EX/P6-34

IAEA-FEC2014, 13–18 October 2014,
St. Petersburg, Russian Federation

Optimization of High Harmonic ECRH Scenario to Extend a Heating Plasma Parameter Range in LHD

T. Shimozuma, H. Igami, S. Kubo, Y. Yoshimura, H. Takahashi, M. Osakabe, T. Mutoh, M. Nishiura[1)], H. Idei[2)], K. Nagasaki[3)], N. B. Marushchenko[4)], Y. Turkin[4)] and the LHD Experiment Group

National Institute for Fusion
1) Graduate School of Frontier Science, the University of Tokyo
2) Research Institute for Applied Mechanics, Kyushu
3) Institute of Advanced Energy, Kyoto University
4) Max-Planck-Institut fuer Plasmaphysik, IPP-EURATOM, Greifswald, Germany

Outline

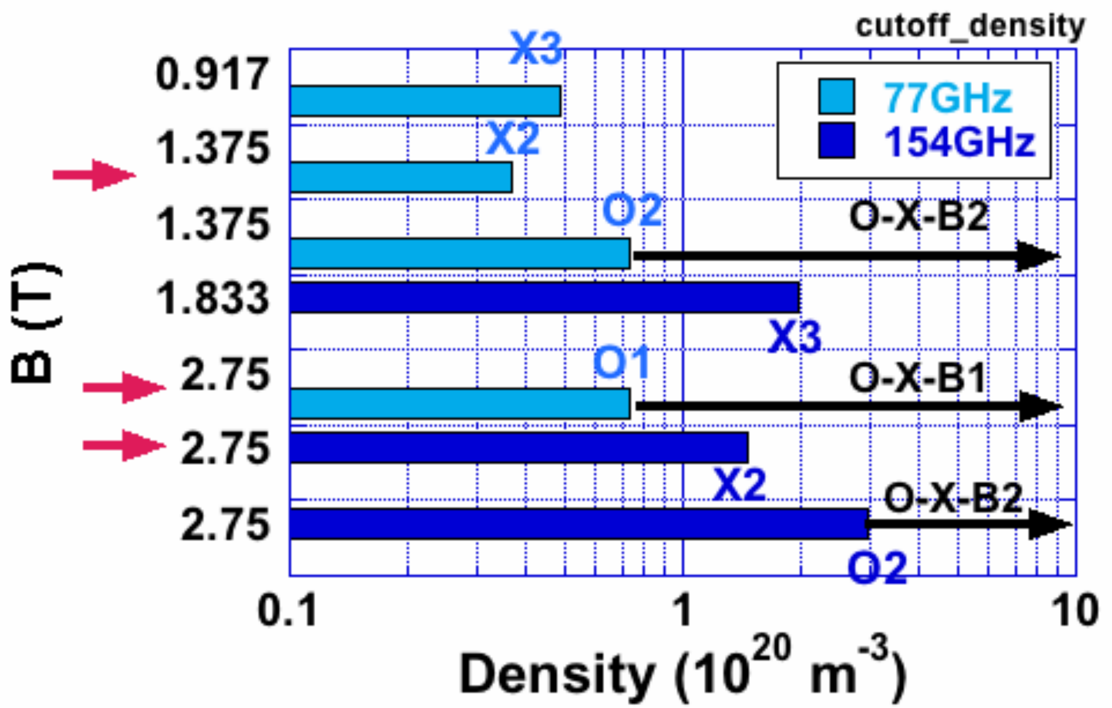
1. Introduction
2. Characteristics of HHECRH :
   - Cut-off density and resonant magnetic field
   - Optical thickness
   - Injection configuration: Consideration from ray-traving calculation results using U- and O-antennas
3. ECRH system in LHD
   - Gyrotrons
   - Antenna system – O-antenna and U-antenna systems
4. O2 mode heating: procedure and experimental results
5. X3 mode heating: procedure of experiment
   - Results of X3 mode heating for U-out antenna case (Experiments and Ray trace calculation)
   - Results of X3 mode heating for O-antenna case (Experiments and Ray trace calculation)
   - Three stepwise power injection experimet
6. Summary

Introduction

- LHD confines high-temperature and high-density plasmas using the external magnetic field generated by fully superconducting magnets. The major radius of the produced plasma is typically 3.6 m and the averaged minor radius is 0.6 m. In LHD, one of the main plasma heating methods is ECRH by high power millimeter–waves.
- The fundamental ordinary (O1) and the second harmonic extraordinary (X2) modes are usually used for plasma production, electron heating, and plasma control due to their high absorption efficiency.
- High harmonic ECRH, especially O2 and X3 modes, is a potential means to extend plasma density and β-value ranges of fusion-relevant plasmas.
- In place of the normally used O1 and X2 modes, sufficient absorption can be expected using even O2 and X3 mode heating scenarios, when the temperature and density of a target plasma are high enough and the injection direction and/or the magnetic field configurations are carefully optimized so that the EC waves may feel resonance over a long distance or pass through several times.

Why is High Harmonic ECRH required?

Possible heating regime for high harmonic ECRH



O2 : Higher cutoff density (×2), same resonant field as X2

X3: Higher cutoff density (×4/3) and lower resonant field than X2 (×2/3)

Extension of plasma heating and controlling regime.

77GHz :

B=0.917T → X3 $4.9\times 10^{19}\ m^{-3}$

B=1.375T → X2 $3.7\times 10^{19}\ m^{-3}$

B=1.375T → O2 $7.4\times 10^{19}\ m^{-3}$

B=2.75T → O1 $7.4\times 10^{19}\ m^{-3}$

154GHz

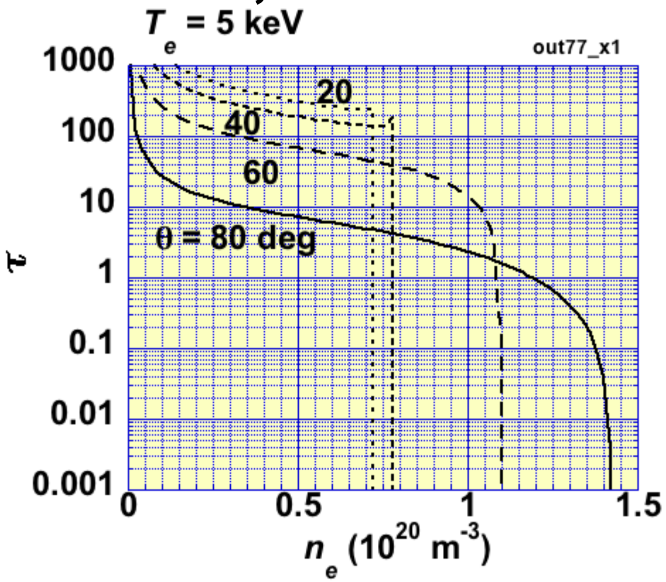
B=1.833T → X3 $19.6\times 10^{19}\ m^{-3}$

B=2.75T → X2 $14.7\times 10^{19}\ m^{-3}$

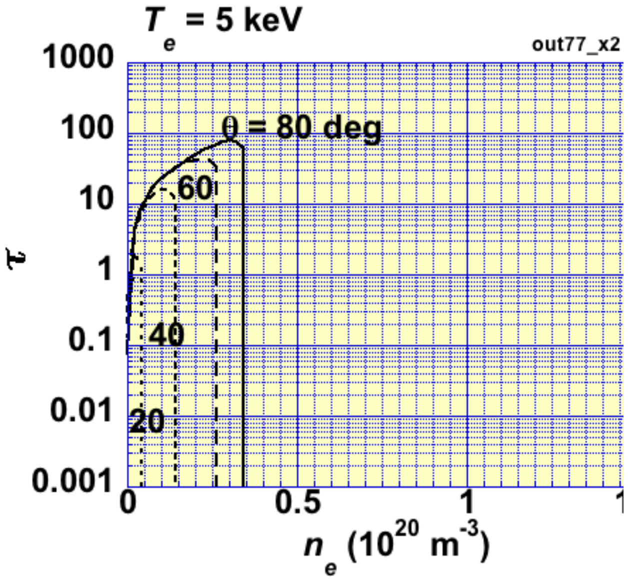
B=2.75T → O2 $29.4\times 10^{19}\ m^{-3}$

Calculation Results of Optical Thickness for 77 GHz Based on the Non-Relativistic Theory

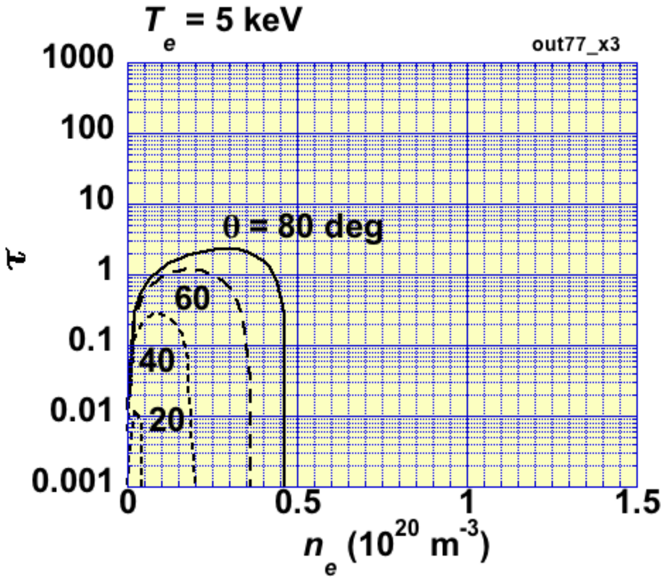
X1, B = 2.75T



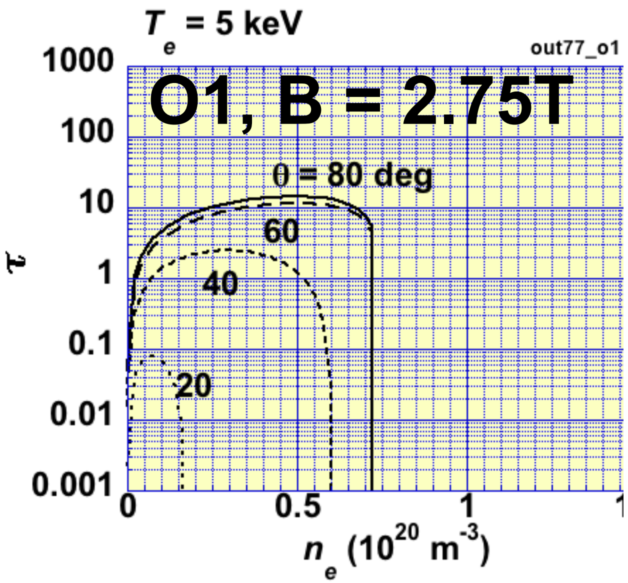
X2, B = 1.375T

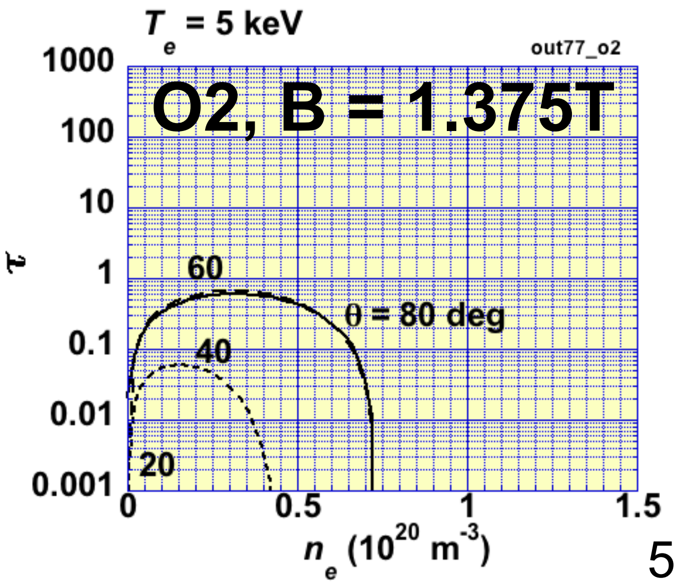


X3, B = 0.917T



***f* = 77GHz**

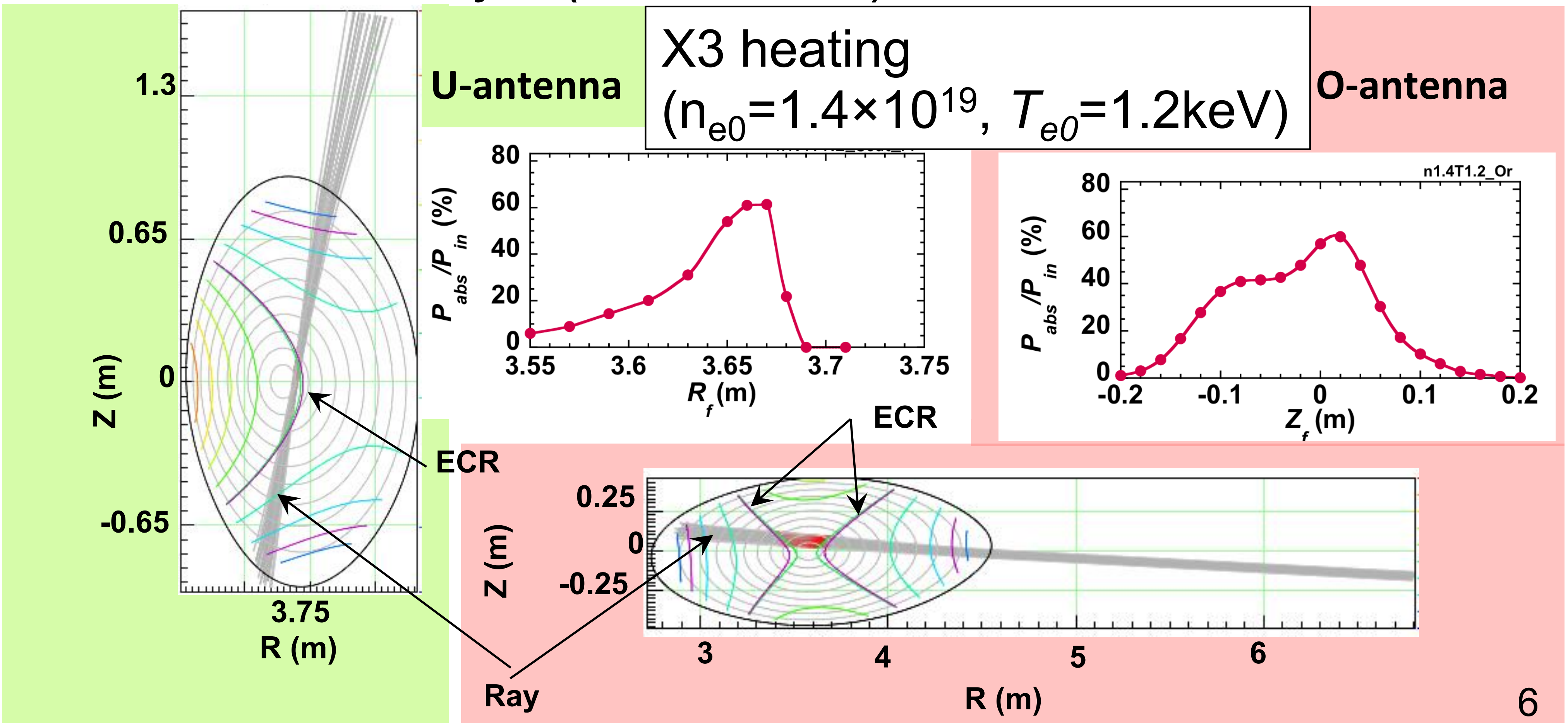




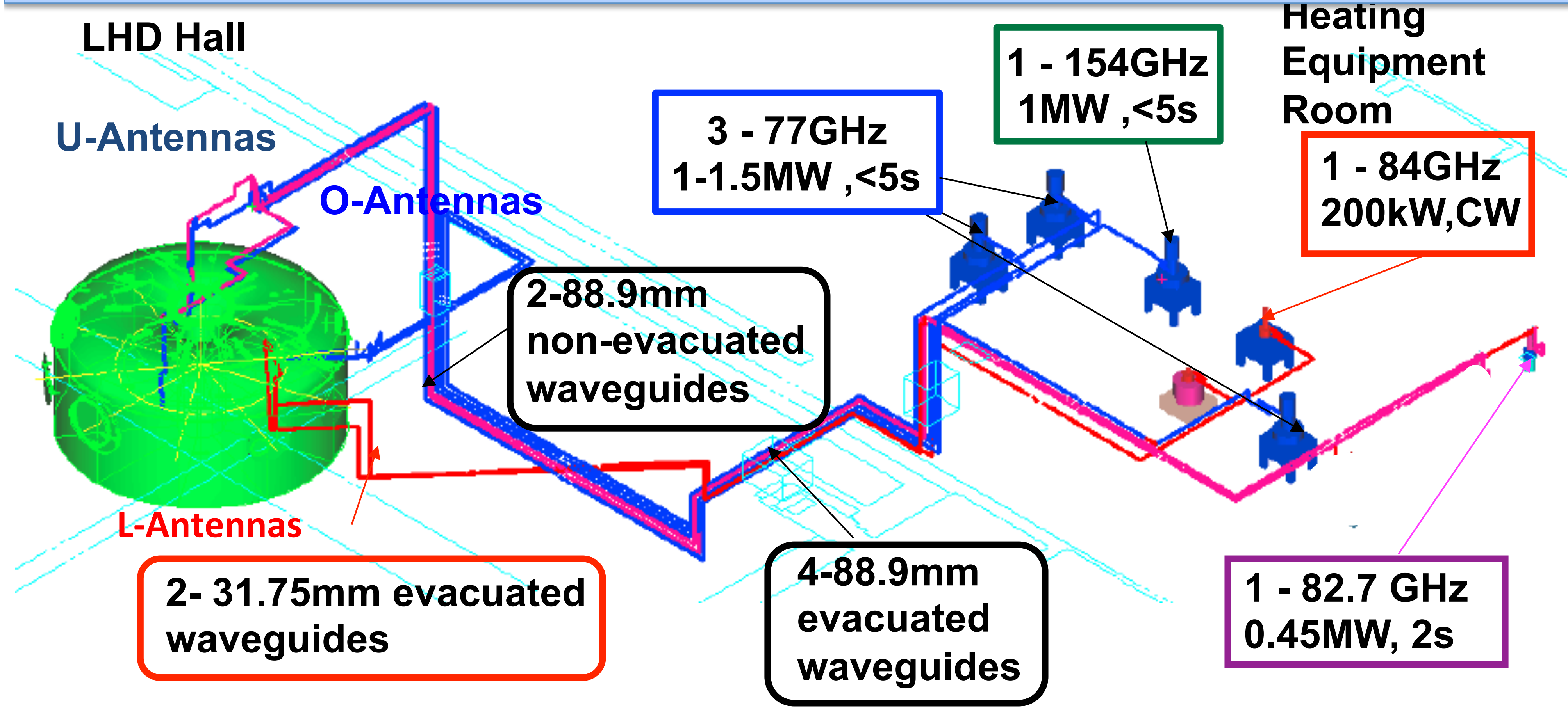
O2, X3 need a long distance resonance

Ray-trace calculation shows good absorption by optimizing magnetic and injection configuration

High harmonic ECRH can be expected as methods with sufficient absorption,
(1) EC beam injection <u>along the ECR over a long distance</u> (U-antenna case)
(2) EC beam injected <u>through the saddle point of the magnetic field strength</u> between two ECR layers (O-antenna case).



ECRH System in LHD (2013)



- 6 set of gyrotrons, 8 transmission lines, antennas are operated.
- , 1-154GHz(New), 3-77GHz and 1-82.7GHz, 1-84GHz CW gyrotrons.
- 4-evacuated and 2-non-evacuated 88.9mm corrugated waveguide system.
- 2- evacuated 31.75mm corrugated waveguide system.

4.6 MW (77 GHz >3 MW, 154GHz 0.9 MW. 82.7GHz) power was totally injected to LHD in the 2013 exp. campaign.

Achieved Operational Parameters of Three 77 GHz and One 154 GHz Gyrotrons

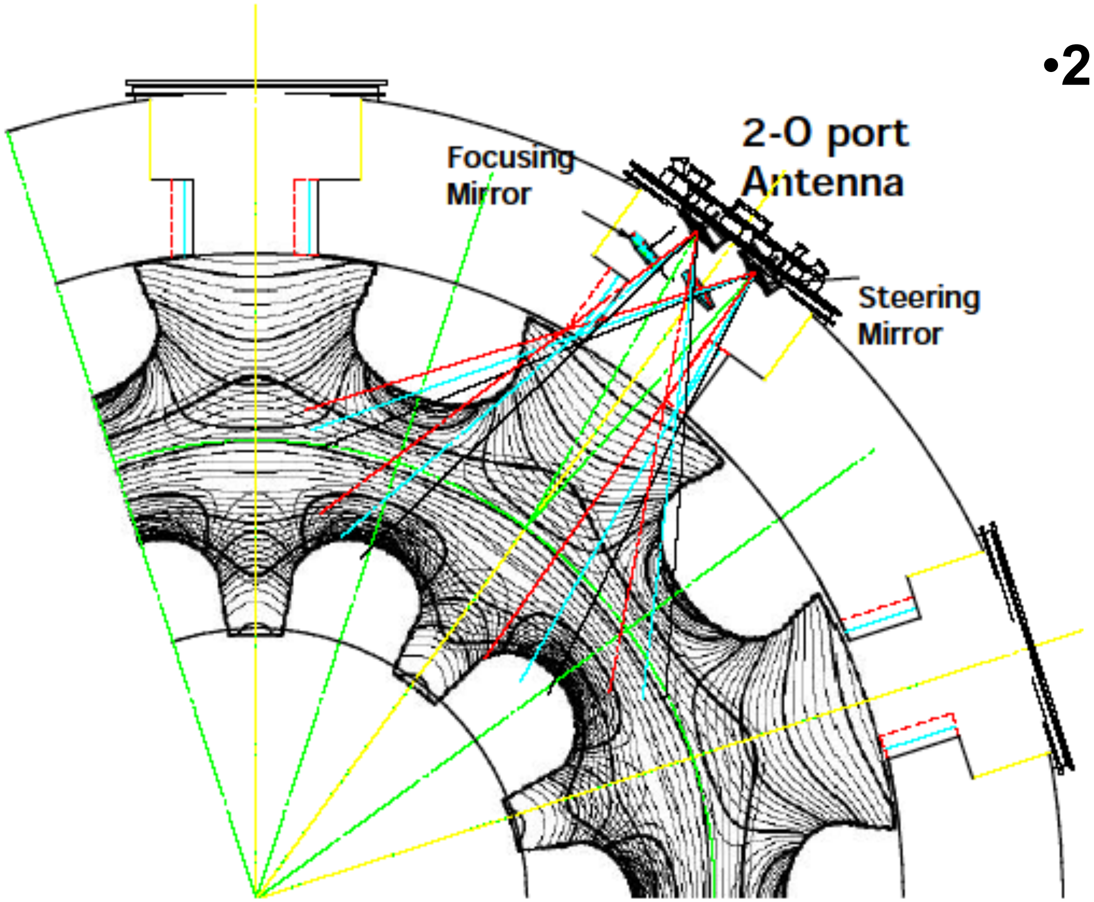
Tube No.	Specification	Pulse Operation <5 s	CW Operation
77GHz #1 R	1 MW/ 5 s 0.3 MW/ CW	1.01 MW (33.0 %) 5 s	0.13 MW (21.7 %) 935 s
	Two step V_A rise	1.41 MW (51.1 %) 0.2 s	
77GHz #2 (R)	1.2 MW/ 5 s 0.3 MW/ CW	1.02 MW (30.3 %) 5 s	*0.24 MW (30.8%) 1800 s *0.3 MW (31.3 %) 165 s
	Two step V_A rise	1.30 MW (43.8 %) 0.45 s	
77GHz #3	1.5 MW/ 2 s 1.2 MW/ 10 s 0.3 MW/ CW	1.53 MW (36.0 %) 1.6 s	*0.30 MW (34.2 %) 1800 s
	Two step V_A rise	1.87 MW (37.2 %) 0.1 s 1.78 MW (37.9 %) 1 s	
154GHz #1	1.0 MW/ 2 s 0.5 MW/ CW	1.015MW (27 %) short	0.35 MW (39.1 %) 1800 s
	Two step V_A rise	1.16 MW (36.9 %) 1.0 s	

Output Power (Efficiency) Pulse width

* improved tube

O-Antenna System (2O-port)

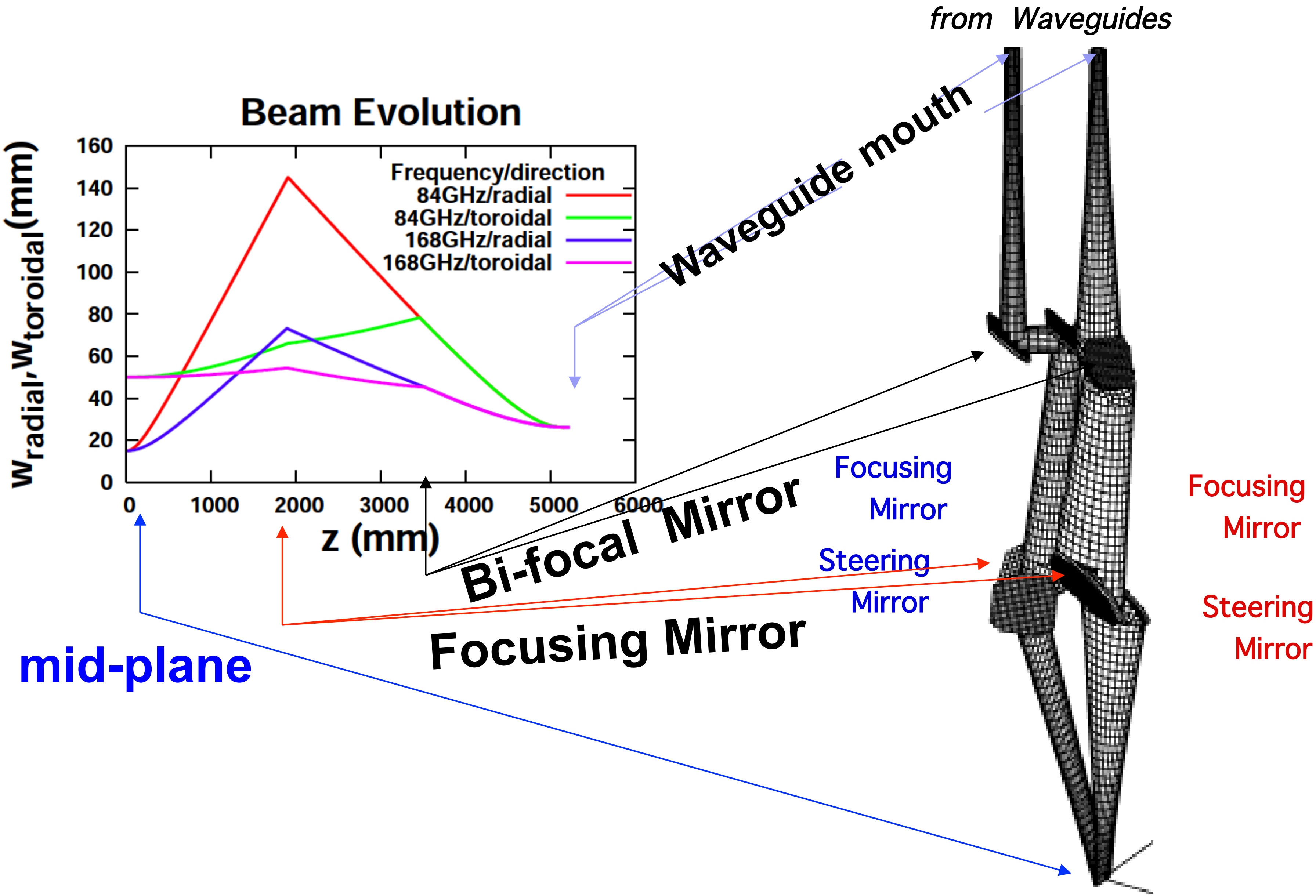
O-antenna is a laterally injection antenna from the outside of a horizontally elongated plasma cross-section



- **2 sets of**
  - **Focusing Mirror**
    - **Symmetric Gaussian Beam**
    - **35 mm waist size at plasma center**
  - **Steering Plane Mirror**
    - **Toroidally +/- 30 degree**
    - **Poloidally +/- 10 degree**

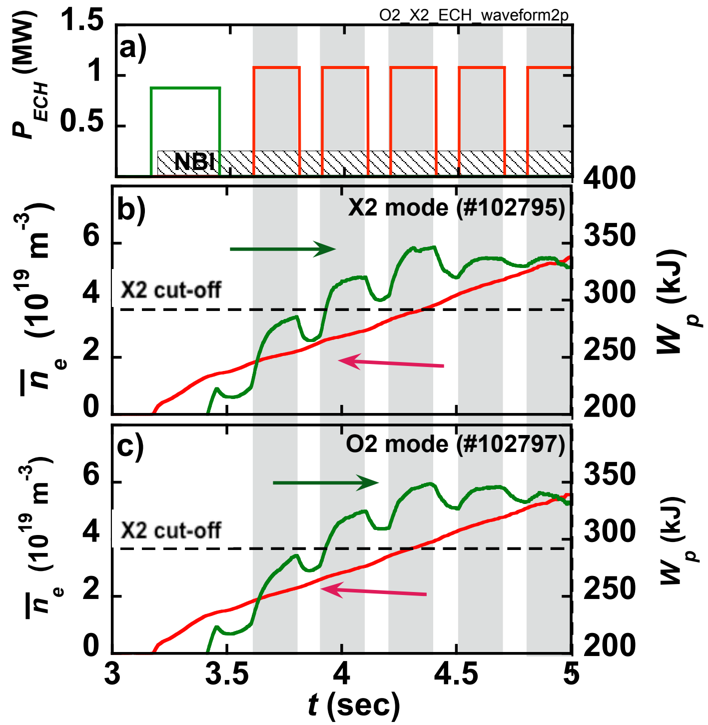
U-Antenna System (5.5U, 9.5U-port)

Elliptical Gaussian Beam Focusing Scheme



Efficient heating was observed for O2 mode heating above X2 cut-off density

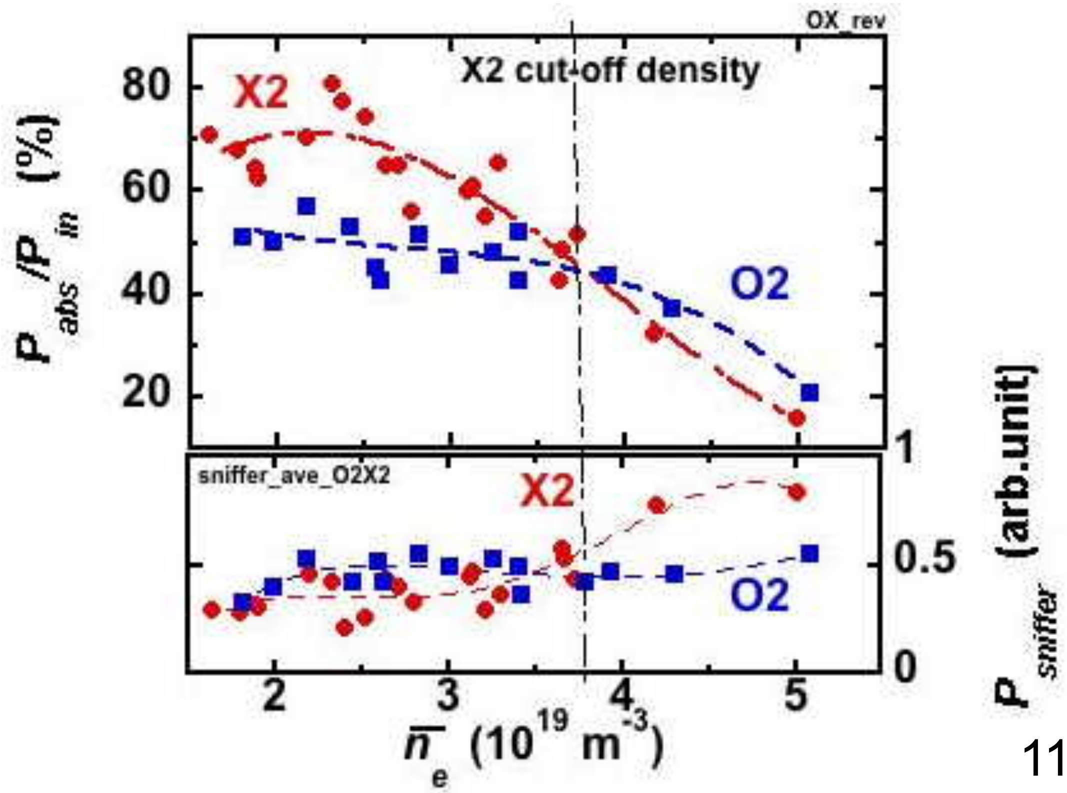
Procedure of the experiment:
Pulse train (0.2s ON, 0.1s OFF) injection from O-antenna during density ramp-up phase



Good O2 absorption above X2 cut-off density

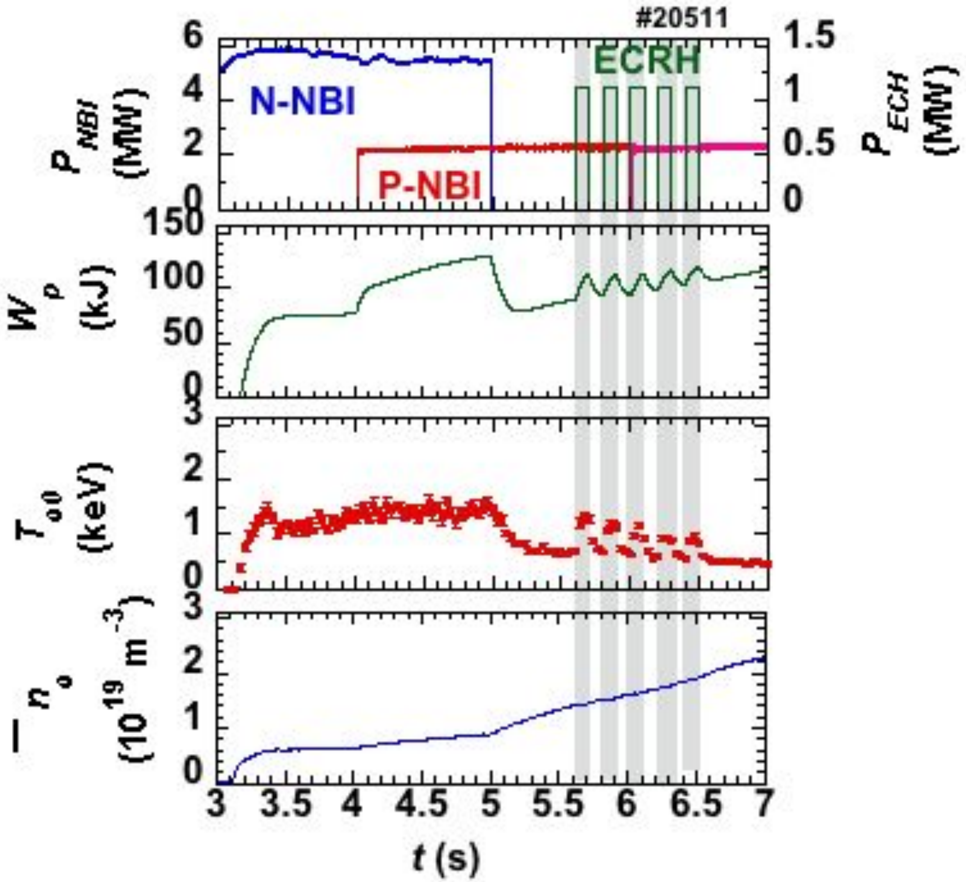
Dependence of absorption rate and scattered power on line-averaged density

Below X2 cut-off density:
X2 → 80% O2 → 50%
Above X2 cut-off density:
X2 → 20% O2 → ~40%



X3 Mode Heating Experiment

Time trace of the injection power and plasma parameters
R_{ax}=3.6 m, B_0= 0.95 T



- **The target plasma was produced by an NBI with negative ion sources (N-NBI, Energy~ 180 keV) and sustained by another NBI with positive ion sources (P-NBI, Energy~ 40 keV.**
- **During a density ramp-up phase, the X3 heating pulse train (0.1s ON and 0.1s OFF, 5 pulses) was injected.**
- **Absorption power was estimated by**

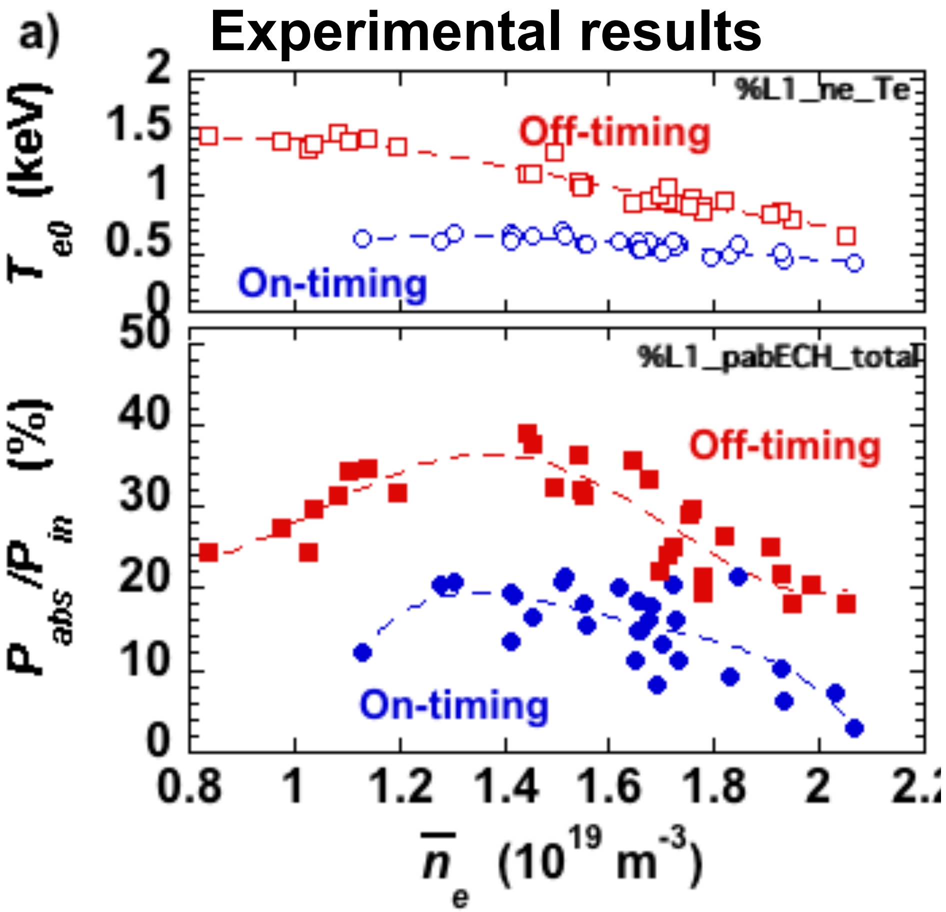
$$p_{abs} = \left(\frac{\mathrm{d}W_p}{\mathrm{d}t}\right)_{t=t_{on}+\delta} - \left(\frac{\mathrm{d}W_p}{\mathrm{d}t}\right)_{t=t_{on}-\delta}$$

- **Remarkable increaces are noticed in W_p and T_e**

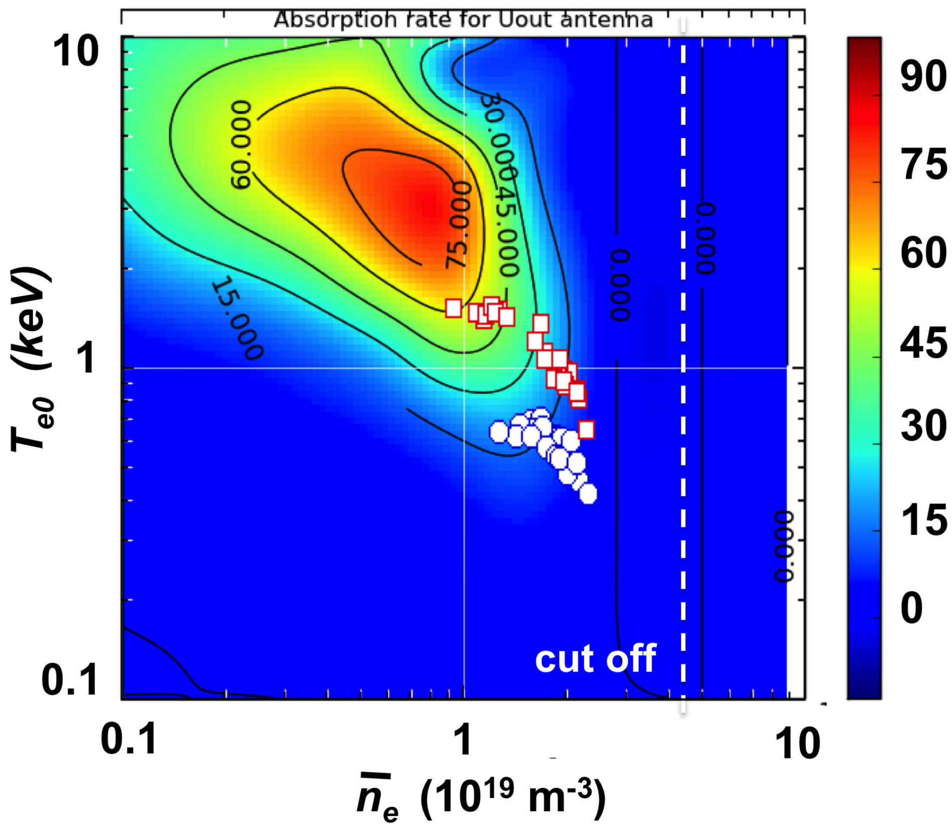
Density Dependence of X3 Absorption Rate - Experimental and Ray-Tracing Results -

Density and temperature dependence of absorption rates for U-antenna injection case

Experimental results



Ray-tracing calculation results

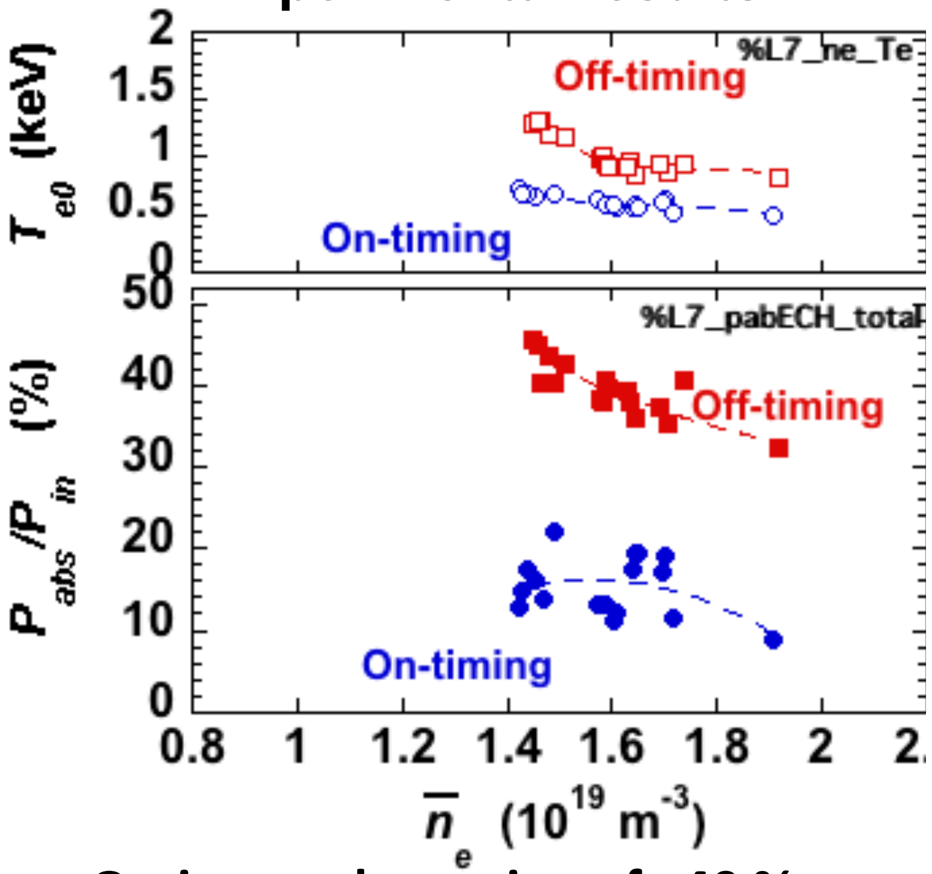


- Optimum absorption of ~40 % was attained around 1.5 × 10^{19} m^{-3}
- Ray-tracing results are well agreed with experimental ones when temperature change of target plasmas were considered.

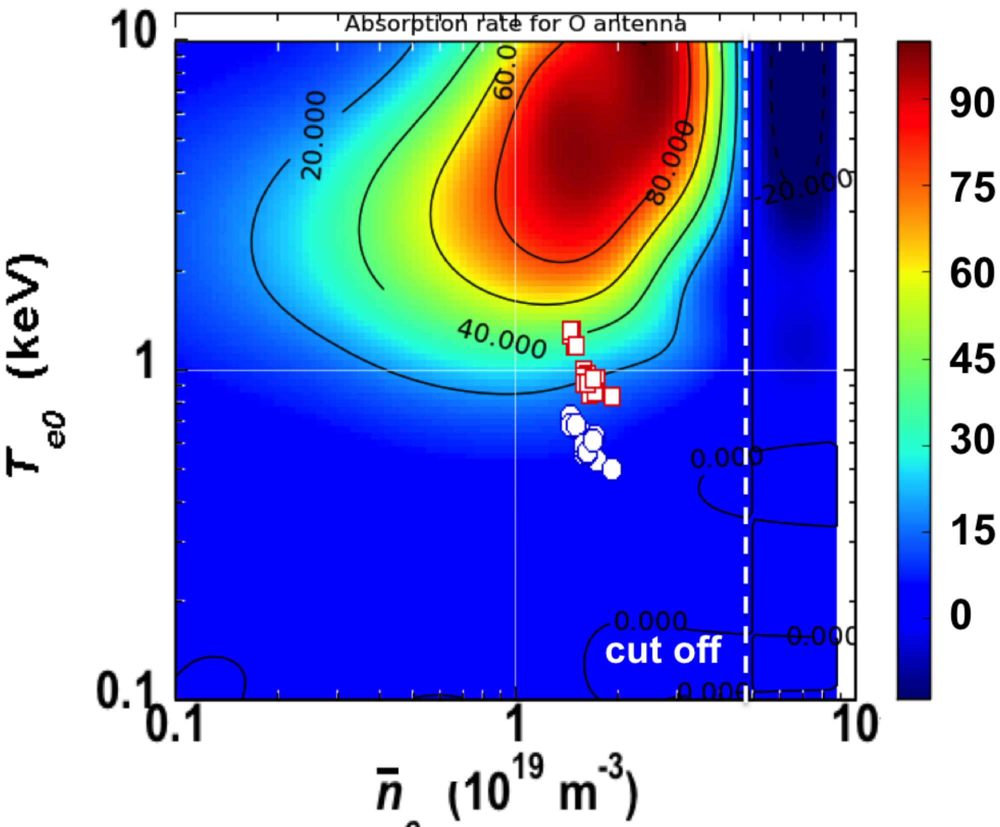
Density Dependence of X3 Absorption Rate - Experimental and Ray-Tracing Results -

Density and temperature dependence of absorption rates for O-antenna injection case

Experimental results



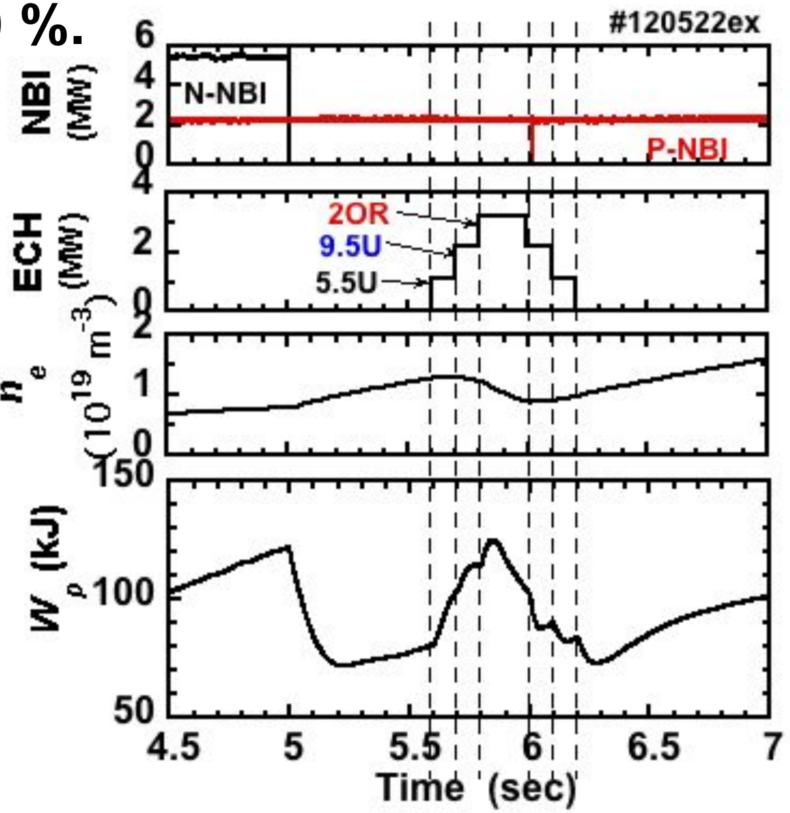
Ray-tracing calculation results

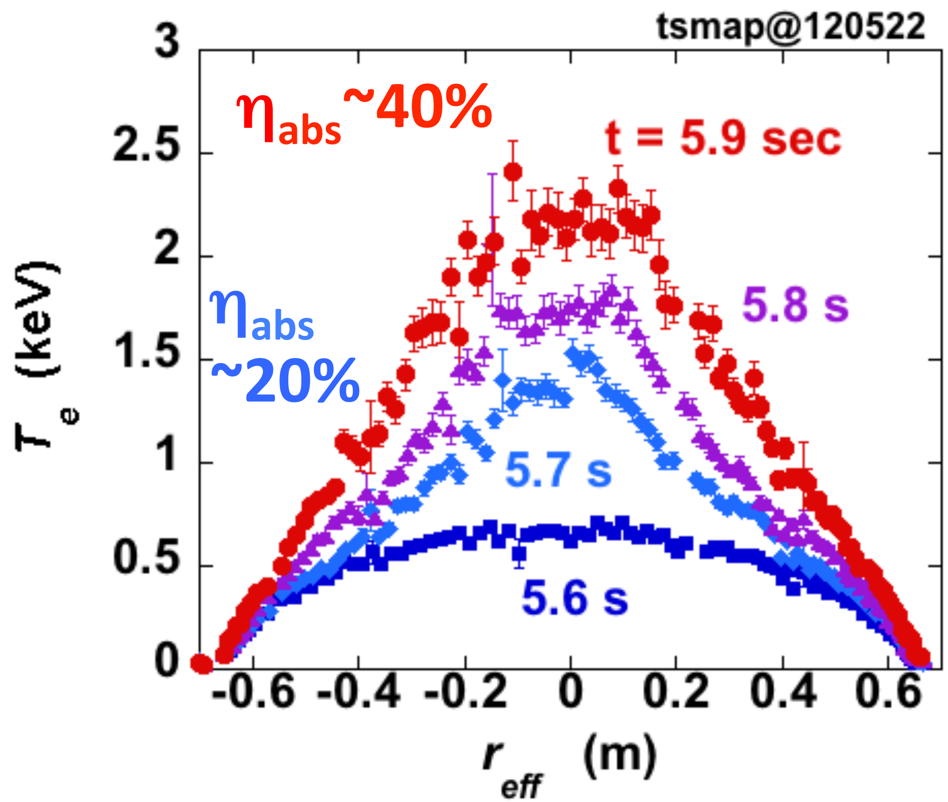


- **Optimum absorption of ~40 % was attained around 1.5 × 10^{19} m^{-3}**
- **Ray-tracing results are well agreed with experimental ones when temperature change of target plasmas were regarded.**

Clear central T_e increase was observed by stepwise injection of X3 mode

- Clear and significant increase of central electron temperature was observed when EC power was injected into a plasma sustained by a perpendicular NBI.
- ΔT_{e0} by stepwise power injection (about 3 MW Max.) from three gyrotrons achieved 1.6 keV.
- Absorption efficiency by the final antenna injection attained about 40 %.





Summary

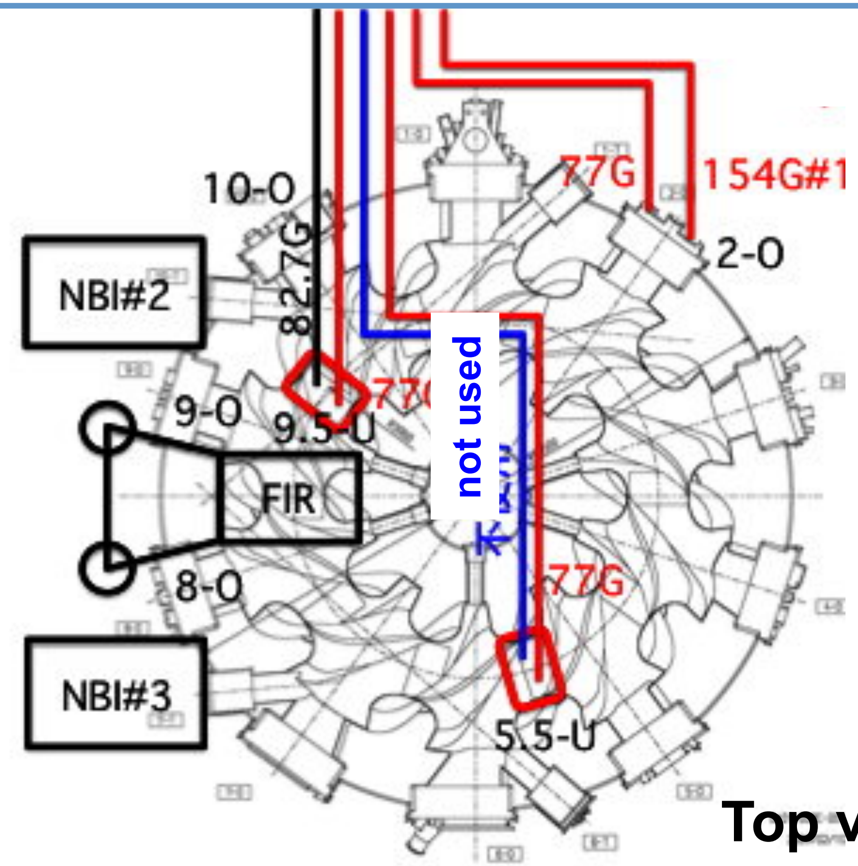
1. Heating characteristics for high harmonic EC heating (O2 and X3 modes) were experimentally investigated.
2. Magnetic and injection configuration could be optimized and analyzed by ray-trace (TRAVIS-Code) calculations.
3. O2 mode heating case:
   - Efficient O2-mode absorption were demonstrated above X2 cut-off density (3.7×10^{19} m^{-3}).
4. X3 mode heating case:
   - Clear and significant increase of central electron temperature was observed when EC power was injected into a plasma sustained by a perpendicular NBI.
   - Stepwise power injection (about 3 MW Max.) from three gyrotrons increased T_{e0} up to 3.5 times of the initial target plasma temperature of 0.6keV. Absorption efficiency by the final antenna injection attained about 40%.
5. Efficient O2 and X3-mode absorptions were attained , when
   (1) the EC beam is injected along the ECR over a long distance, and
   (2) injected through the saddle point of the magnetic field strength between two ECR layers.

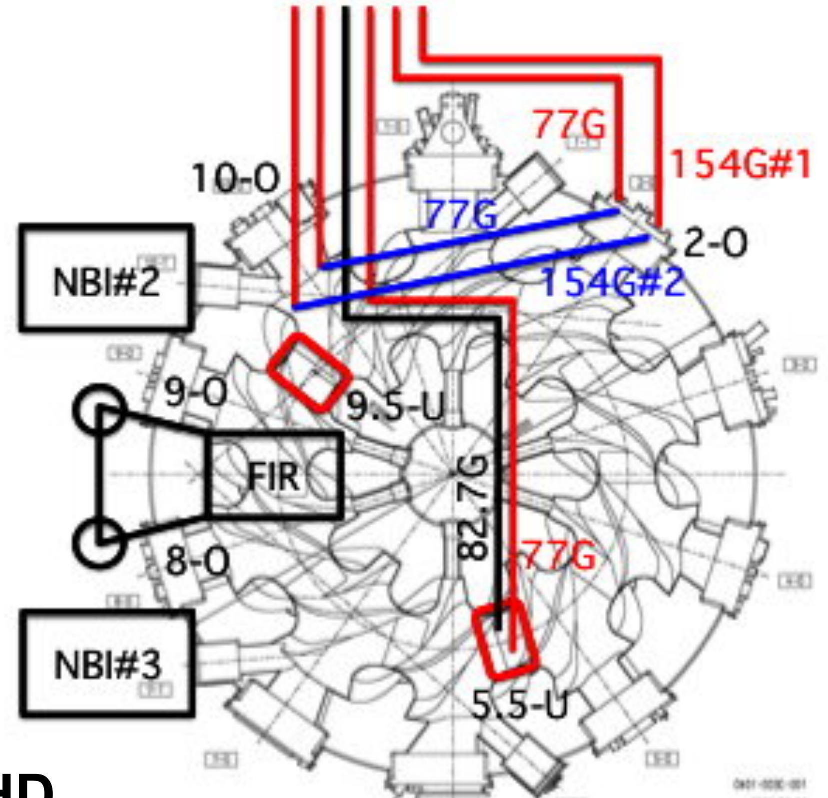
Upgrade of the ECRH System

- **2nd 154 GHz / 1.2 MW Gyrotron was manufactured, will be installed, tested and used for plasma heating**
- **Concentrate the antennas to O-port. Two → Four antennas**

Up to 2013
3 U-antennas: 77GHz × 2, 82.7GHz
2 O-antennas: 77GHz, 154GHz

From 2014
2 U-antennas: 77GHz, 82.7GHz
4 O-antennas: 77GHz × 2, 154GHz × 2





Top view of LHD