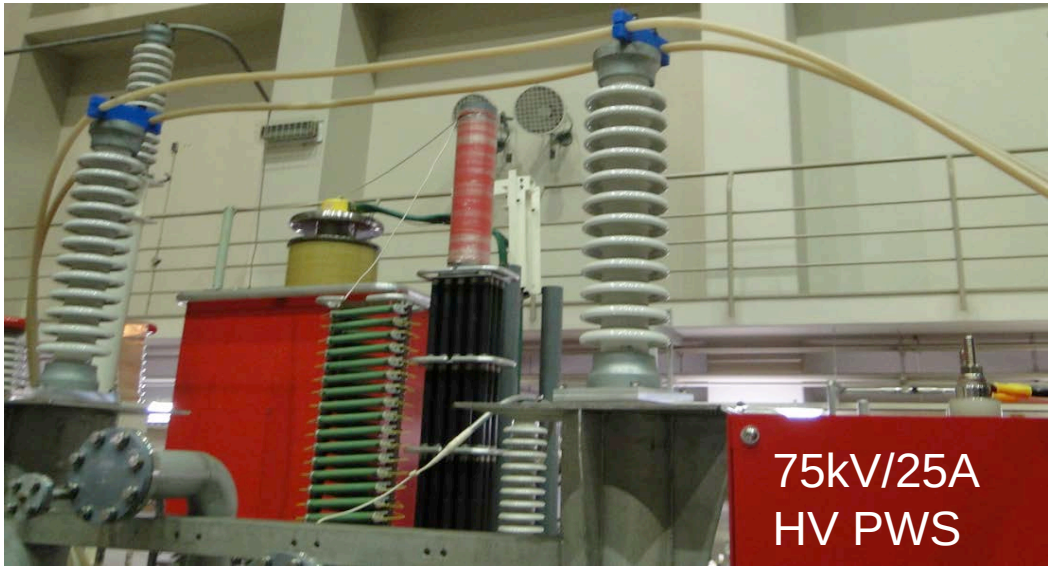
600 kW power level is available with Kyushu Univ. Power Supply.
The oscillating efficiency is improved to attain more than 1MW output.

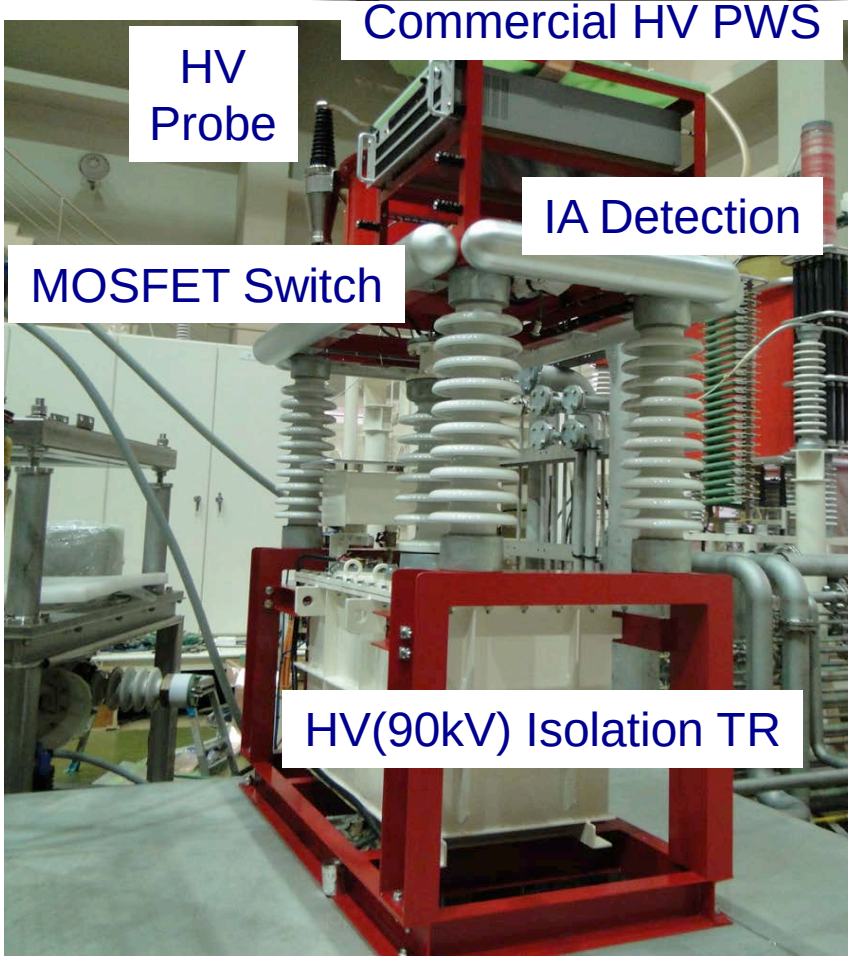
Power Supply System for 28GHz Gyrotron

- Commercial HV PWS (50kV/80mA) has been prepared.
- MOSFET HV switch system was developed for fast HV cut.

50kV / 80 mA

Commercial HV PWS

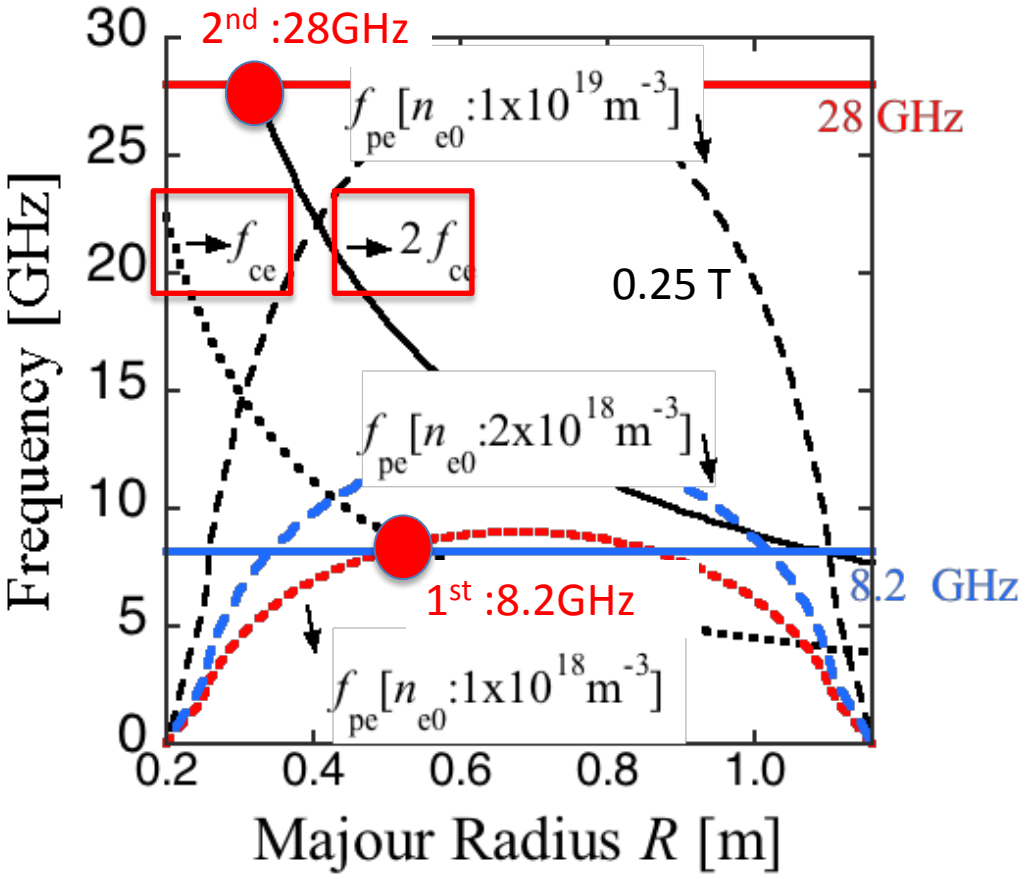


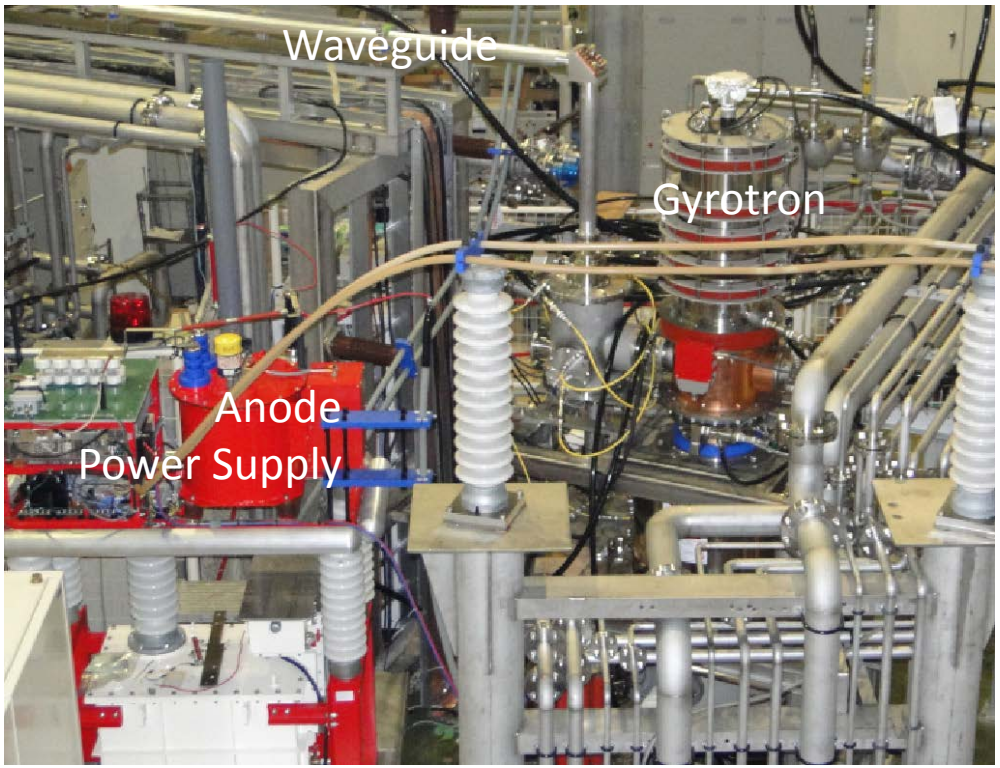


The Cathode HV (75kV/25A) was prepared for a previous 170 GHz gyrotron with diode MIG gun in the TRIAM-1M tokamak experiments.

- Fast Anode HV cut within 1μs after IA OC detection
- Fast Cathode HV cut within 5.6μs after IA OC detection

Experimental Scenario





EBWH/CD Exp. Scenario :

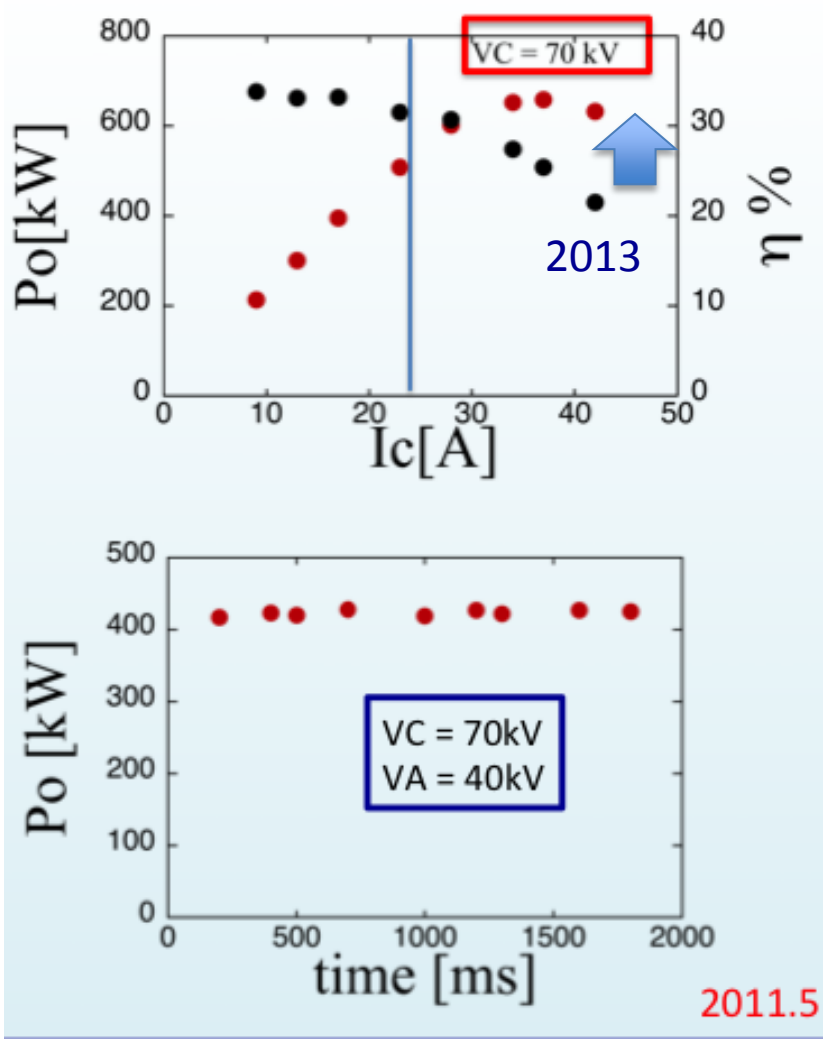
1) 1st : 8.2 GHz: production
2) 2nd : 28 GHz : density ramp-up
3) 1st : 8.2 GHz : EBWCD

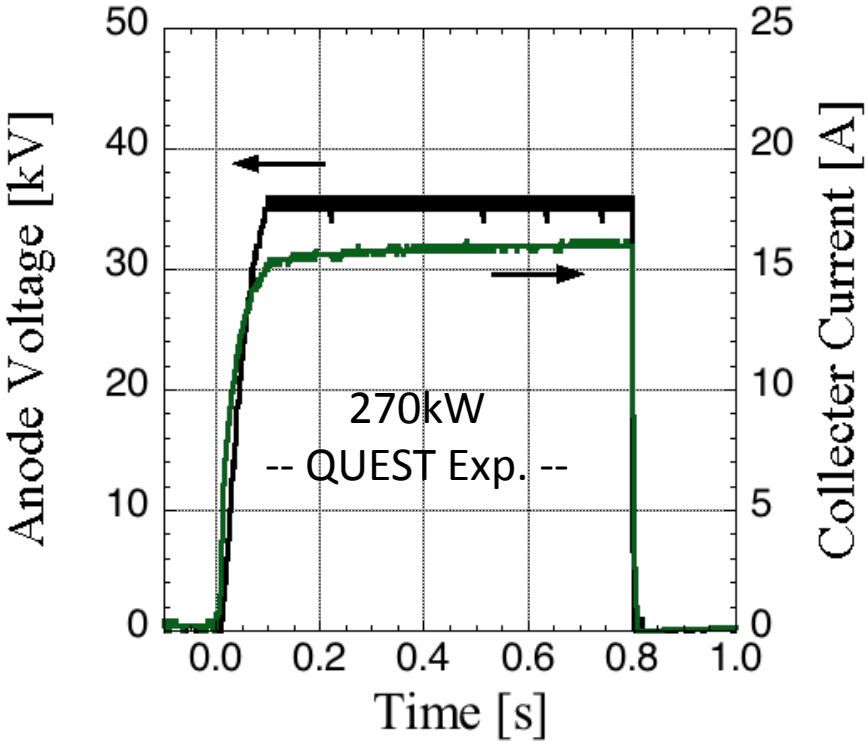
ECH/CD Exp.

Plasma start-up and sustainment
with assistance of 8.2 GHz injection

28GHz Gyrotron Operation in Kyushu

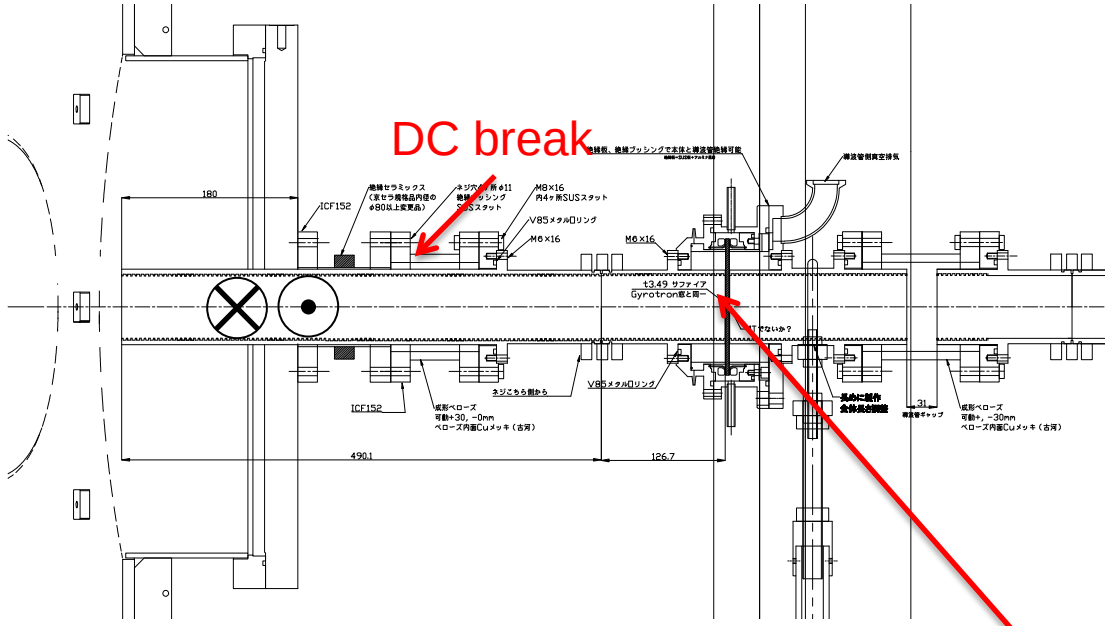
-- Tsukuba test stand --

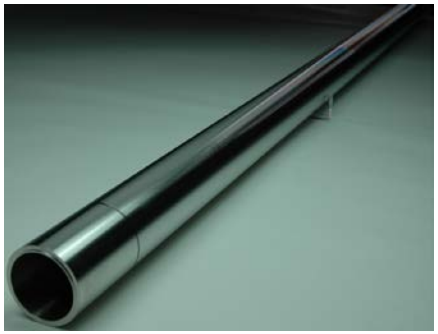




Gyrotron was operated with the power supply of Kyushu University at the Vk of 70kV.

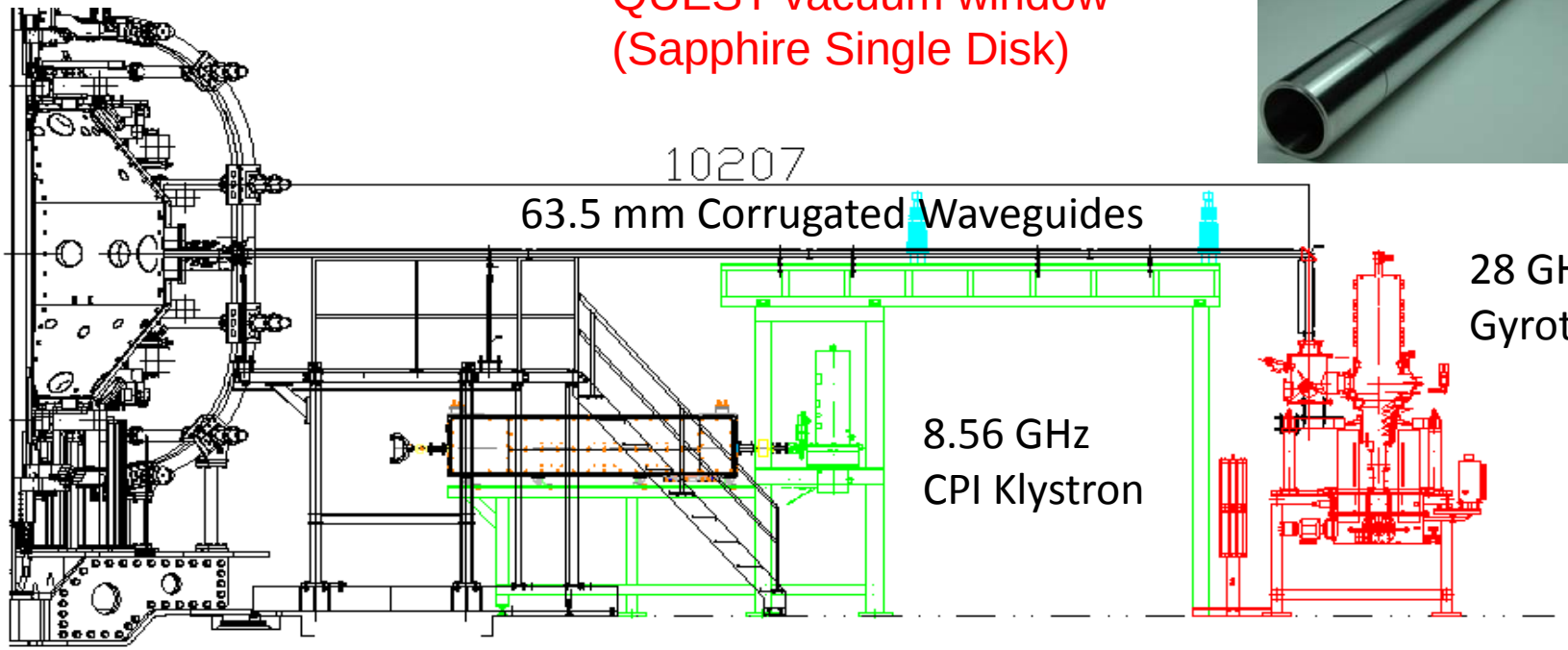
500kW (with 10% MOU loss)
450kW (with 10% MOU loss)
--- Dummy load ---



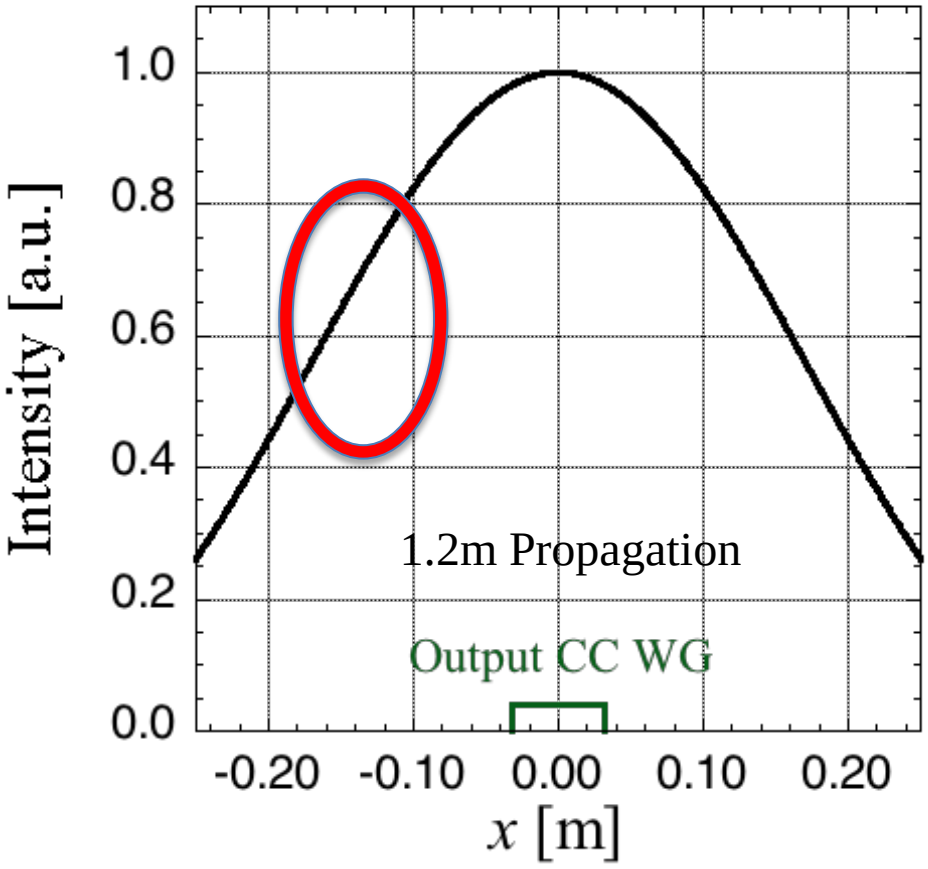


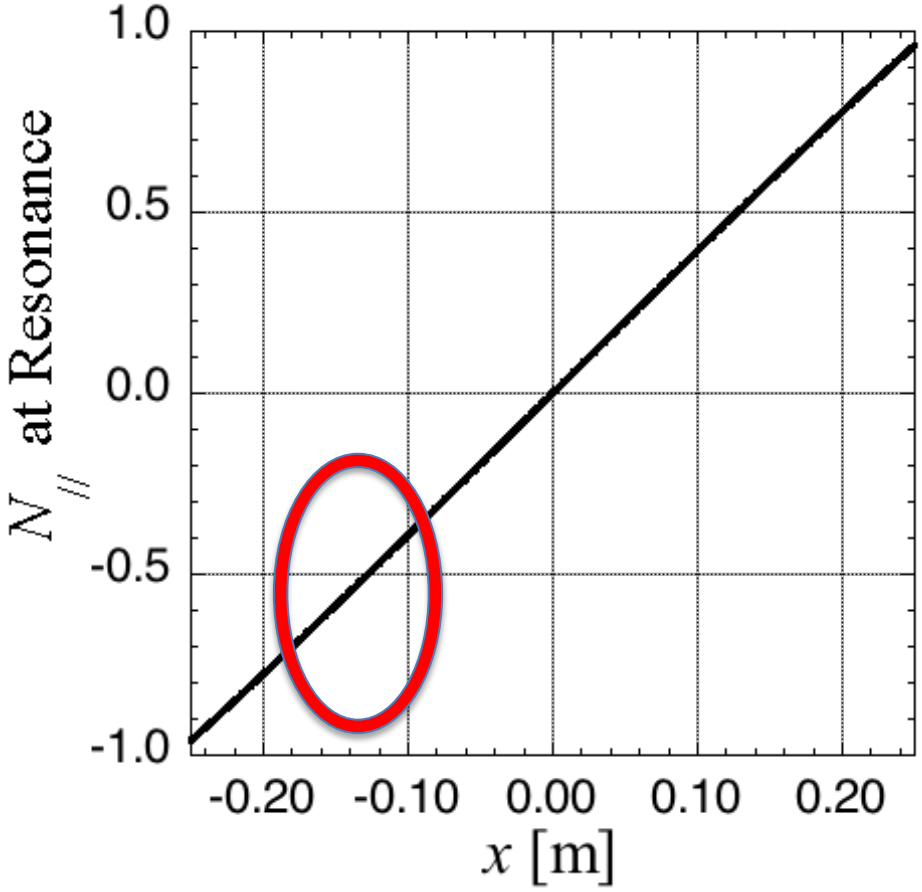
QUEST vacuum window
(Sapphire Single Disk)

QUEST



28GHz Incident Condition



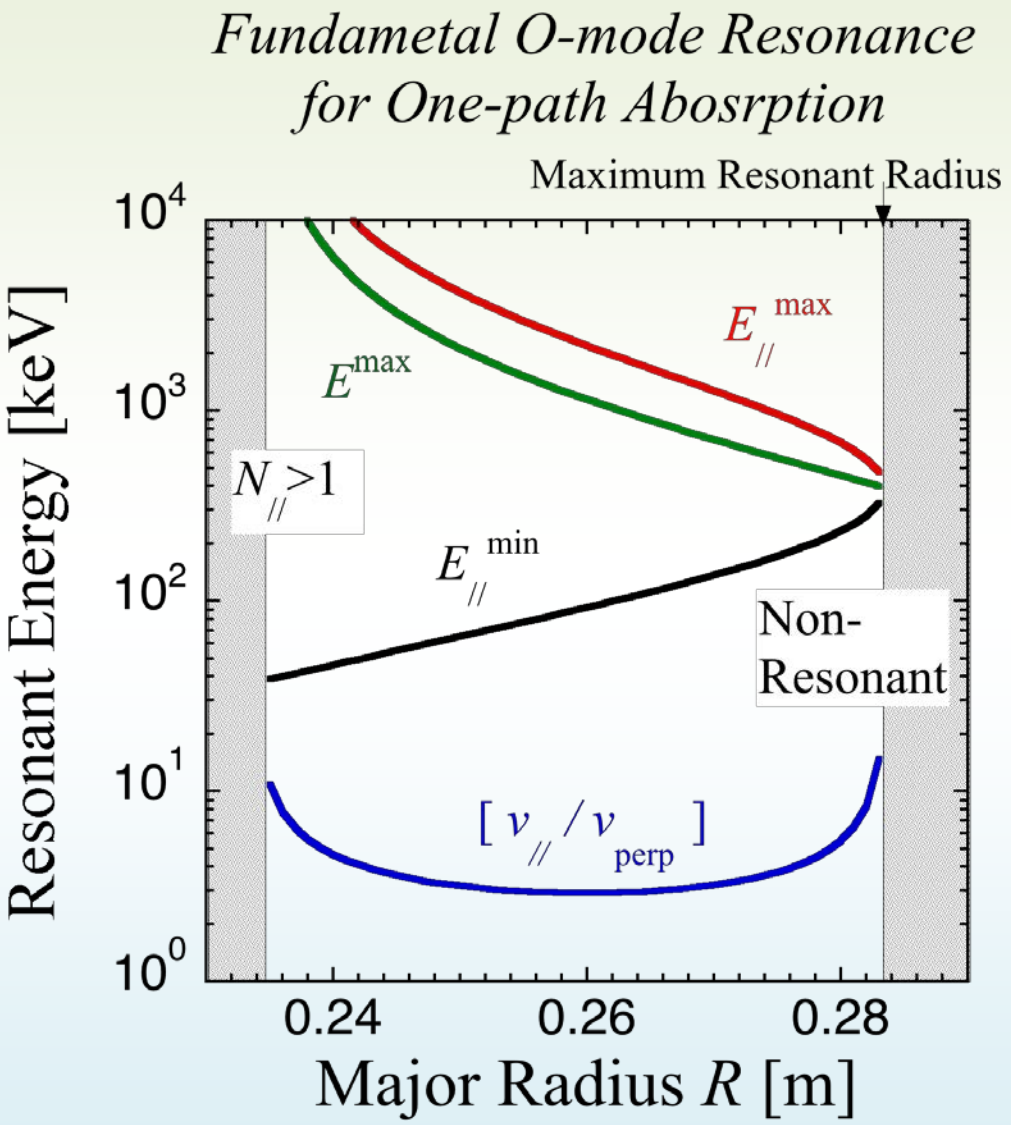


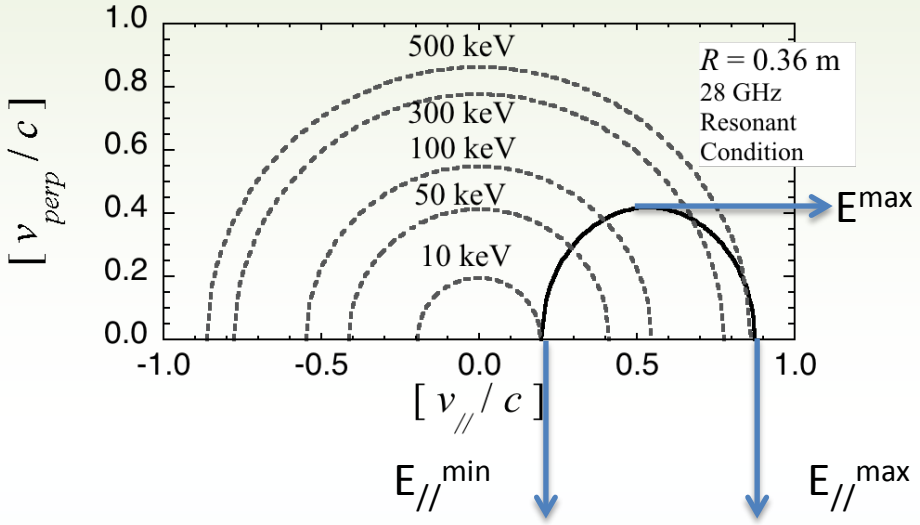
WG Launcher was installed at $R \sim 1.5$m.
Cold Resonance of 28 GHz
is located at $R \sim 0.32$m.

RN//=const.

The beam is launched with rather large $N//$ > 0.5, even for perpendicular injection.

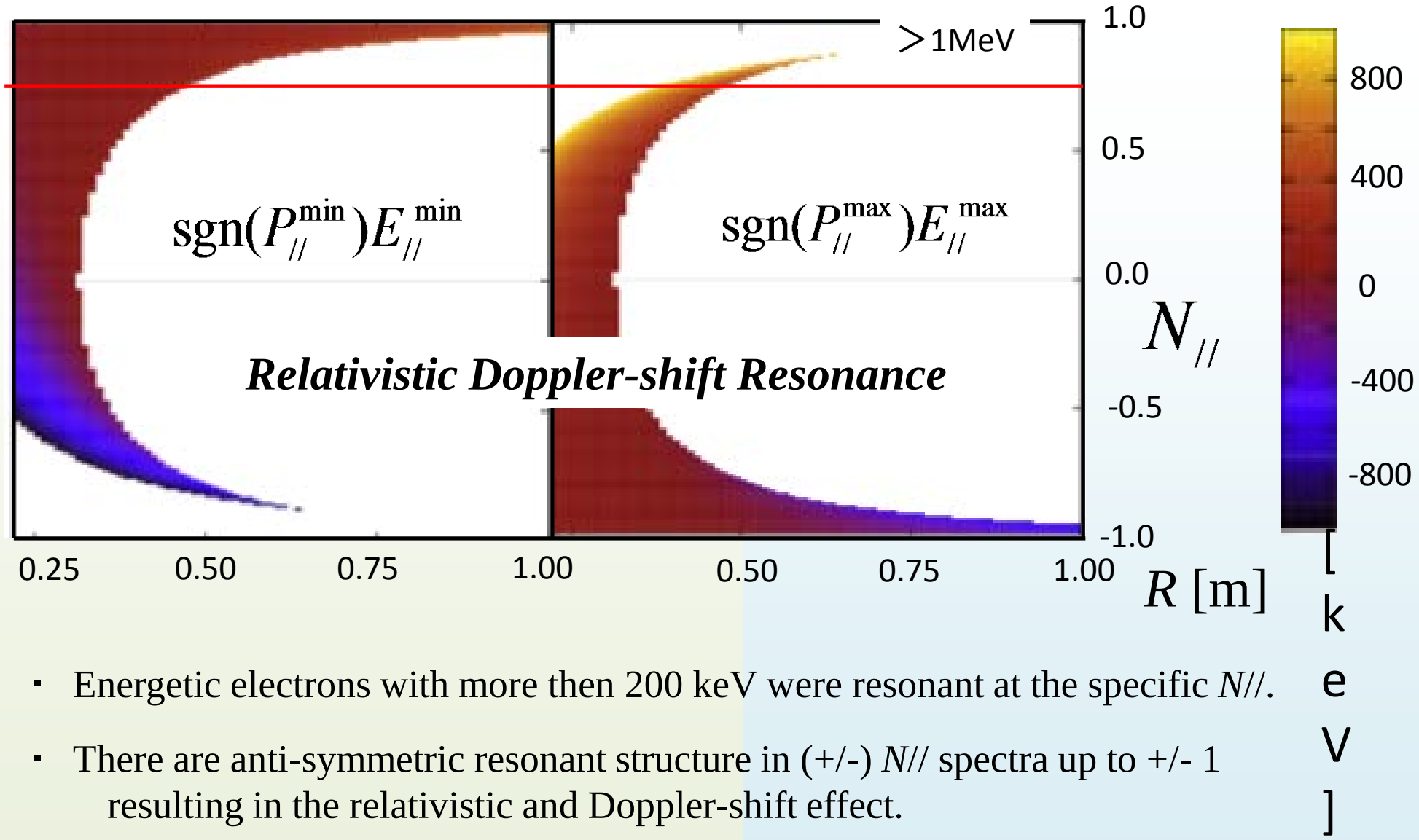
28 GHz Incident Condition [1st Resonance Condition]





High energetic electrons more than 40 keV were resonant or the incident 28 GHz O-mode due to the Doppler shifted effect in the one-path absorption.

2nd harmonic ECH/ECCD【Multiple Wall Effect】



- Energetic electrons with more then 200 keV were resonant at the specific *N*//.
- There are anti-symmetric resonant structure in (+/-) *N*// spectra up to +/- 1 resulting in the relativistic and Doppler-shift effect.

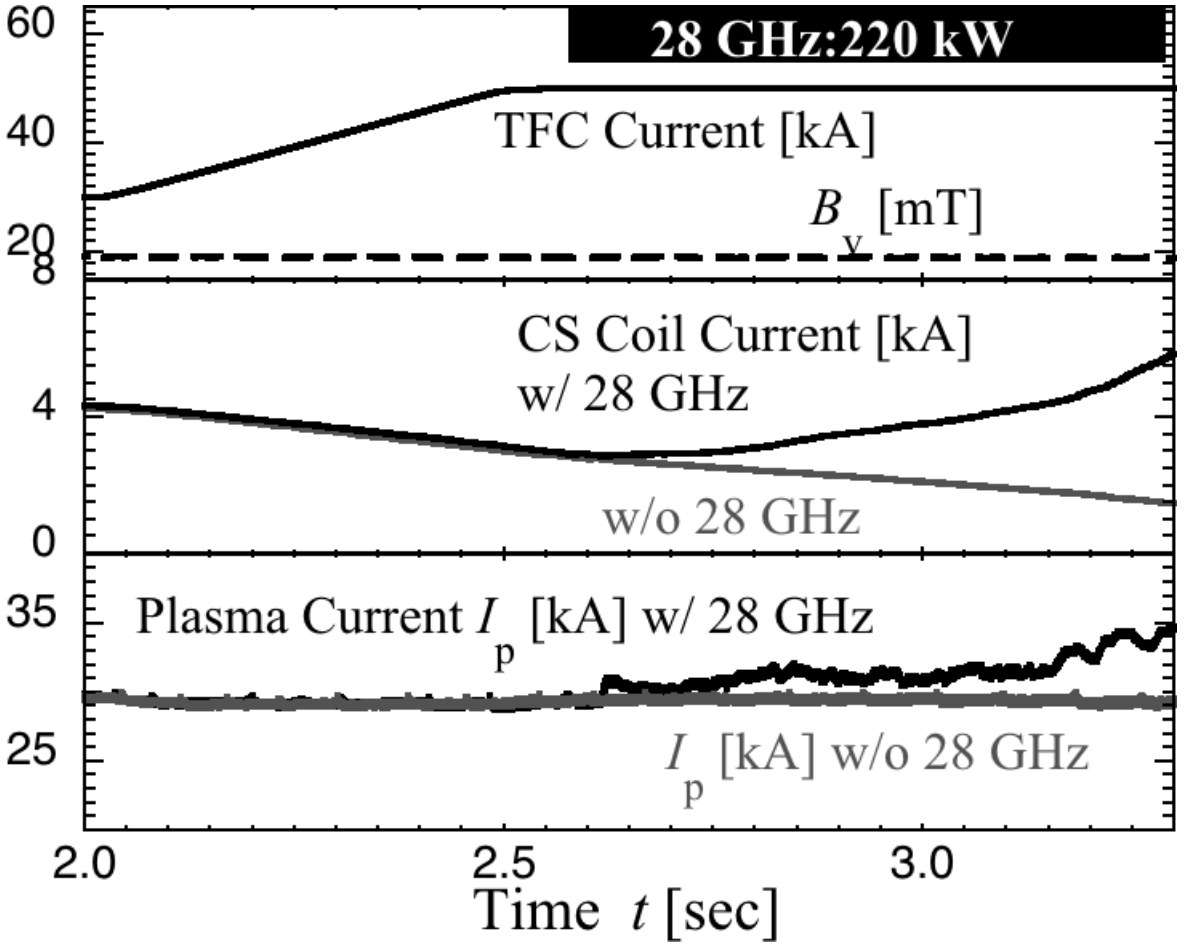
2nd harmonic 28 GHz Off-axis ECCD effect

Although the plasma current has been controlled with the feedback, it began to increase by the 28 GHz injection against retarding electric field by ramp-up of the CS coil current.

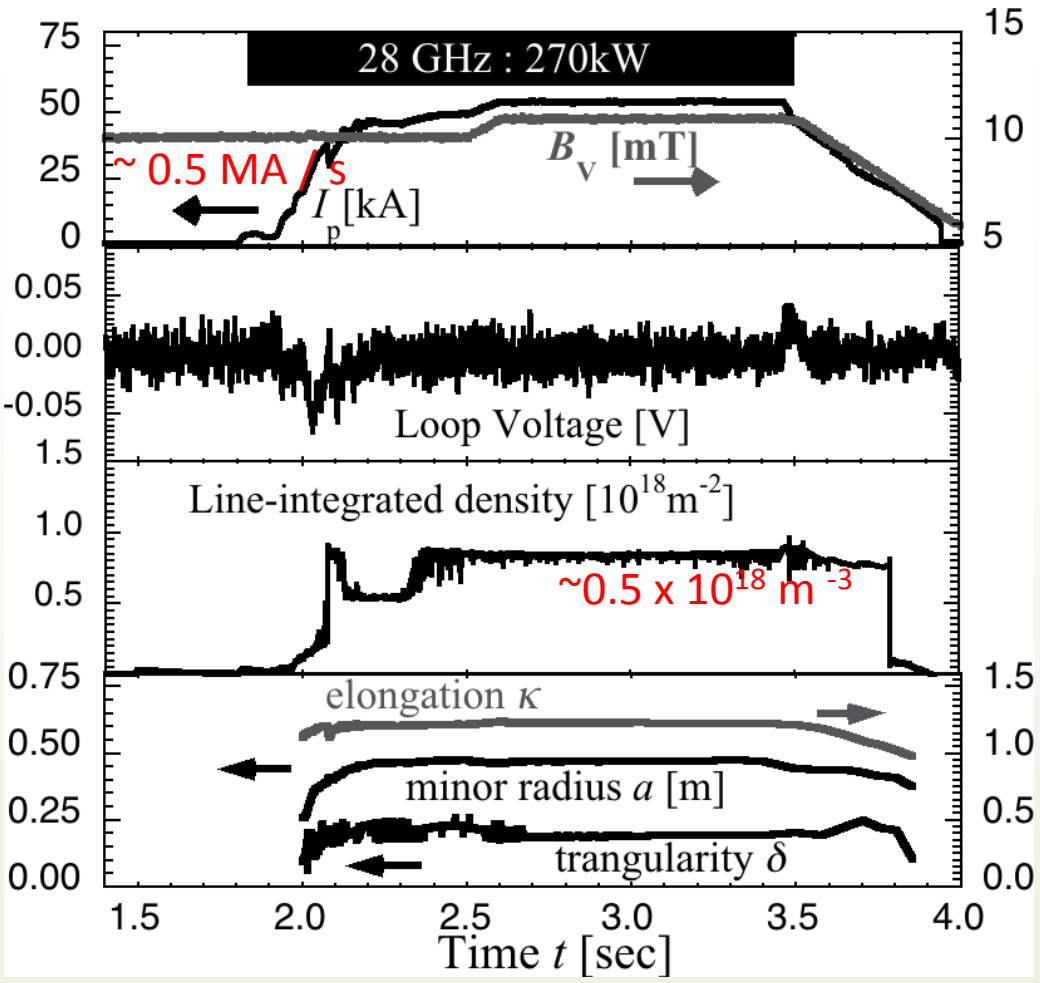
Recharging phenomena in the CS coil power supply were clearly observed.

The plasma current was fully driven only by the 2nd harmonic off-axis 28 GHz injection.

Target : 30kA Ohmic discharge



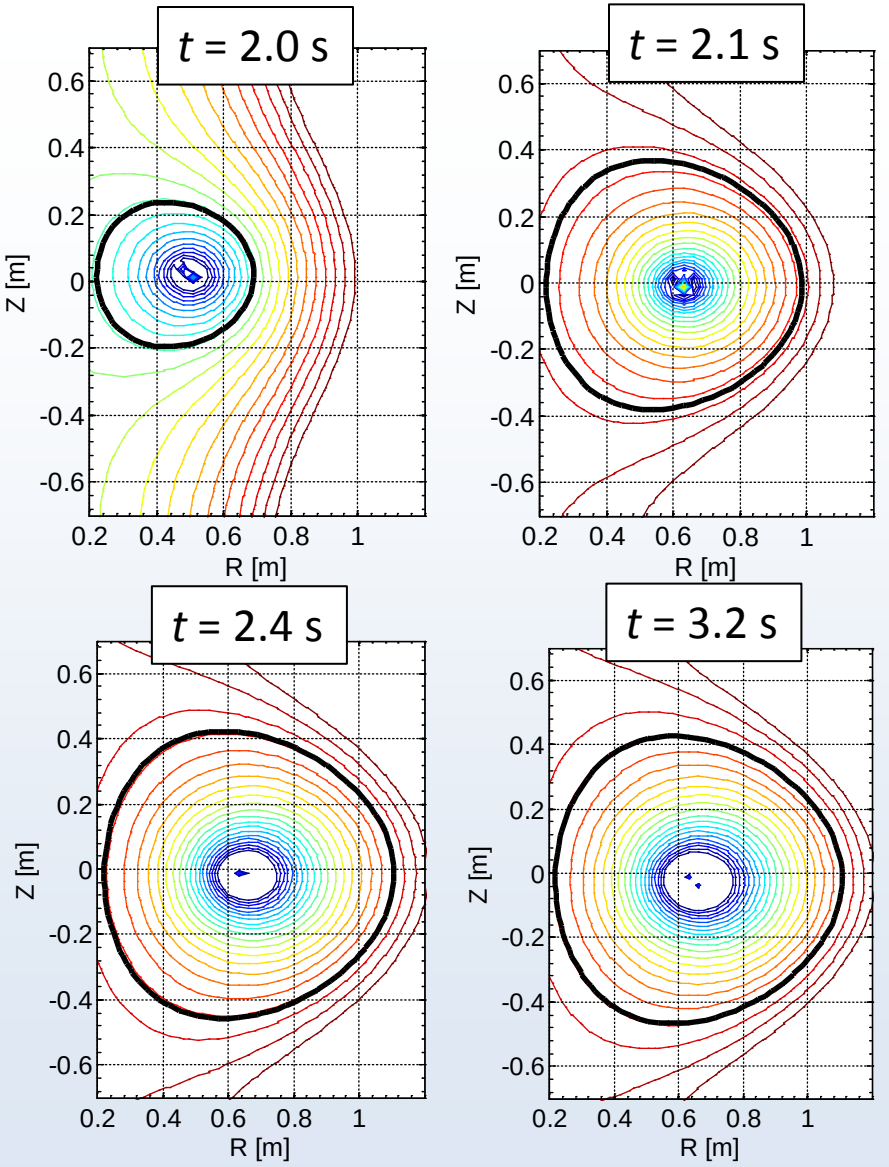
54 kA Plasma Sustainment in Low Aspect Ratio Configuration



$R_{ax} = 0.67$ m

$A = 1.4$

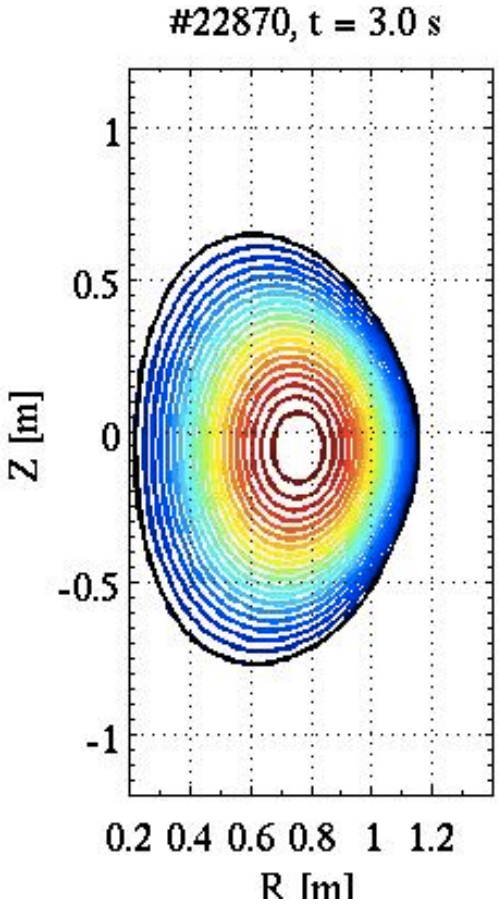
Plasma current of 54 KA was non-inductively sustained for 0.9 s by only 28 GHz injection.

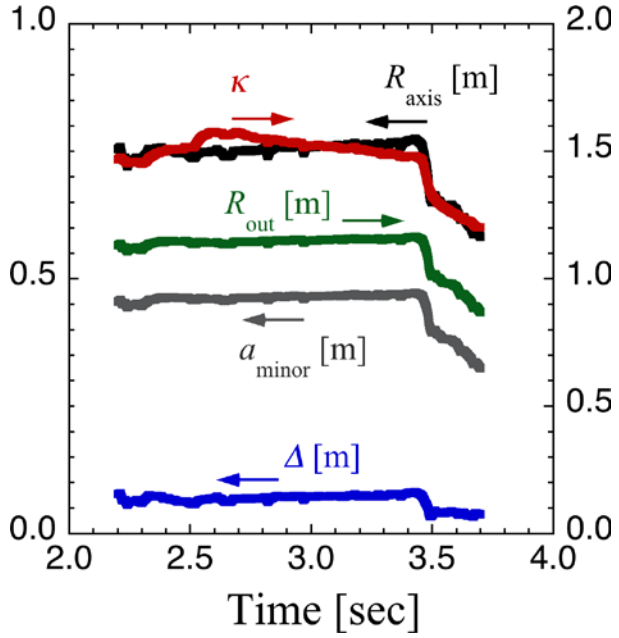


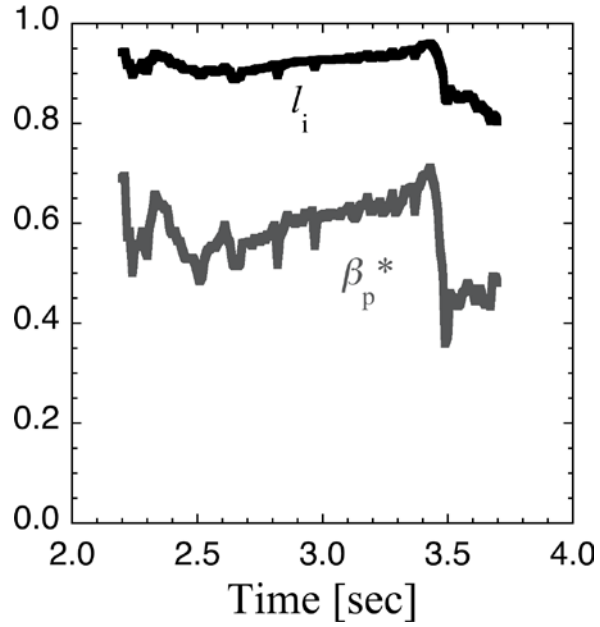
Plasma shaping was almost kept for 1.3 sec (from 2.2 s to 3.5 s)

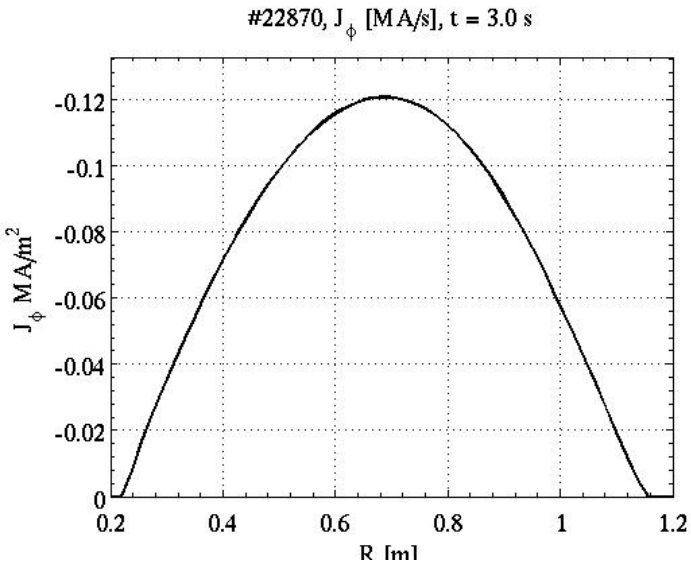
54 kA Plasma Sustainment in Low Aspect Ratio Configuration

EFIT Analysis









$\kappa \sim 1.5$

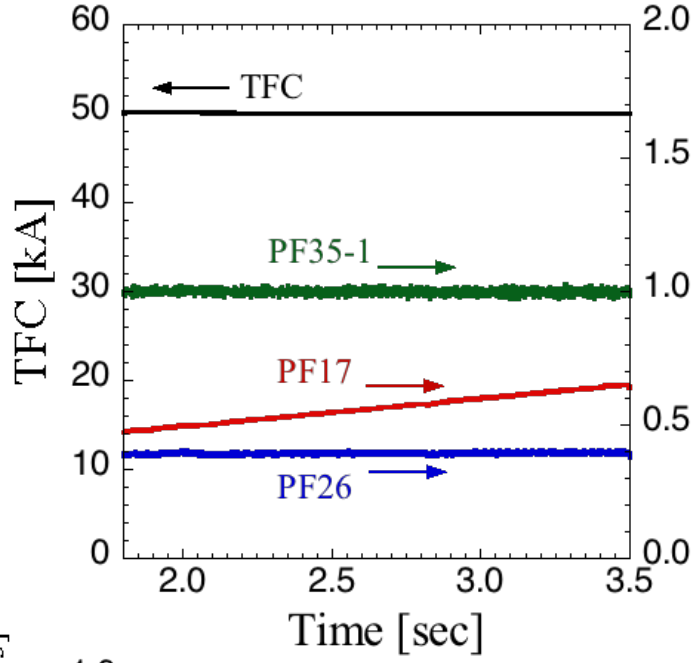
$R_{out} \sim 1.2$ m

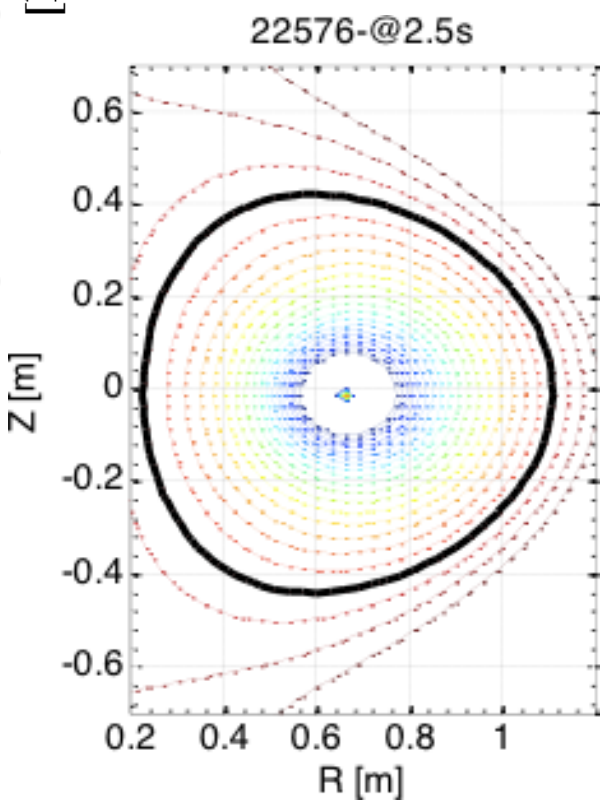
$a \sim 0.45$ m

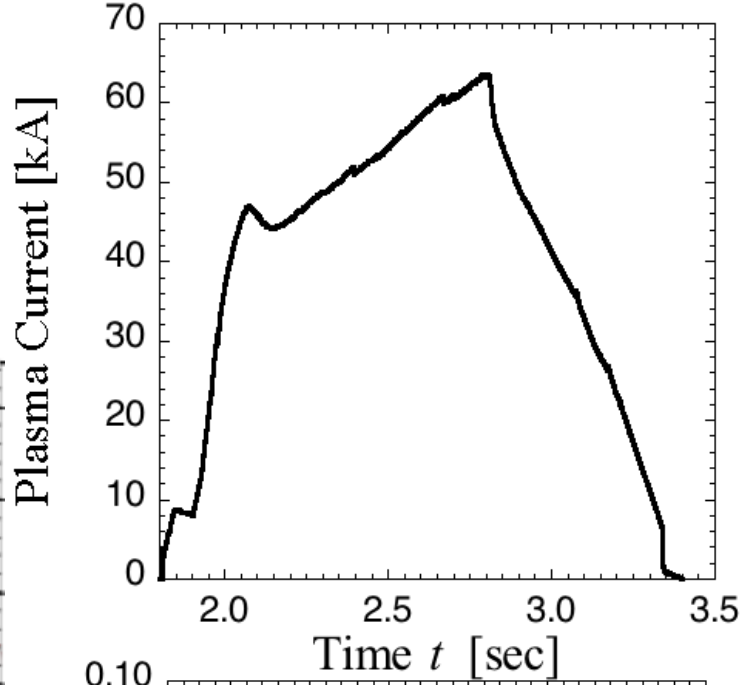
$\Delta < 0.1$ m

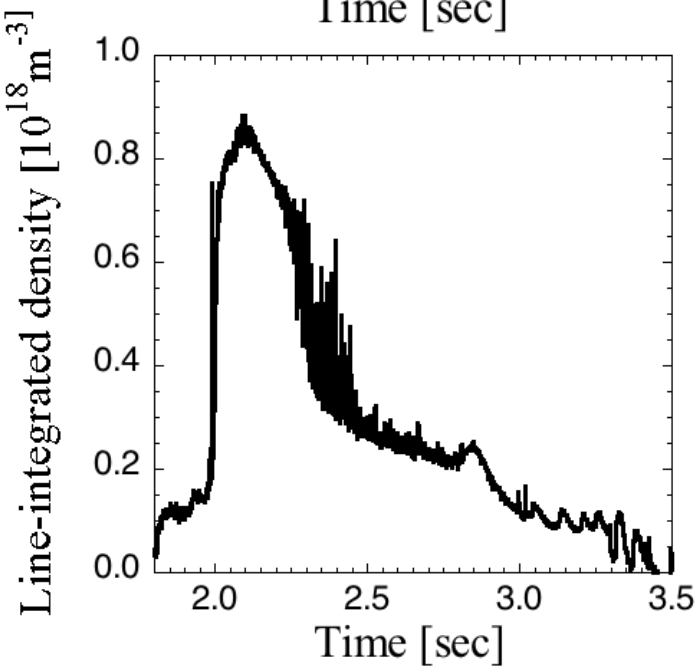
$\beta_p^* \sim 0.6$

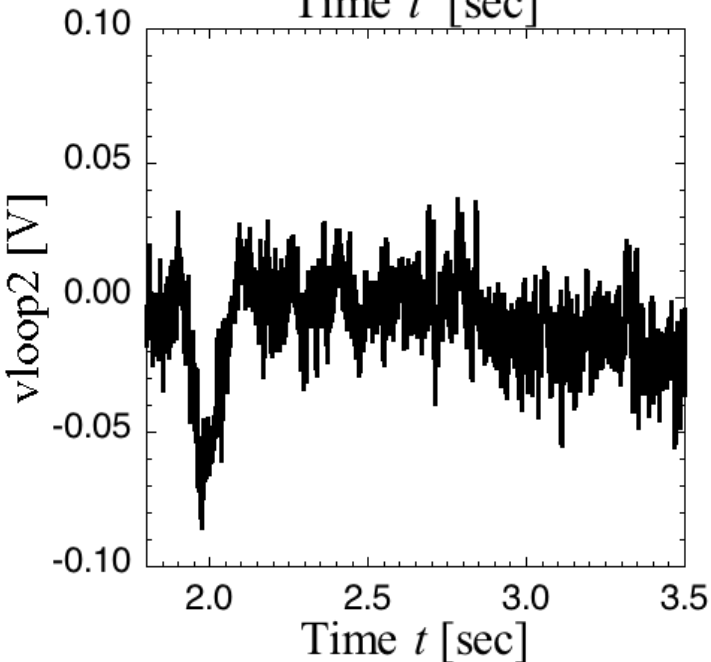
Non-inductive Start-up and Ramp-up [28 GHz]











Density Jump in superposed 28 GHz / 8.2 GHz injections

The gas fueling was applied at t = 2.9 sec to increase the density.

The operating parameters including the gas fueling were identical in the shots.

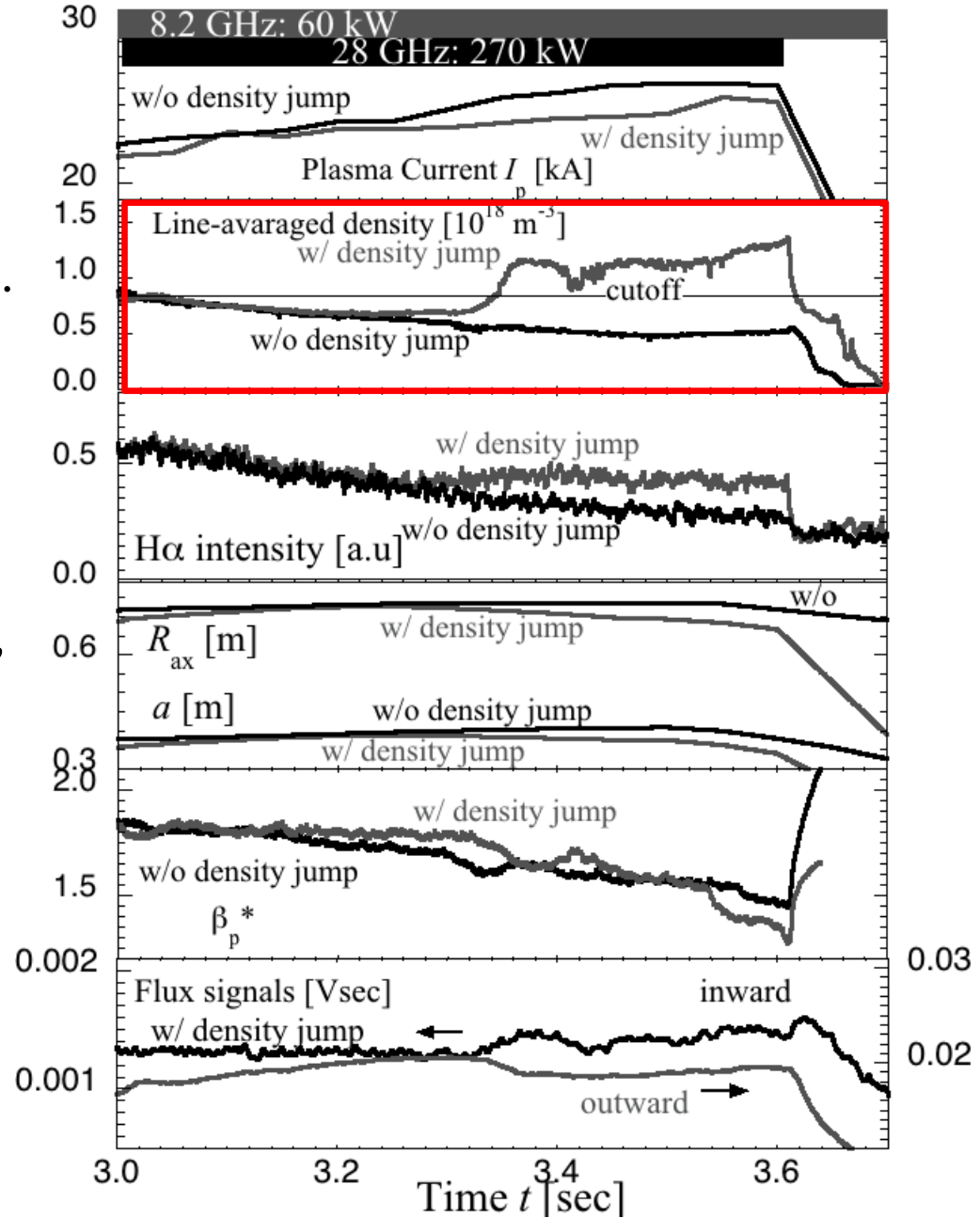
The Ha intensity was kept, and R_{ax} and a were slightly decreased in the density jump case.

I_p was once decreased, but was recovered finally.

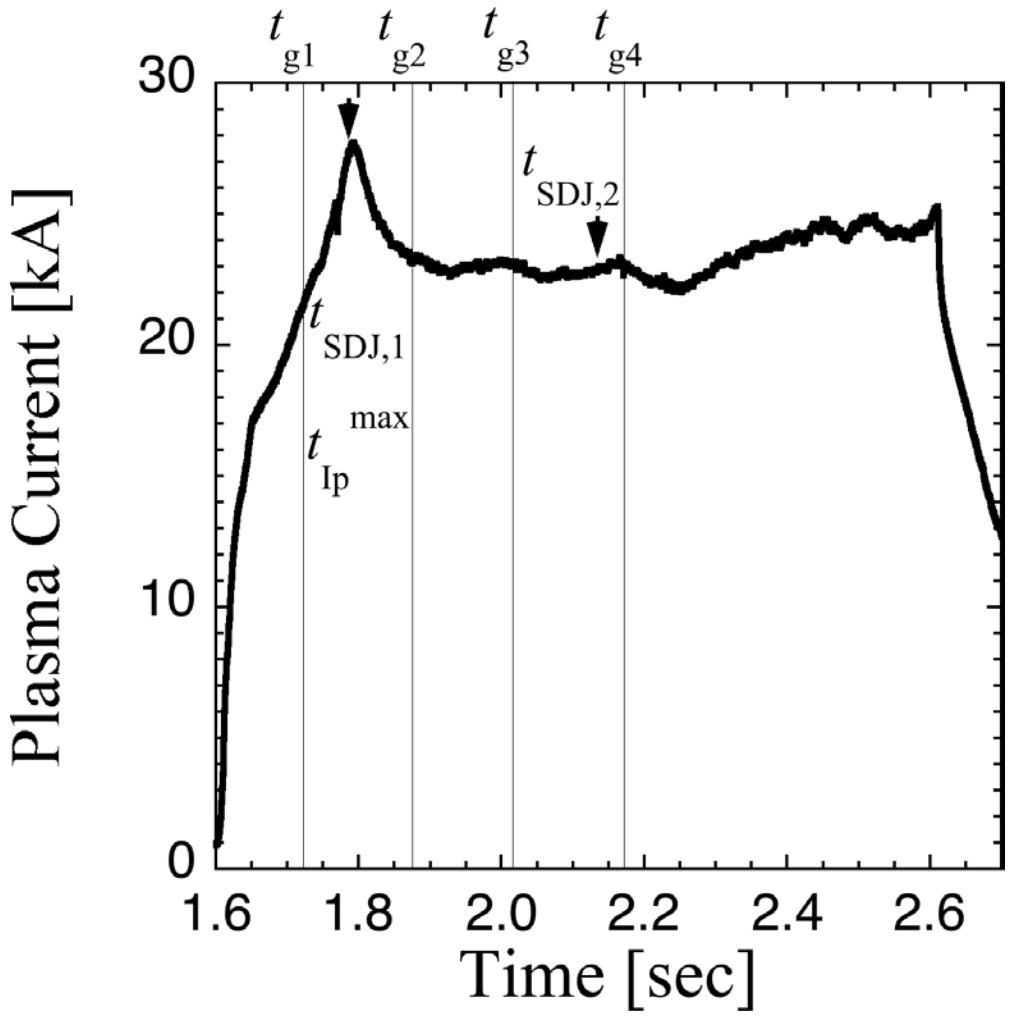
β_p* was first decreased by the decrement of a, and secondarily by the increment of I_p.

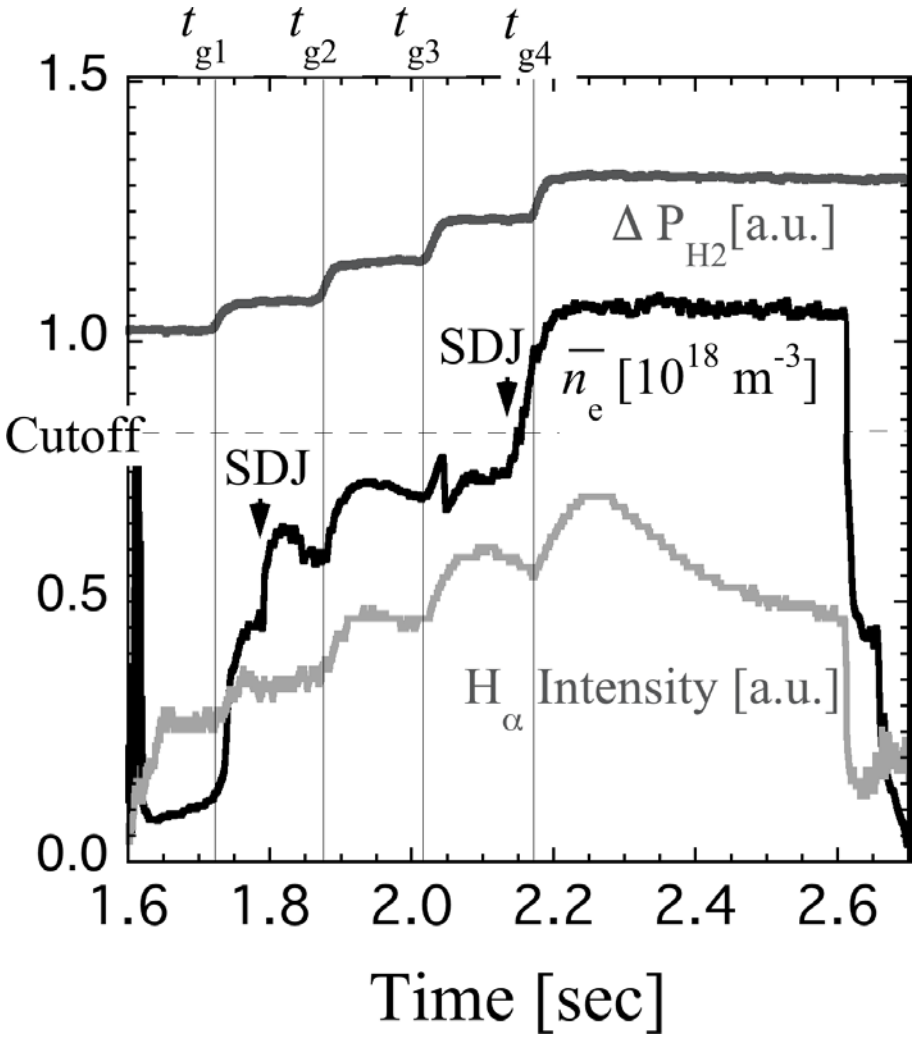
The plasma was self-organized to be more stable shaping, and then I_p was recovered in the high-density plasma.

The flux signals showed inward shift of plasma current distribution, suggesting from the decrement of R_{ax}.

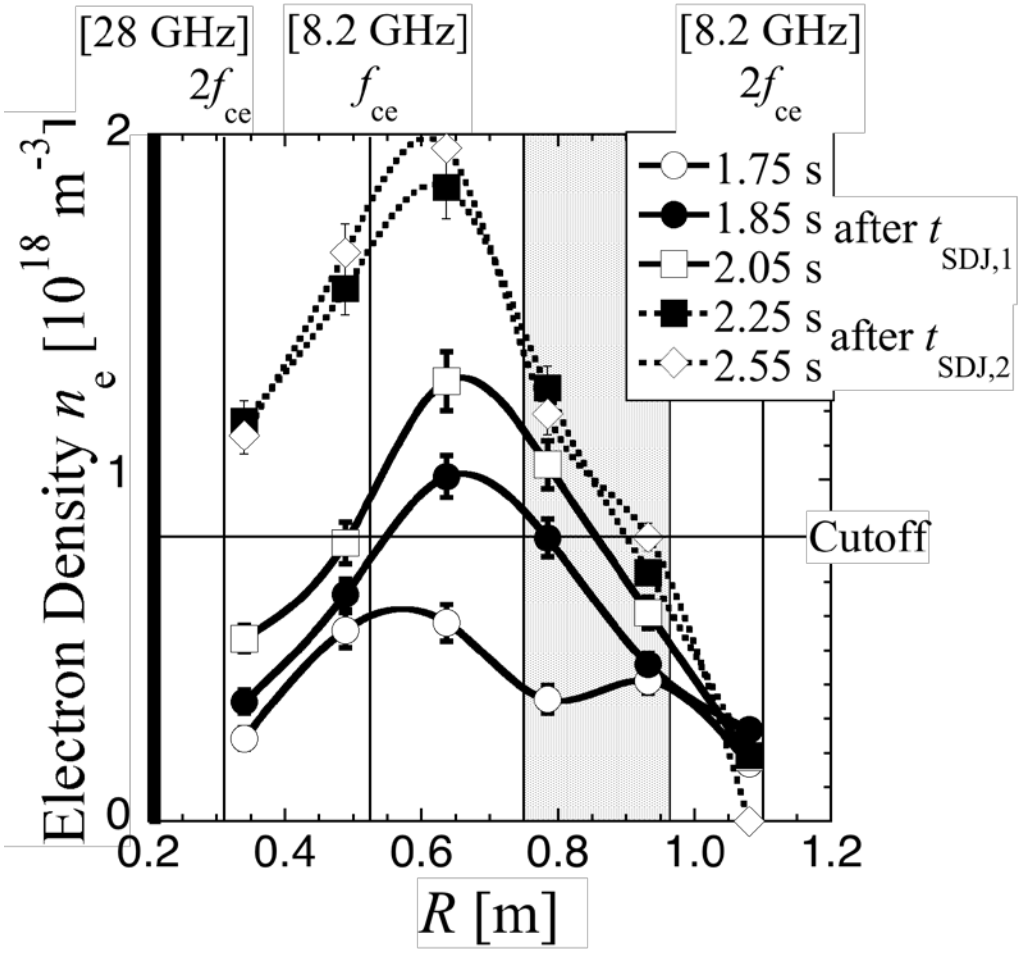


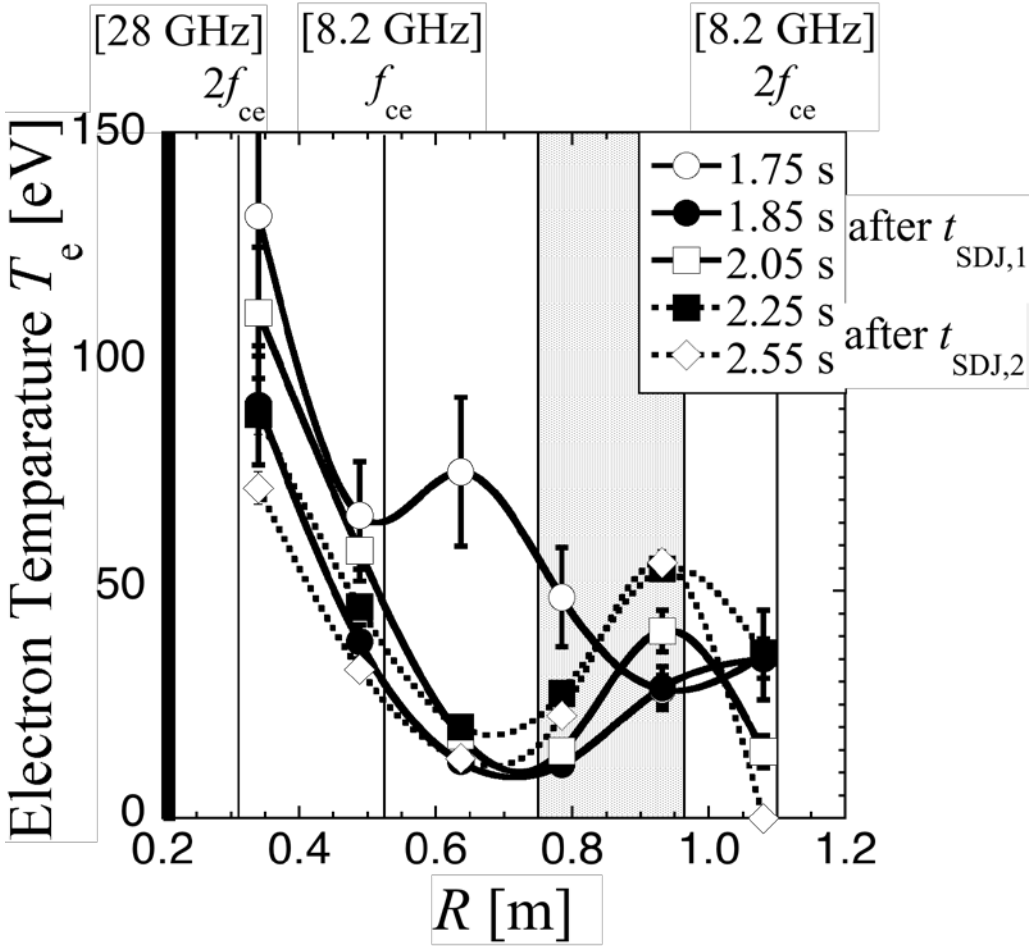
High Density Operation [8.2 GHz + 28 GHz]



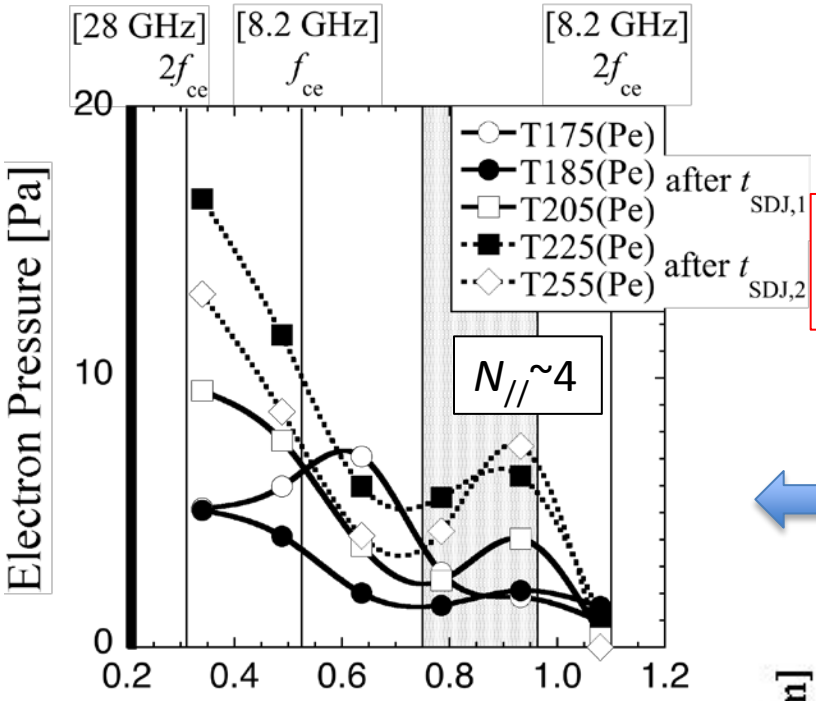


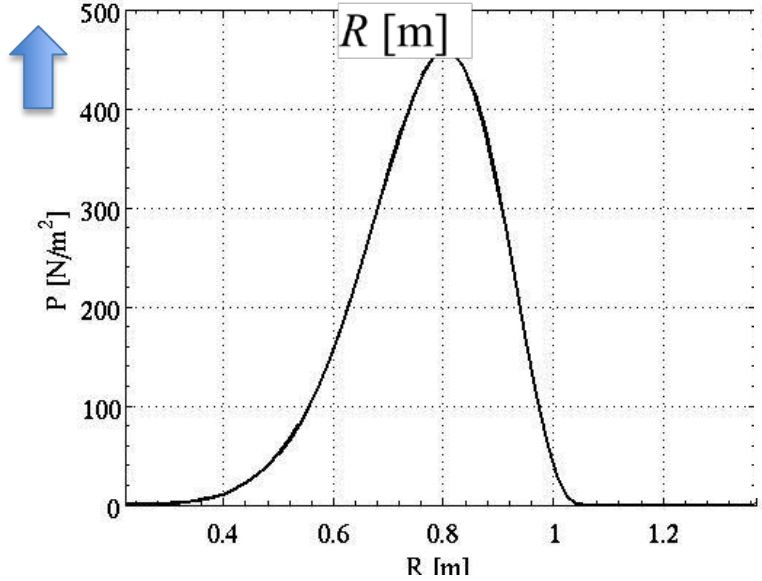
High Density Operation [8.2 GHz + 28 GHz]



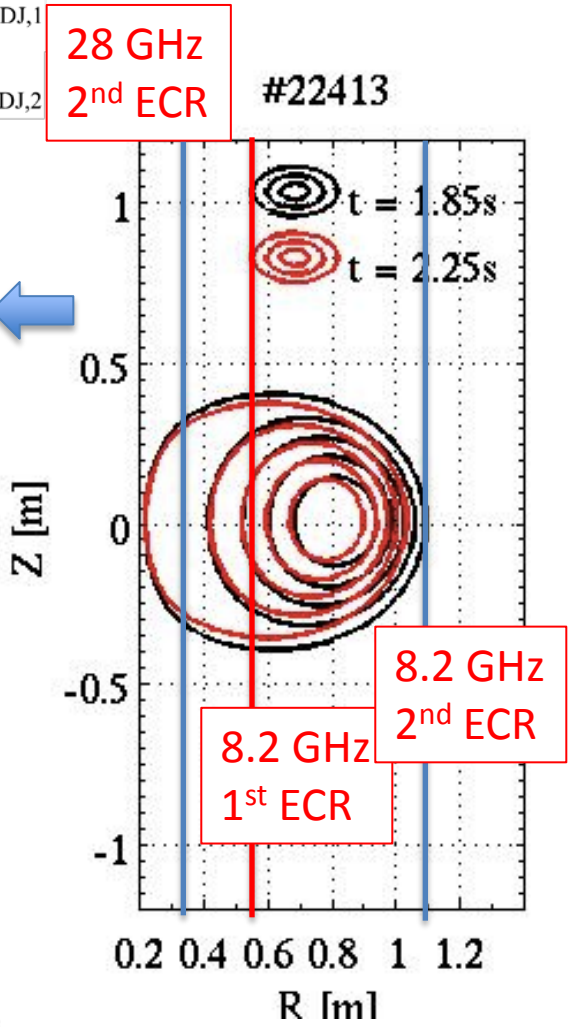


High Density Operation [8.2 GHz + 28 GHz]





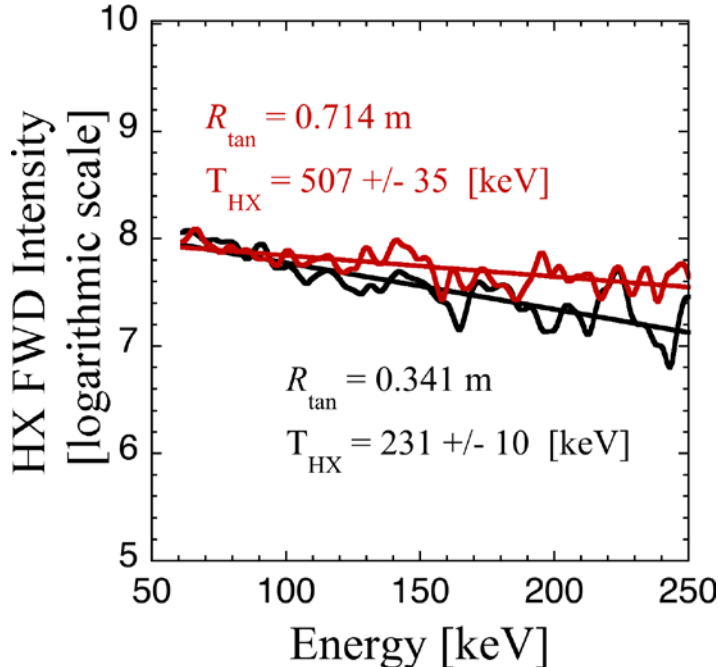
EFIT 解析



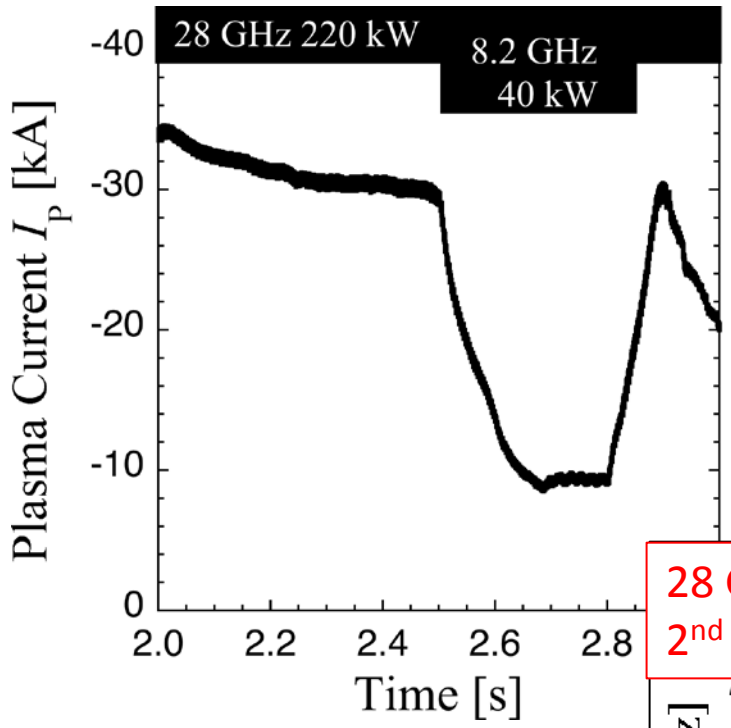
遮断密度を超える密度で
加熱効果を確認

平衡を担うプラズマ圧力は
高電子寄与が大

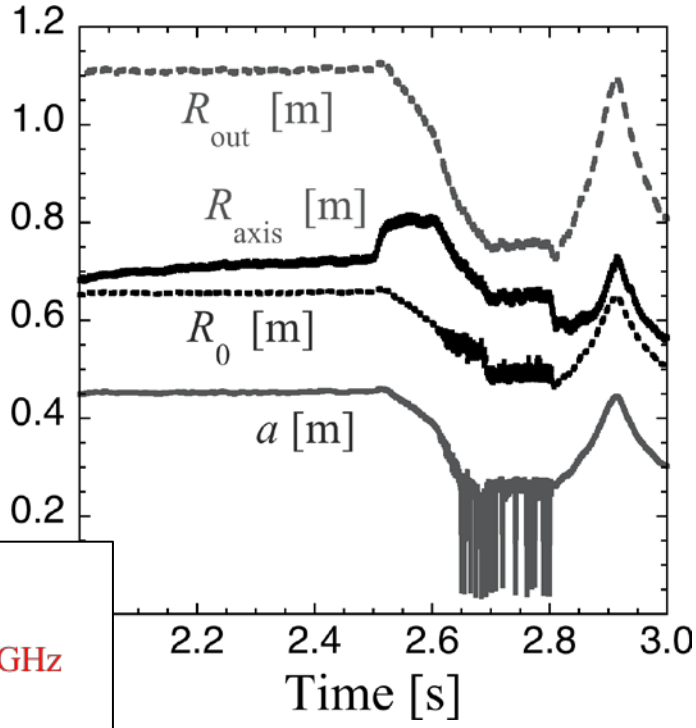
（接線）観測位置に応じて、
加熱エネルギー範囲に差



Superposed 8.2 GHz Injection to 28GHz target plasma



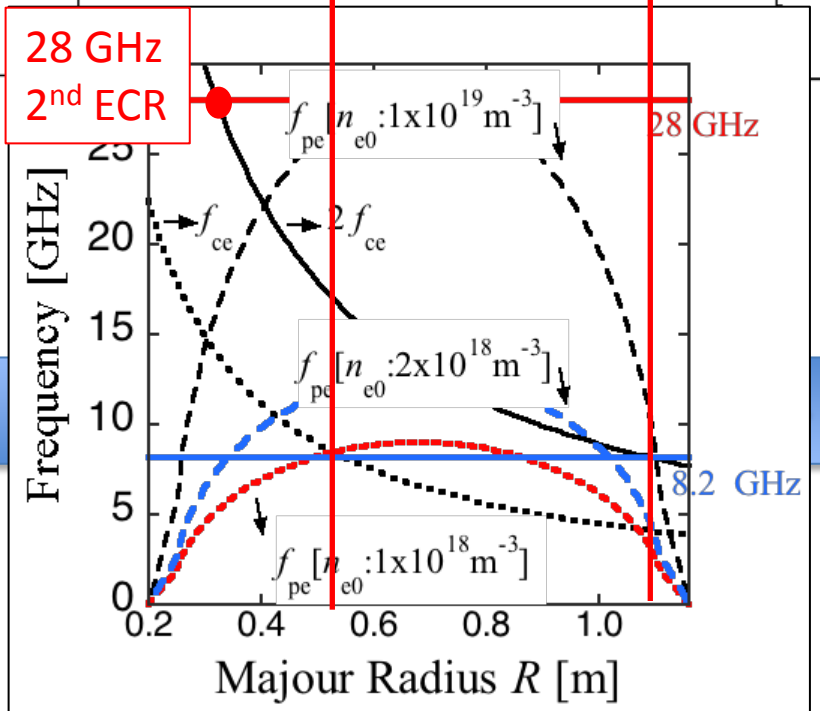
プラズマ電流は
顕著に減少



8.2 GHz
1st ECR

8.2 GHz
2nd ECR

28 GHz
2nd ECR



8,2 GHz 重畳入射
で ~10 kA まで減少

安定に平衡を維持

電流中心が一旦、
外側に、後内側に
シャフラノフシフトが
大きくなる

プラズマが小さく
なって平衡を維持

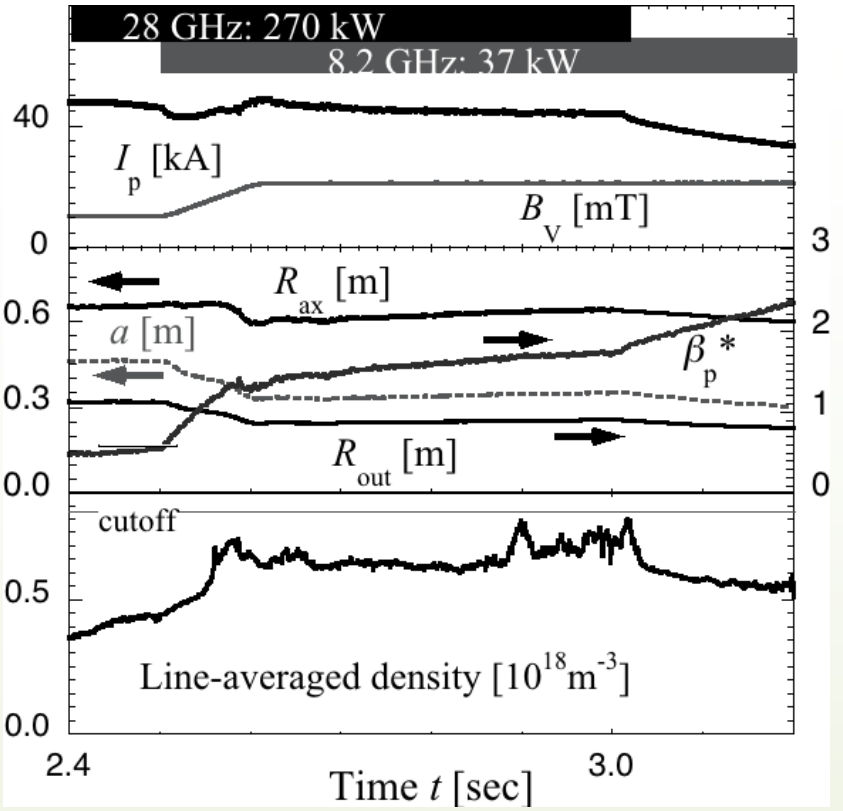
Superposed 8.2 GHz Injection to 28GHz target plasma

50 kA plasma was started and ramped up with the 28 GHz injection, and then the 8.2 GHz RF power was injected to the target plasma.

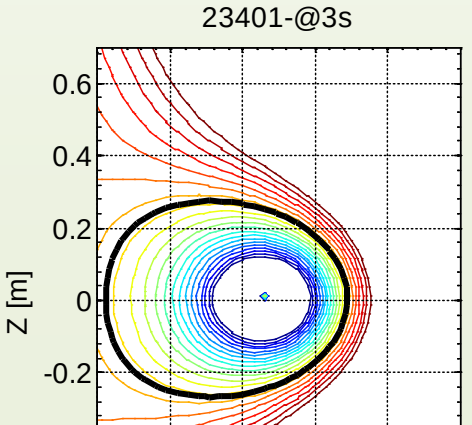
The 50 kA plasma was sustained by strong B_v at β_p*~1.5 where was also stable in the density jump study.

The density began to increase spontaneously under the stable configuration at β_p*~1.5, but was not beyond the cutoff.

High current non-inductive EBWCD experiments are planned in spontaneous or gas fueling over dense plasmas under the stable plasma shaping.



w/ 28 GHz・8.2 GHz
at t = 3 s



Summary

- Bi-directional collaboration among National Institute for Fusion Science, Tsukuba Univ. and Kyushu Univ. has been begun since 2011.

  2011-2012: Preparation of Anode Power Supply System and Gyrotron Tank
  2012-2013: Installation of Gyrotron System and Transmission Line
  2013- QUEST Experiments

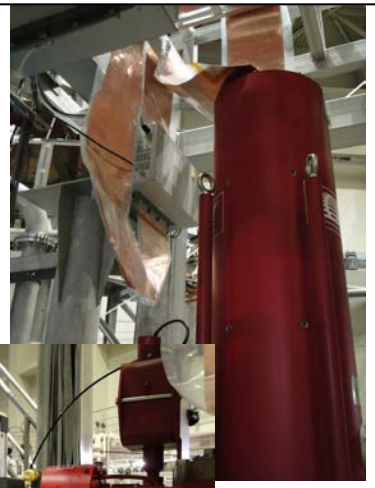
- 28 GHz Electron Cyclotron Current Drive (ECCD) effect was clearly observed in ohmically heated plasmas with feedback regulation of Center Solenoid (CS) coil current in 2^{nd} harmonic inboard off-axis heating scenario.

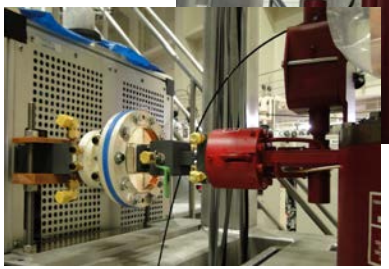
- In non-inductive current drive experiments only by the 28 GHz injection, 54 kA plasma current was sustained for 0.9 sec. High non-inductive plasma current of 66 kA was also attained by the 28 GHz ECH/ECCD.

- Density jump across 8.2 GHz cutoff density was observed in superposed 28 GHz / 8.2 GHz injections.

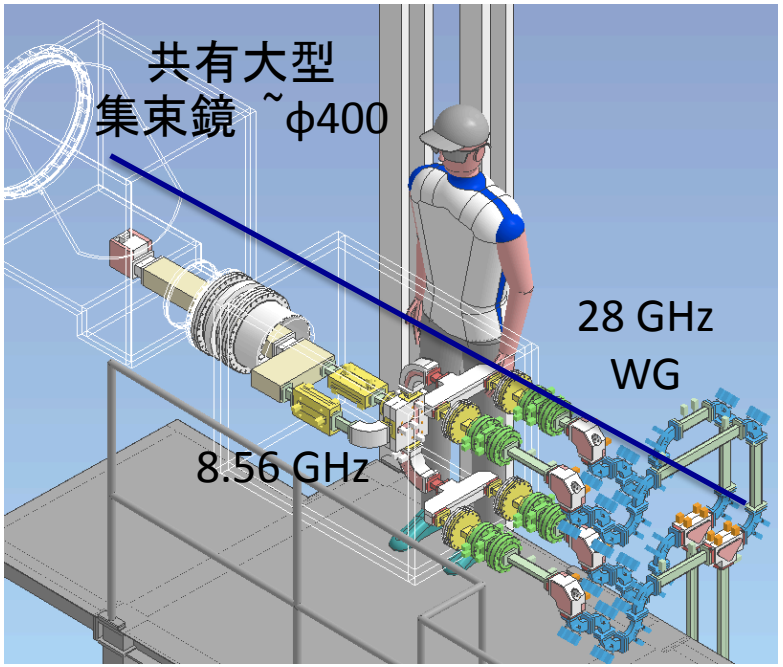
- The 50 kA plasmas were sustained by the 8.2 GHz injection to the 28 GHz target plasma if the stable plasma shaping was obtained.

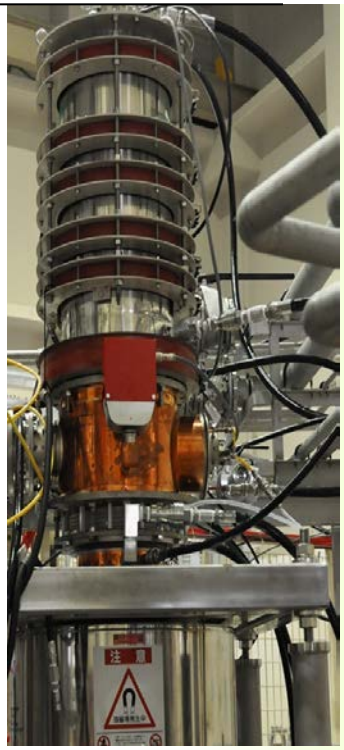
8.5 GHz / 28 GHz システムを用いた新たな実験





8.56 GHz
クライストロン管
200 kW CW





28 GHz
ジャイロトロン管
400 kW 2秒

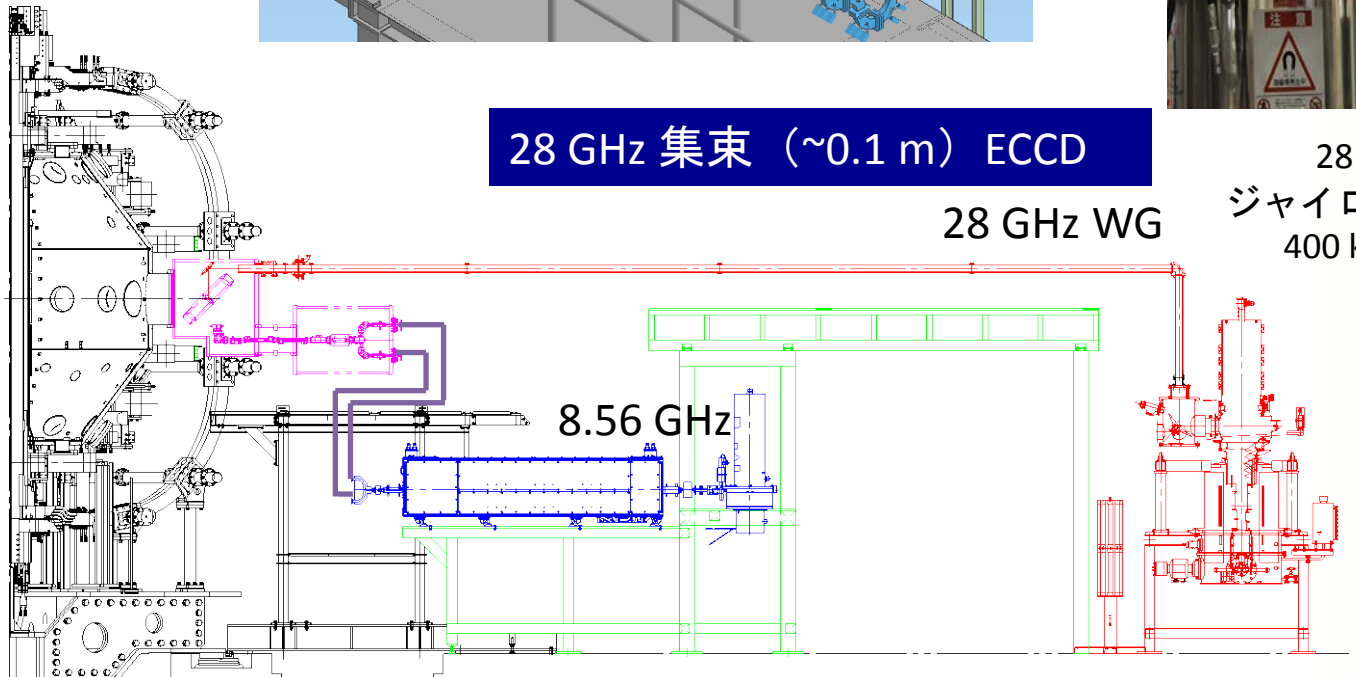
CW
連続

28 GHz 集束（~0.1 m）ECCD

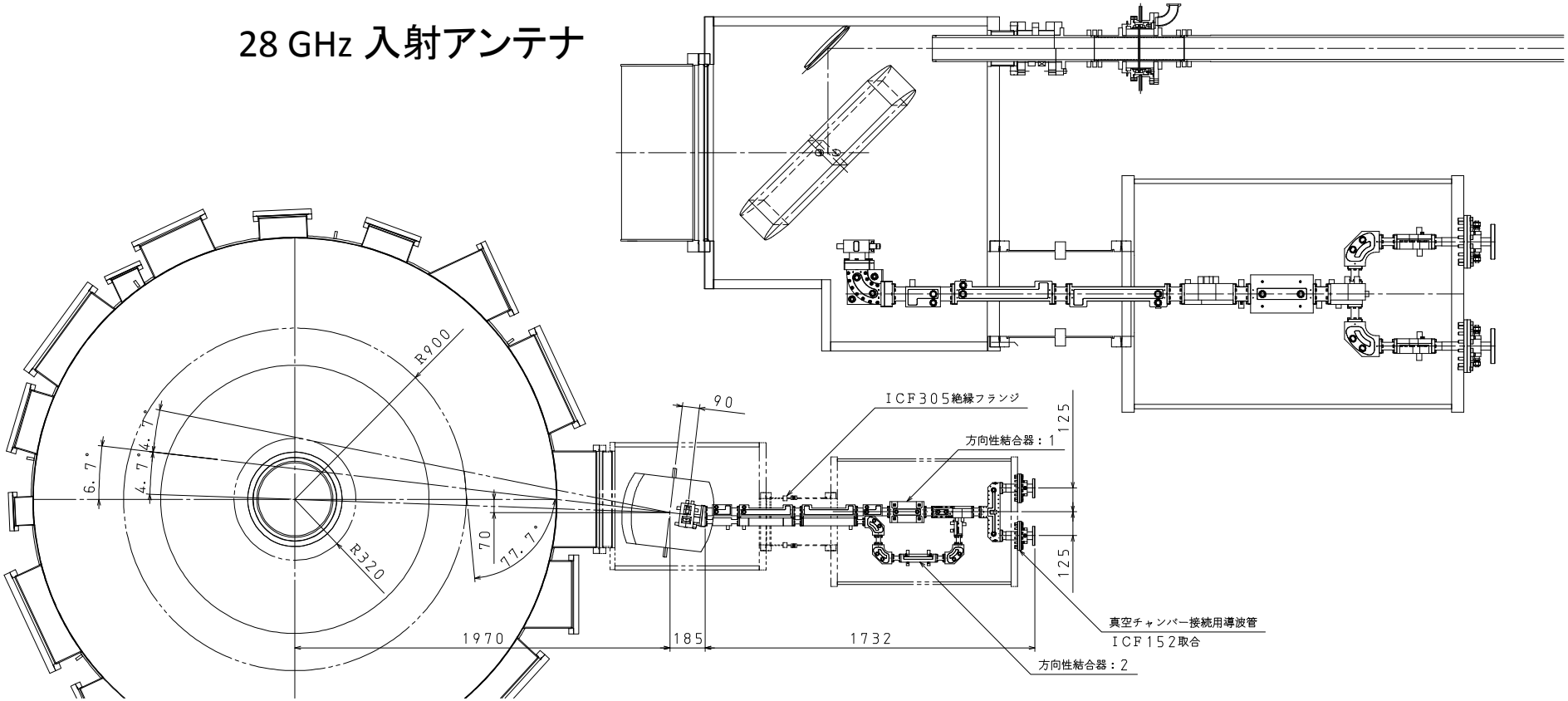
共有高電圧電源
共有集束アンテナ

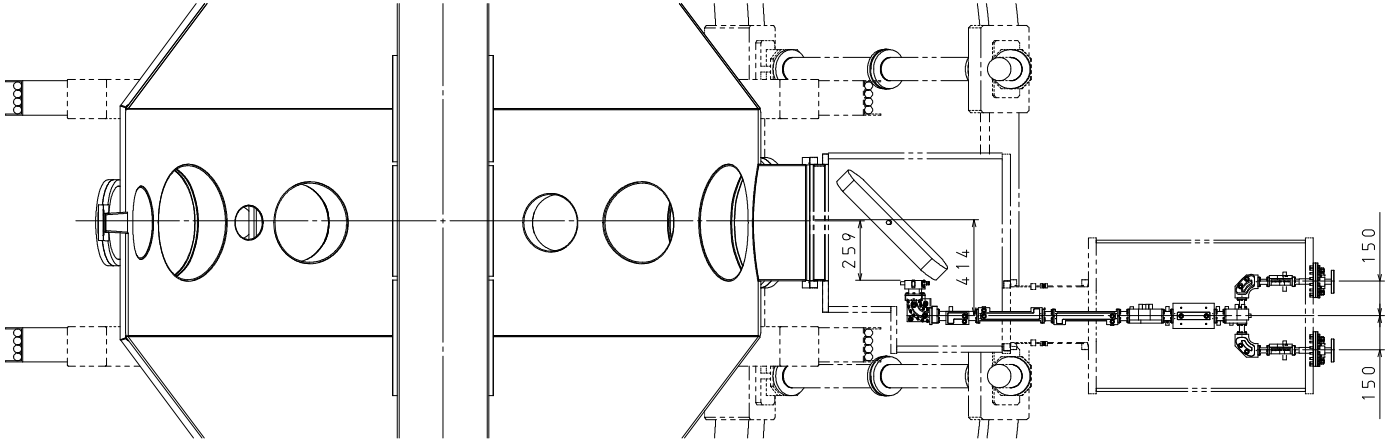
個別システム
同時入射

電子バーンシュタイン波電流駆動



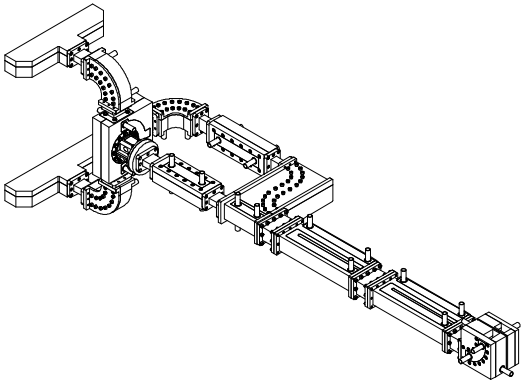
28 GHz 入射アンテナ

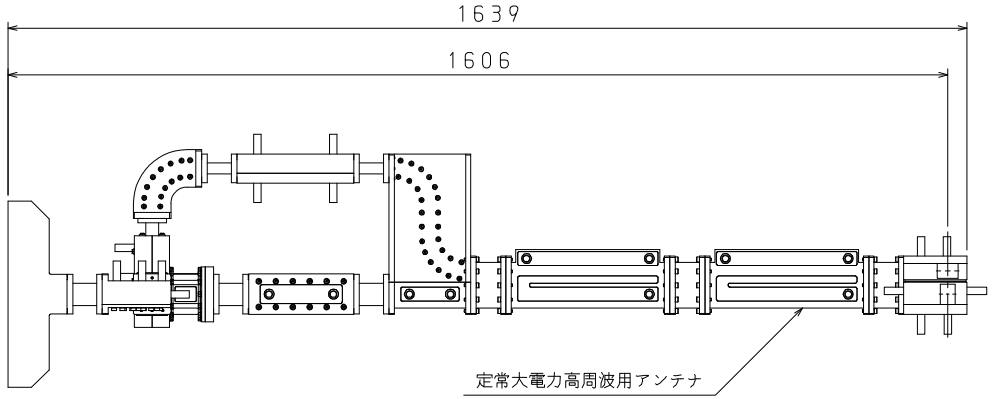


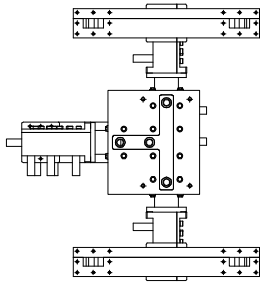


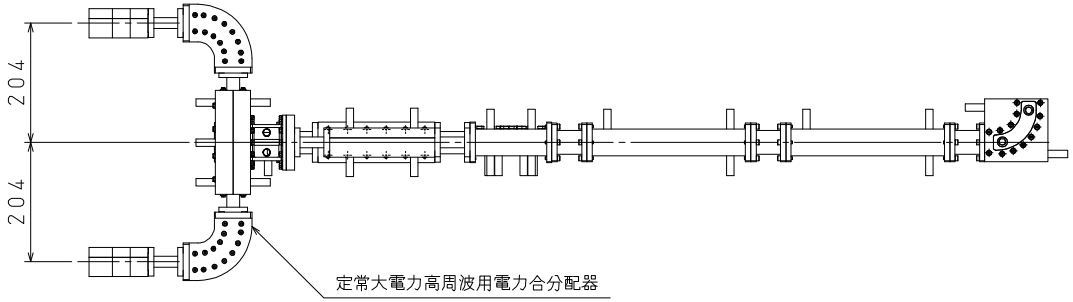
8.5 GHz 入射アンテナ

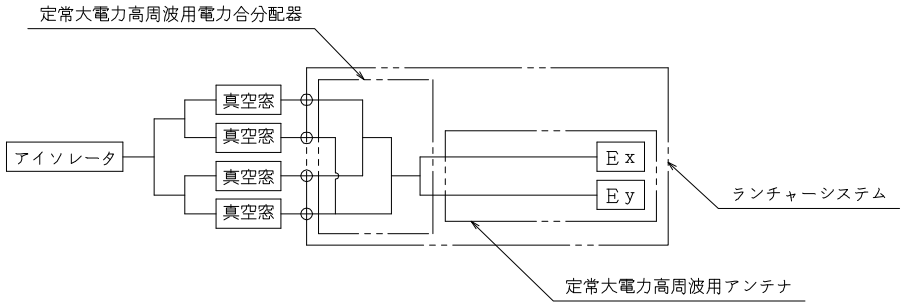
8GHz帯定常動作大電力ランチャー




1639
1606
定常大電力高周波用アンテナ

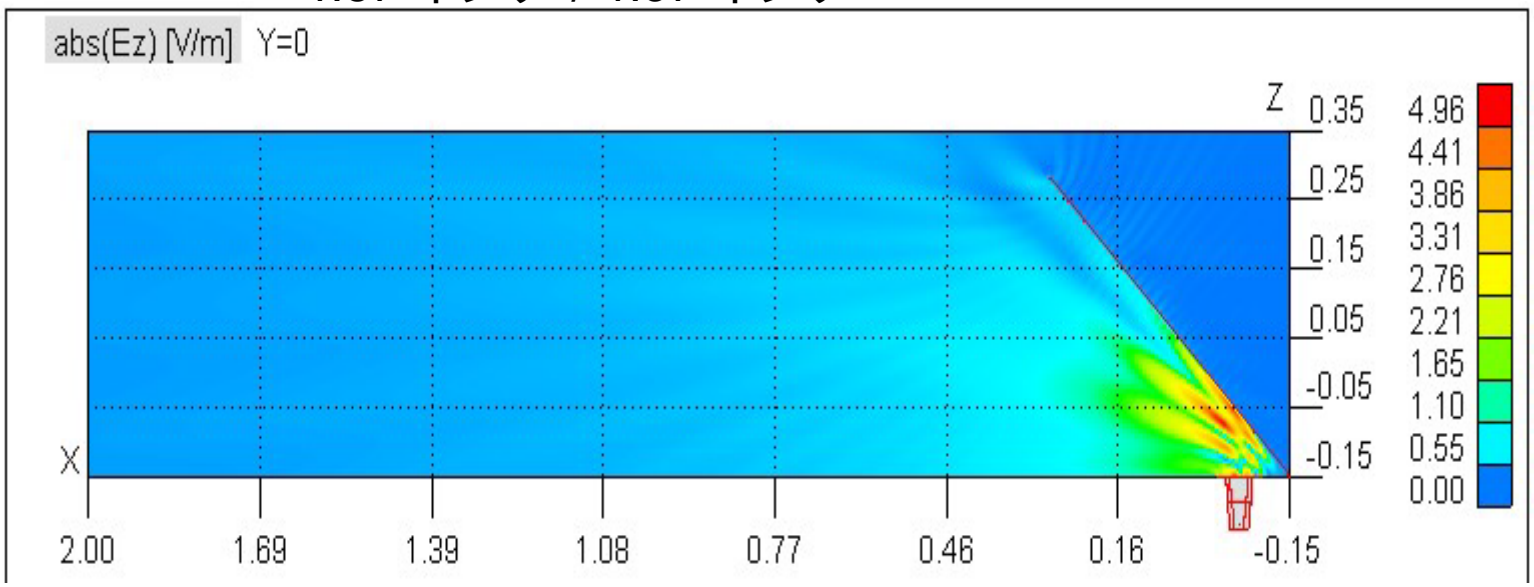


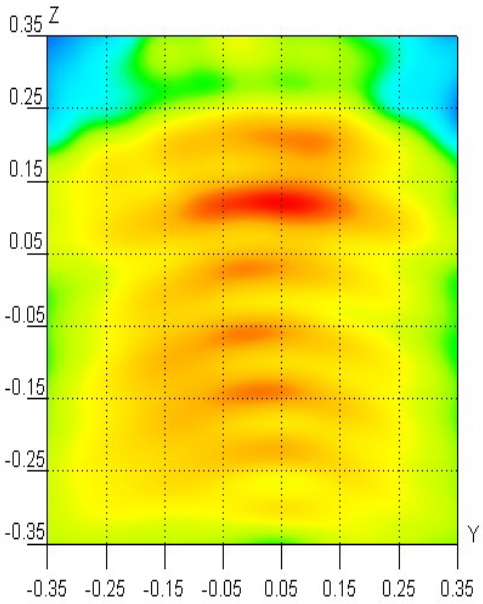

204
204
定常大電力高周波用電力合分配器

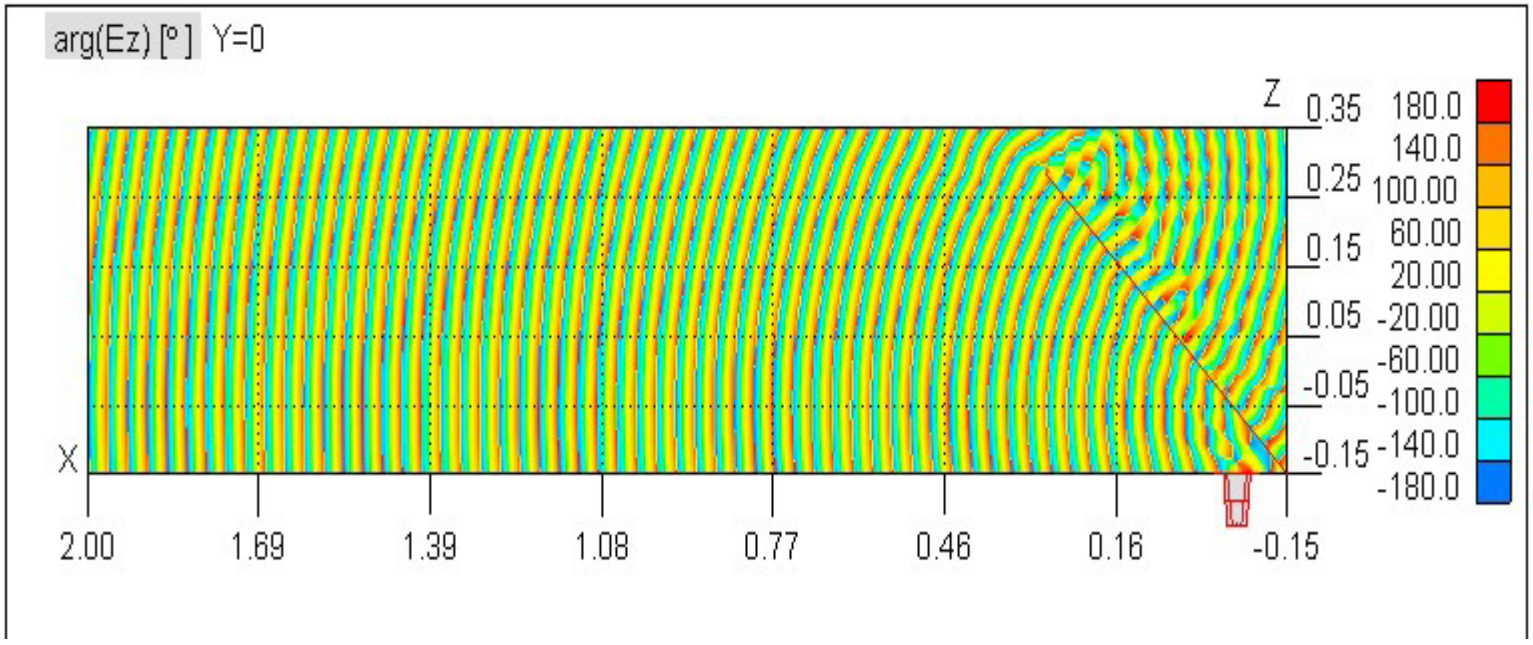

定常大電力高周波用電力合分配器
アイソレータ
真空窓
真空窓
真空窓
真空窓
Ex
Ey
ランチャーシステム
定常大電力高周波用アンテナ

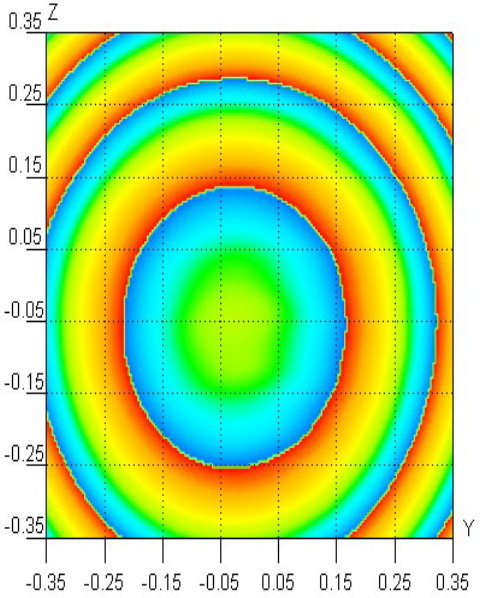
大電力高周波経路図

1.87 インチ / 1.37 インチ

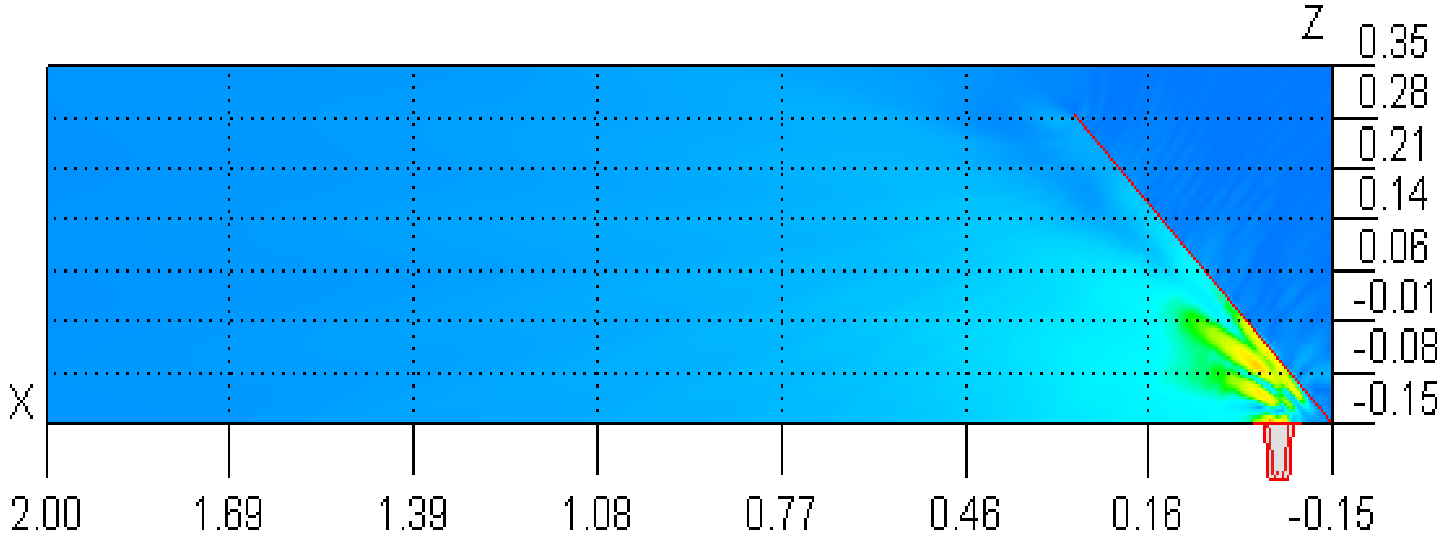


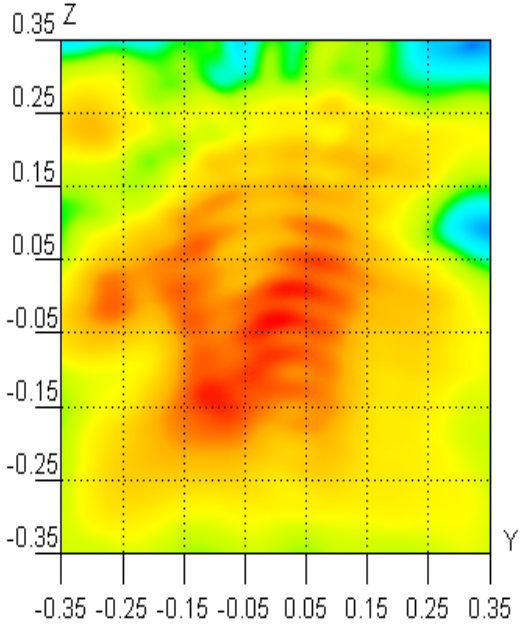


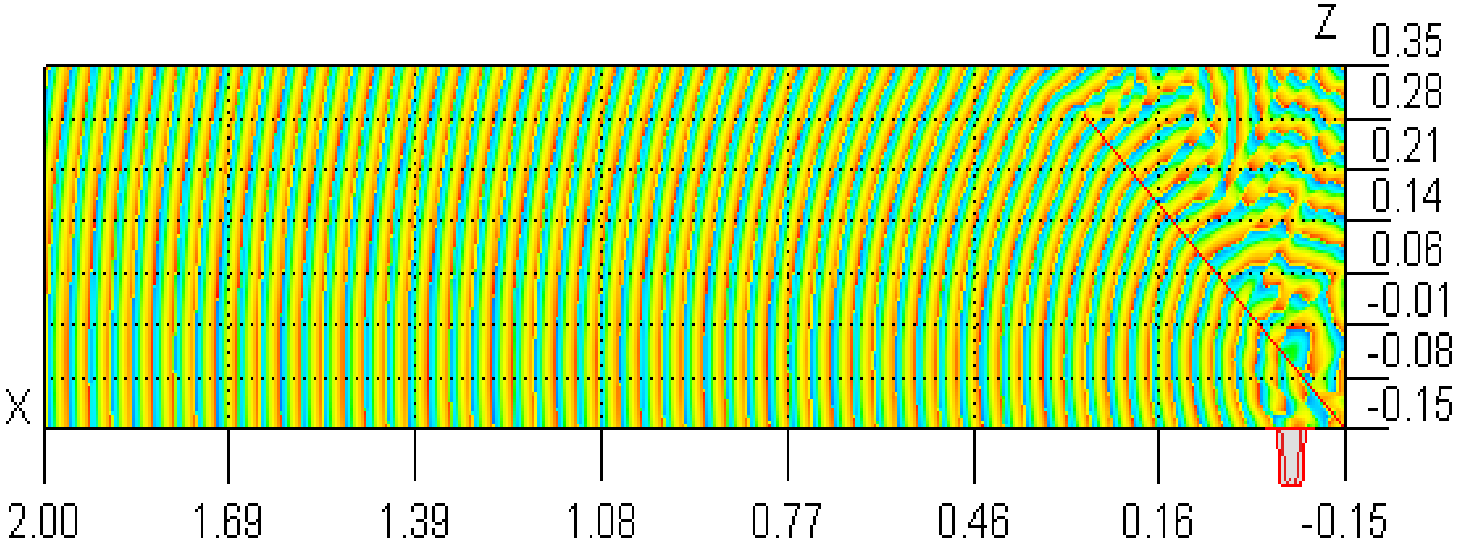


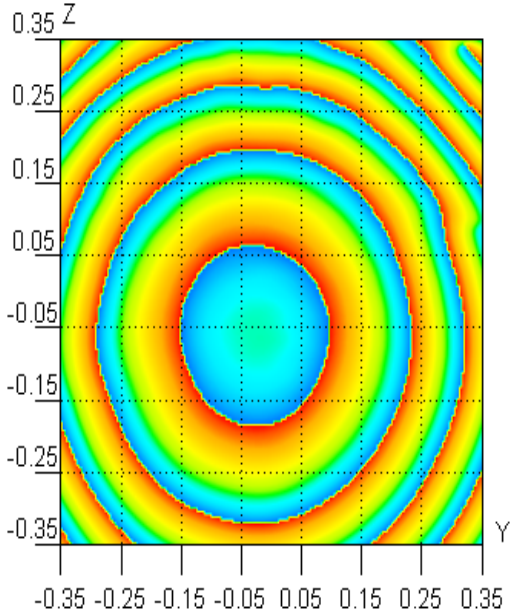


1.87 インチ／35.1mm 1.382インチ

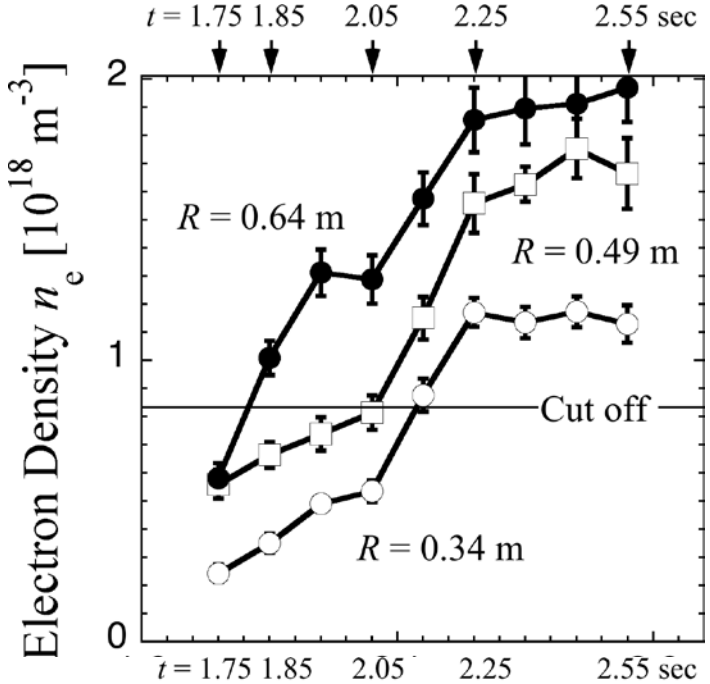


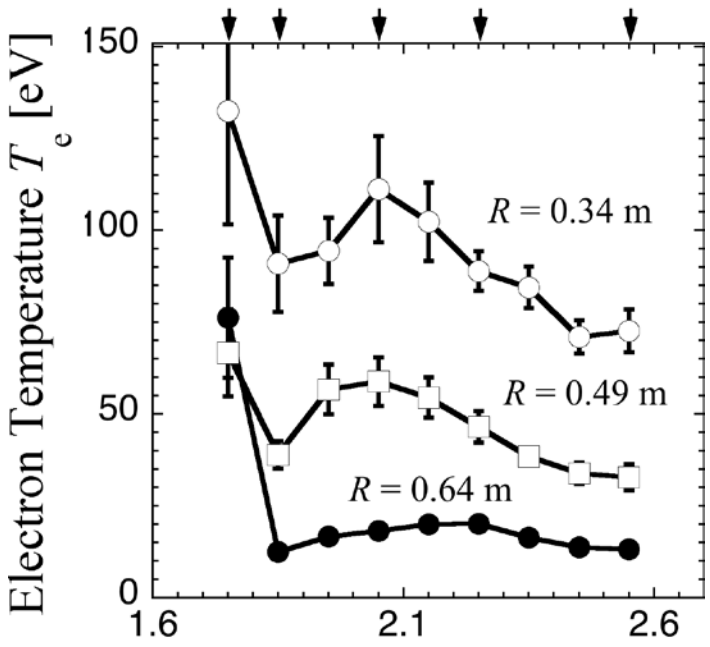


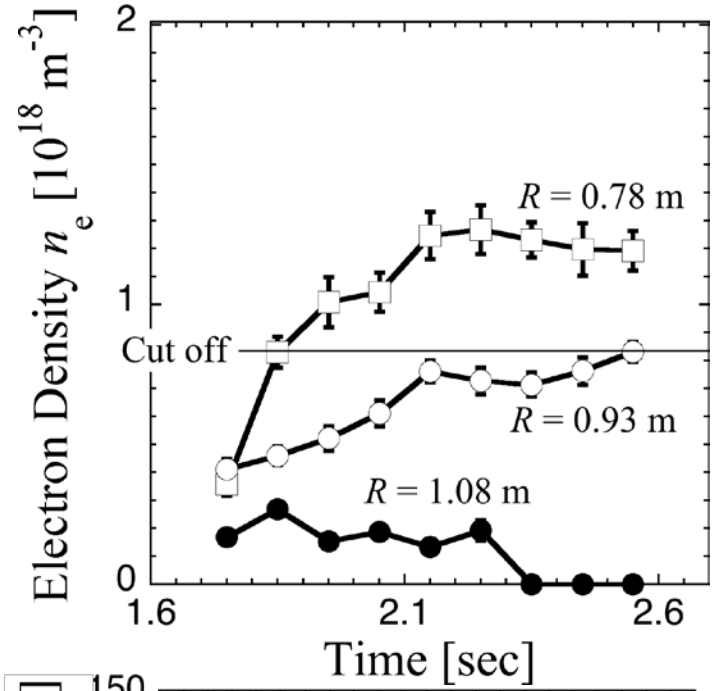


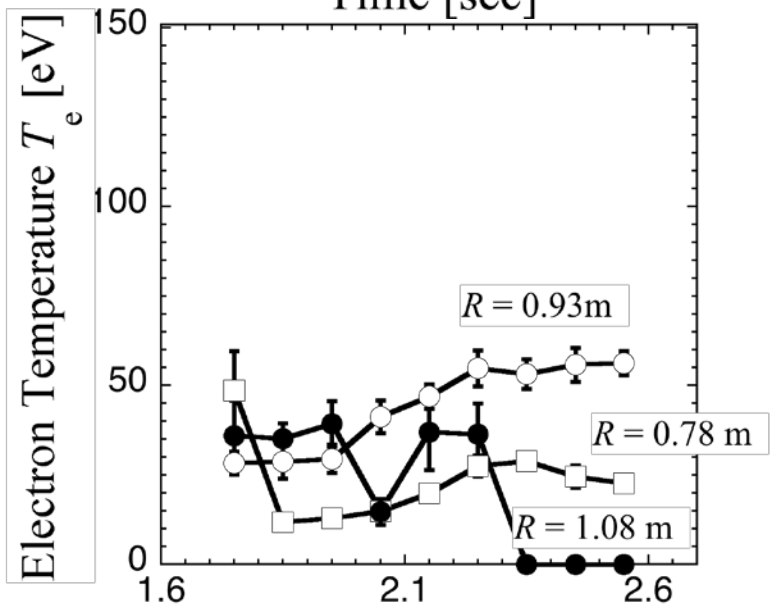


High Density Operation [8.2 GHz + 28 GHz]

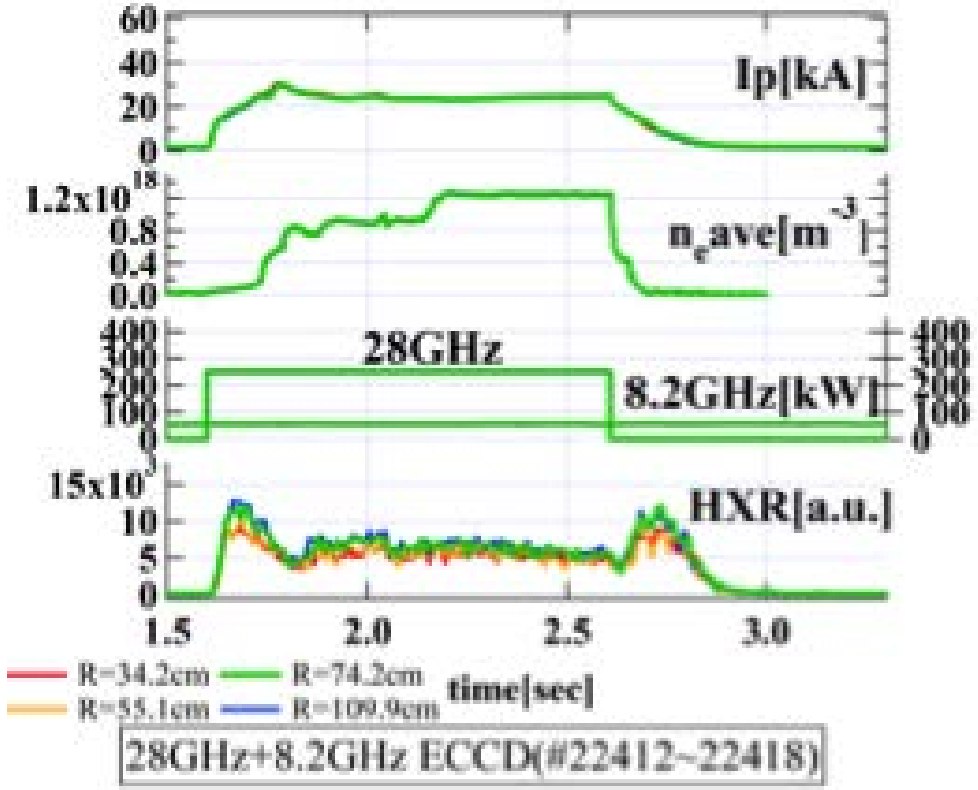


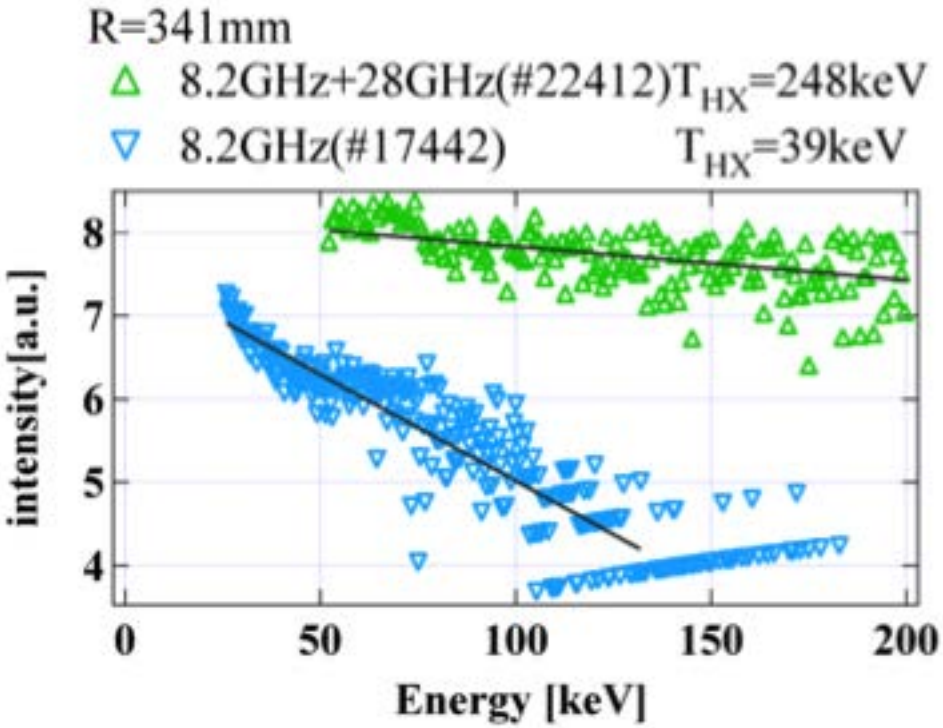






High Density Plasma in 28 GHz and 8.2 GHz injections





Hard X-ray intensities with more than 100 keV energy were measured in the non-inductive high density plasma.