19th International ST Workshop, September 18-22, 2017
Seoul National University - Hoam Faculty House

Overdense Plasma Production by Electron Bernstein Wave in the LATE Device

H. Tanaka, Y. Nozawa, R. Kajita, Y. Omura, H. Shirai, Y. Sakai,
J. Ootani, K. Gotou, W. Tsukamoto, T. Noguchi, M. Uchida, T. Maekawa

Graduate School of Energy Science, Kyoto University, Japan

Outline

1. Introduction

2. Non-inductive Production of Highly Overdense ST Plasma by EBW

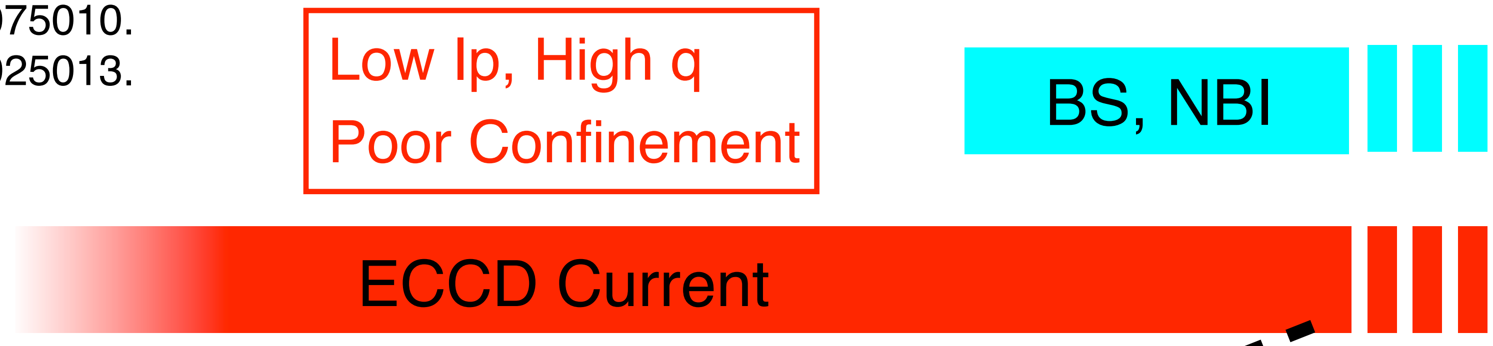
3. Confinement of High Energy Tail Electrons Which Carry the Toroidal Plasma Current

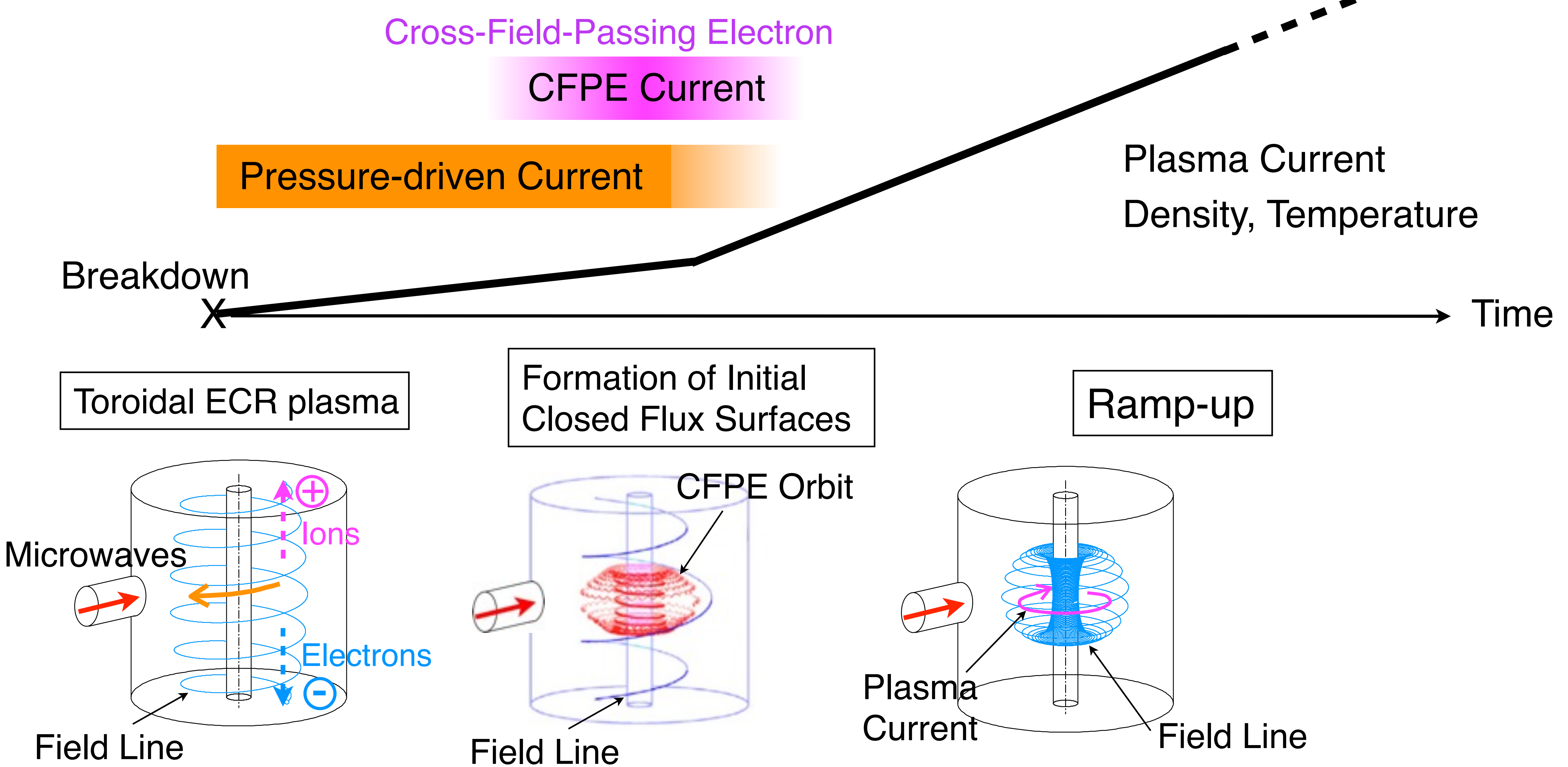
4. Magnetic Activities and Intermittent Plasma Ejection Phenomena in an Overdense ST Plasma sustained by EBW

5. Summary

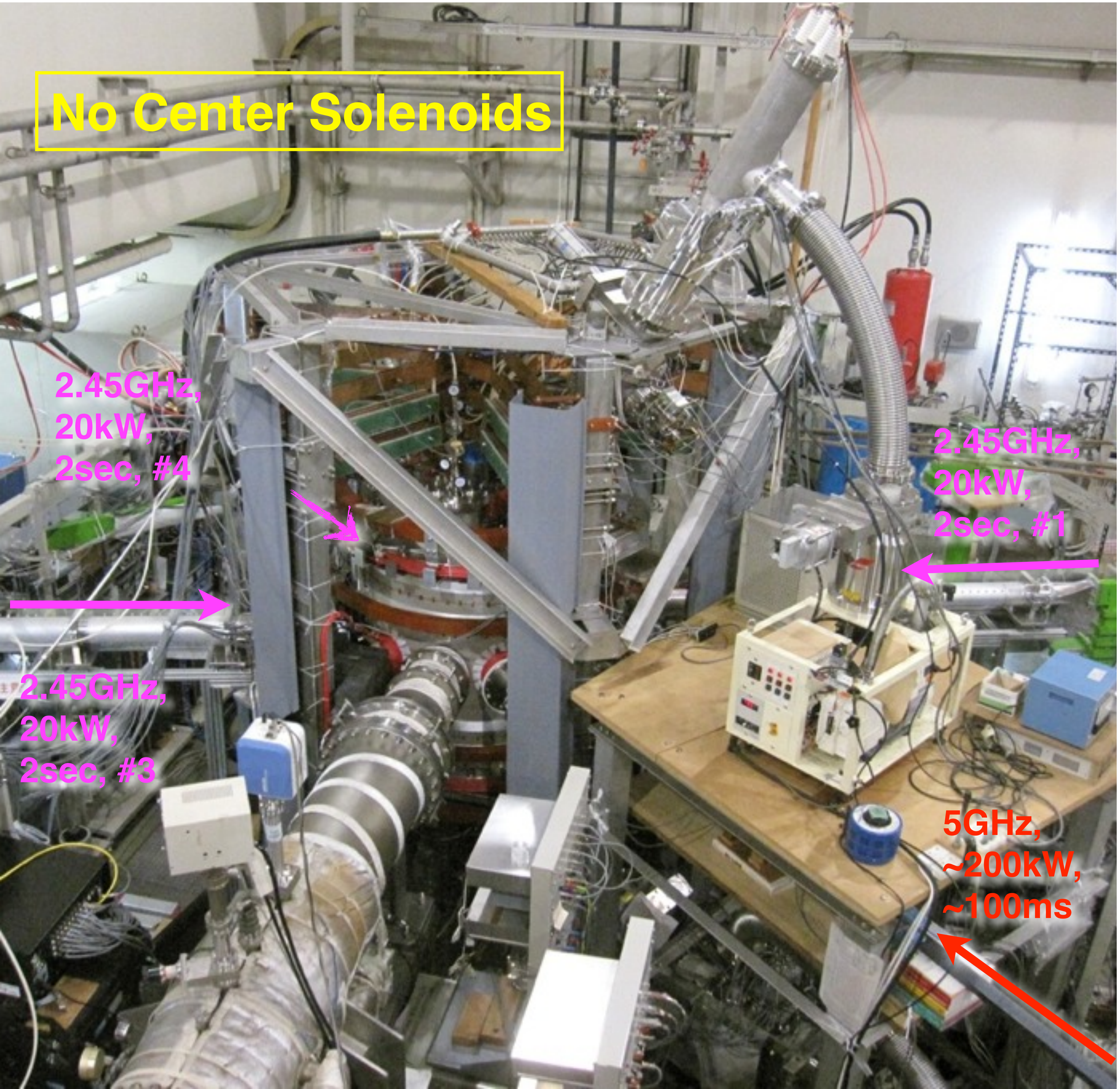
Objectives : Non-inductive Start-up by ECH/ECCD

* S. Nishi, et al., Plasma Phys. Control. Fusion, 52 (2010) 065011.
* S. Nishi, et al., Plasma Phys. Control. Fusion, 52 (2010) 125004.
* K. Kuroda, et al., Plasma Phys. Control. Fusion, 57 (2015) 075010.
* K. Kuroda, et al., Plasma Phys. Control. Fusion, 58 (2016) 025013.
* T. Yoshinaga, et al., Phys. Rev. Lett., 96 (2006) 125005.
* T. Maekawa, et al., Nucl. Fusion, 52 (2012) 083008.
* M. Uchida et al., Phys. Rev. Lett., 104 (2010) 065001.
* M. Uchida, et al., Nucl. Fusion, 51 (2011) 063031.
* H. Tanaka, et al., Nucl. Fusion, 56 (2016) 046003.





LATE (Low Aspect ratio Torus Experiment)



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

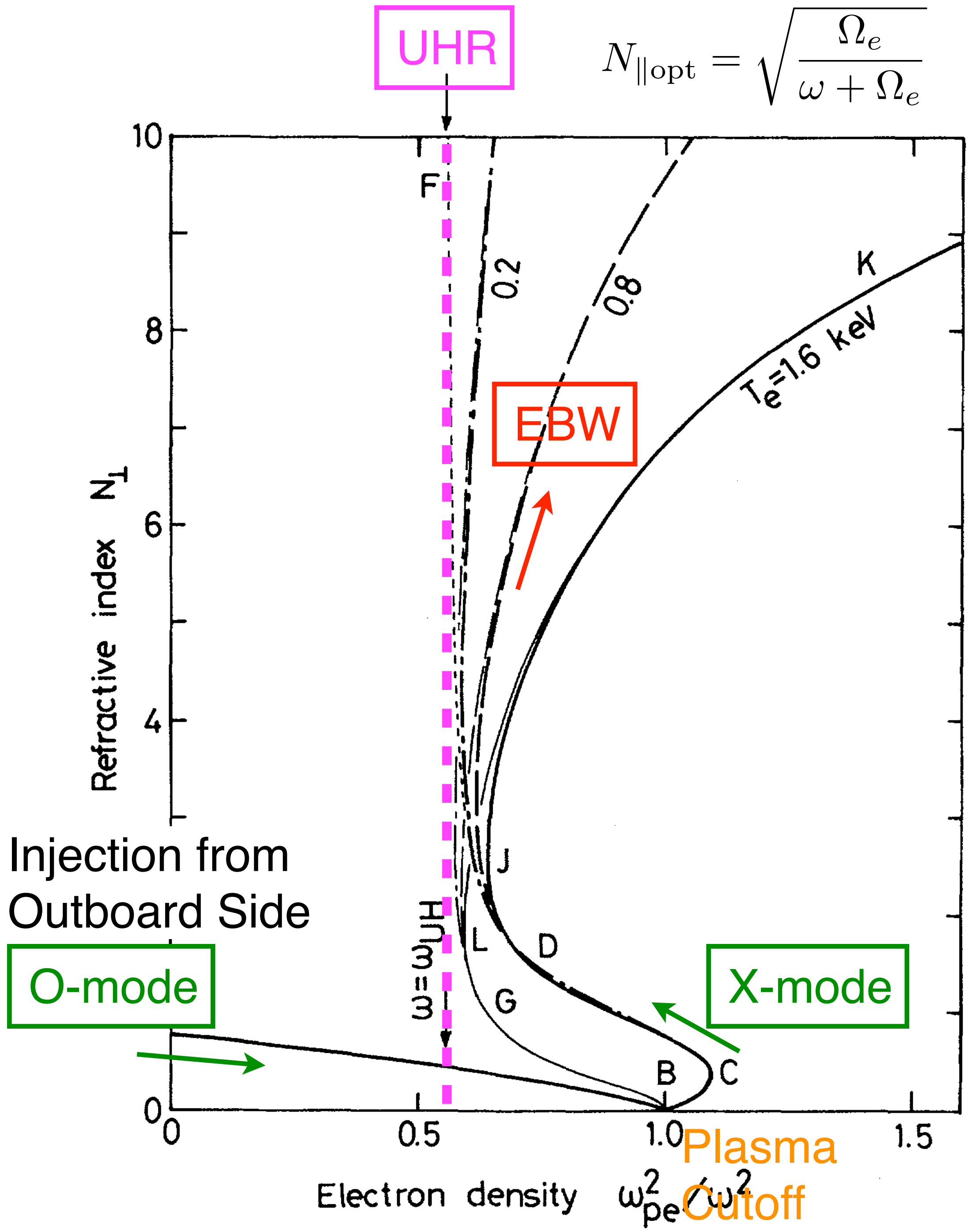
Vertical Field @ R = 25 cm
- Bv ≦ 250 G, 2 sec

Microwave Sources :
- 5 GHz
  - 200 kW, 0.1 sec
  - 1 klystron
- 2.45 GHz
  - 20 kW, 2 sec,
  - 4 magnetrons

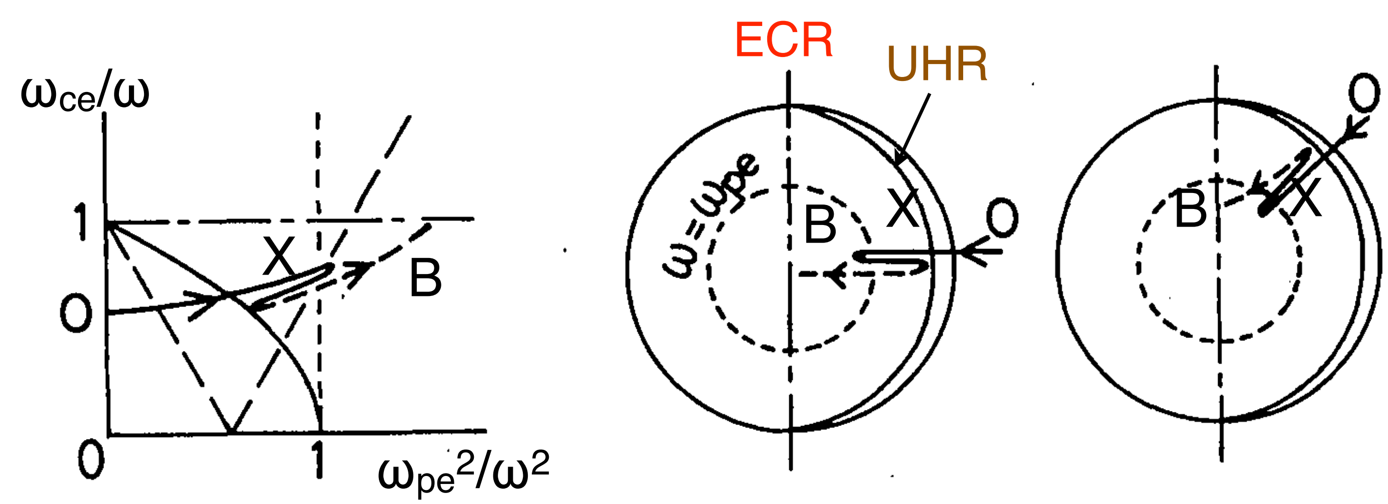
Diagnostics :
- Magnetic Measurement (17 Flux Loops, 14 AT Probes)
- 4 ch 70 GHz Interferometers
- XUV Cameras (20ch x 2)
- Fast CCD Camera
- Visible Light Spectrometer
- 4 ch HX PHA system
- HX pin-hole camera
- HIBP system (Rb+, 20kV)

EBW Excitation with Outboard Injection

Outboard side (low field side) injection is needed from reactor design.



--> O-X-B mode conversion



Mode conversion from O-mode to Slow X-mode is optimum when

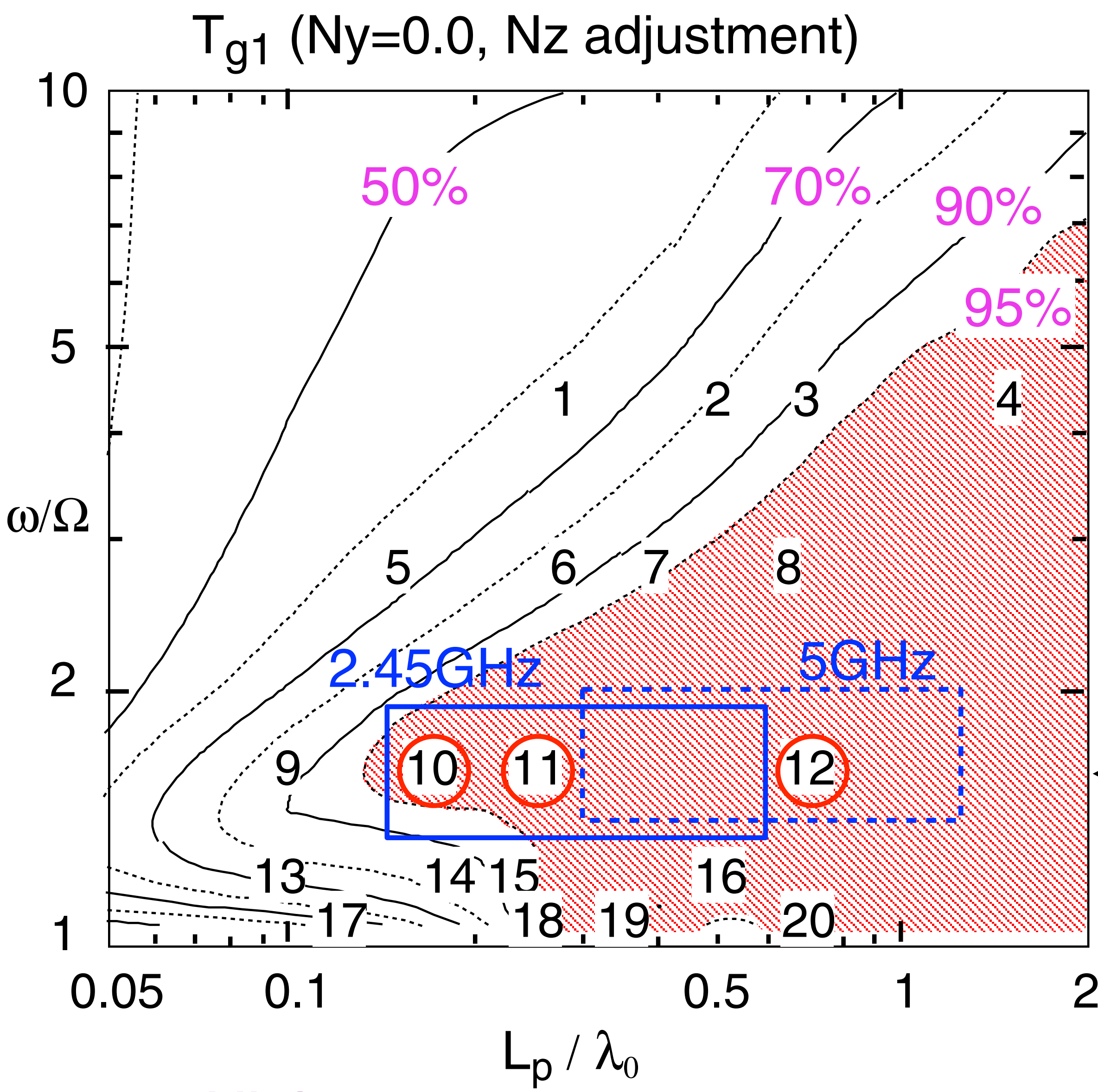
$$N_{\parallel opt} = \sqrt{\frac{\Omega_e}{\omega + \Omega_e}} \quad \text{(at the plasma cutoff)}$$

EBW is converted from Slow X-mode at Upper Hybrid Resonance (UHR).

Maekawa et al., Phys. Rev. Lett. 40 (1978) 1379

Maekawa et al., J. Phys. Soc. Jpn. 48 (1980) 247

Optimal Polarization for EBW Mode Conversion



Appropriate combination of O and X modes (Polarization Adjustment) gives optimal coupling to EB waves when density gradient is steep.

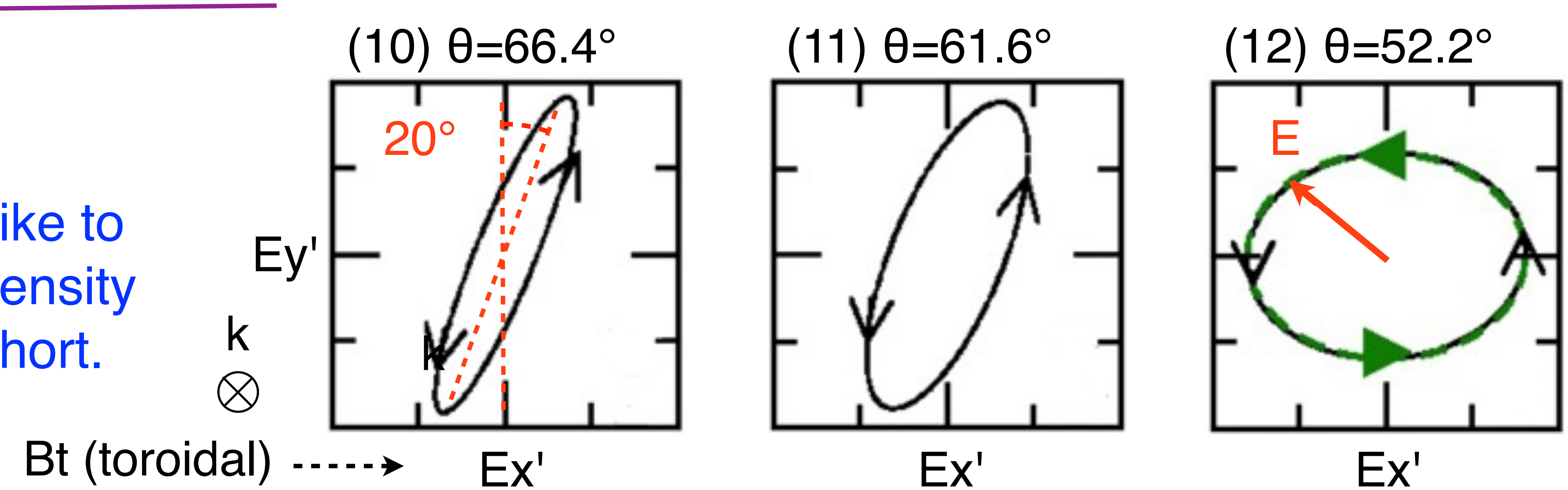
(Igami et al., PPCF 48 (2006) 573)

ω/Ω=1.67

in the case of R_{cutoff} = 35.5 cm and R_{ECR} = 21.3 cm

Higher n_e

Optimized polarization changes from O-mode like to X-mode like when the density scale length becomes short.



1. Introduction

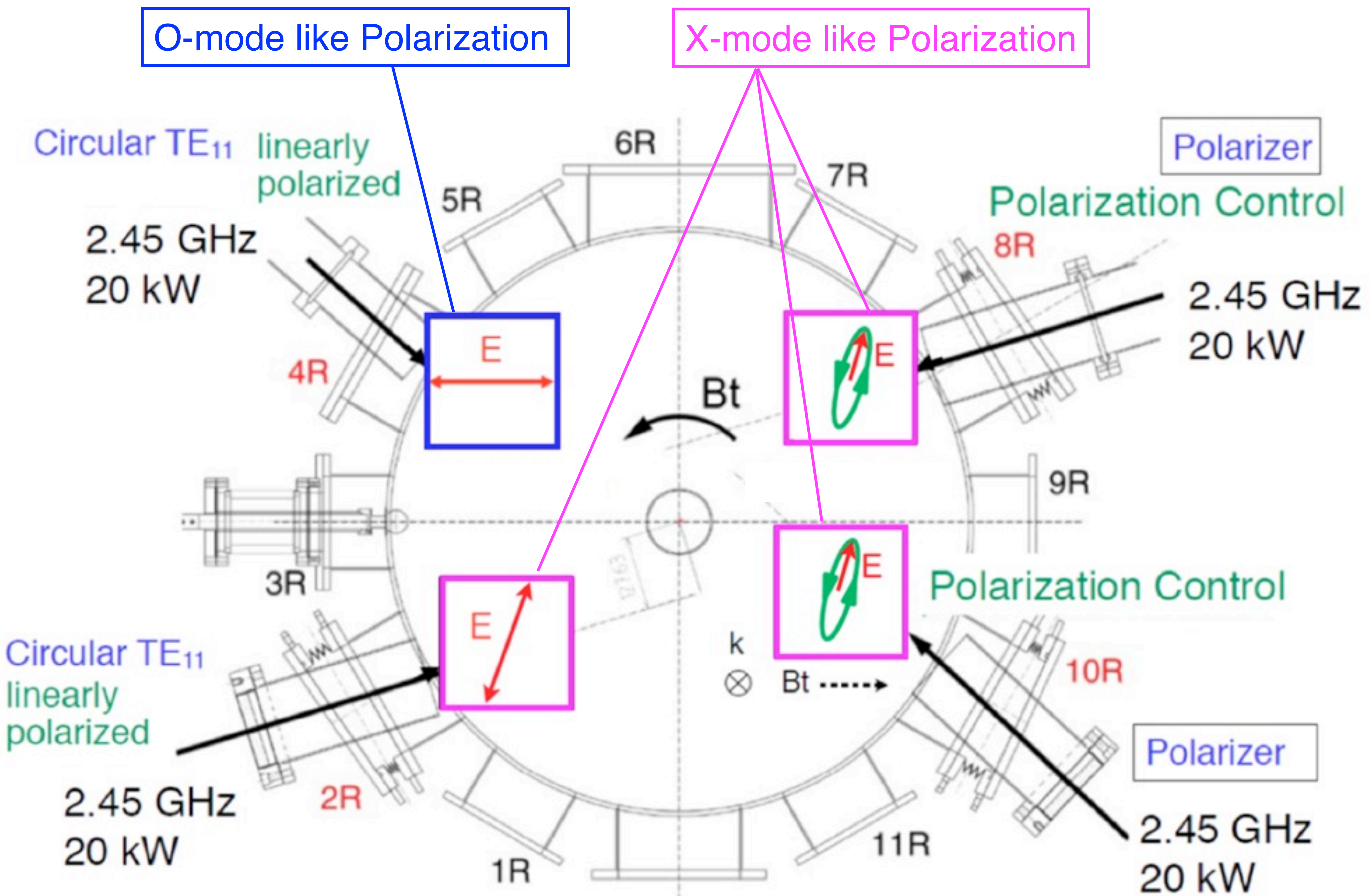
2. Non-inductive Production of Highly Overdense ST Plasma by EBW

3. Confinement of High Energy Tail Electrons Which Carry the Toroidal Plasma Current

4. Magnetic Activities and Intermittent Plasma Ejection Phenomena in an Overdense ST Plasma sustained by EBW

5. Summary

2.45 GHz Microwave Launching System

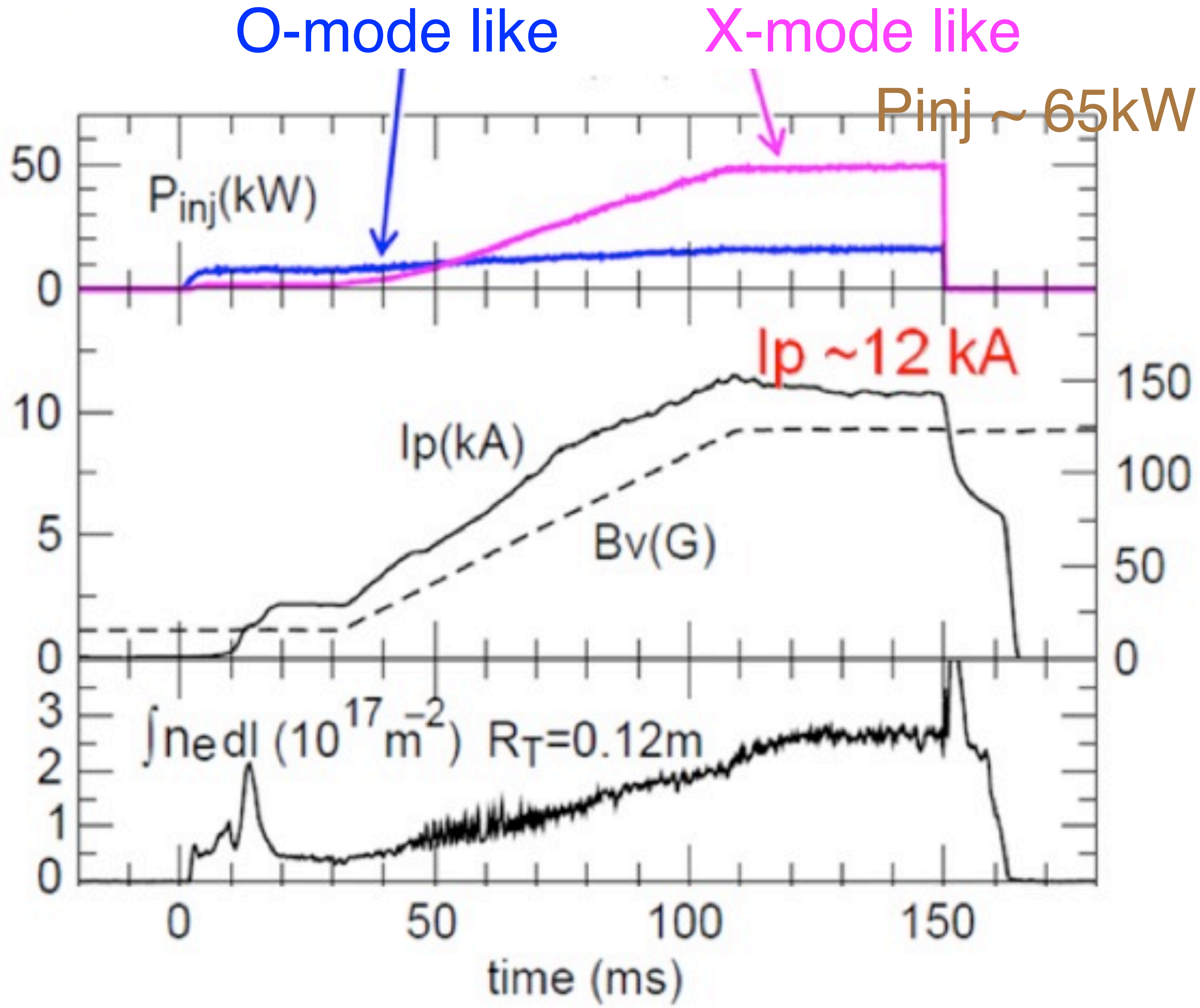


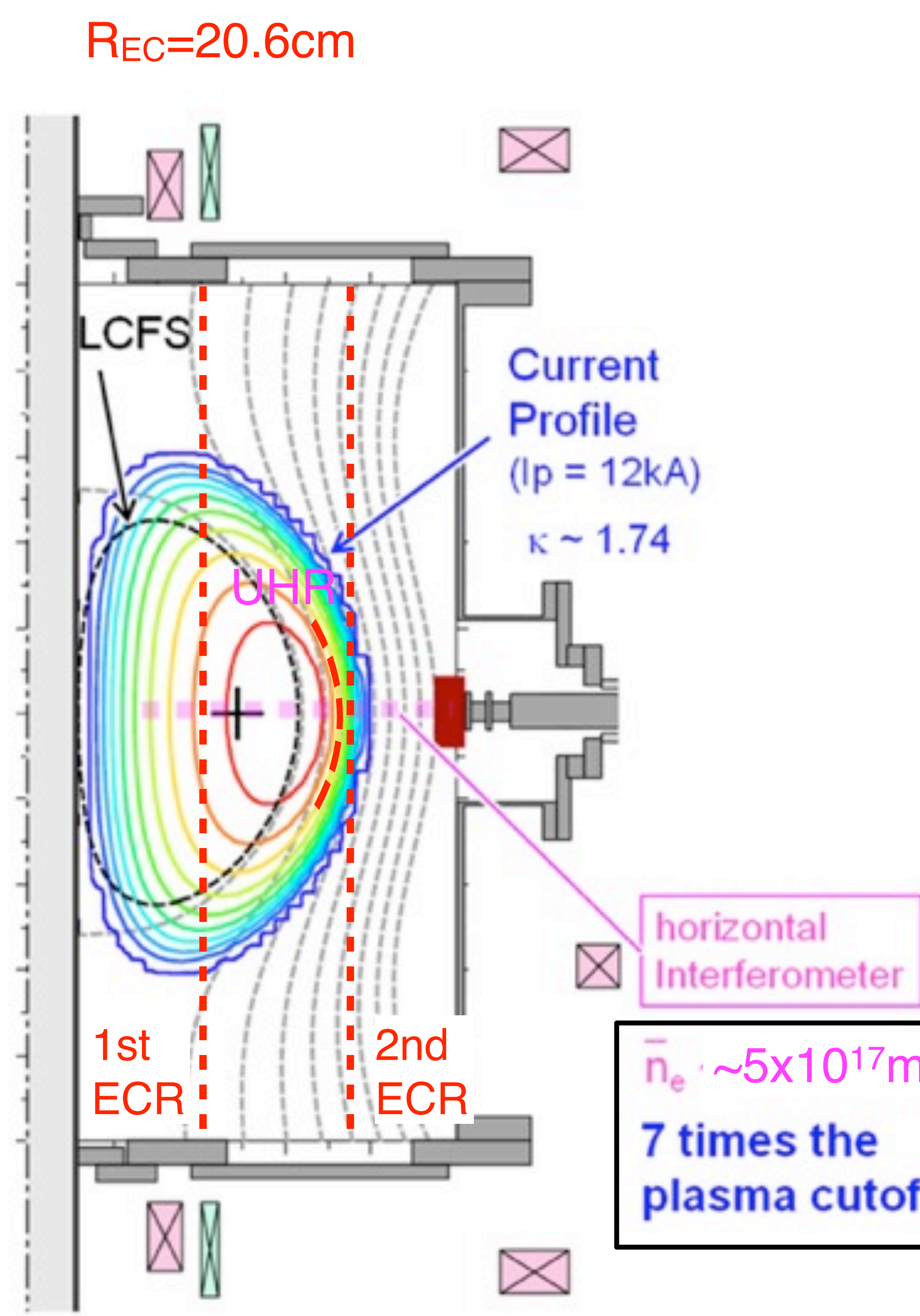
EBW Start-up in the 1st Propagation Band with 2.45 GHz

EBW Start-up with large fraction of X-mode like polarization at the last stage.

The 2nd EC resonance layer is located outboard side of UHR layer.

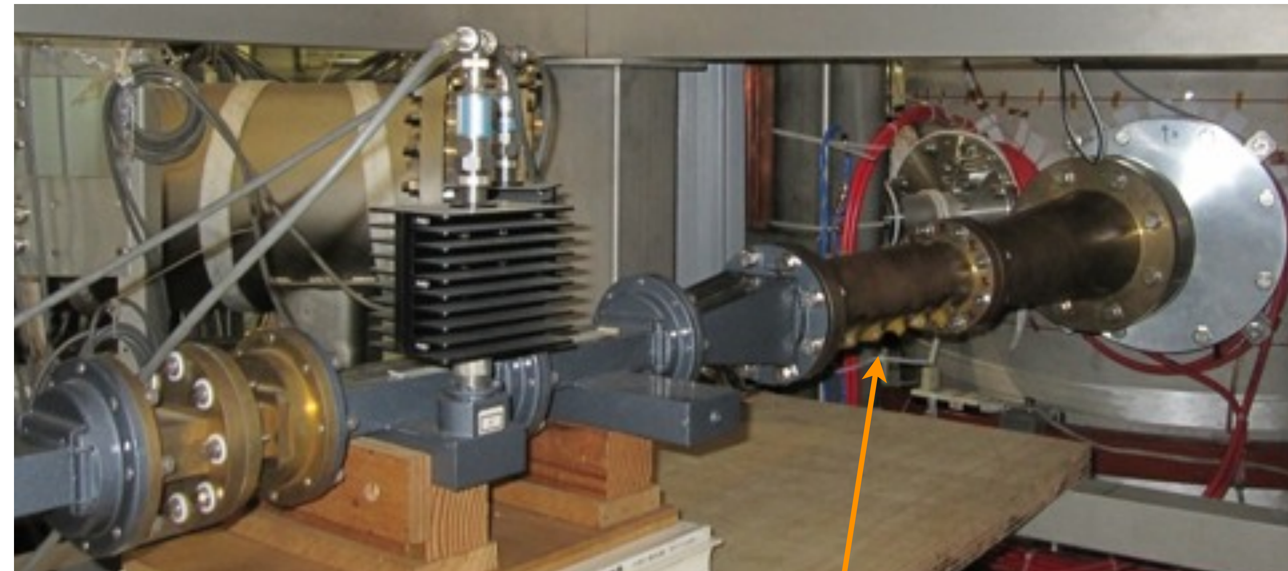
Itc=1.5kA,
Bt=0.072T

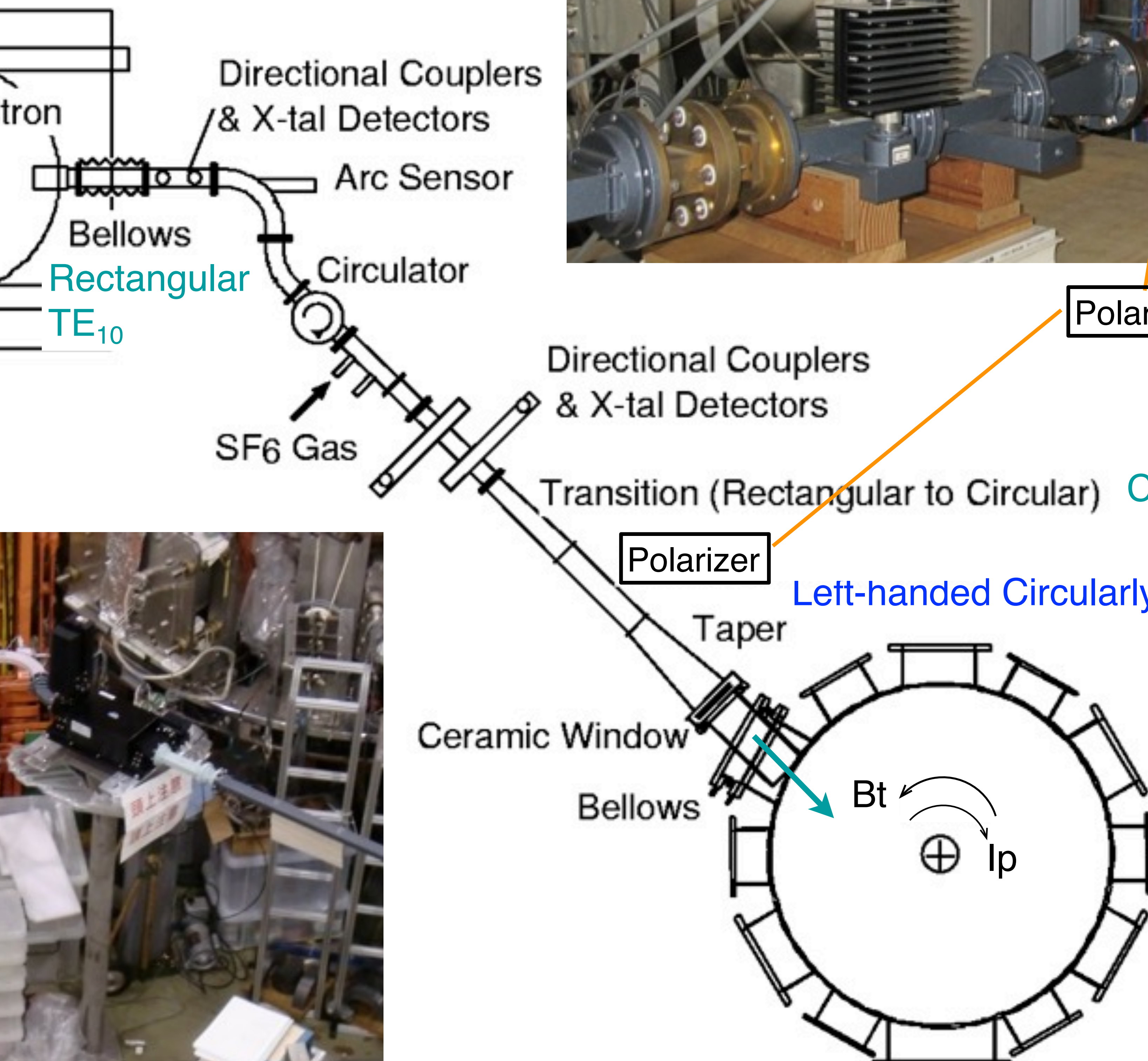




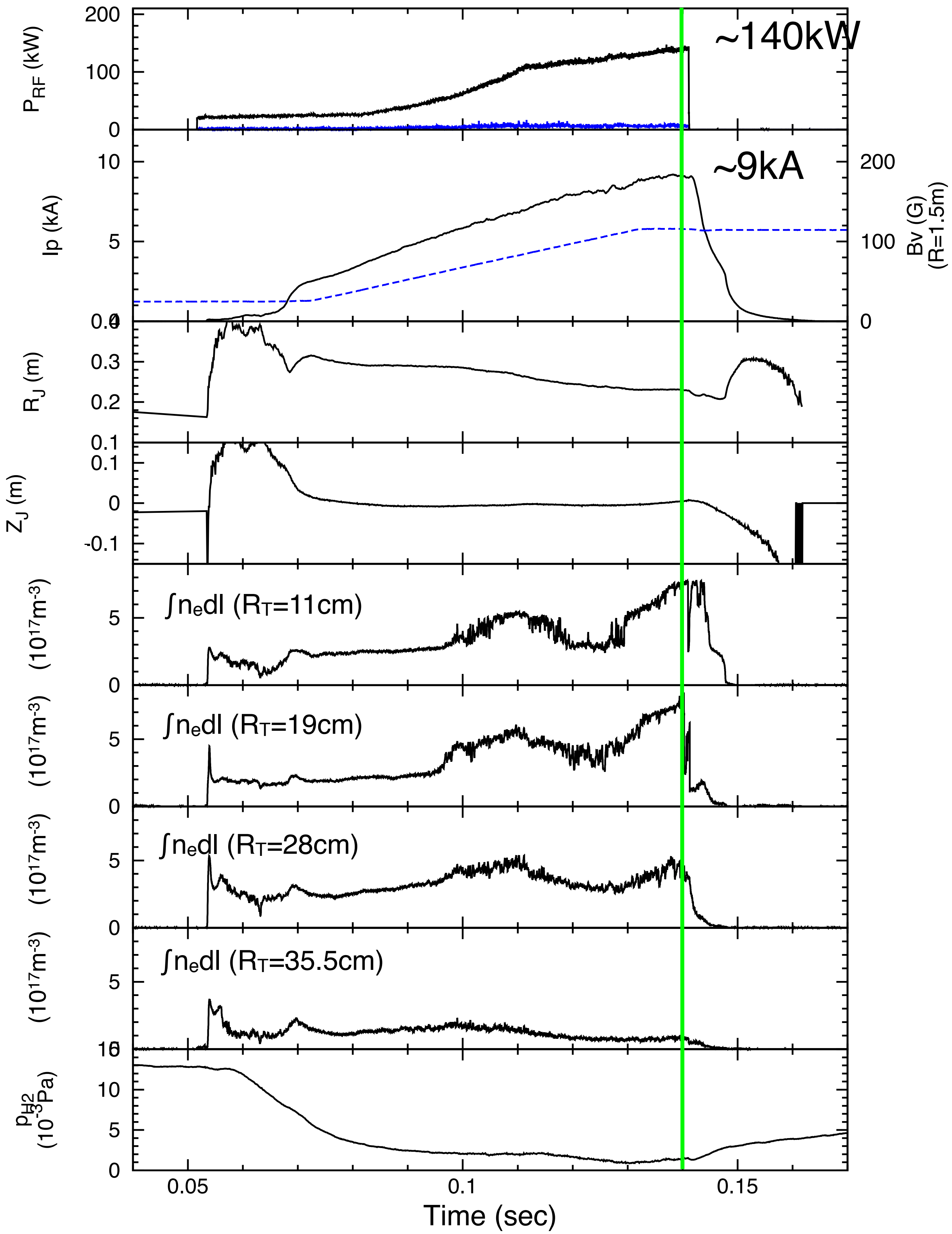
$\bar{n}_e$ ~5x10^{17}m^{-3}
7 times the plasma cutoff

5GHz ECH System



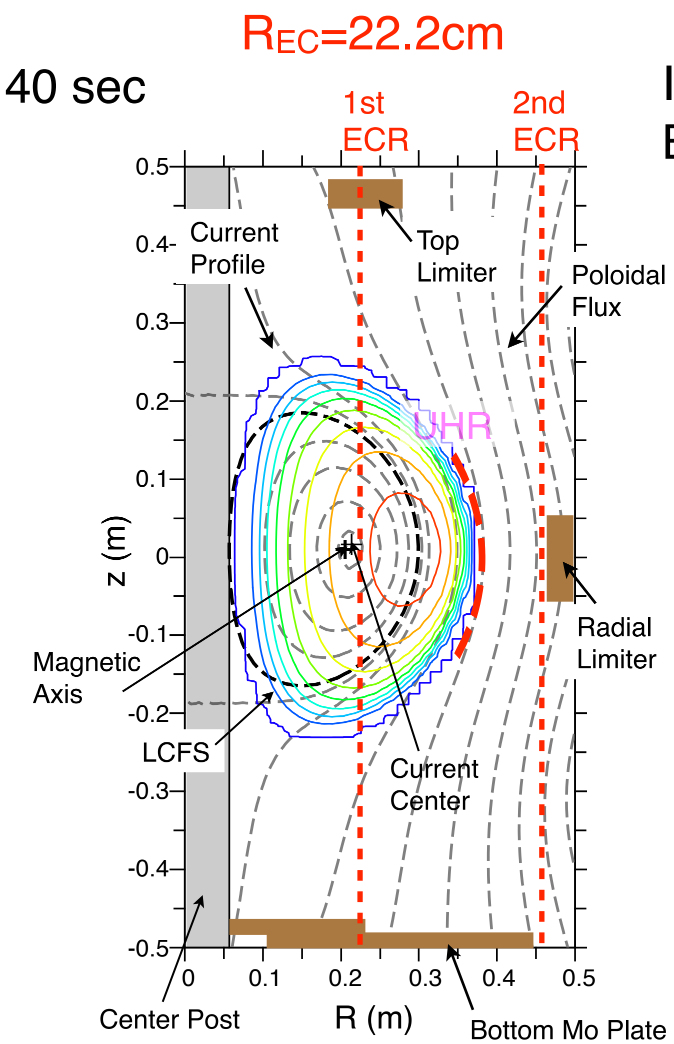


EBW Start-up in the 1st Propagation Band with 5GHz

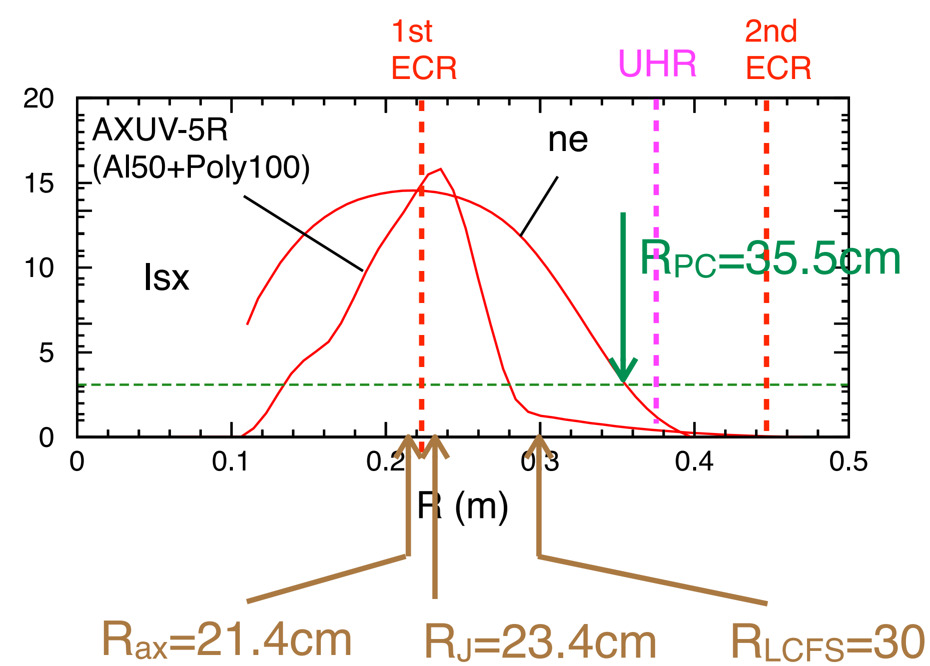


t = 0.140 sec

Itc=3.3kA,
Bt=0.158T

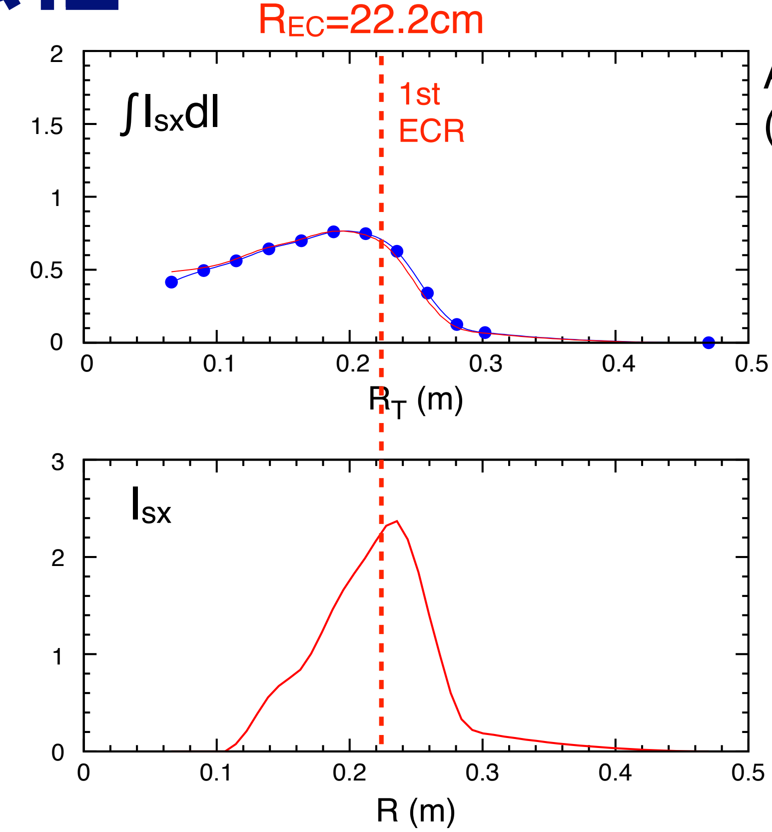


n_0 ~1.5 x 10^{18} m^{-3}

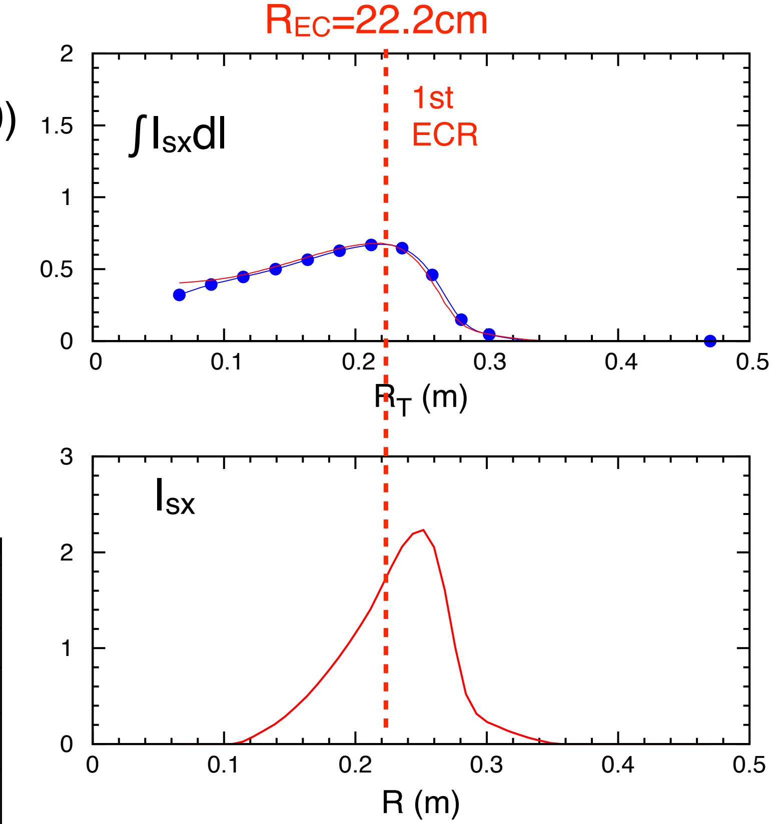


Estimation of Te at the Plasma Center

AXUV-5R (Al50+Poly100)

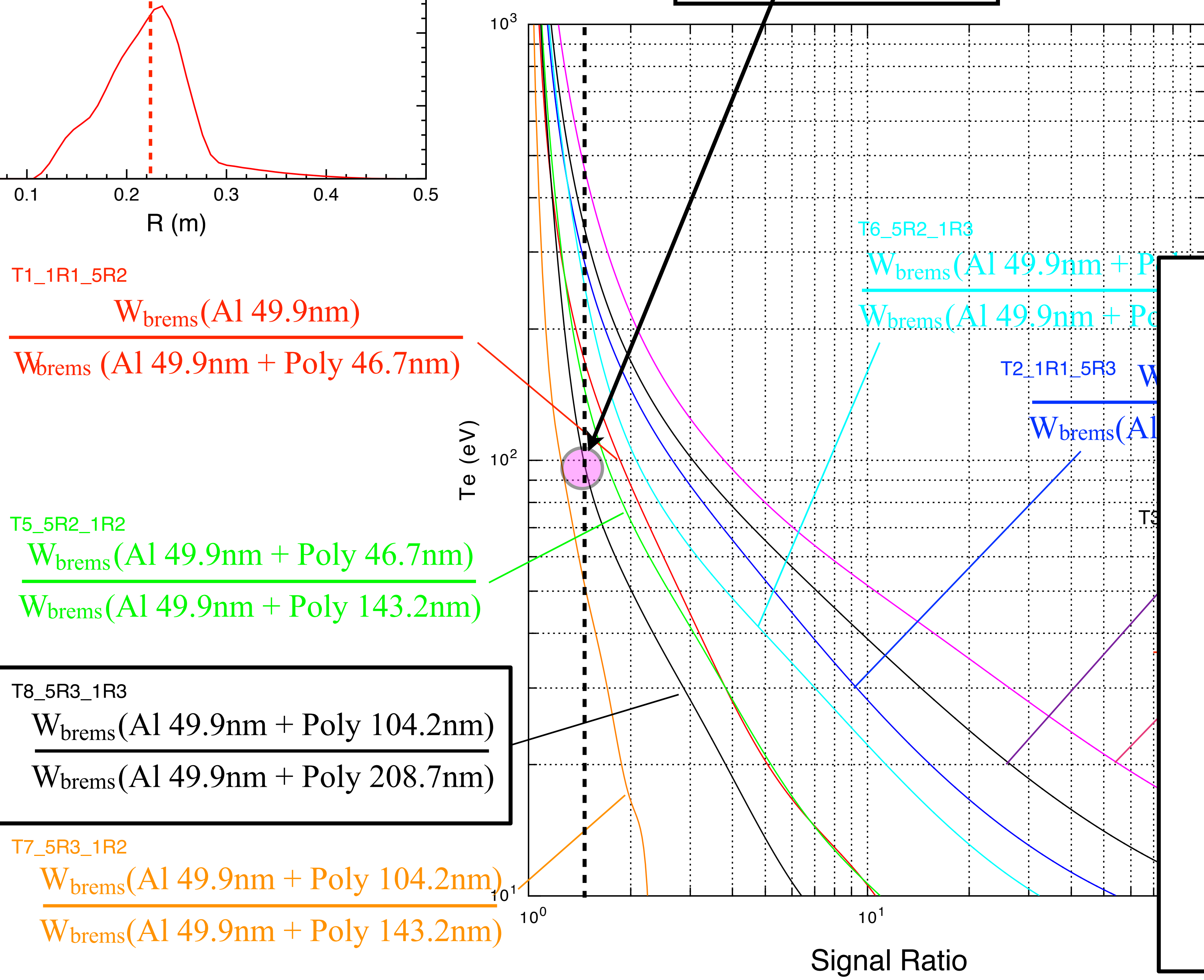


AXUV-1R (Al50+Poly200)

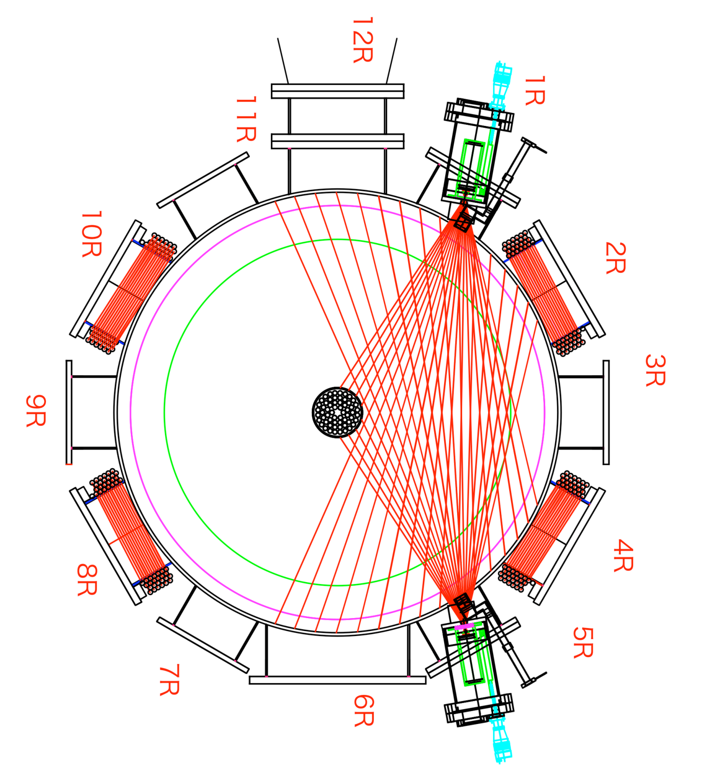


Good electron heating at the plasma core

Te ~ 100 eV



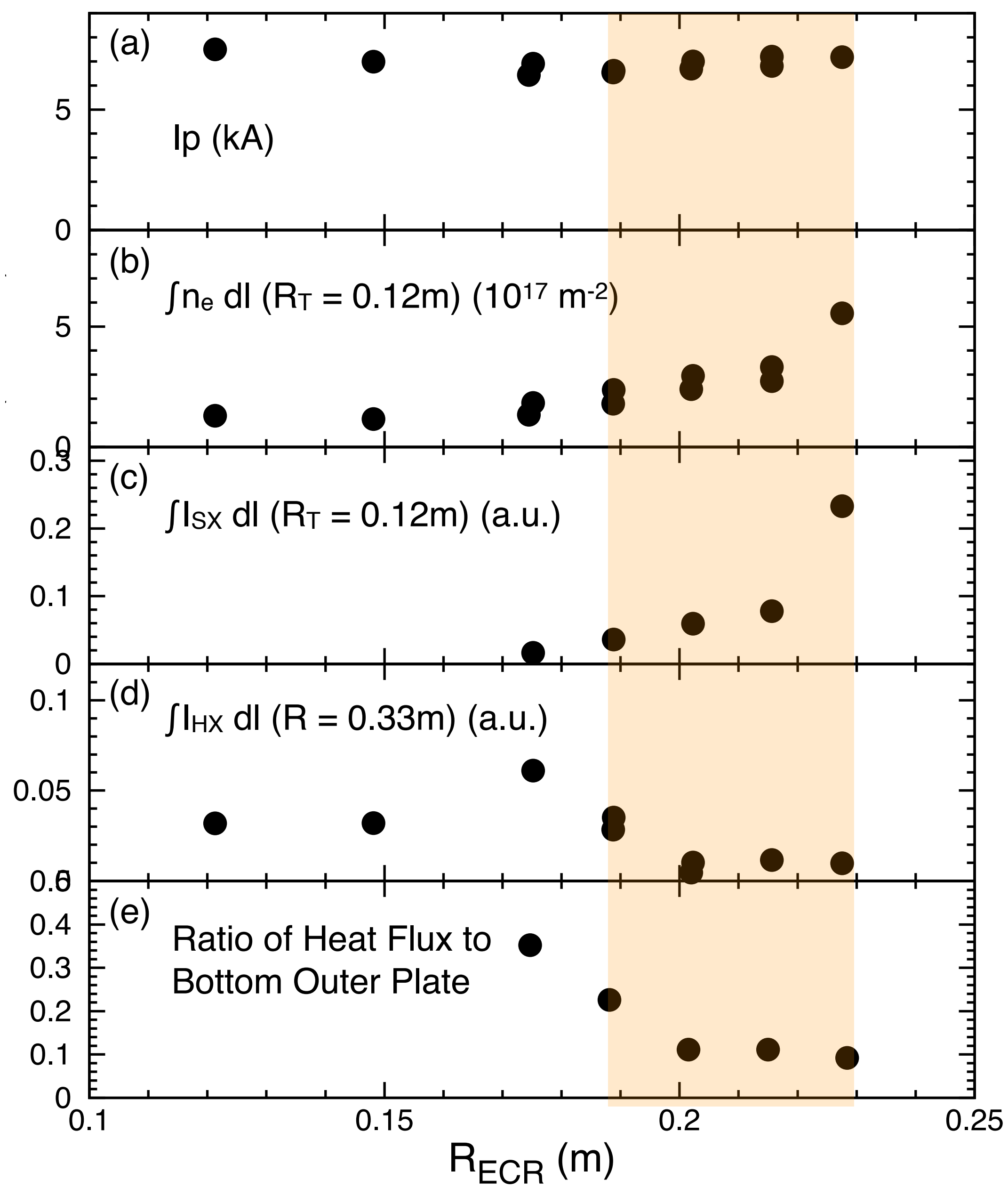
20ch XUV~SX-ray cameras with different absorbers.

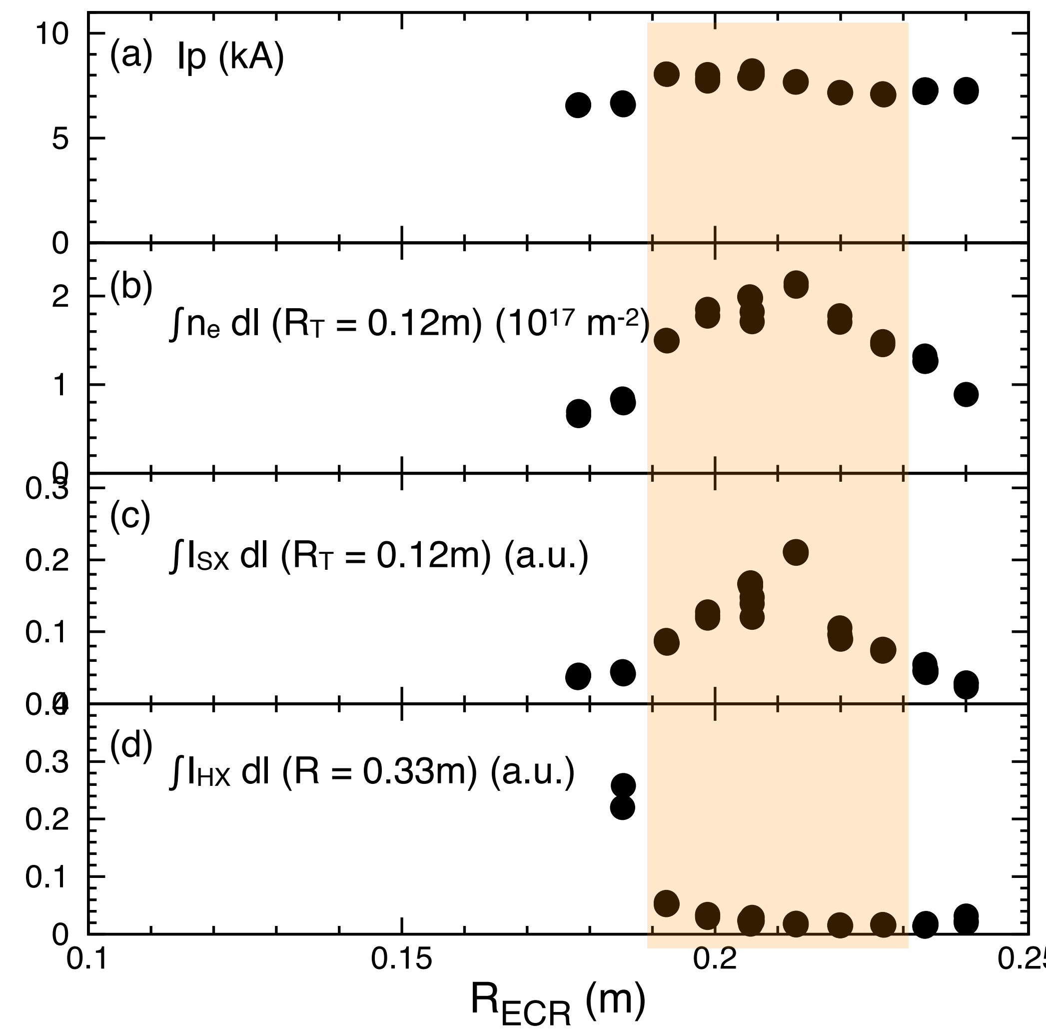


Bt Dependences for 5GHz and 2.45 GHz Microwaves

The density increases when the 2nd ECR layer is located at the outboard side of the upper hybrid resonance (UHR) layer, which means that the EB wave is excited in the 1st propagation band.

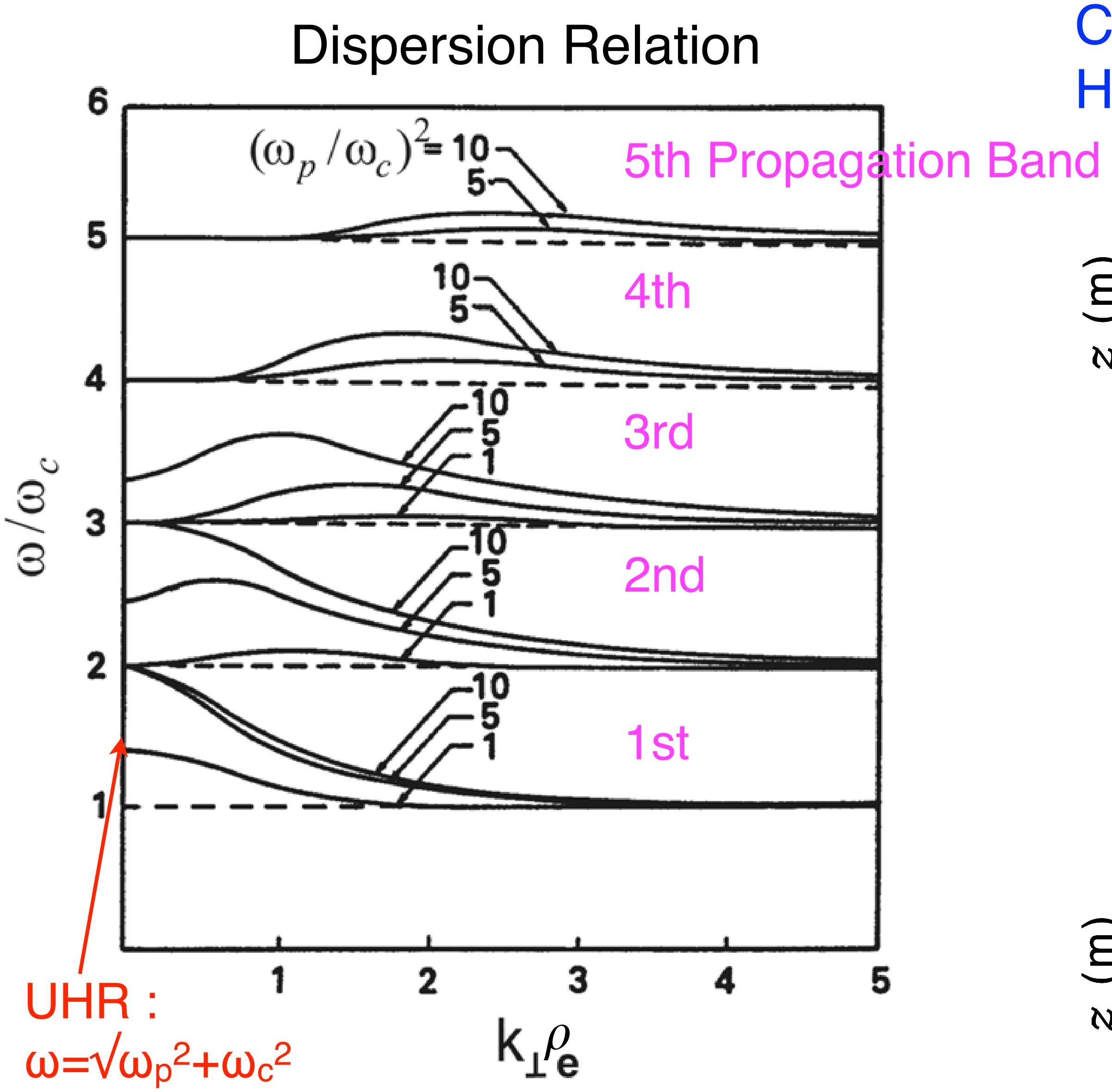
Such Bt dependence is observed at two different microwave frequencies.

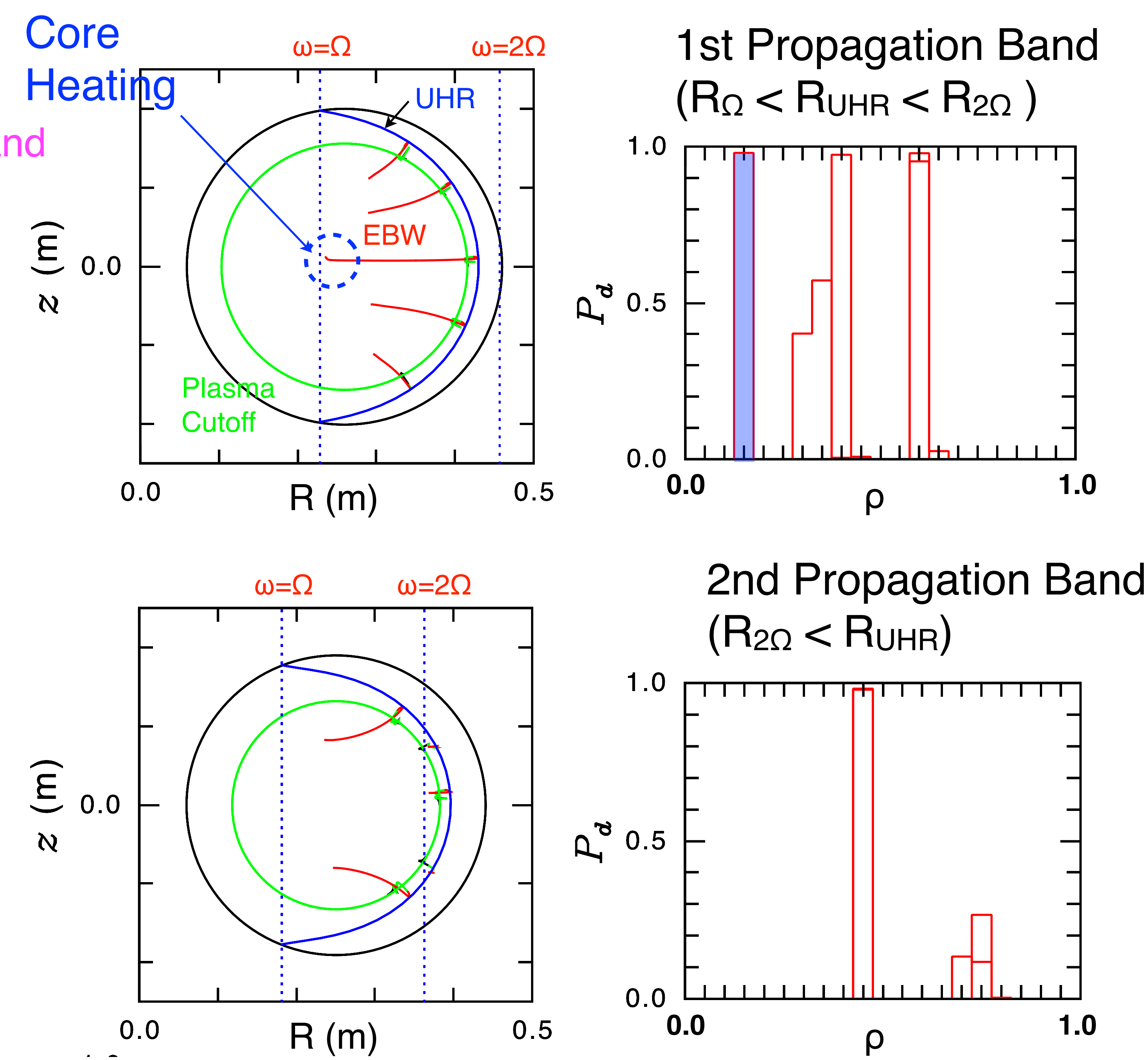




EBW Ray and Deposition Profile

The position of the UHR layer on the midplane is usually located near the outboard wall almost independently on the magnetic field strength in overdense ST plasmas.
For the 1st propagation band, the distance between the fundamental ECR layer and the 2nd ECR layer is wide enough to locate the fundamental ECR layer at the plasma core and the effective heating is expected.





Crawford & Tataronis, J. Appl. Phys. **36** (1965) 2930

1. Introduction

2. Non-inductive Production of Highly Overdense ST Plasma by EBW

3. Confinement of High Energy Tail Electrons Which Carry the Toroidal Plasma Current

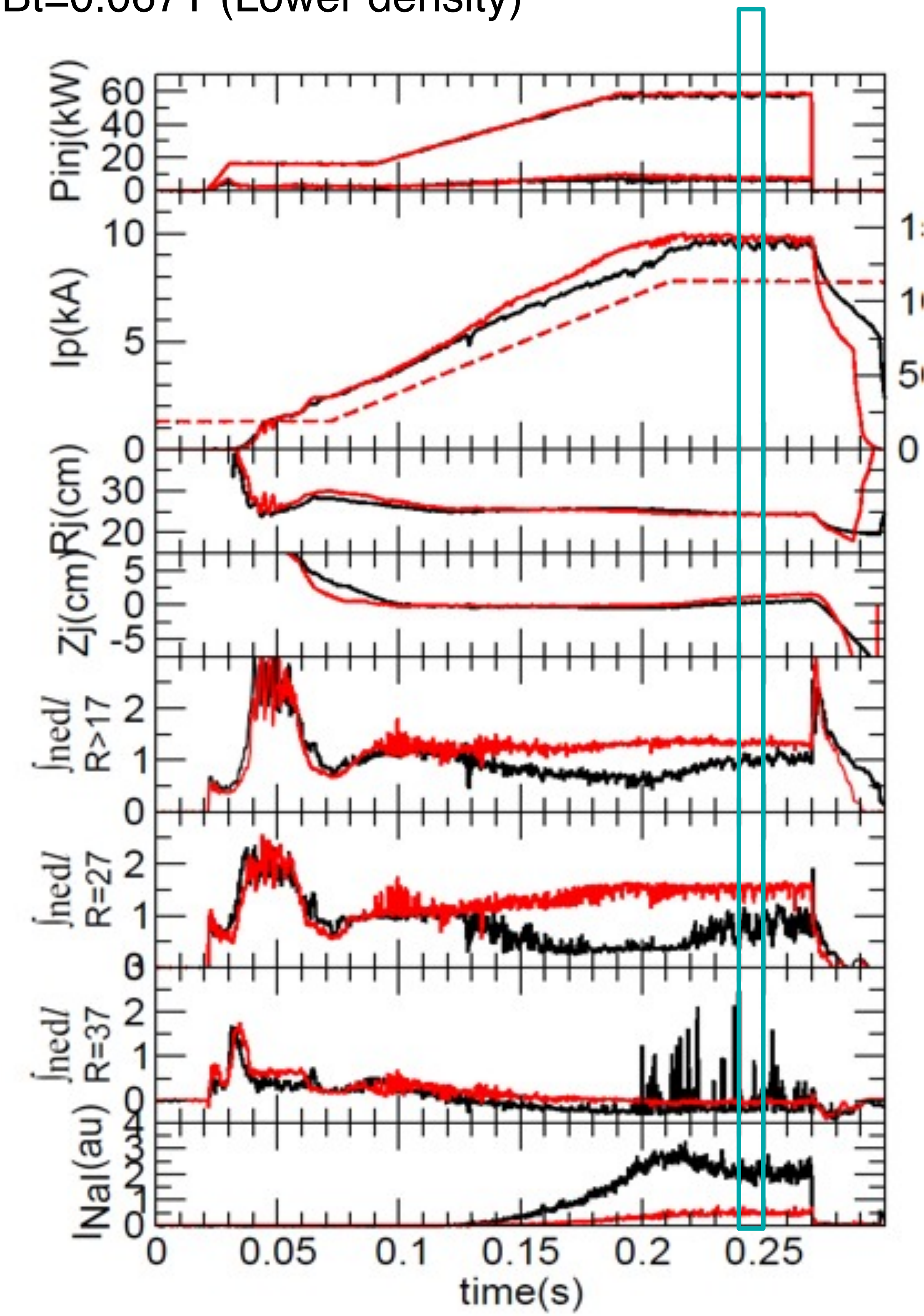
4. Magnetic Activities and Intermittent Plasma Ejection Phenomena in an Overdense ST Plasma sustained by EBW

5. Summary

Hard X-ray Energy Spectra

2.45GHz
Bt=0.072T (Higher density)
Bt=0.067T (Lower density)

t=0.24~0.25 s
gate25

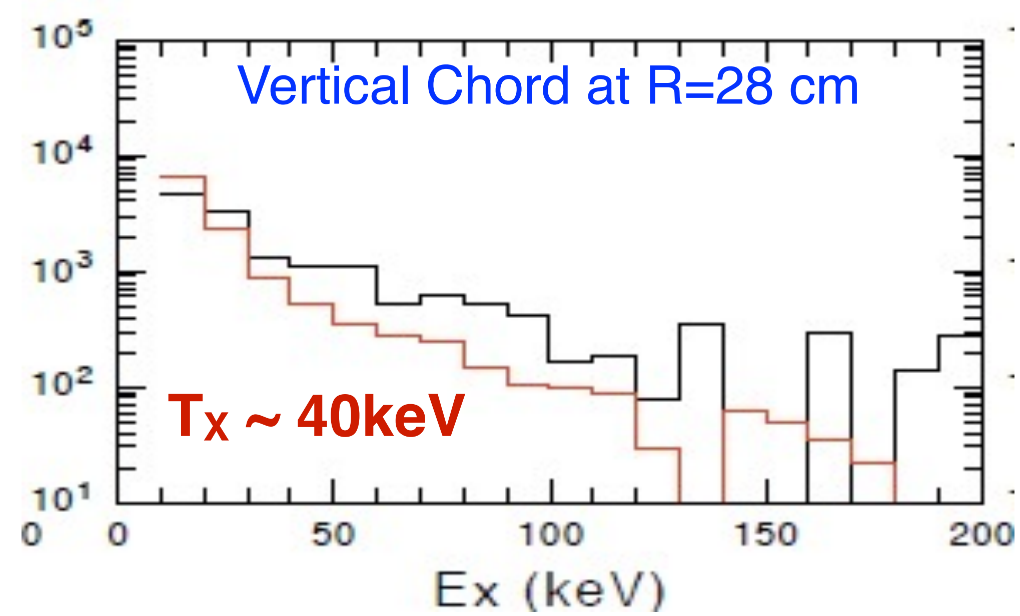


(When the 2nd EC resonance layer is near UHR or inner side of it, the density becomes low.)

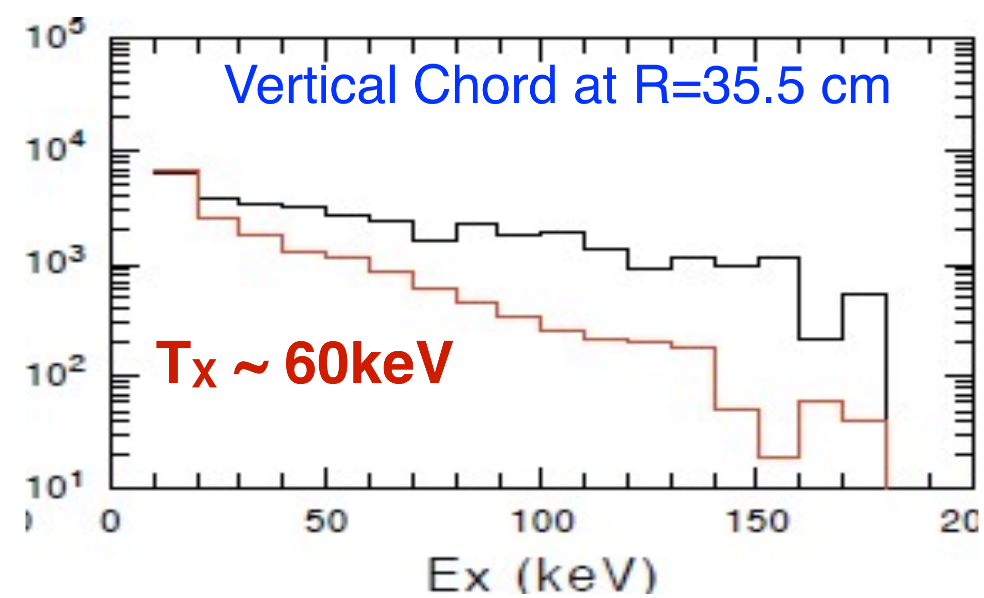
Tail electrons with energy ~40 keV carry the plasma current ~10kA

$n_{tail} / n_{bulk} \sim 0.01$

Photon counts



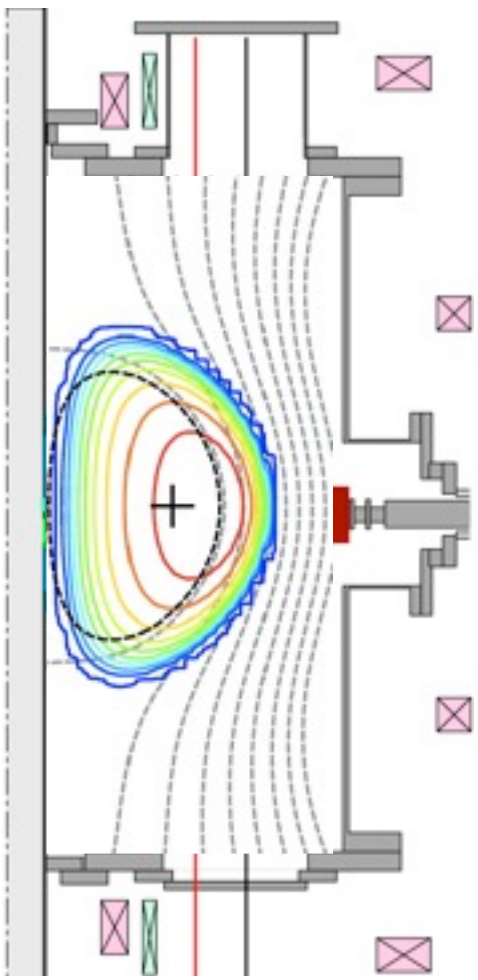
Photon counts



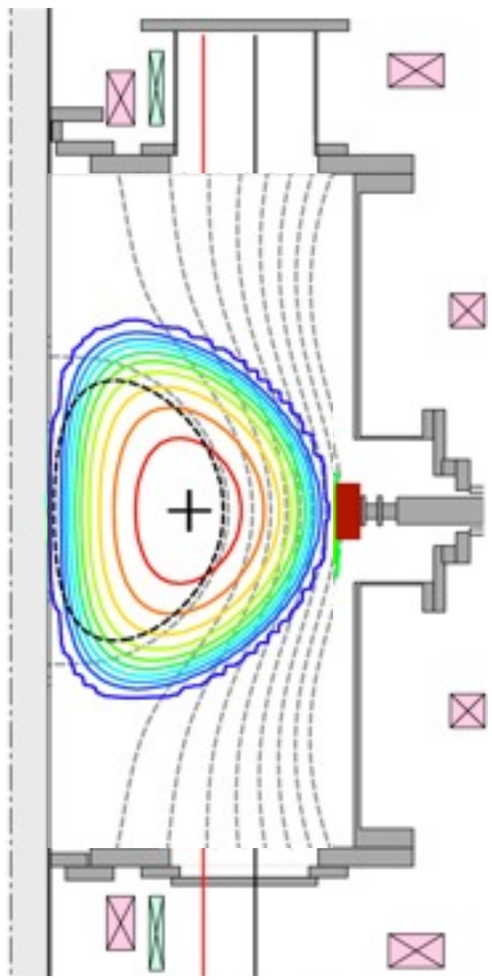
Equilibrium Pressure Profile Estimated from Magnetic Measurement

Plasma current density profile : j

Higher density
(Bt = 0.072 T)
(R_{EC}=20.6cm)



Lower density
(Bt = 0.067 T)
(REC=19.2cm)



Wp ~ 25J, Pinj ~ 60kW

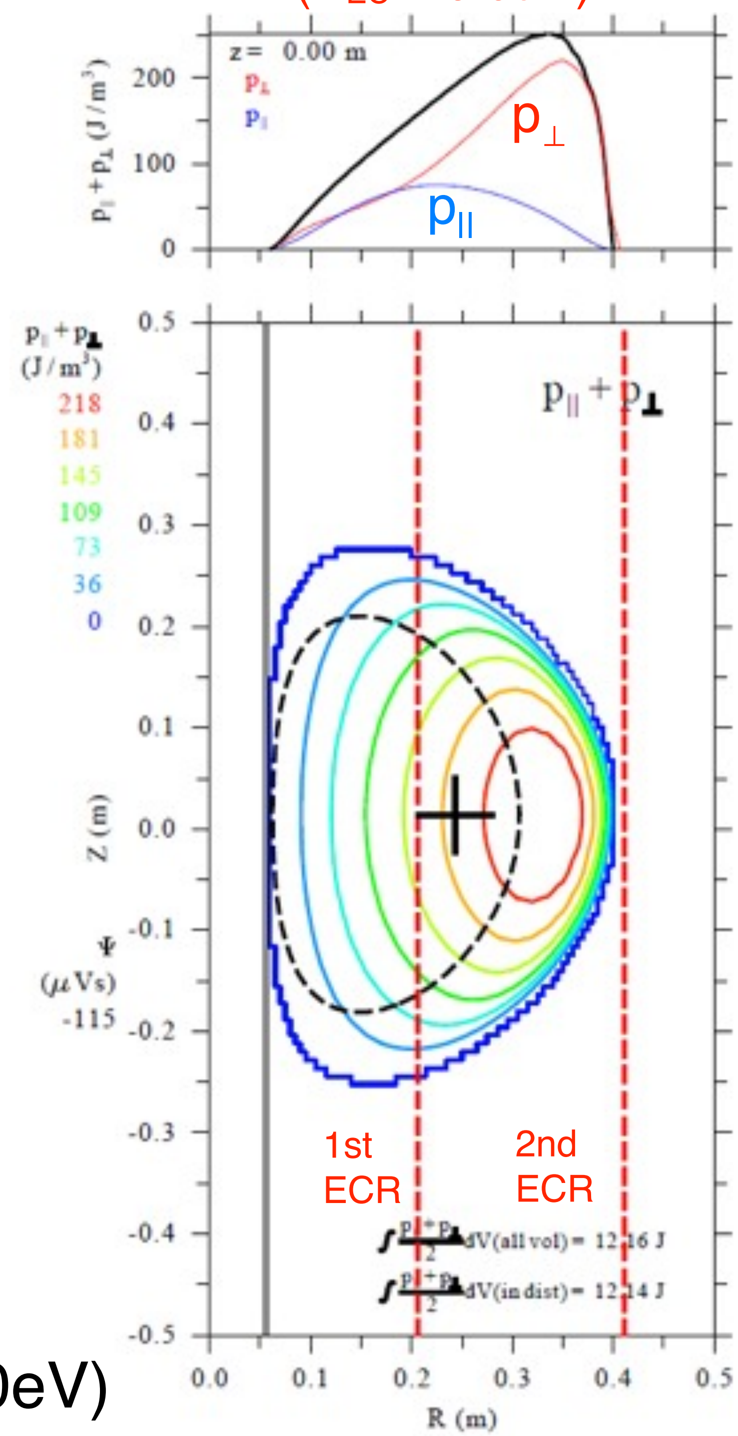
τ_c = Wp/Pinj ~ 0.4 ms

Wbulk ~ 1J (ne=$0.5\times10^{18}m^{-3}$, Te=100eV)

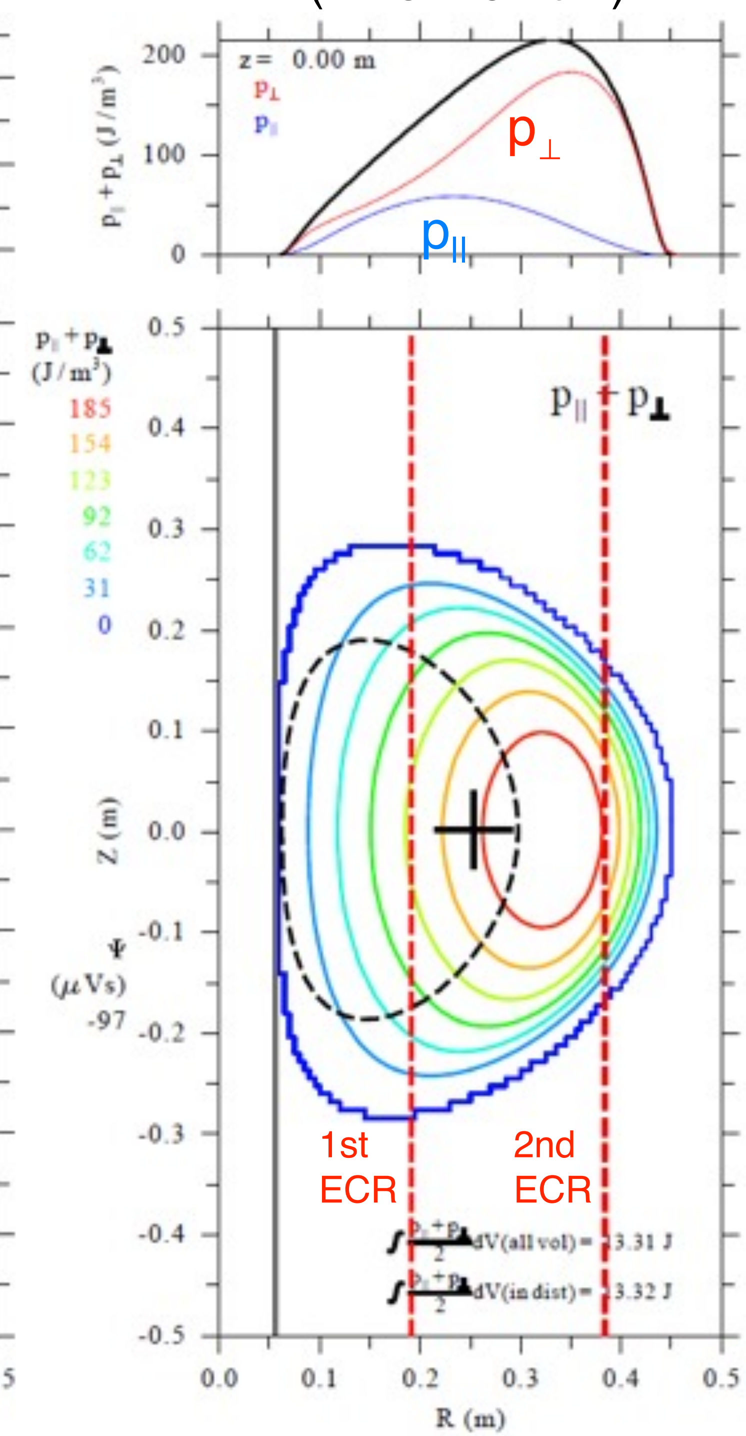
Pressure profile is estimated from equilibrium analysis

$j\times B = \nabla \cdot P \quad (P = P_{\perp} I + (P_{//} - P_{\perp})bb)$ and $\nabla \cdot j = 0$

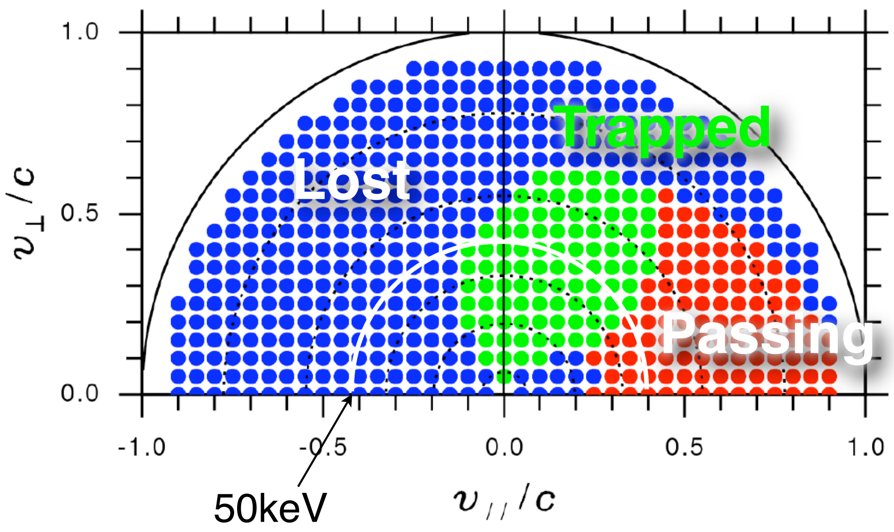
Higher density
(Bt = 0.072 T)
(R_{EC}=20.6cm)



Lower density
(Bt = 0.067 T)
(REC=19.2cm)

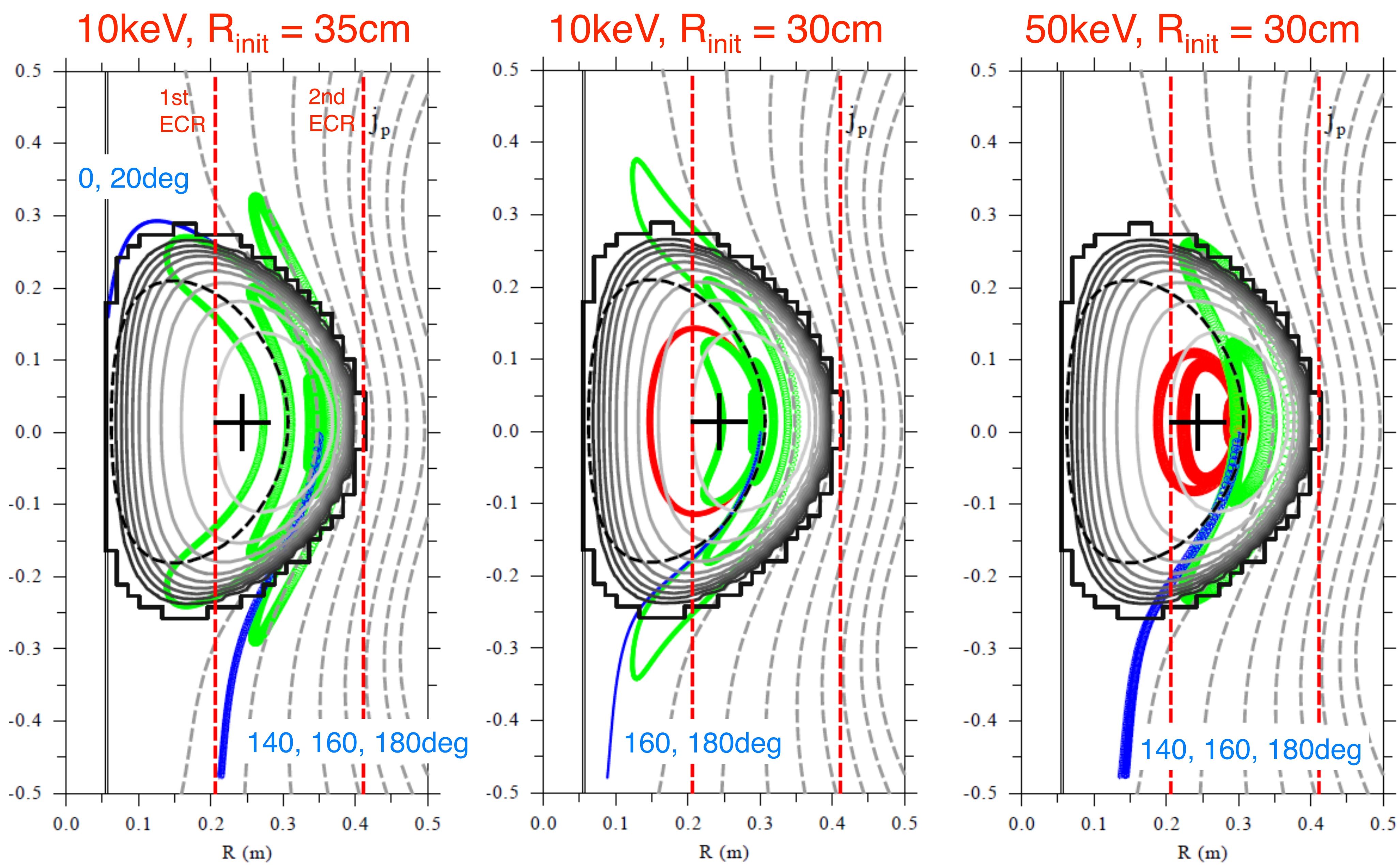


Examples of Tail Electron's Orbits



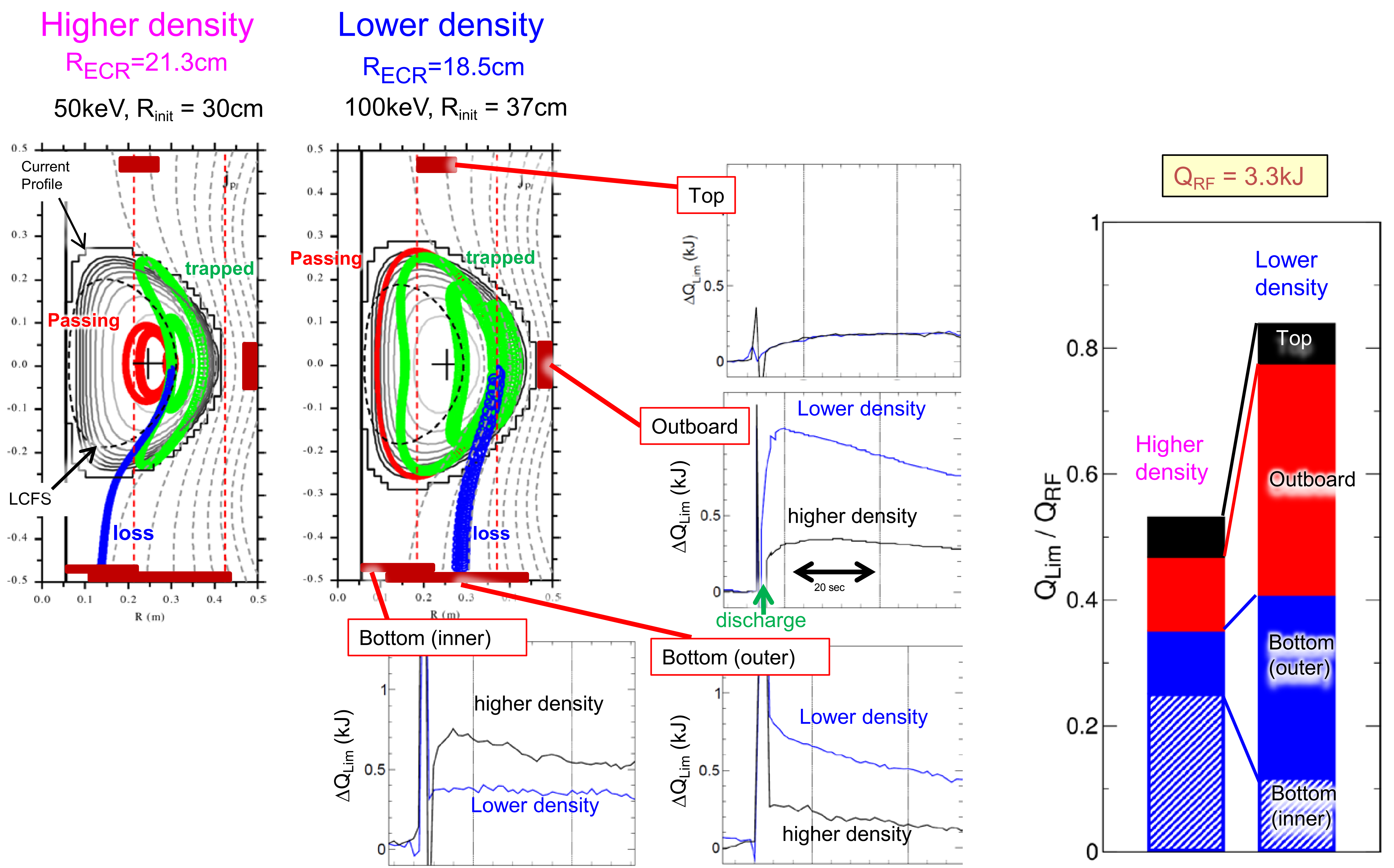
Collisionless orbits

Passing electrons
Trapped electrons
Lost electrons



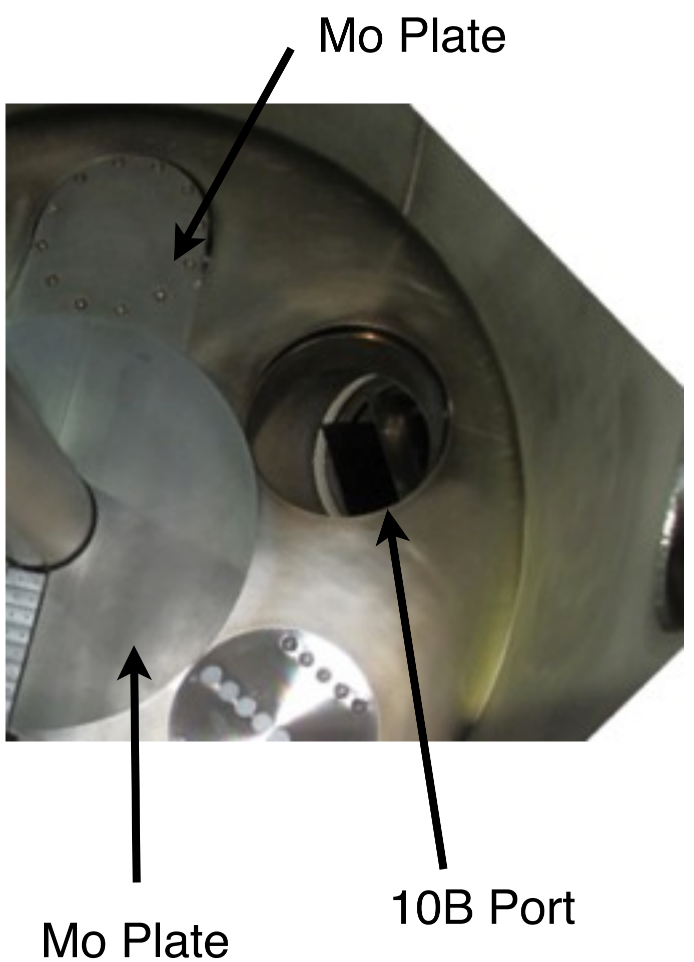
Heat Flux to the Limiter Decreases in the High Density Discharge

Heat flux to the limiters is due to the direct loss of high energy electrons.

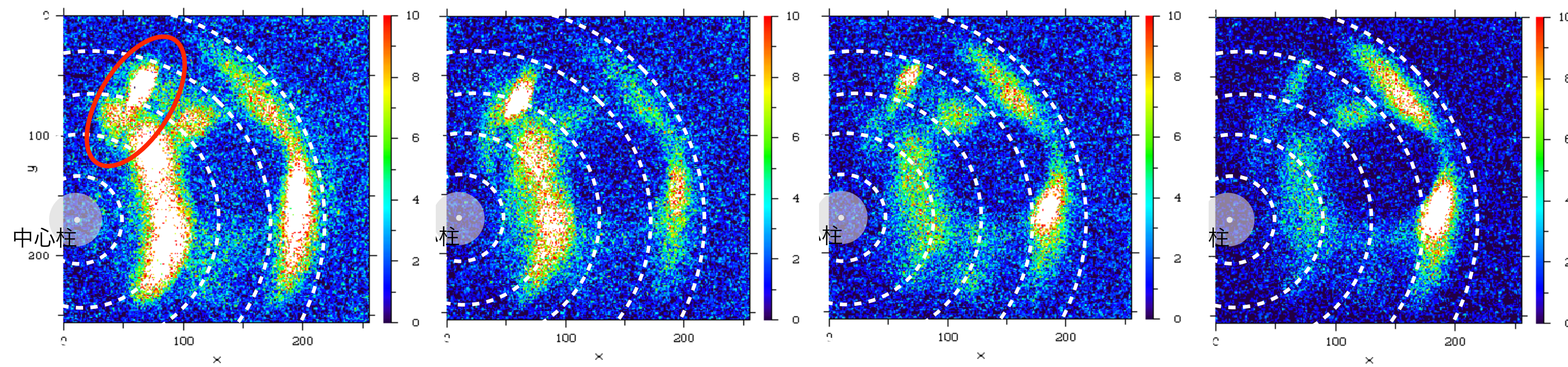


Hard X-ray Emission From the Bottom Flange

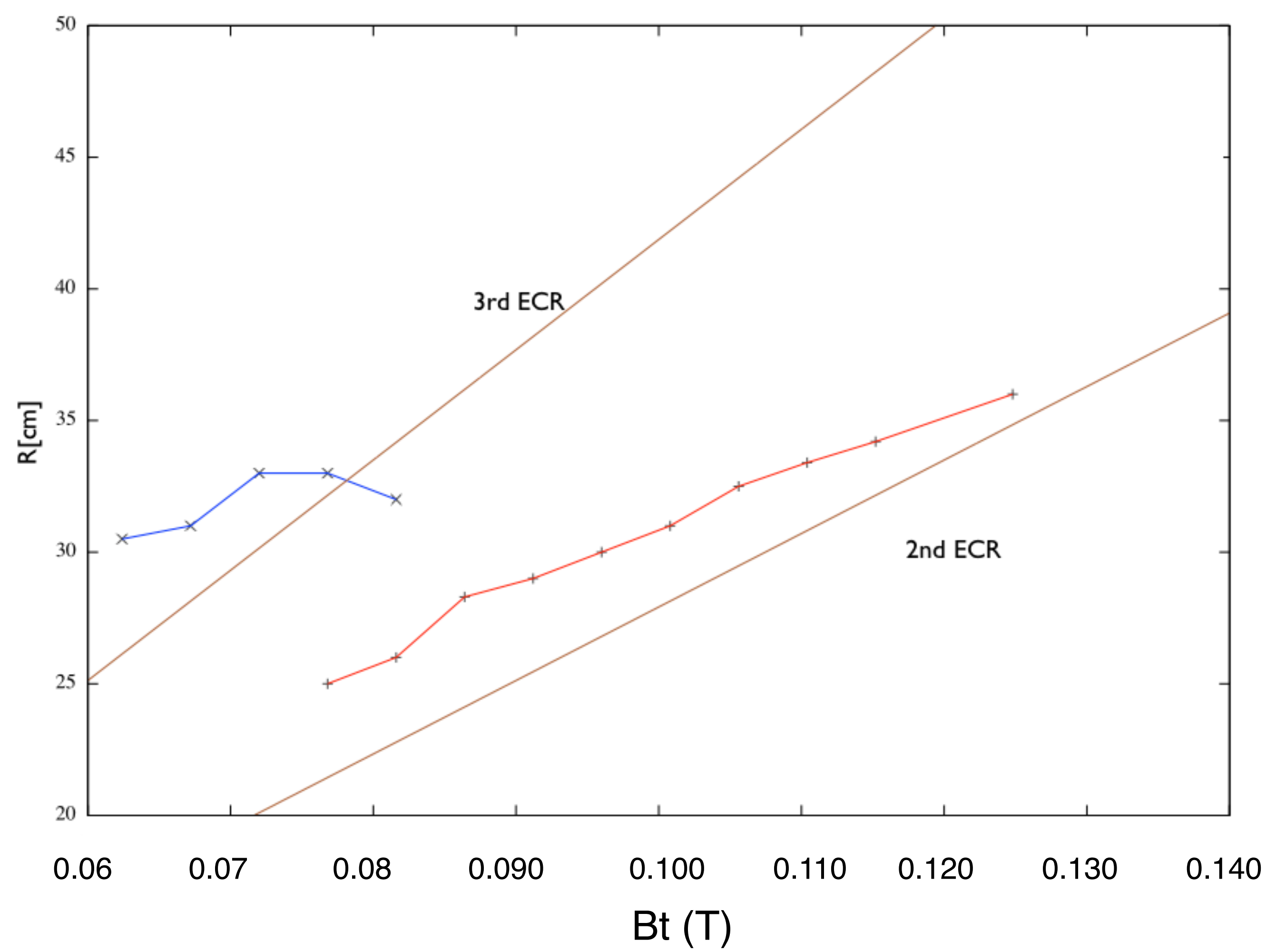
Visible Light CCD Image



HX (Ex > 40keV) Image (Preliminary Results)



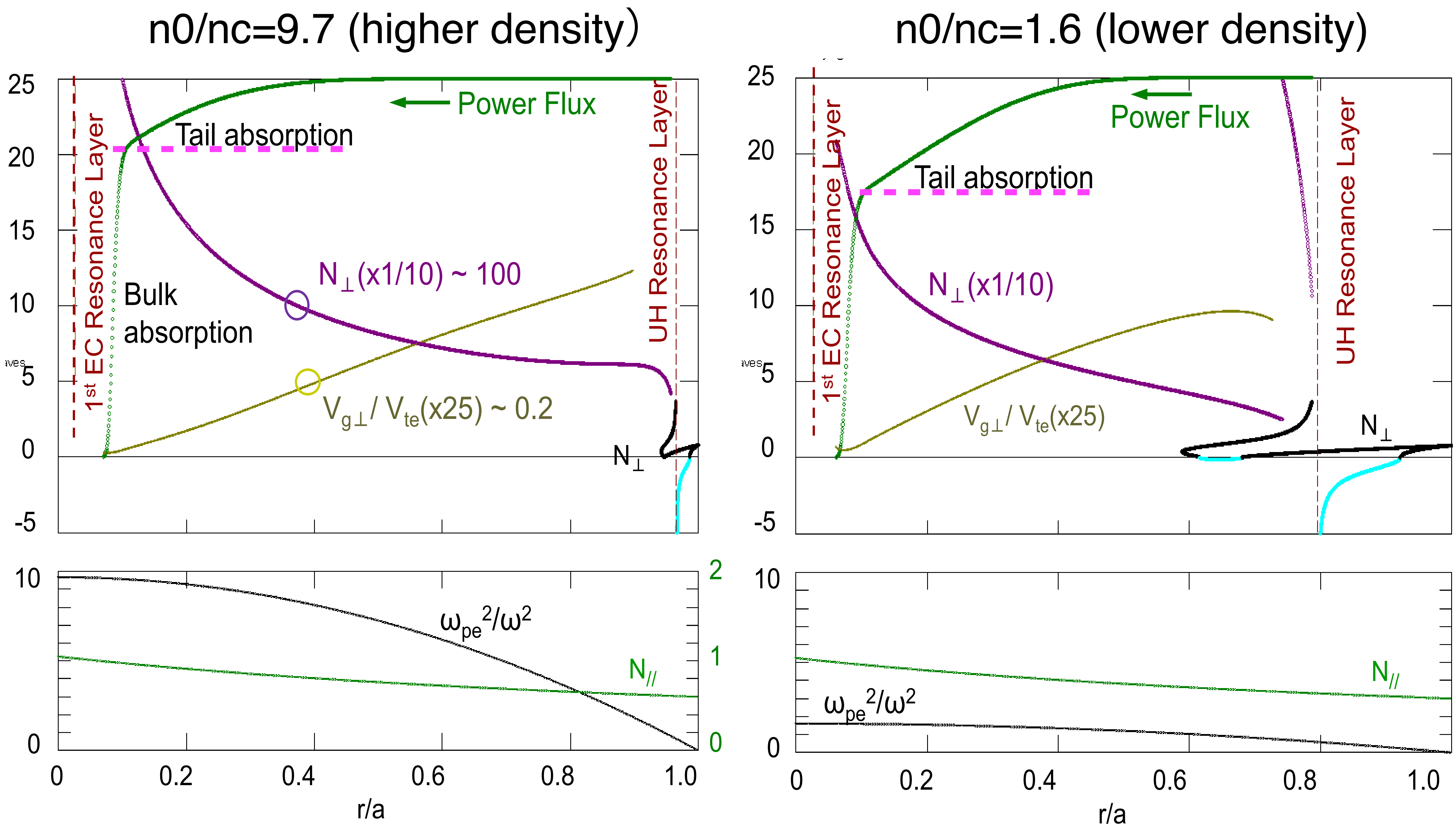
Bt = 0.0720T 0.0912T 0.1152T 0.1296T



Calculation of EBW Absorption by Bulk and Tail Electrons

f=2.45GHz
R0=0.24m
a=0.18m

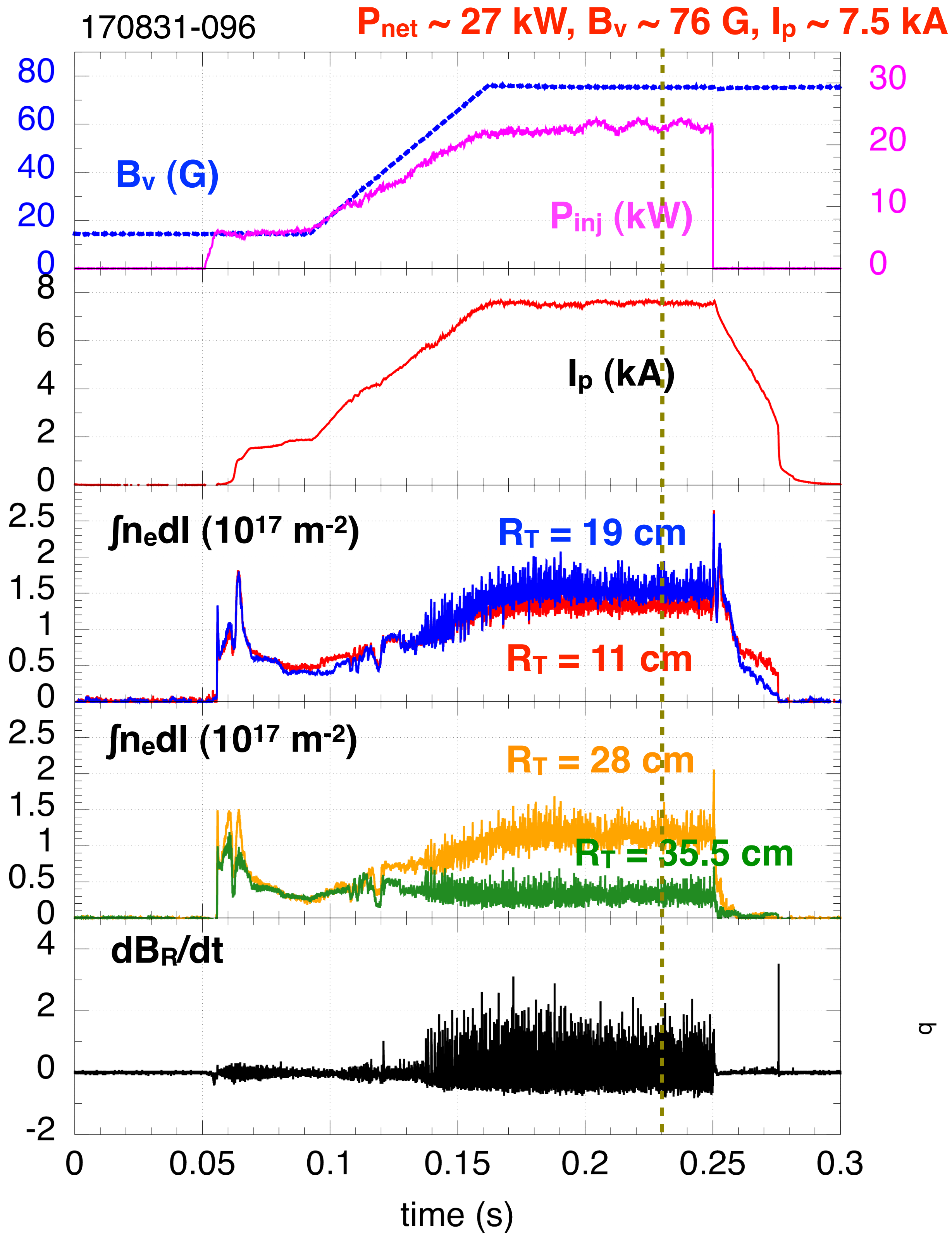
Te=100eV
Th=20keV, Ip=10kA
Nz0=0.6

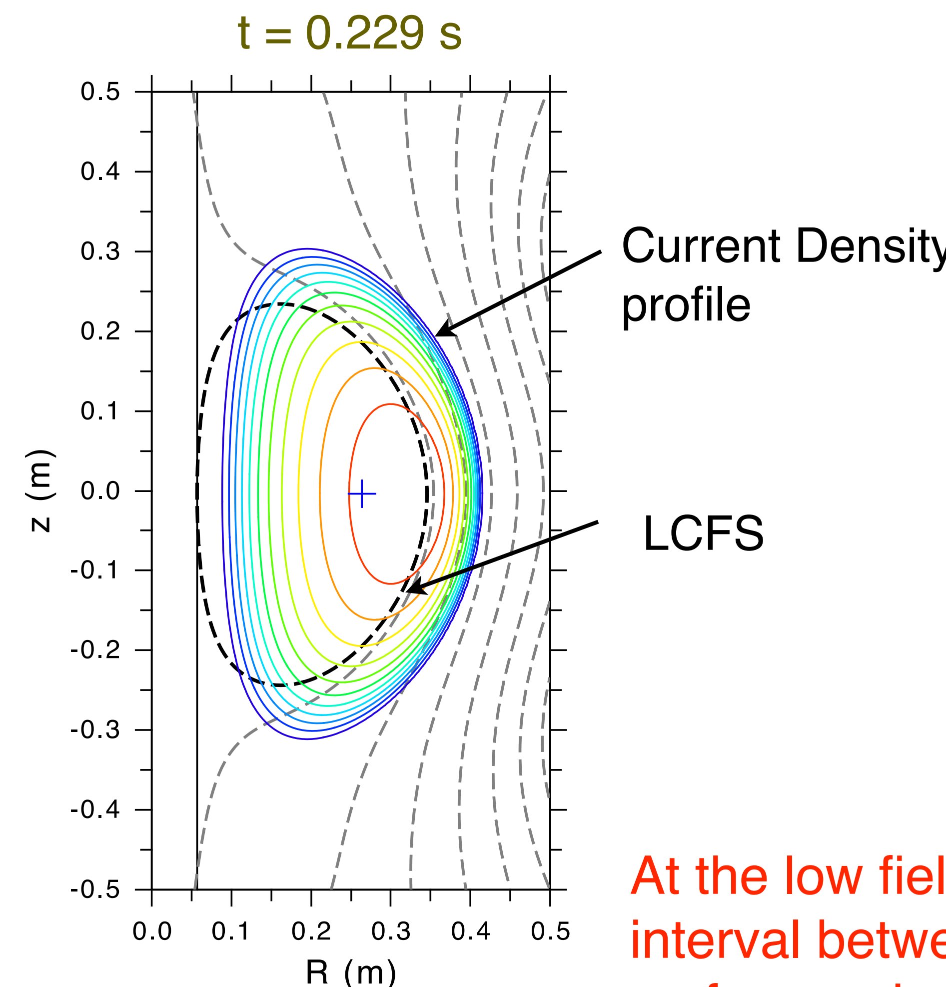


1. Introduction
2. Non-inductive Production of Highly Overdense ST Plasma by EBW
3. Confinement of High Energy Tail Electrons Which Carry the Toroidal Plasma Current
4. Magnetic Activities and Intermittent Plasma Ejection Phenomena in an Overdense ST Plasma sustained by EBW
5. Summary

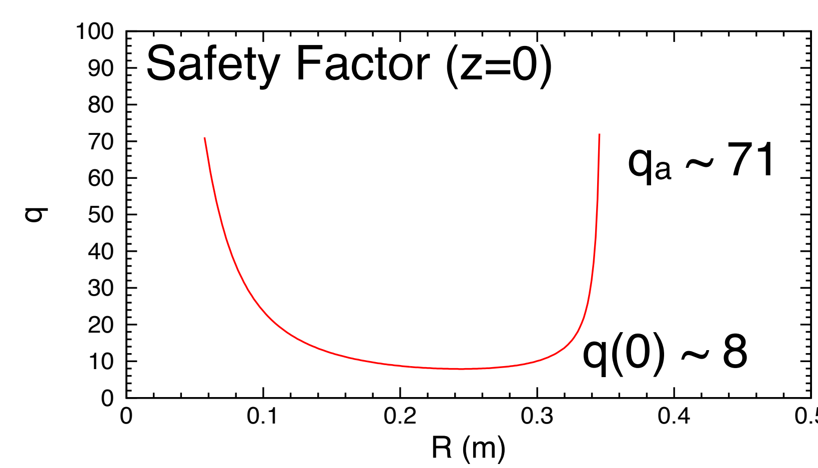
Typical Discharge Waveforms

Magnetic activities and Density Fluctuations are observed in highly overdense plasma produced by 2.45 GHz



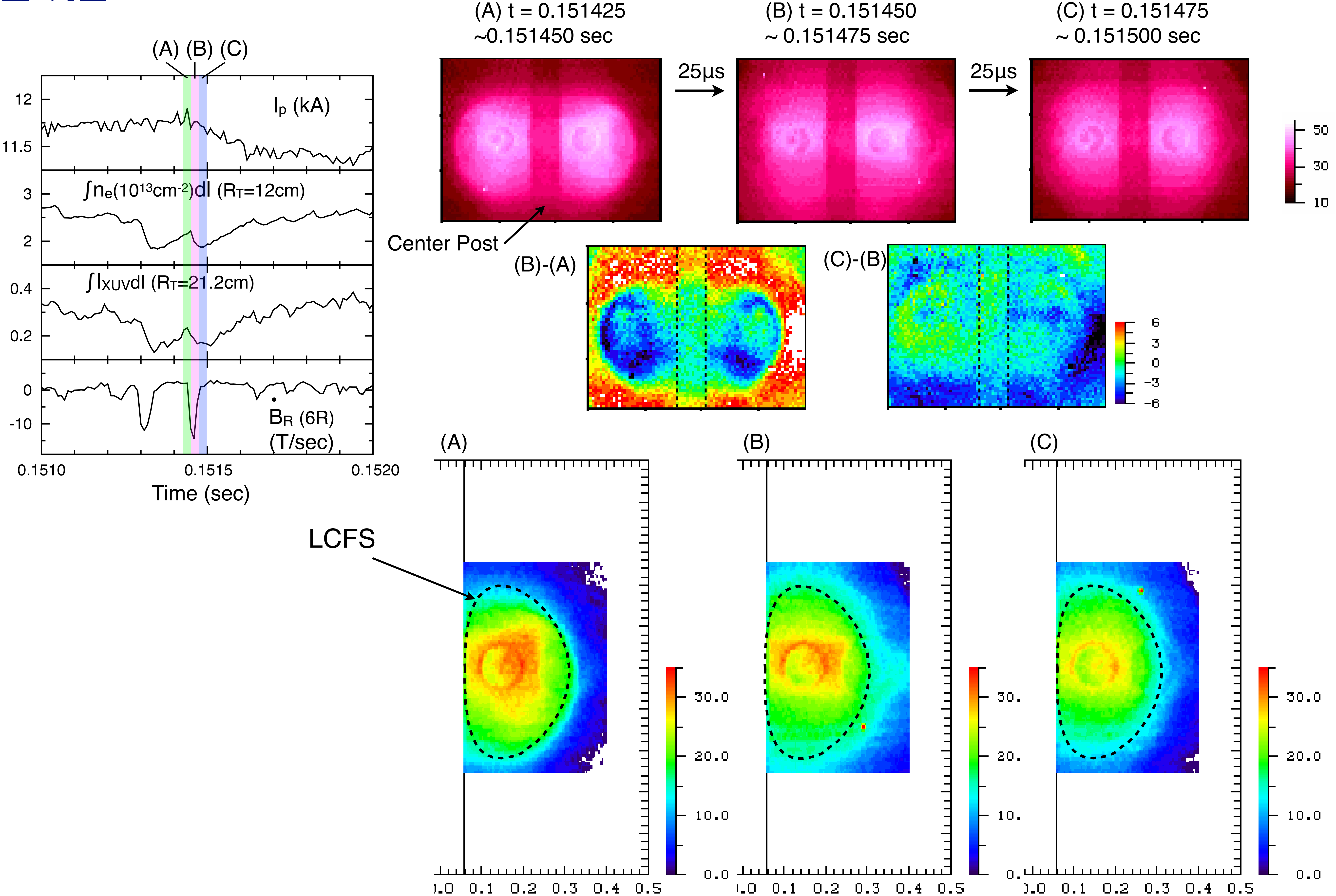


At the low field side, interval between rational surfaces ~ ion Larmor radius ~ 0.7 cm*

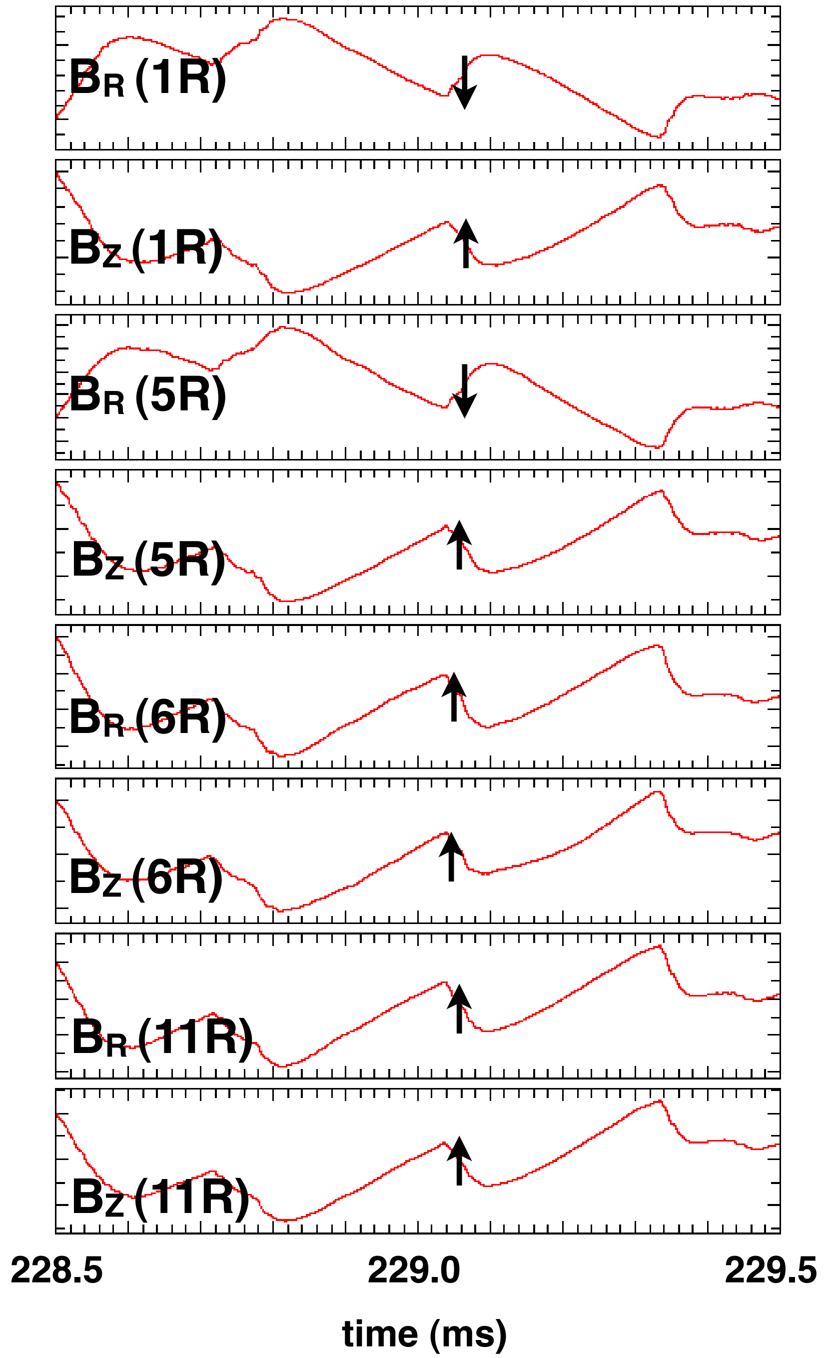


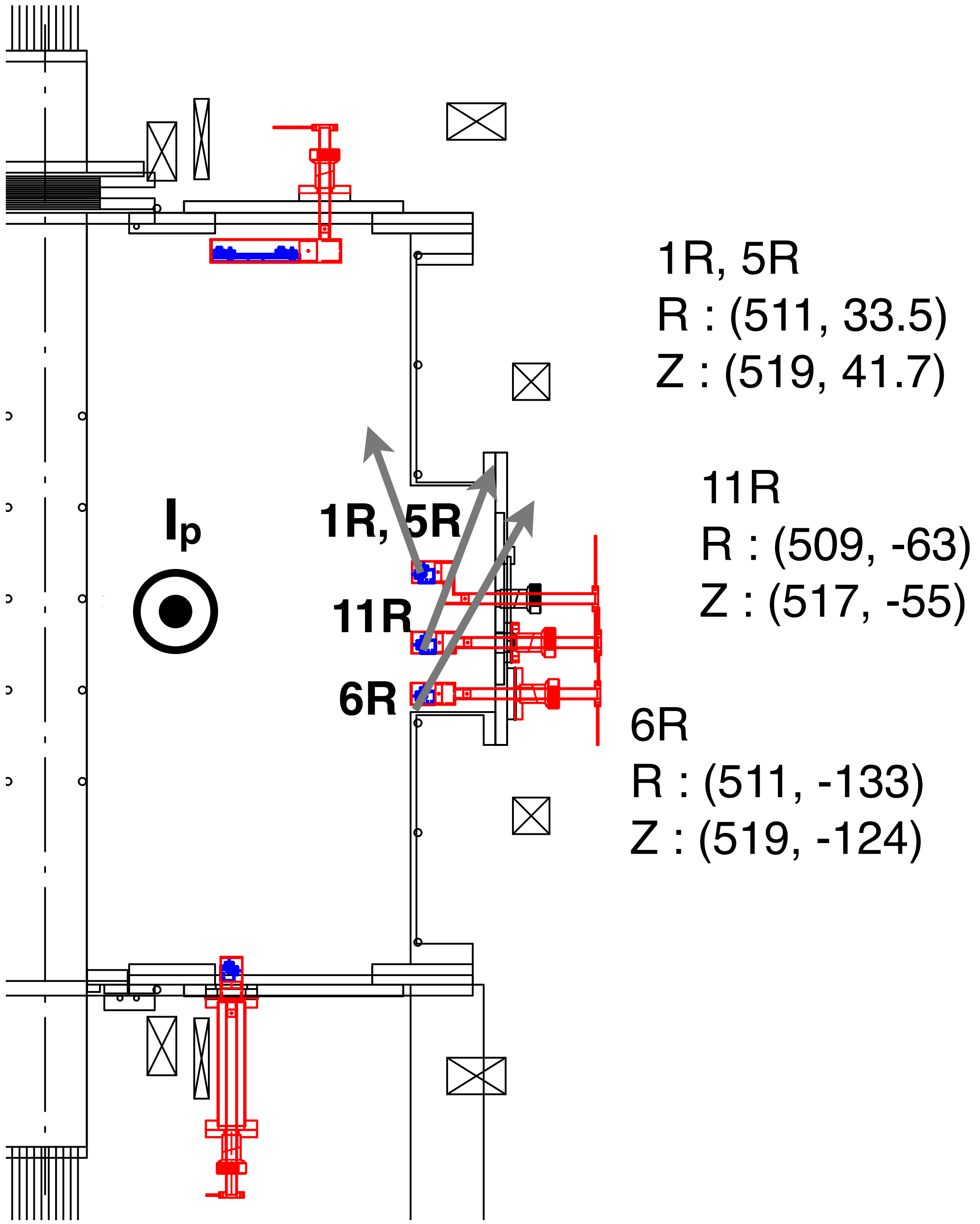
T_i ~ 10 eV by Spectroscopy (Doppler broadening)

Plasma is Ejected Through LCFS

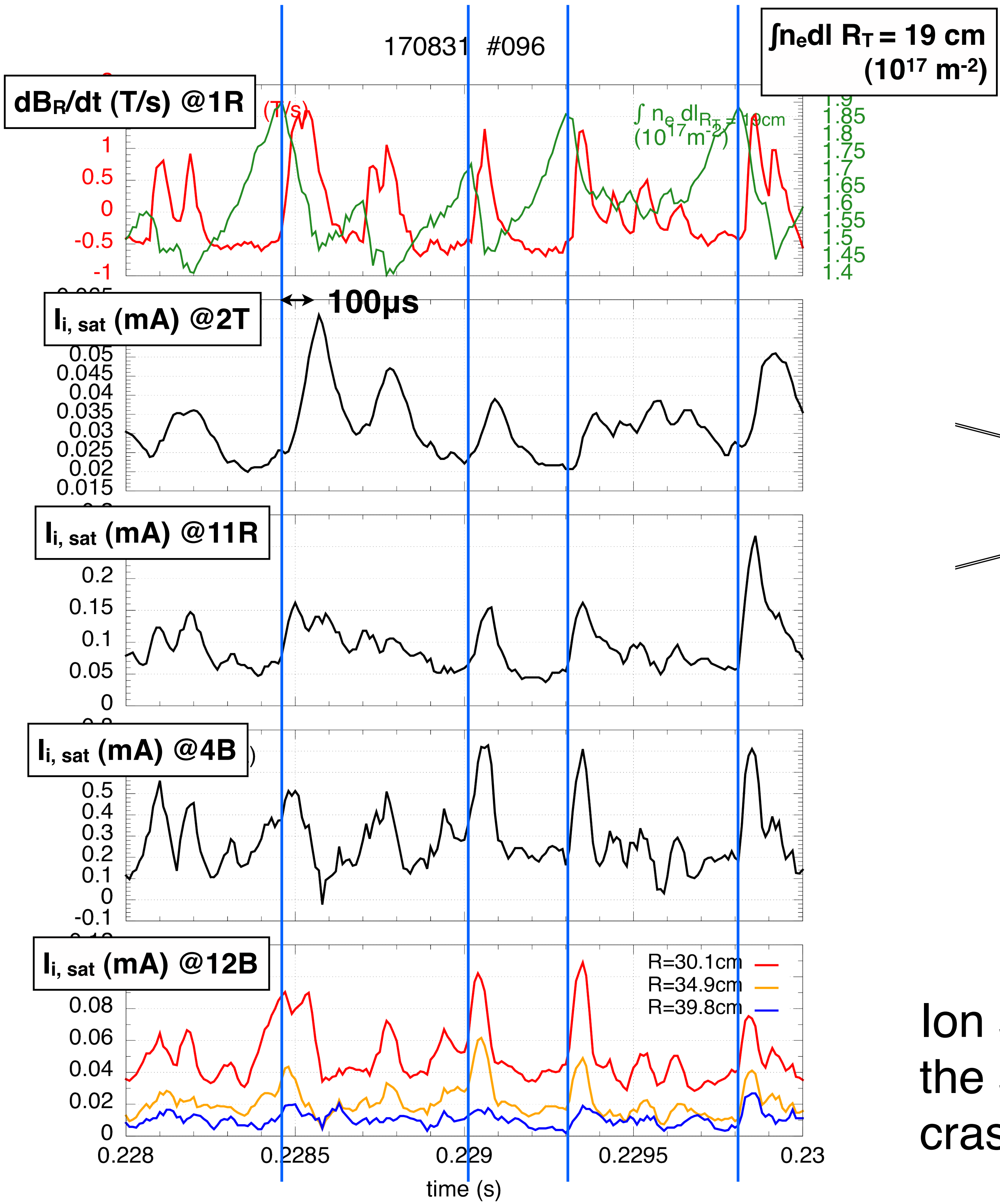


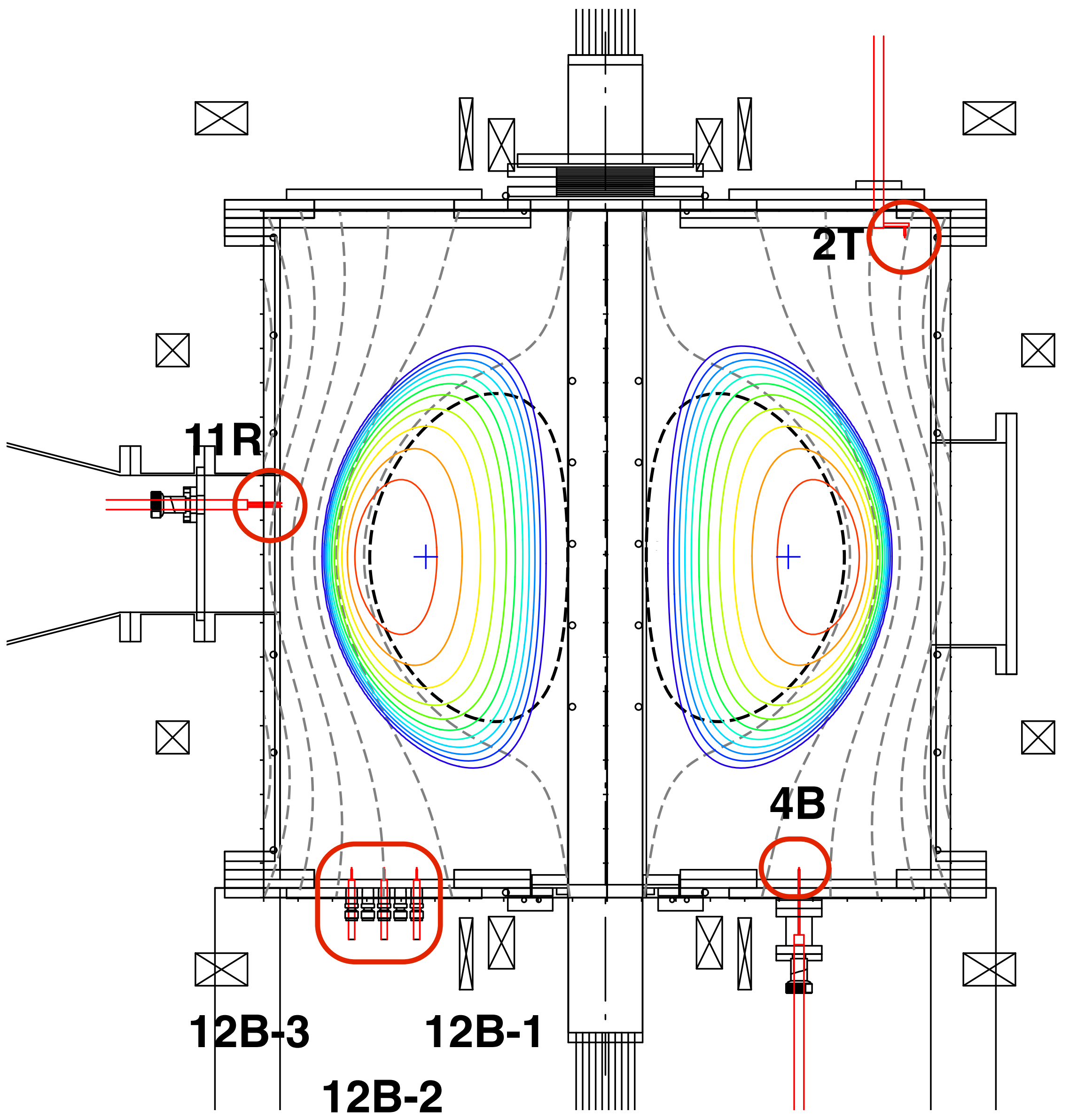
Poloidal Field Changes Such As Ip Decreases At The Event





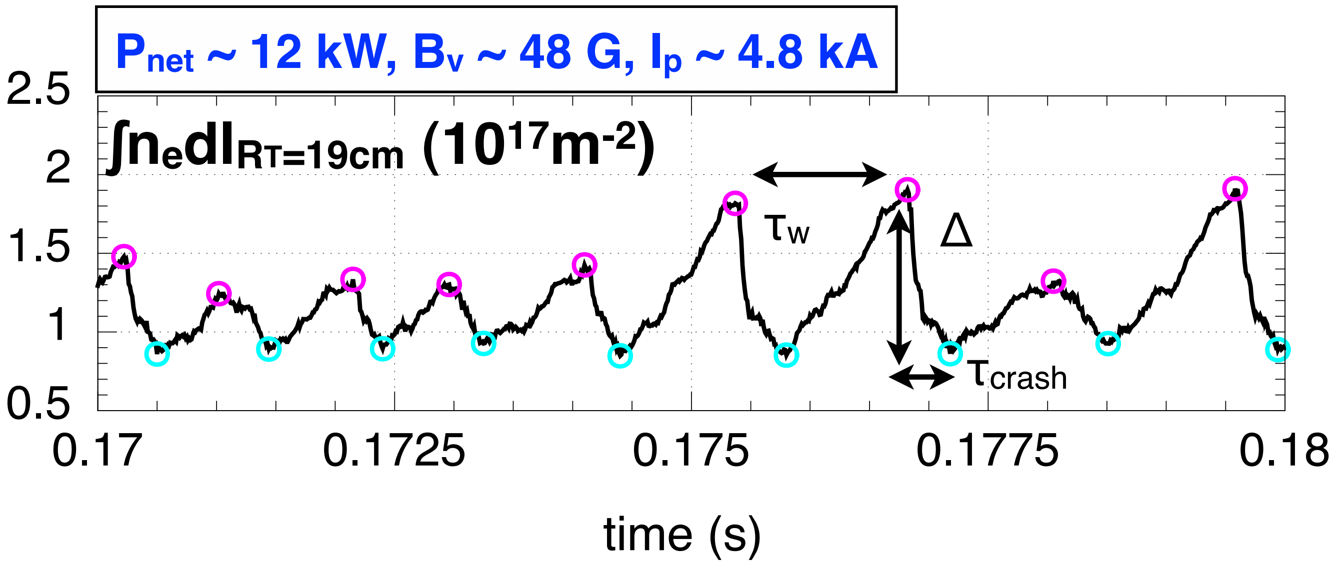
Change of Scrape-off Plasma

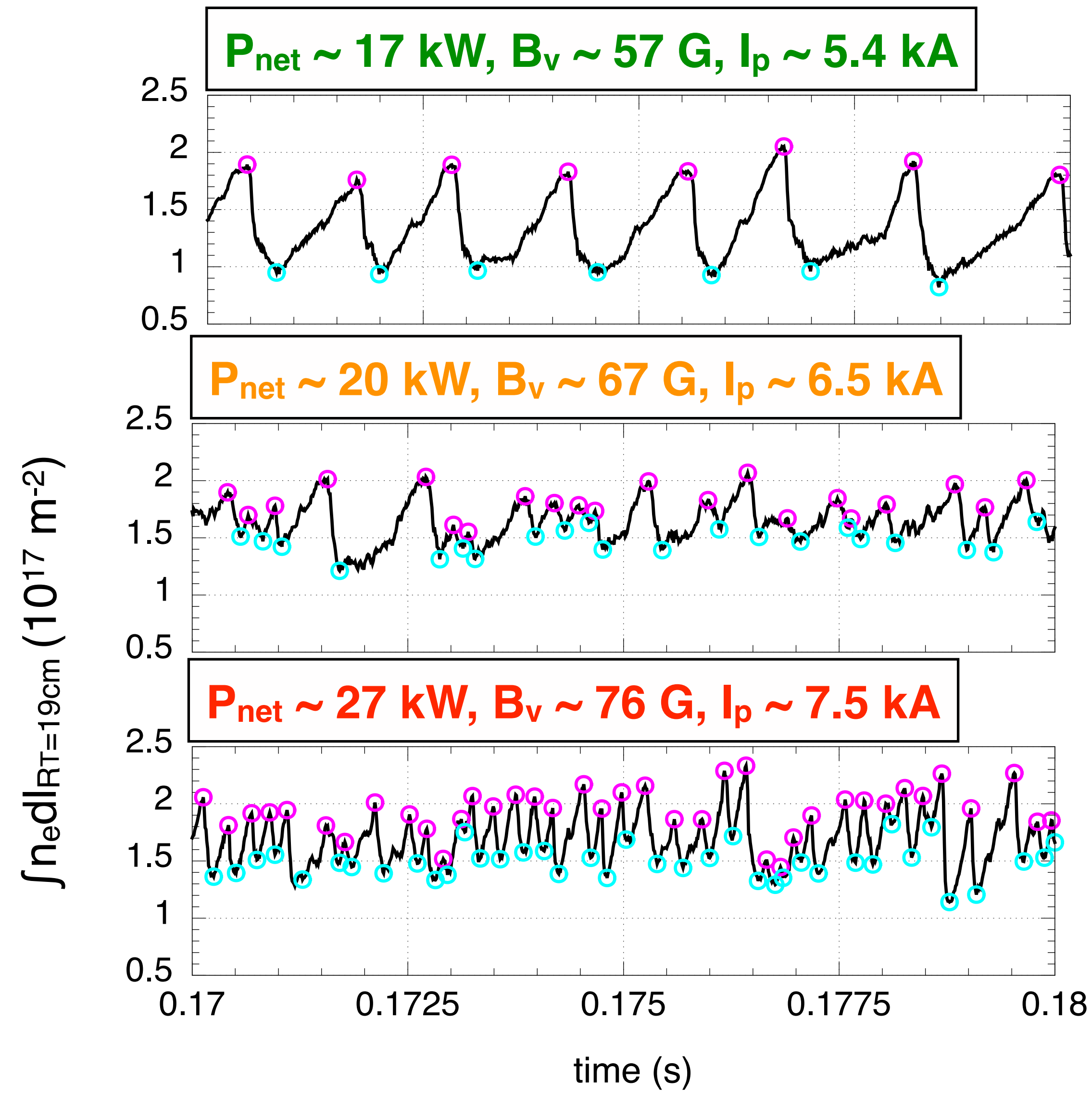




Ion saturation currents measured at the scrape-off region increase at the crash events.

Time Evolution of Line Density





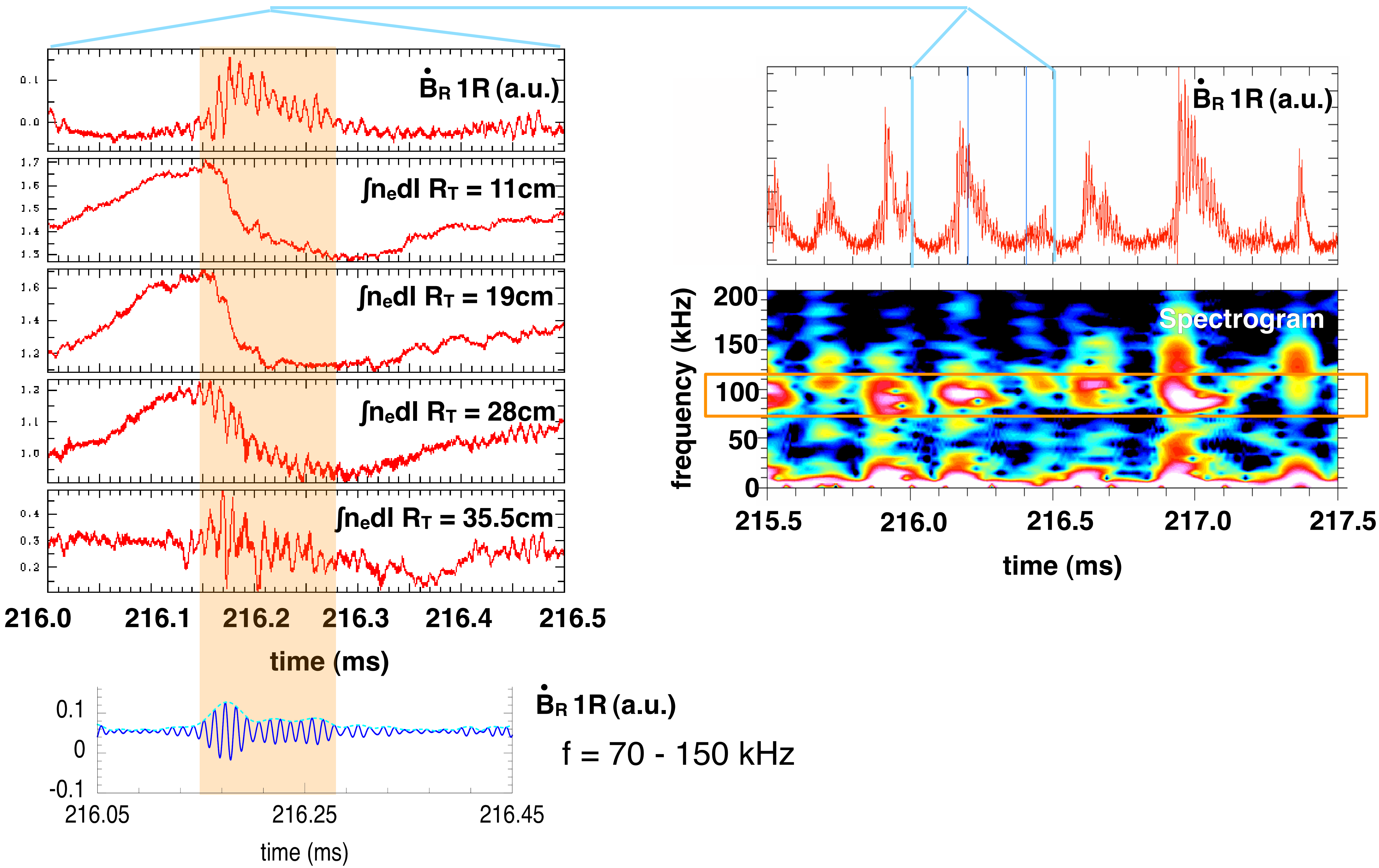
Intermittent Occurrence of Crash Events

* Slow ramp : interval time T_w
* Fast crash : crash time τ_{crash}
* Amplitude : Δ

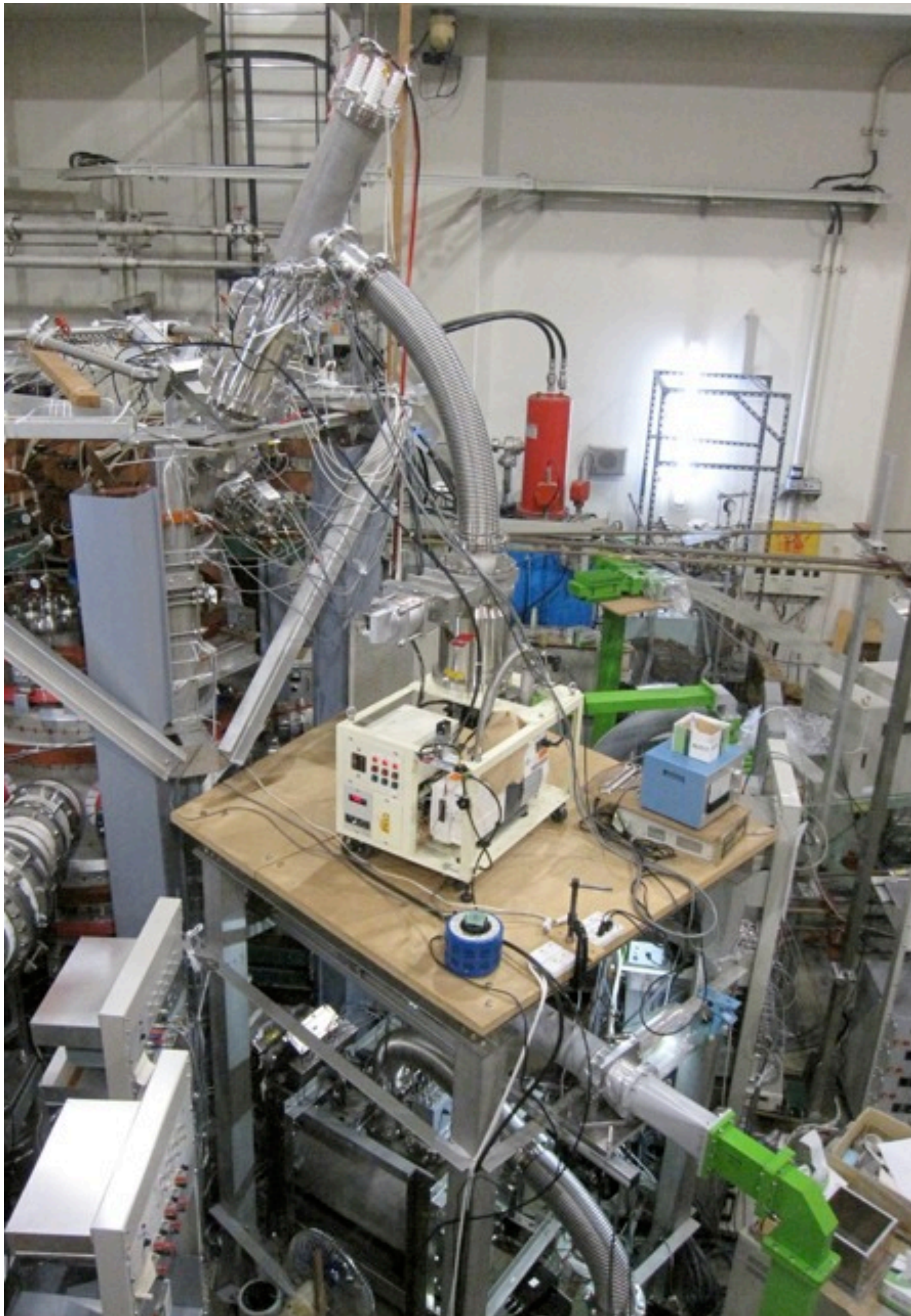
* Interval time becomes shorter as plasma current and injected power increase.
* Crash time becomes shorter as plasma current and injected power increase.
* Amplitude becomes larger as the peak density increases.
  Amplitude becomes smaller as plasma current and injected power increase.

Oscillations (f ~ 100 kHz) During the Crash

Data obtained by 10MHz A/D converters

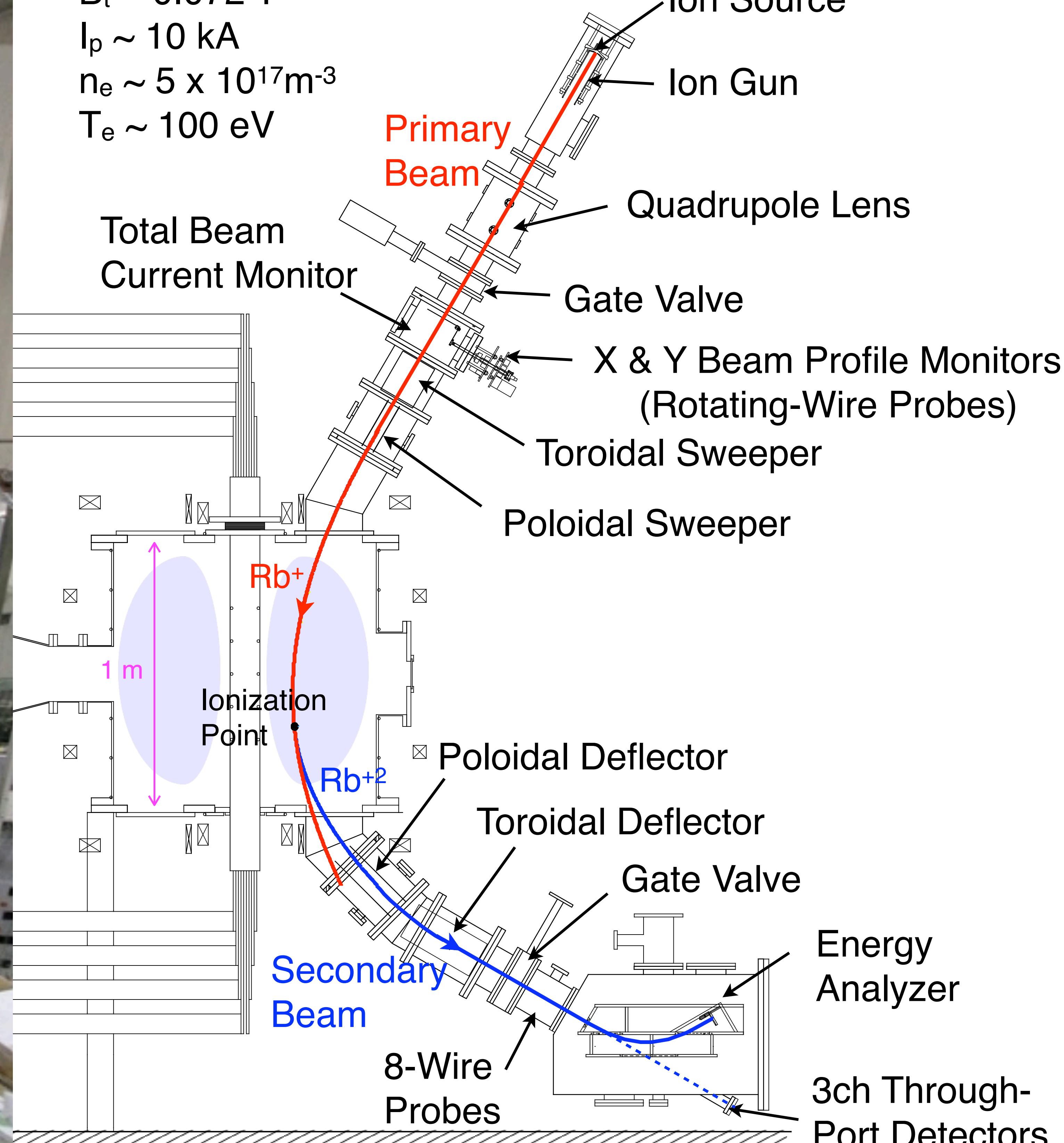


Heavy Ion Beam Probe System for LATE



Target Plasma Parameters

$B_t \sim 0.072$ T
$I_p \sim 10$ kA
$n_e \sim 5 \times 10^{17} m^{-3}$
$T_e \sim 100$ eV

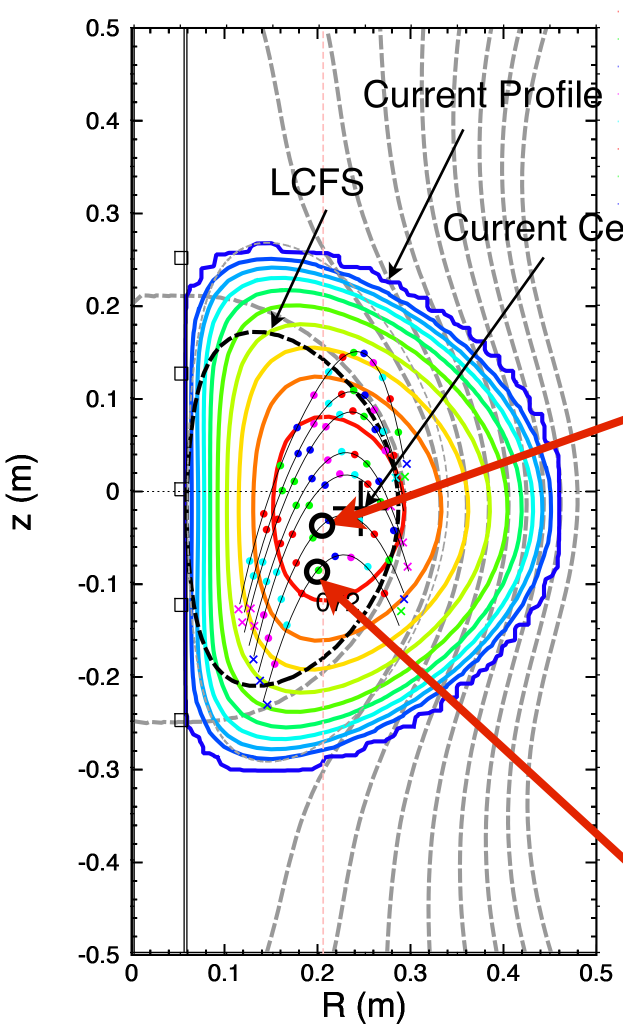


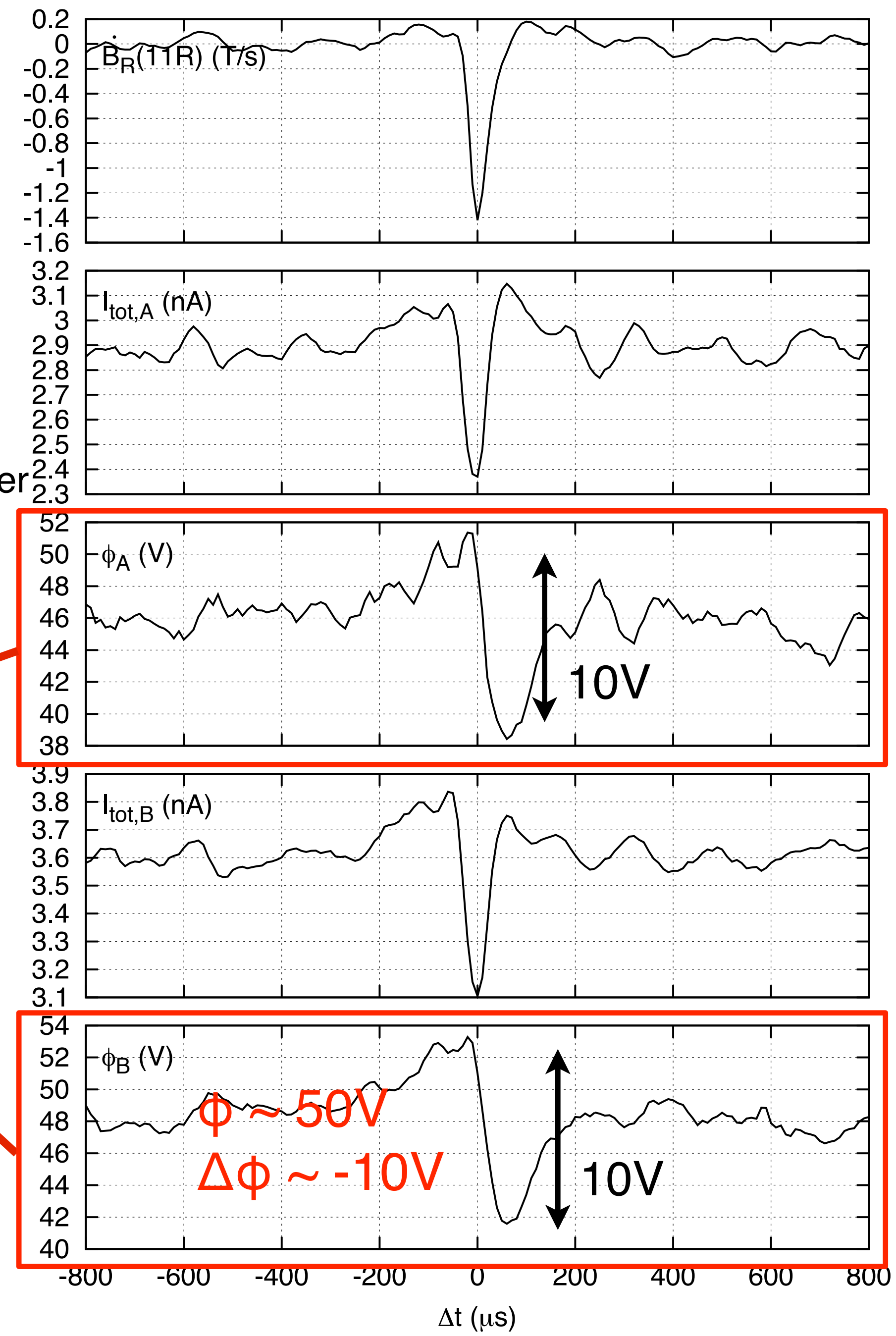
Potential Change during an Event

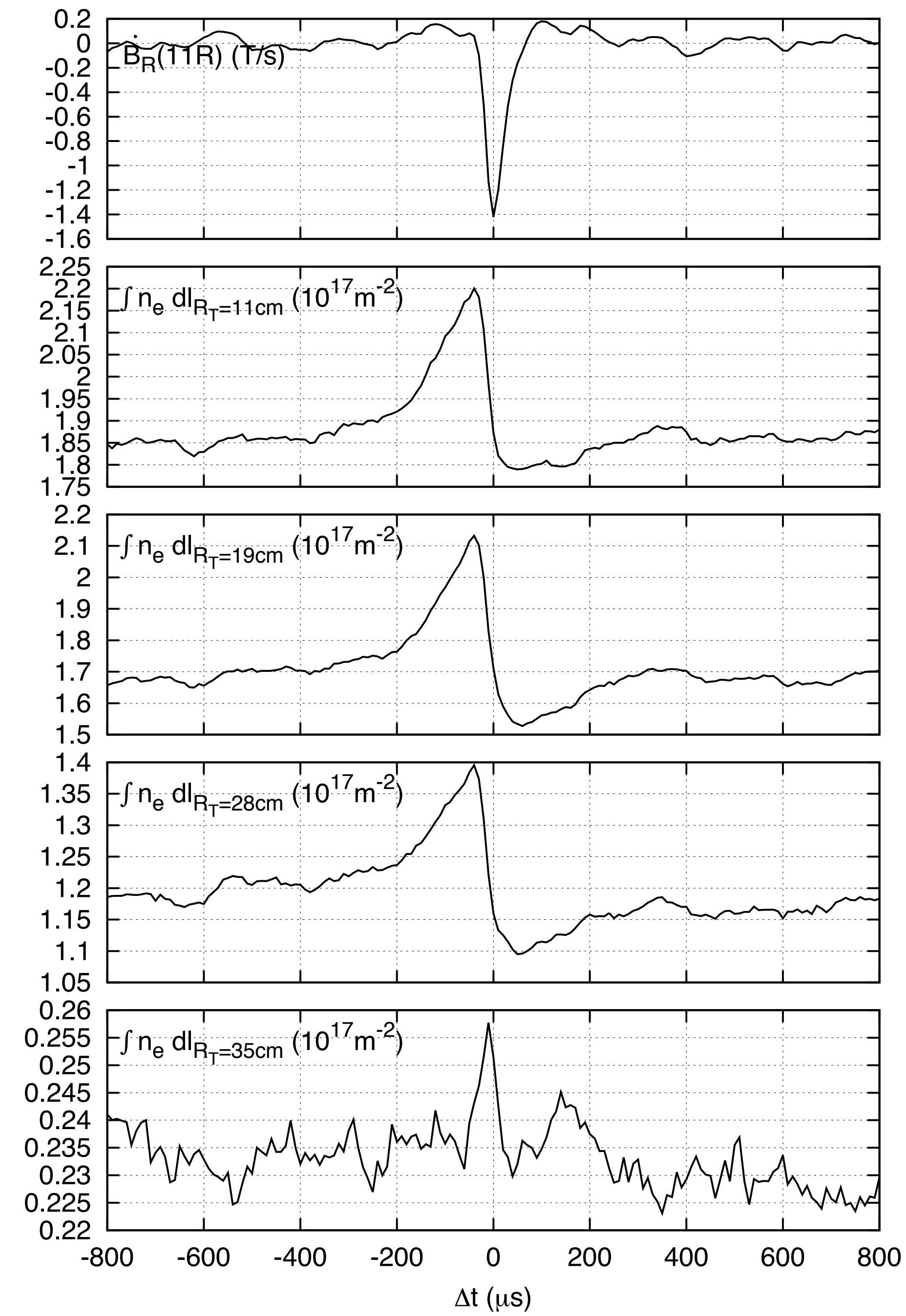
reference sig. : MP-11R-dBR
threshold = -4σ+μ (σ : std. dev., μ : mean value)
number of averaged event ：73

conditional averaging during t = 0.17 ~ 0.25 sec

(Preliminary Results)
170125-072
t=0.200sec







Summary

* Highly overdense ST plasmas are produced non-inductively with EBW mode-converted via O-X-B scheme when EBW is excited in the 1st propagation band and the fundamental EC resonance layer is located in the plasma core.

* Plasma current is carried by high energy tail electrons with average energy of some tens of keV and with population of ~1/10 of the bulk electrons.
  The bulk electron temperature is ~100 eV and the density is 6 ~7 times the plasma cutoff density, but the pressure is ~ 1/10 of the total pressure. The high energy tail electrons have 90% of the total pressure.

* The global confinement time is less than 1ms.
  Absorbed microwave energy is mainly lost to the limiter and the vessel walls by the electrons' orbit loss.
  In the case of higher density discharges, population of high energy tail electrons in the low field side is reduced and the heat flow to the limiter and the vessel walls decrease.

* Intermittent events of plasma ejection through LCFS occur when the plasma current and the density increase, which may limit the density increase.
  Preliminary measurement by HIBP shows that the positive potential (ϕ~50V) decreases by $\Delta\phi$~ -10V and returns back during the event.