

Electron cyclotron plasma ramp-up through effective acceleration of energetic electrons and bulk electron heating in QUEST

Overview of RF (ECHCD) system in QUEST



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1. QUEST: Recent Progress in QUEST
2. Energetic and bulk electron heating by oblique and perpendicular injections
3. Overview of RF (ECHCD) system in QUEST

QUEST: Recent Progress in QUEST

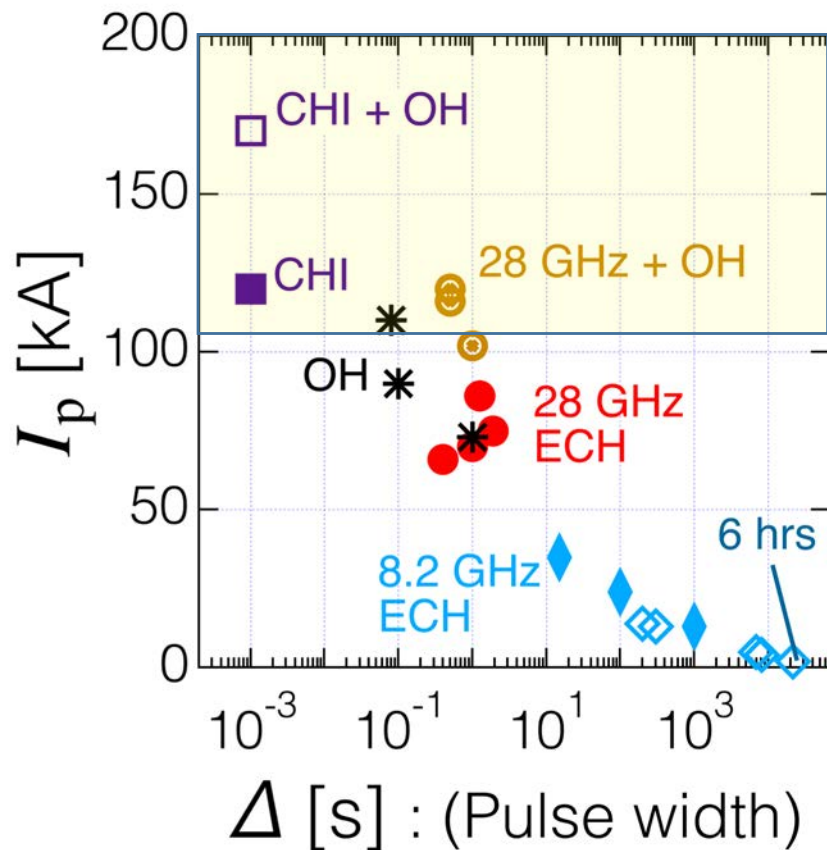
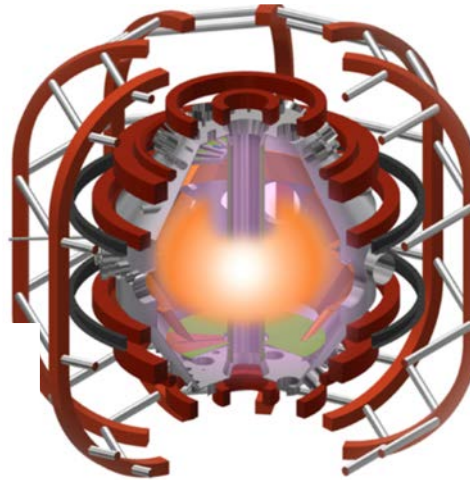
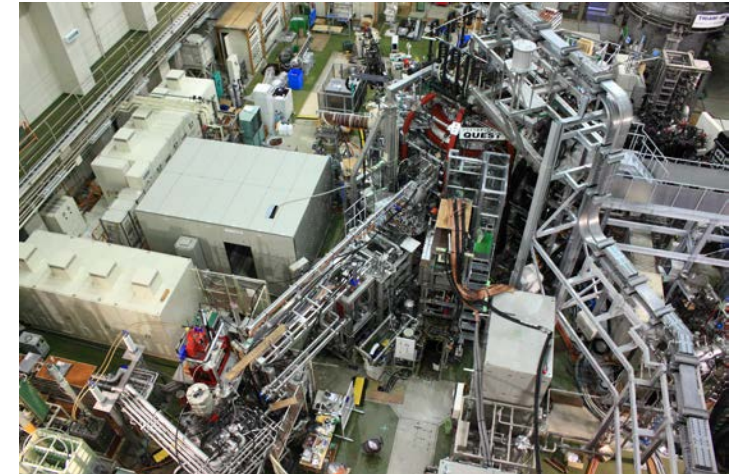
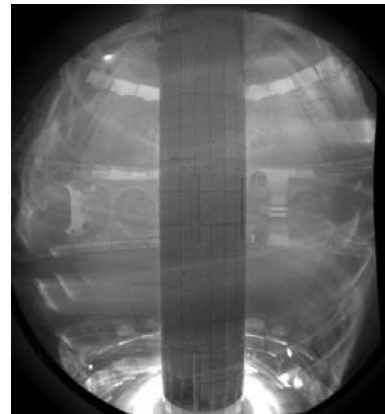
QUEST

$R \sim 0.68 \text{ m}$

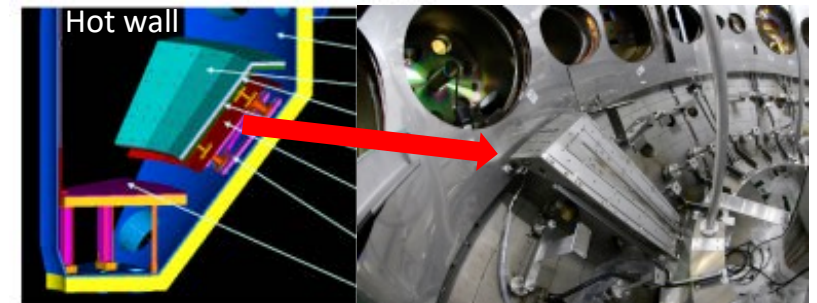
$a \sim 0.4 \text{ m}$

[in 2024]

$B \sim 0.25 \text{ T CW} \rightarrow B \sim 0.5 \text{ T}$
(for 1-2 s)



CHI Plasma



Hot 1st wall
673 K operation

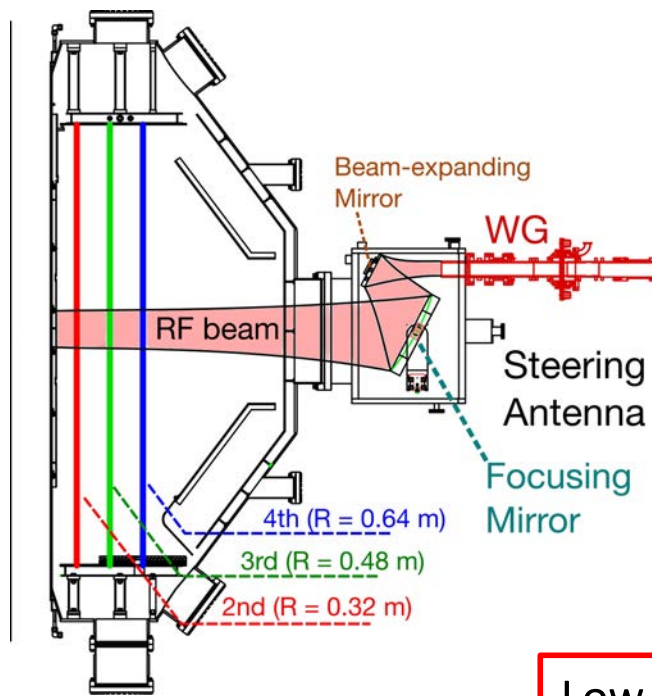
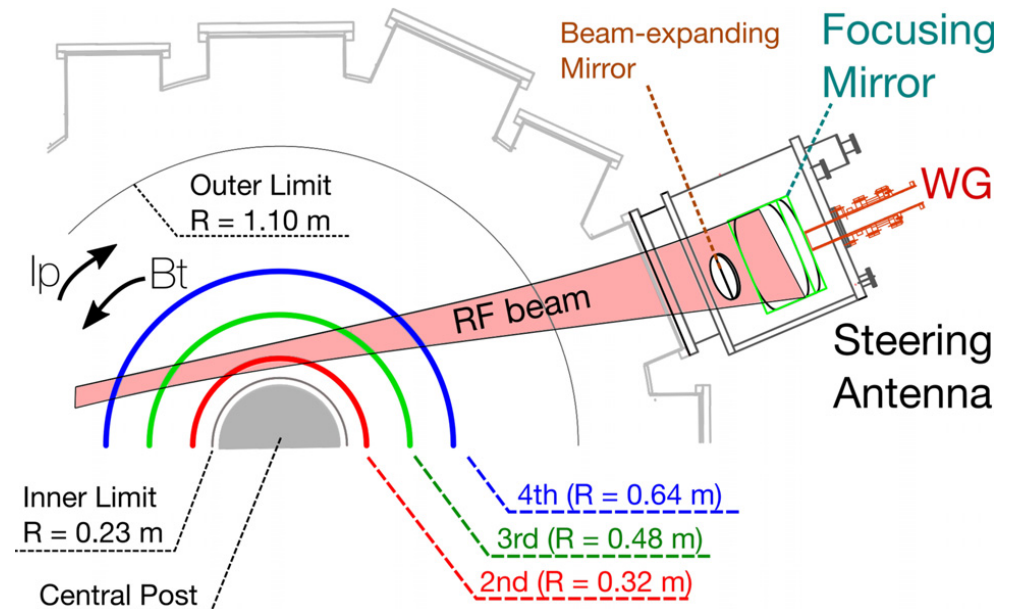


Electron cyclotron plasma ramp-up through effective acceleration of energetic electrons and bulk electron heating in QUEST

1. 28 GHz QO Launcher system on QUEST
 2. Energetic and bulk electron heating
 3. Ray tracing [TASK/WR]
 4. Relativistic Doppler-shifted resonance in momentum space
 5. Some experimental results on bulk heating
-

28 GHz QO launcher system on QUEST

Onchi+
PoP (2019)



<https://aip.scitation.org/doi/10.1063/5.0031357>

Low power test results

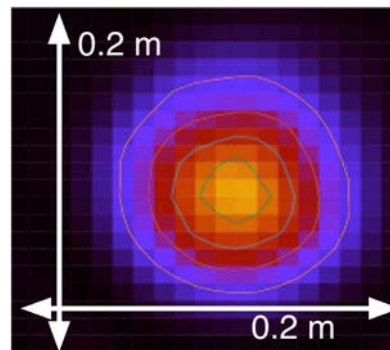
Beam focusing:

Deposition control
(real space)

$N_{//}$ spectrum control
(momentum space)

relativistic Doppler-shift effect

~ 5cm
beam size

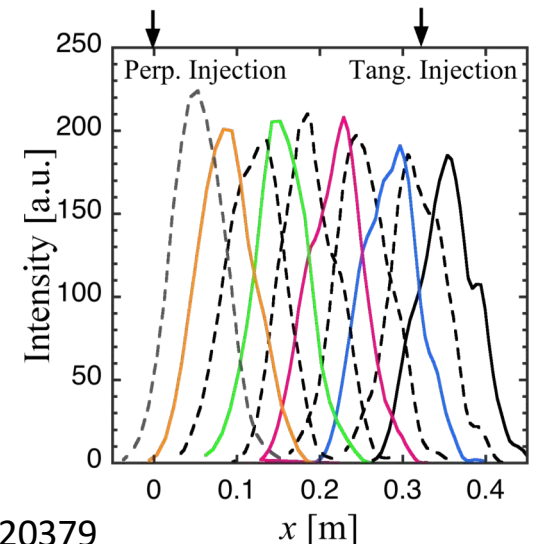


Idei+ FED (2019)

Beam steering:

$N_{//}$ control
(momentum space)
relativistic Doppler-
shift effect

$0 < N_{//} < 1$



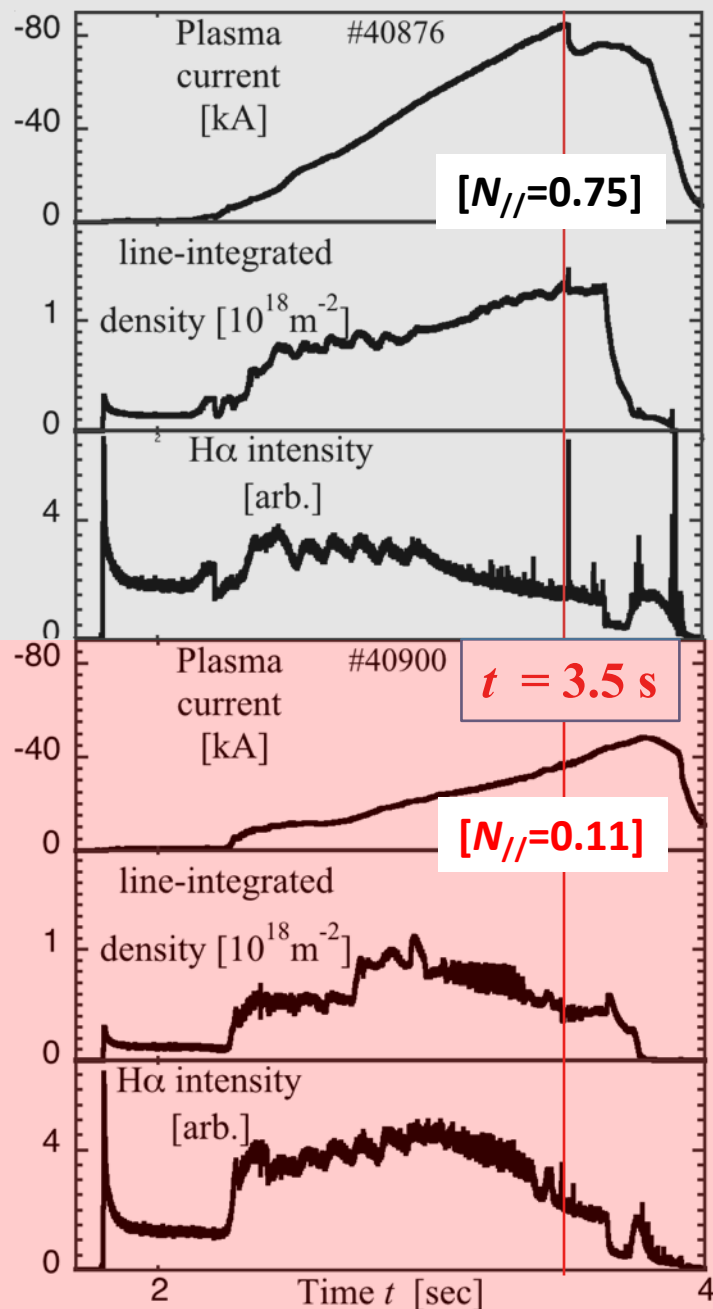
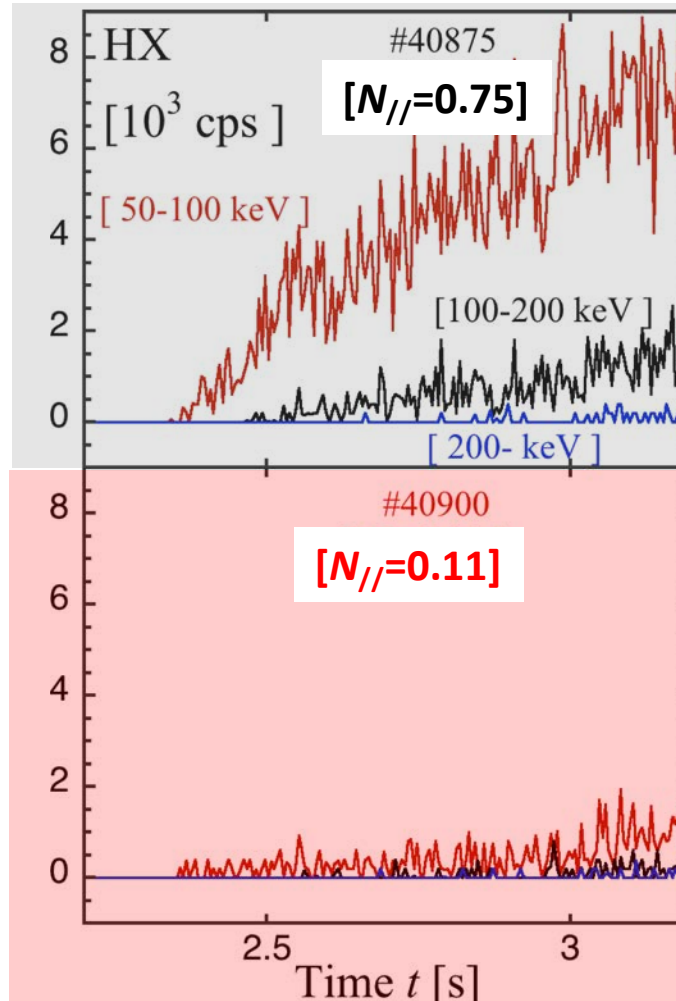
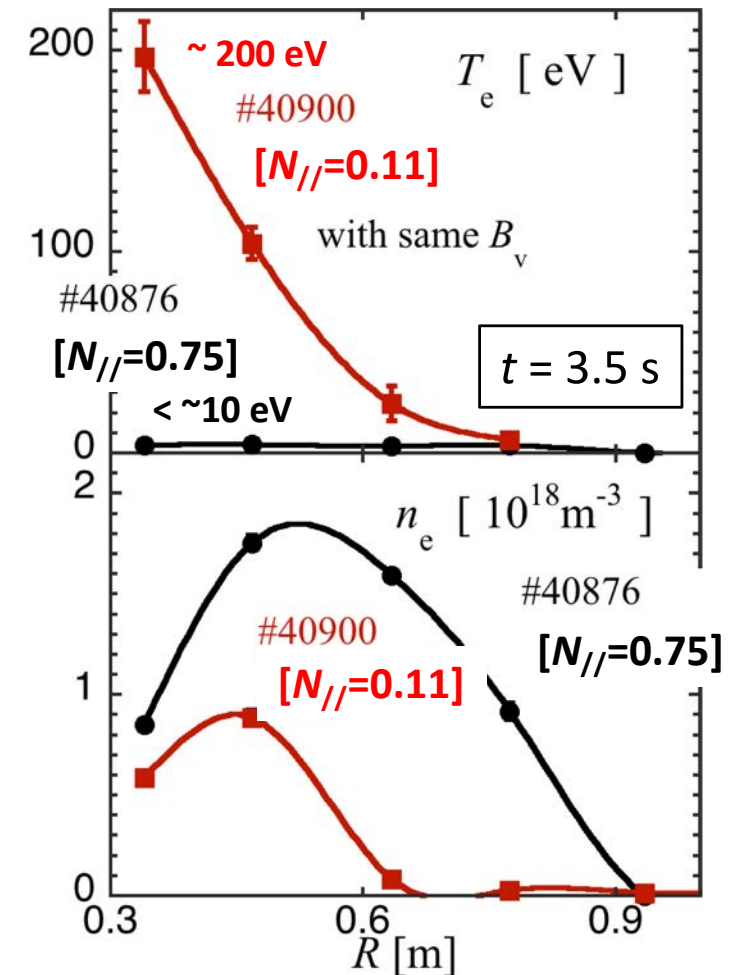


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Energetic and bulk electron heating

$N_{//}$ scan exp.



$[N_{//}=0.75]$

$[N_{//}=0.11]$

T_e



Bulk heating

HX, I_p



Energetic electron heating



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Ray Tracing [TASK/WR]

$$: n = n_0(1 - \rho^2)^1$$

$$: T = T_0(1 - \rho^8)^1$$

❖ $n_0 = 2, 3, 4, 5 \times 10^{18} \text{ m}^{-3}$

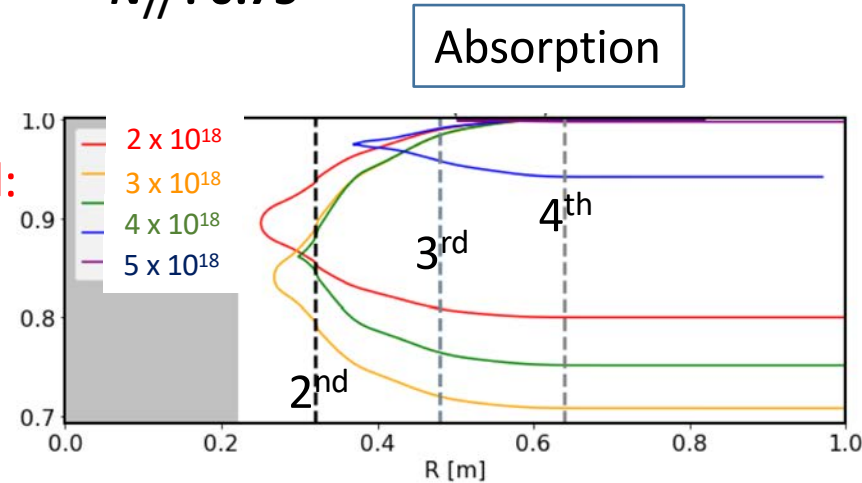
(60 keV as measured:
3 %)

❖ Bulk $T_0 = 30 \text{ eV}$

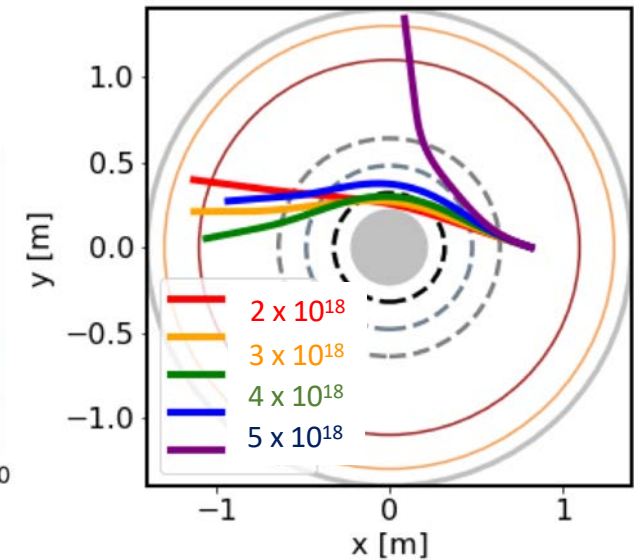
❖ $T_e = 60 \text{ keV}$

❖ Plasma region
($R = 0.22 - 0.82 \text{ m}$)

$N_{//} : 0.75$

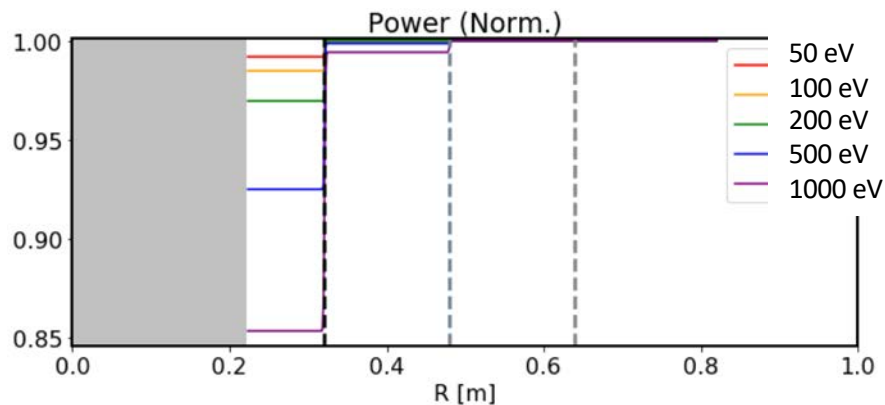
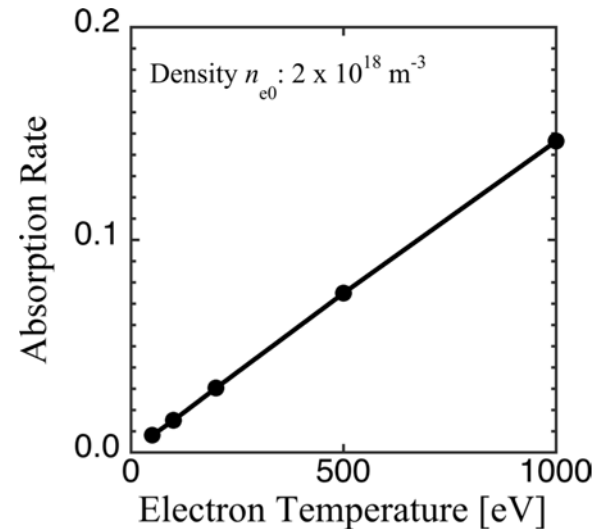


The rays are bending
around center post
at 2nd harmonic ECR



$N_{//} : 0.11$

Only Bulk Electron



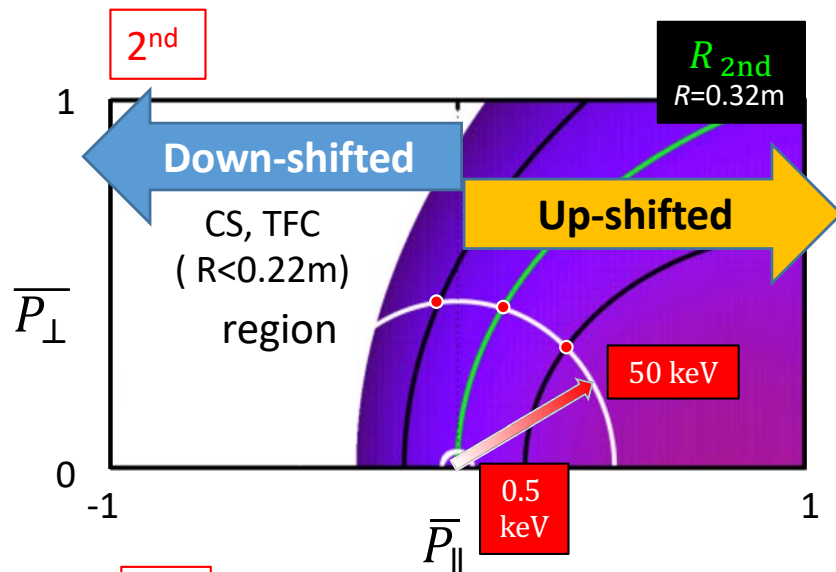
When the electron are
heated to 500-800 eV level,
the absorption becomes
significant (~10 %).



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[$N_{//}=0.75$] : Resonance position and energy



Relativistic Doppler-shifted Resonance

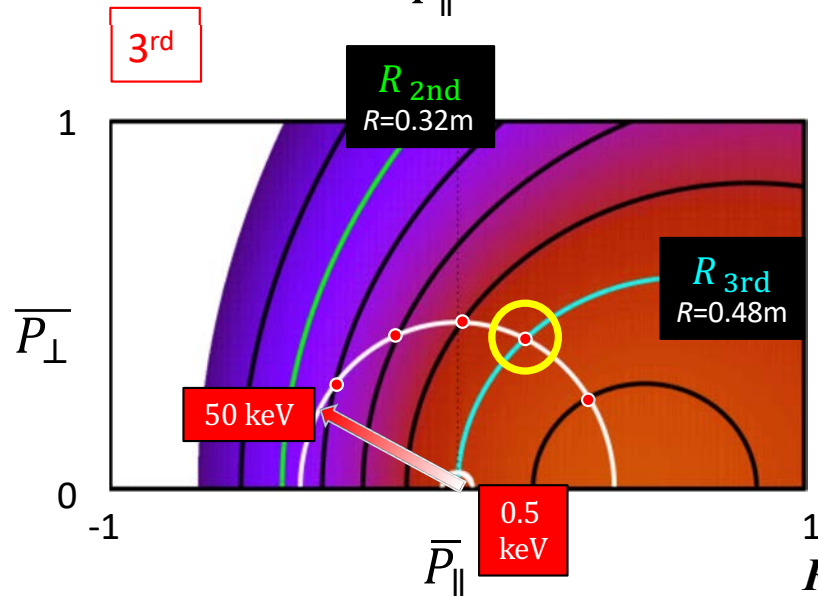
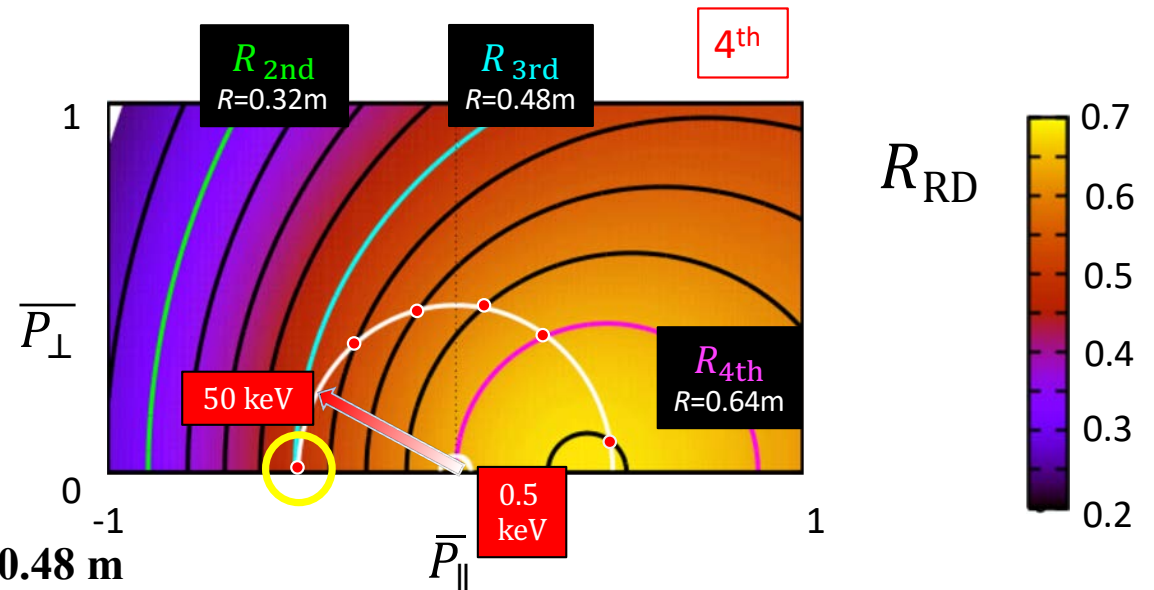
$$\gamma \left[1 - N_{//} \left(\frac{v_{//}}{c} \right) \right] = \frac{nf_{ce}}{f} \quad \begin{array}{l} \text{relativistic } (\bar{P}_{//}, \bar{P}_{\perp}) \\ \text{Doppler-shifted } (\bar{P}_{//}) \end{array}$$

$$\bar{P}_{//} = m \gamma v_{//} / (mc) \quad \bar{P}_{\perp} = m \gamma v_{\perp} / (mc) \quad \gamma = \sqrt{1 + \bar{P}_{//}^2 + \bar{P}_{\perp}^2}$$

Resonance ellipse

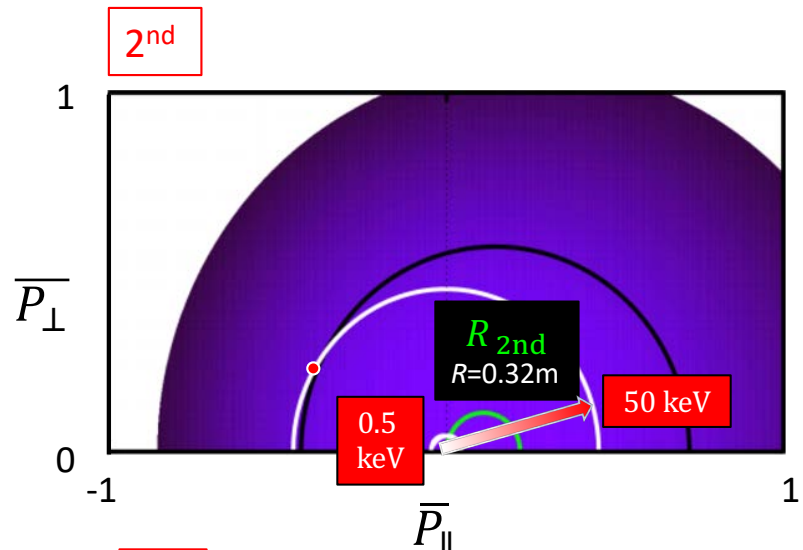
$$\left(1 - N_{//}^2(R_{RD}) \right) \bar{P}_{//}^2 - 2N_{//} \frac{nf_{ce}(R_{RD})}{f} \bar{P}_{//} + 1 + \bar{P}_{\perp}^2 - \left(\frac{nf_{ce}(R_{RD})}{f} \right)^2 = 0$$

$$N_{//} R_{RD} = \text{const.}, \quad f_{ce} R_{RD} = \text{const.} \quad (\bar{P}_{//}, \bar{P}_{\perp}) \Rightarrow R_{\text{res}}$$



3rd up-shift > 4th down-shift

$[N_{//}=0.11]$: Resonance position and energy



$N_{//} = 0.75$:

2nd ; limited in up-shifted resonance

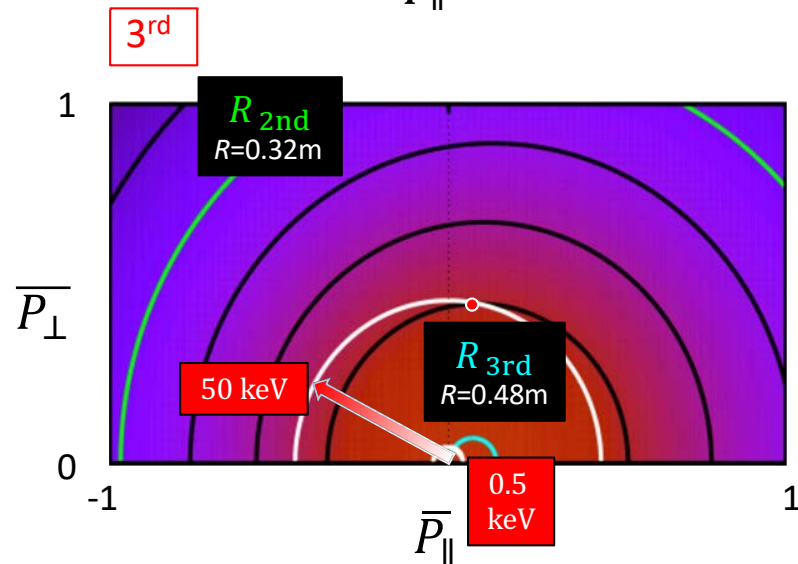
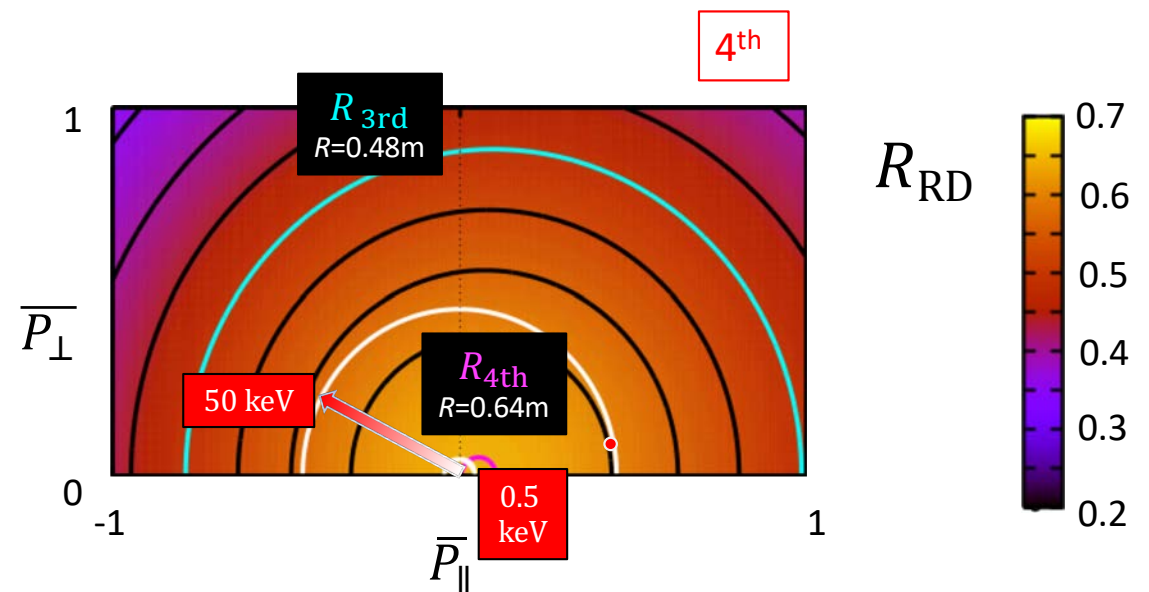
***n*-th Higher harmonics** ; Overlapping between

(n-1)-th up-shift and *n*-th down-shift

effective up-shifted resonance heating in wide region

$N_{//} = 0.11$:

Resonance areas are not expand well.





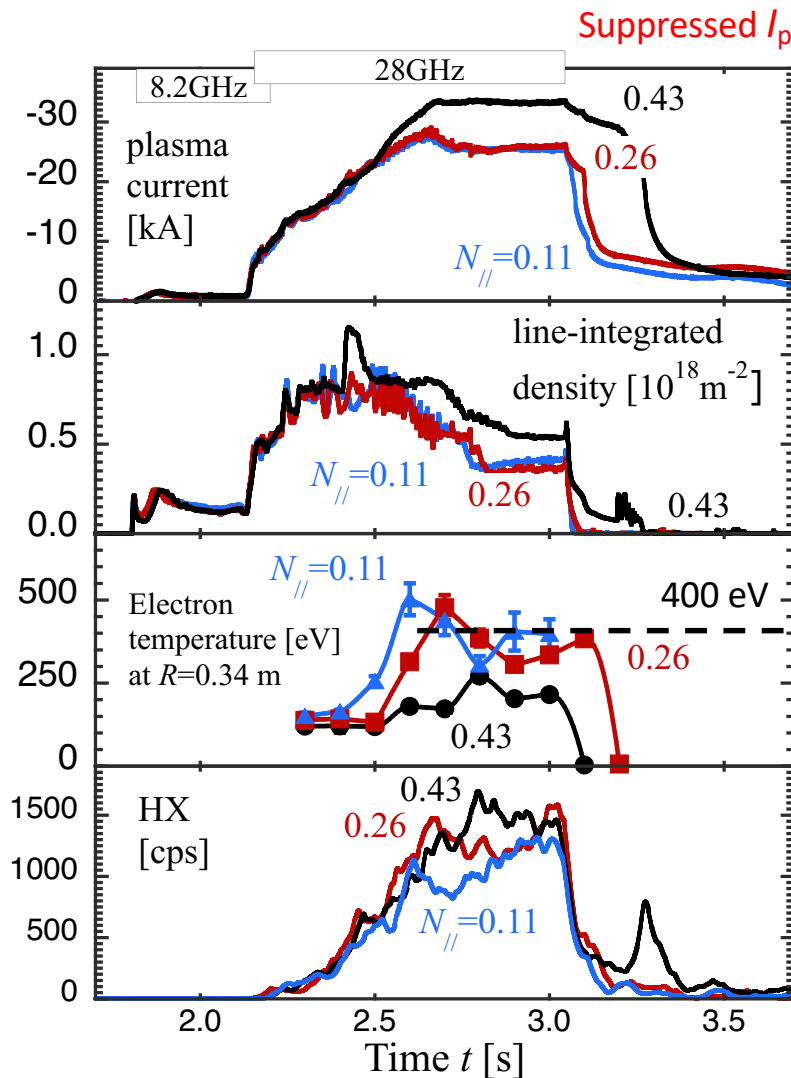
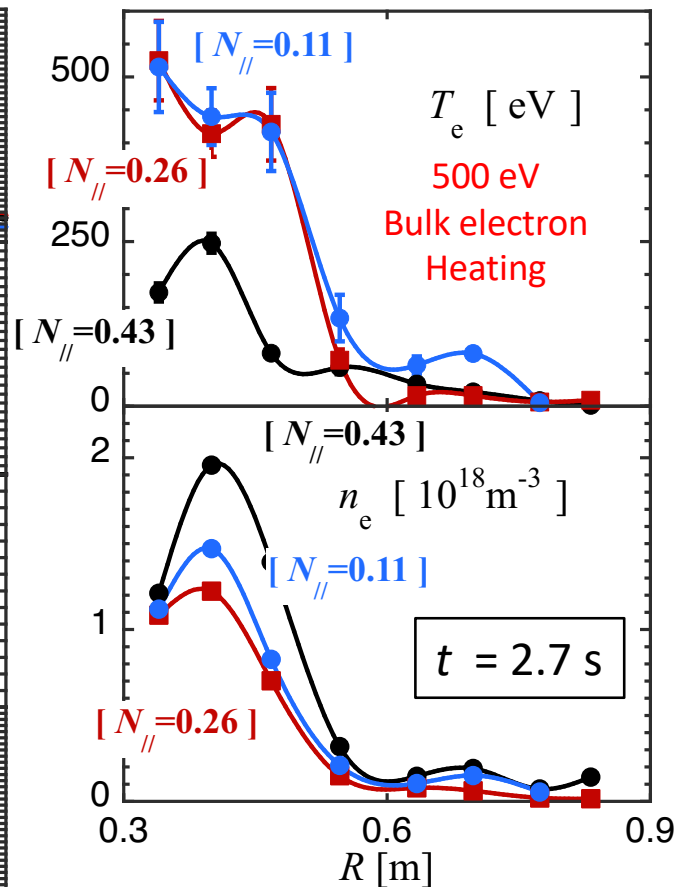
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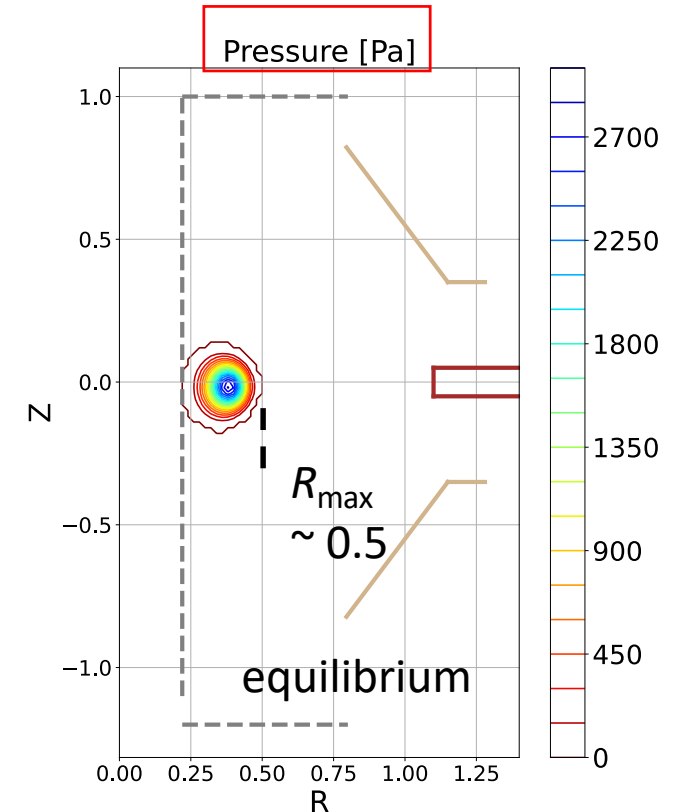
Bulk electron heating up to 500 eV

Quasi-perpendicular:
 $N_{//} = 0.11, 0.26, 0.43$

with $N_{//} = 0.11$
 high B_v
 $V_{loop} = 0.05$ V



High electron temperature of 500 eV was attained with quasi-perpendicular injections.



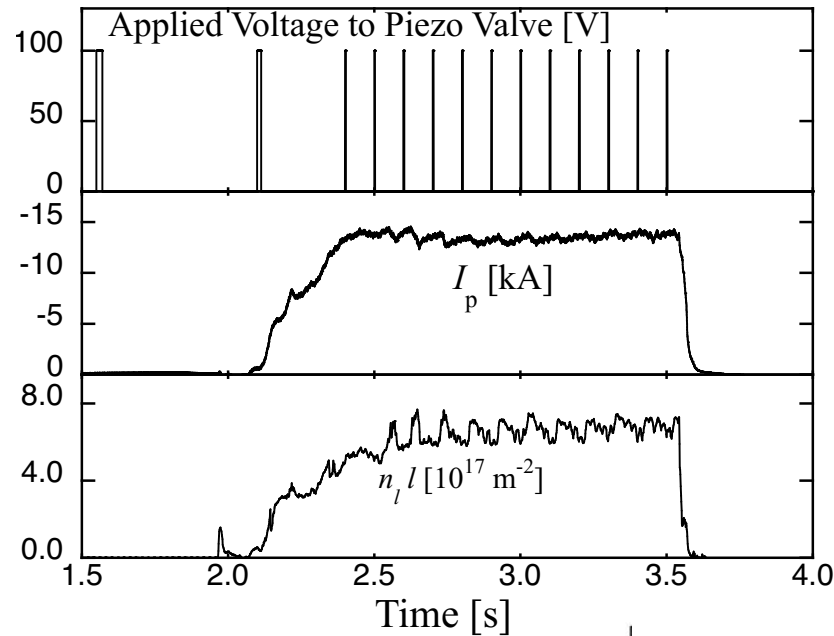
Wide energy-range electrons are in resonance near $R=0.34$ m.

High pressure

Heat exchange to bulk electrons as well as the 28-GHz wave heating ?

Large-sized plasma with ~ 100 eV $\sim 1.0 \times 10^{18} \text{m}^{-3}$

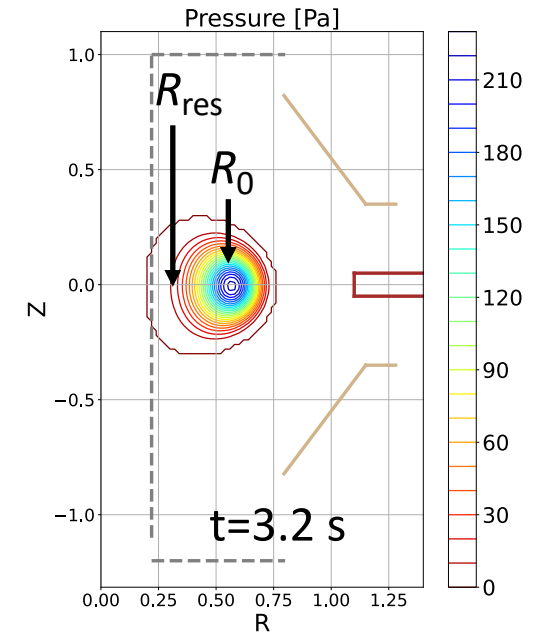
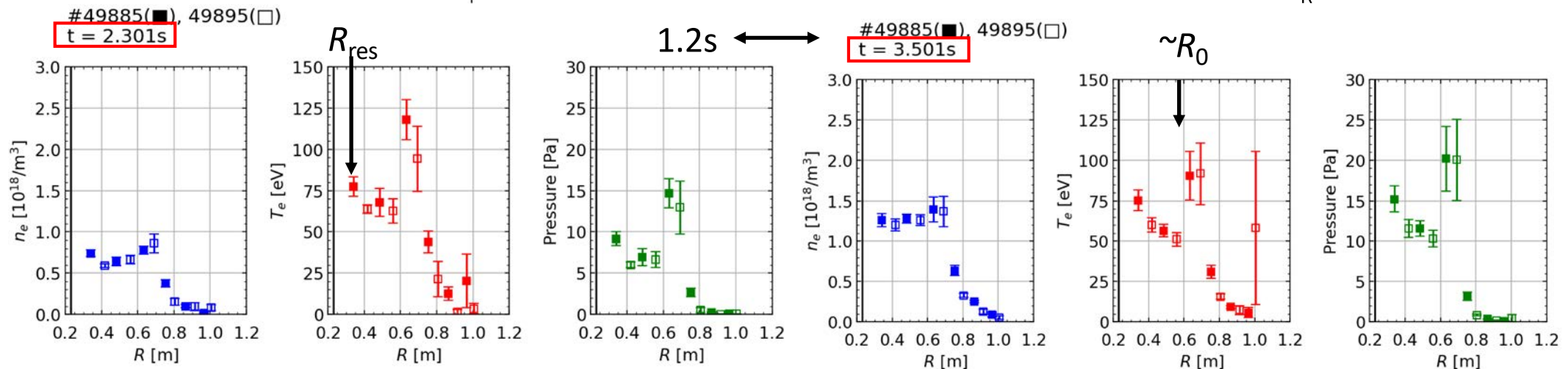
with $N_{//} = 0.11$
low B_v
 $V_{\text{loop}} = 0$



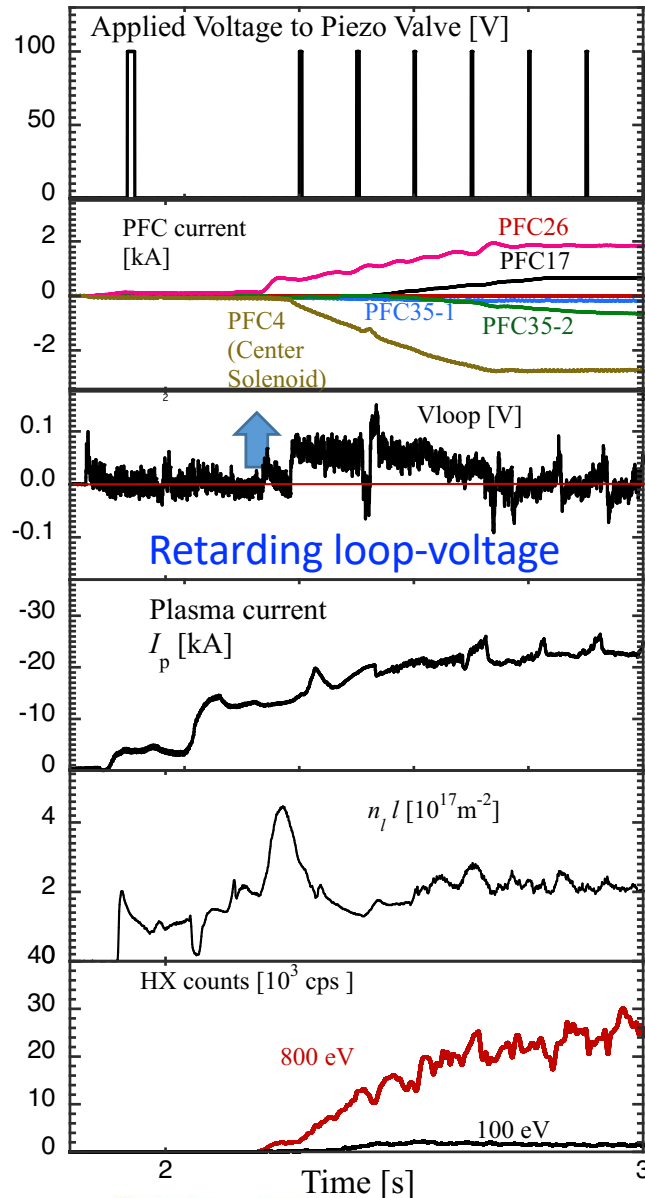
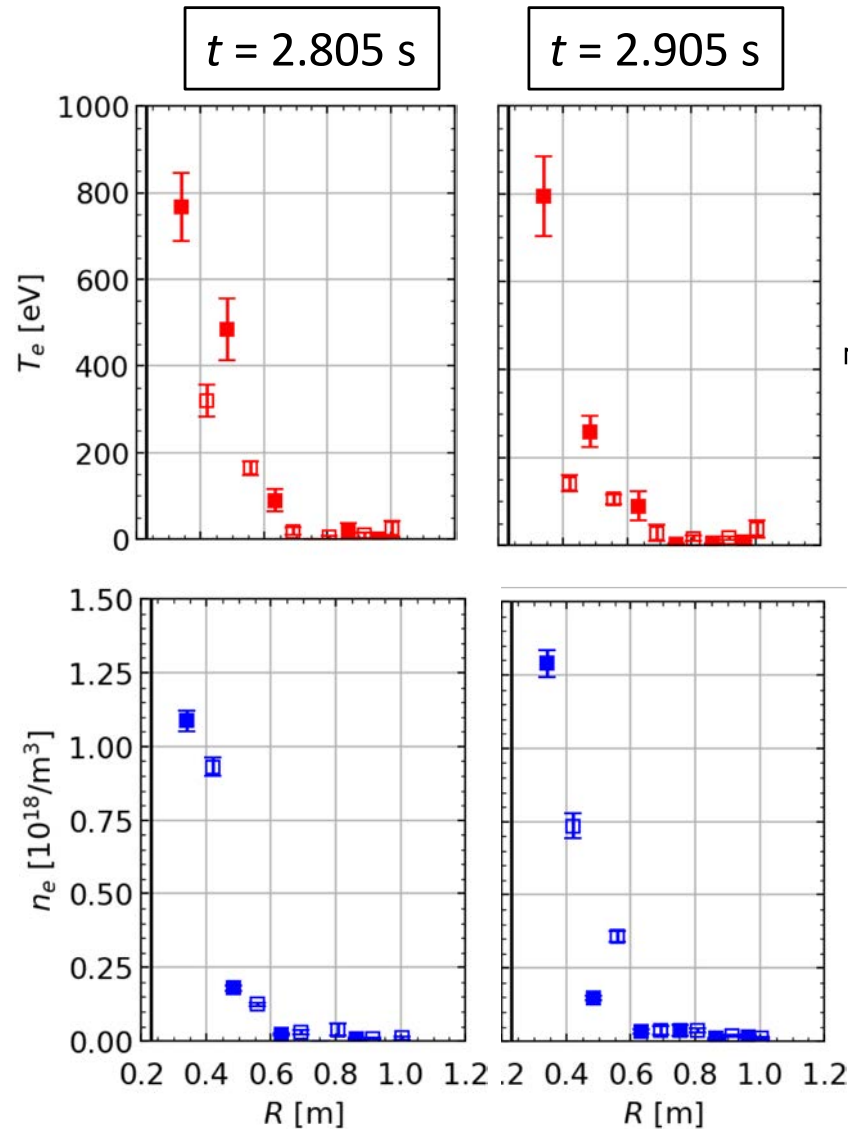
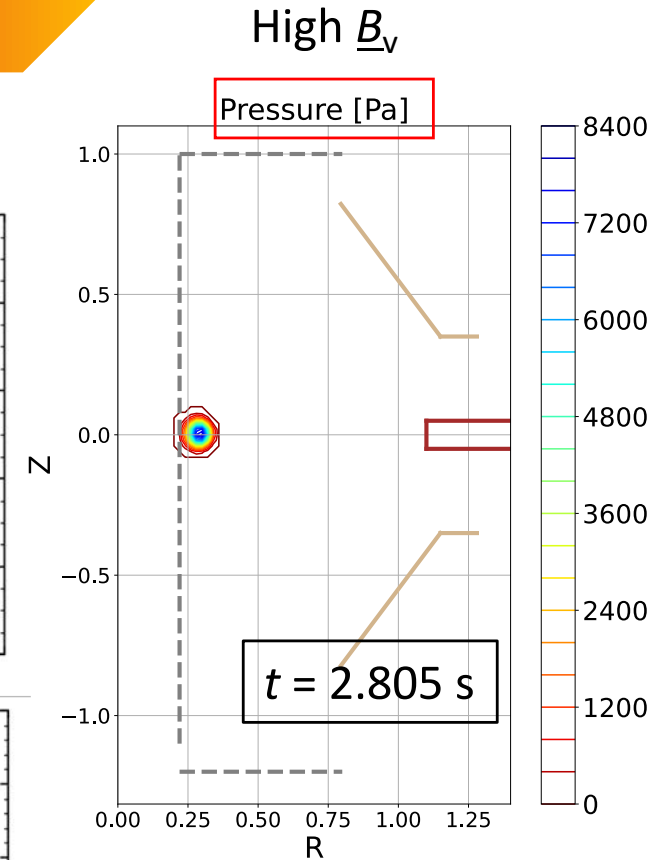
Gas fueling : suppression of energetic electron growth

Relatively low I_p of 12 kA and T_e of ~ 100 eV were maintained for 1.2 s at n_e of $1 \times 10^{18} \text{m}^{-3}$.

The relatively high T_e of ~ 100 eV was in a R range between R_0 and the outer same flux surface for the 2nd resonance at $R=0.34$ m.



Bulk heating and suppression of energetic electron growth in the ramp-up phase



The resonance areas in a single path of the beam are limited for wide energy-range electrons due to the weak Doppler-shift effect.

Strong EC interactions for wide energy-range electrons with a 5-cm narrow incident beam



Overview of RF (ECHCD) system in QUEST

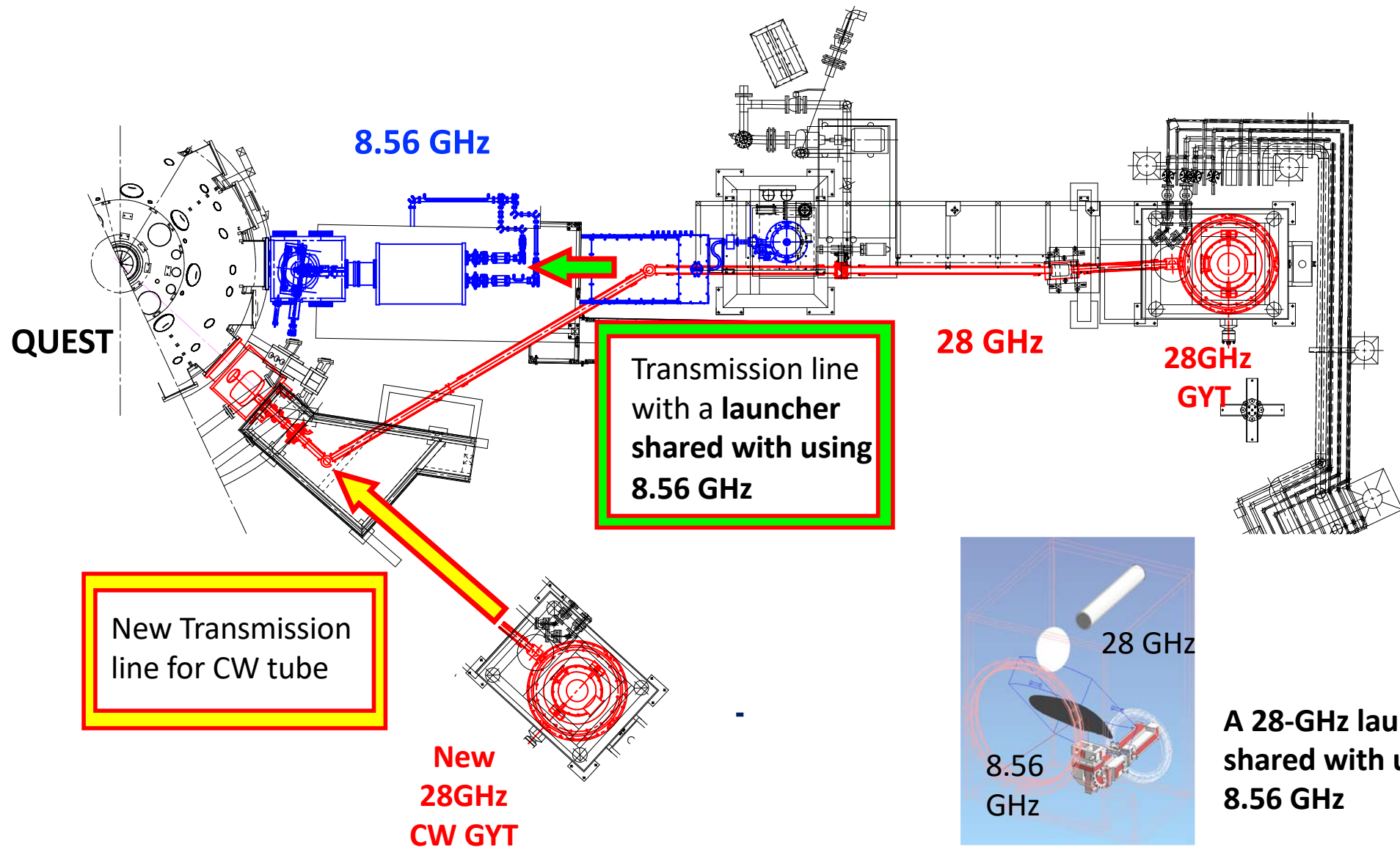
Two 28 GHz systems (and 8.56 GHz system)
(with a new CW gyrotron)

A second 28-GHz ECHCD system is in development to provide oblique and perpendicular simultaneous injections.

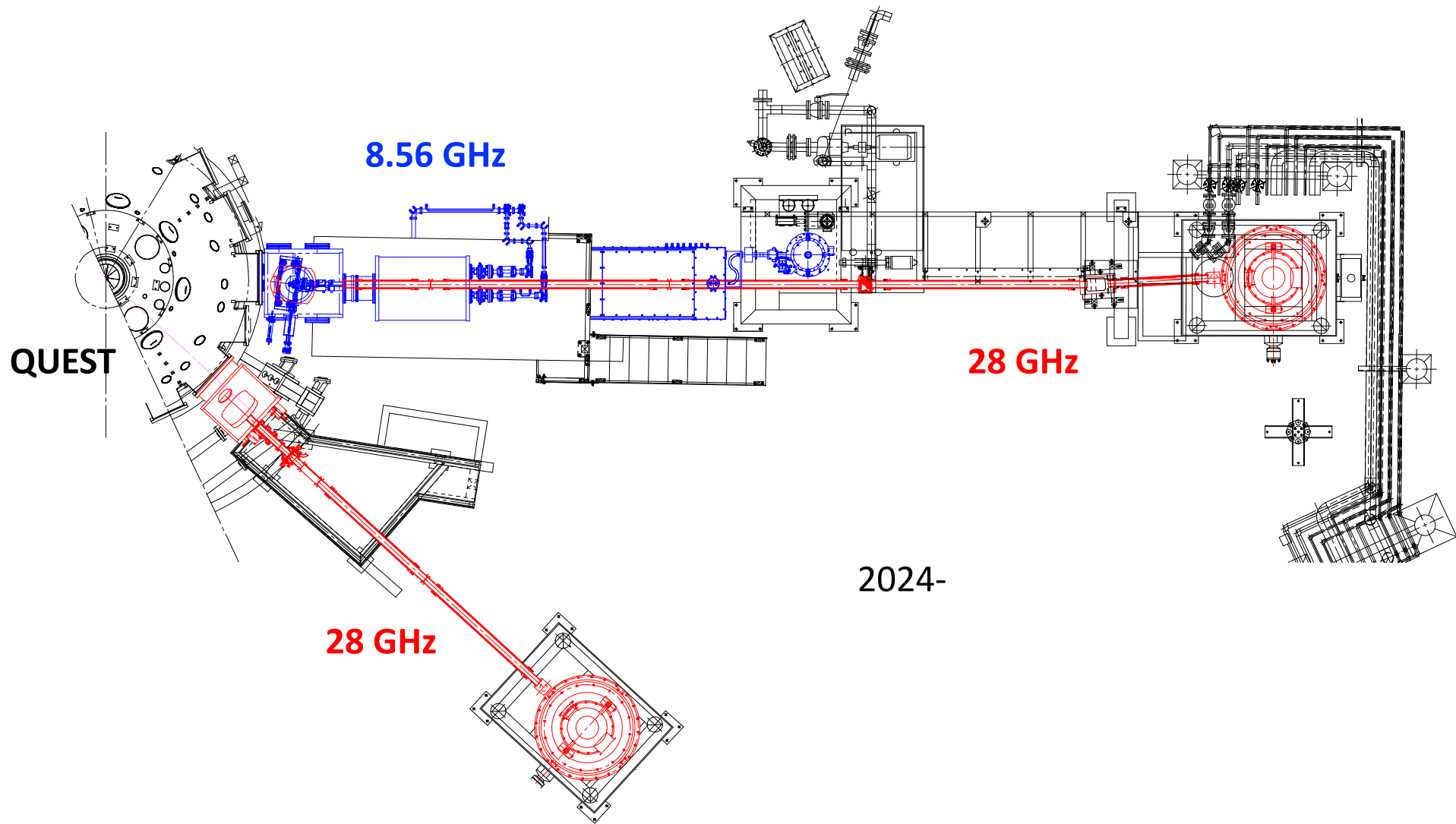
Doubled toroidal magnetic field : 0.5 T (pulse)

High field side injection for EBWHCD experiments

Two Transmission lines for 28GHz



Two Transmission lines for 28GHz





Overview of RF (ECHCD) system in QUEST

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High field side injection for EBWHCD experiments

Doubled toroidal magnetic field : 0.5 T (pulse)

DC-DC Converter

0.25 T [CW]

50 kA x 16 turn (8 TFC)

50 kA / 60 V CW PS



0.5 T [pulse ~ 2 s]

100 kA x 16 turn (8 TFC)

100 kA / [≥ 120 V] PS



Lithium Capacitor Power Supply

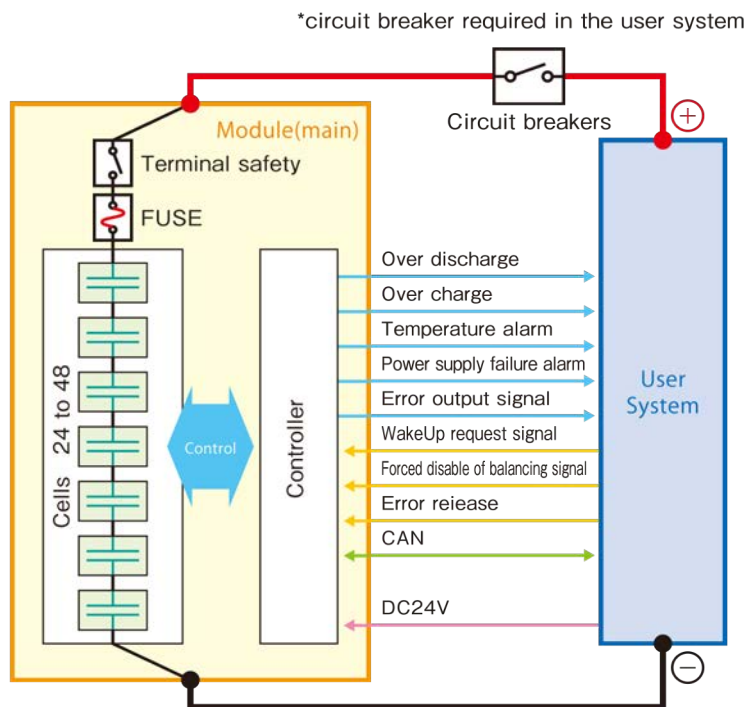
48 series

Voltage:

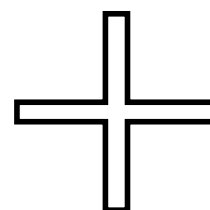
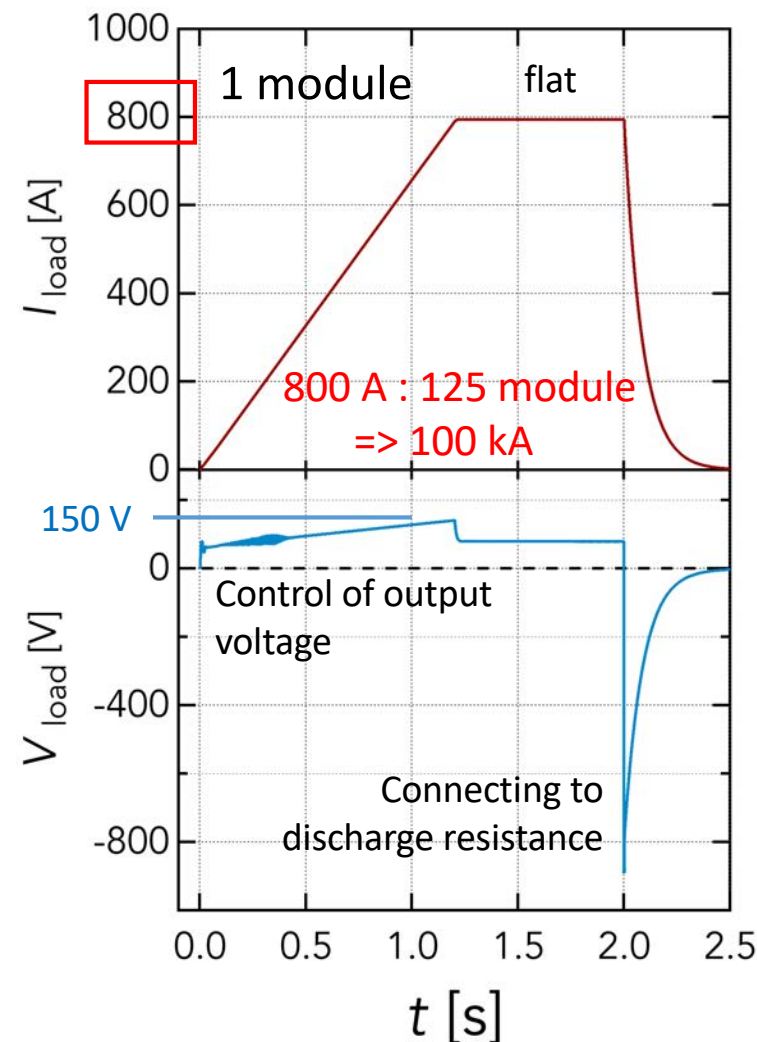
3.8 x 48

= **182.4 V**

1 cell:
2300F
3.8 V



125 modules



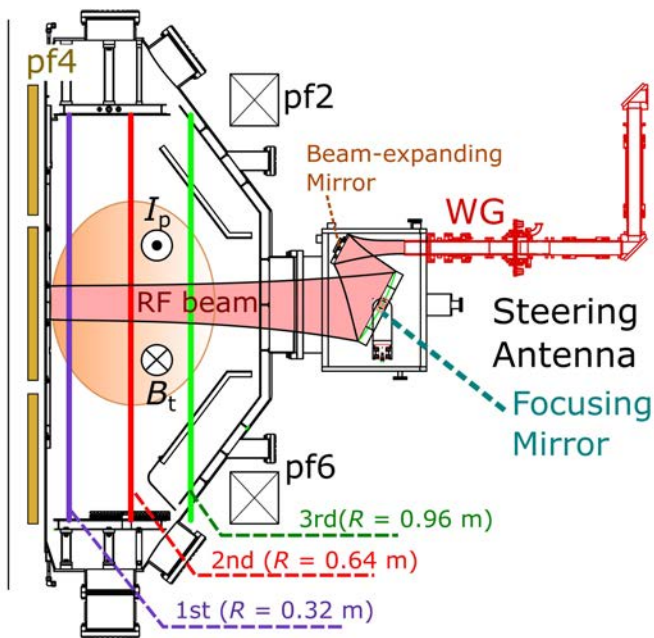
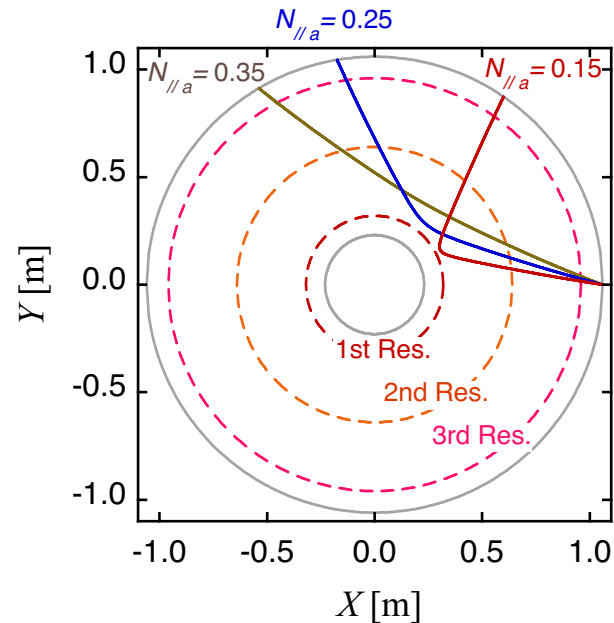
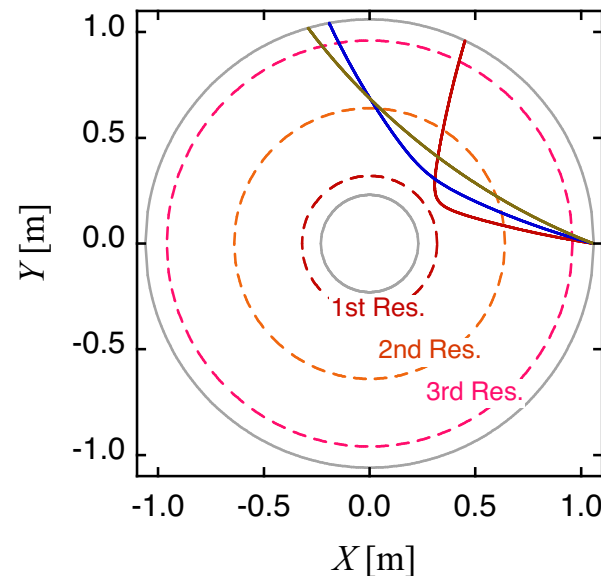
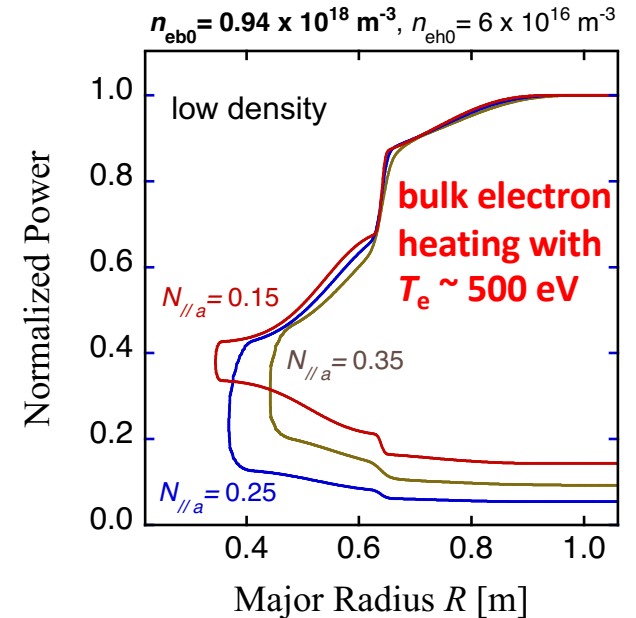
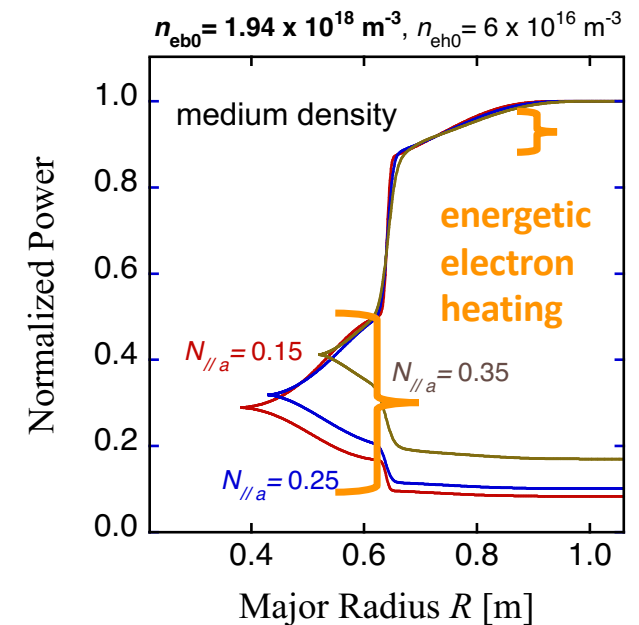
<https://musashi-es.co.jp/en/products/highvoltage.html>

One of experimental scenarios at 0.5T

Central 2nd ECHCD +
Inboard 1st ECHCD

DOPPLER-SHIFT RESONANCE
BEYOND R -CUTOFF

WITH HIGH ECCD EFFICIENCY





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(with a new CW gyrotron)

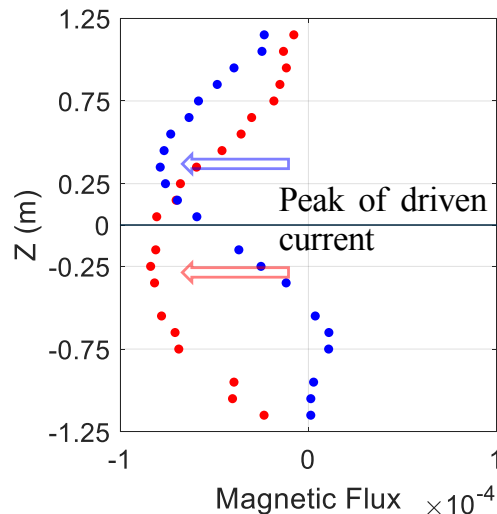
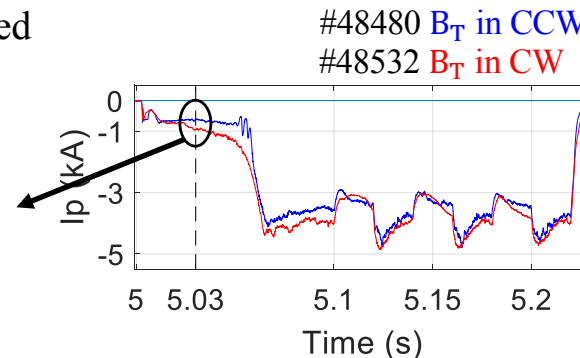
A second 28-GHz ECHCD system is in development to provide oblique and perpendicular simultaneous injections.

Doubled toroidal magnetic field : 0.5 T (pulse)

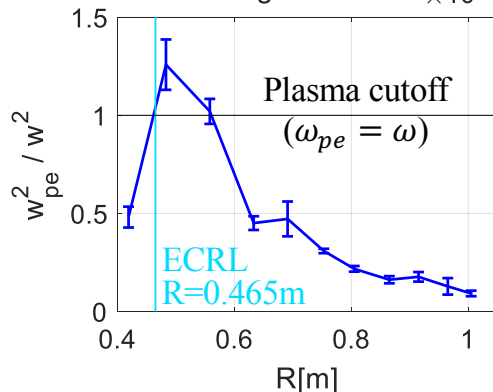
High field side injection for EBWHCD experiments

HFS X-B experiment

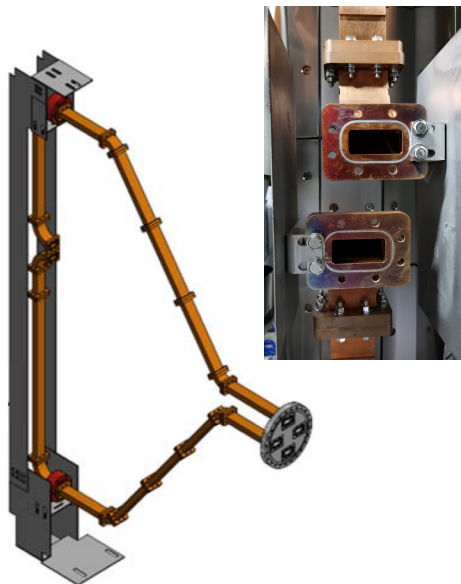
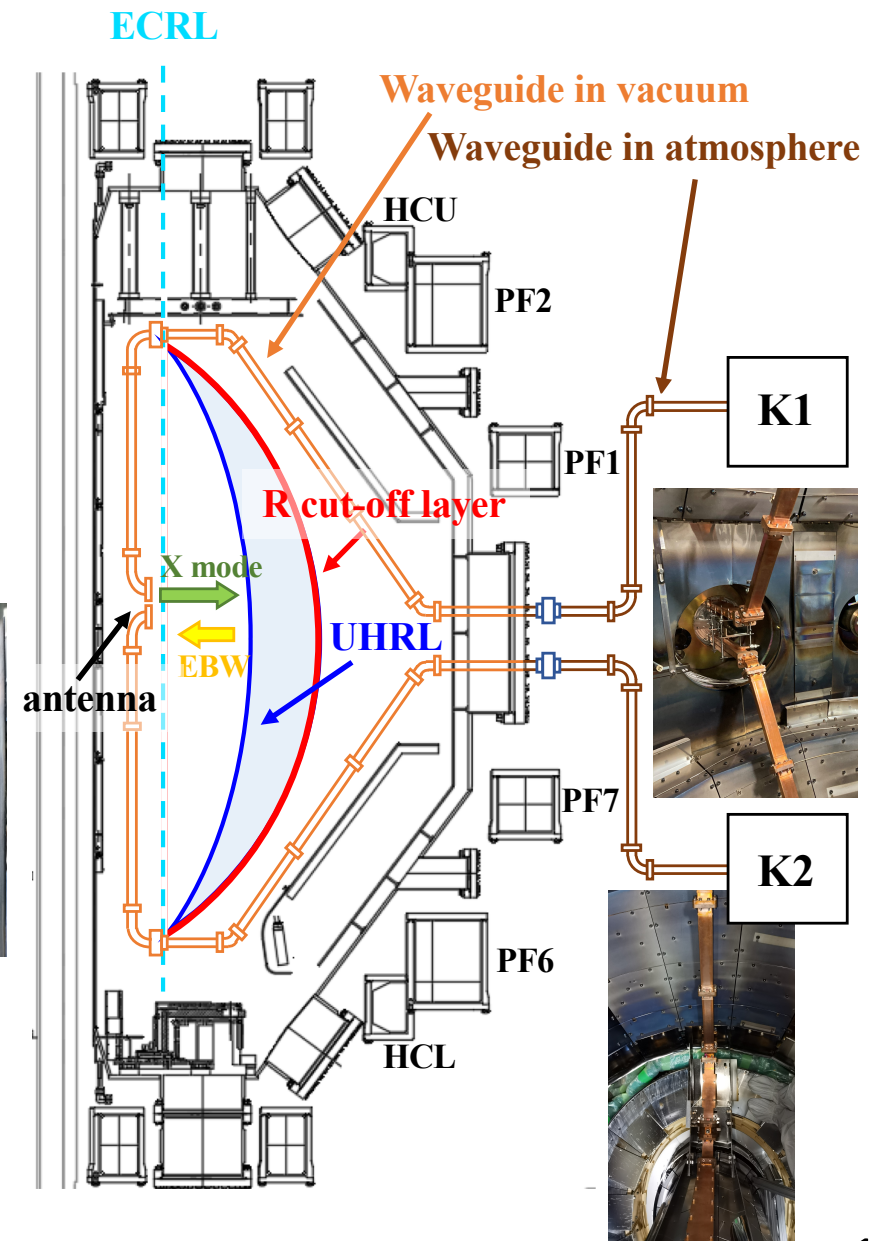
- X-mode ECW was injected perpendicularly via antenna on HFS
- Magnetic flux at center stack was measured
- n-index > 0.3 was applied



- ✓ EBWCD in OFS was confirmed qualitatively by inverting B_T direction.



- ✓ Over-dense plasma that exceeded plasma cutoff density was measured near the EBW absorption position.



Summary

- [Effective **acceleration of energetic electrons** and **heating of bulk electrons** are observed in the oblique and quasi-perpendicular injection.
- [In the oblique injection, the up-shifted resonance areas are widely expanded by the strong Doppler-shifted effect for energetic electrons involving higher harmonics.
The second harmonic down-shifted resonance is cut out by the strong relativistic shift effect for energetic electrons.
Energetic electrons is efficiently accelerated, and high plasma current of 80 kA is attained.
- [In the quasi-perpendicular injection, the resonance areas are limited for wide energy-range electrons due to the weak Doppler-shifted effect in single path absorption.
With lower vertical field, the relatively large-sized plasma is attained with 100 eV electron temperature and 10^{18} m^{-3} density.
High electron temperatures of 500-800 eV are attained in small-sized plasma with high vertical field.
- [A second 28-GHz ECHCD system is in development to provide oblique and perpendicular simultaneous injections.
- [A new TFC power supply system is in development for doubled field (0.5 T) operations.
A second harmonic and fundamental ECHCD scenario is introduced, which is expected to conduct high efficiency ECCD experiments with high one path absorption (90 %).