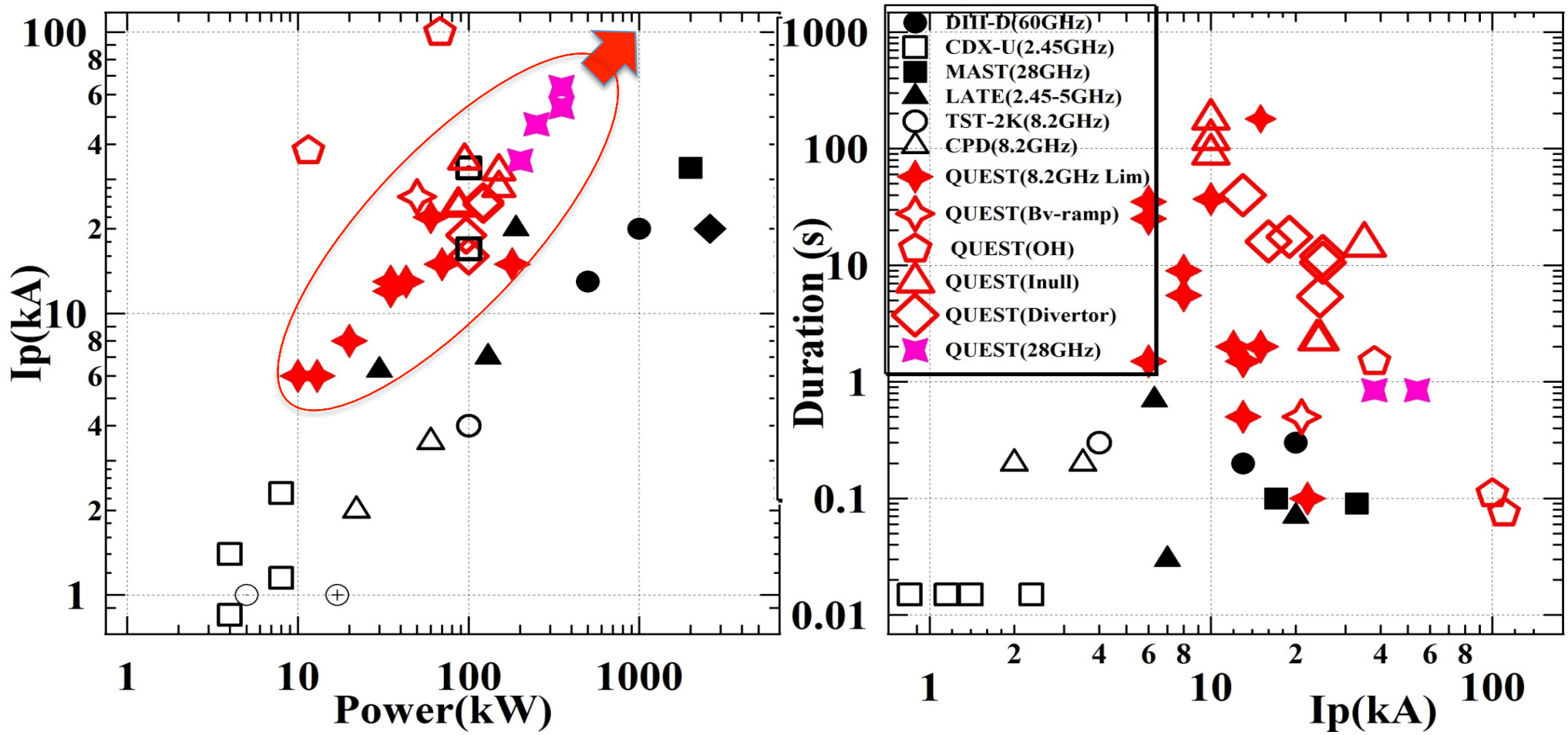
QUEST 装置における28GHz ジャイロトロンシステムを用いた連携研究の最近の成果とPWI研究の進展

九州大学 QUEST チーム
筑波大学 GAMMA-10/PDX グループ

2011-2012: ジャイロトロン電源・周辺機器整備
2012-2013: ジャイロトロン管据付・発振調整

2013~ : QUEST における加熱・電流駆動実験

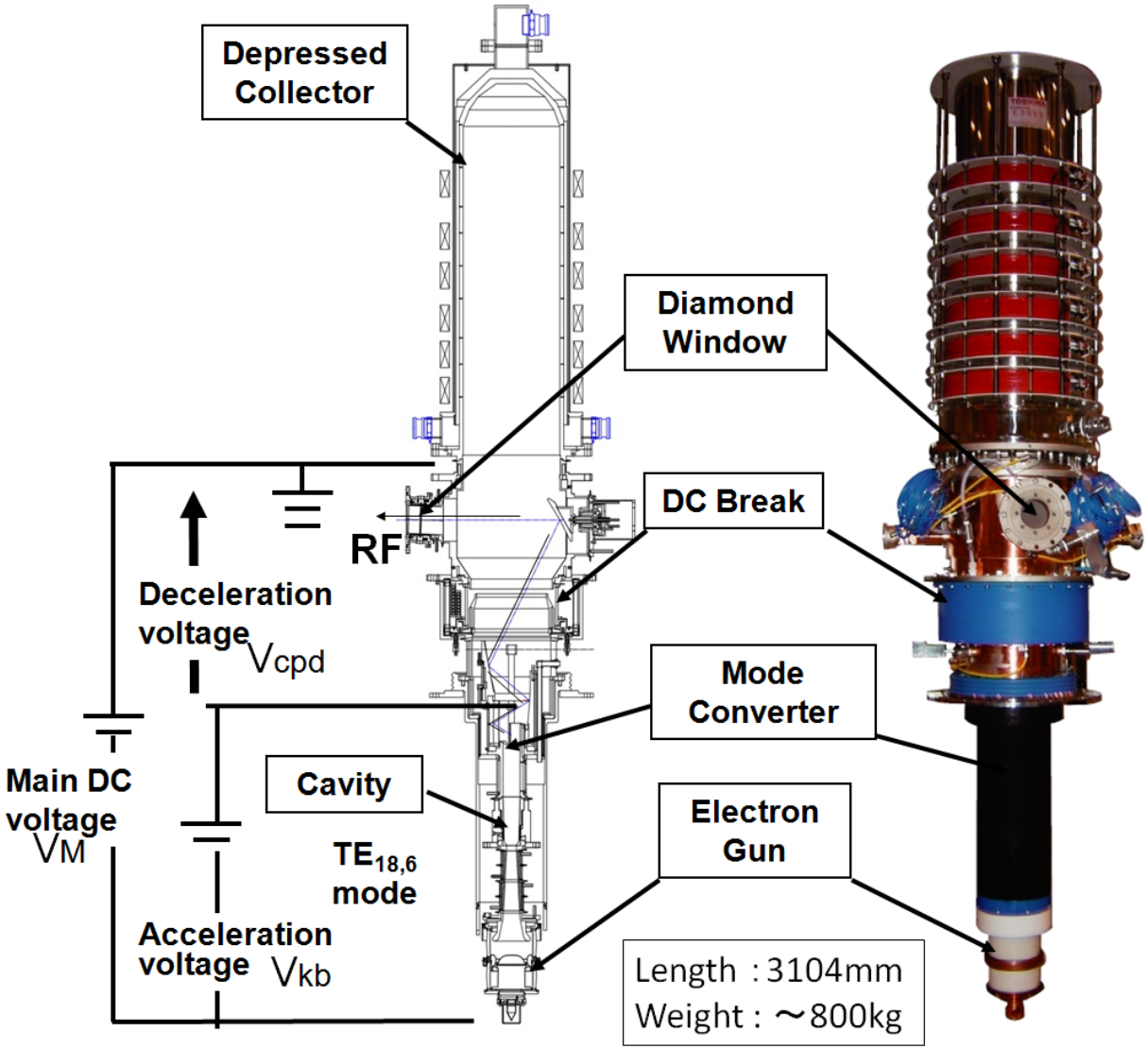
Non-inductive Operation in QUEST



Gyotron Development at Tsukuba University [28GHz]

【High Power mm-Wave Source】

QUEST Advanced Fusion Research Center



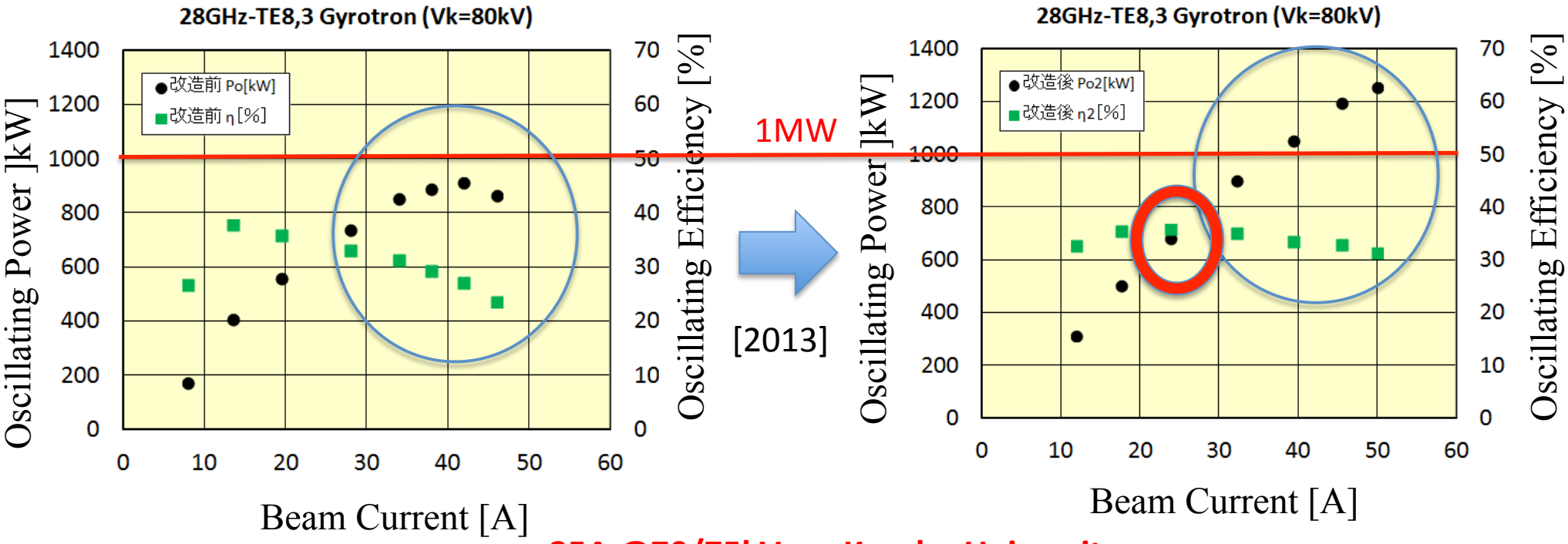
28 GHz gyrotron has been developed for Gamma-PDX projects at Tsukuba University by themselves.

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

Gyotron Development at Tsukuba University [28GHz]

【High Power mm-Wave Source】

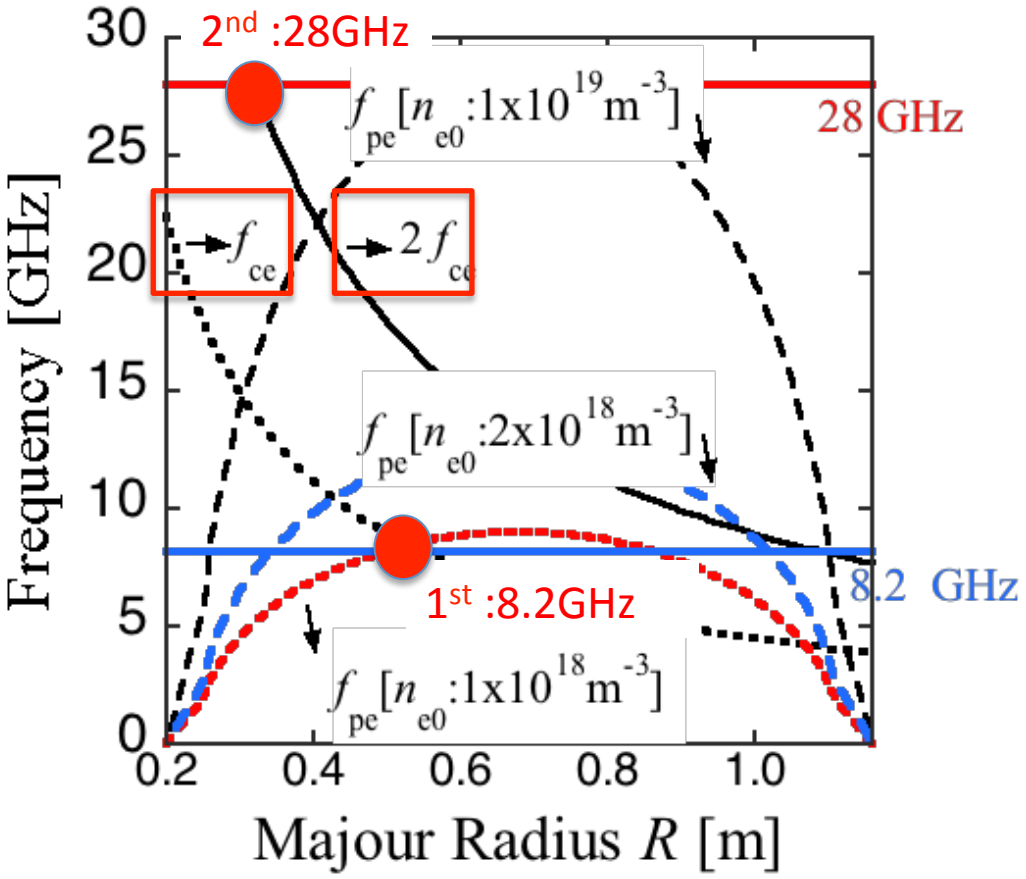
QUEST Advanced Fusion Research Center

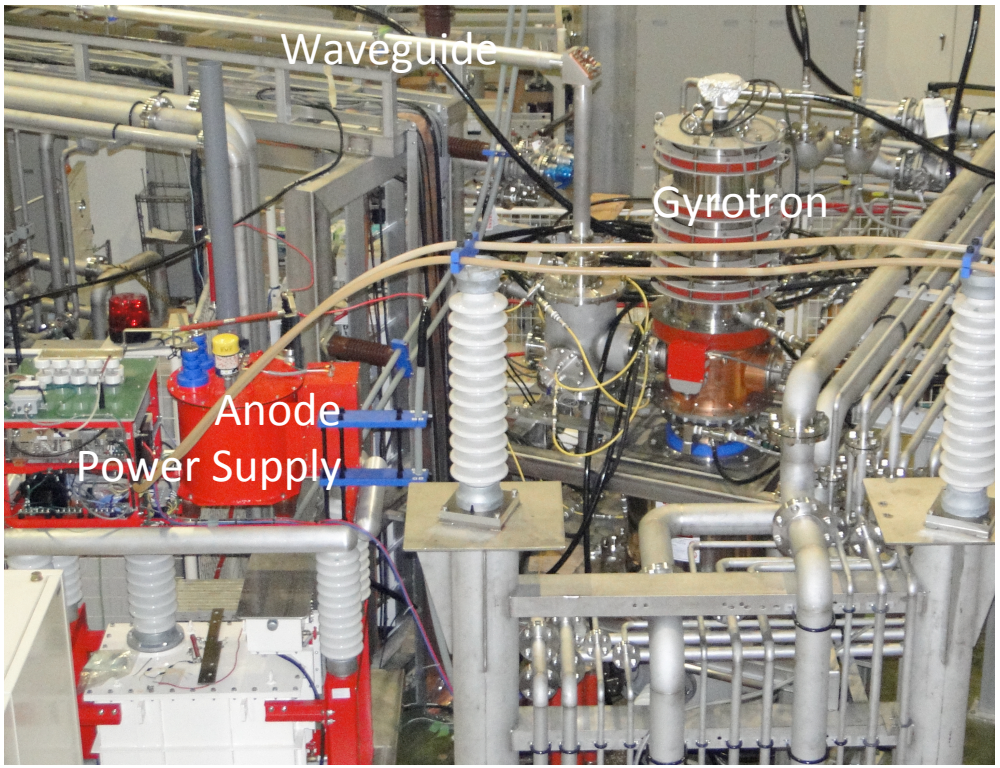


25A @70/75kV ---- Kyushu University

600 kW power level is available for 2s injection.
The oscillating efficiency is improved to attain more than 1MW output.

[2013-] mm-Wave Heating and Current Drive [28GHz]





EBWH/CD Exp. Scenario :

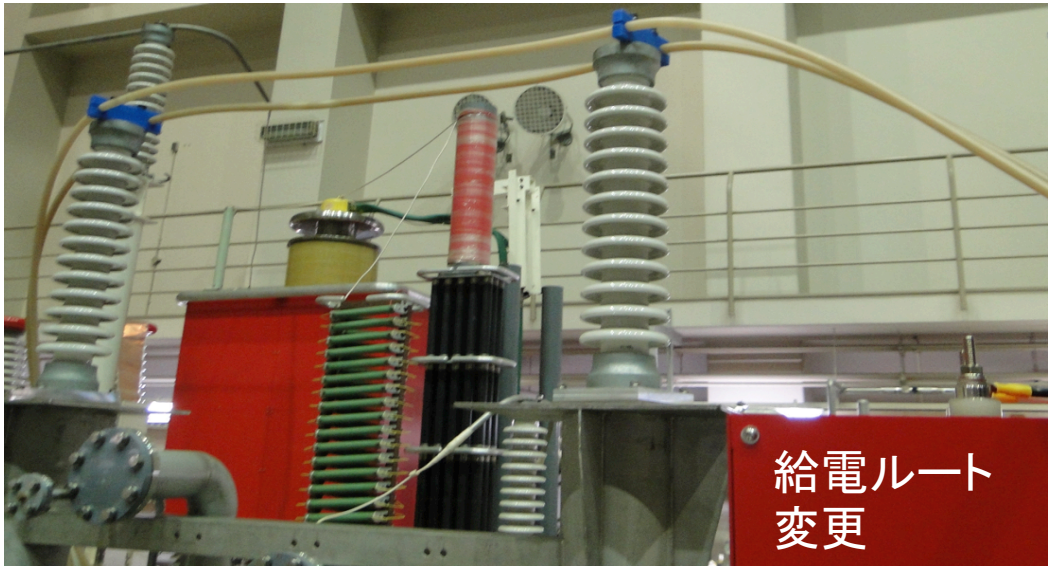
1) 1st : 8.2 GHz: production
2) 2nd : 28 GHz : density ramp-up
3) 1st : 8.2 GHz : EBWCD

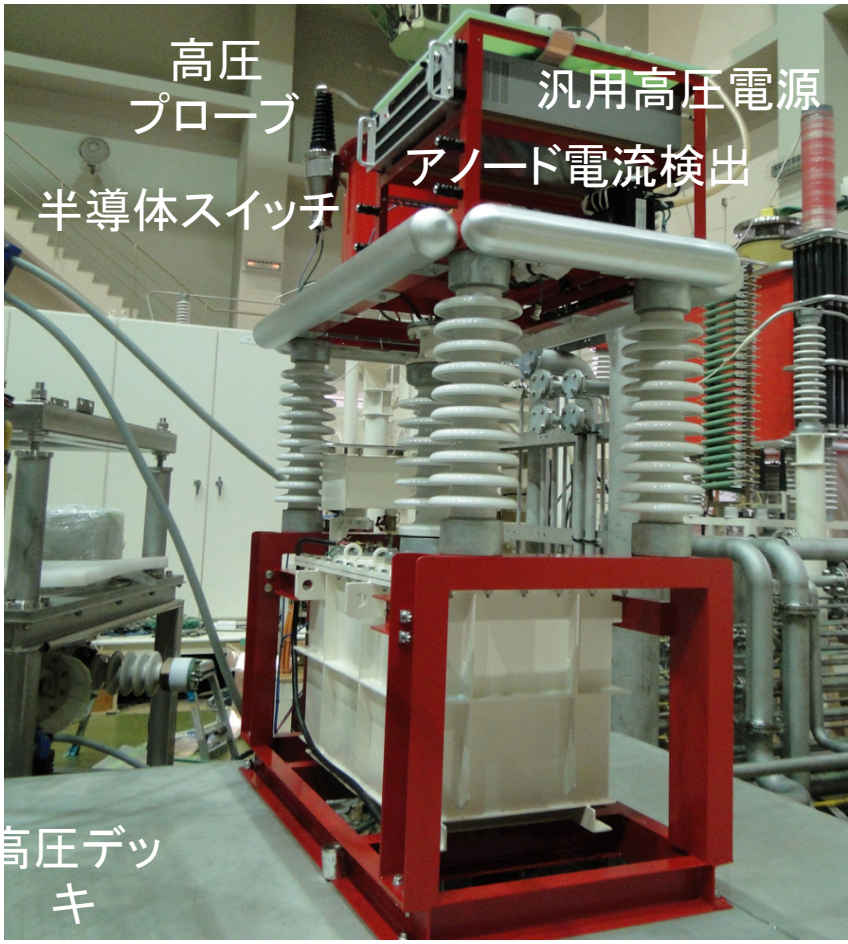
ECH/CD Exp.

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

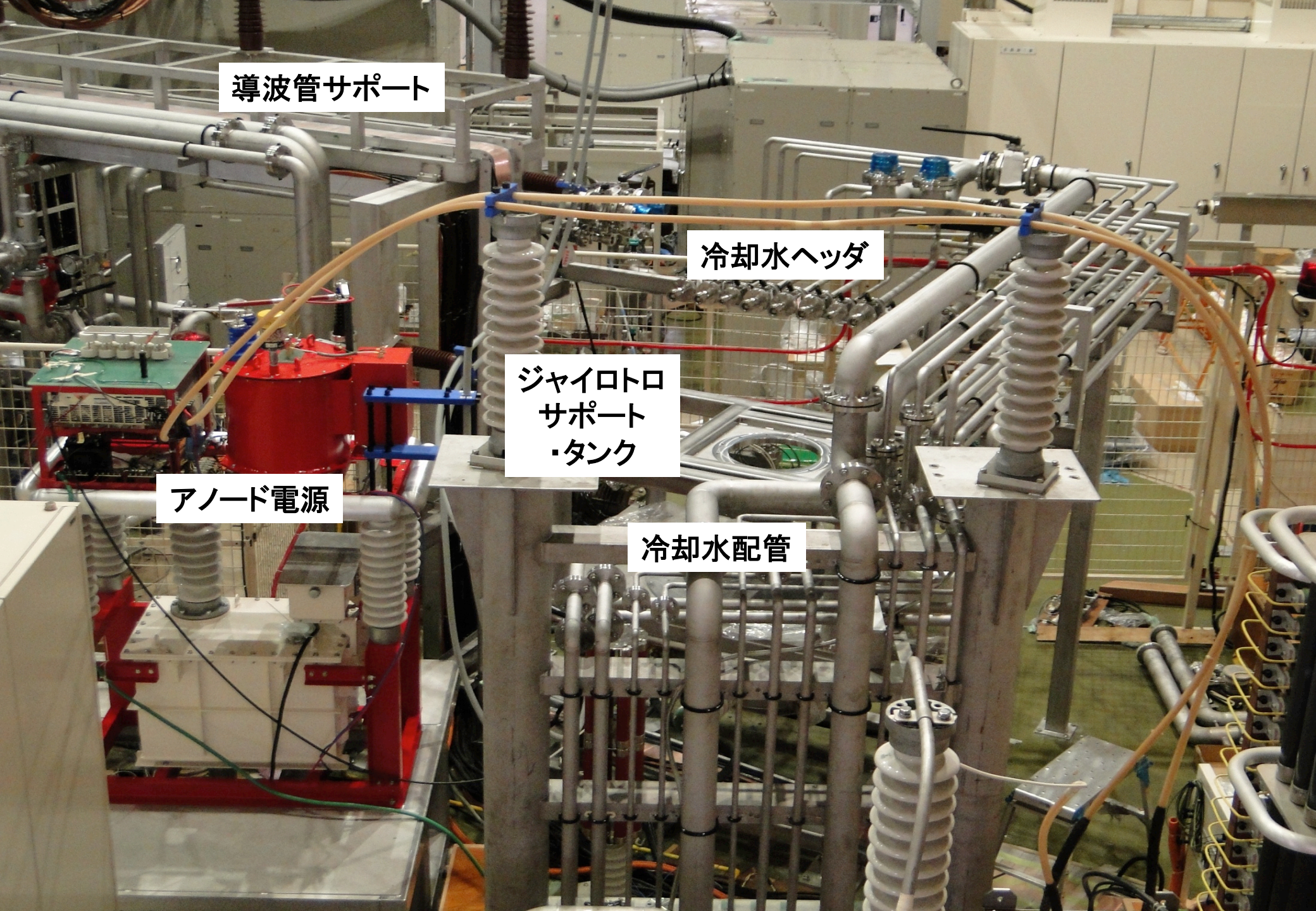
28GHz ジャイロトロン管電源系の整備

・コレクタ電圧・電流の制御（定常大電力クライストロンとの共用）
・ジャイロトロンタンク整備
・アノード電源部（電源、スイッチング、インターロック）の整備



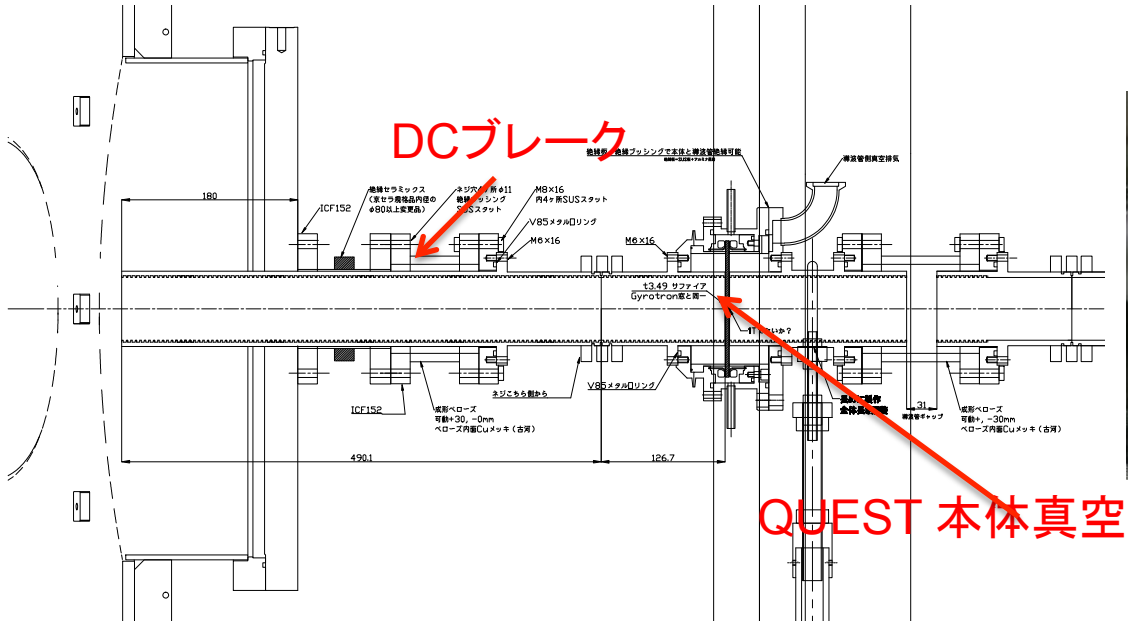


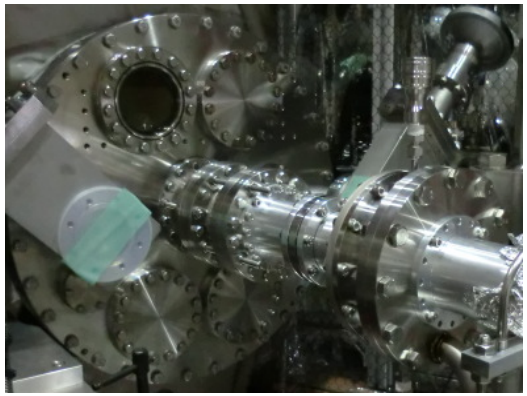
・耐電圧試験：　75kV 10分　良好
・アノード過電流検出でのアノード電圧：
　　高速遮断　1μs以下
・アノード過電流検出でのカソード電圧
　　高速遮断　5.4μs(10μ以内が条件）
・耐ノイズ試験: クローバ動作でも、大きなノイズなし

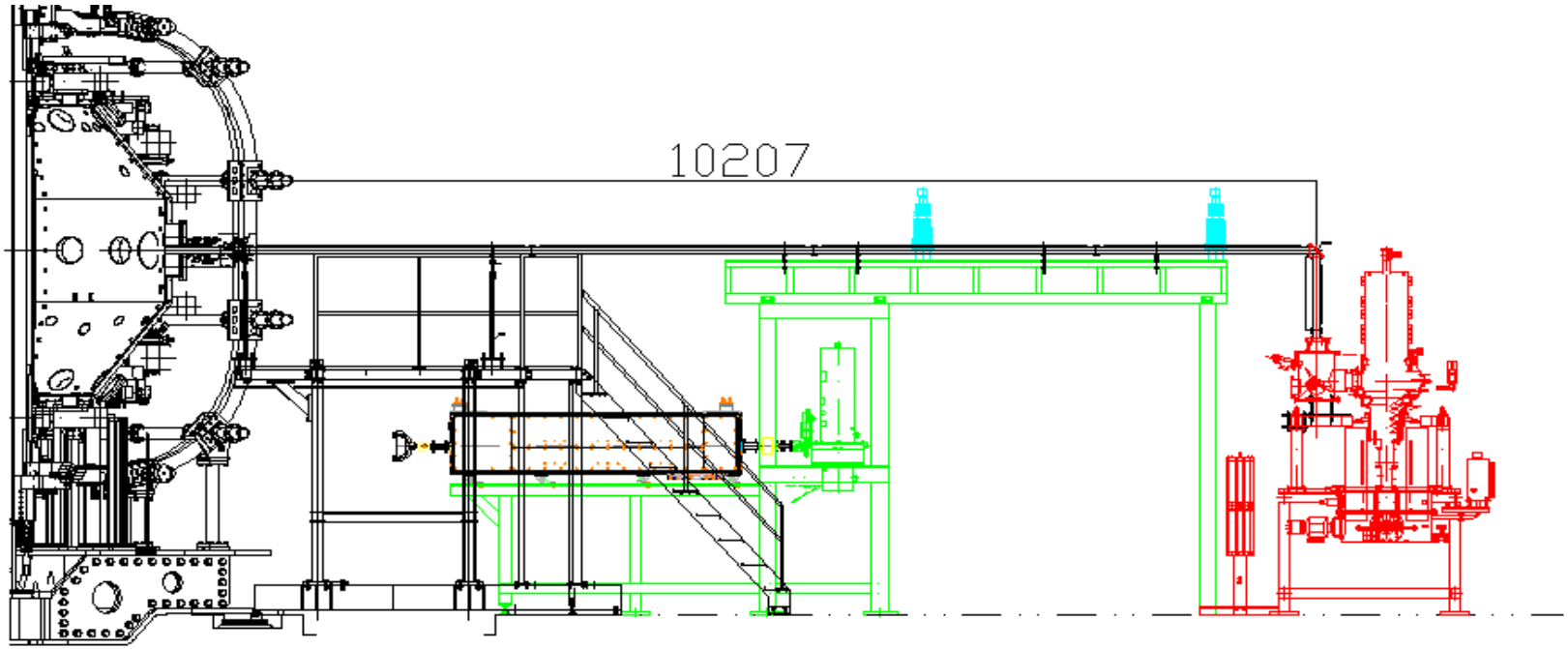

導波管サポート
冷却水ヘッダ
ジャイロトロ
サポート
・タンク
アノード電源
冷却水配管

Installation of Gyrotron System in QUEST

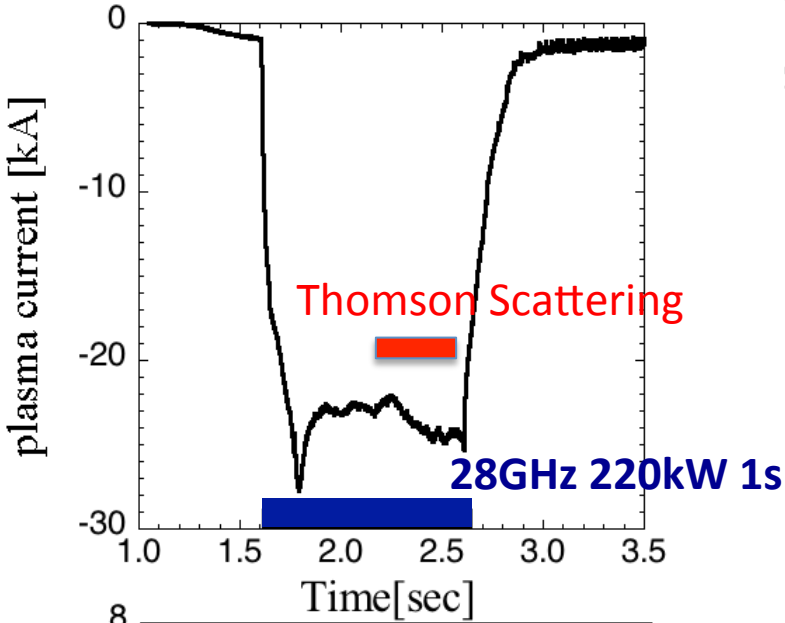
３月２１日：SCM, FC75 チラー、コイル電源等の搬入、据付
３月２２日：ジャイロトロン管の搬入

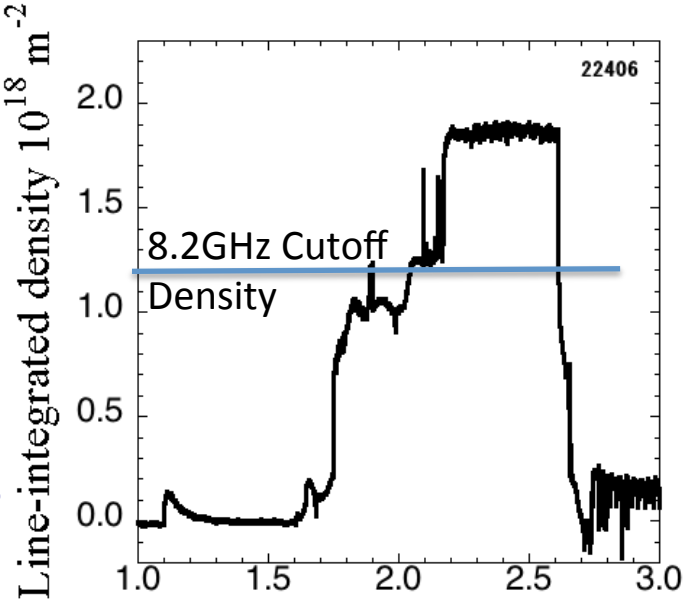

DCブレーク
180
ICF152
M8×16
M6×16
V85メタルOリング
ICF152
490.1
126.7
QUEST 本体真空窓

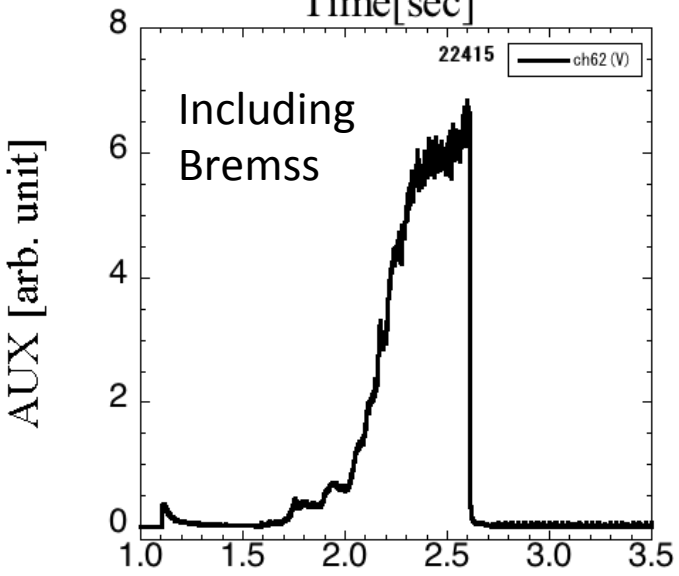


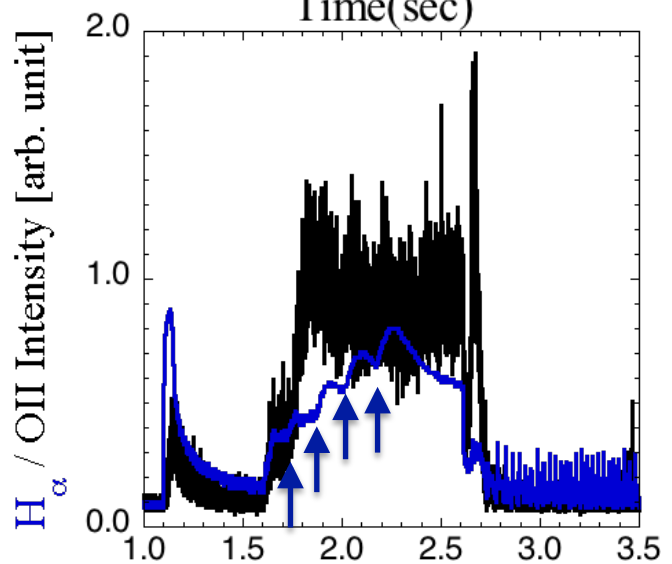

10207

Non-inductive Start-up and Sustainment [28GHz]
High Density Operation

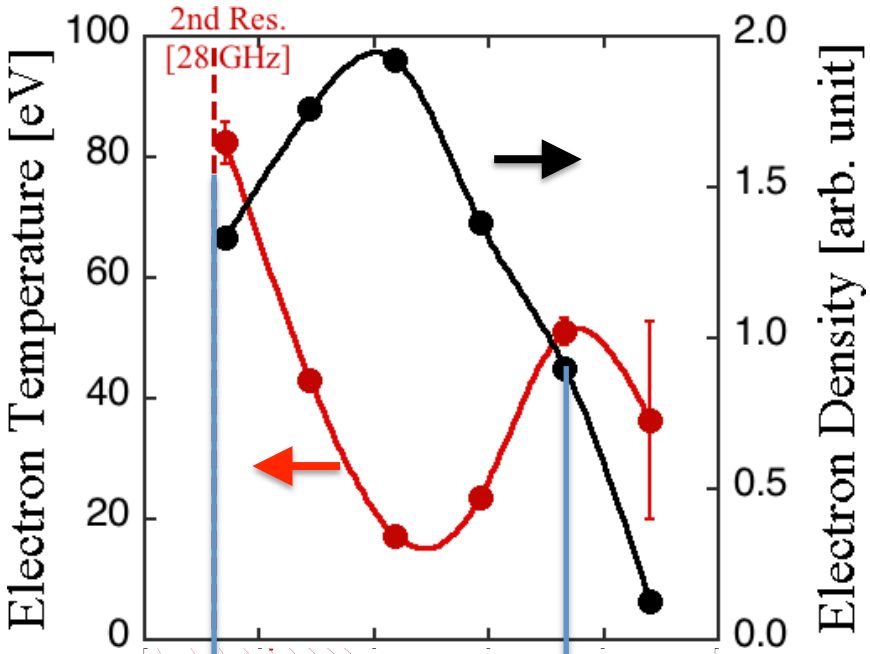


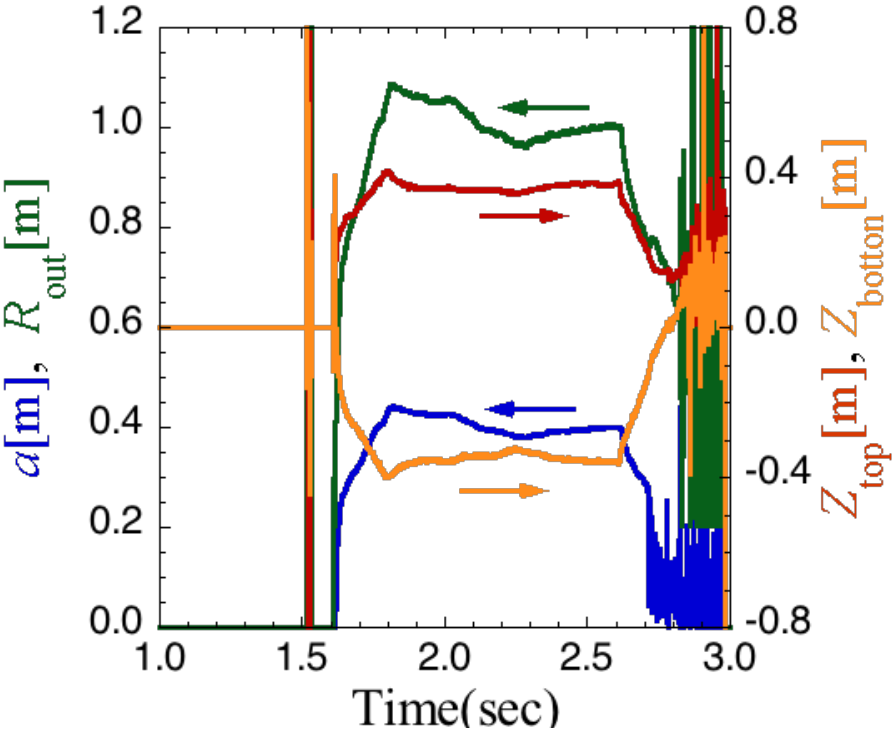


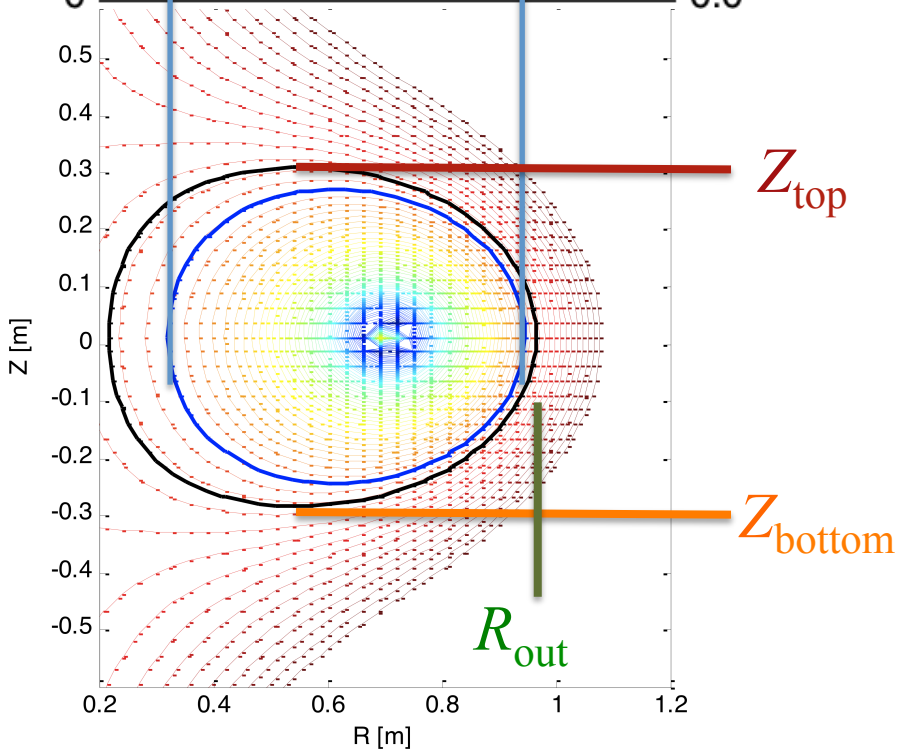


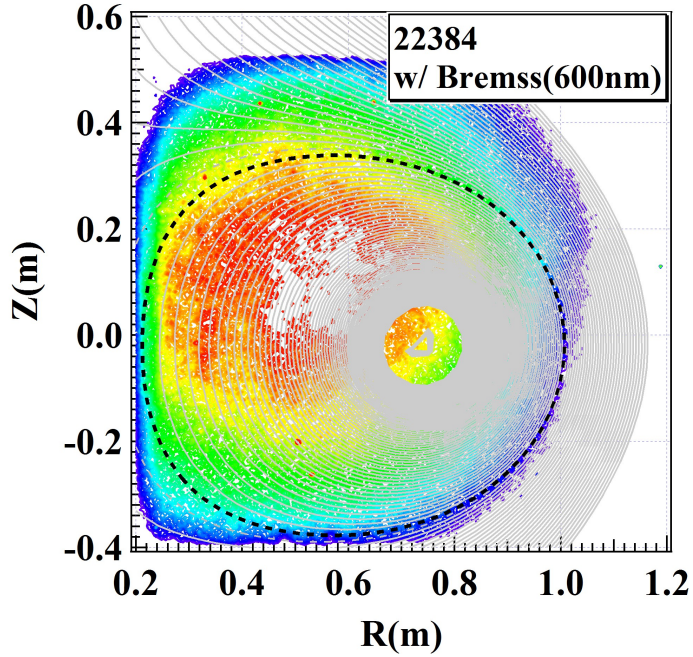


4 gas puffings


2nd Res.
[28IGHz]
Electron Temperature [eV]
Electron Density [arb. unit]


a[m], R_out[m]
Z_top[m], Z_botton[m]
Time(sec)


Z_top
Z_bottom
R_out
Z [m]
R [m]


22384
w/ Bremss(600nm)
Z(m)
R(m)

Non-inductive Start-up and Sustainment [28GHz]
Low Density / High Temperature Operation

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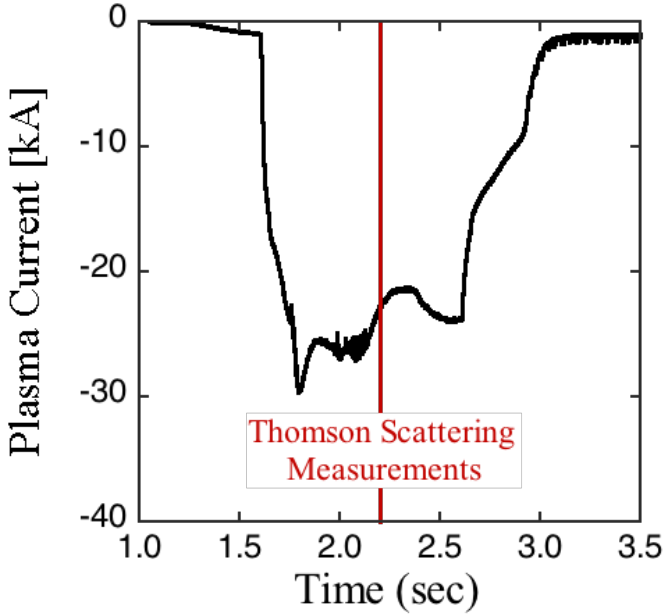
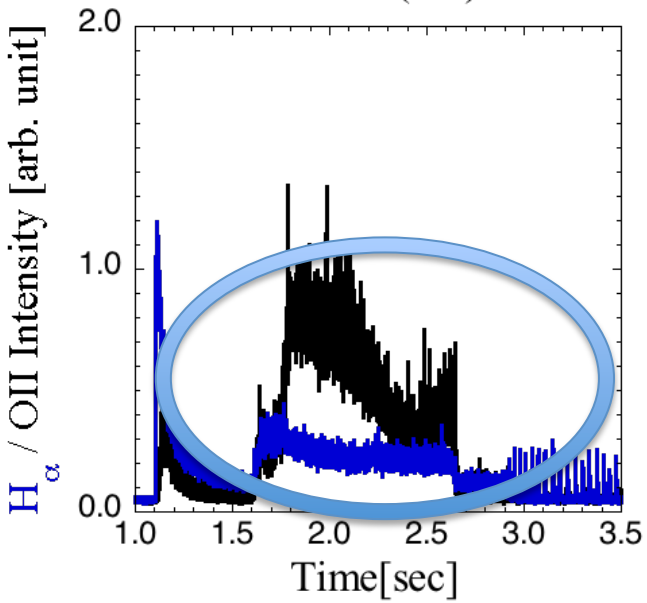
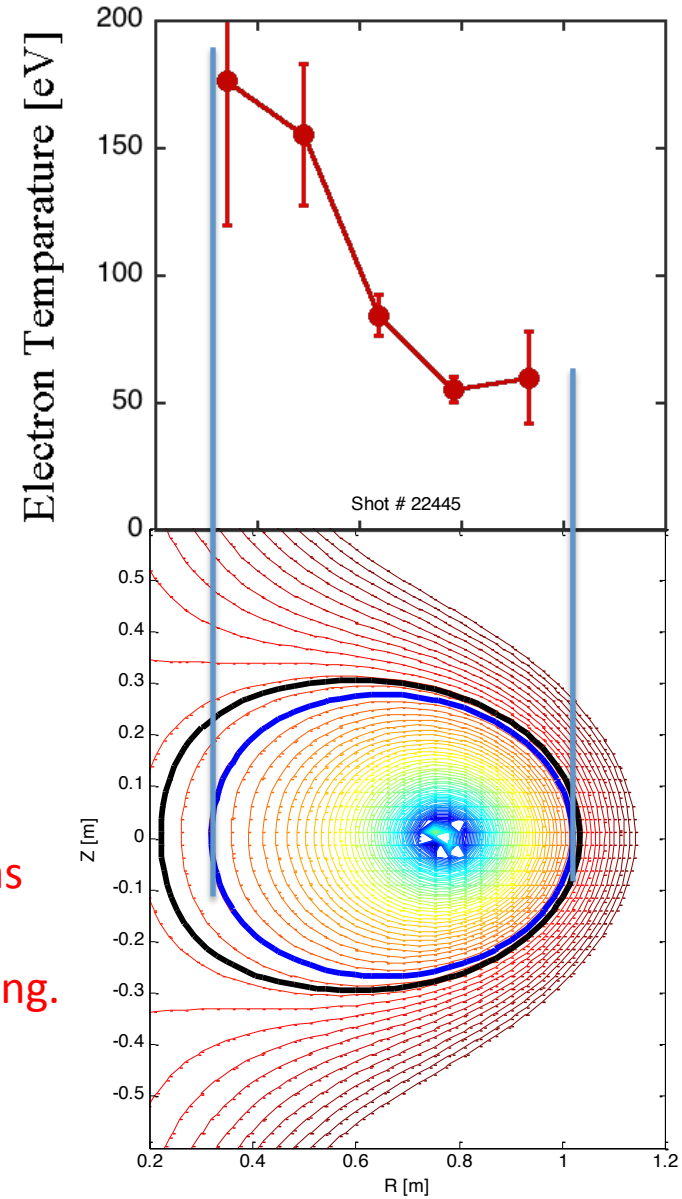


The plasma current of 25 kA was sustained in low density plasma.

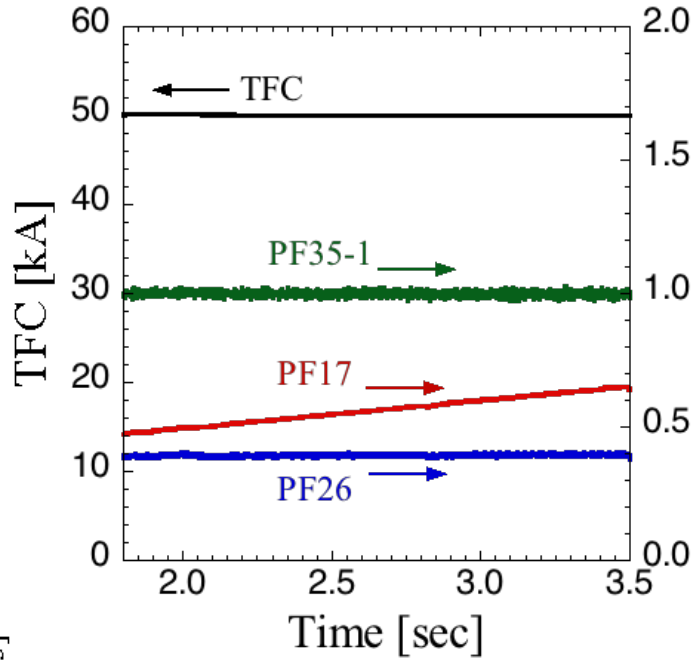
28GHz 220kW 1s

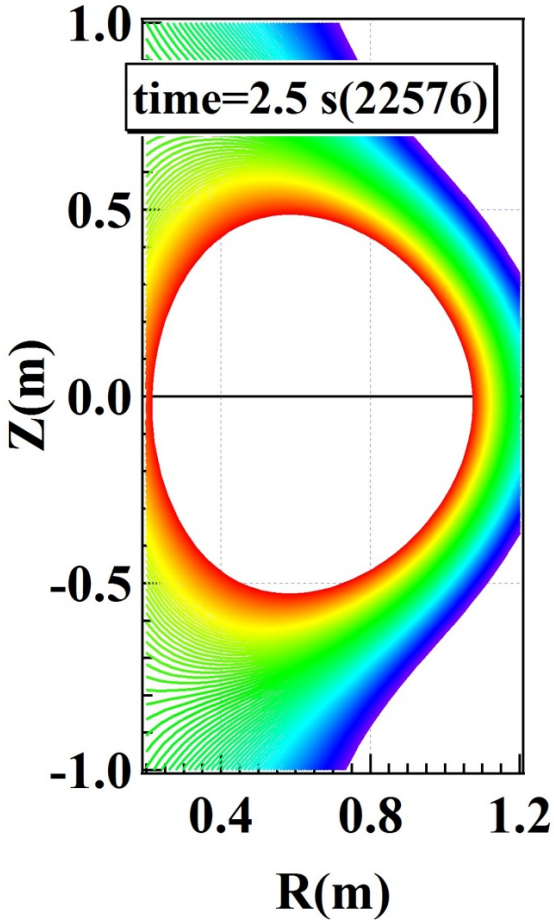


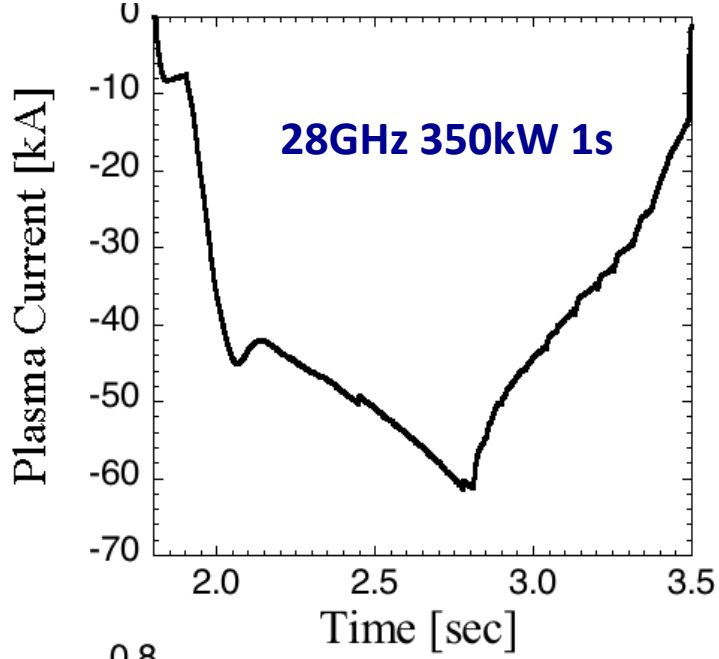
The density was as low as a half of 8.2 GHz cutoff density with no gas puffing.

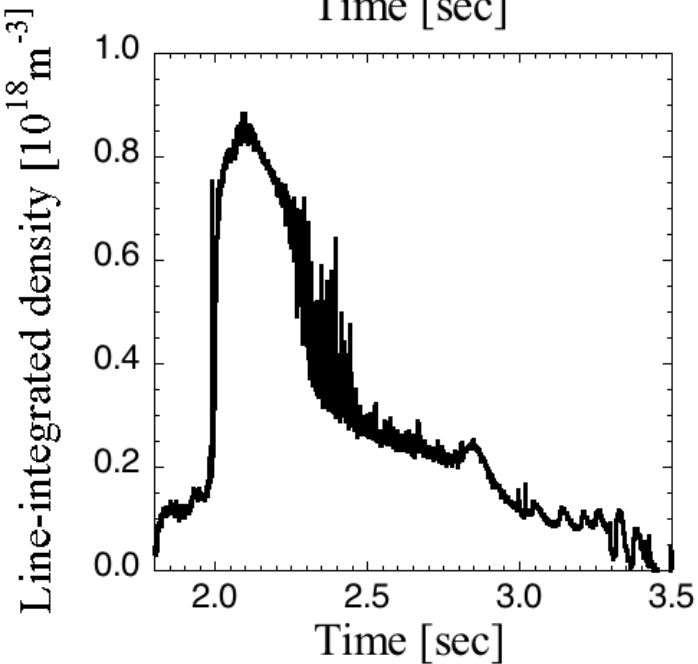


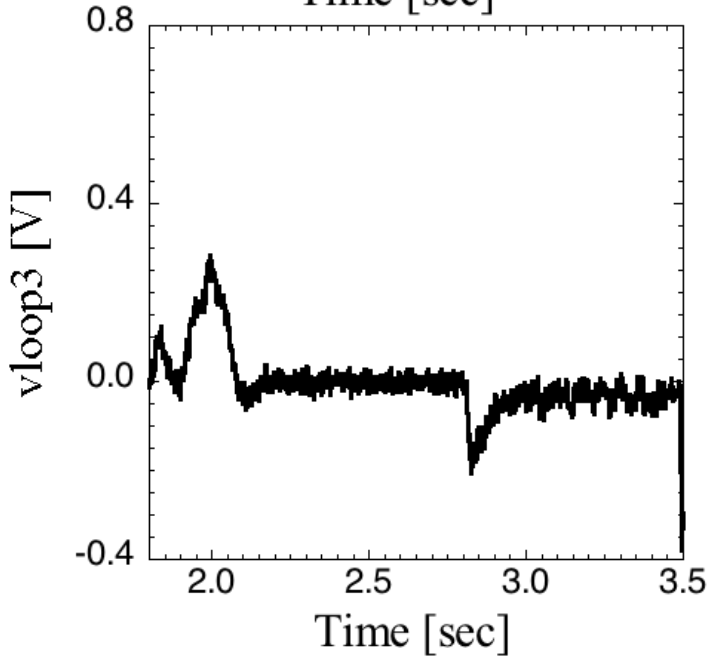
Non-inductive Start-up and Ramp-up [28 GHz]



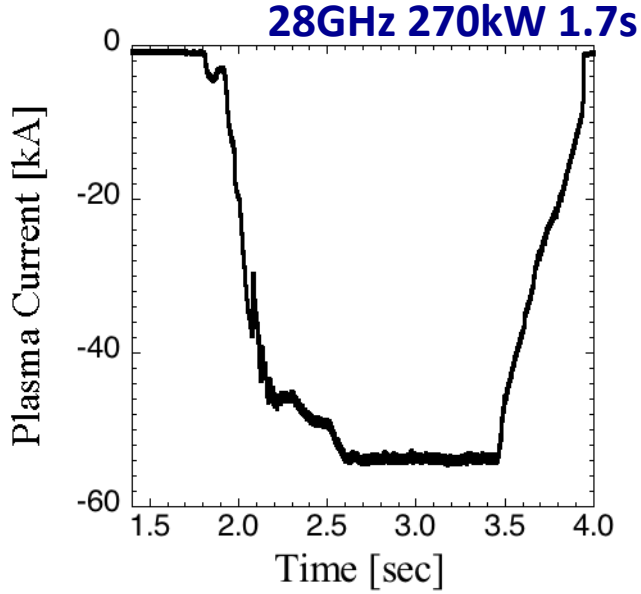


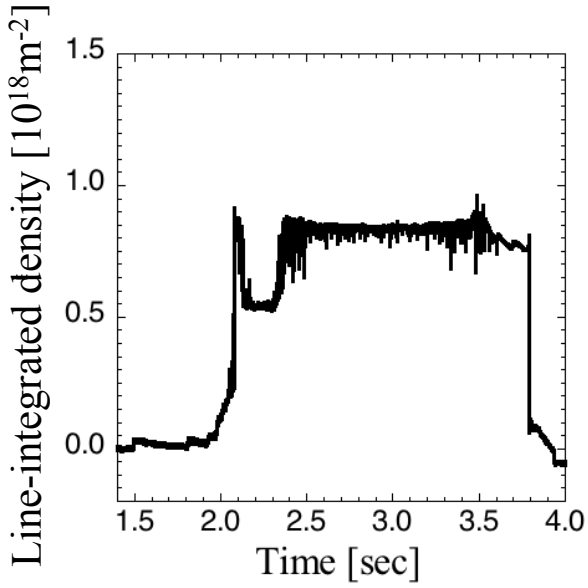


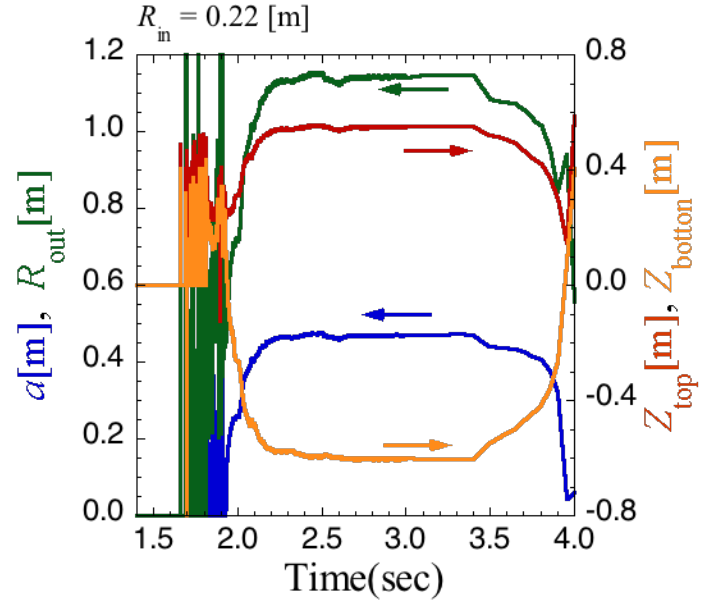


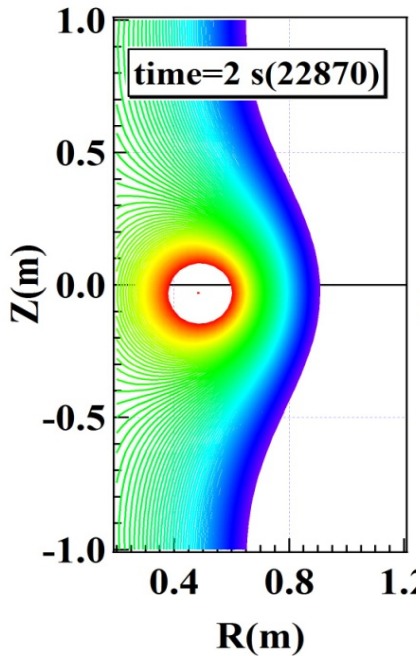


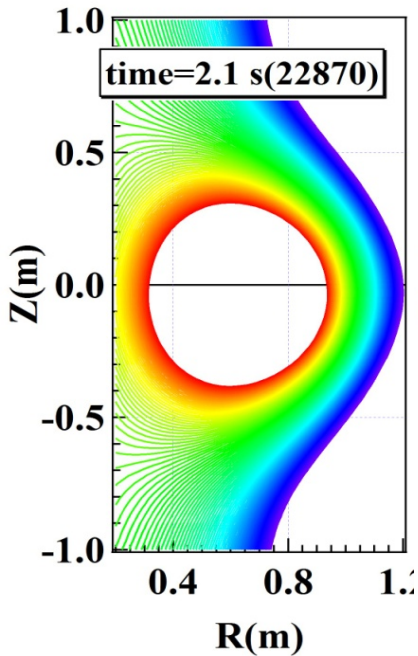
Non-inductive Start-up and Sustainment [28 GHz]

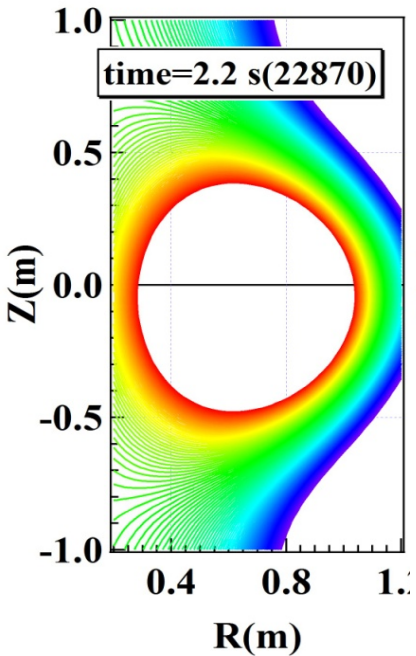


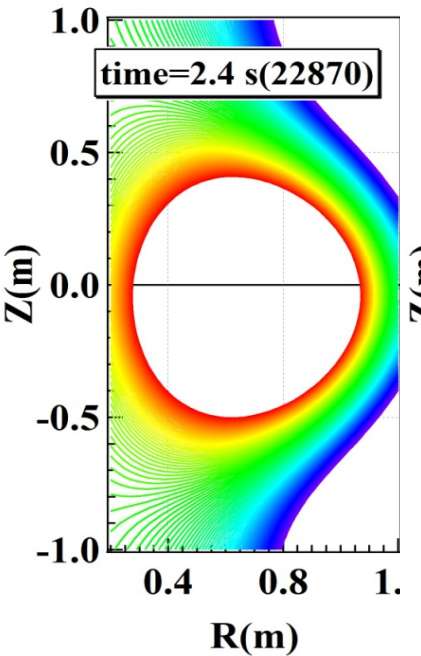


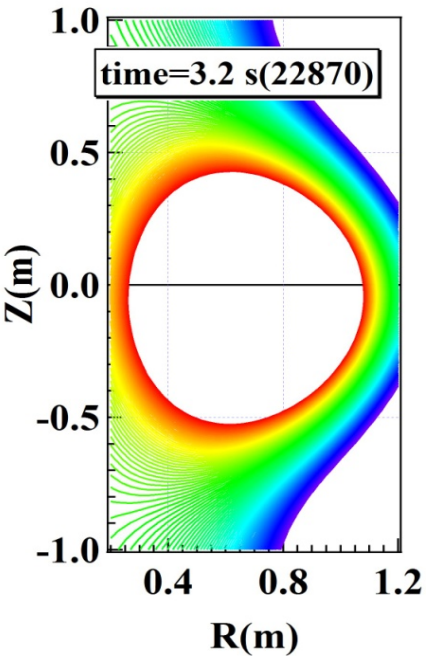




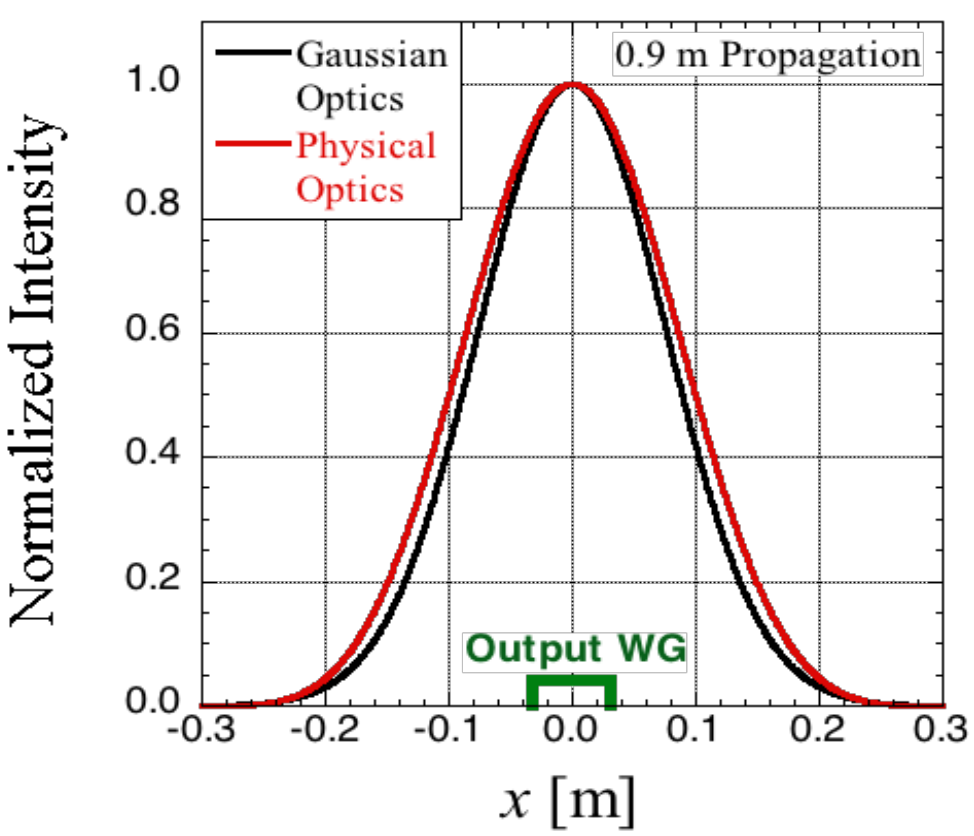


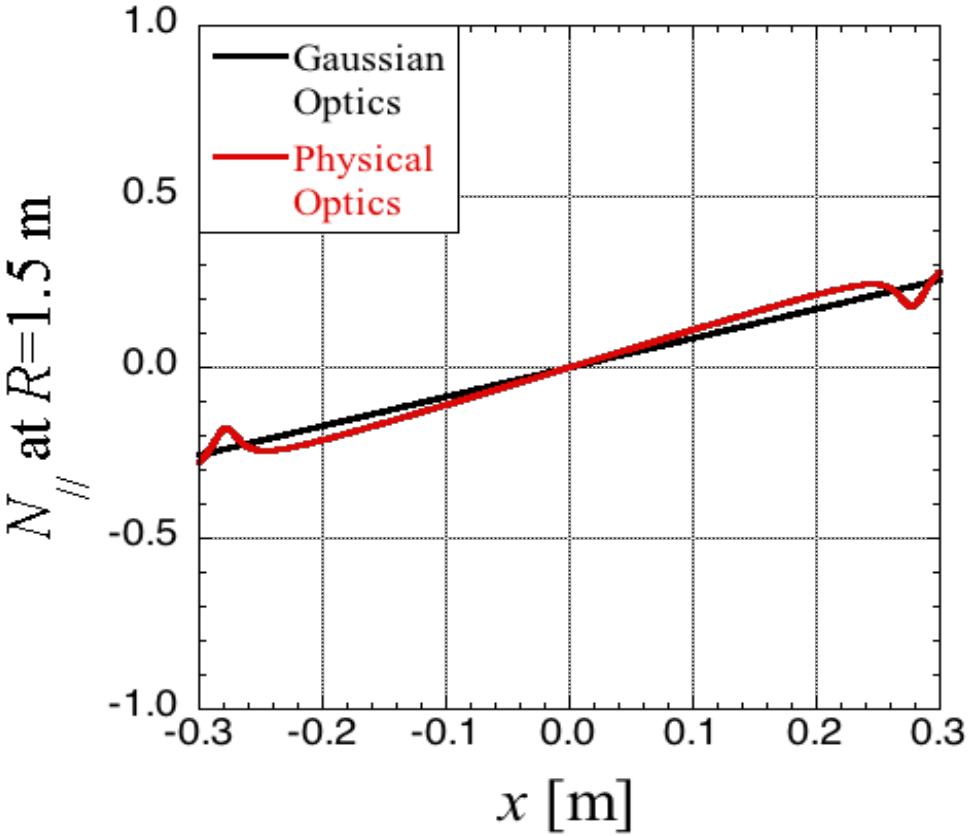






28GHz 入射条件





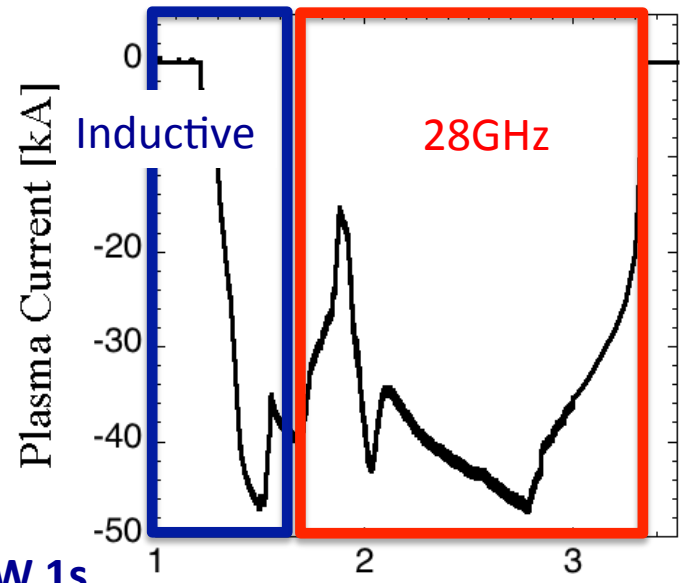
R～1.5mで放射
Cold Resonance は0.32m

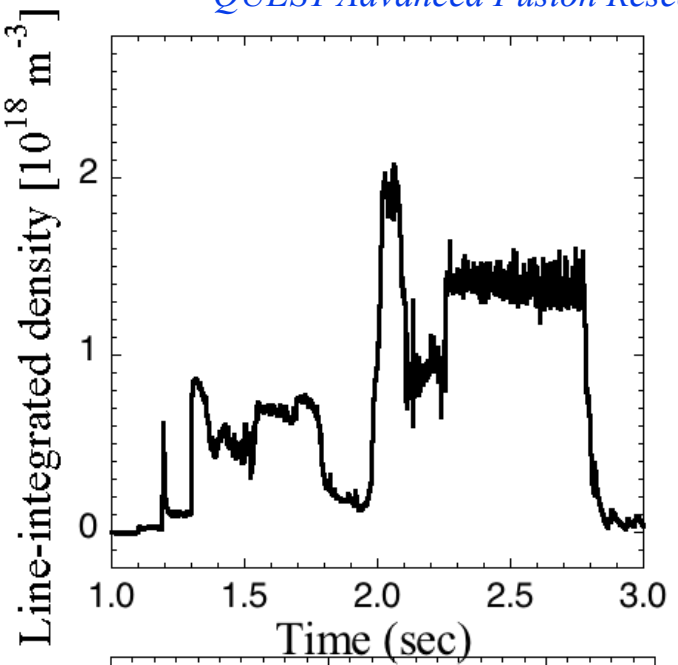
$RN\phi$=const.

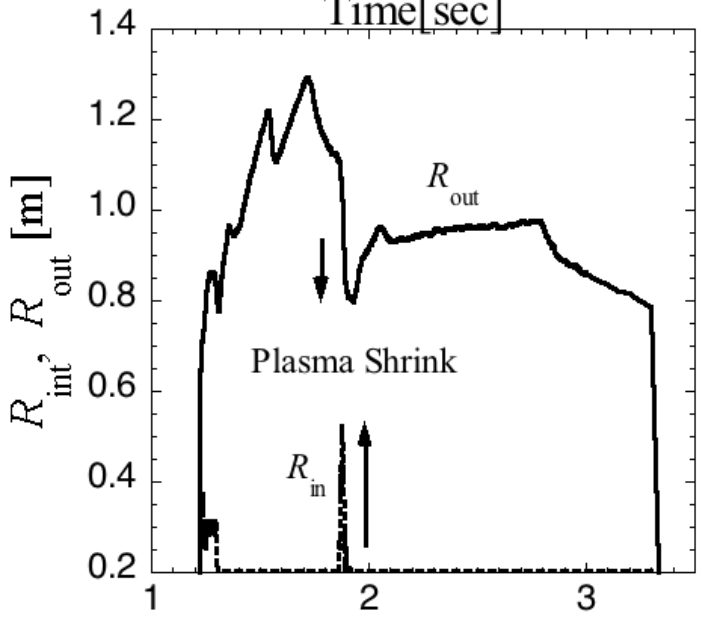
垂直入射でも$N\phi \sim 0.4$ 程度の斜め入射成分を持つ

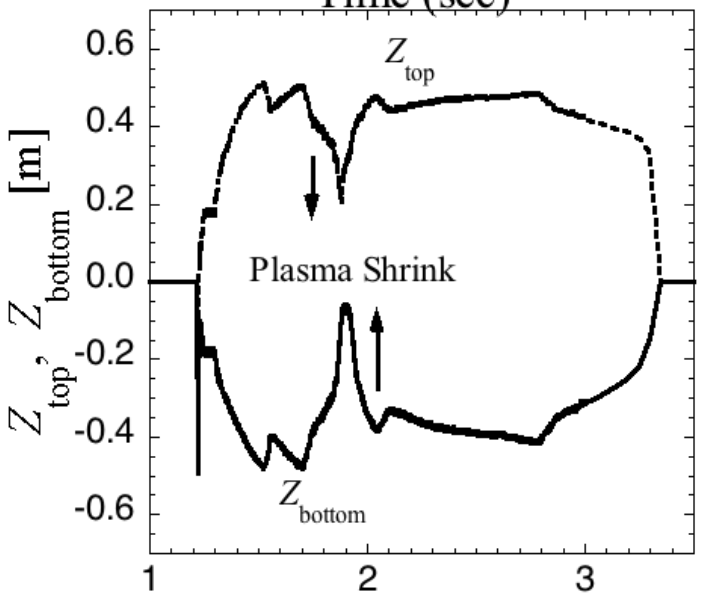
Inductive Start-up and Non-inductive Sustainment [28GHz]
High Current Operation

28GHz 350kW 1s



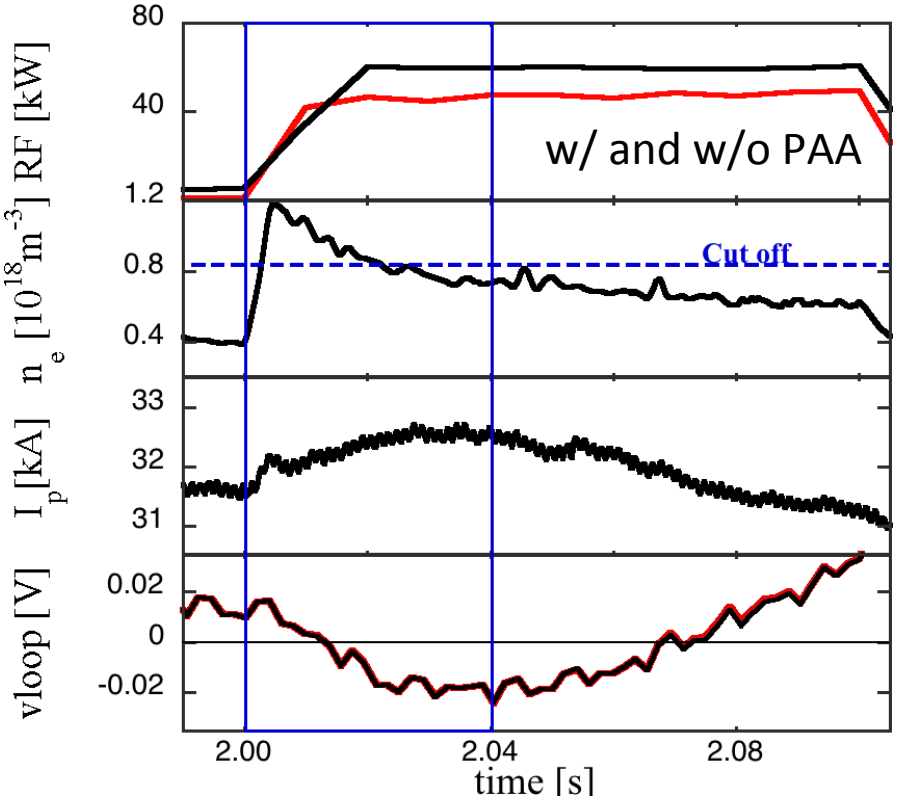




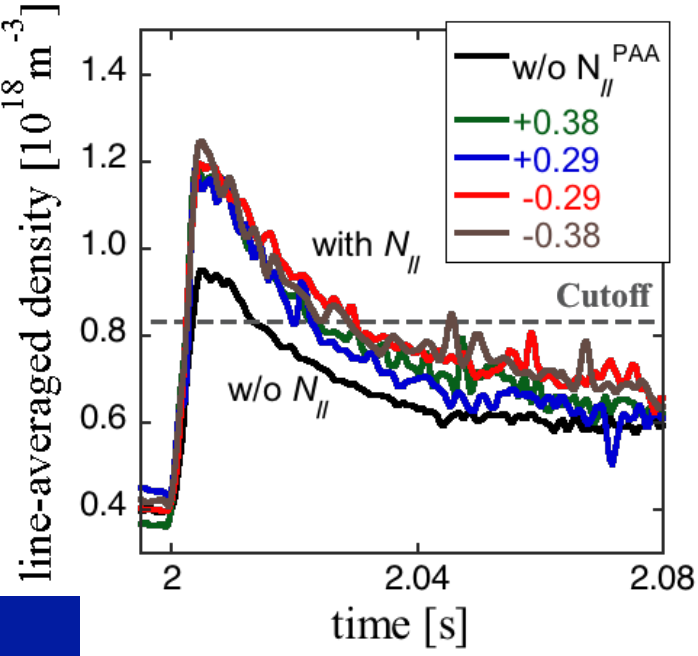


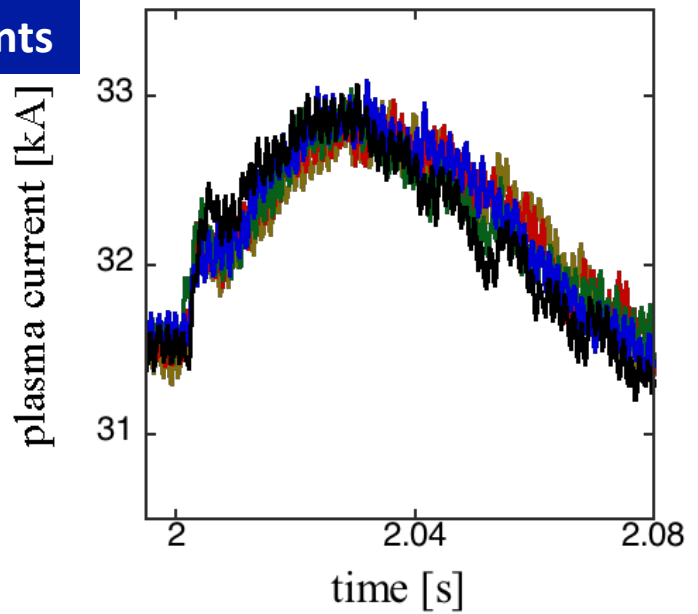
Superposed RF Injection to Ohmic Plasma

RF power is injected into the 30 kA ohmic plasmas controlled by feedback regulation of the center solenoid coil current to maintain the constant plasma current.



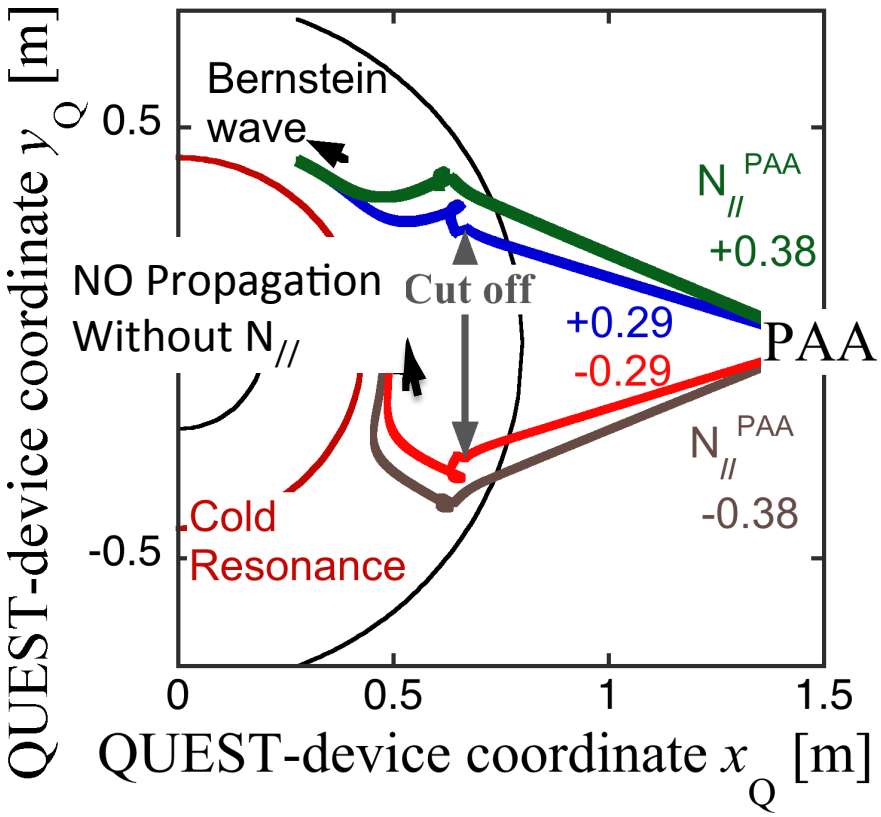
$N_{//}$ scan Experiments

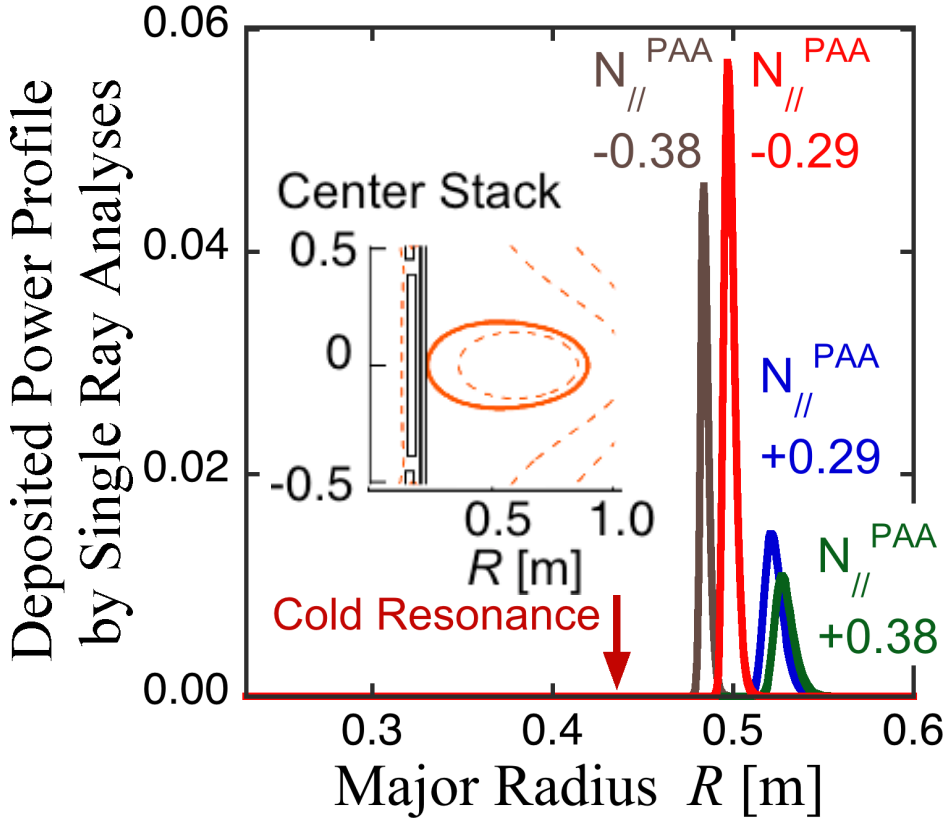




The densities are clearly increased beyond the cutoff by the RF injection with $N_{//}$, compared to the perpendicular (without *N//*) injection, while the changed plasma currents and loop voltages do not depend on the incident $N_{//}$ conditions well.

Propagation and Deposition Analysis with TASK/WR + α code





- The minus (-) sign of $N^{PAA}_{//}$ is changed into positive (+) $N_{//}$ along the propagation after the mode conversion.
- Any incident (+/-) $N^{PAA}_{//}$ becomes large positive (+) value in the Bernstein wave-propagation, and are +2 +4 at the Doppler- shifted absorption layers, expecting Fish-Boozer effects so as to increase the plasma current.

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

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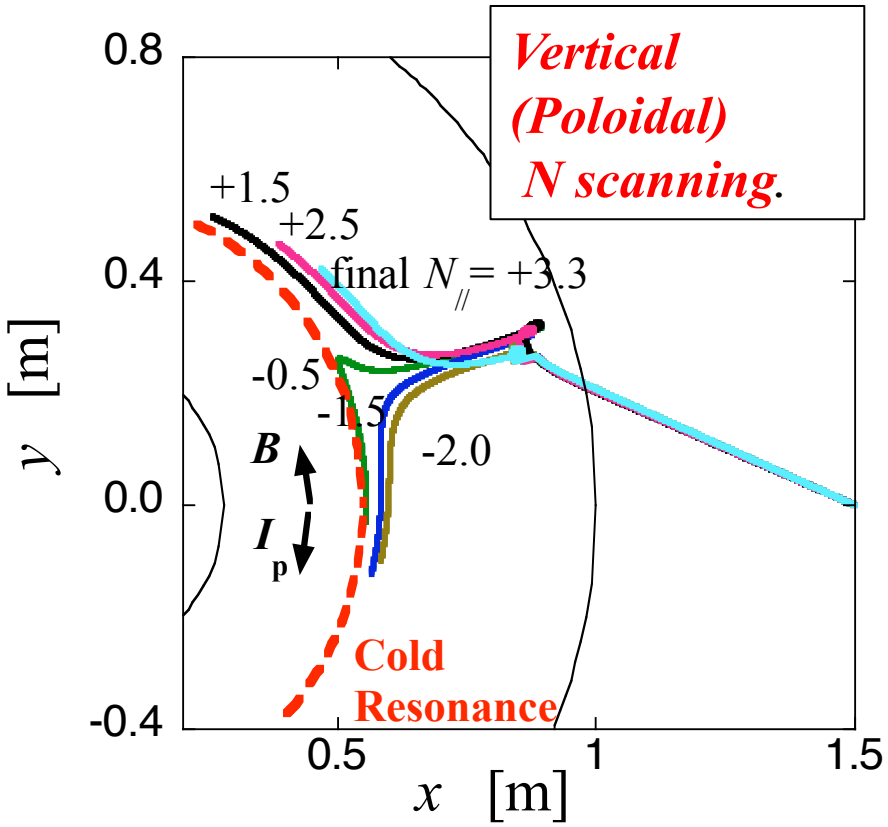
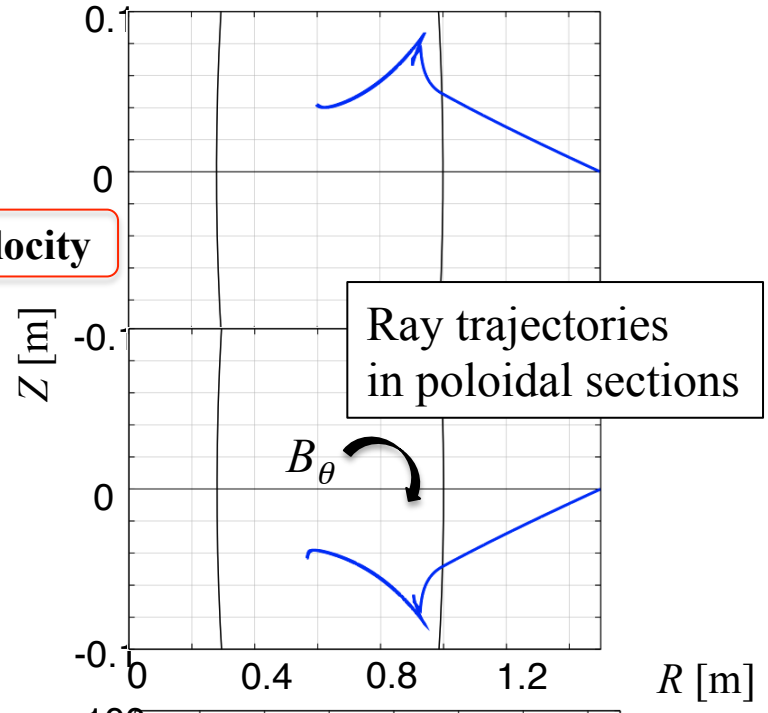


In the electrostatic B-wave, N_θ or k_θ contribution is dominant in the $N//$ evolution not near the mid-plane of the torus.

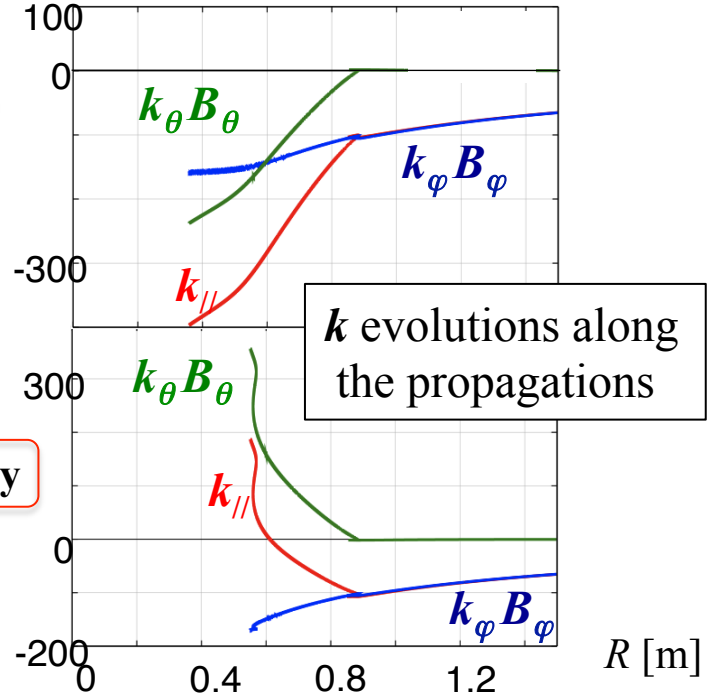
$$k_{||} = \frac{k_\theta B_\theta + k_\phi B_\phi}{B}$$

Group Velocity



$|k_\theta B_\theta| >> |k_\phi B_\phi|$

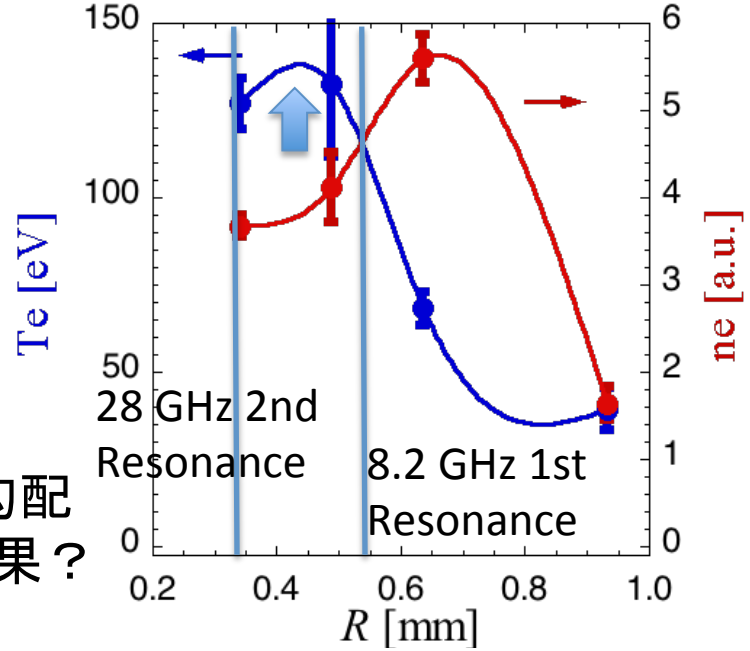
Phase Velocity



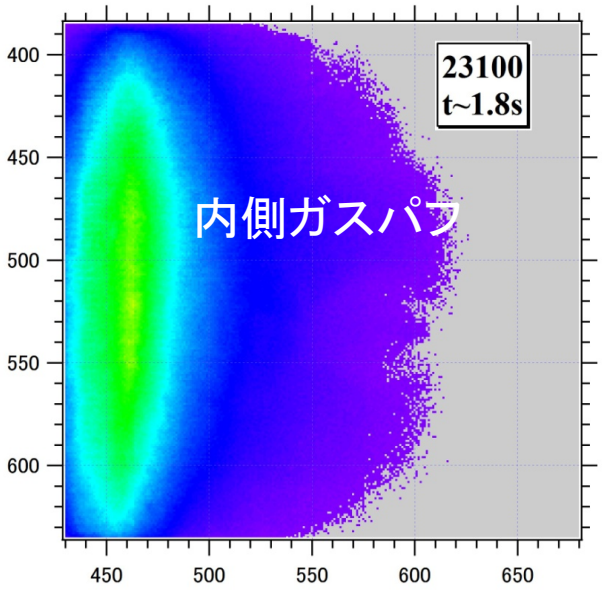
密度勾配調整への試み　内側→外側ガスパフ

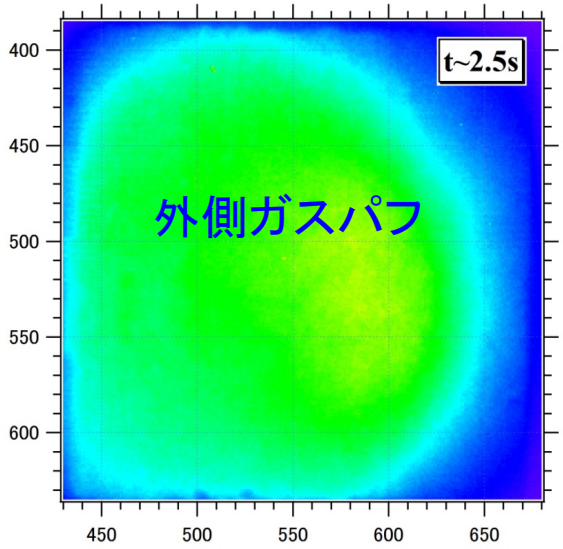
外側ガスパフでの高密度運転・密度勾配調整への試み

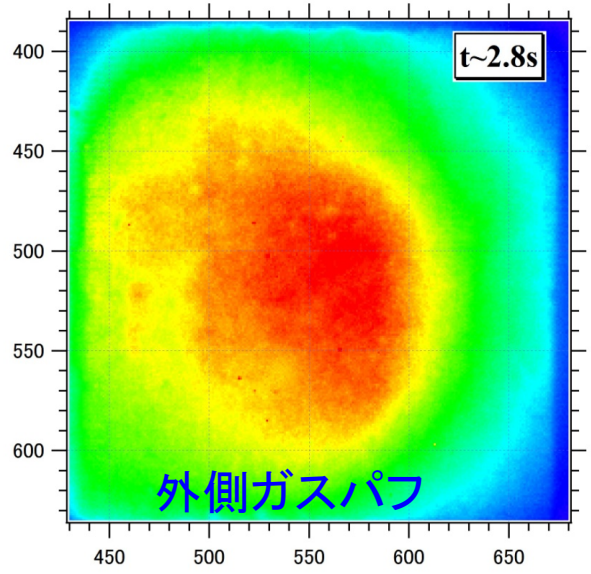
- 2 x $10^{18}$$m^{-3}$：高密度化
- 上下対称



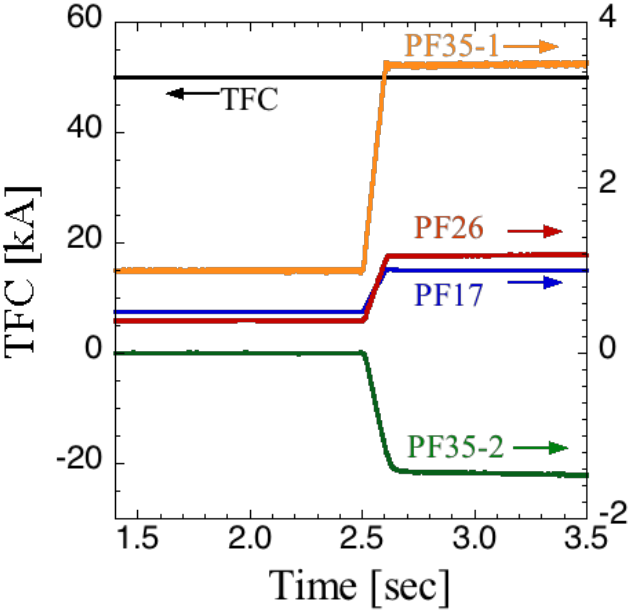
周辺（R~0.8m付近）で、高い密度勾配
8.2 GHz 共鳴層付近で加熱効果？



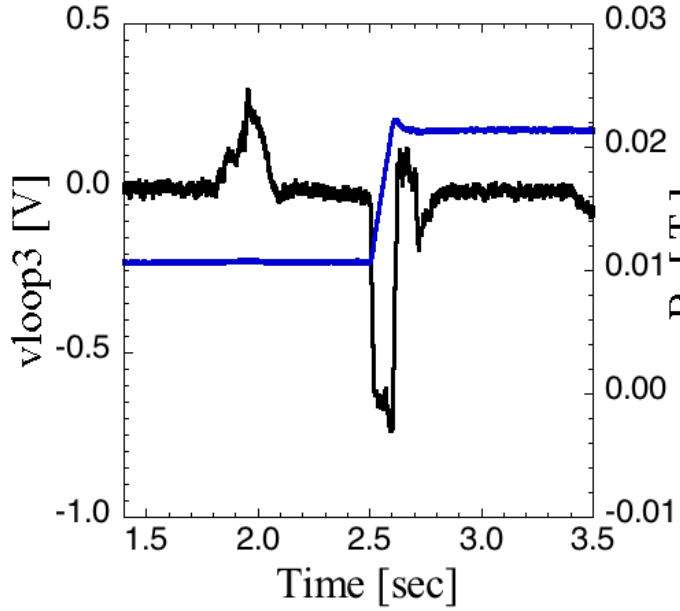


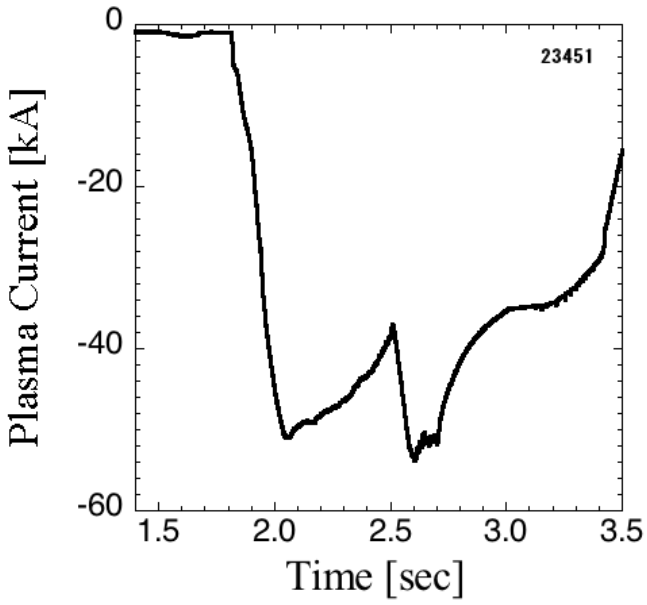


PF35-2 による縦長断面制御

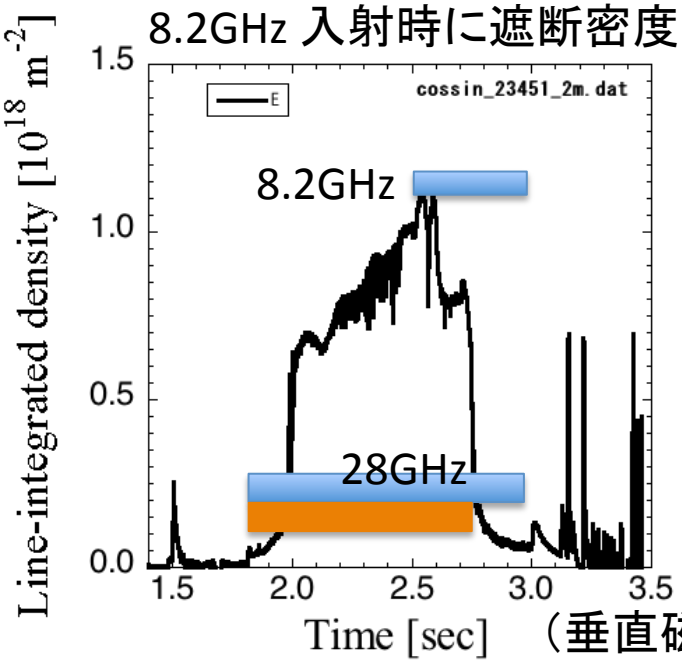


8.2GHz 入射時に Bz~0.02T

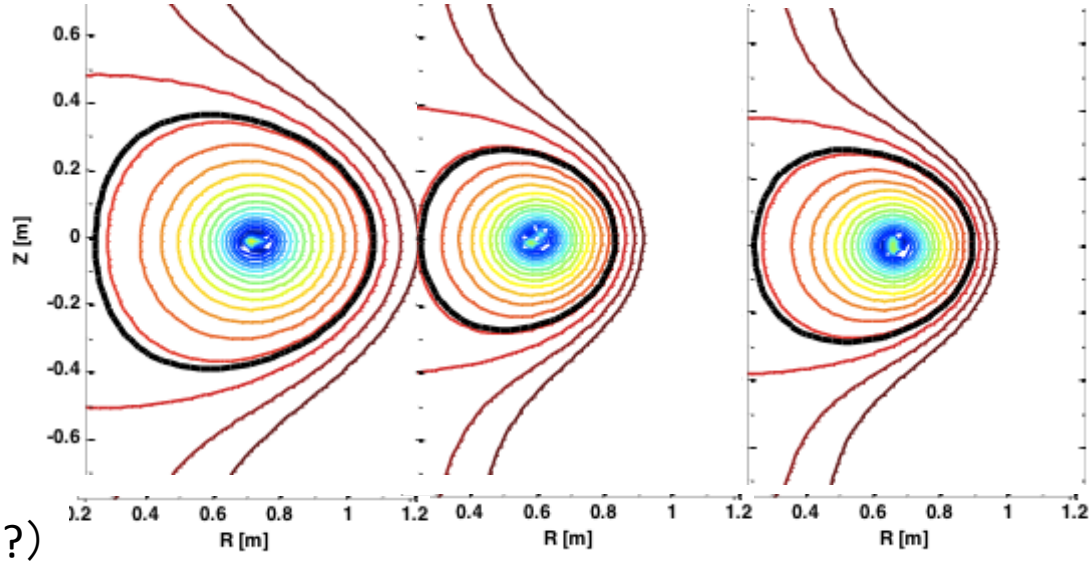




8.2GHz 入射時に遮断密度

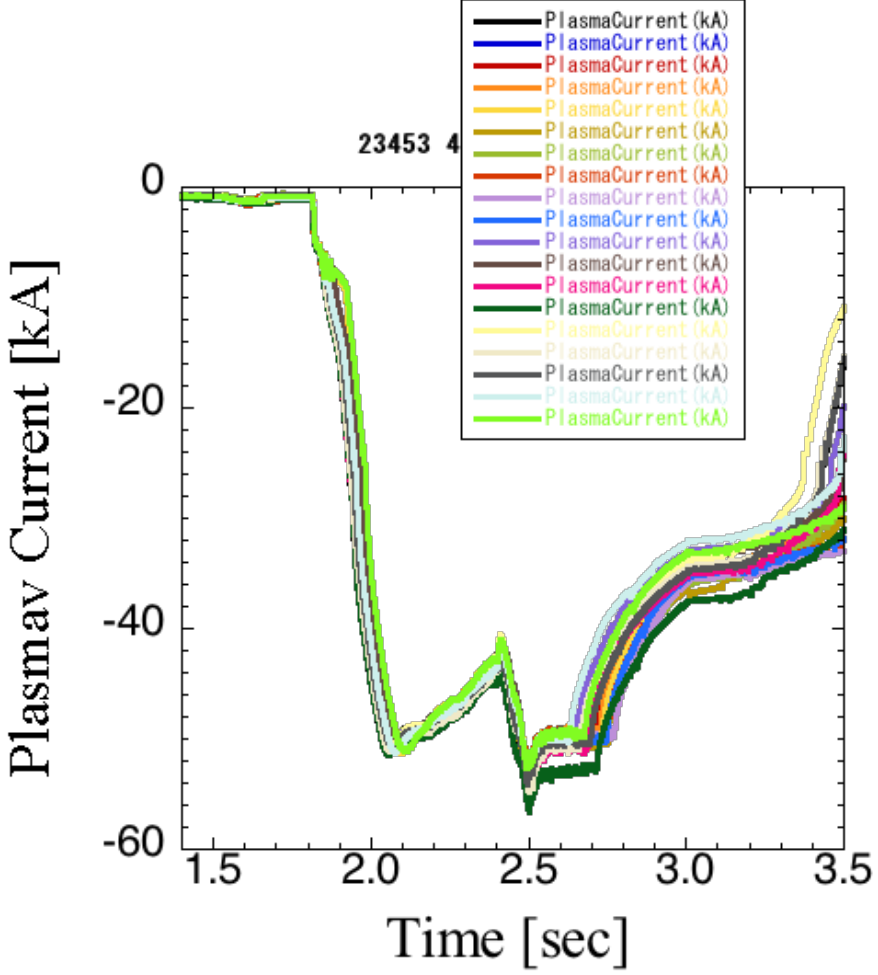


28 GHz → 28 + 8.2 GHz



（垂直磁場の影響?）

1.3 s 設定が < 1s



N_θ, N_ϕ, 偏波面スキャン

再現性の範囲を超えた明確な N_θ, N_ϕ, 偏波面依存性はない。

8.2 GHz入射 で電流増加する条件なし

今後の予定:

トムソン散乱計測で8.2GHz 重畳入射時の電子温度・密度分布計測

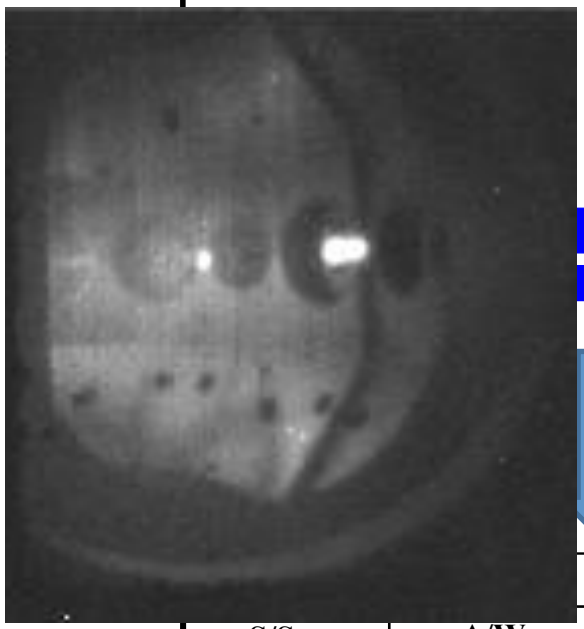
モード変換条件の検討 → 入射条件の考察

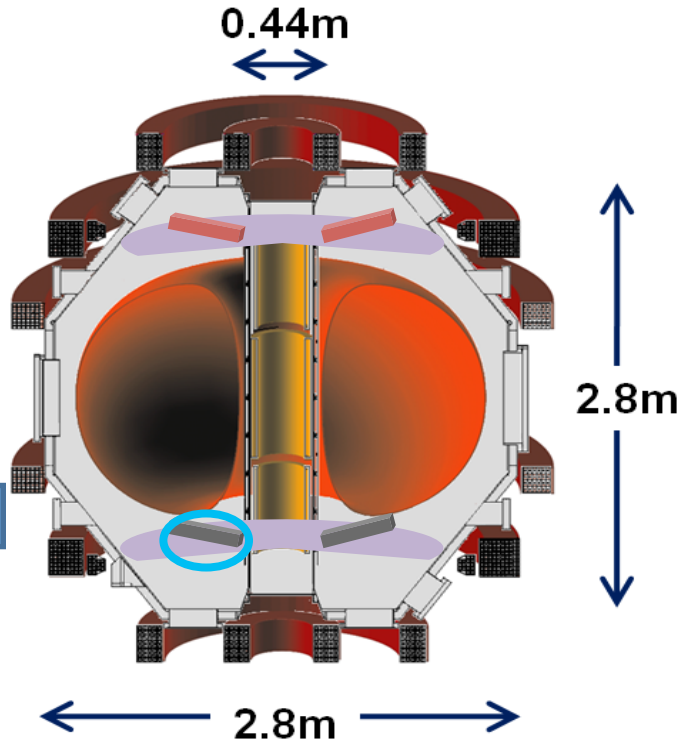
8月28日: 電源改修で 450kW 入射調整 完了 ~150ms 発振 → **600 kW**

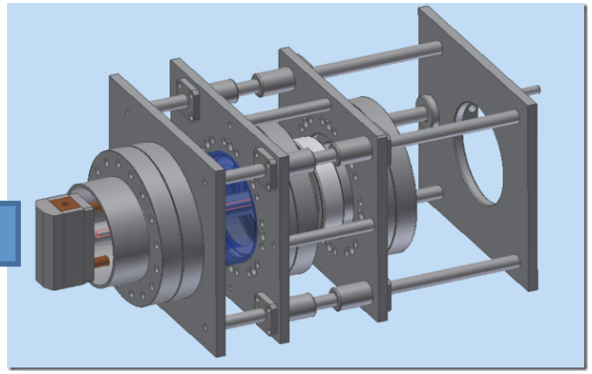
9月: 450kW 1s 実験

できれば、引き続き、斜め入射アンテナシステムを準備し、本格的なECHCD 実験を目指したい

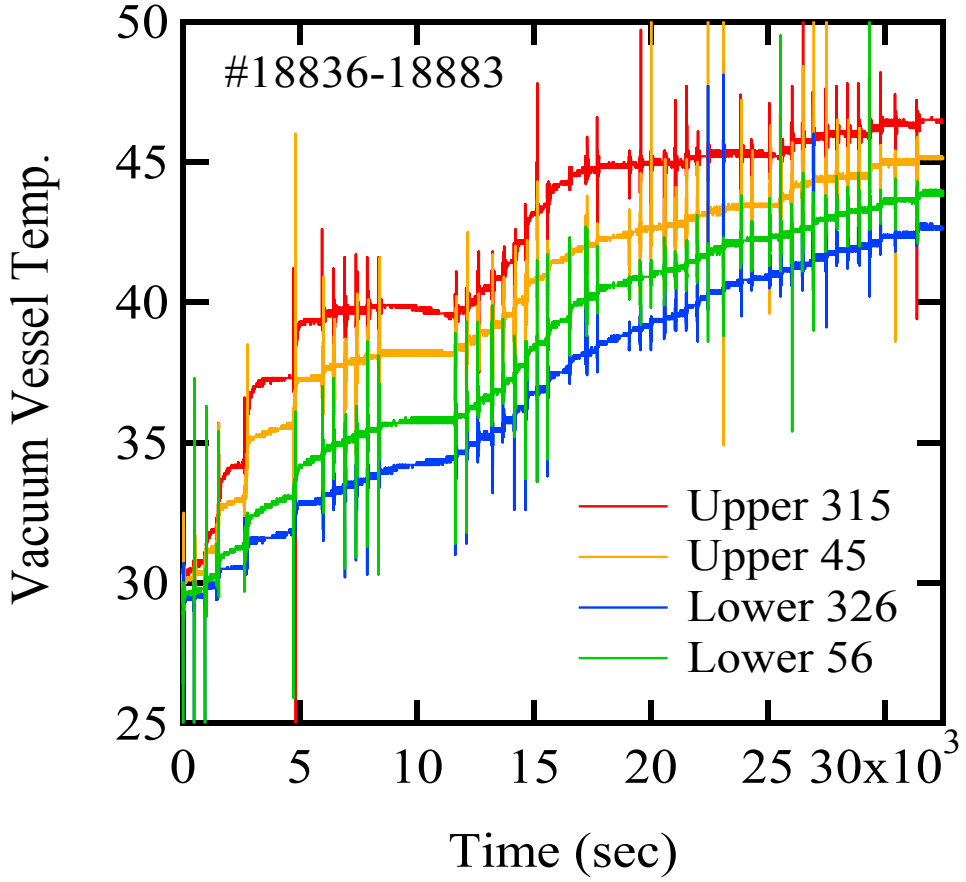
Historical development for SSO on QUEST



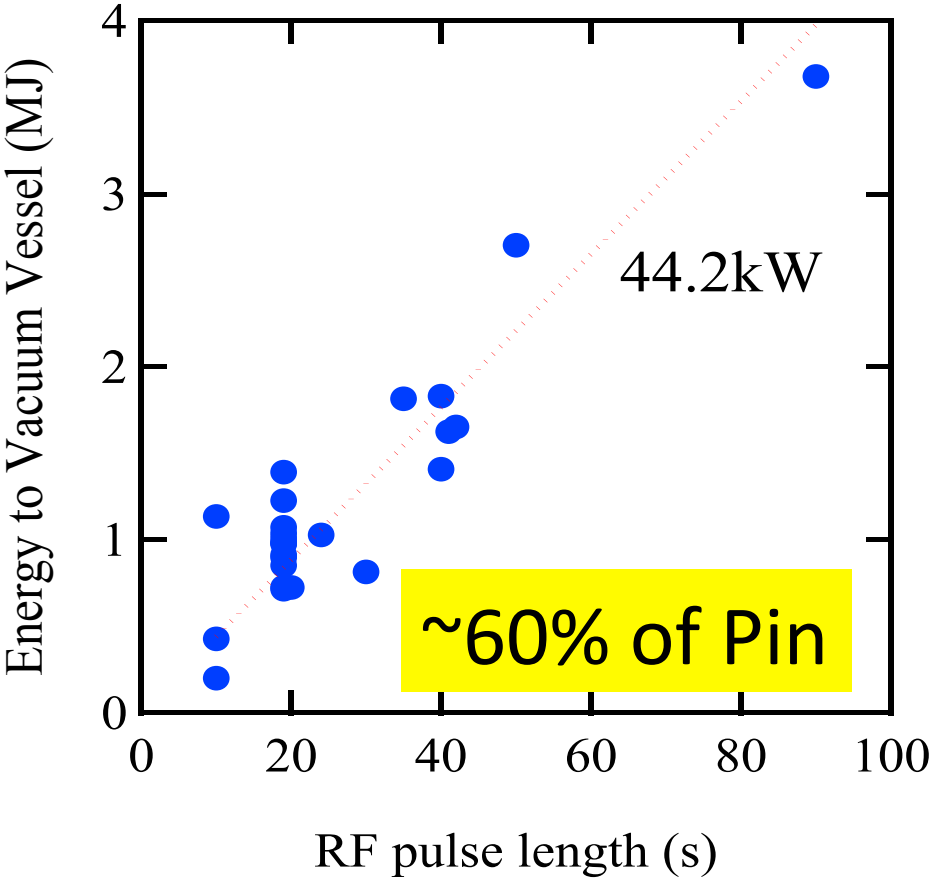




How to estimate deposited power to the vacuum vessel

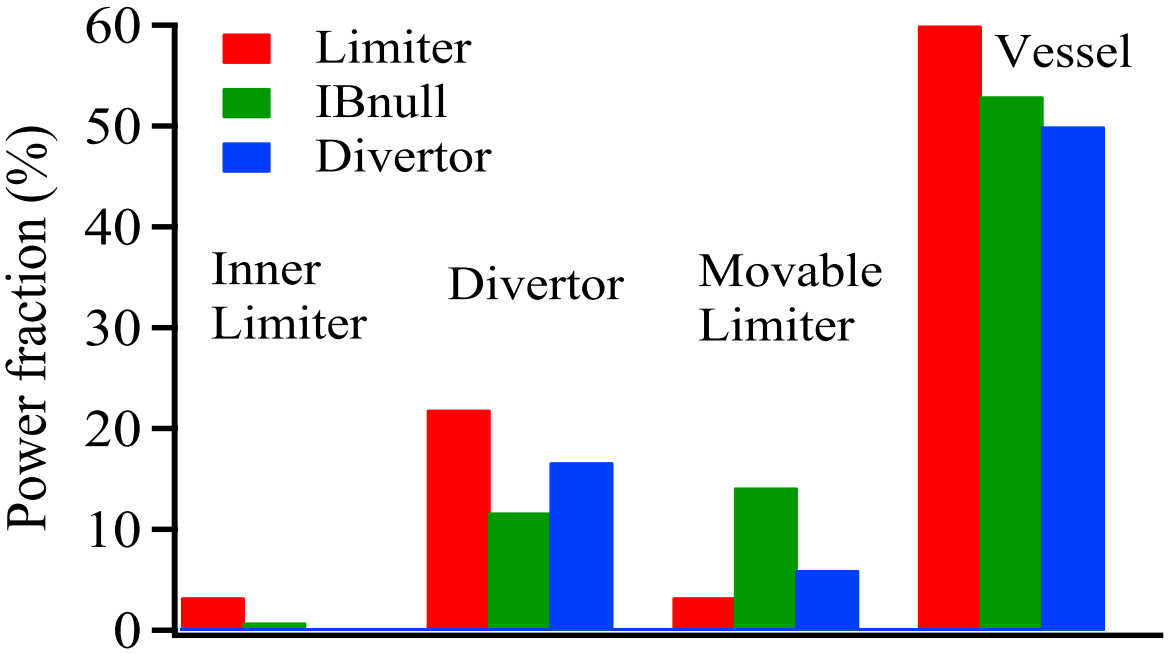


Vacuum vessel temperature is a good monitor of deposited energy, because thermal insulation of the vessel is quite good as shown in the temperature flatness during lunch time.

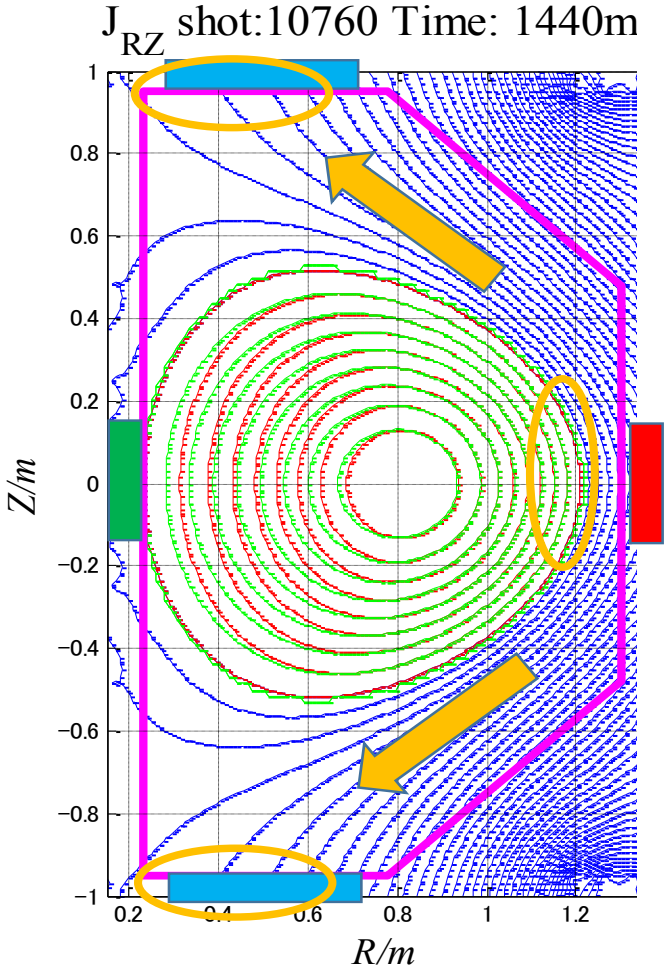


Injected power was 70kW and 63% of the injected power was deposited on the vacuum vessel.

Calorimetric measurement was applied to investigate heat load distribution in various magnetic configuratio



Summary of heat load distribution on various magnetic configuration. Inner limiters locate on center stuck, and divertor limiters on divertor plates, and a movable limiter locates on outer vessel.



Various types of magnetic configurations are applied.

Limiter , Non-inductive SN Divertor , High βp (Natural Divertor)

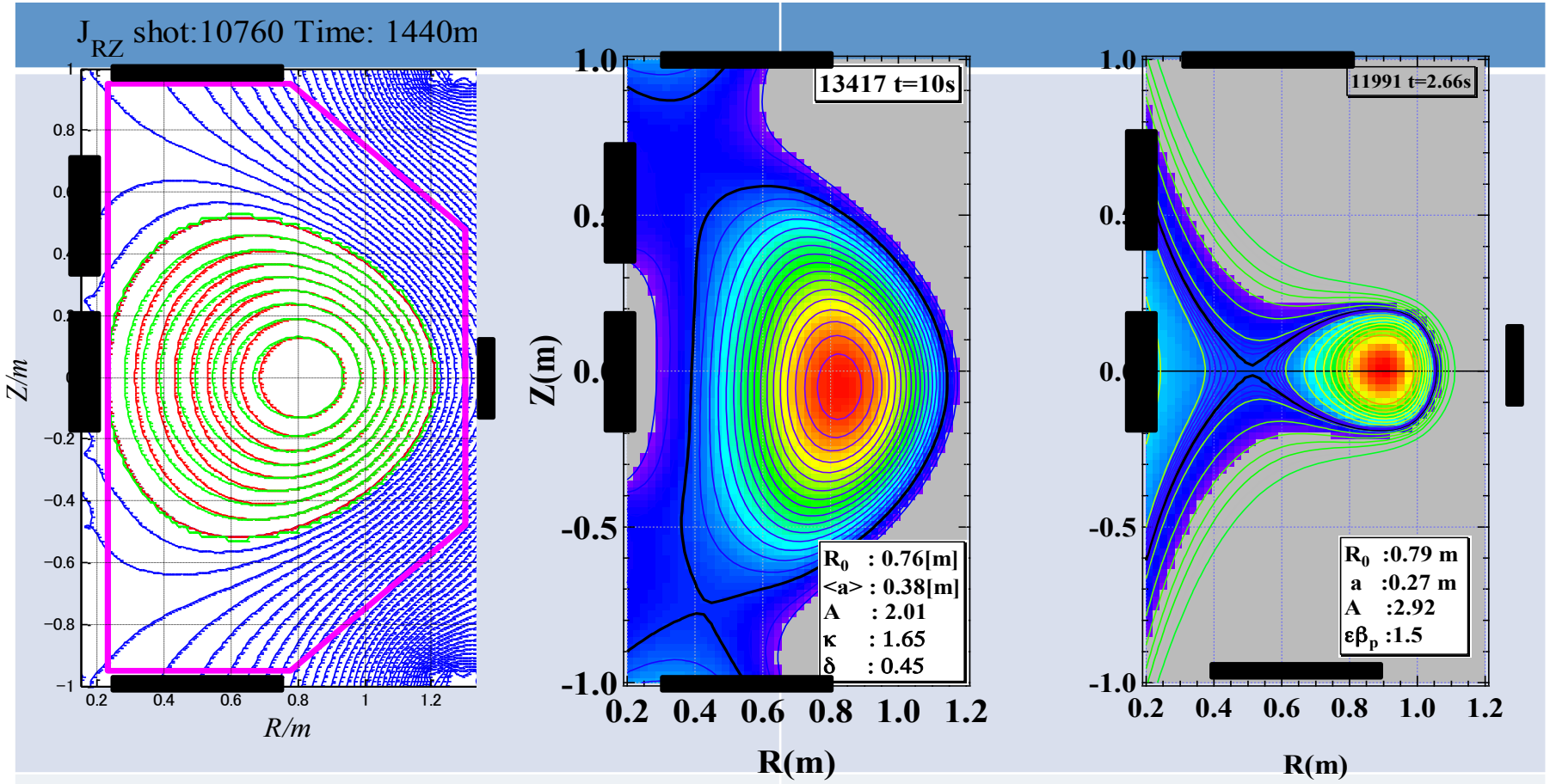


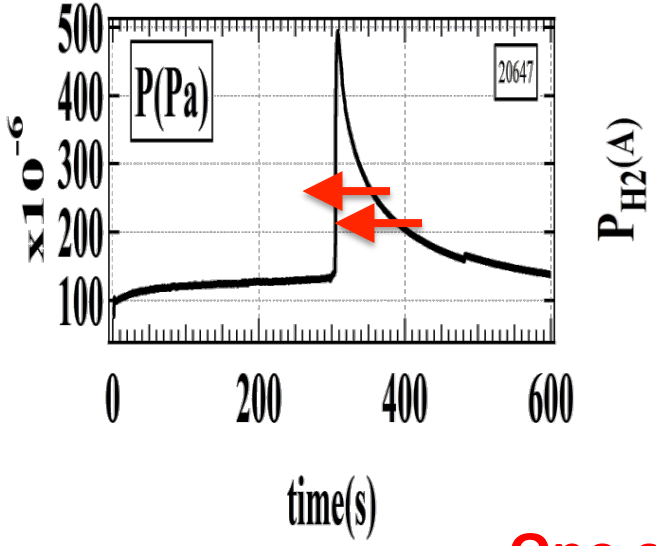
Fig. 1 Typical waveform of (a)I_p, (e) $b_p+l_i/2$ and R,(f) P_{rf} and B_v

Fig. 2 (L) standard SN divertor and (R) high b_p plasma with a natural divertor.

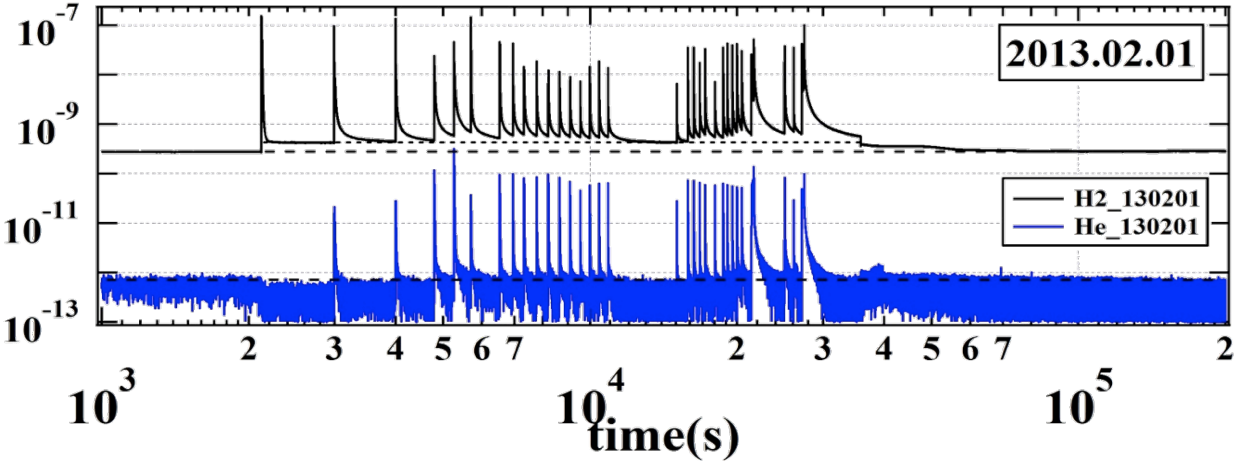
A=1.4 **2.0** **2.9**

Three time scales of interest in particle balance

One Shot

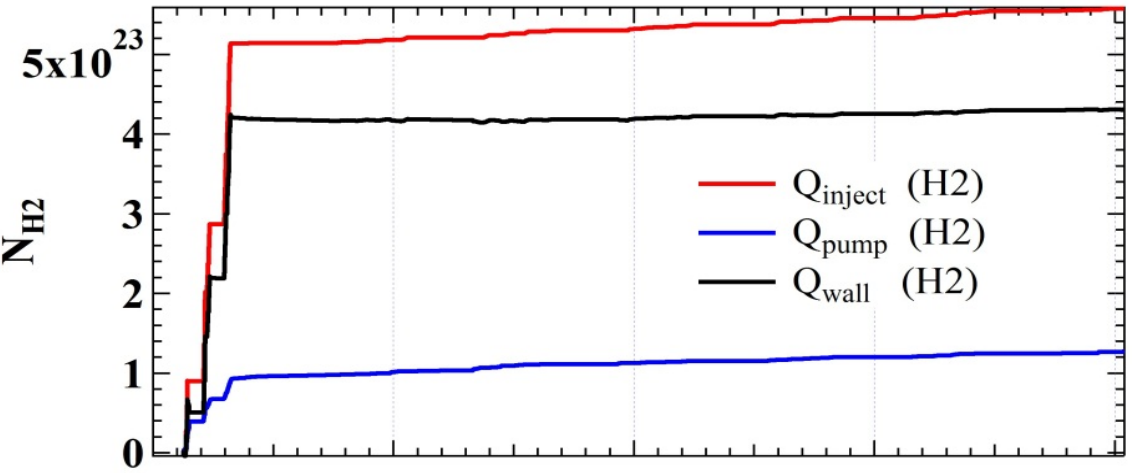


One day



One experimental campaign

ECRDC



2012 _6/11～7/27（50days）

Q_{gas} Red : total amount of Gas

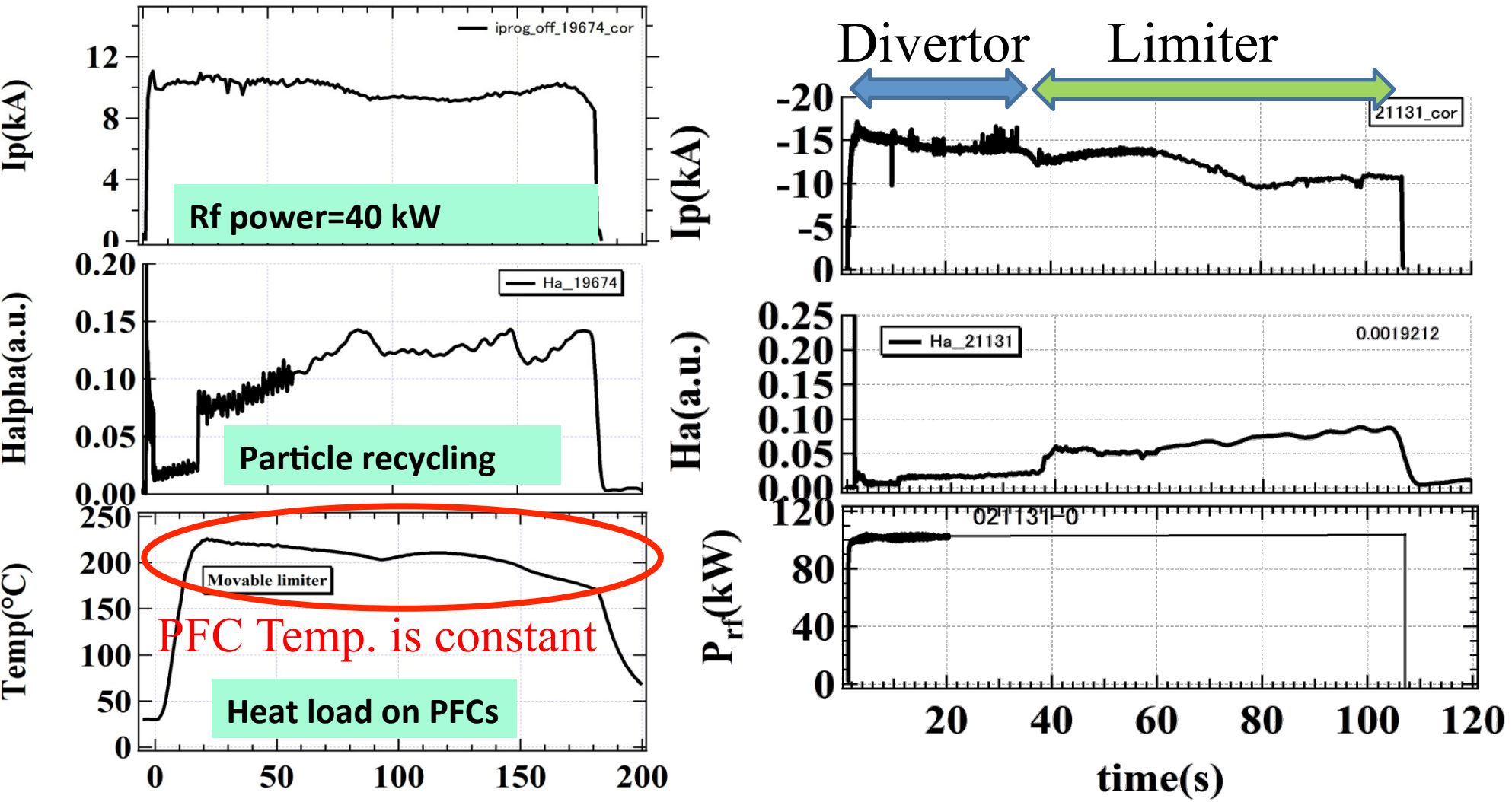
Q_{pump} Blue : total pumped gas particles

Q_{wall} black : wall retention

Total discharge duration <<< 50 days

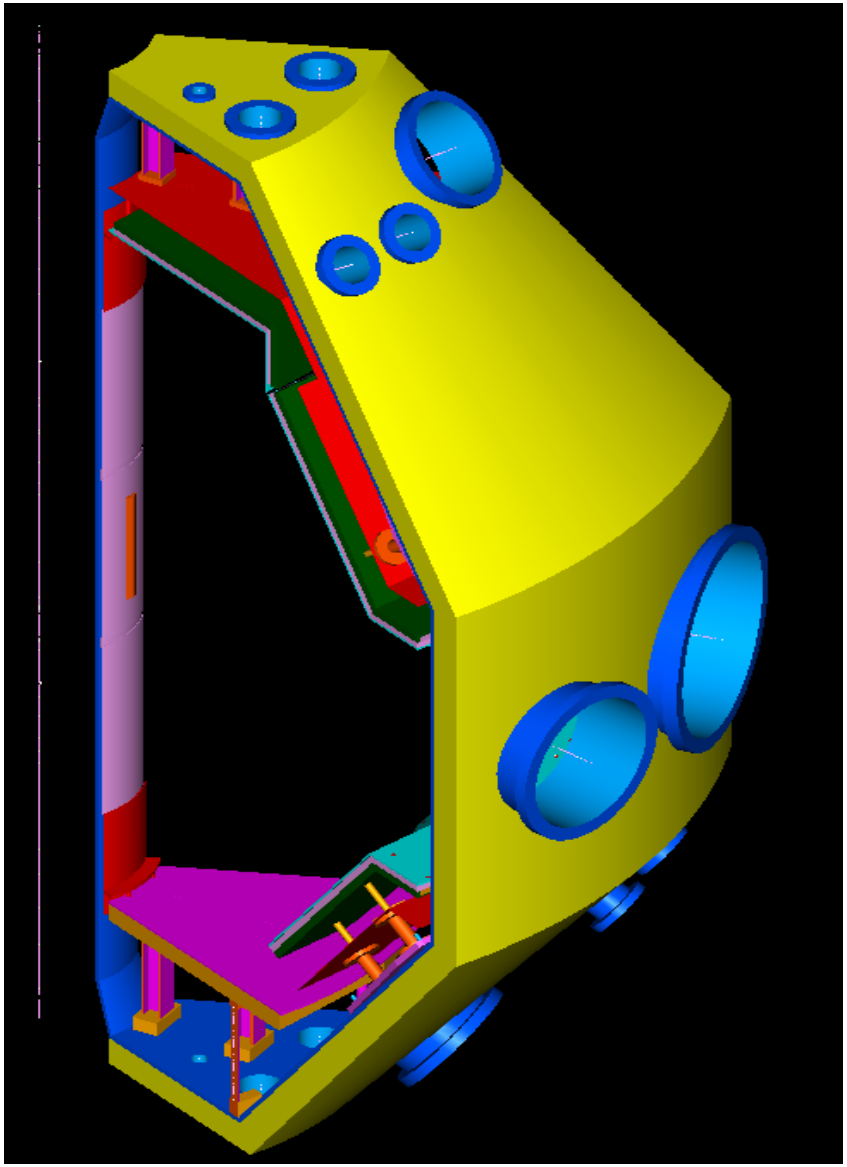
$$Q_{wall} = Q_{gas} - Q_{pumped}$$

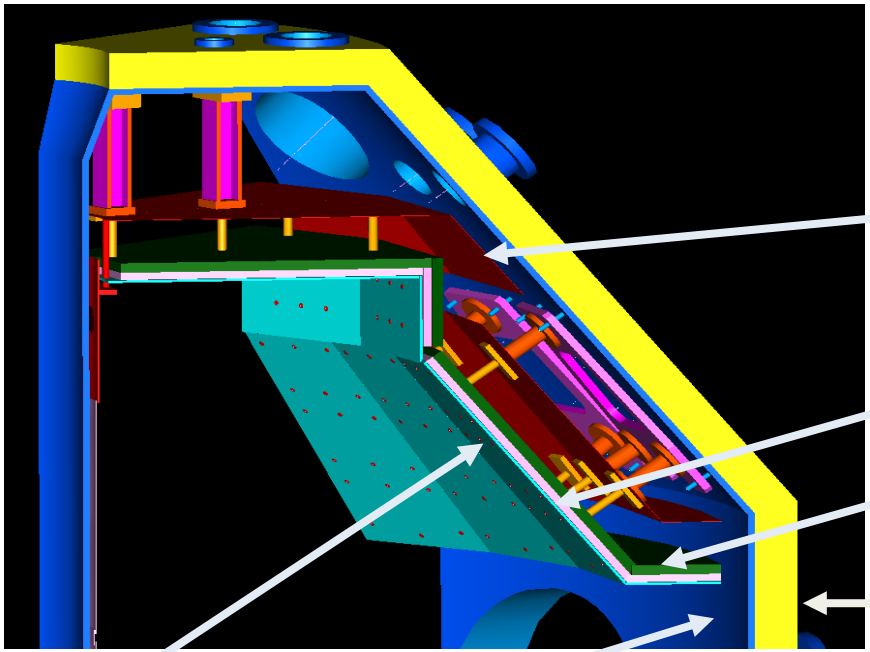
Heat load can be removed in SSO on QUEST

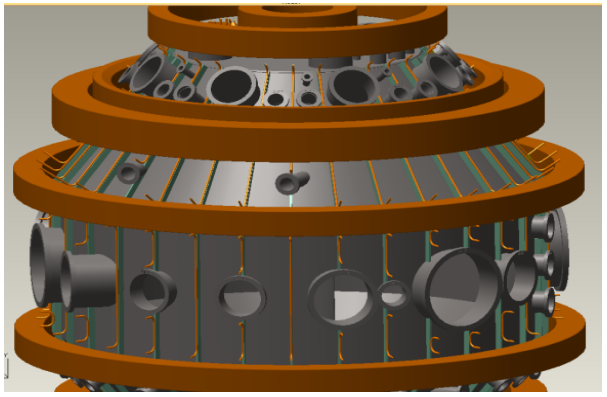


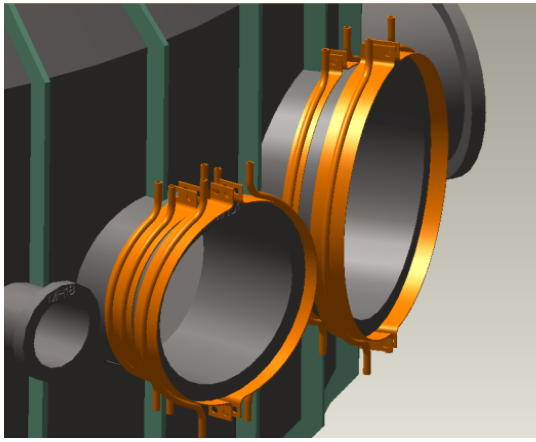
3 min in IBN@ 40 kW with cooling the limiters and for 107 s @ 100 kW in SN-Lim. These were demonstrated without using recycling FB control.

Future Plan – Hot wall –









Some cooling channels will be installed on the vessel