Overview of Low Aspect ratio Torus Experiment (LATE): Recent Results and Plans

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Outline

* Experimental Result

  Non-Inductive Formation of Spherical Tokamak by EBW

  Direct Measurement of EBW Wave Pattern

  (Guo et al., Plasma Phys. Control. Fusion 64 (2022) 035008)

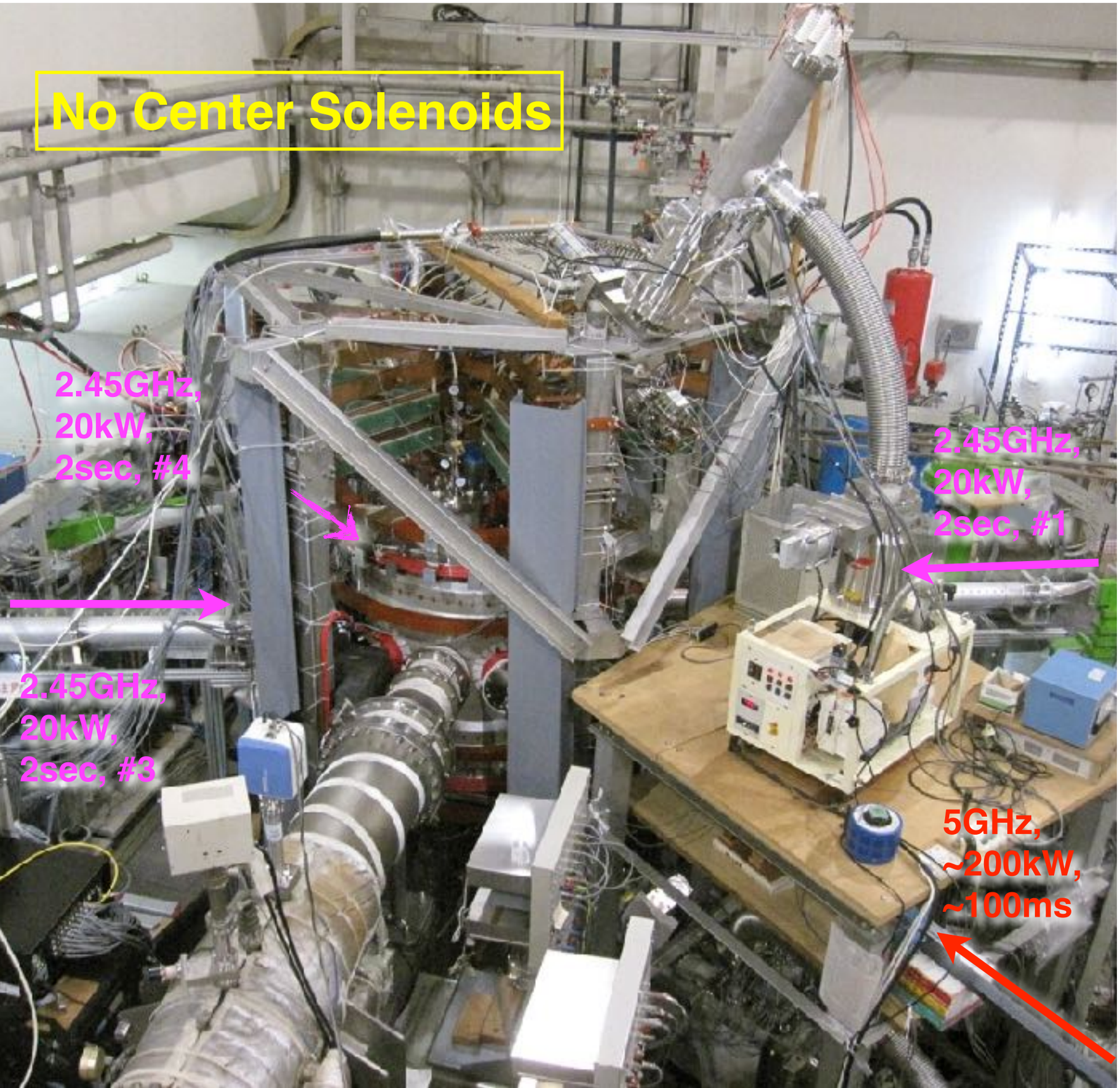
  (Guo et al., Plasma and Fusion Research 17 (2022) 1401024)

* Future Plan

  New Vacuum Vessel

  Development of Soft X-ray CT System

LATE Device



Cylindrical Vacuum Vessel :
- R = 5.7 ~ 50 cm
- Z = -50 ~ 50 cm
- A ≧ 1.24

Toroidal Field @ R = 25 cm
- Bt ≦ 1.6 kG, > 0.13 sec

Vertical Field @ R = 25 cm
- Bv ≦ 250 G, 2 sec

Microwave Sources :

5 GHz
- 200 kW, 0.1 sec
- 1 klystron

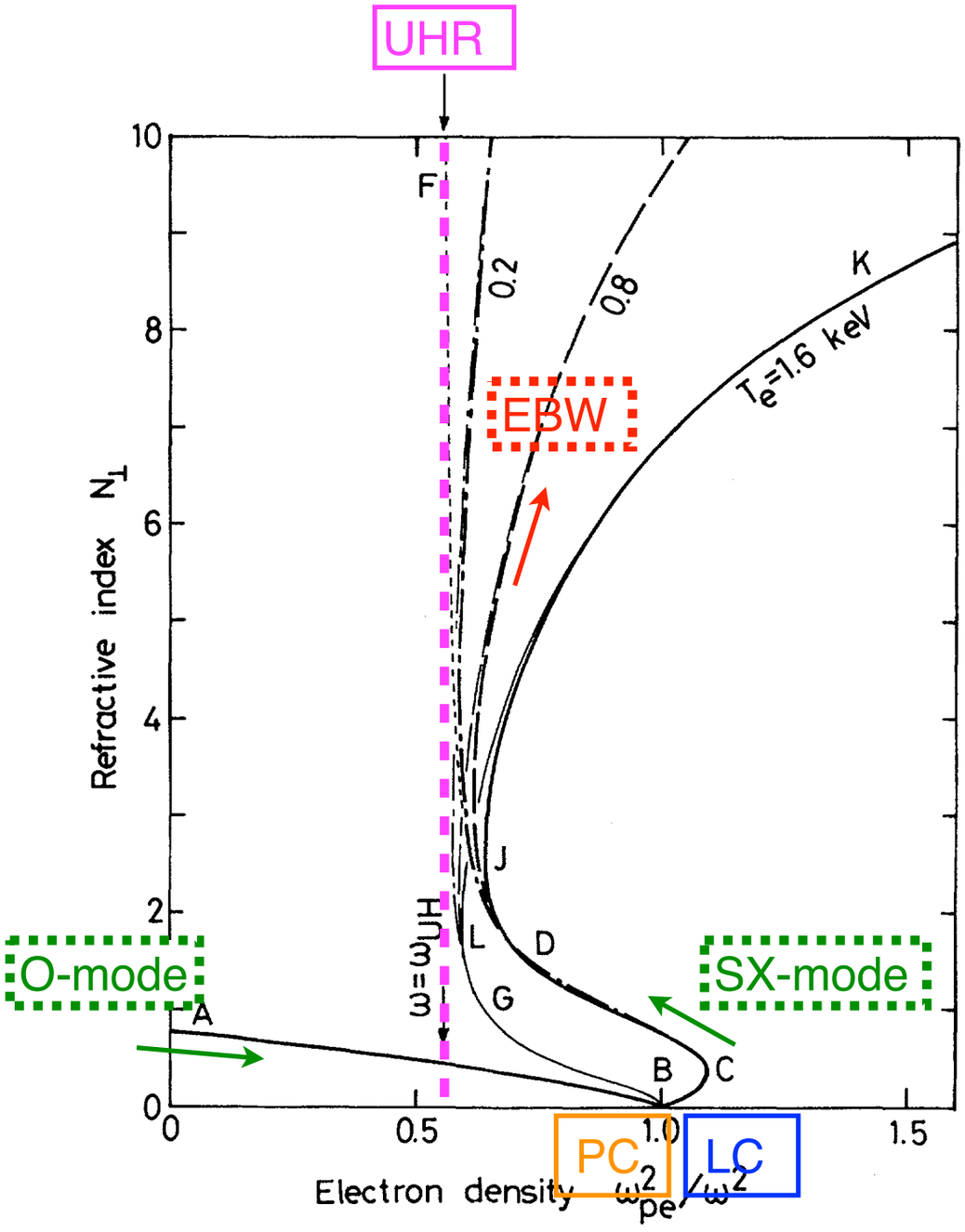
2.45 GHz
- 20 kW, 2 sec,
- 4 magnetrons

Diagnostics :
- Magnetic Measurement
  - (17 Flux Loops, 46 MPs)
- 4 ch 70 GHz Interferometers
- Fast CCD Camera
- Visible Light Spectrometer
- 4 ch HX PHA system
- HX pin-hole camera
- AXUV pin-hole camera
- HIBP system (Rb+, 20kV)

EBW Excitation via O-X-B Mode Conversion

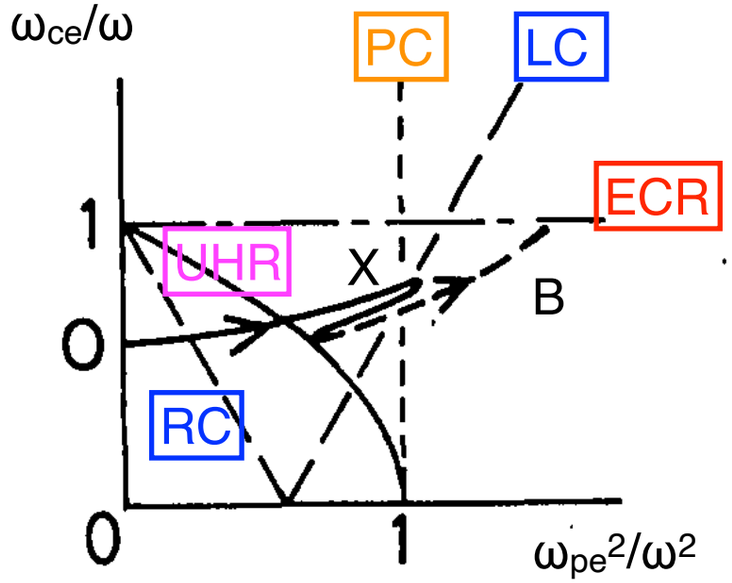
Maekawa et al., Phys. Rev. Lett. 40 (1978) 1379
Maekawa et al., J. Phys. Soc. Jpn. 48 (1980) 247

Outboard (low field) side injection
in the case of rather long density scale length

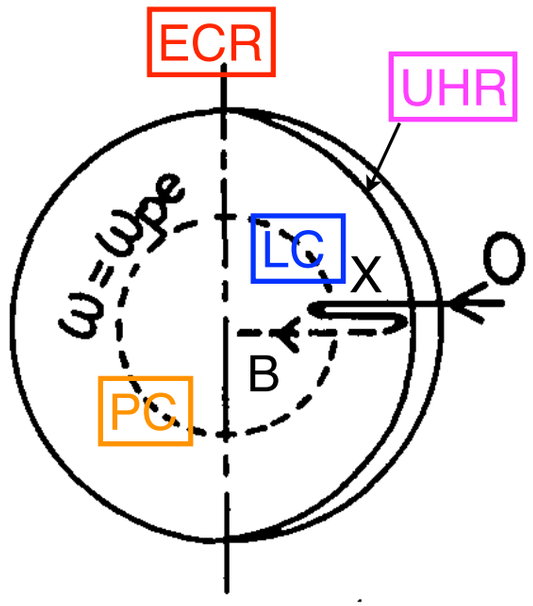


$$N_{\parallel \mathrm{opt}} = \sqrt{\frac{\Omega_e}{\omega + \Omega_e}}$$

(CMA diagram)

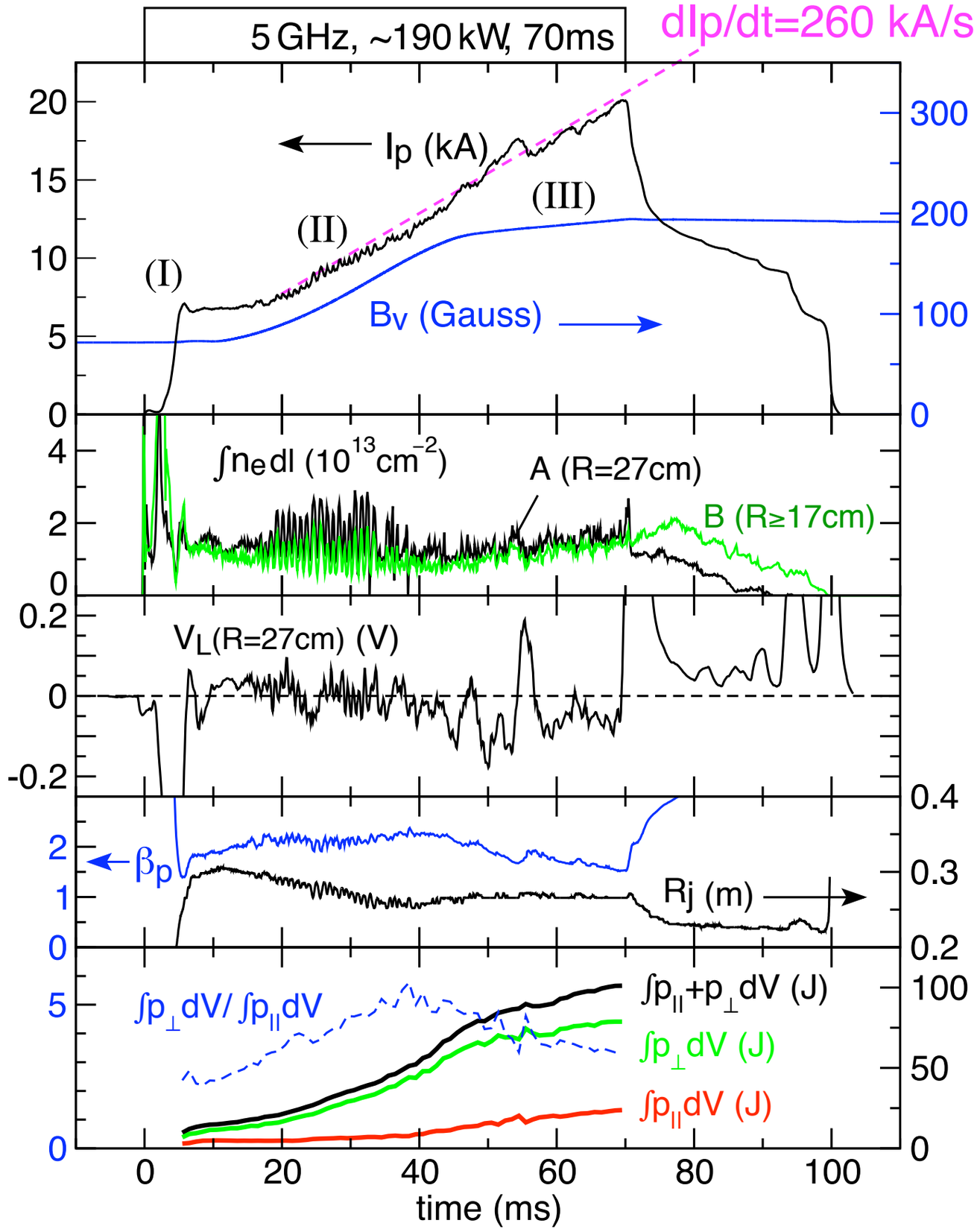


(tokamak : poloidal cross section)



Formation of ST by ECH/ECCD

M. Uchida et al., Phys. Rev. Lett. 104 (2010) 065001.



Discharge evolves in three stages

(I) Closed flux surfaces is formed under steady Bv.

(II) Ip ramps up with a ramp of Bv.

(III) Ip still ramps up even with a very slow ramp of Bv.

→ Negative V_L(~ -0.1V) by induction of Ip ramp.

βp ~1.5 due to tail electrons

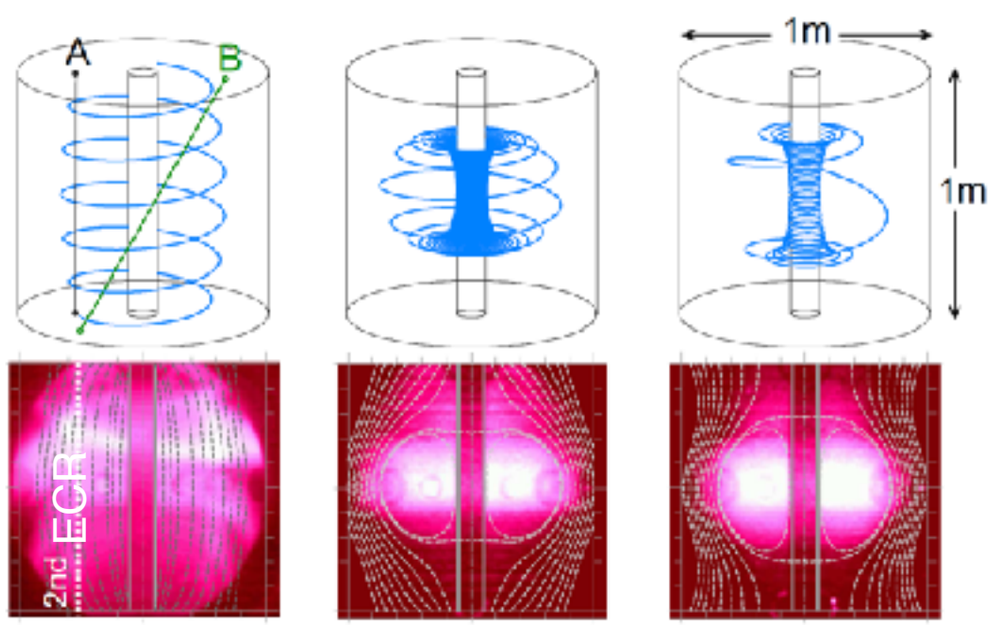
(βp-bulk ~ 0.05) when Ip = 20kA

→ tail electrons' energy ~ 100 keV

line-averaged density > plasma cutoff density

$n_e \sim 4 \times 10^{17}$ m^{-3} ~ 1.3 x n_c (3.1×10^{17} m^{-3})

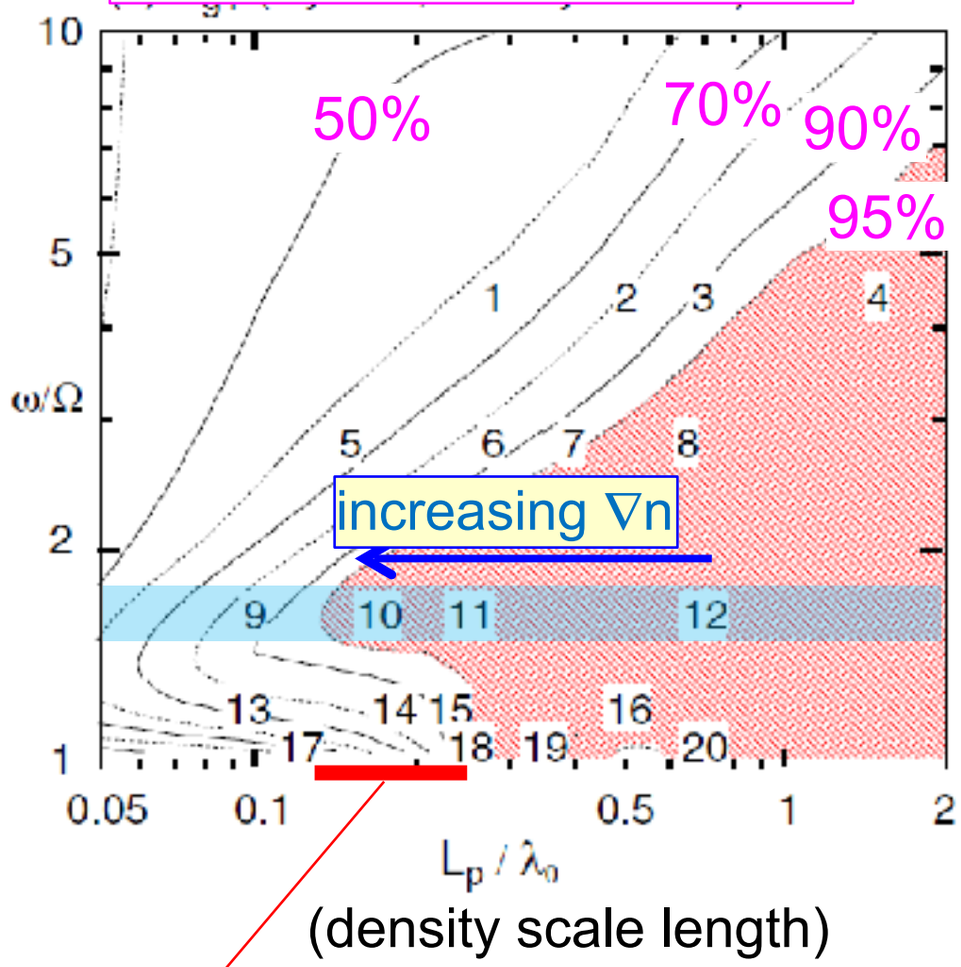
→ ECCD by EBW with high N//



Ip=0 Ip=7 kA Ip=20 kA

Optimal Injection Polarization for Mode Conversion to EBW

Conversion rate of optimal injection mode

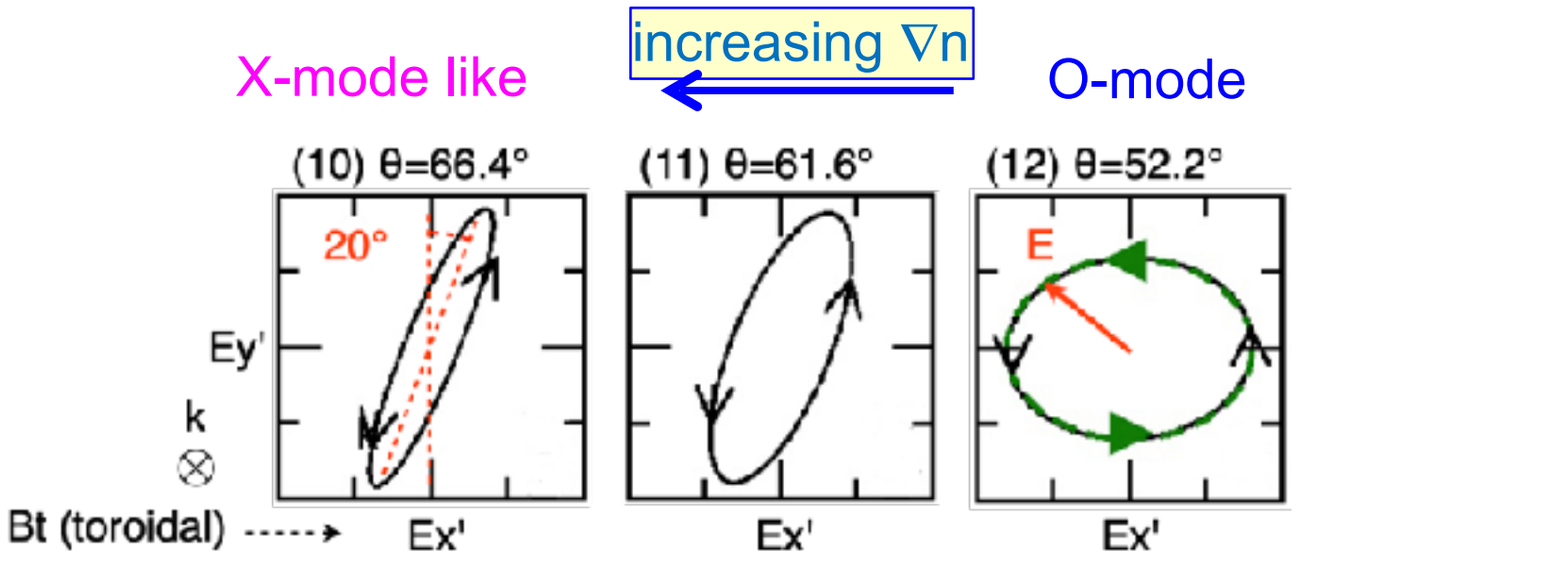


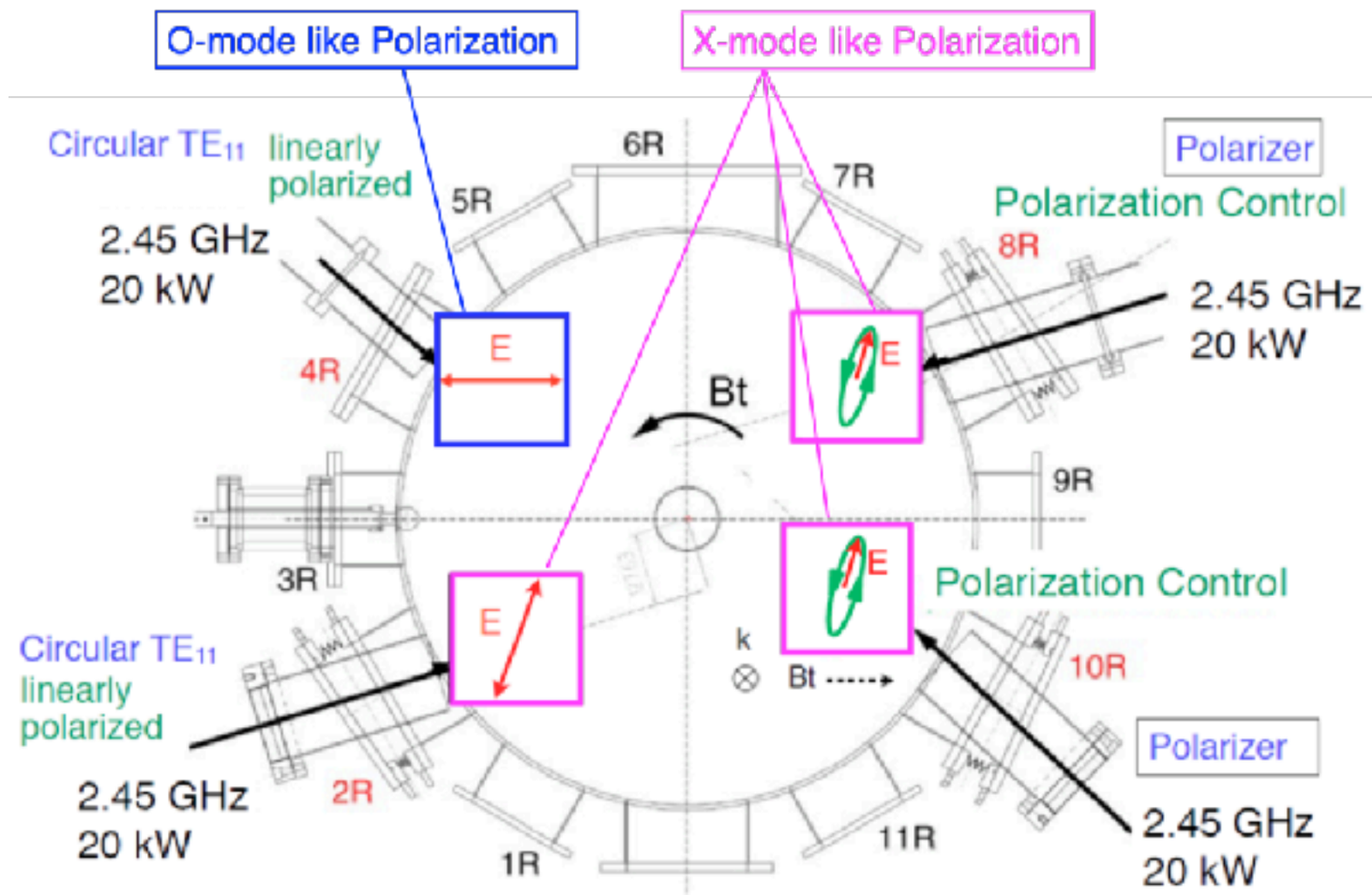
(density scale length)

Final stage at Ip ~ 10kA

[H. Igami, et.al., PPCF 48 573(2006)]

Optimal injection polarization

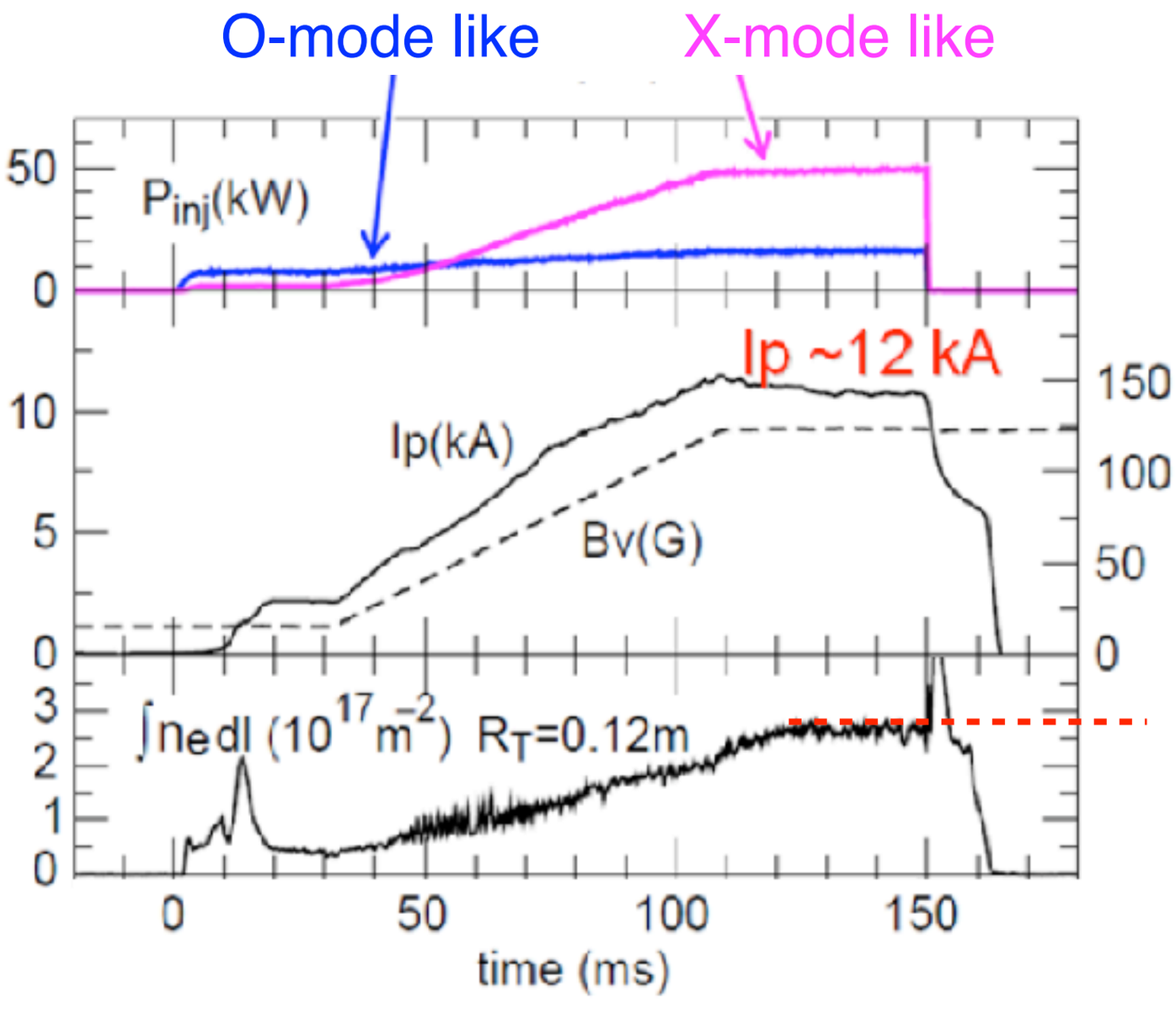


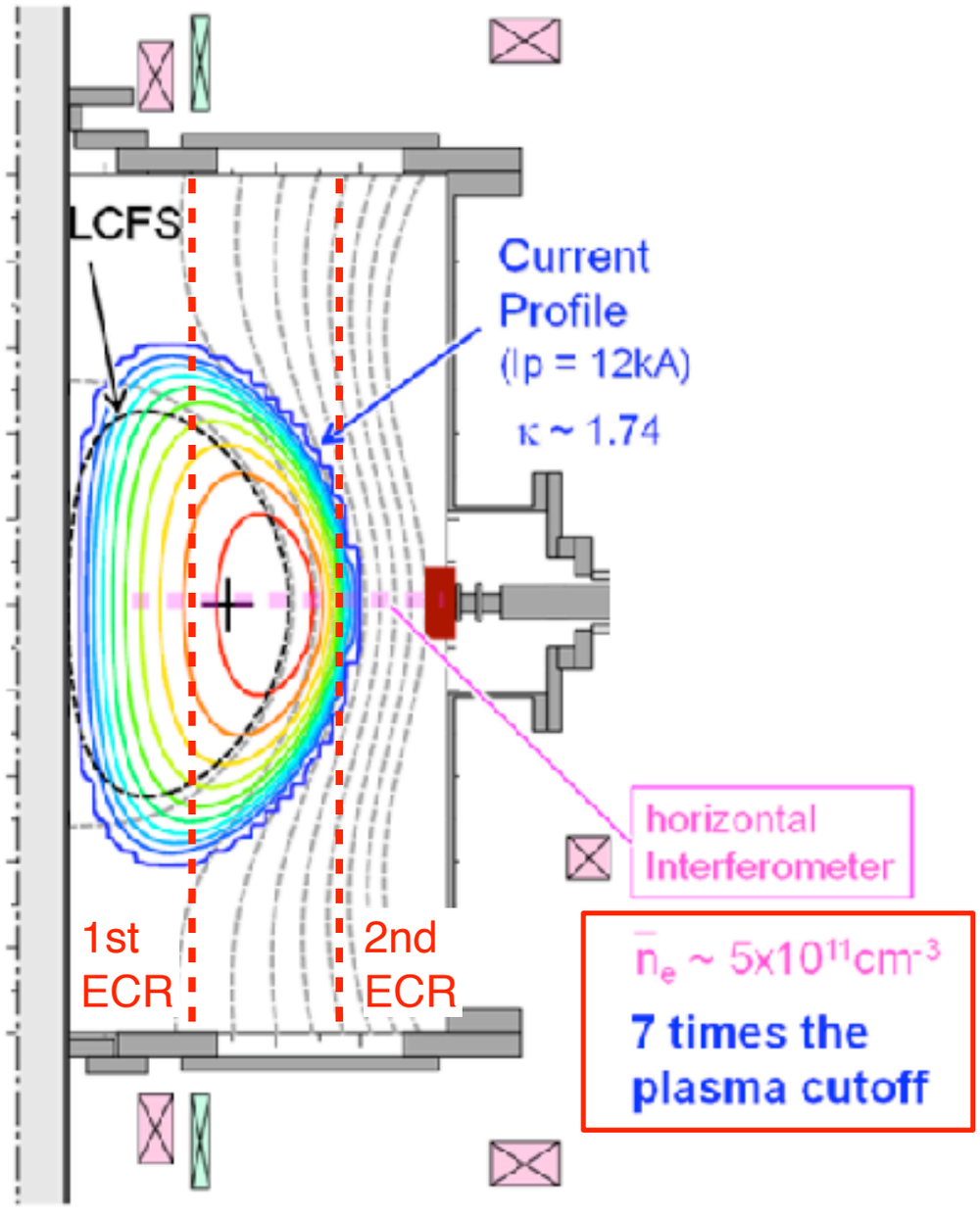


Production of Highly Overdense ST Plasma

A highly overdense ST plasma is produced when the UHR layer located between the fundamental and the second ECR layer and EBW is excited at the first propagation band.

By increasing X-mode component as the density increases, plasma current increases up to 12 kA (~20% increment), while the density is nearly the same.





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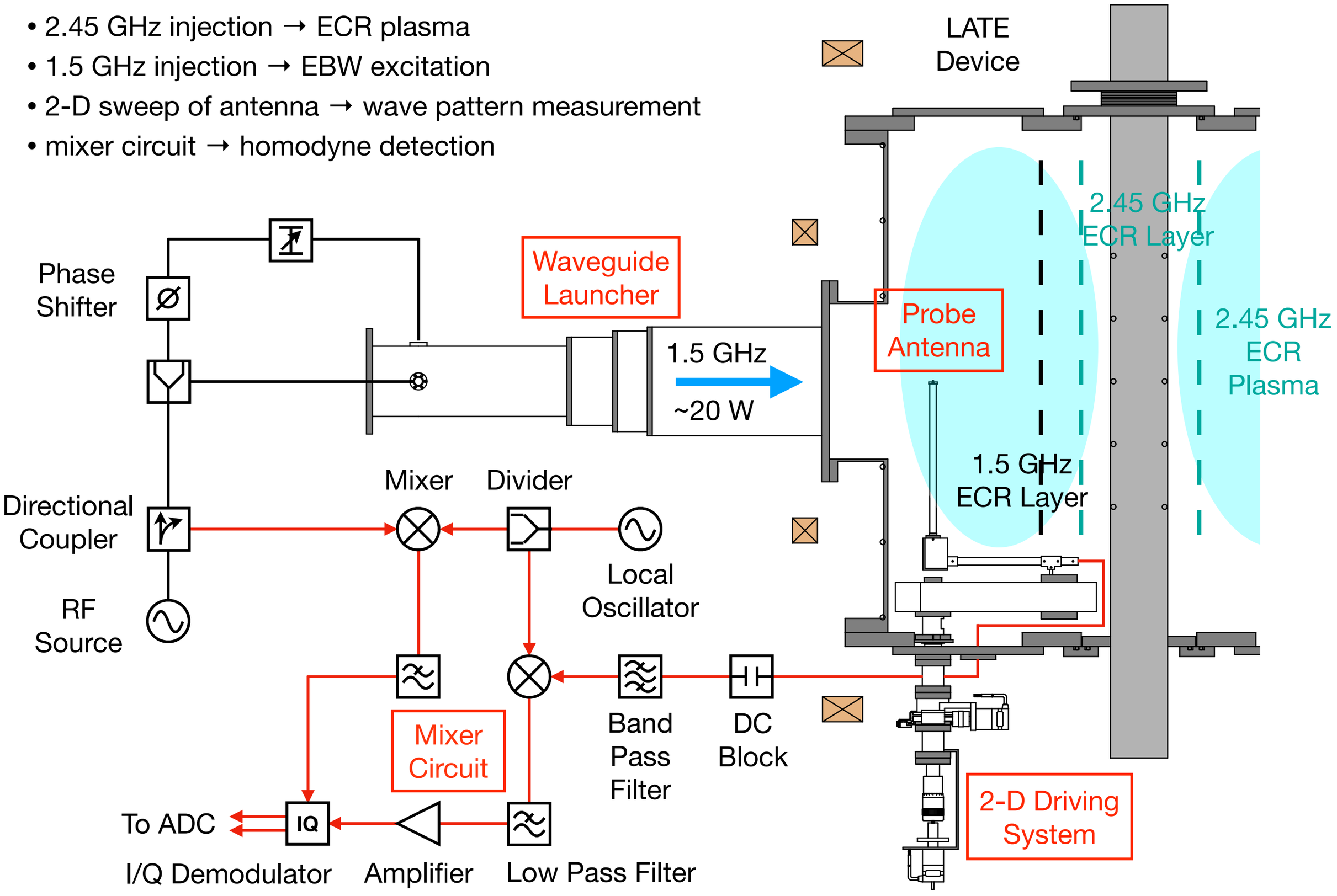
New Vacuum Vessel

Development of Soft X-ray CT System

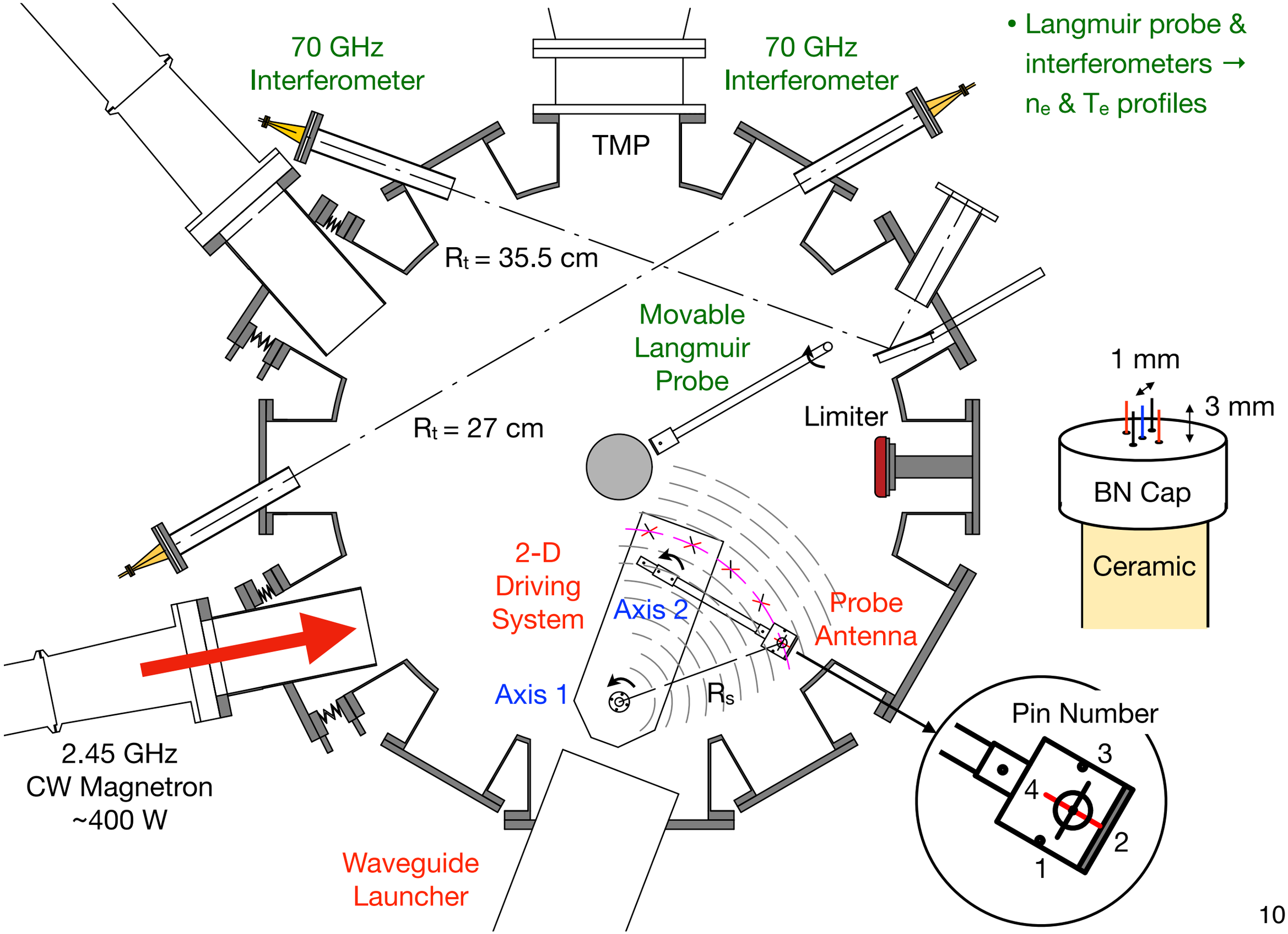
Excitation and Detection System (Side View)

- 2.45 GHz injection → ECR plasma
- 1.5 GHz injection → EBW excitation
- 2-D sweep of antenna → wave pattern measurement
- mixer circuit → homodyne detection



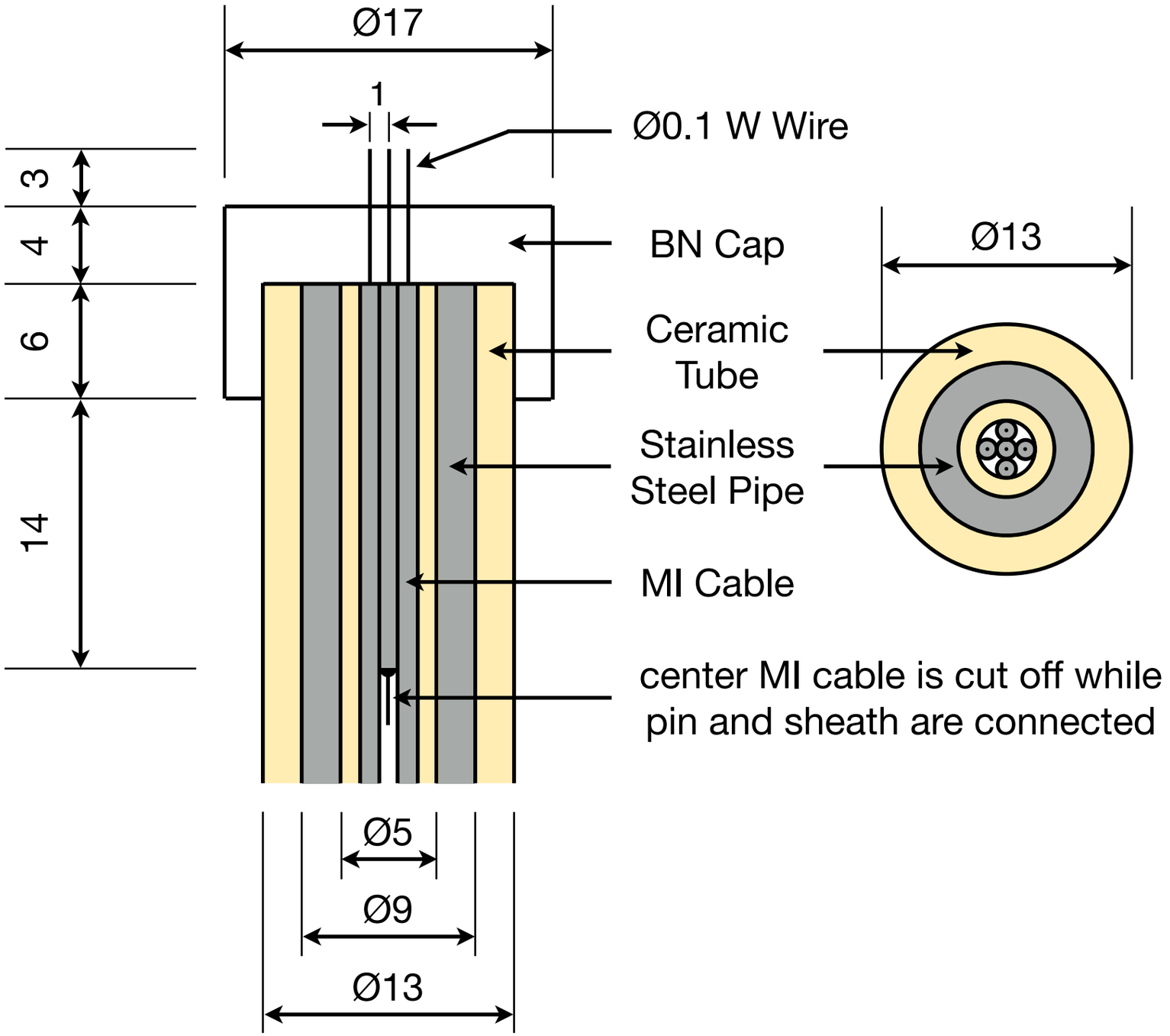
Excitation and Detection System (Top View)

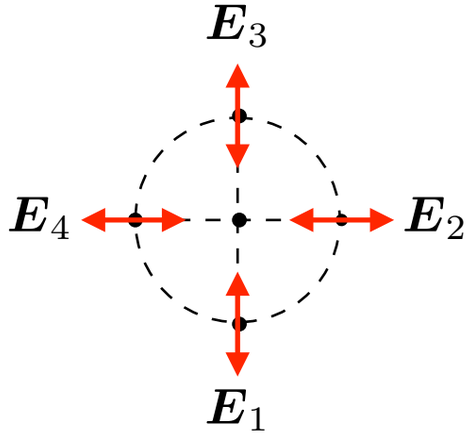
- Langmuir probe & interferometers → n_e & T_e profiles



5 Pin-Type Probe Antenna

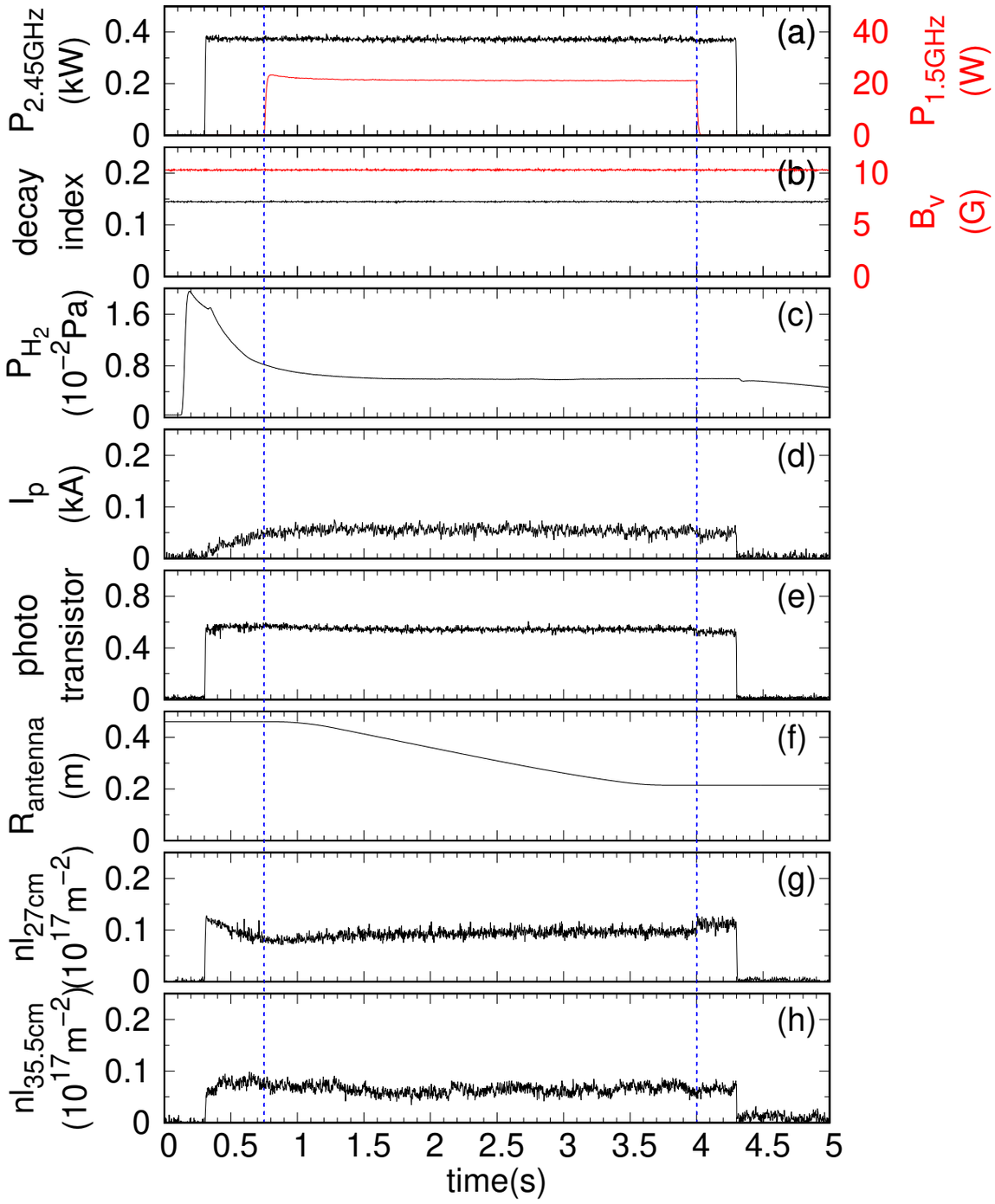
- five-pin type, firstly used in similar experiments
- potential difference between center pin and corner pin is measured
- highly sensitive to short-wavelength (mm-level) electrostatic waves

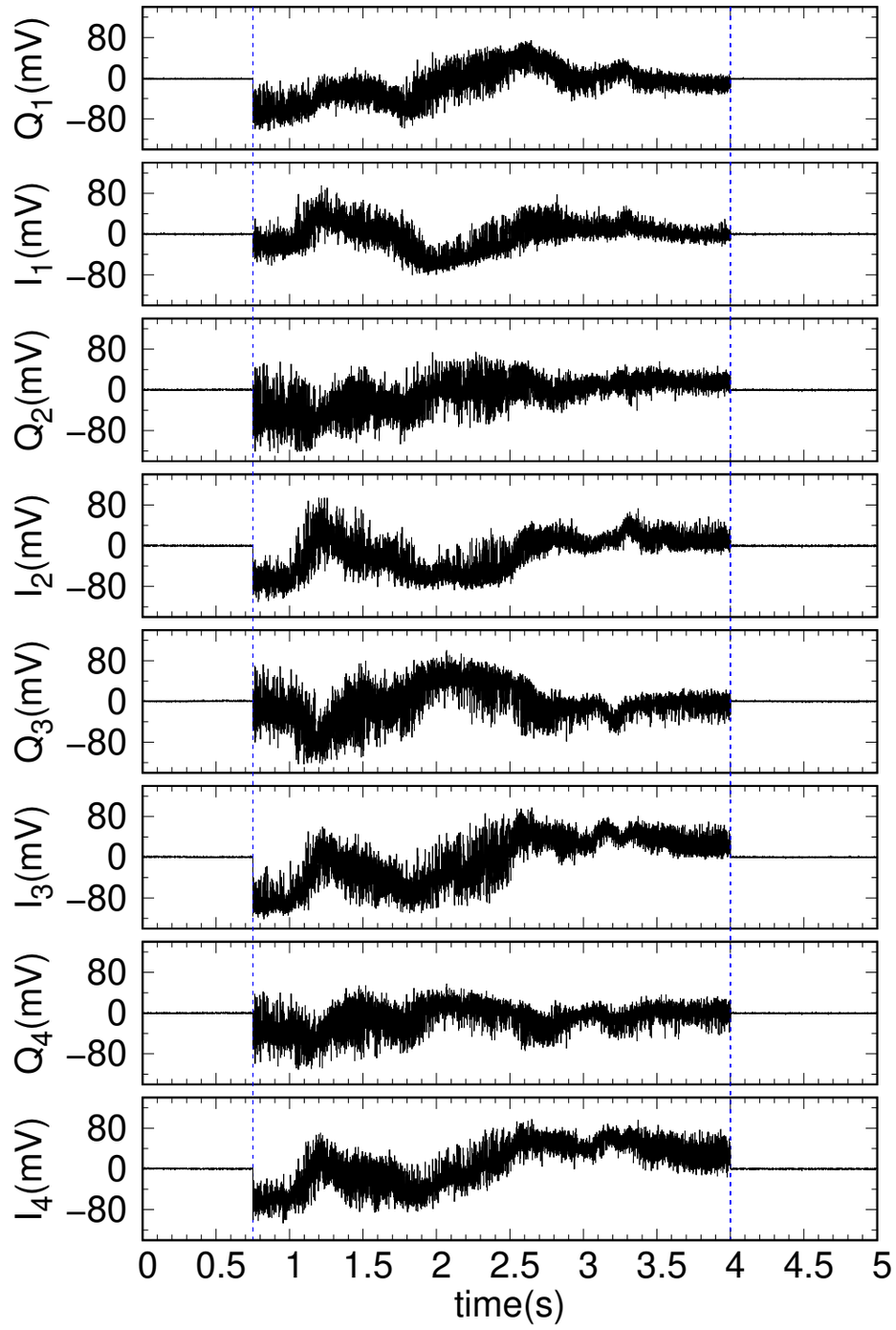




Discharge Waveform and I/Q Signals (O-Mode Injection)

- steady state → 0.75 ~ 4.0 s
- R_s = 220 mm, S/N ratio ~ 20



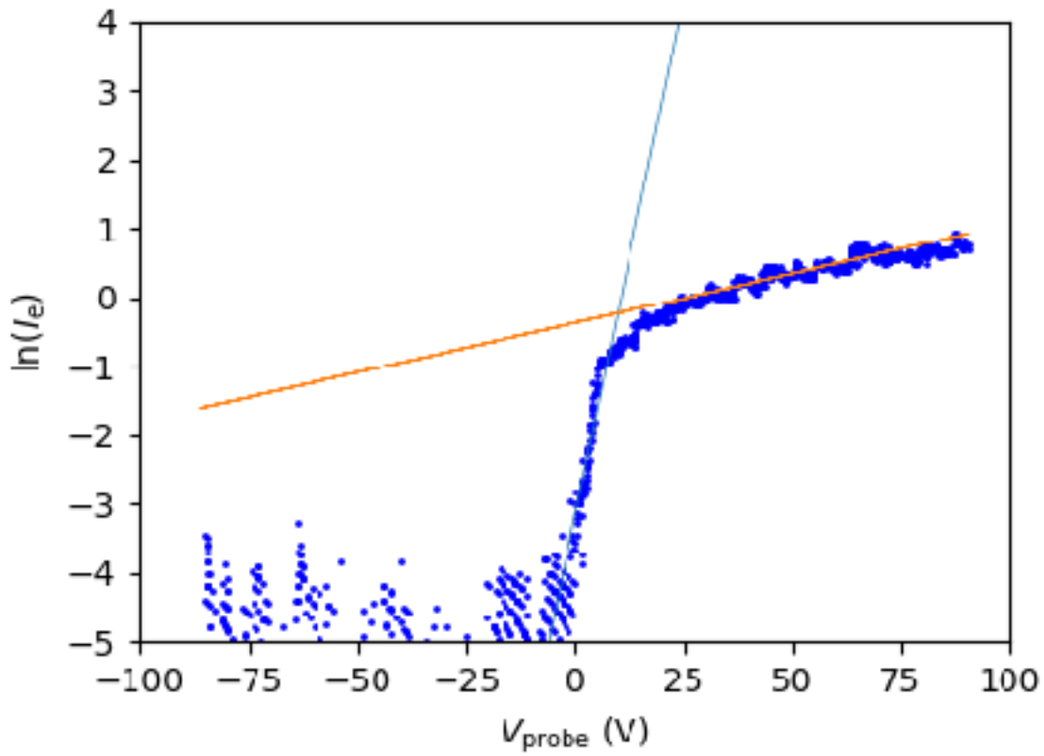


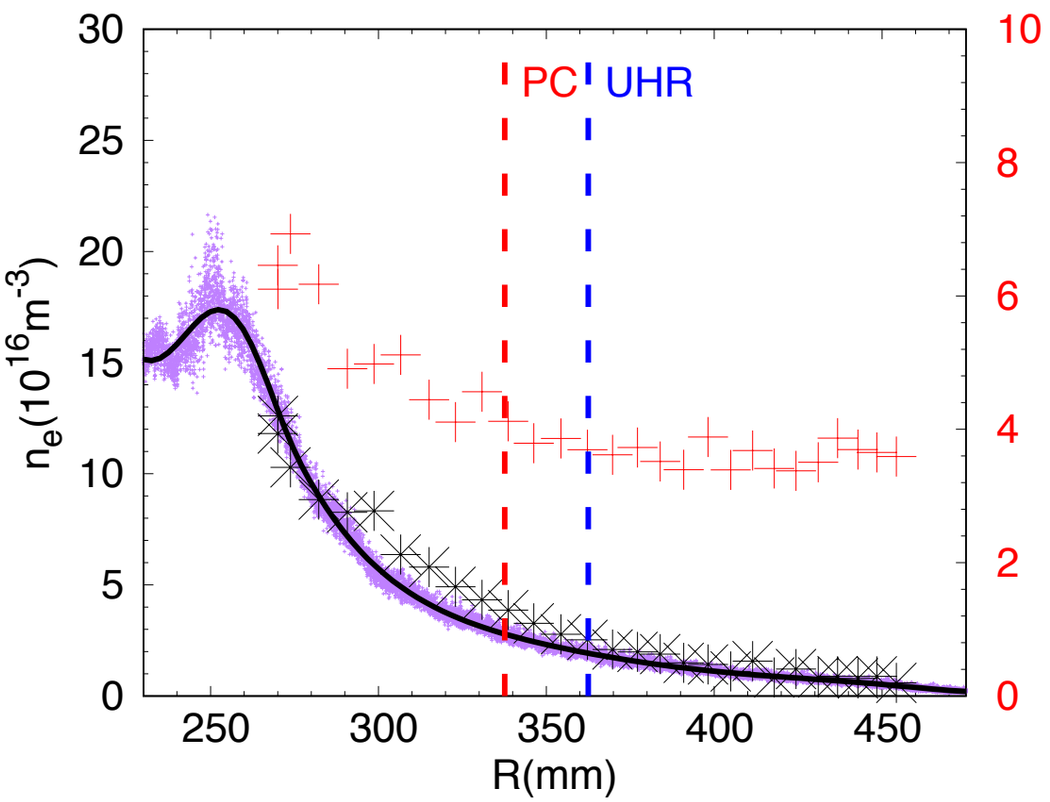
Density & Temperature Profiles

- density and temperature points from I-V characteristics
  - sawtooth voltage, fixed position during 1 shot

- density profile from ion saturation current profile and fitting curve
  - constant negative voltage, sweeping during 1 shot

$$nl_{R_\mathrm{t}} = 2 \times \int_0^{\sqrt{R_0^2 - R_\mathrm{t}^2}} \mathrm{factor} \times f\left(\sqrt{x^2 + R_\mathrm{t}^2}\right) \mathrm{d}x \qquad \mathrm{factor} = 10.7 \times 10^{16} \mathrm{m}^{-3}/\mathrm{mA}$$



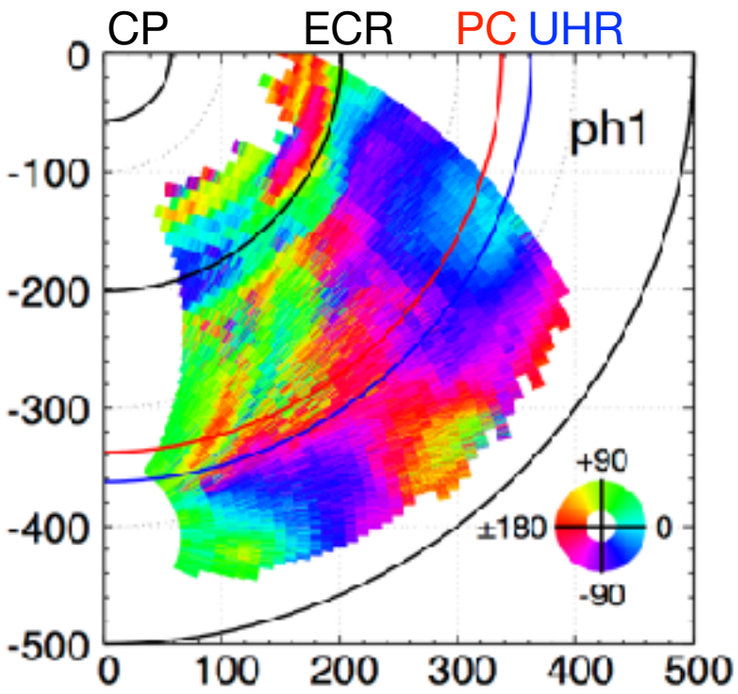


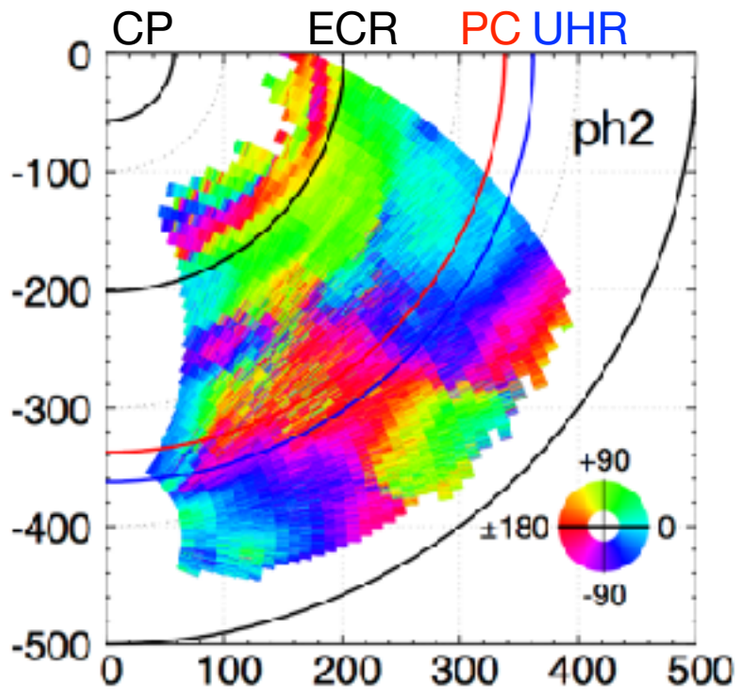
- overdense plasma for 1.5 GHz microwave
- low electron temperature

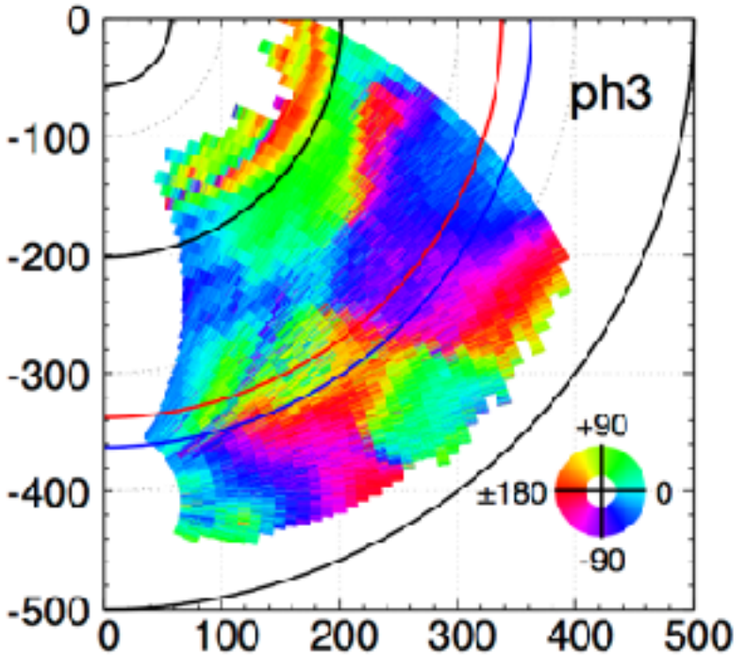
  → decrease EBW wavelength, increase collisional damping rate, protect probe antenna

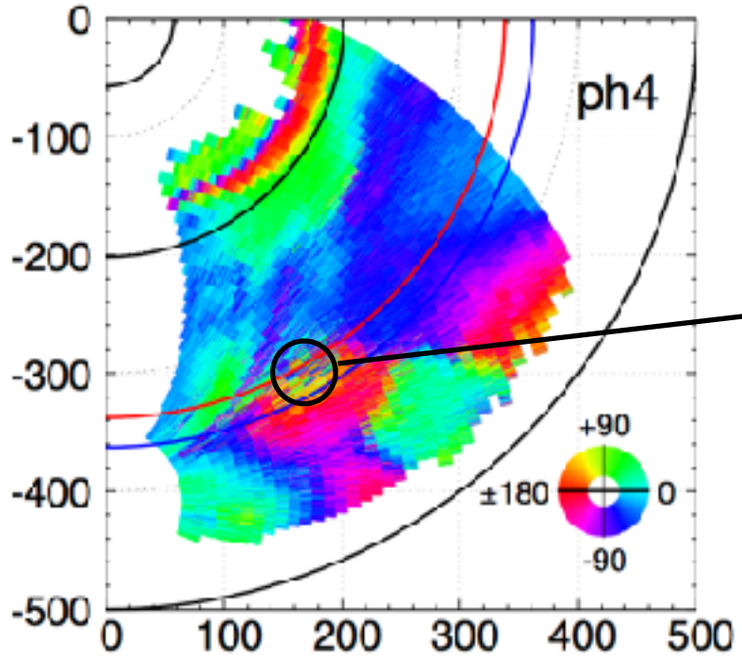
2-D Wave Pattern of Phase (O-Mode Injection)

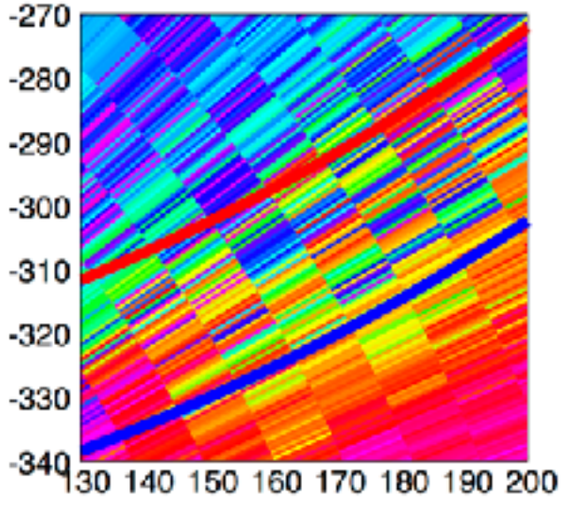
- **rapid phase change pattern** is observed for pin 4
- **localized** near UHR layer





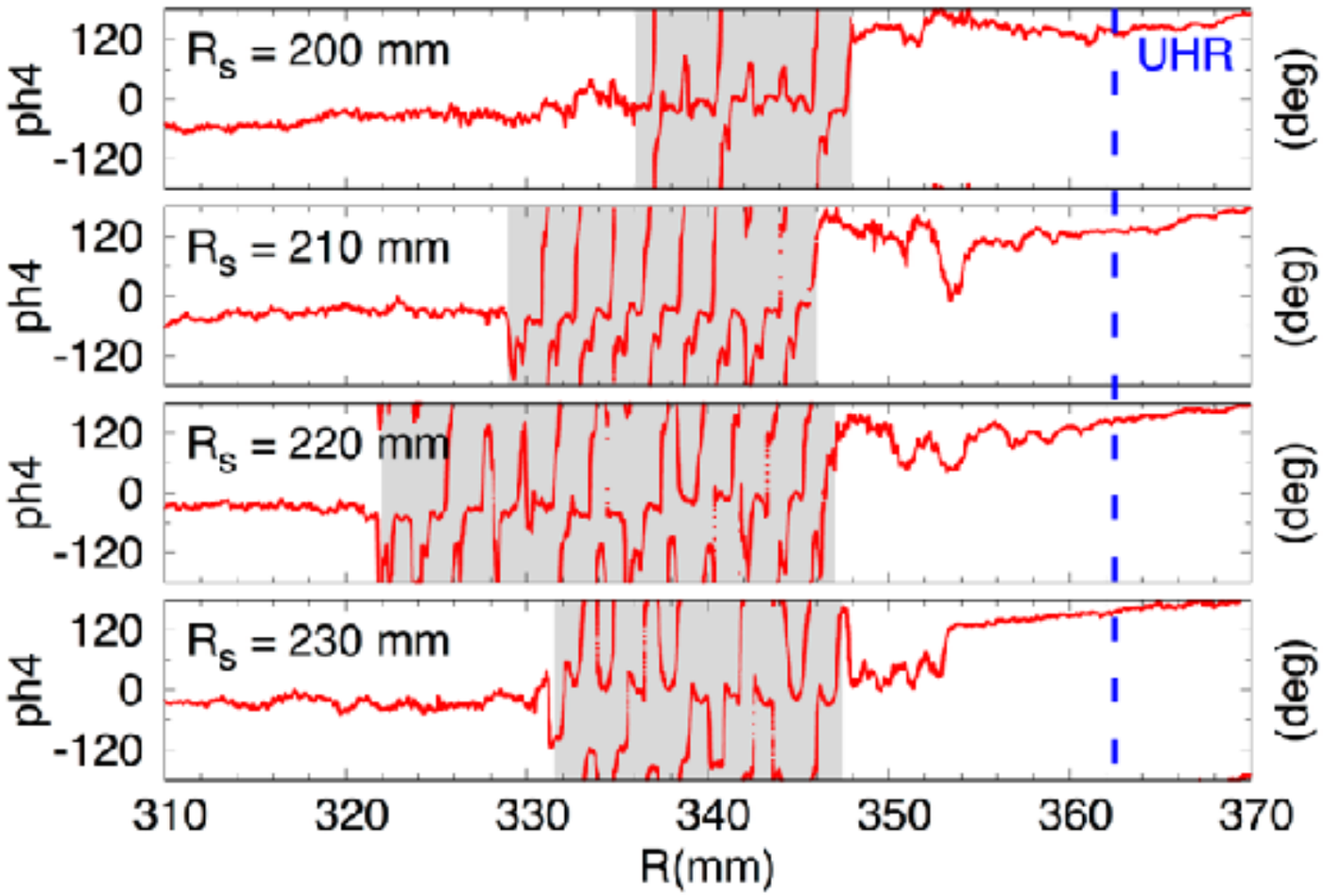






1-D Wave Pattern of Phase (O-Mode Injection)

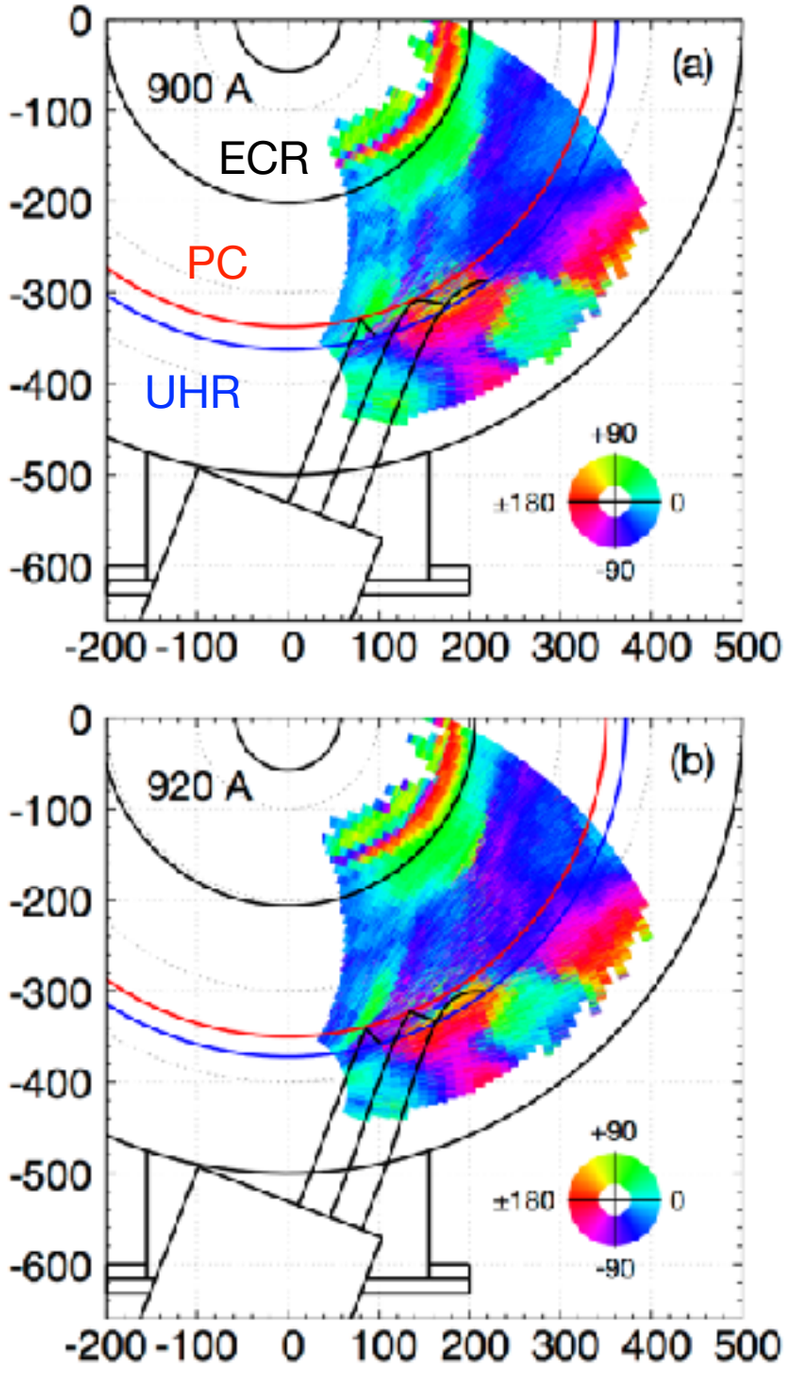
- rapid phase change pattern → **short wavelength (~2 mm)**
- phase decreases when moving inside (high field side) → **backward wave**
- pin 4 direction is almost same as antenna moving direction → **electrostatic**

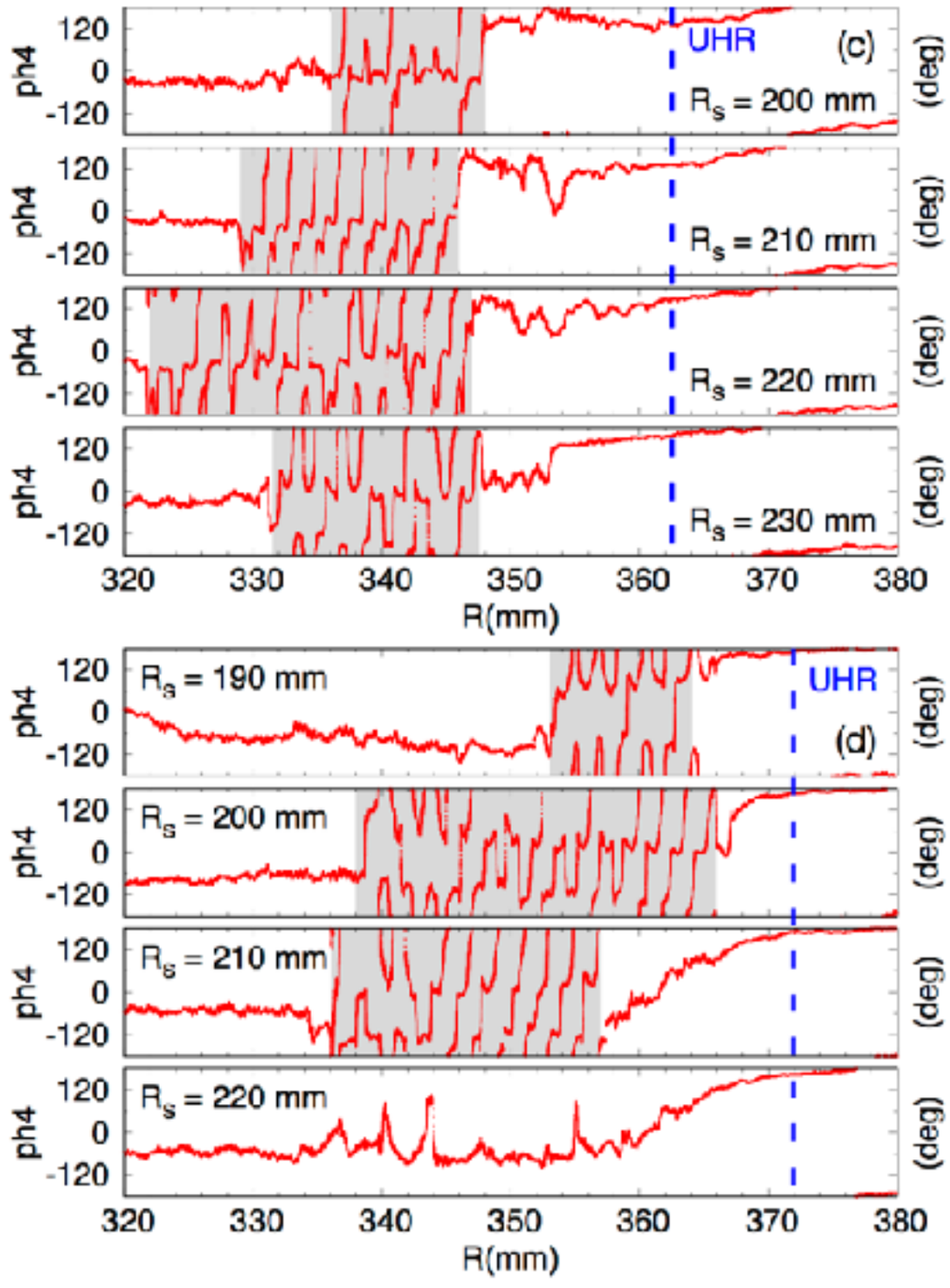


- **EBW-like wave pattern** (first-time direct detection in torus plasma)
- only appears in a localized region (3 x 3.5 cm) near UHR layer

B_t Adjustment (O-Mode Injection)

- position and size of short-wavelength region have changed, but still localized



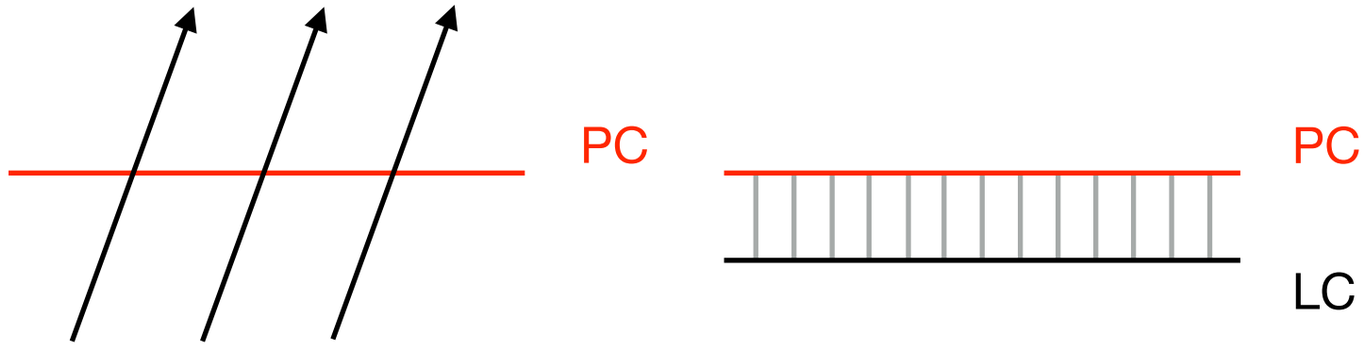


Localized Observation

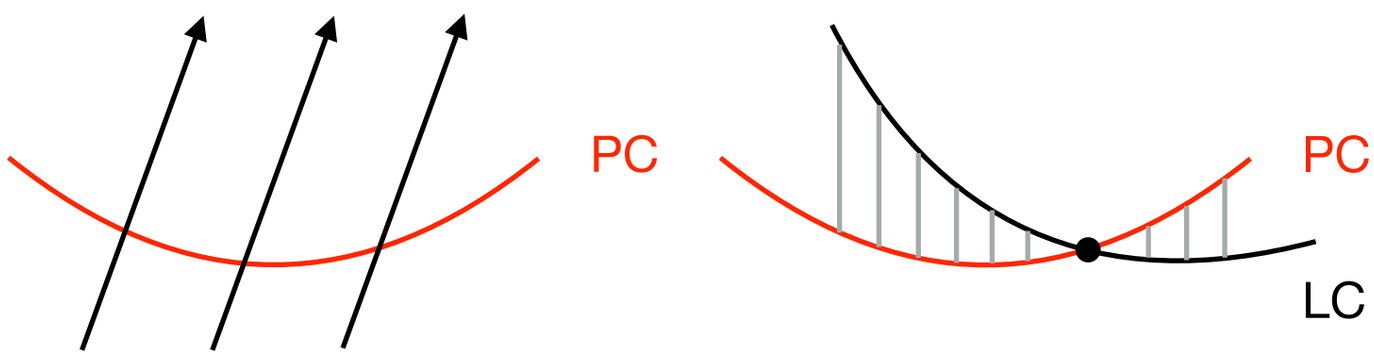
- toroidally localized
  - PC and LC

$$\omega = \omega_{\mathrm{p}} \qquad \omega = \omega_{\mathrm{L}} = \frac{1}{2}\left[\left(\omega_{\mathrm{c}}^2 + \frac{4\omega_{\mathrm{p}}^2}{1 - N_z^2}\right)^{1/2} - \omega_{\mathrm{c}}\right]$$

  - two layers are parallel in 1-D case



- wave N_z have a wide distribution on PC layer due to its curvature in 2-D case
- LC layer becomes a curve and there is an **intersection point** between PC and LC
- O-X mode conversion efficiency is high near the intersection point
- total conversion efficiency is dependent on **wave energy spatial distribution** and **evanescent region shape**



$$\omega_{\mathrm{p}} = \omega_{\mathrm{L}}$$

$$N_z \sim 0.611$$

Localized Observation

- radially localized
  - generalized EBW dispersion function (Pesic, 1984)

$$1+\frac{1}{k^2\lambda_{\mathrm{D}}^2}\times\frac{1+z_0\sum_{\mathrm{n}=-\infty}^{\infty}\mathrm{e}^{-\mu}I_{\mathrm{n}}(\mu)Z(z_{\mathrm{n}})}{1+\mathrm{i}z_{\mathrm{c}}\sum_{\mathrm{n}=-\infty}^{\infty}\mathrm{e}^{-\mu}I_{\mathrm{n}}(\mu)Z(z_{\mathrm{n}})}=0$$

$$k=(k_z^2+k_\perp^2)^{1/2}\qquad\lambda_{\mathrm{D}}=v_{\mathrm{th}}/\sqrt{2}\omega_{\mathrm{p}}$$

$$z_{\mathrm{n}}=(\omega+i\nu-\mathrm{n}\omega_{\mathrm{c}})/k_z v_{\mathrm{th}}\qquad z_{\mathrm{c}}=\nu/k_z v_{\mathrm{th}}\qquad\mu=0.5k_\perp^2 v_{\mathrm{th}}^2/\omega_{\mathrm{c}}^2$$

$$N_z\sim 0.611\qquad\nu\sim 5\times 10^7\mathrm{s}^{-1}$$

- complex value of perpendicular wave number

$$k_\perp=2679.5-334.5i\mathrm{m}^{-1}$$

- several cm damping length due to low T_e

$$\lambda_\perp=2\pi/\mathrm{Re}(k_\perp)=2.3\mathrm{mm}\qquad\lambda_{\mathrm{damping}}=2\pi/\mathrm{Im}(k_\perp)=1.9\mathrm{cm}$$

1-D Kinetic Full Wave Simulation

(Ram & Schultz, Phys. Plasmas 7 (2000) 4084.)

$$\frac{d\mathbf{F}_K}{d\xi} = i\mathbf{A}_K \cdot \mathbf{F}_K$$

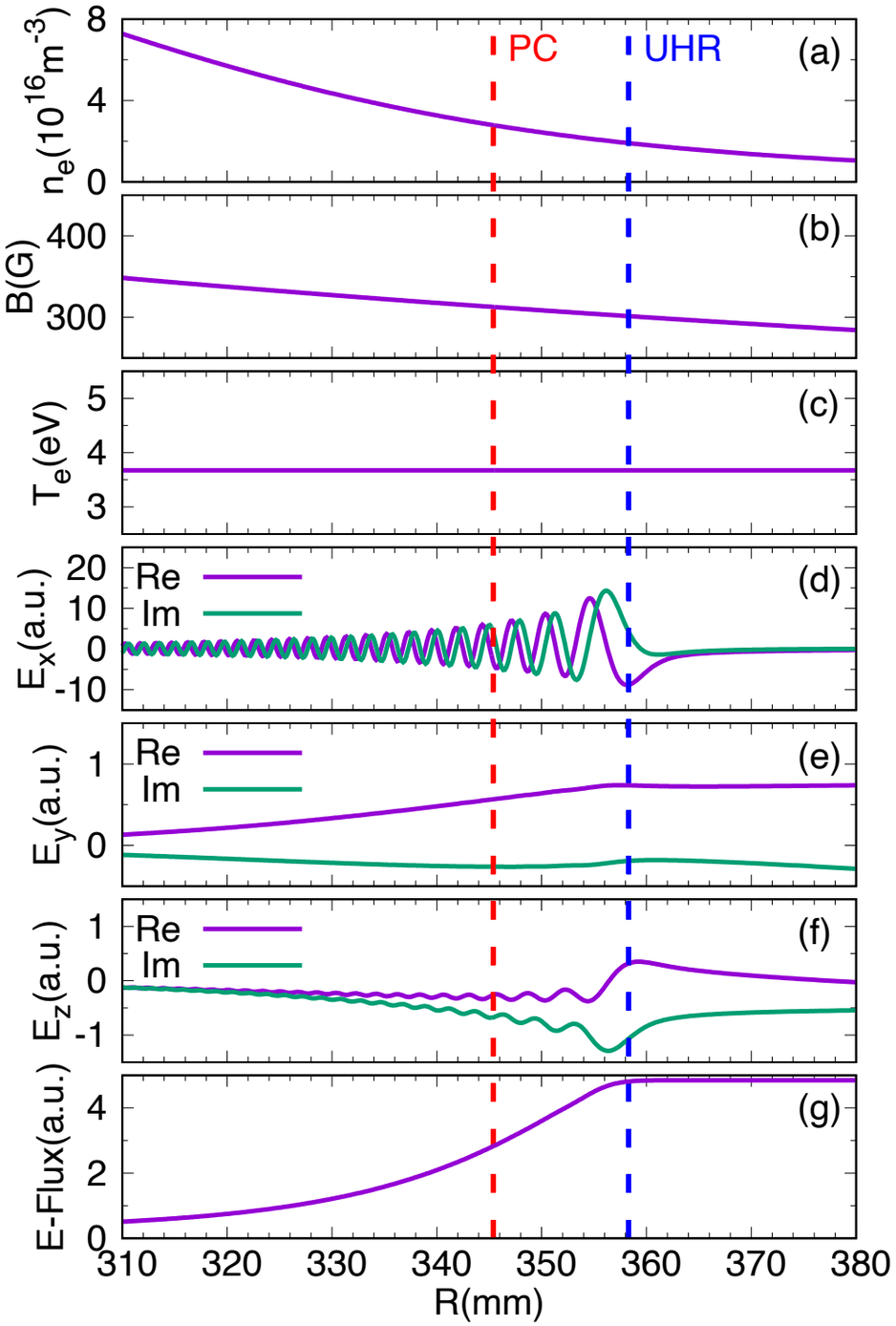
$$\mathbf{F}_K^T = \left[E_x, E_y, E_z, \left(i\widetilde{\chi}E_x'\right), cB_z, \left(-cB_y\right)\right]$$

$$\mathbf{A}_K = \begin{bmatrix} 0 & 0 & 0 & -\widetilde{\chi}^{-1} & 0 & 0 \\ n_y & 0 & 0 & 0 & 1 & 0 \\ n_z & 0 & 0 & 0 & 0 & 1 \\ K_{xx} & \chi_{xy} & \chi_{xz} & 0 & n_y & n_z \\ -\chi_{xy} & K_{yy} - n_z^2 & \chi_{yz} + n_y n_z & 0 & 0 & 0 \\ -\chi_{xz} & \chi_{yz} + n_y n_z & K_{zz} - n_y^2 & 0 & 0 & 0 \end{bmatrix}$$

$$\widetilde{\chi} = \frac{-3\omega_{\mathrm{pe}}^2 \widetilde{\omega}^2}{\left(\widetilde{\omega}^2 - \omega_{\mathrm{ce}}^2\right)\left(\widetilde{\omega}^2 - 4\omega_{\mathrm{ce}}^2\right)} \left(\frac{v_{T_e}}{c}\right)^2$$

$$n_z = 0.611 \qquad \widetilde{\omega} = \omega + i\nu \qquad \nu = 5 \times 10^7 \mathrm{s}^{-1}$$

- EBW collisional damping is included
- similar B_t, n_e, T_e profiles with experiments



- O-mode injection
- EBW can be excited (89.8% conversion efficiency)
- 2 mm wavelength
- several cm damping length

* Experimental Result

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New Vacuum Vessel

Development of Soft X-ray CT System

Shut Down for Renovation of Experiment Building

LATE was shut down and disassembled in May 2021

All the materials except large power supplies were moved in June 2021

WT-3 Tokamak was removed and scrapped.

Plasma Wave Experiment Building

Repair works for floors, walls, water piping,
electric piping and air duct

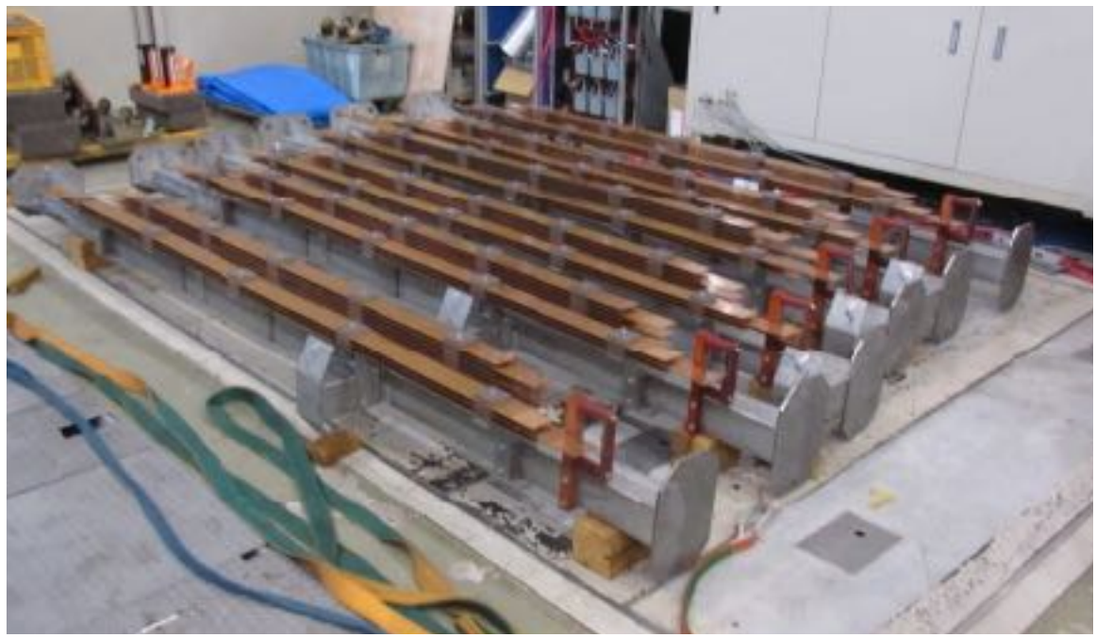
Construction period from August 2021 to February 2022

Advanced Energy Science Laboratory

All the materials were moved back again in May 2022

Re-assembling of LATE begun in June 2022

Disassembling on May 27, 2021

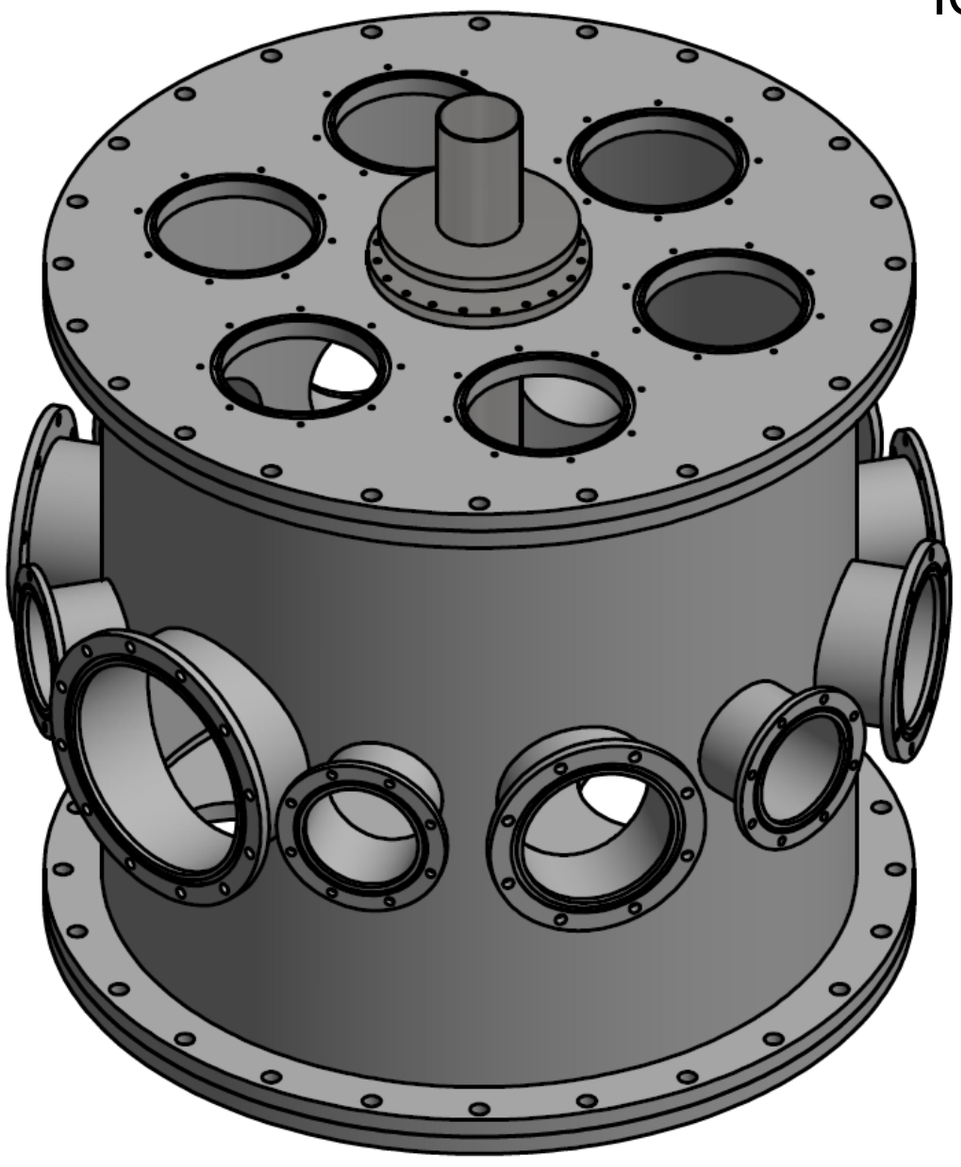


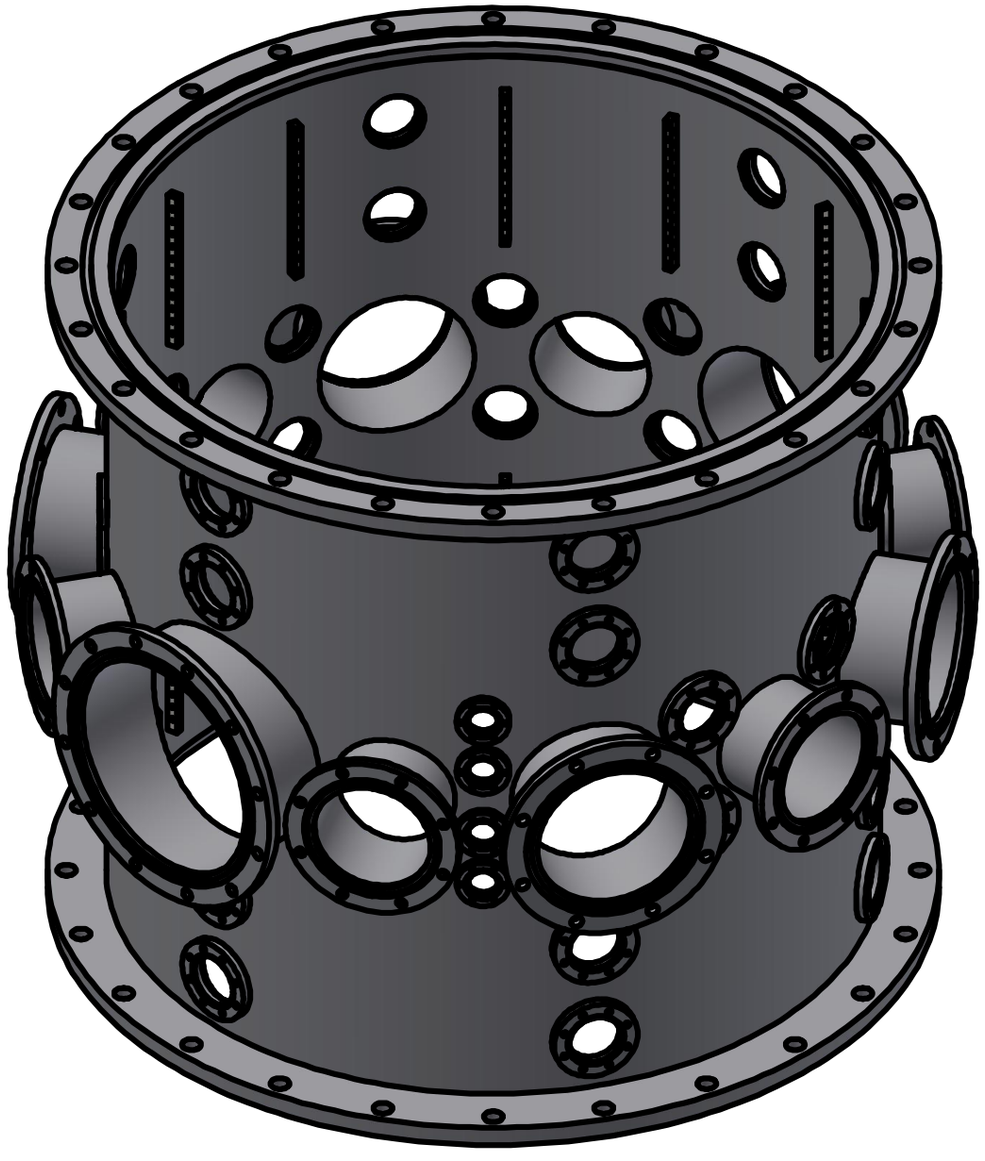
New Vacuum Vessel

New Radial Port
- ICF70 : 8
- ICF114 : 40

New Top & Bottom Port
- ICF70 : 6
- ICF114 : 12

66 additional ports in total





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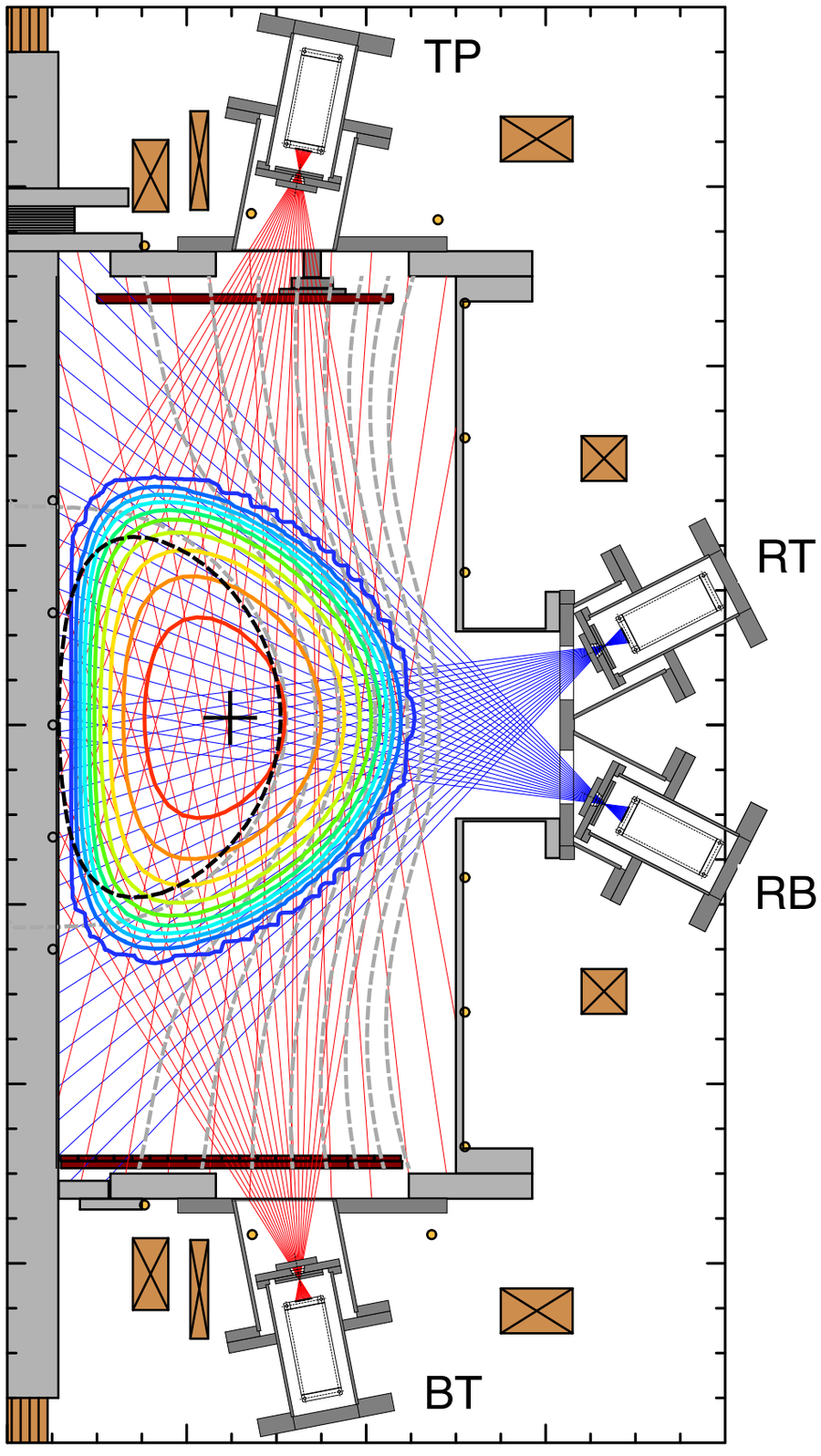
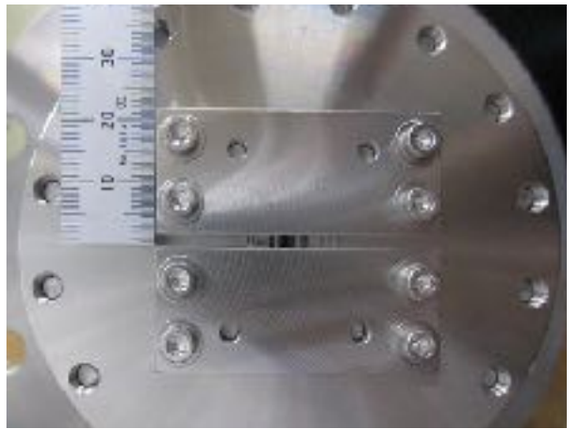
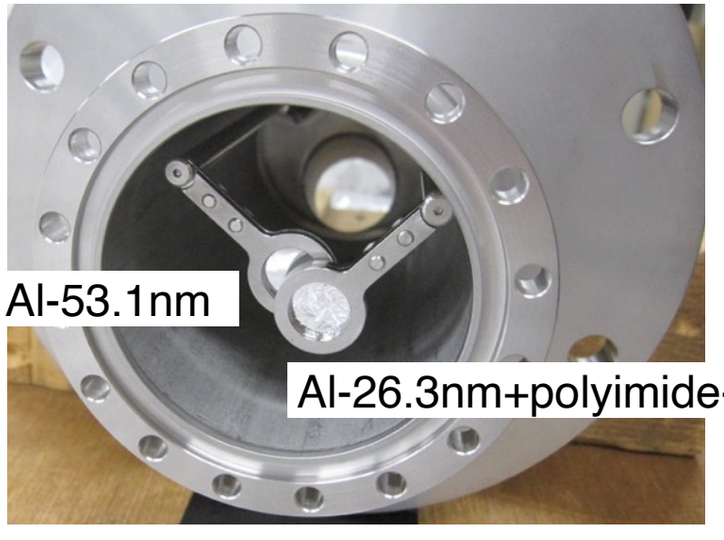


* Four pin-hole cameras on a poloidal plane
* 20 ch AXUV detector array
* two thin-film absorbers





Plan

ECH/ECCD with ECW/EBW for non-inductive start-up and ramp-up

Combined effect of EBI (< 20 keV) and ECH/ECCD

Intermittent Plasma Ejection Phenomena

* SX CT in poloidal cross section with 4 x 20ch pin-hole cameras

Diagnostics ... re-installation

* HIBP (Na^+, K^+, Rb^+, Cs^+, < 30 keV)
* Radial SX profile with 2 x 20ch pin-hole cameras
* 4 + 2 ch 70GHz interferometer system
* 32 (poloidal) + 14 (toroidal) magnetic probes
* HX PHA with 4 CdTe detectors
* Fast CCD Camera
* Visible Light Spectroscopy