Study on non-inductive EBW Heating using direct XB mode conversion in VEST

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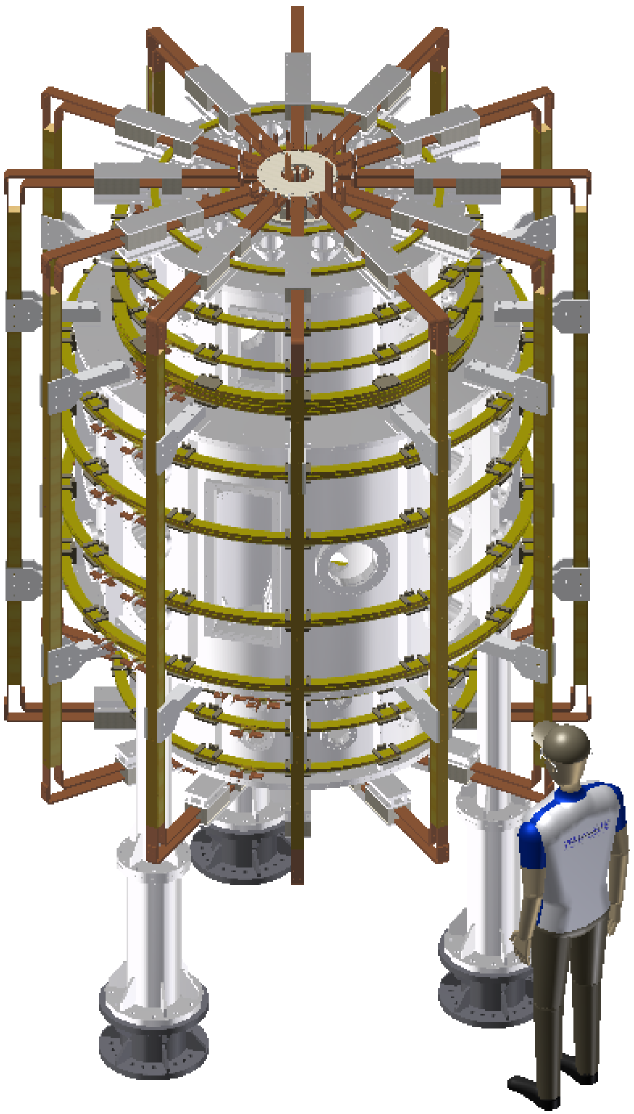
Outline

- Introduction
- EBW Heating Experiments in linear device
  - EBW heating by collisional damping with direct XB conversion
  - Direct XB mode conversion via multiple wall reflection
- EBW Heating Experiments in VEST
  - EBW collisional heating in pure TF and TPC pre-ionization
  - Low loop voltage startup with EBW collisional heating
- Summary & References

VEST : the first Spherical Torus in Korea



Versatile Experiment Spherical Torus

- Objectives
  - Basic research on a compact, high-β ST (Spherical Torus)
  - Study on **innovative start-up, non-inductive H&CD, and innovative divertor concept**, etc
- Specifications

	Initial Phase	Future
Chamber Radius [m]	0.8 : Main Chamber 0.6 : Upper & Lower Chambers	
Chamber Height [m]	2.4	
Toroidal B Field [T]	**0.1**	0.3
Major Radius [m]	**0.43**	0.4
Minor Radius [m]	**0.33**	0.3
Aspect Ratio	**>1.3**	>1.3
Plasma Current [kA]	**~70 kA**	100
Elongation	**~1.6**	2.5
Safety factor, q_a	**~3.5**	~3

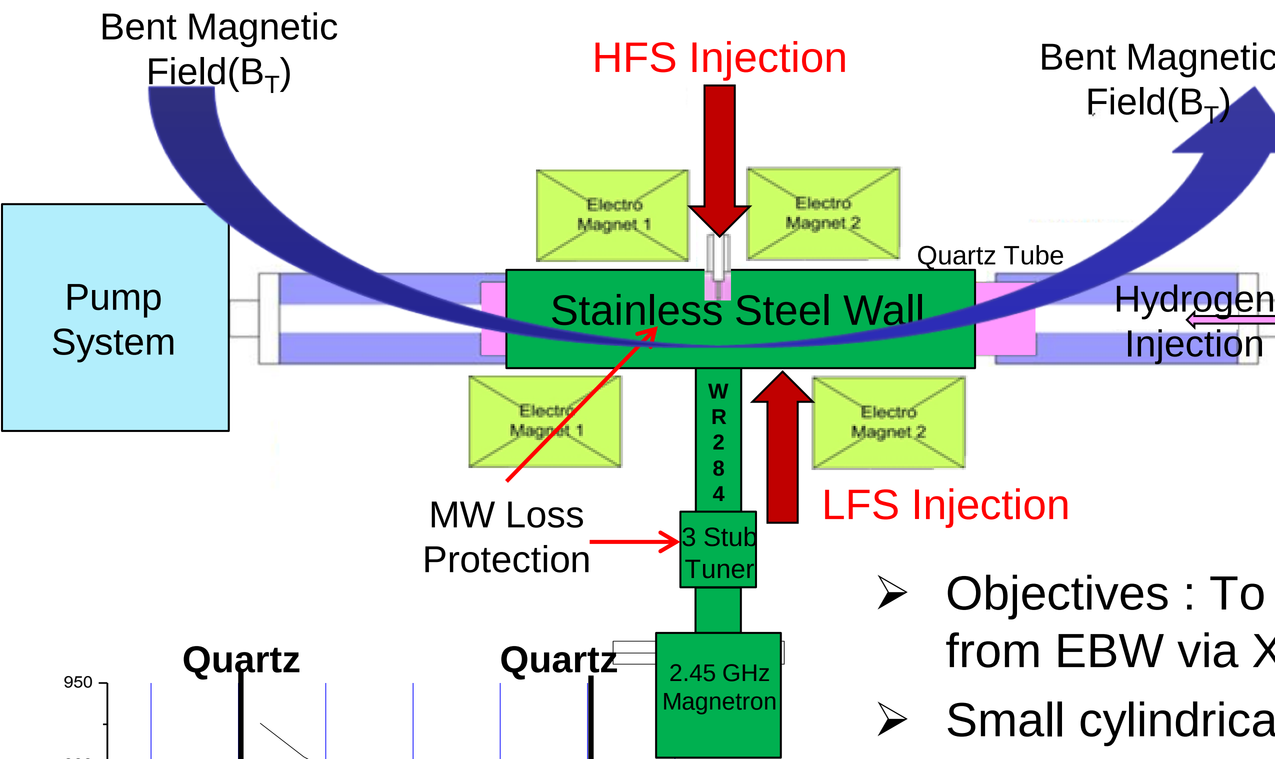
Motivation & Objective

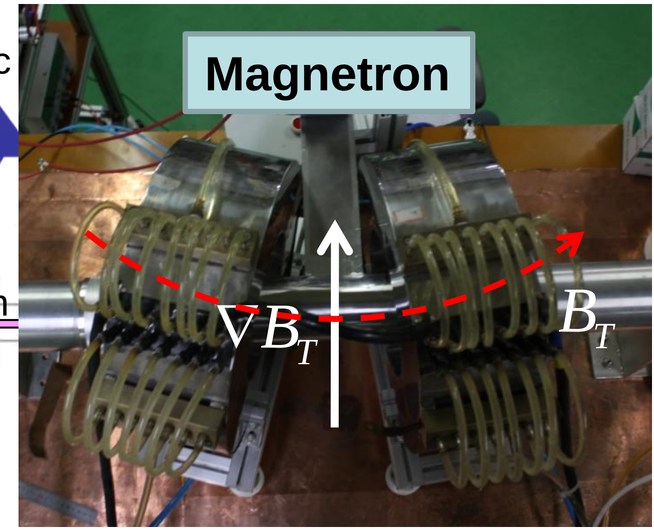
➢ Electron Cyclotron Heating(ECH) is widely used for various purposes in fusion device that the pre-ionization, local heating and current drive. Especially non-inductive current drive and startup using ECH is essential for Spherical Torus (ST) which has lack of space for the center stack. But ECH in ST shows the limitations due to low toroidal field.

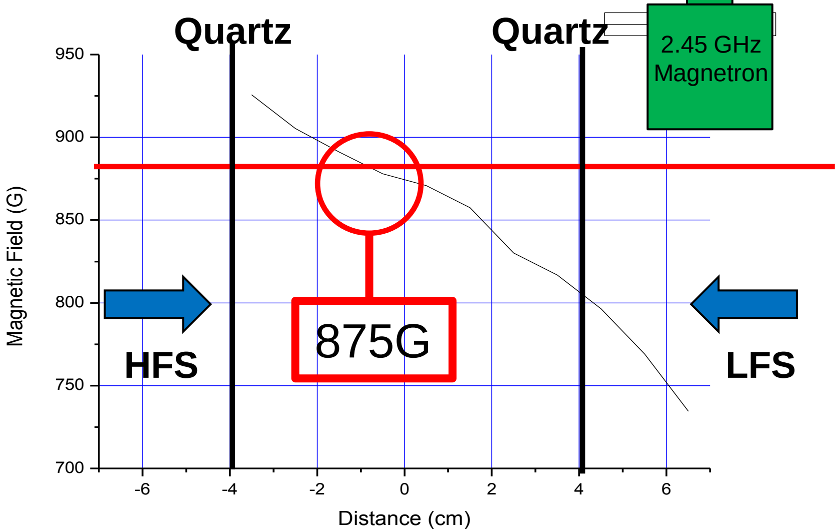
➢ An EBW(Electron Bernstein Wave) which has no cutoff density, has been proposed as a promising alternative for heating and current drive in ST that it is impossible for ECH due to density limit.

EBW	OXB (O cutoff & UHR)	OXB (CS & UHR)	XB (UHR)
Pros	Excellent results in theory and experiment		Simple design Single Mode conversion
Cons	Complex Scenario Density fluctuation Angular dependant	Complex Scenario Need : polarizer Limit of O cutoff	Limit of R cutoff – tunneling effect Control on density profile
Device	MAST[1], NSTX[2], QUEST[3]		LATE[4], TST-2[5], CDX-U[6]

Experimental Setup



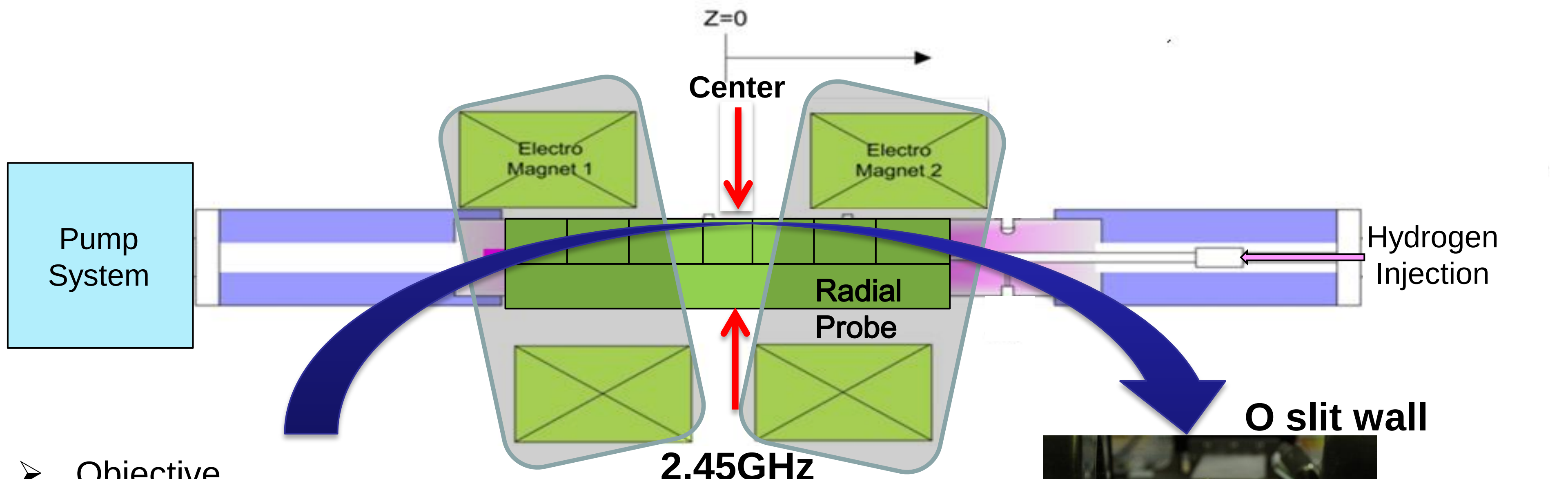




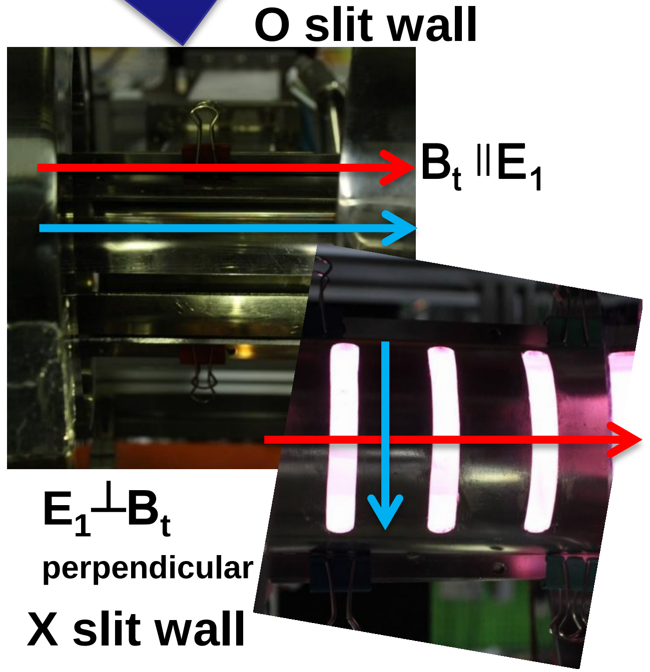
- Objectives : To find the feasibility of ECH from EBW via XB mode conversion.
- Small cylindrical device with axial magnetic field bent similar to tokamak
- Possible to change the direction of MW injection mode – LFS&HFS
- Easily changeable of magnetic field and MW power – movable location of ECR
- Antenna : open waveguide(WR284)

18th international Spherical Torus Workshop on November 4th 2015, at PPPL

Experimental Setup : Wall with X/O Polarized Slit

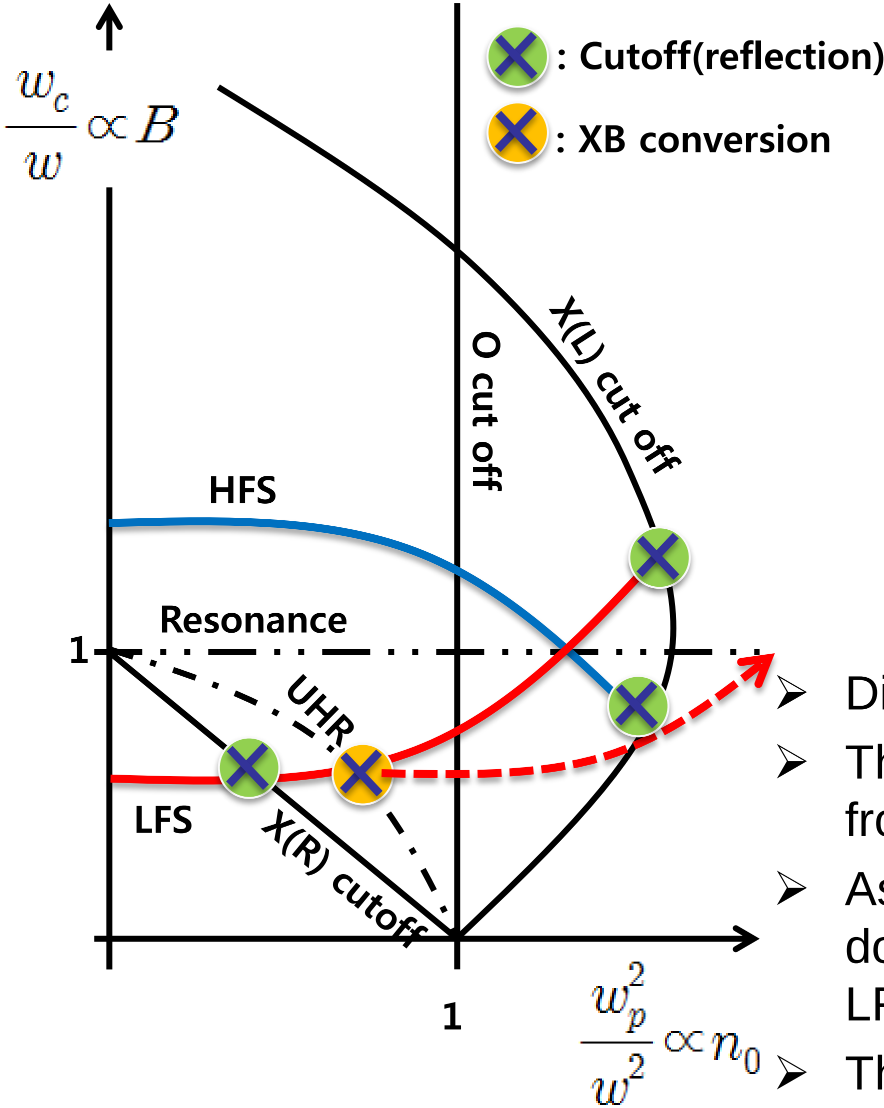


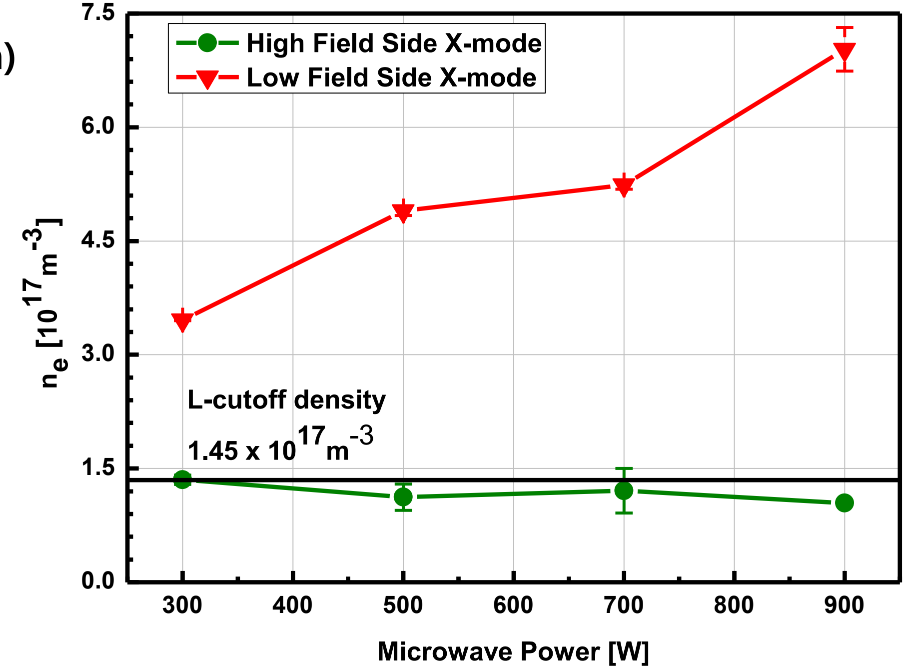
- Objective
  - Confirm the effect of EBW mode conversion on the wall reflection with polarized slit
- The wall is possible to change the position along the injection and opposite side.
- X/O slit : The wall with slits that reflects the X/O mode wave
  - Formation of polarized wave with specific direction to radiate the electric field of wave perpendicular/parallel on the magnetic field
  - The other wave with different direction will pass through the slit



ECH Experiment in linear device

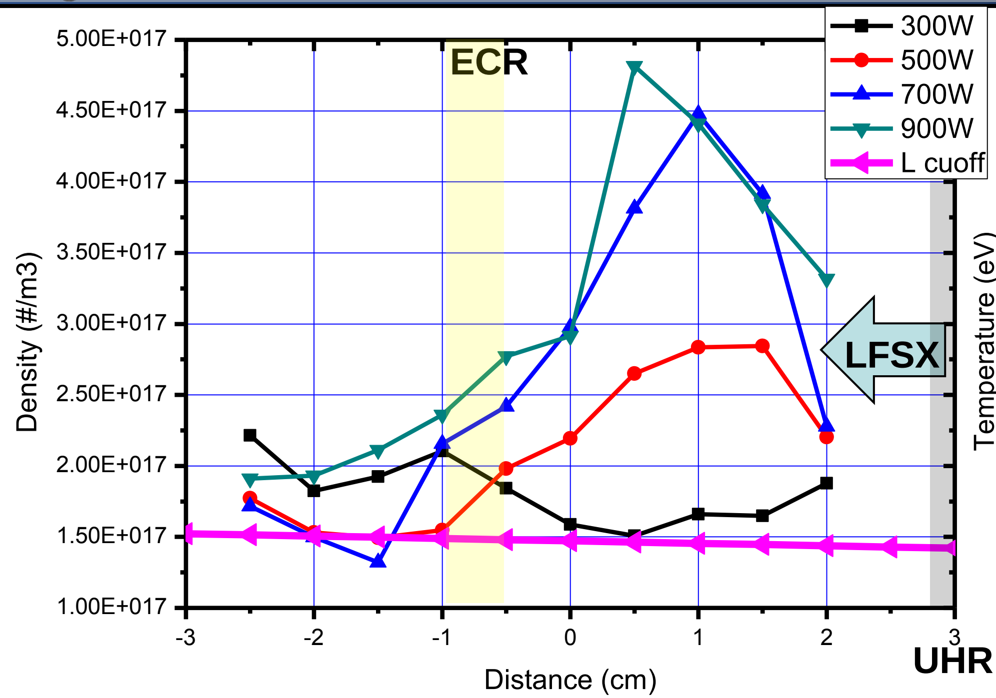
Over-dense plasma generation

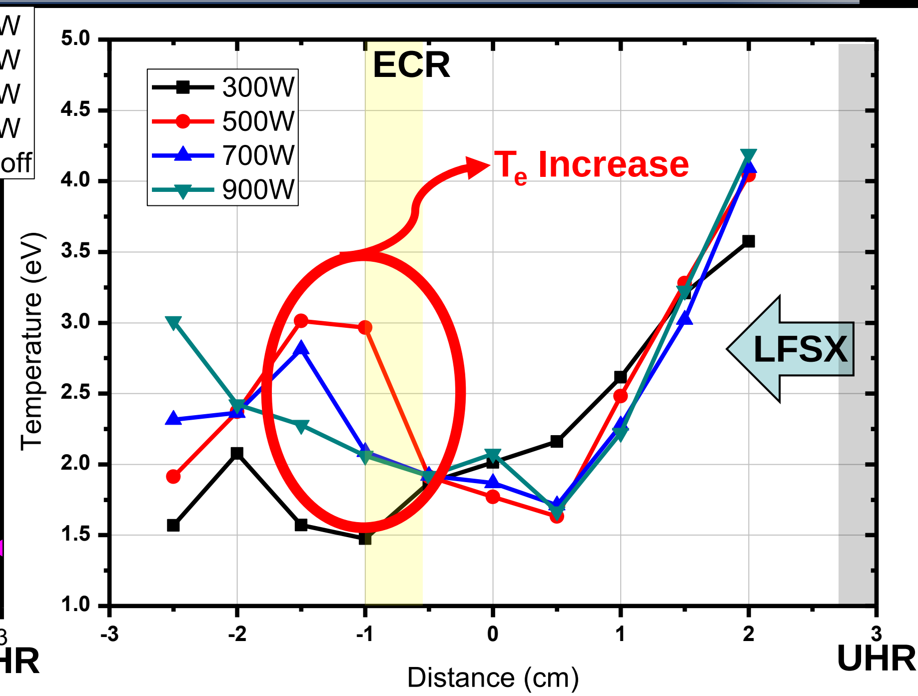




- Diagnostics – measured at r = 0
- The plasma with higher electron density generates from LFS X mode than from HFS X mode.
- As shown in CMA diagram, LFSX/HFSX injection does not exceed R/L cutoff but in the experiment LFSX injection overcomes the L cutoff.
- The feasibility of EBW via XB mode conversion might be shown.

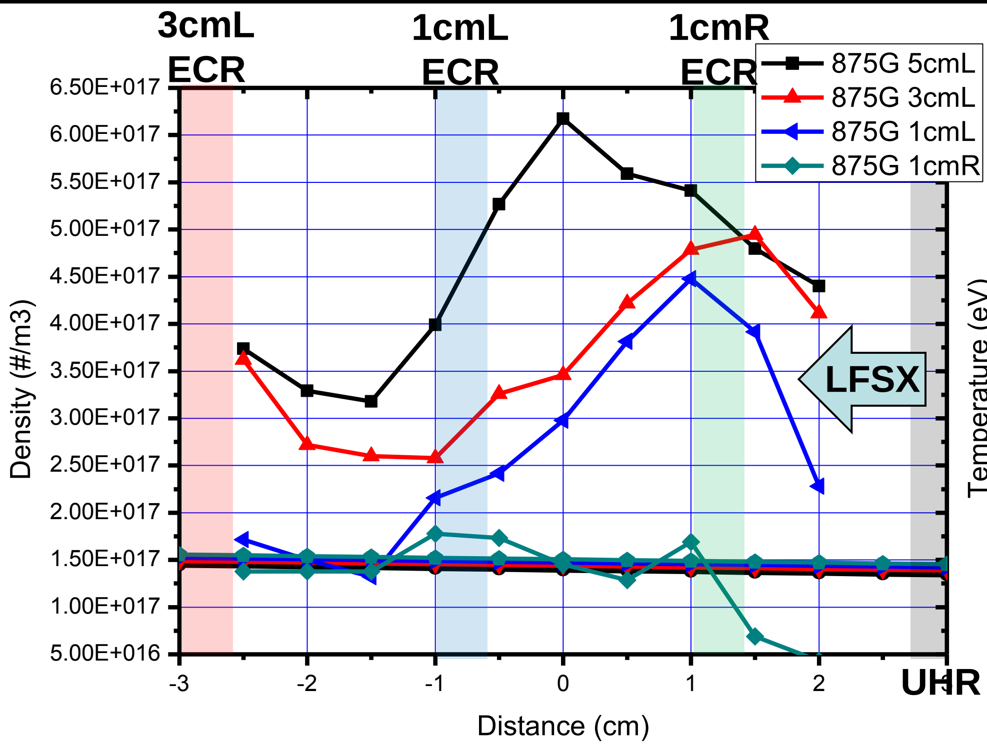
The n_e & T_e Profile along the MW Power

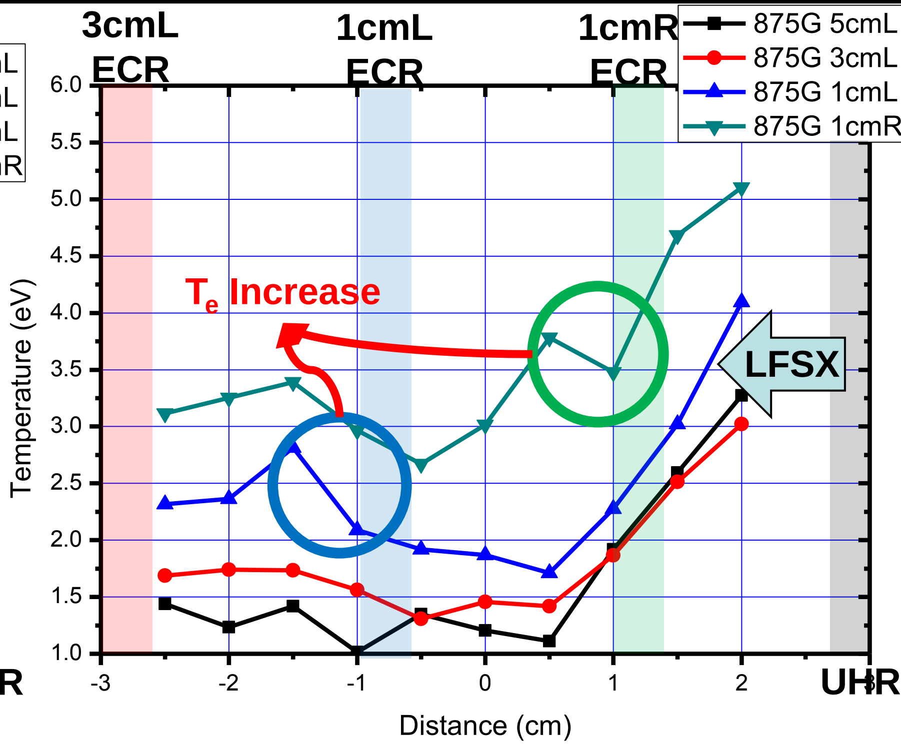




- Over-dense plasma generation and electron temperature increase near ECR
  - To confirm the feasibility of XB conversion
  - At the lower power, density peak does not exist but when the MW power increases, over-dense plasma generates and density peak forms between UHR and ECR – Steep density gradient near UHR
  - EBW collisional damping propagating to ECR in low T_e [7~9]
  - T_e increase near ECR : ECH effect from some part of the converted EBW

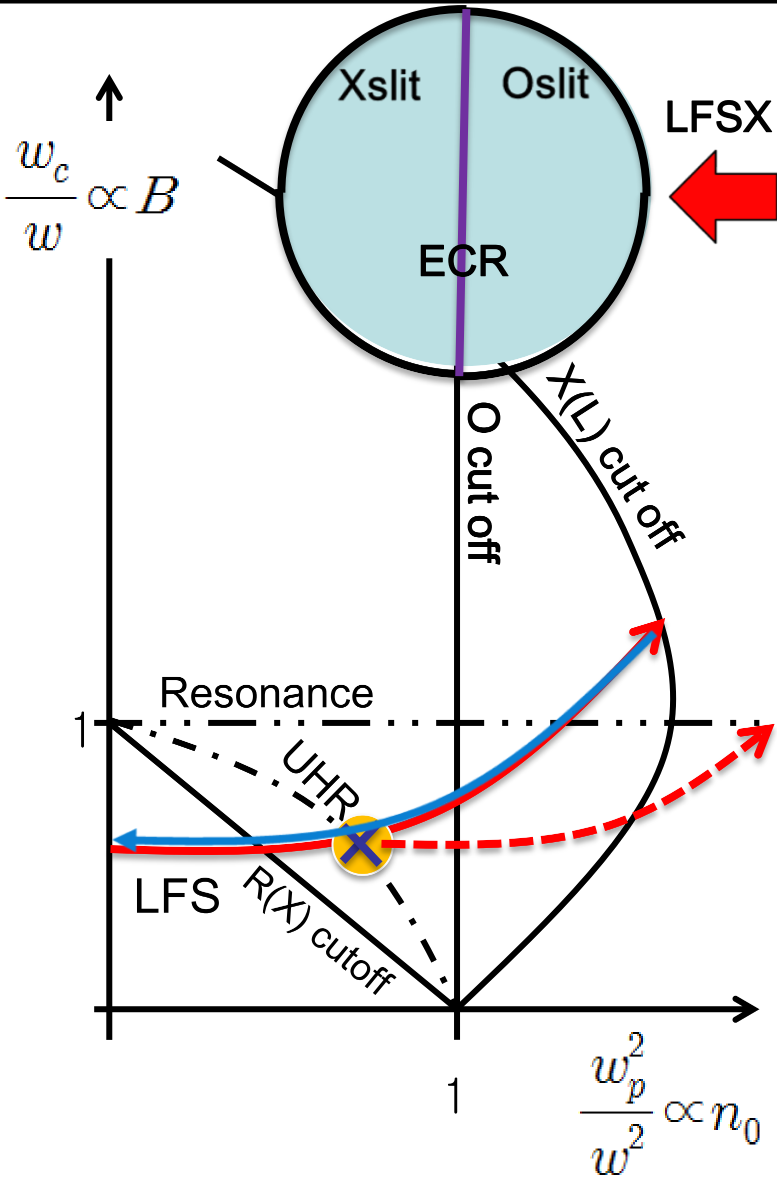
The n_e & T_e Profile along the Magnetic field

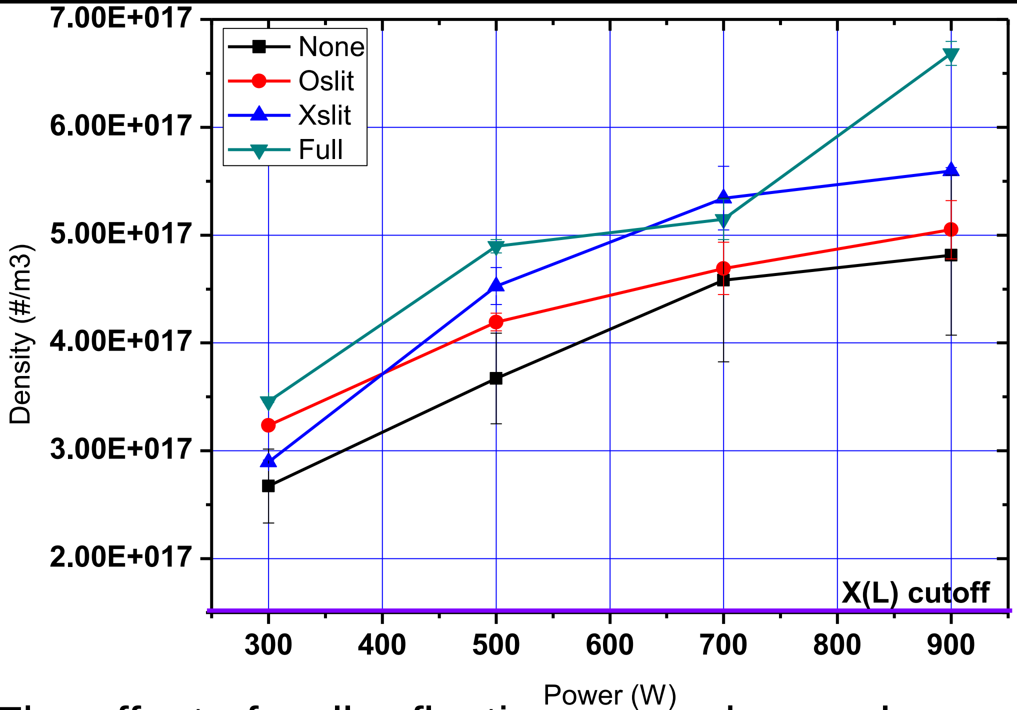




- Over-dense plasma generation and temperature increase near ECR
  - Over-dense plasma : EBW collisional damping propagating to ECR in low T_e
  - Generation of higher density plasma at the lower magnetic field
    - The higher density near UHR at the lower magnetic field
  - Movement of the electron temperature rising region along ECR layer
  - Feasibility of plasma heating by EBW collisional damping with XB conversion

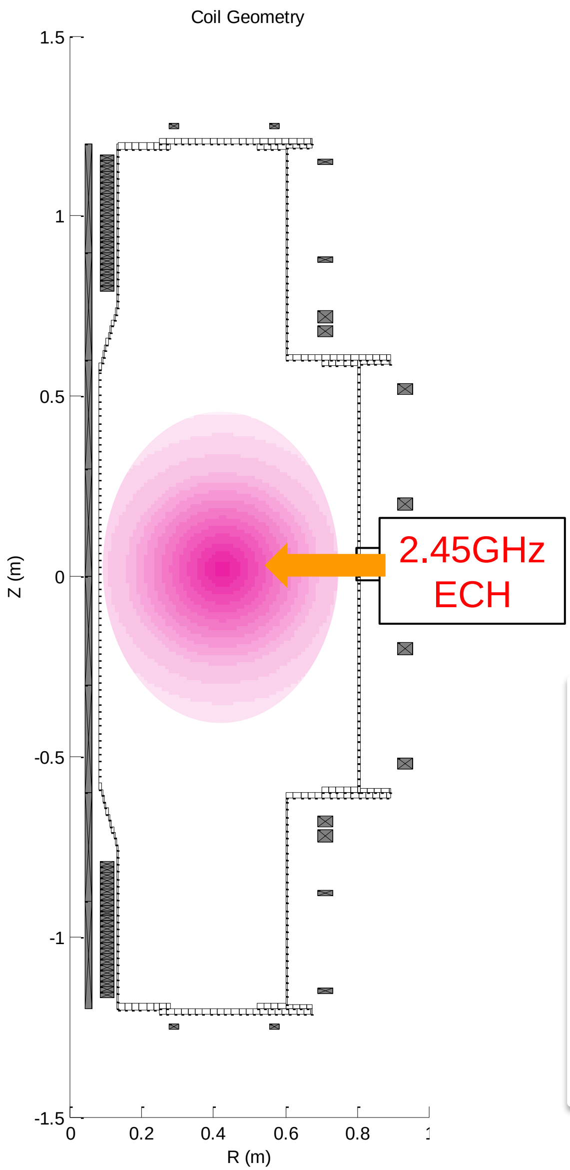
LFSX Injection with Polarized Wall

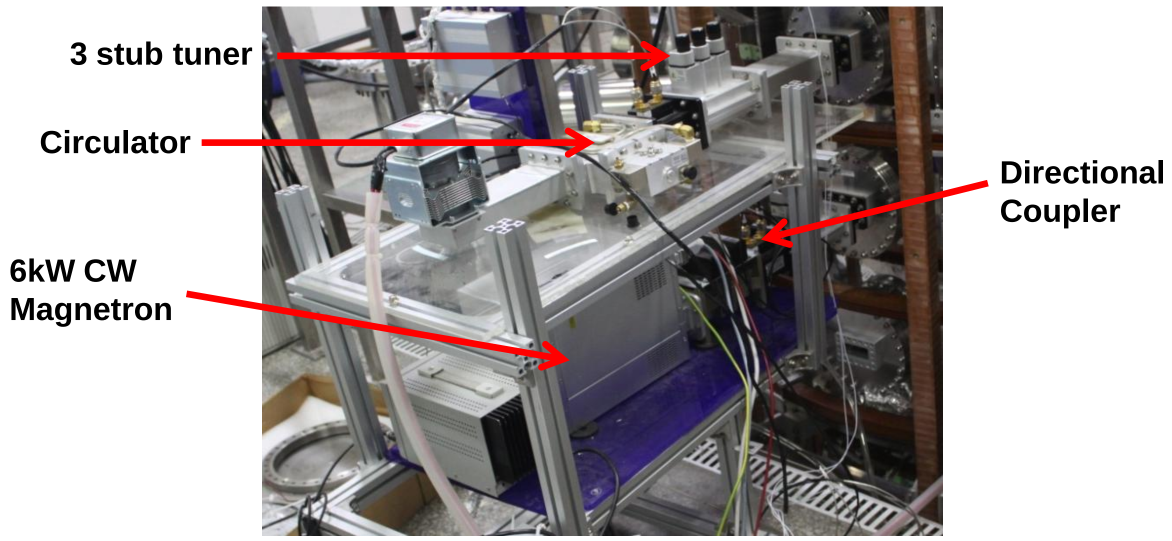




- The effect of wall reflection : over dense plasma
- Oslit wall : similar to the none wall
  - No effect of the reflected O wave
  - Single pass absorption(Direct XB)
- Xslit wall – similar to the full wall (VEST)
  - Multi pass absorption(reflected X wave)
- The XB mode conversion in VEST to make over dense plasma (power density : ~5.0×10^{15} #/m^3·W)

2.45 GHz CW ECH System of VEST





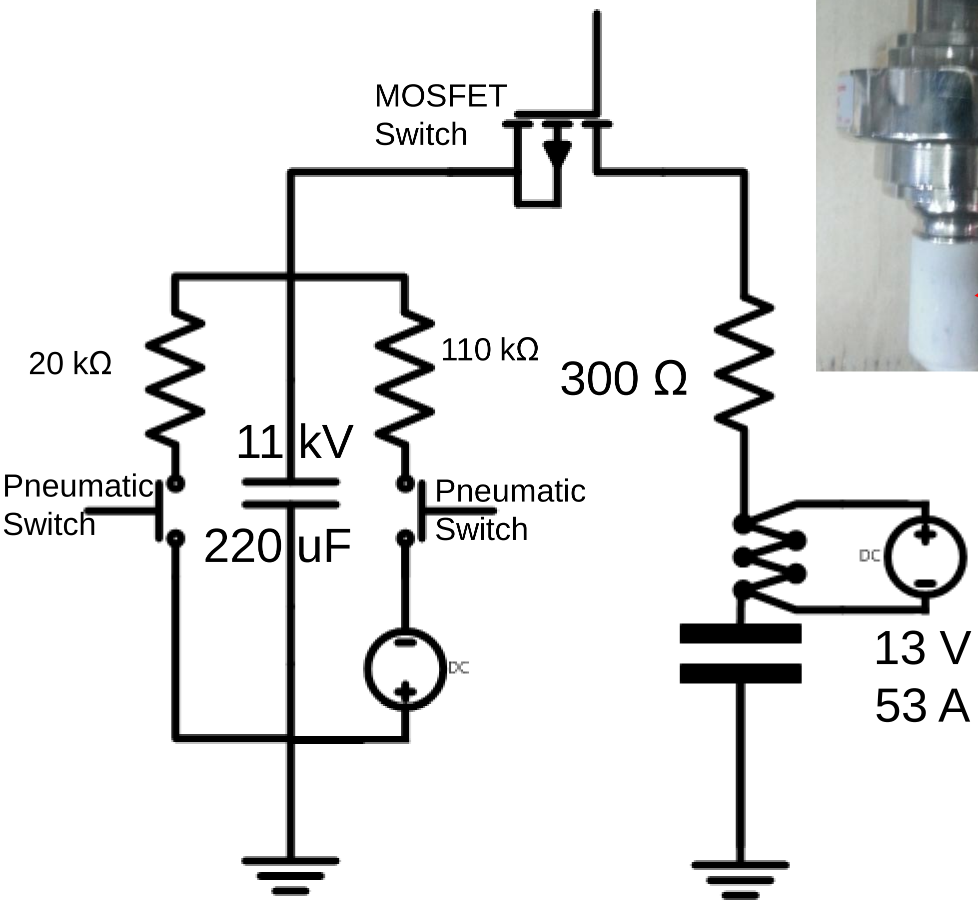
➢ CW ECH System

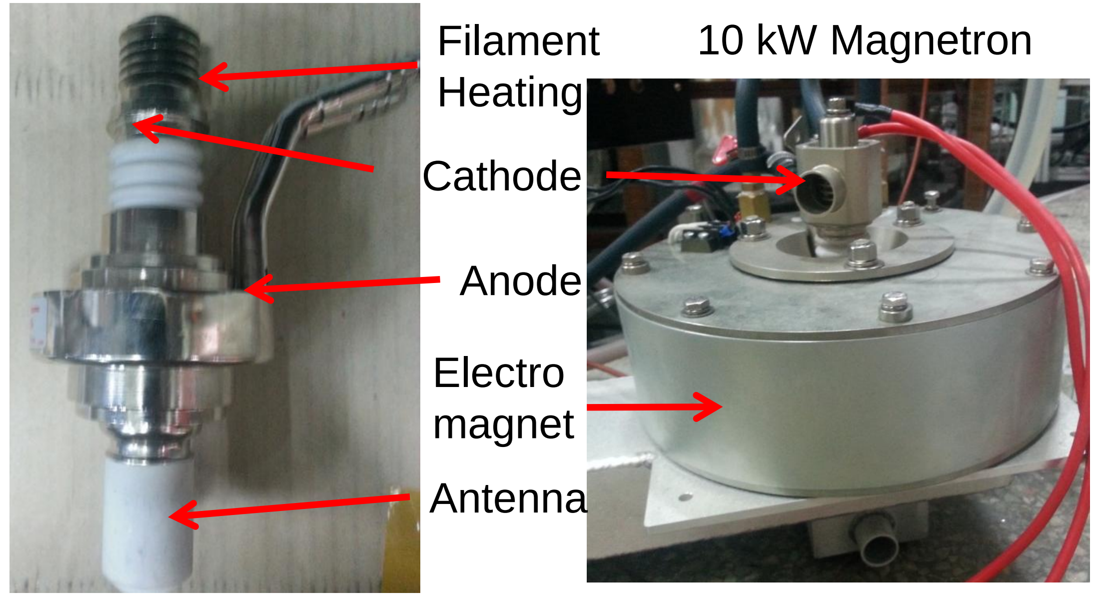
- Commercial microwave power supply (6 kW 2.45 GHz: 1ea)
- Low field side launching
- For main chamber
- X/O mode injection

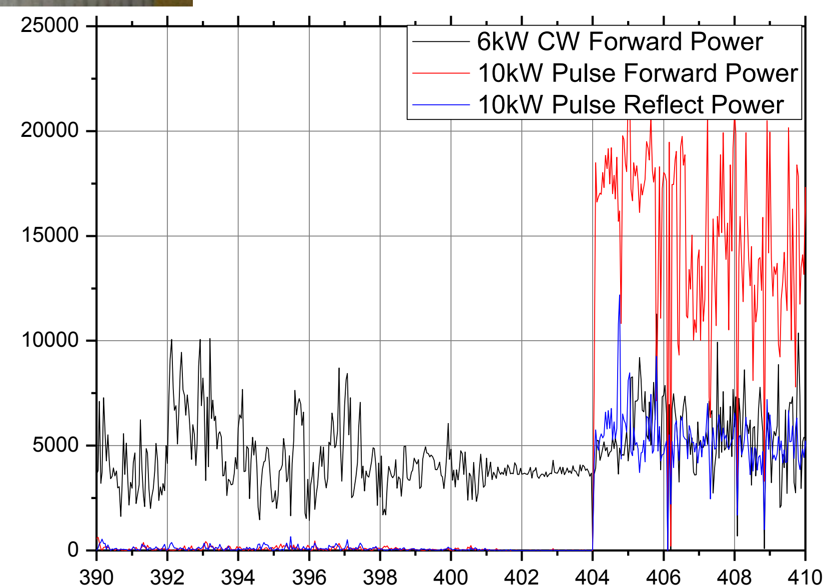
➢ Pulse ECH System

- Cost-effective homemade magnetron power supplies (10 kW : 1ea, 3 kW : 4ea)
- Low field side launching
- Easily movable (upper, main and lower chamber)
- X/O mode injection
- Pulse duration, trigger time

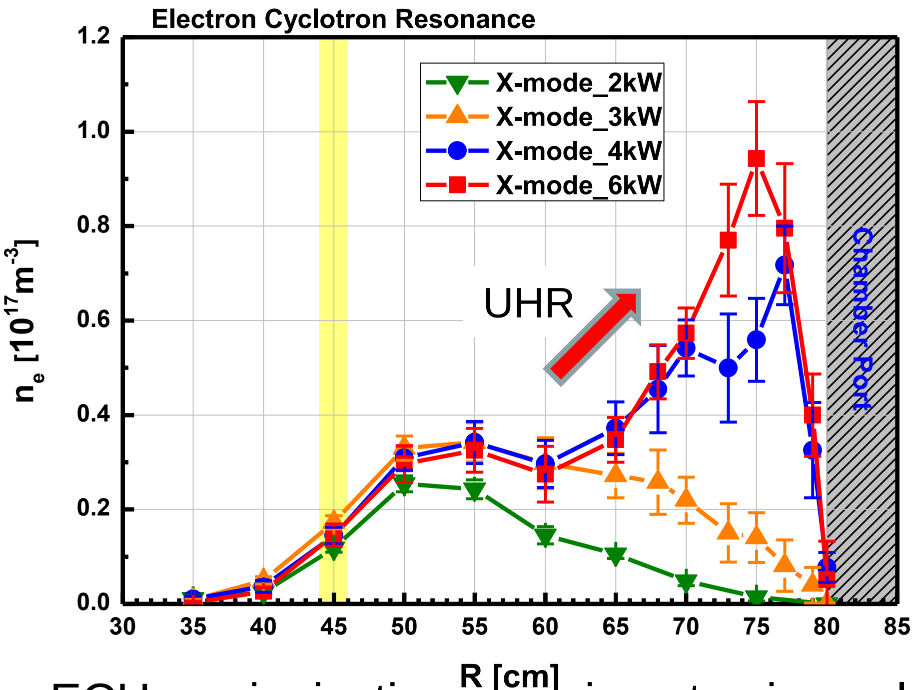
2.45 GHz pulse ECH System of VEST

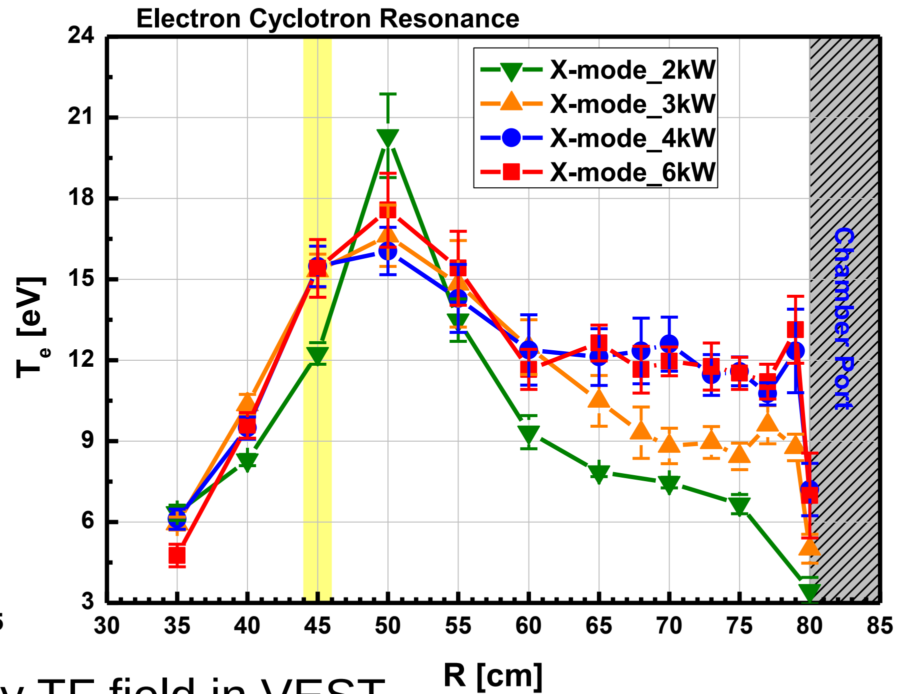






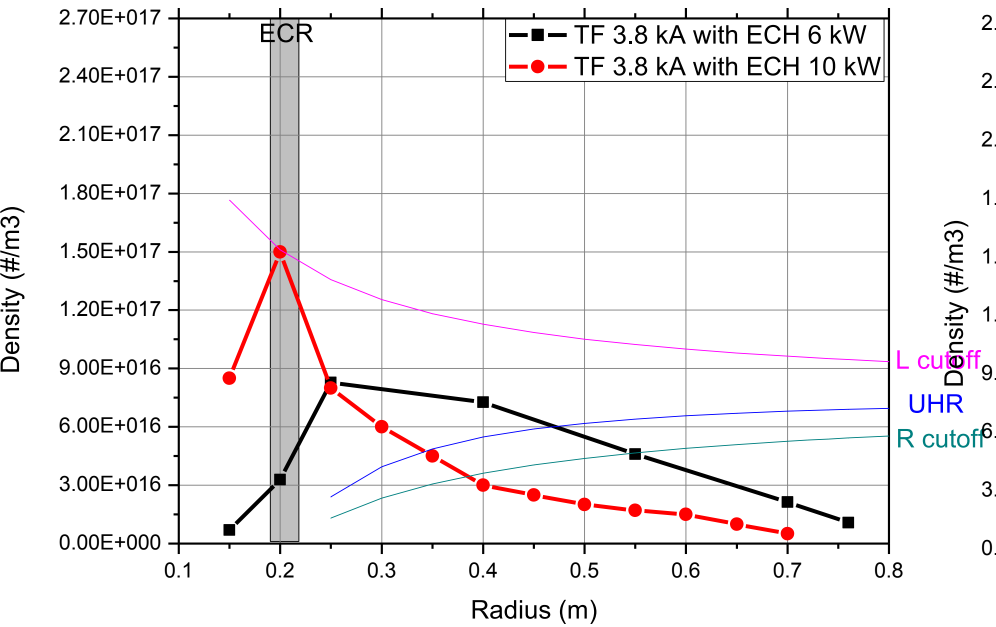
Pre-ionization Experiment – MW power

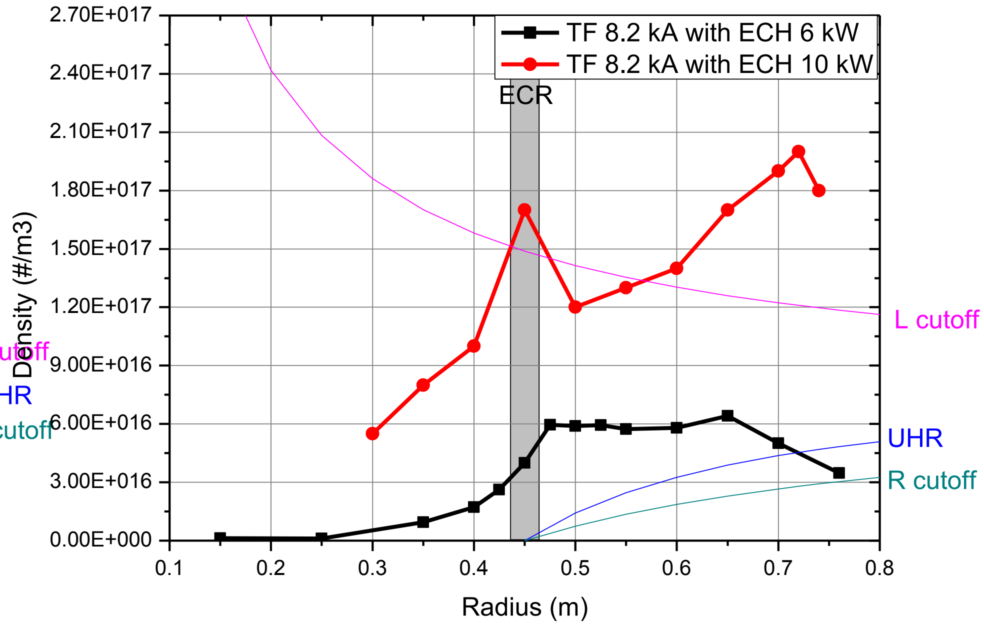




- ECH pre-ionization experiment using only TF field in VEST
  - Based on the linear device results, the pre-ionization experiments are performed.
  - At the lower power, density peak exists near ECR but when the MW power increases that means the electron density buildup, the density peak moves – Steep density gradient near UHR
  - Density peak formation between UHR and ECR : EBW collisional damping propagating to ECR in low T_e [7~9]
  - T_e increase near ECR : ECH effect from some EBW and non-converted X wave

ECH Pre-ionization Experiment with Pure TF





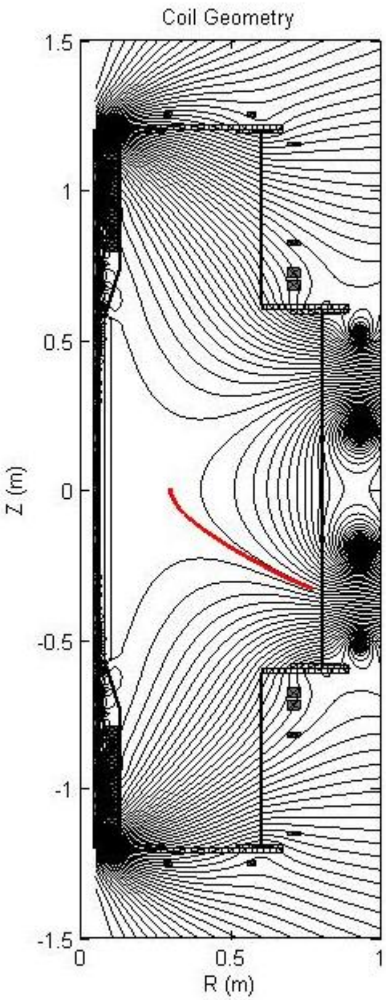
- Pure TF + ECH pre-ionization experiment
  - In case of 3.8 kA, high density plasma generates near ECR with ECH 6 & 10 kW
  - In case of 8.2 kA, over dense plasma generation over L cut off density and plasma density peak exists near UHR : Collisional damping with XB conversion
  - Power density in the linear device (~6.0×10^{16} #/m^3·W) :
    - It is expected that higher pre-ionization density with higher ECH 10 kW power
  - In case of 3.8 kA, the density peak exists near the ECR layer but in case of 8.2 kA, the mode conversion efficiency increases that in the similar position of UHR and cutoffs and collisional damping of EBW makes the density peak.

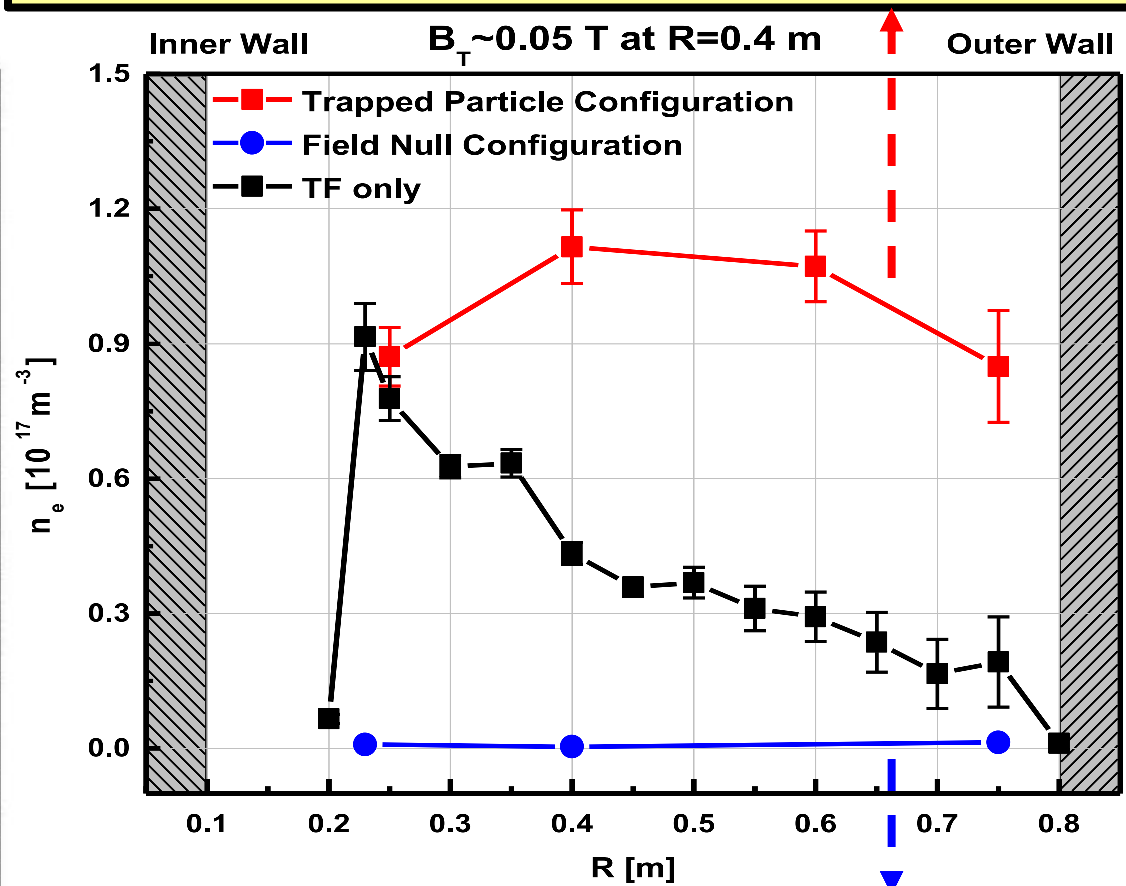
Enhancement of pre-ionization under TPC

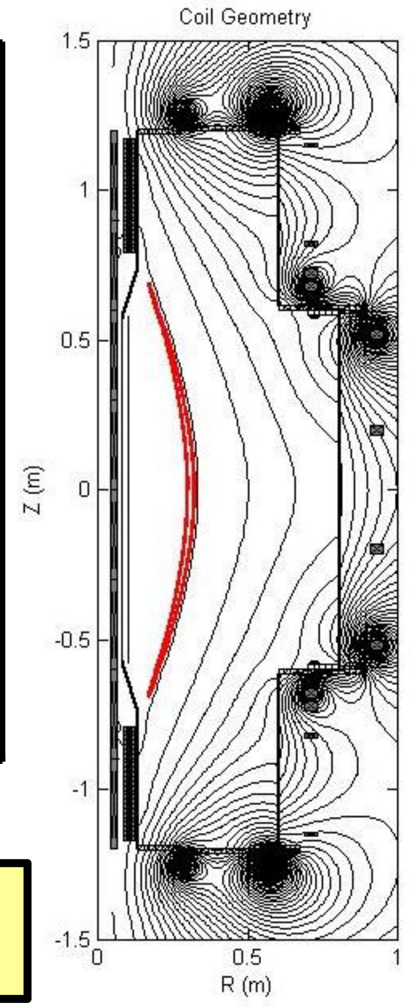
Field Null Configuration

Significant enhancement of pre-ionization under TPC (Trapped Particle Configuration)

Trapped Particle Configuration

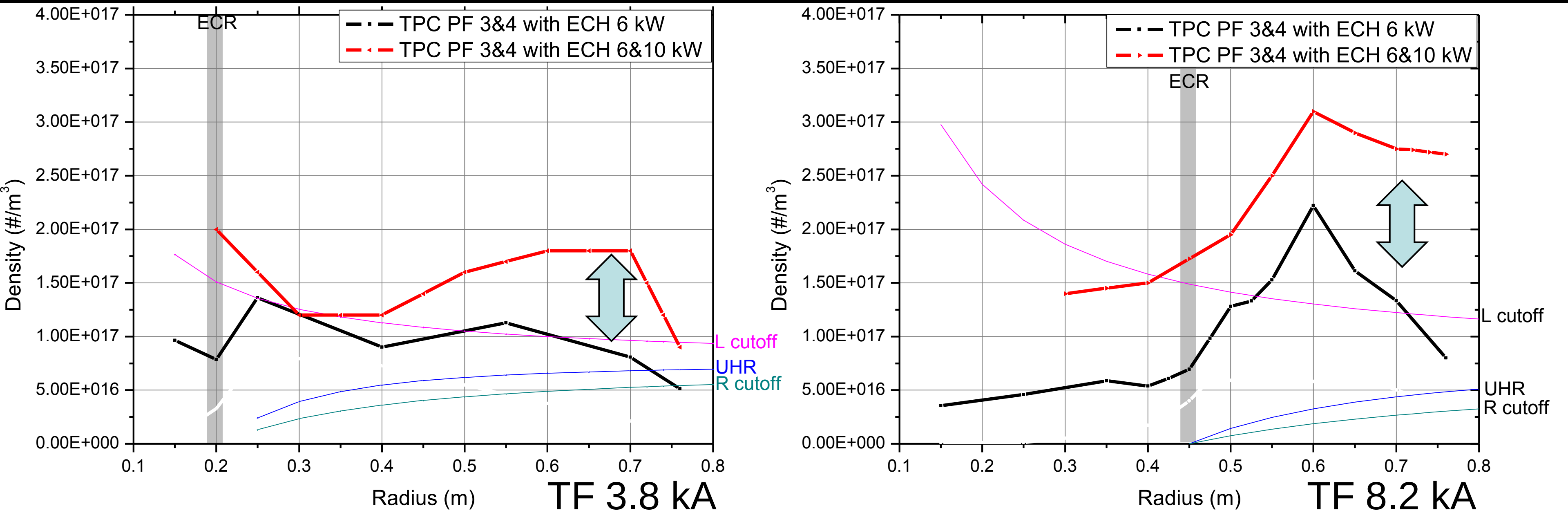






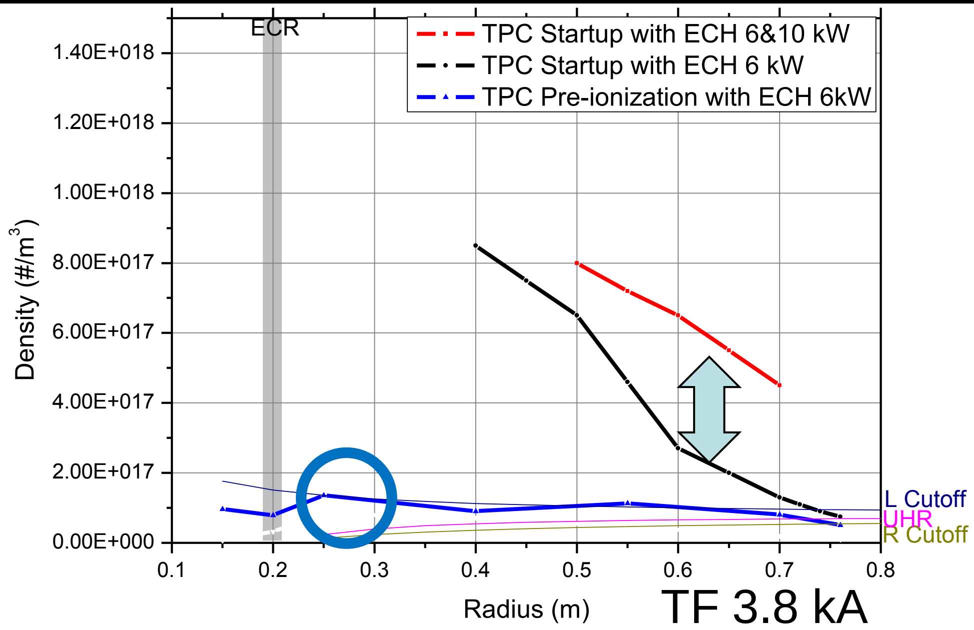
Severe degradation of pre-ionization under field null

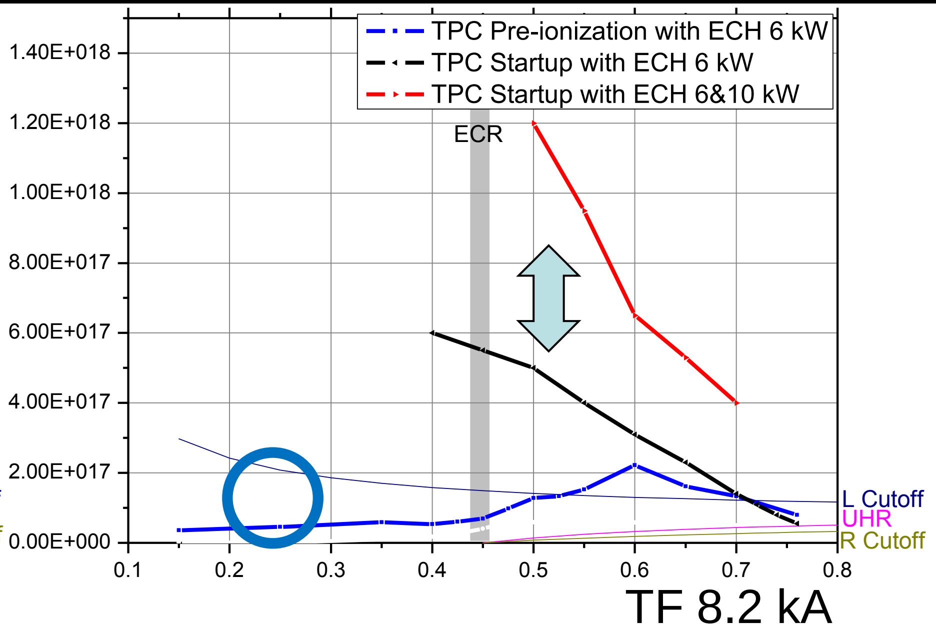
EBW collisional heating in TPC pre-ionization plasma



- EBW collisional heating occurs with TPC pre-ionization plasma
  - The mode conversion efficiency is calculated with 1-d full wave simulation[10]
    - In case of TF 3.8 kA, broad density profile makes low MC conversion coefficient (0.0105) but in case of TF 8.2 kA, steep density gradient exists near UHR and relatively high MC coefficient (0.2625)
  - Additional 10 kW pulse ECH power is supplied when TPC enhances pre-ionization plasma
    - Over dense plasma generation near UHR showing collisional EBW heating
    - In case of 3.8 kA, low MC efficiency (0.0105→0.4819) has slight increase in density but in case of 8.2 kA, high MC efficiency (0.2526→0.756) has large rise in density due to steep density gradient and magnetic field.

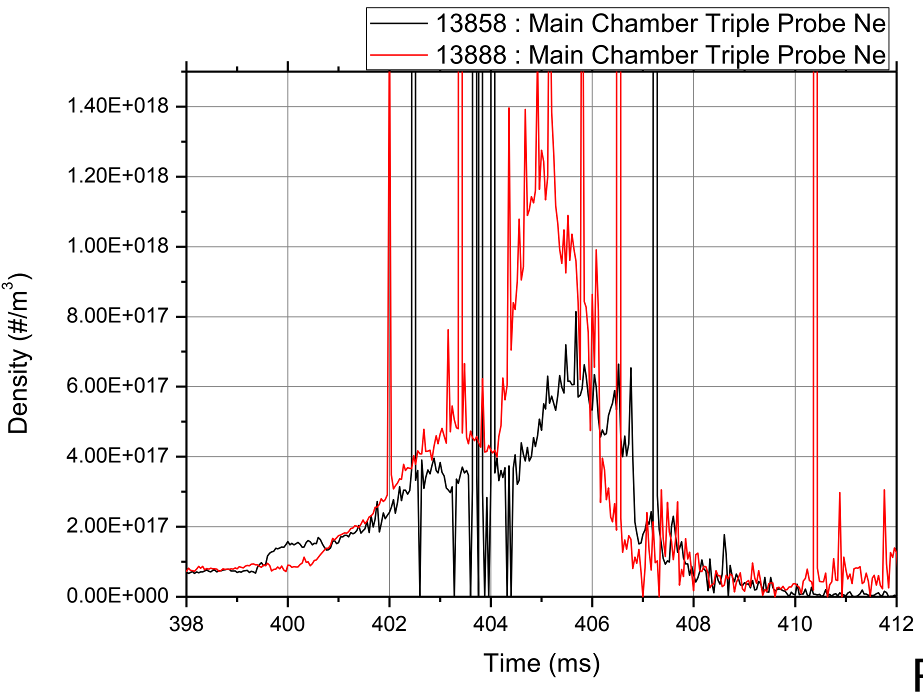
EBW collisional heating during TPC startup (1)

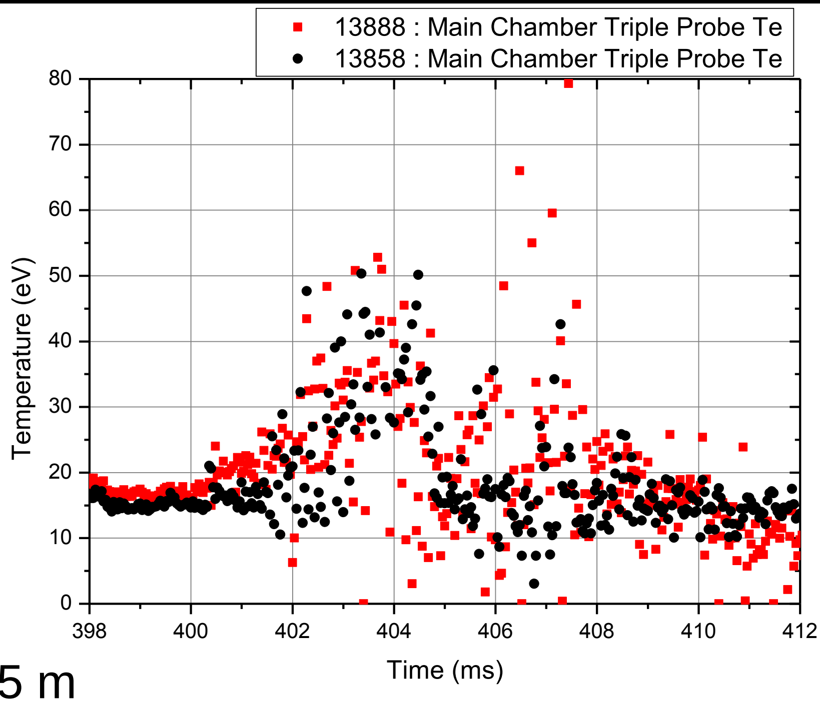




- EBW collisional heating occurs during TPC startup
  - The low loop voltage startup experiments using TPC have been performed.
  - The mode conversion efficiency is calculated with 1-d full wave simulation when the plasma density reaches the density peak[10]
    - The MC coefficient of TF 3.8 kA (0.3655) has larger than that of TF 8.2 kA (0.1536) due to the pre-ionization density near inboard that has strong loop voltage and it shows the different plasma current ramp-up rate

EBW collisional heating during TPC startup (2)

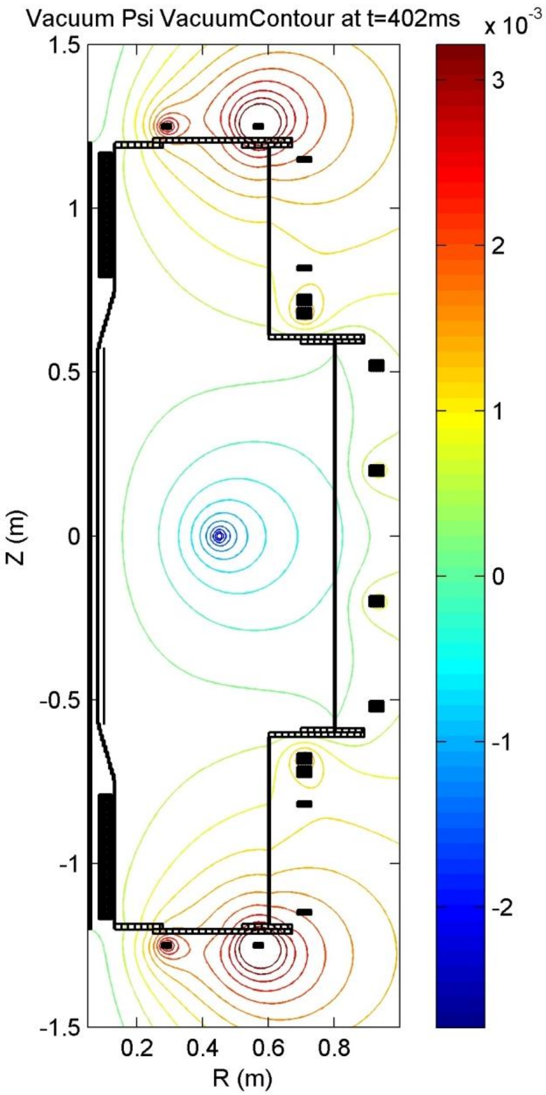


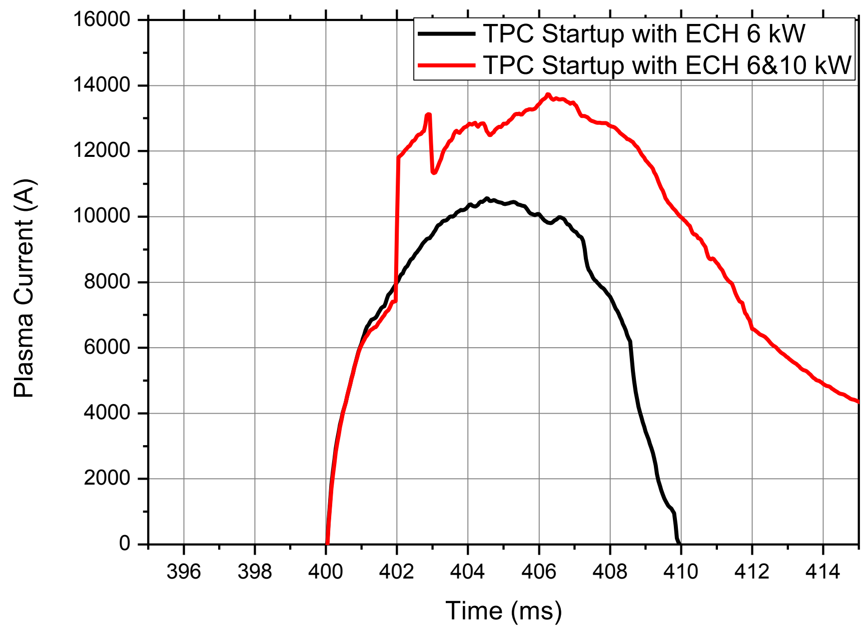


R = 0.5 m

- EBW collisional heating occurs during TPC startup
  - 13858 (TPC startup with 6 kW), 13888 (TPC startup with 6 & 10 kW)
  - The additional 10 kW pulse ECH injection has occurred at 402 ms.
    - In case of TF 8.2 kA, the MC coefficient has dramatically increased (0.1536 →0.966) and the electron density and temperature increases rapidly (405 ~ 407 ms)
    - The feasibility of strong heating in the closed flux surface (R=0.5 m) is confirmed and EBW collisional damping (density increase) and temperature rise near ECR layer shows the evidence of EBW heating.

EBW collisional heating during TPC startup (3)



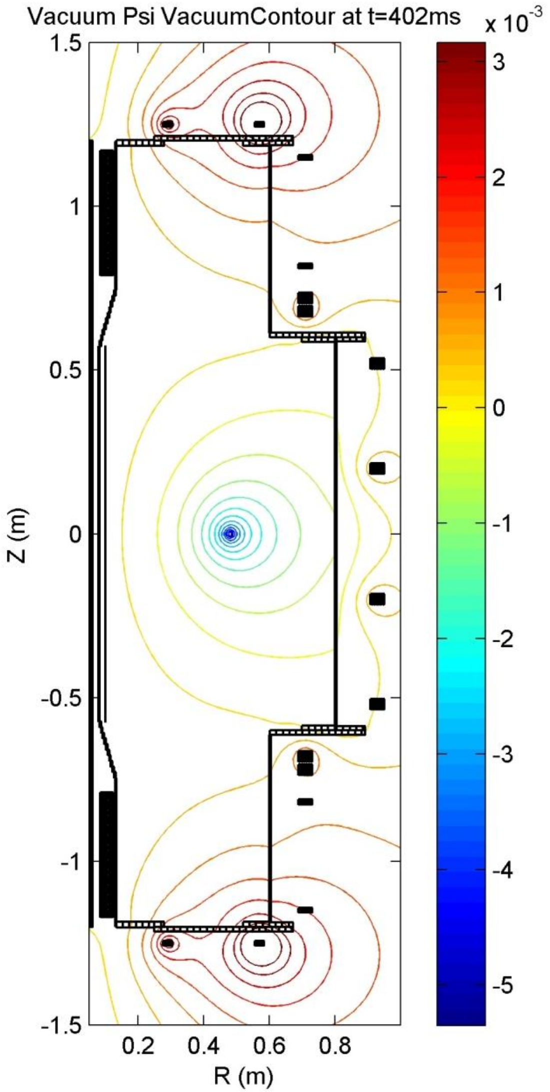


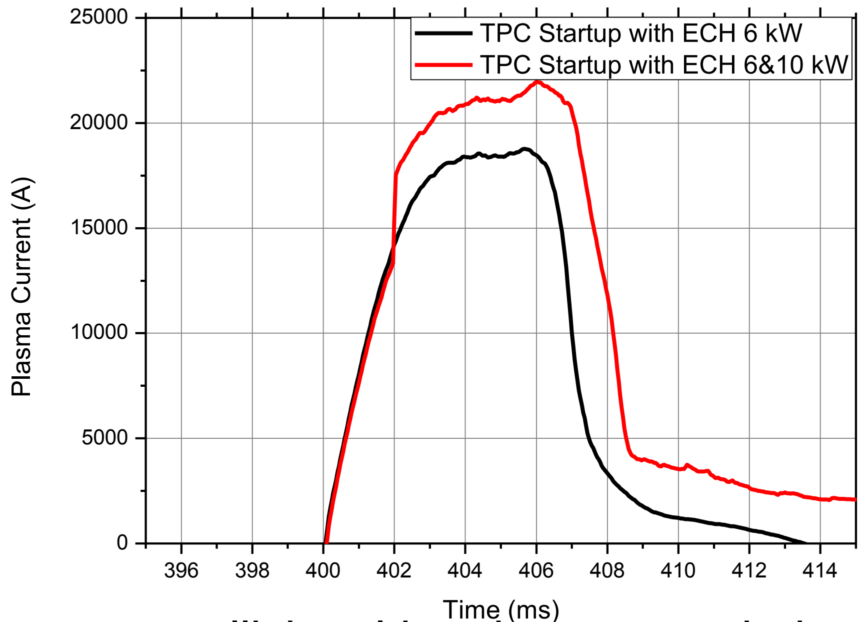
TF 3.8 kA

EBW collisional heating occurs during TPC startup

- The plasma current has the increase at the time additional 10 kW pulse ECH injection as well as electron density and temperature.
- Also the plasma current has the longer pulse duration with EBW heating.

EBW collisional heating during TPC startup (4)





TF 8.2 kA

- EBW collisional heating occurs during TPC startup
  - The plasma current has the increase at the time additional 10 kW pulse ECH injection as well as electron density and temperature.
  - Also the plasma current has the longer pulse duration with EBW heating.

Summary

- In the linear device, over dense plasma is generated by LFS X mode injection and the electron temperature peaks near ECR, indicating the presence of direct XB mode conversion and EBW collisional heating and the wall reflection with O/X polarized slit has affected to the ECH power absorption via single and multi pass, showing the feasibility of the heating of reflected X mode microwave and direct XB mode conversion.

- Based on the linear devices experiment results, the VEST pre-ionization experiments have been performed and increase of T_e near ECR and n_e near UHR is occurred at the similar result in linear device and enhanced pre-ionization plasma using TPC has been strengthened via direct XB mode conversion and collisional heating near outboard region compared to the MC efficiency from 1-d full wave simulation.

- The EBW heating experiment has been performed in low loop voltage startup using TPC and it is observed that the strong heating in the closed flux surface (R=0.5 m), EBW collisional damping (density increase), temperature rise near ECR layer and plasma current & duration increases that tells EBW heating during startup.

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