18th International Spherical Torus Workshop (ISTW 2015) and 2015 US-Japan Workshop on ST Plasmas,
Princeton University, 3-6 November 2015

# Recent Results on Non-inductive Formation of Spherical Torus by Electron Bernstein Wave Heating and Current Drive in LATE

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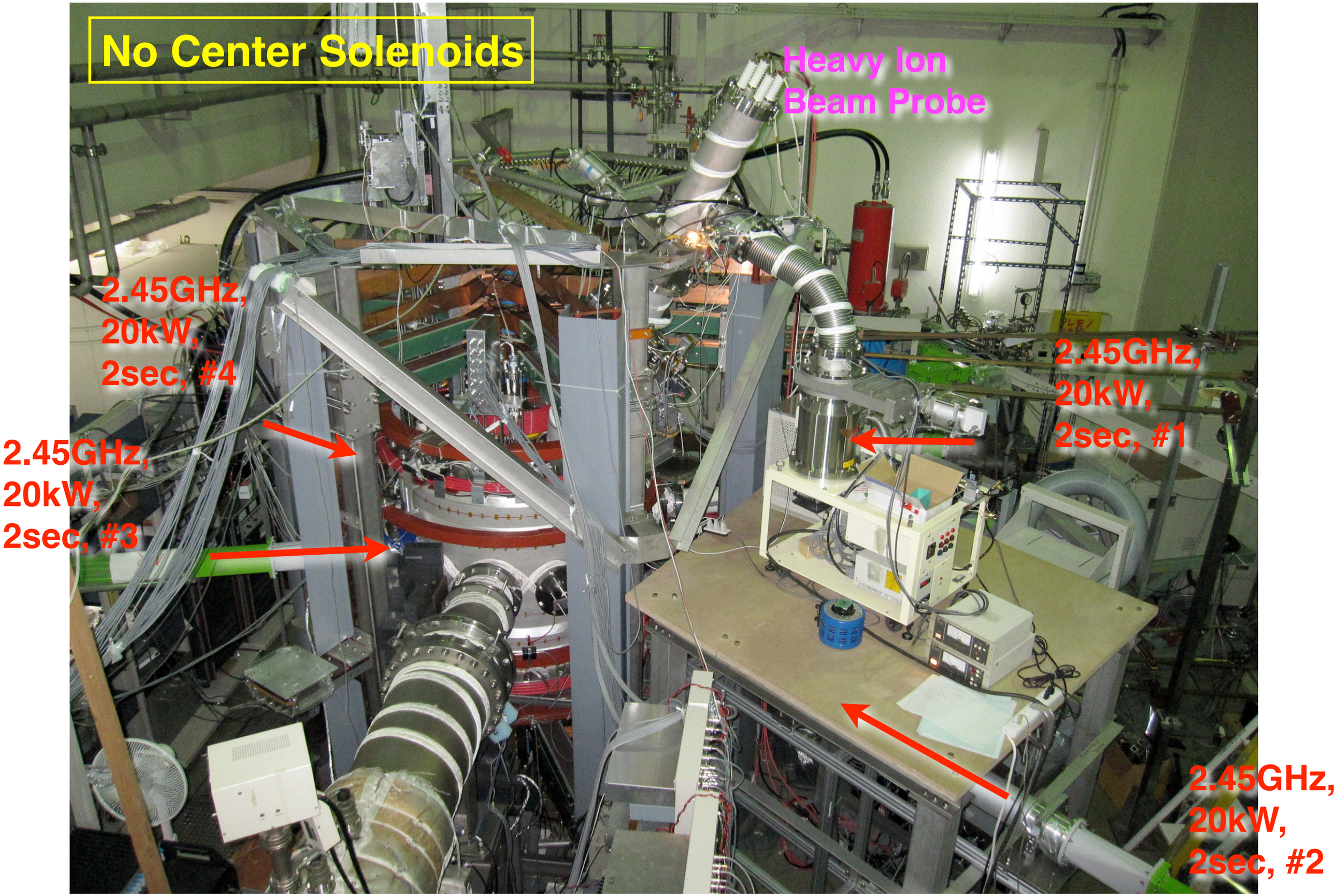
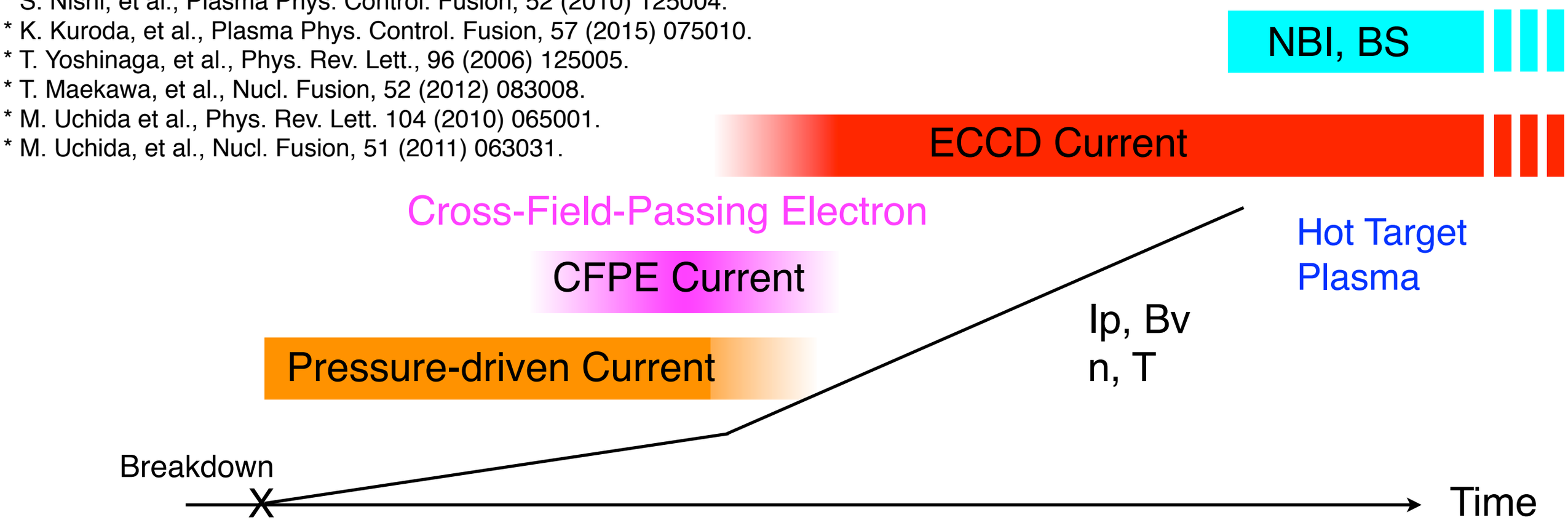
# LATE (Low Aspect ratio Torus Experiment)



# Research Objective : Non-inductive Start-up by ECH/ECCD

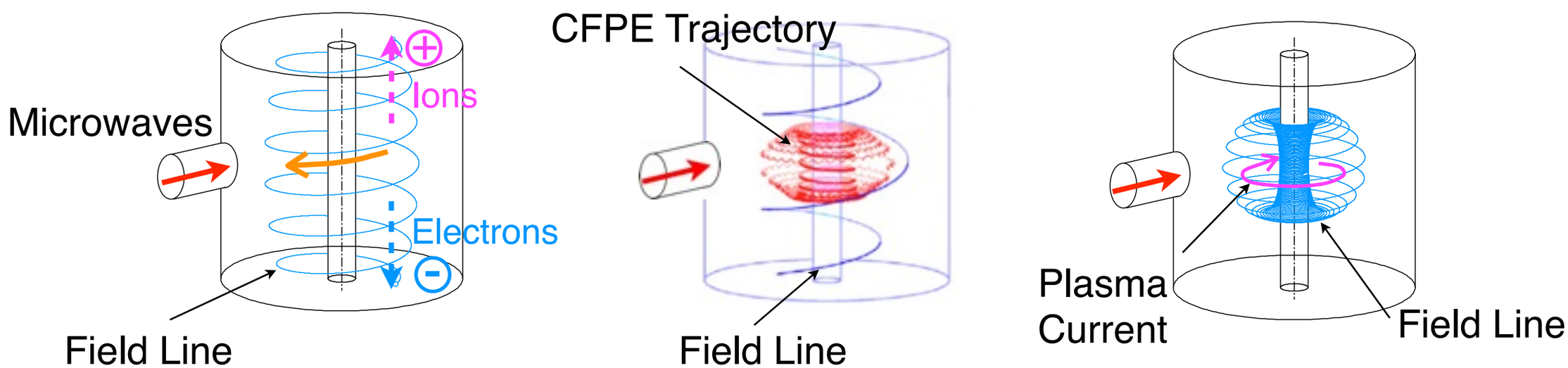

* S. Nishi, et al., Plasma Phys. Control. Fusion, 52 (2010) 065011.
* S. Nishi, et al., Plasma Phys. Control. Fusion, 52 (2010) 125004.
* K. Kuroda, et al., Plasma Phys. Control. Fusion, 57 (2015) 075010.
* T. Yoshinaga, et al., Phys. Rev. Lett., 96 (2006) 125005.
* T. Maekawa, et al., Nucl. Fusion,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


Toroidal ECR Plasma

Formation of Closed Flux Surfaces

Ramp-up



# Outline

* Non-inductive Startup Experiment with 2.45 GHz Microwave.

Excitation of EBW at the 1st Propagation Band and
Polarization Control for Optimal Mode-Conversion
to Achieve a High-Density and High-Current Plasma

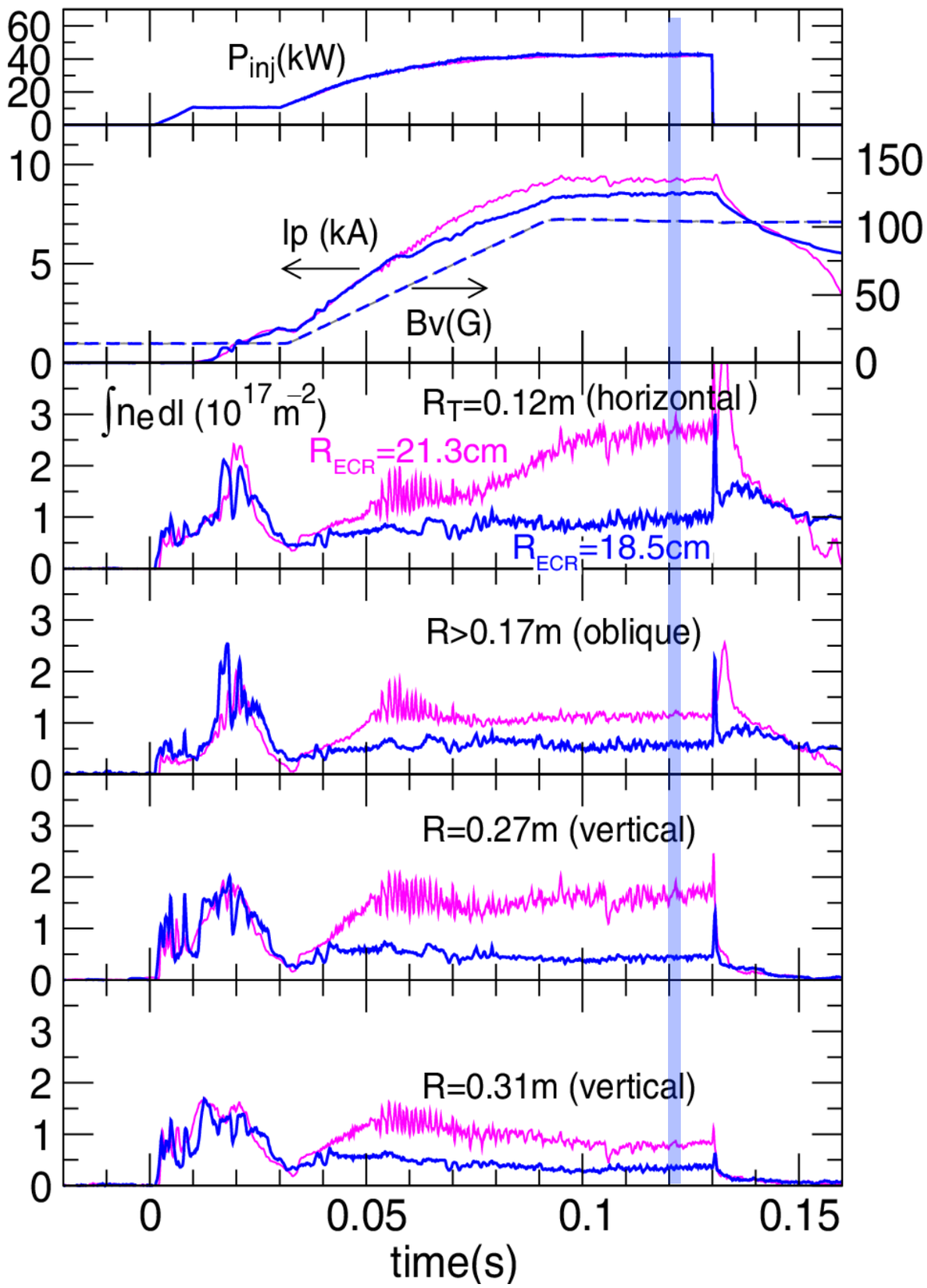
* Non-inductive Startup Experiment with 5GHz Microwave

Excitation of EBW at the 1st Propagation Band
to Achieve a High-Density Plasma

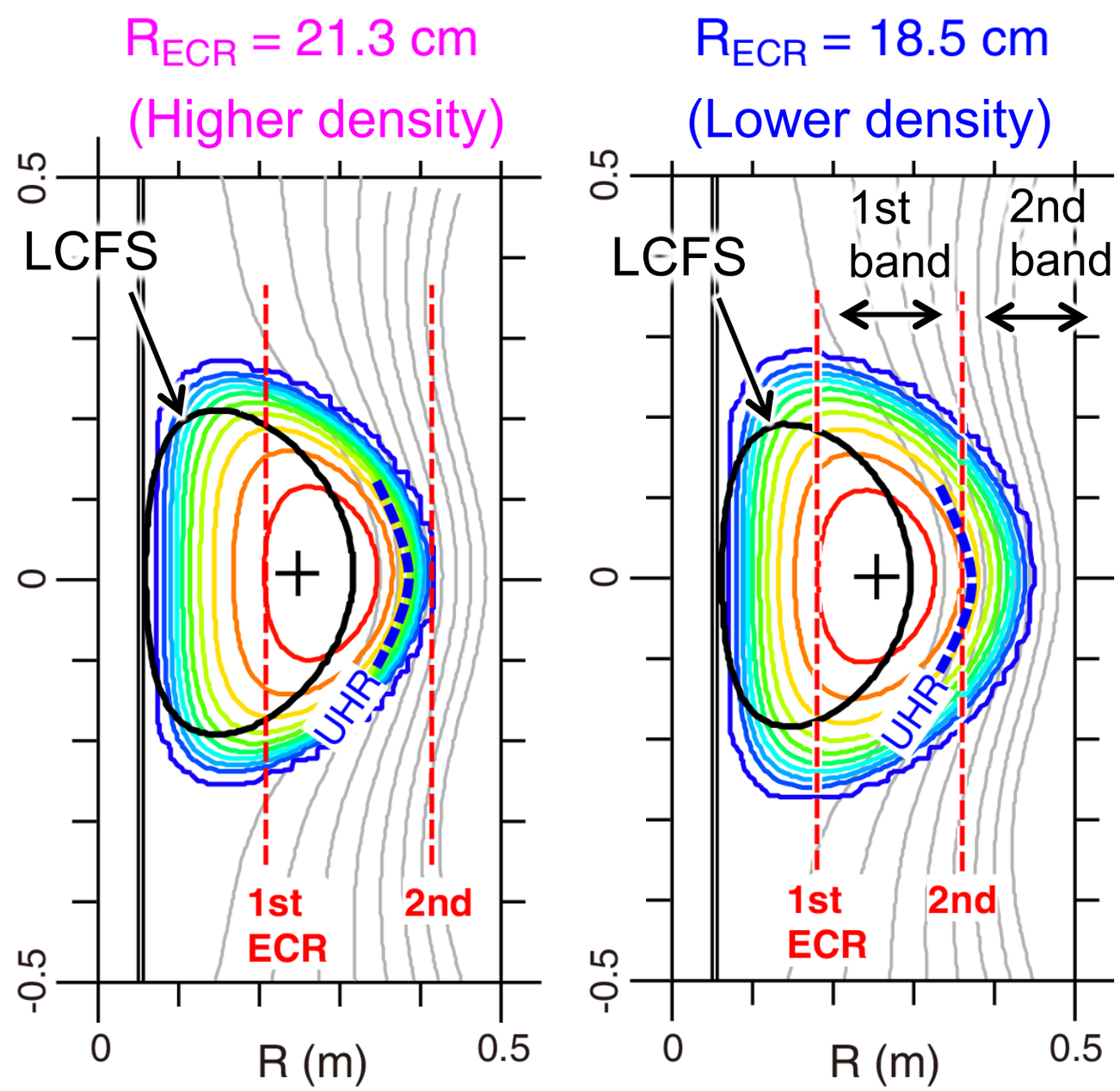
* Space Potential Measurement by HIBP in a ST Plasma
Produced Non-inductively by EBW with 2.45 GHz Microwave.

# A High-Density Plasma with ~7 Times the Cutoff DensityDensity

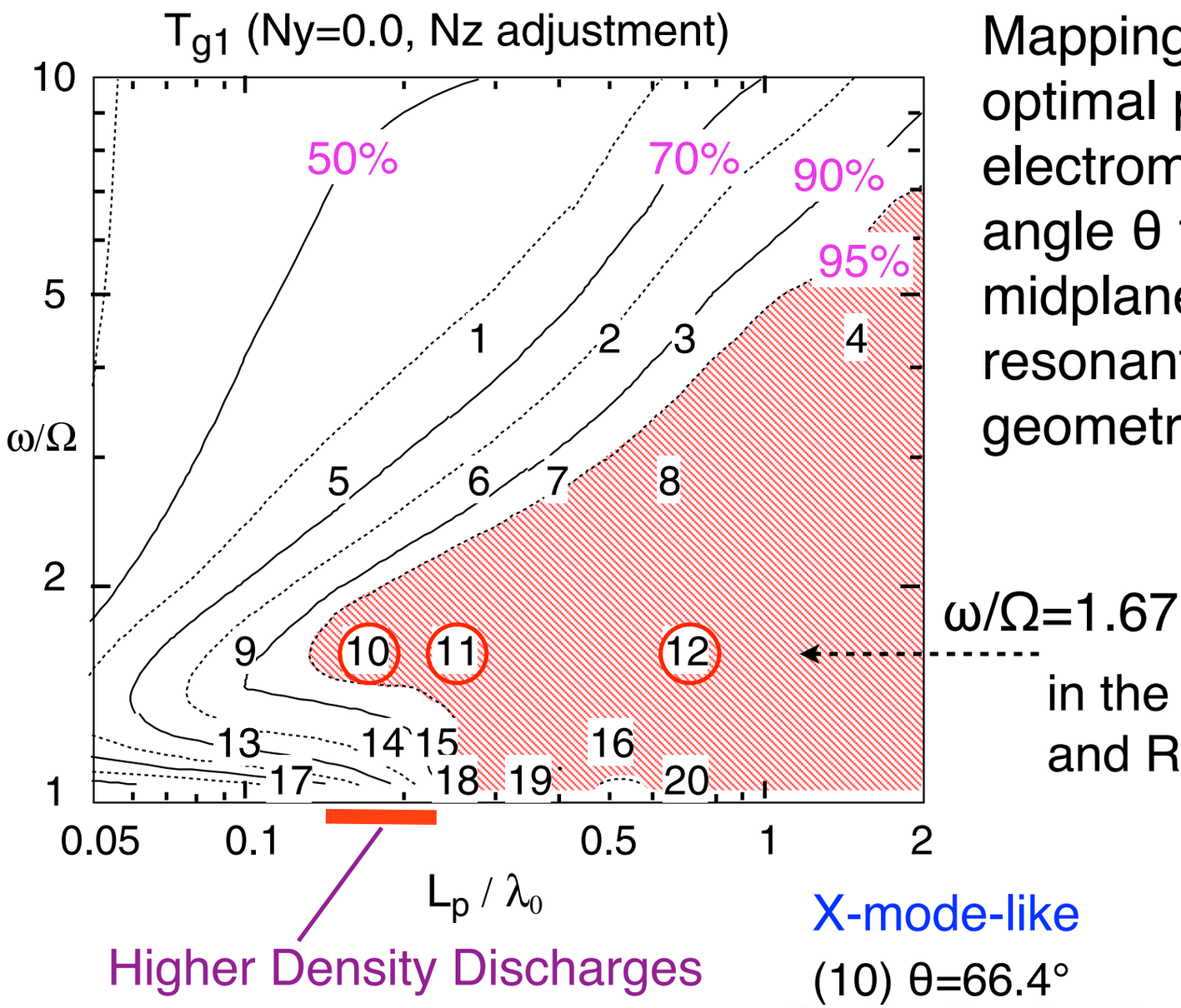
O-mode Injection




A high-density plasma with ~7 times the cutoff density is produced when EBW is excited at the 1st propagation band.



# Optimal Polarization for EBW Mode Conversion

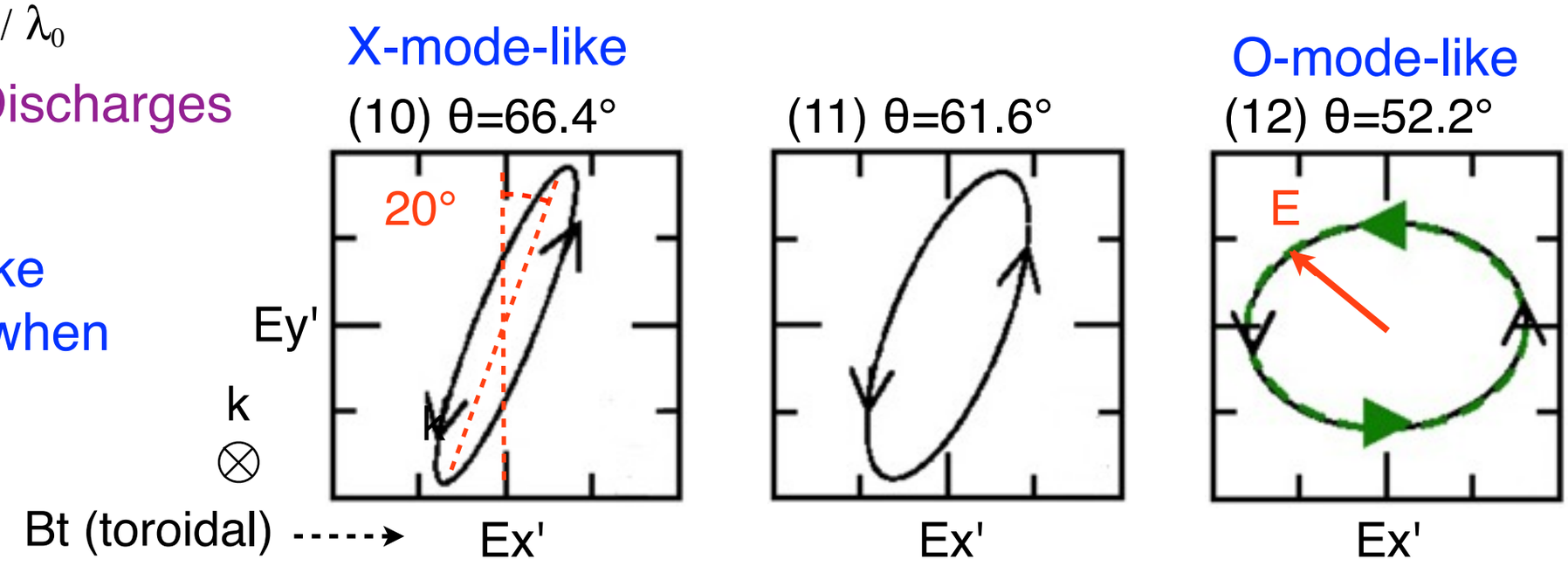



Mapping of mode conversion efficiency for optimal polarization when an electromagnetic wave is injected at an angle θ to the magnetic field on the midplane, calculated with the cold plasma resonant absorption model in the slab geometry.

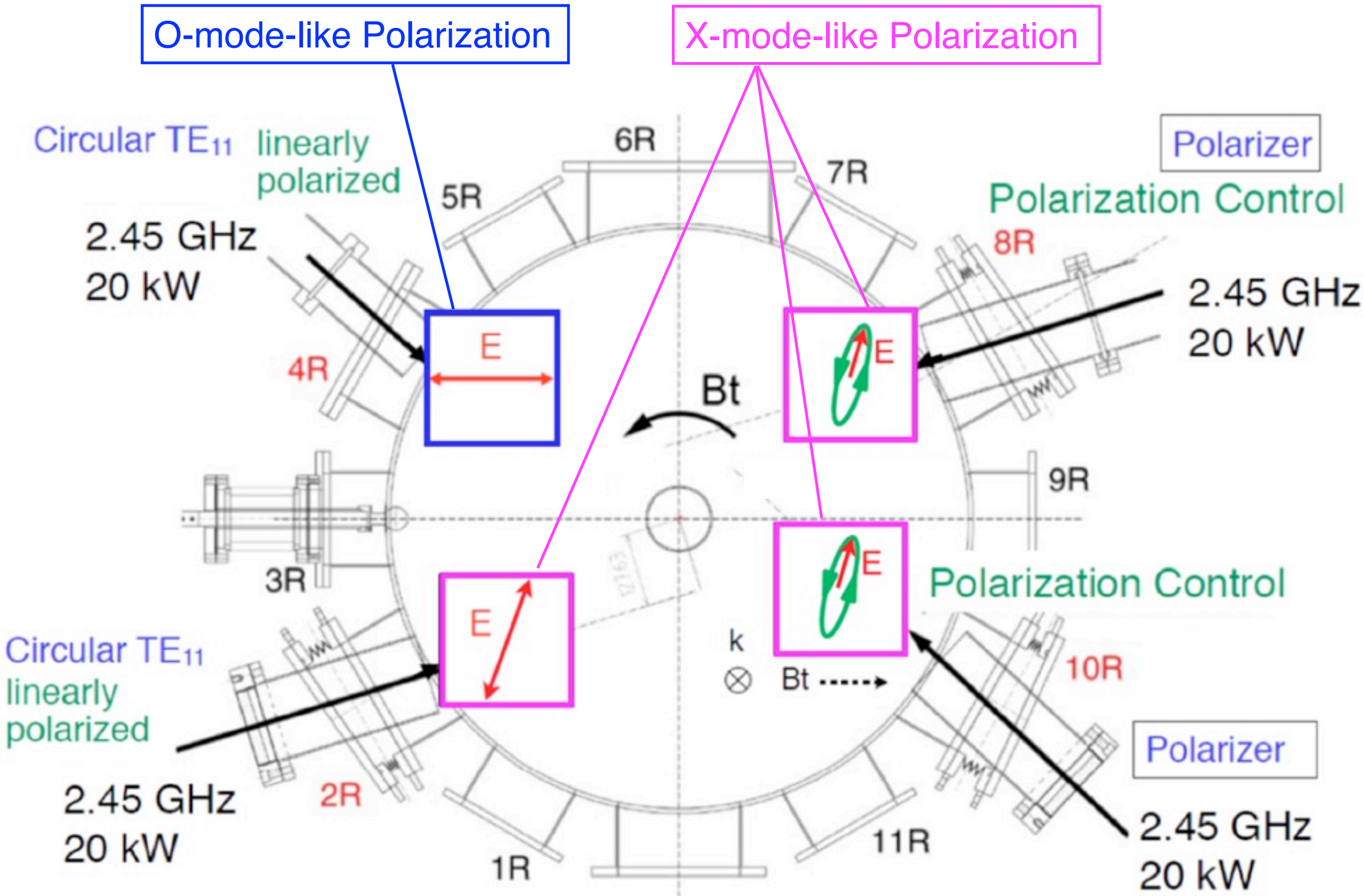
(Igami et al., PPCF 48 (2006) 573)

in the case of $I_{TF}$ = 93kA, $R_{cutoff}$ = 35.5 cm and $R_{ECR}$ = 21.3 cm for ω/2π = 2.45GHz

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



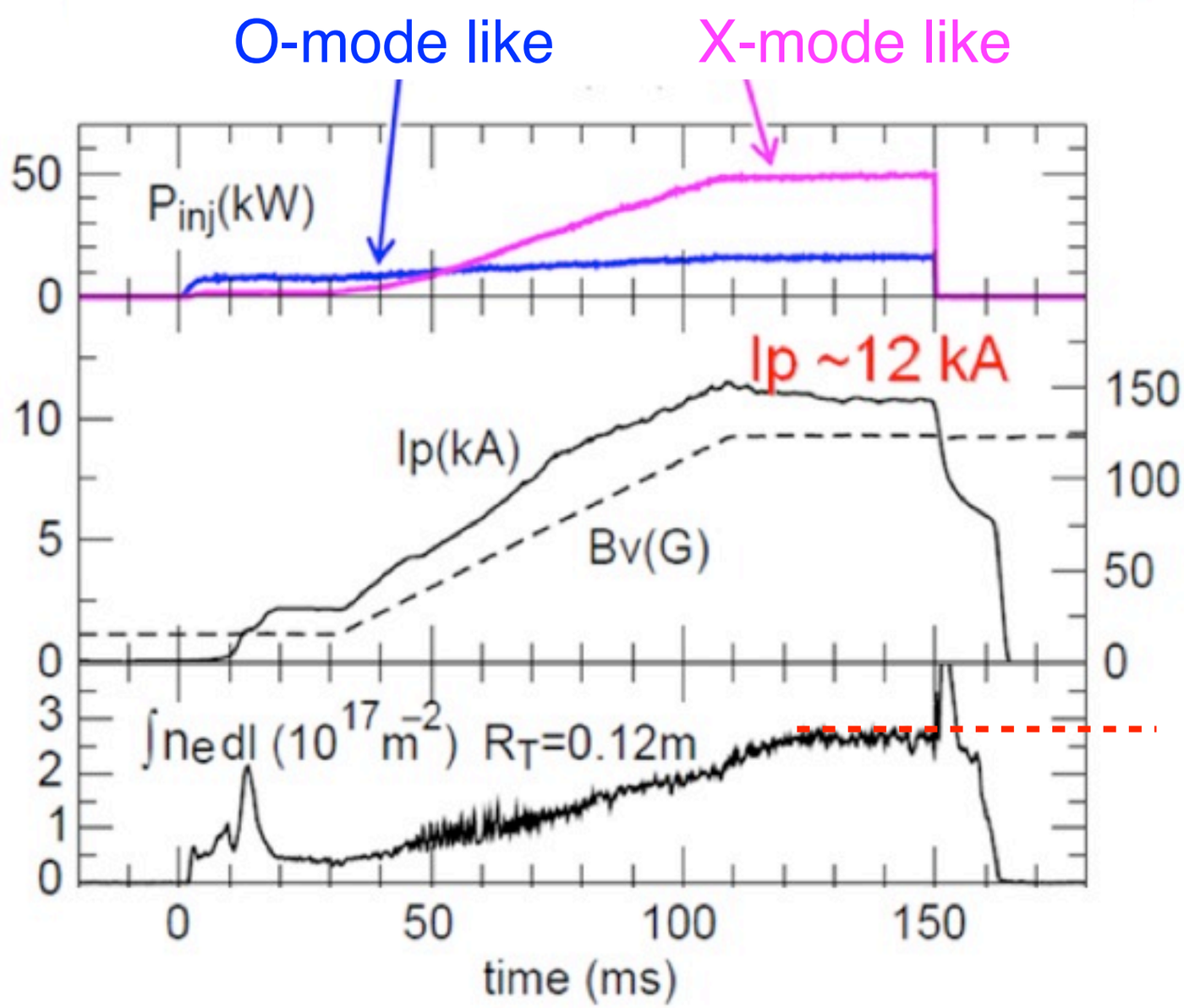
# X-mode-like Polarization Injection from 3 Ports

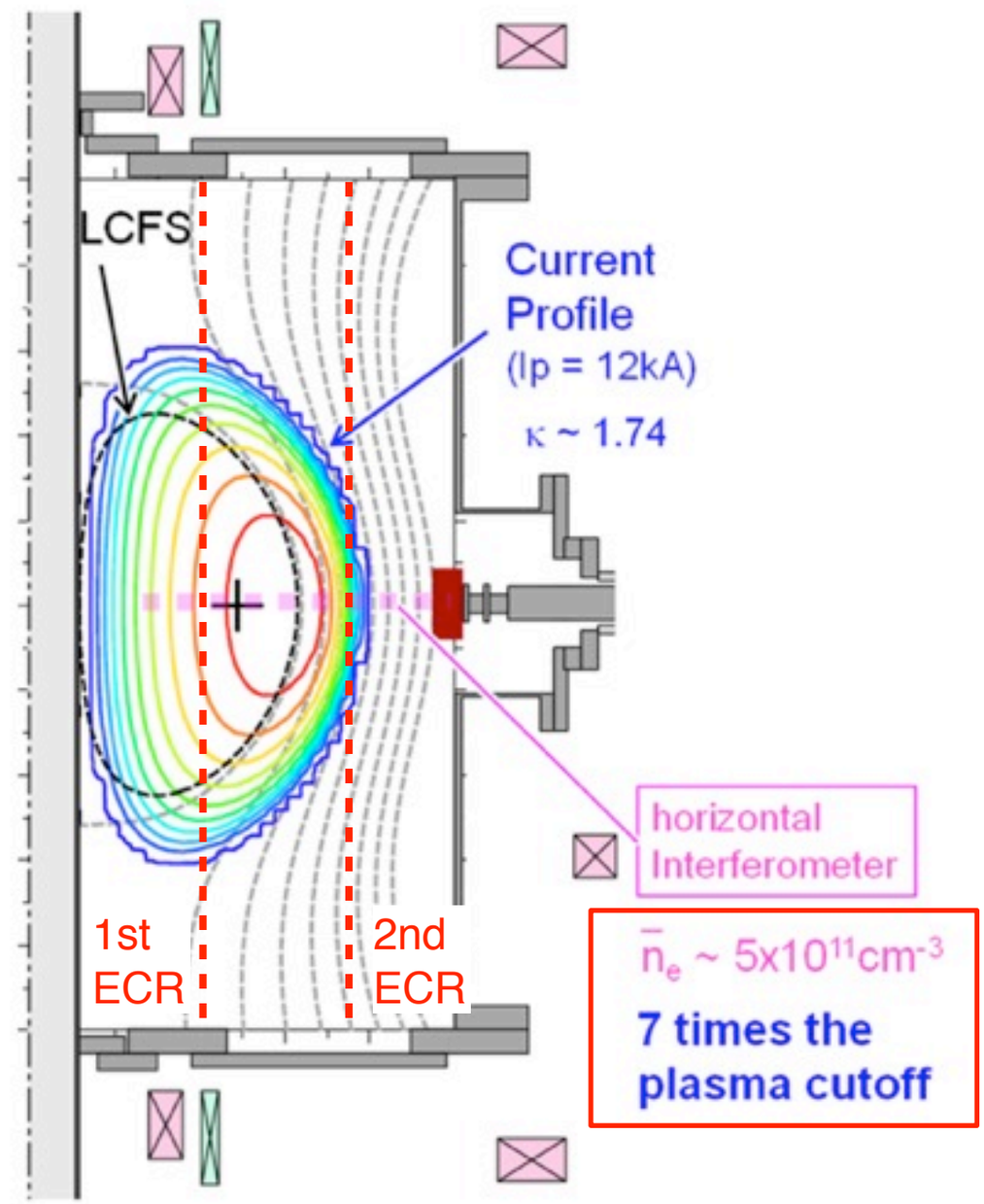


# EBW Start-up with large fraction of X-mode-like polarization at the last stage

Plasma current increases up to 12 kA (~20% increment), while the density is nearly the same.

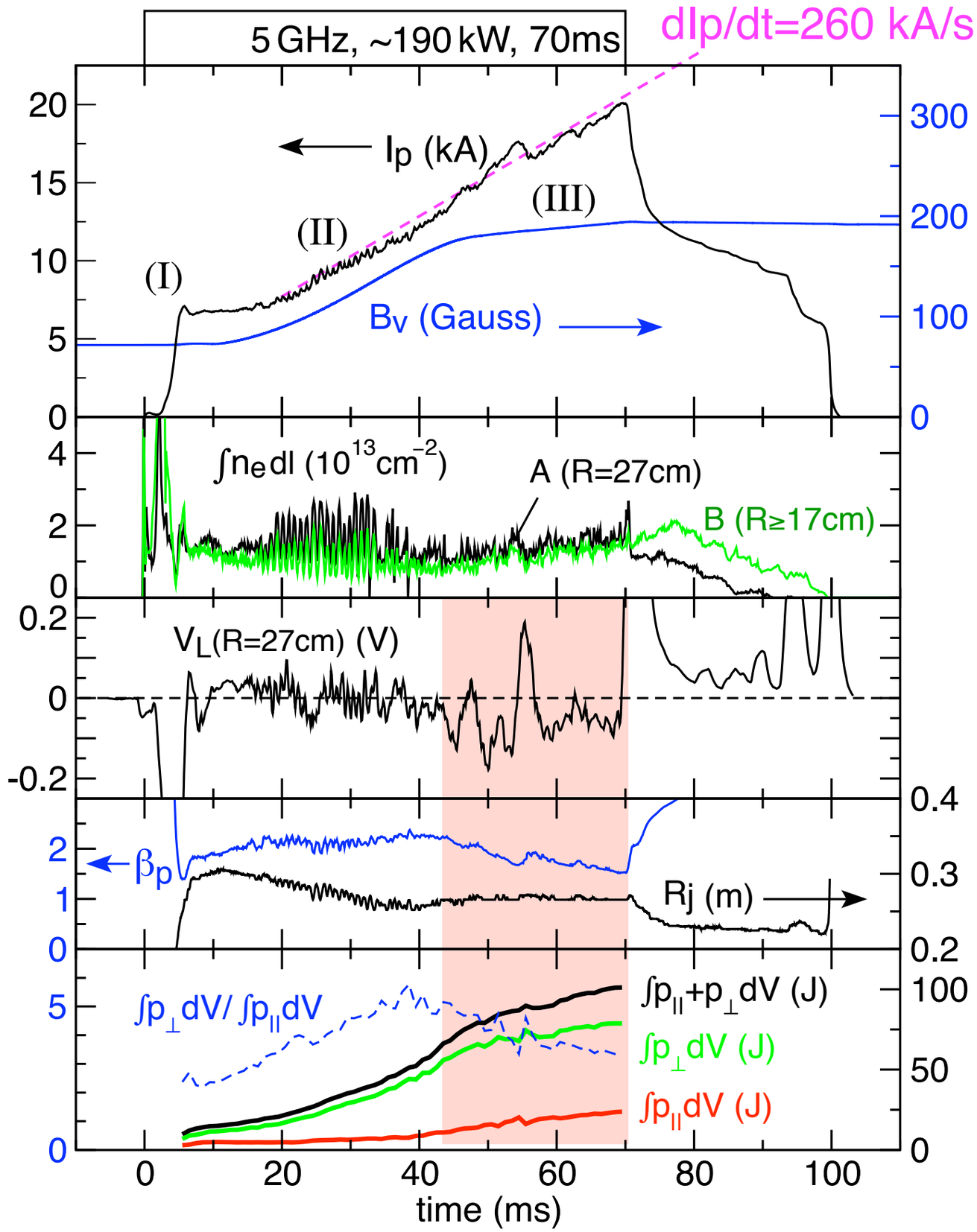
The increment amount of EB wave power by the better mode conversion may be consumed by tail electron heating which occurs in the lower field side due to the Doppler shift effect.



# Non-inductive Startup with 5 GHz (Previous Exp.)

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

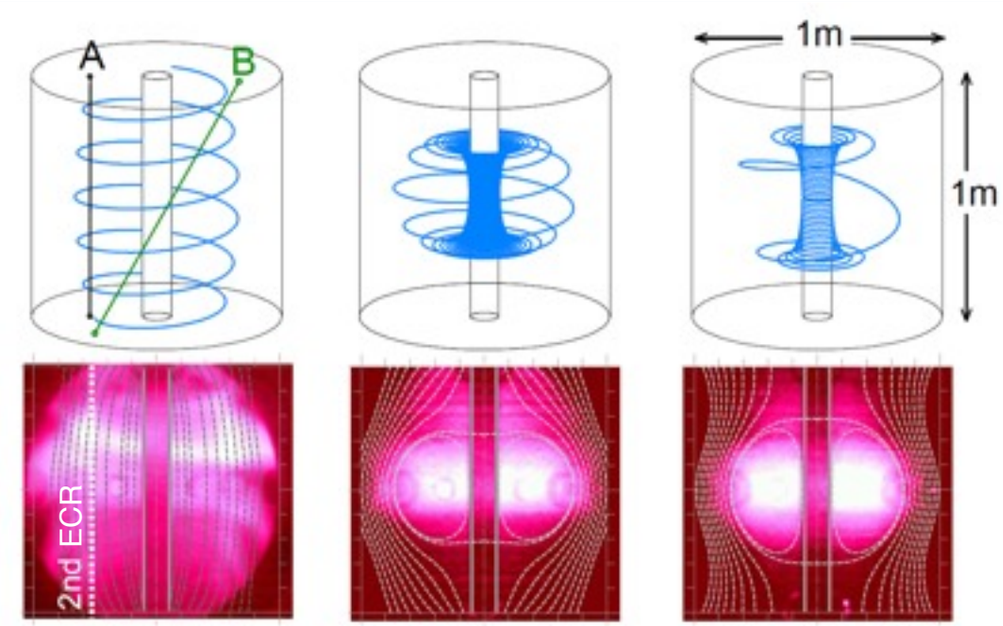
( βp-bulk ~ 0.05 ) when Ip = 20kA

--> tail electrons' energy ~ 100 keV

line-averaged denisty > plasma cutoff density

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

--> ECCD by EBW with high N//



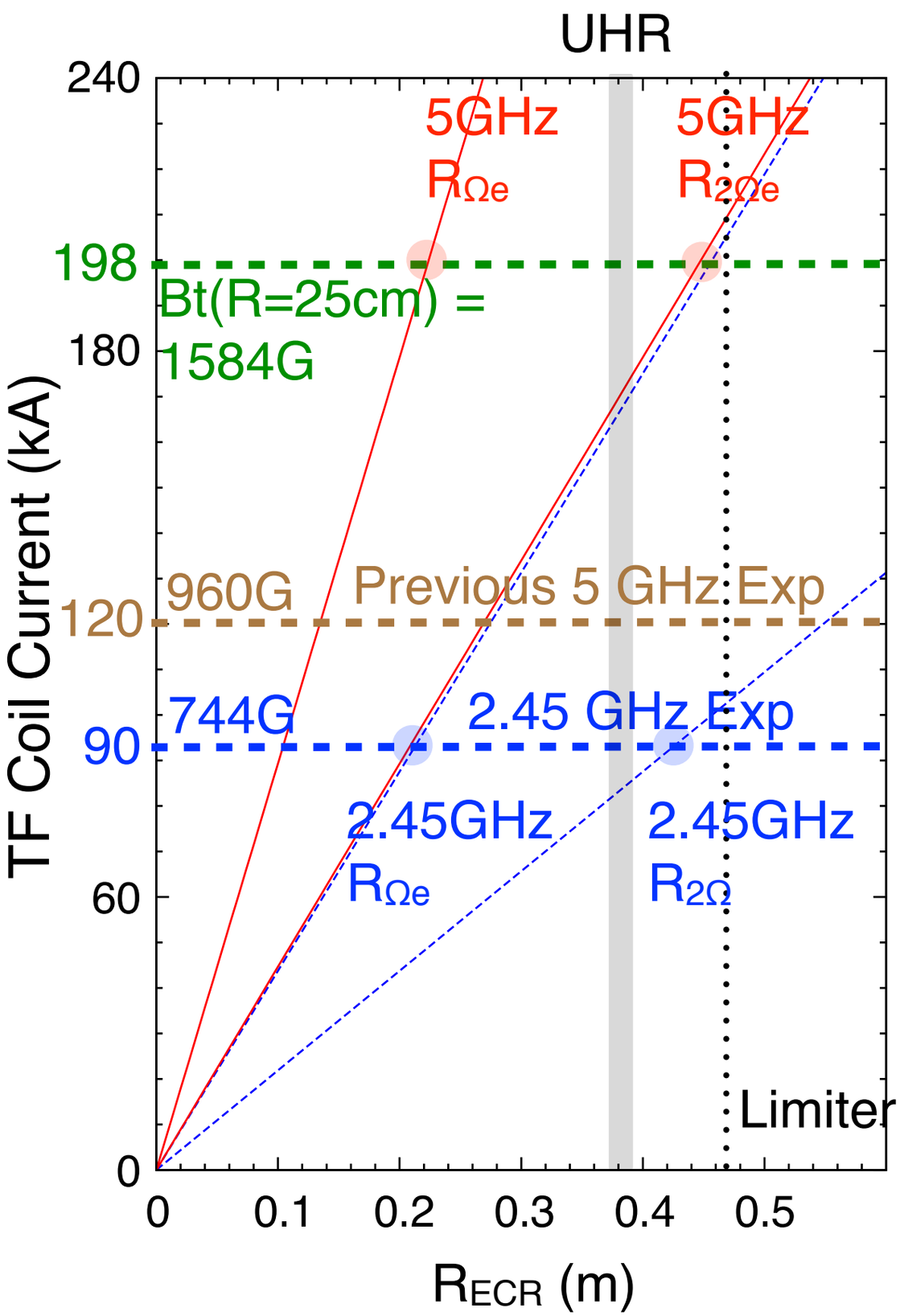

Ip=0 Ip=7 kA Ip=20 kA

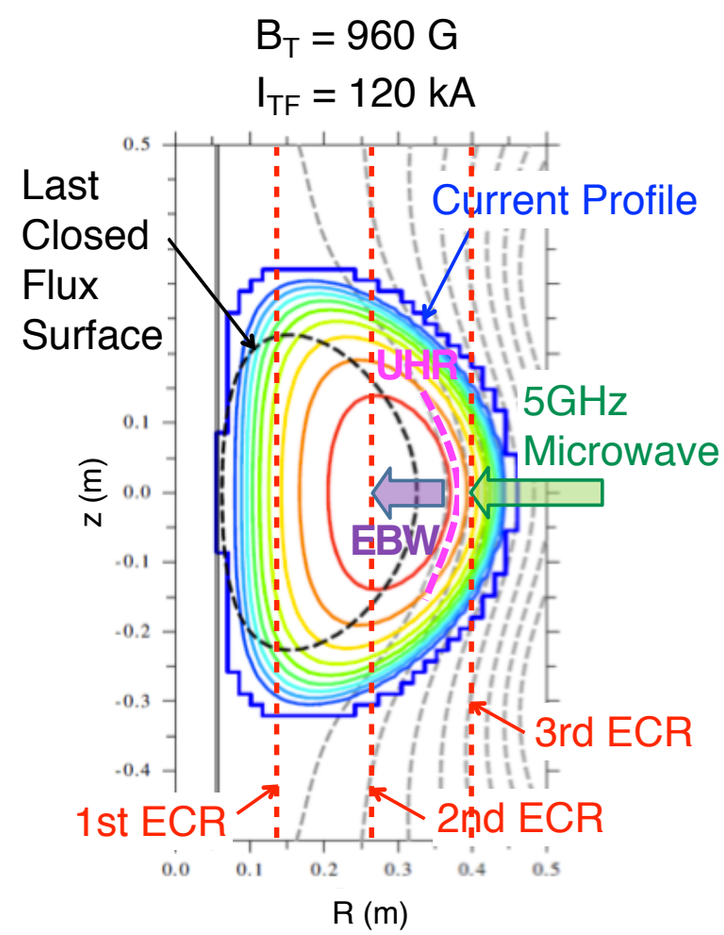
# Upgrade of TF Power Supply for Fundamental EBWH/CD at 5GHz

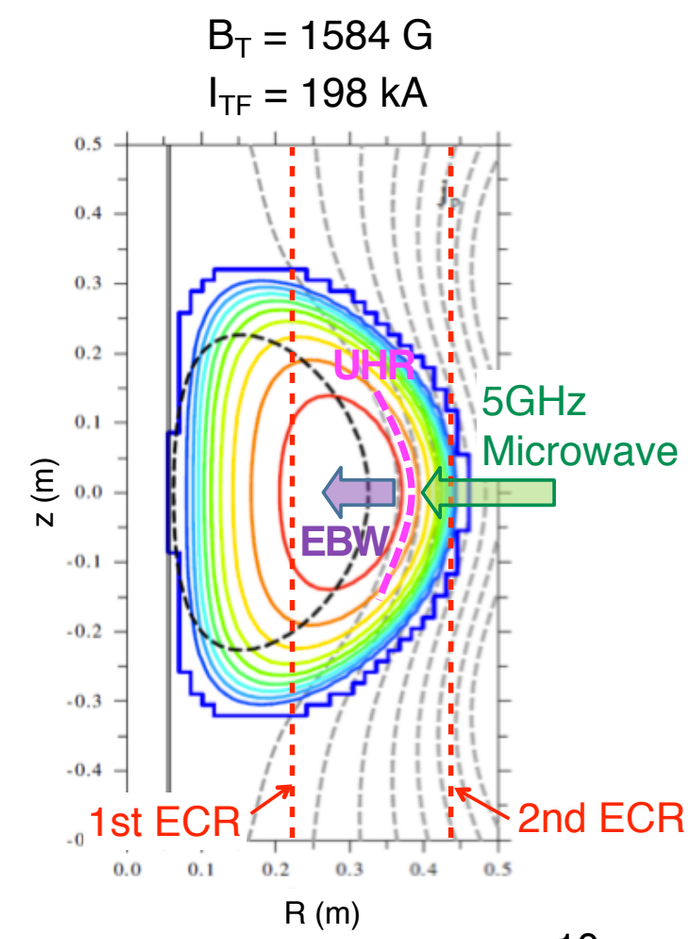
Max. P.S. current is 3.4kA with ~100ms flat top duration ... $I_{TF}$ = 204 kA

In the case of 5 GHz and $I_{TF}$ = 198 kA, $R_{\Omega e}$ = 22.2 cm, $R_{2\Omega e}$ = 44.3 cm

Excitation of EBW at the first propagation band with 5 GHz

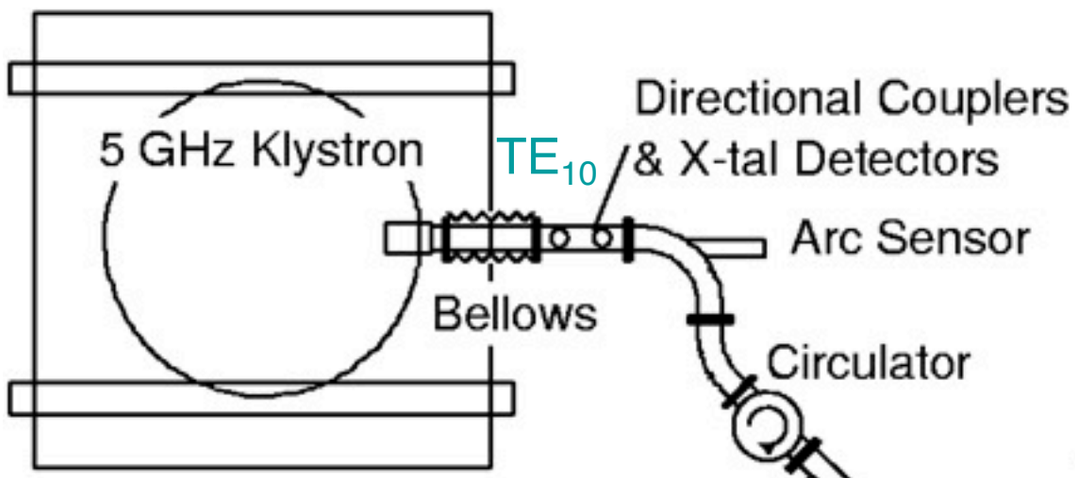


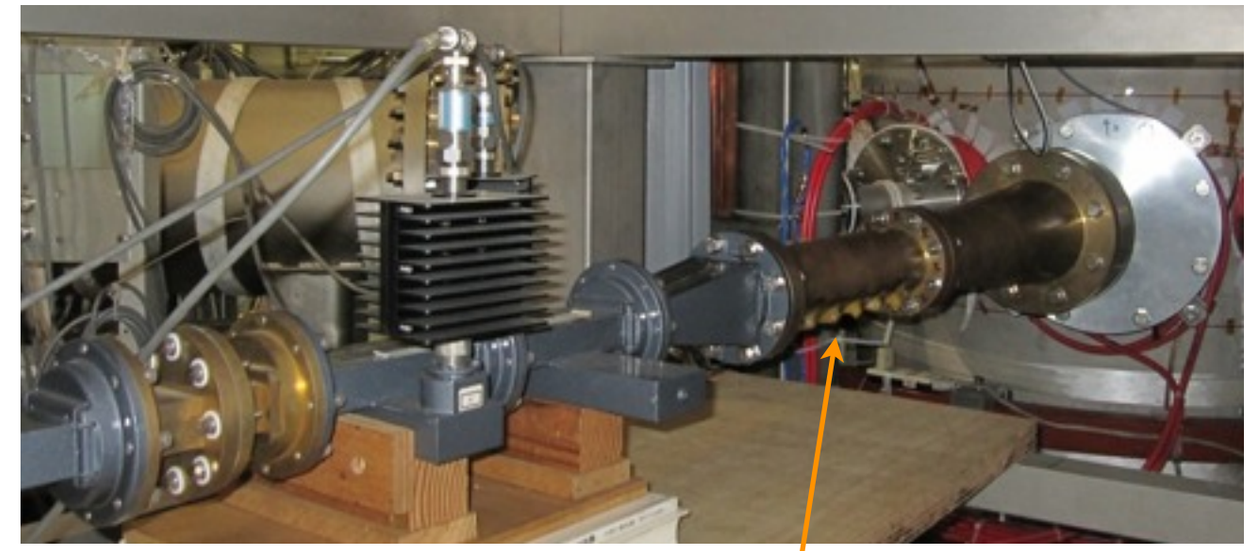



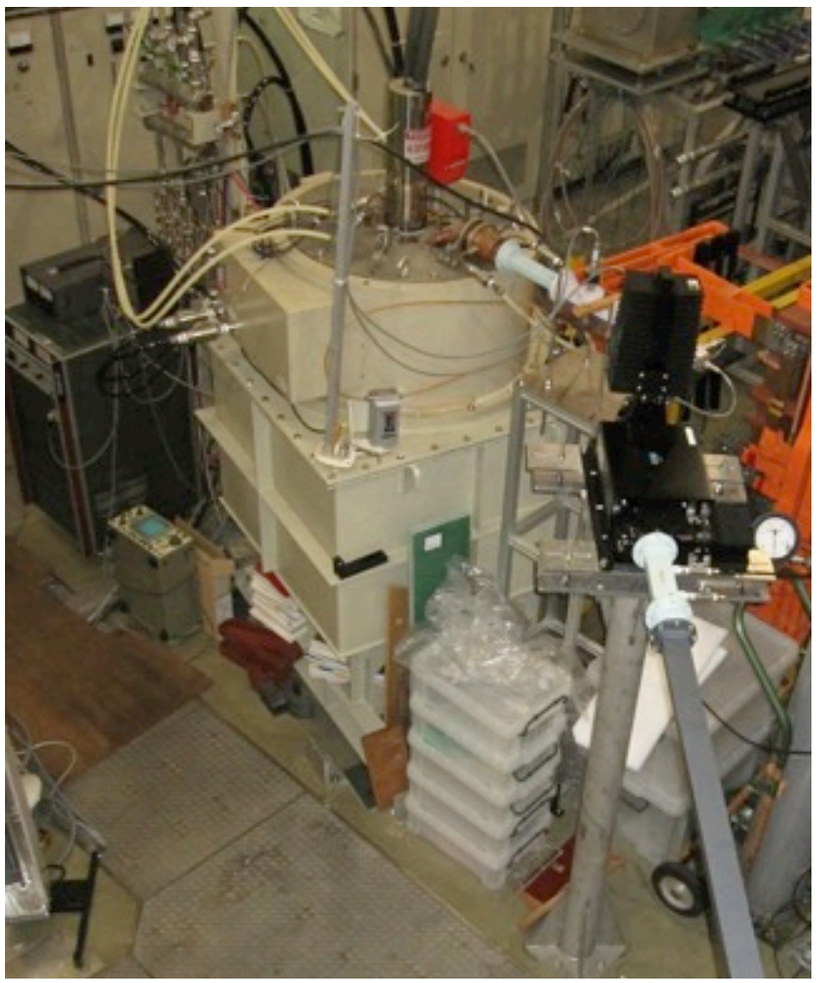
# 5GHz Launching System

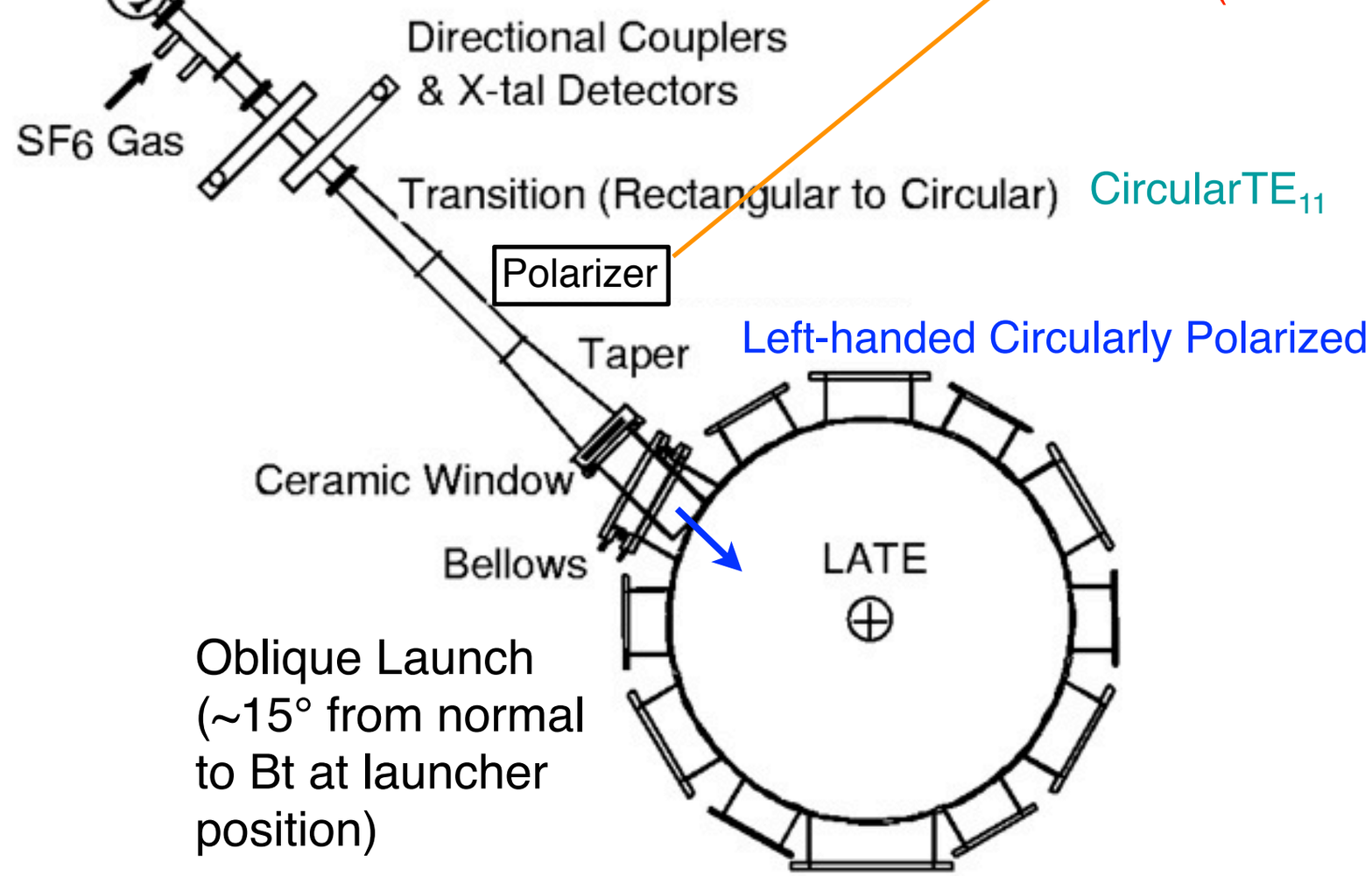
~ 200 kW, ~80 ms



Polarizer (1/4 λsection)

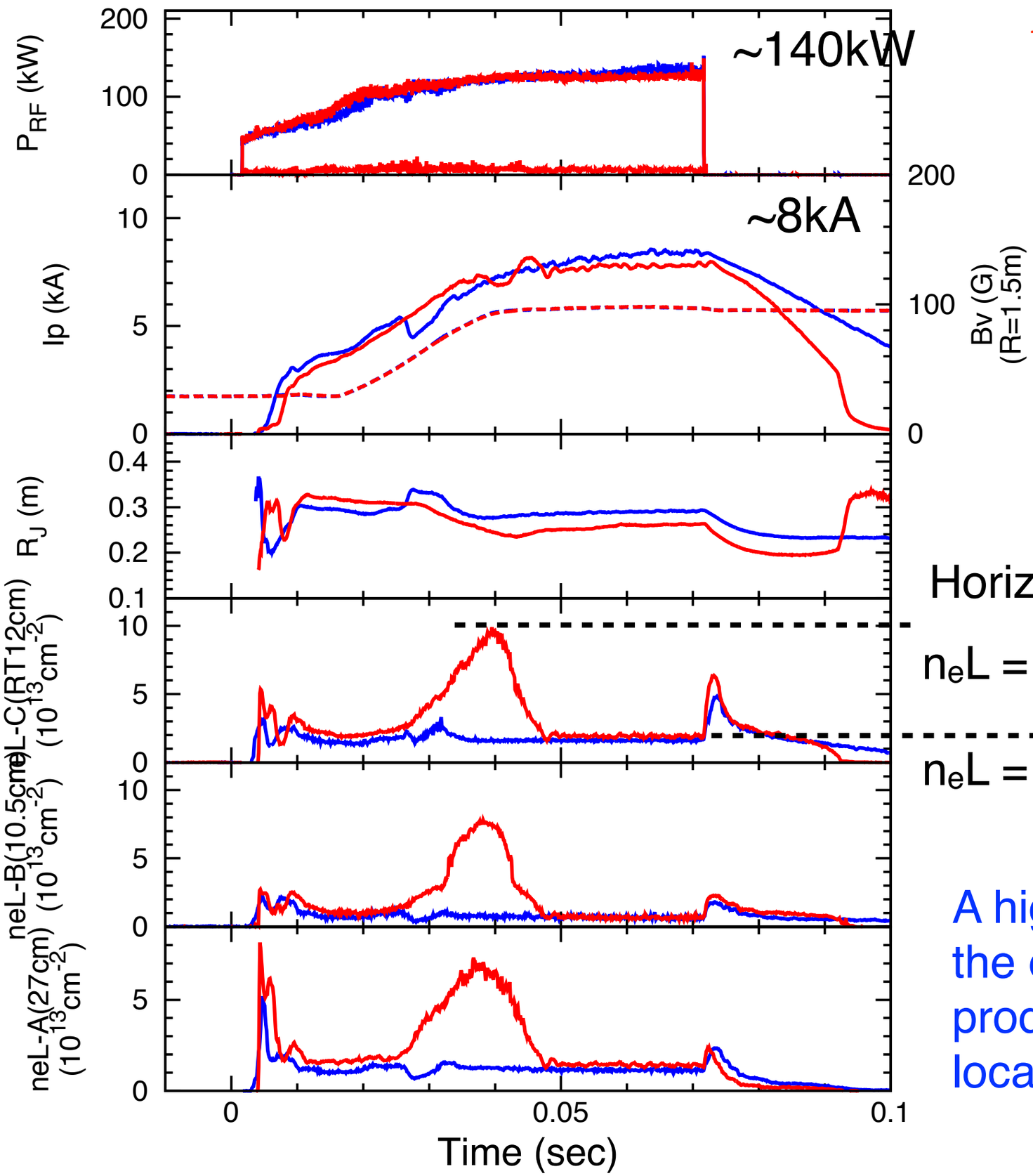





Oblique Launch (~15° from normal to Bt at launcher position)

# A High-Density Plasma with 5 GHz Microwave

151007-065 : $I_{TF}$=144kA, $R_{\Omega}$=16.1cm, $R_{2\Omega}$=32.2cm
151007-069 : $I_{TF}$=180kA, $R_{\Omega}$=20.2cm, $R_{2\Omega}$=40.3cm



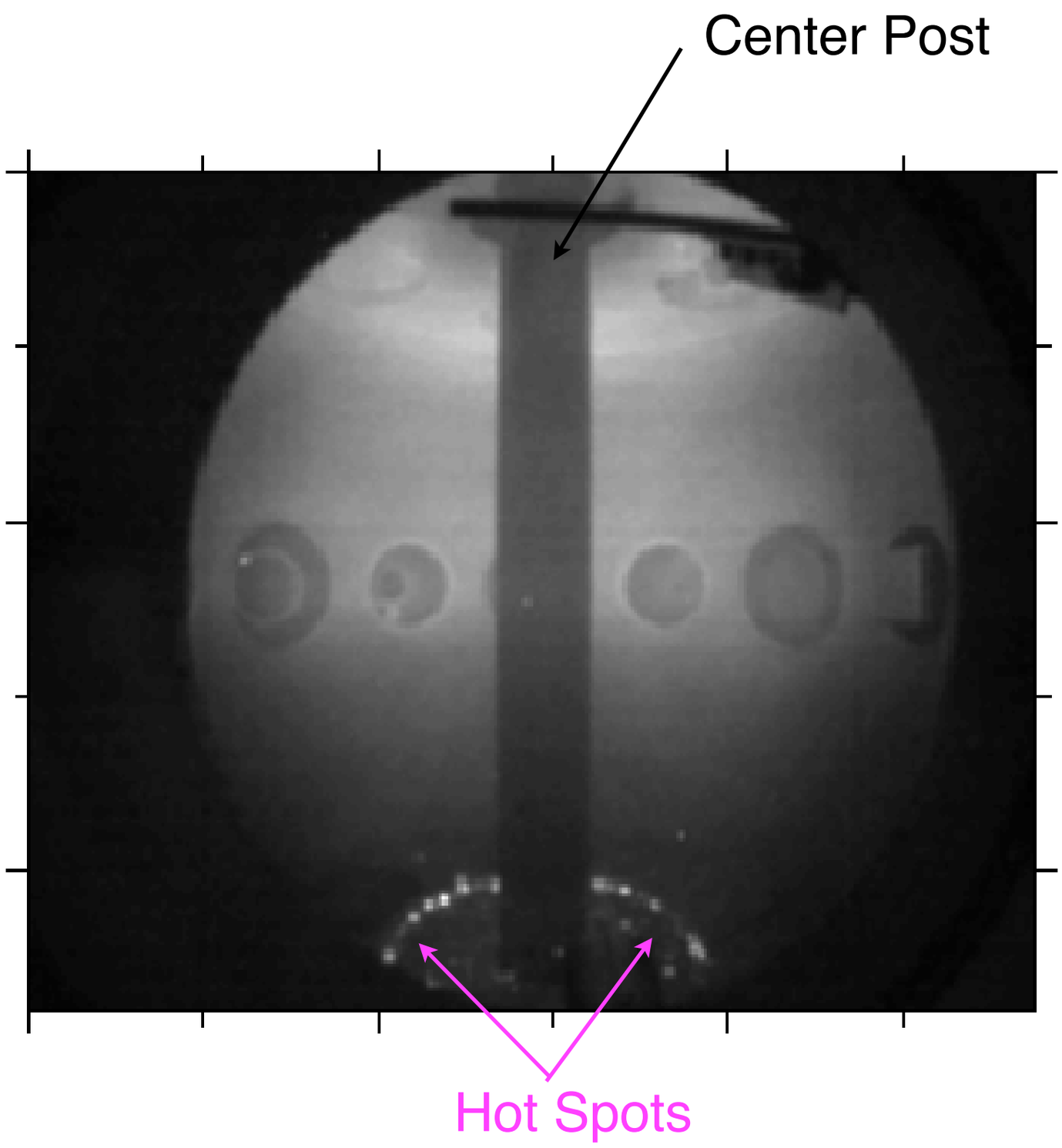

Horizontal Chord at $R_T$=0.12m

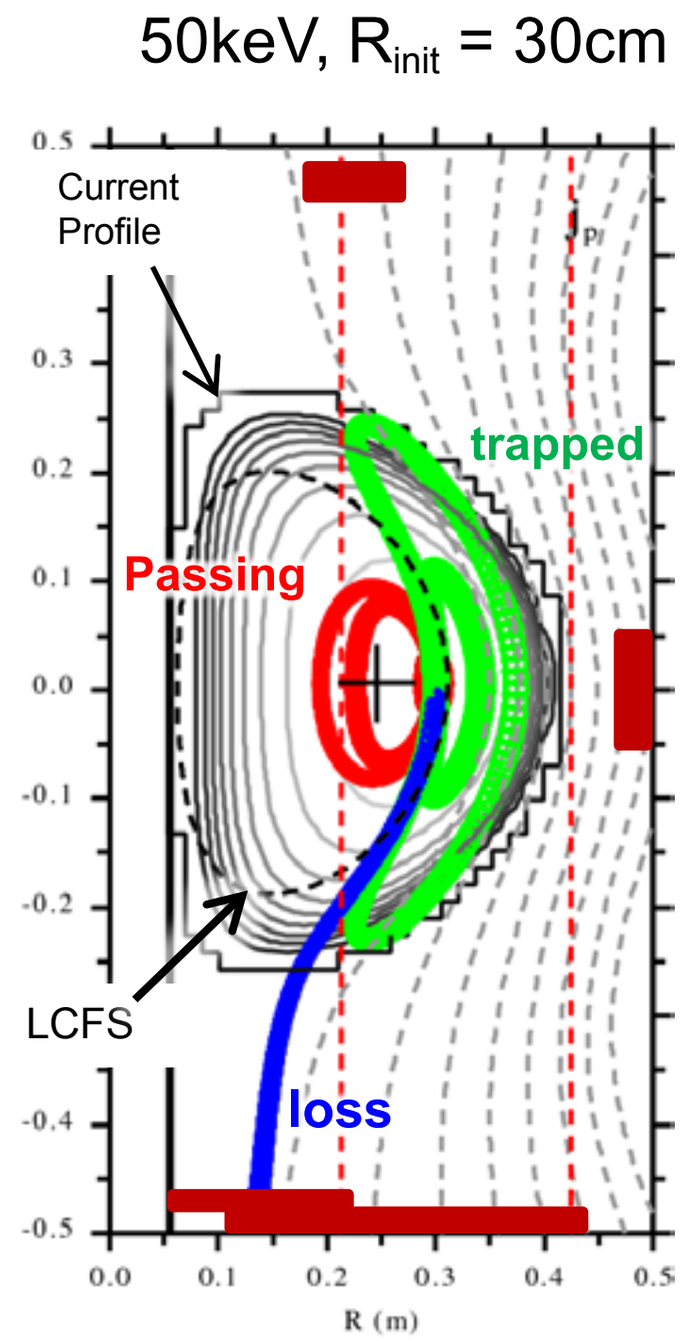
$n_eL = 1 \times 10^{18}$ m$^{-2}$ ... $\langle n_e \rangle = 1.7\times10^{18}$ m$^{-3}$

$n_eL = 2 \times 10^{17}$ m$^{-2}$ ... $\langle n_e \rangle = 3.5\times10^{17}$ m$^{-3}$

A high-density plasma with ~5.5 times the cutoff density is transiently produced when the 2nd ECR layer is located > 40 cm.

# Density Decreases When Hot Spots Appear on the Bottom Mo Plate

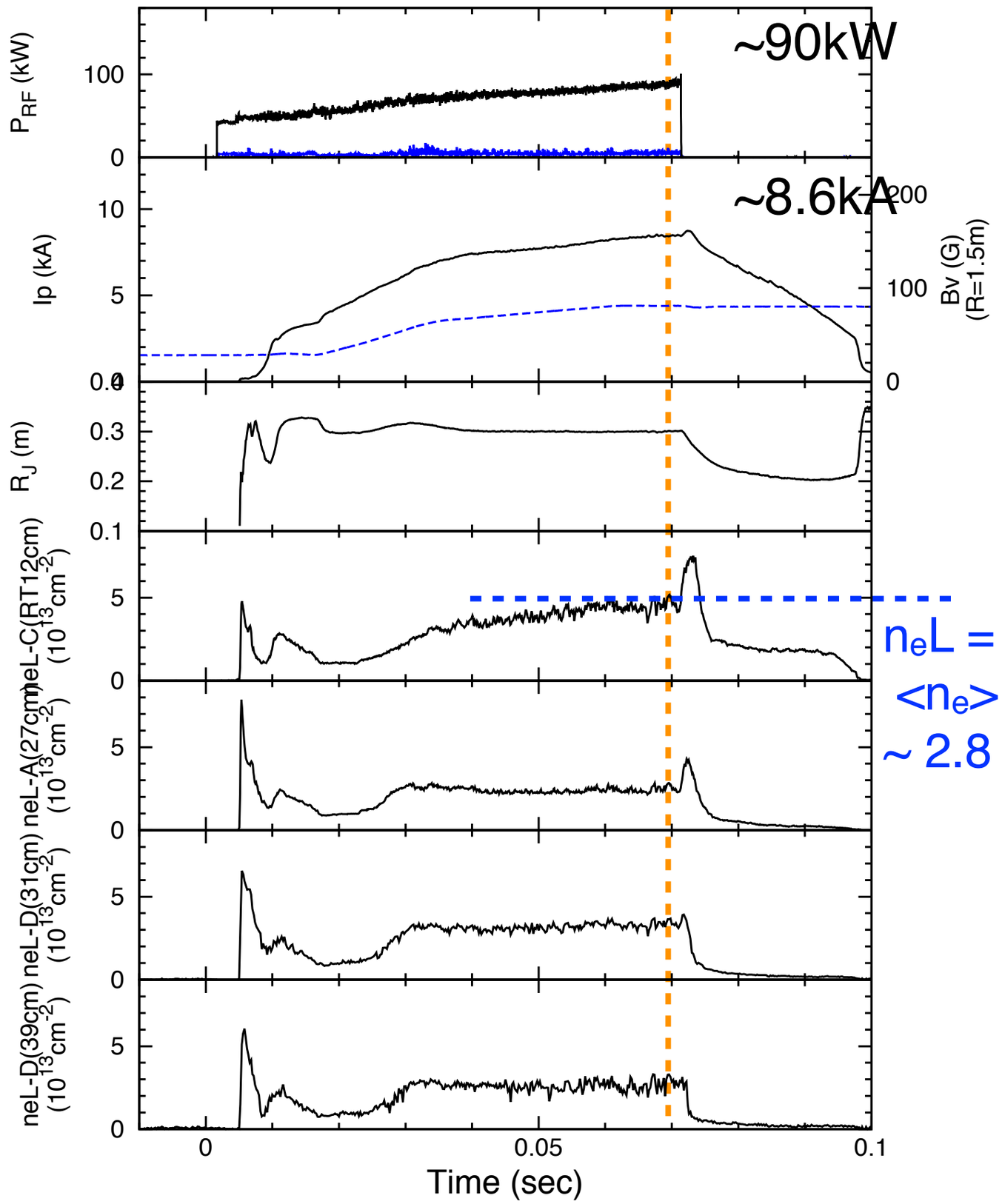



the loss of high energy electrons produced by EBW.

# Low Power injection & Wall conditioning Keep The Density

151015-093 : $I_{TF}$=198kA, $R_{\Omega}$=22.2cm, $R_{2\Omega}$=44.3cm

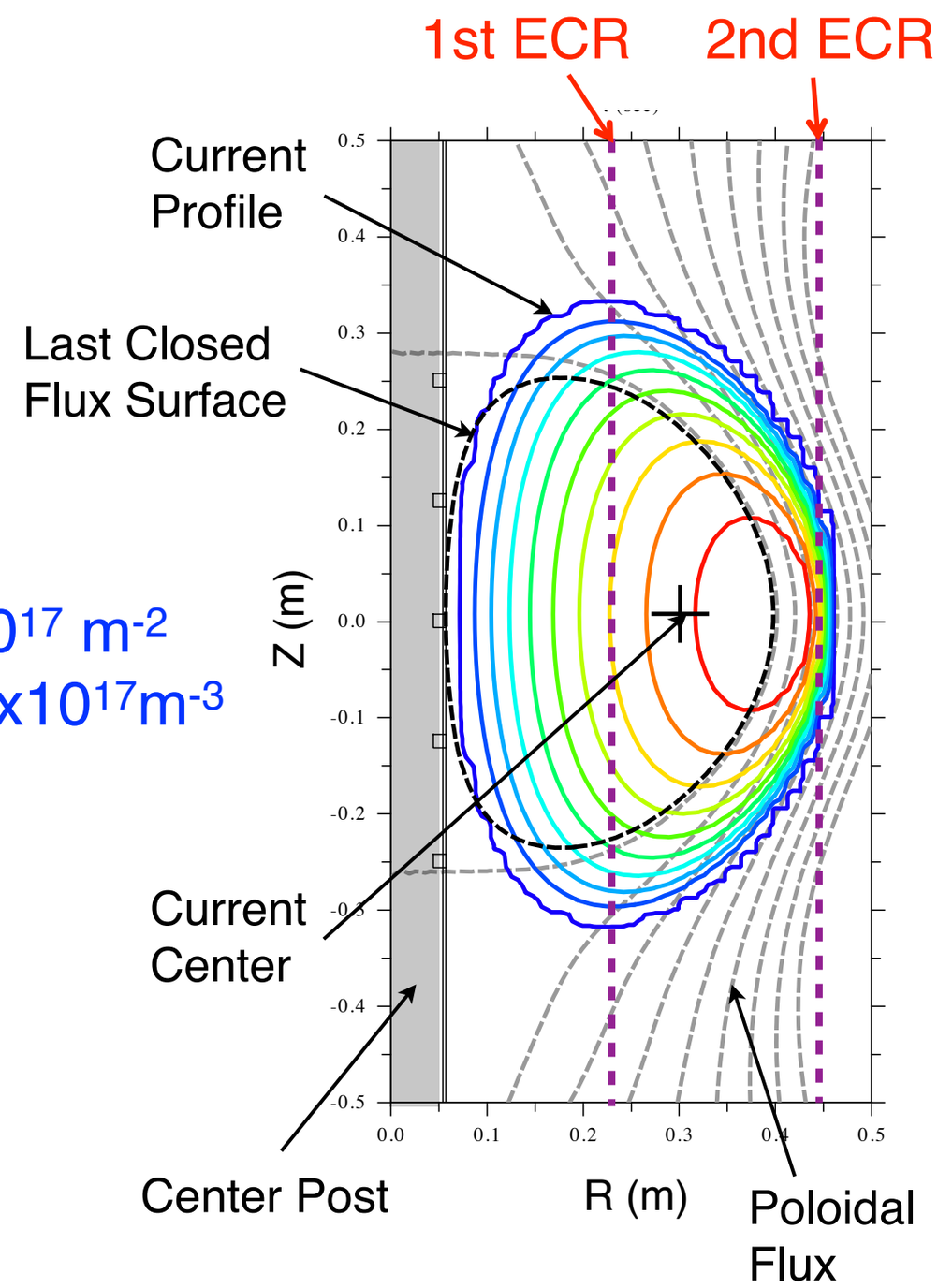



$n_eL = 5 \times 10^{17}$ m$^{-2}$

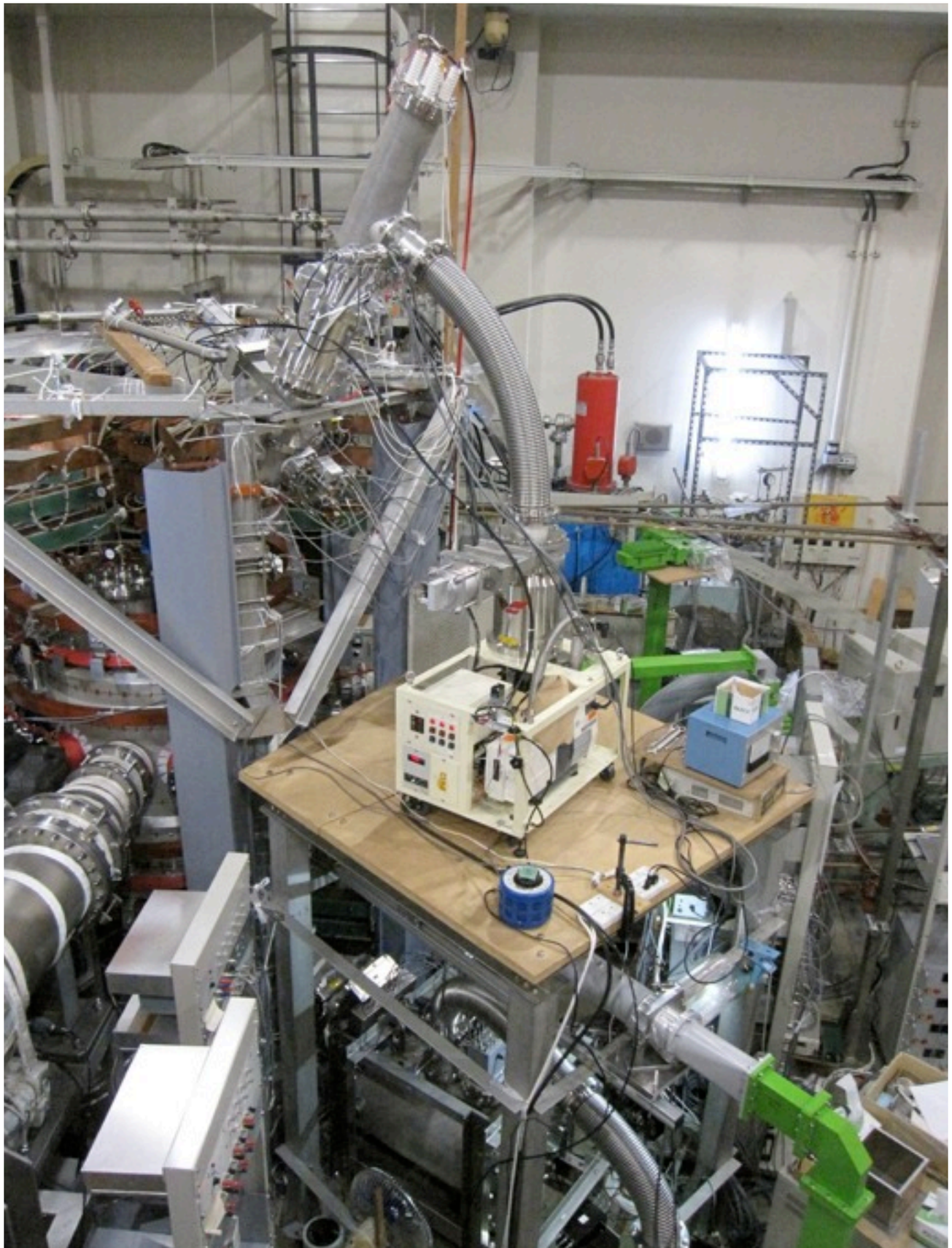
$\langle n_e \rangle = 8.8 \times 10^{17}$m$^{-3}$

$\sim 2.8\ n_c$

t=0.070sec, Ip~8.6kA

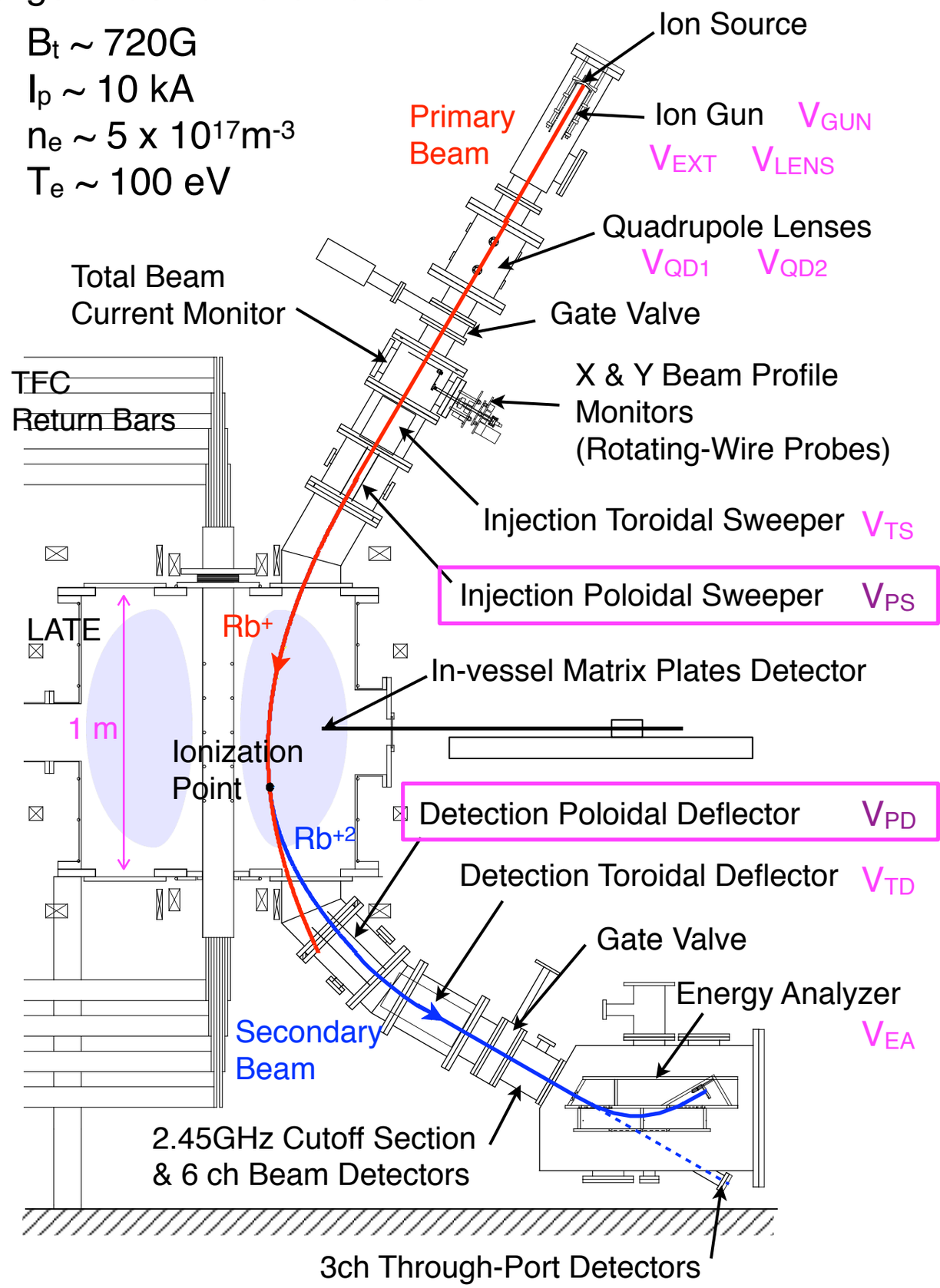


# HIBP System in LATE

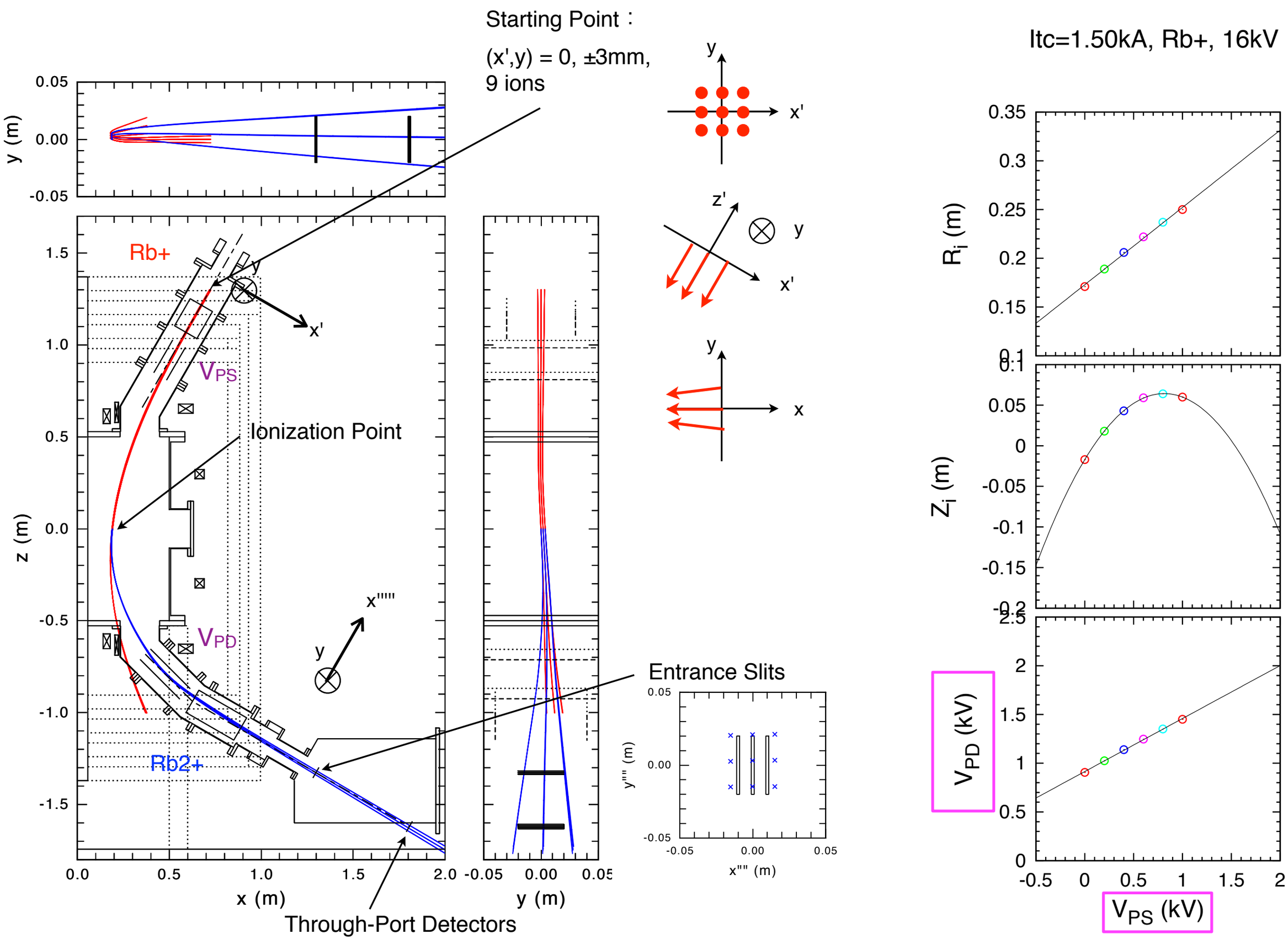


Target Plasma Parameters

$B_t \sim 720G$
$I_p \sim 10$ kA
$n_e \sim 5 \times 10^{17} m^{-3}$
$T_e \sim 100$ eV

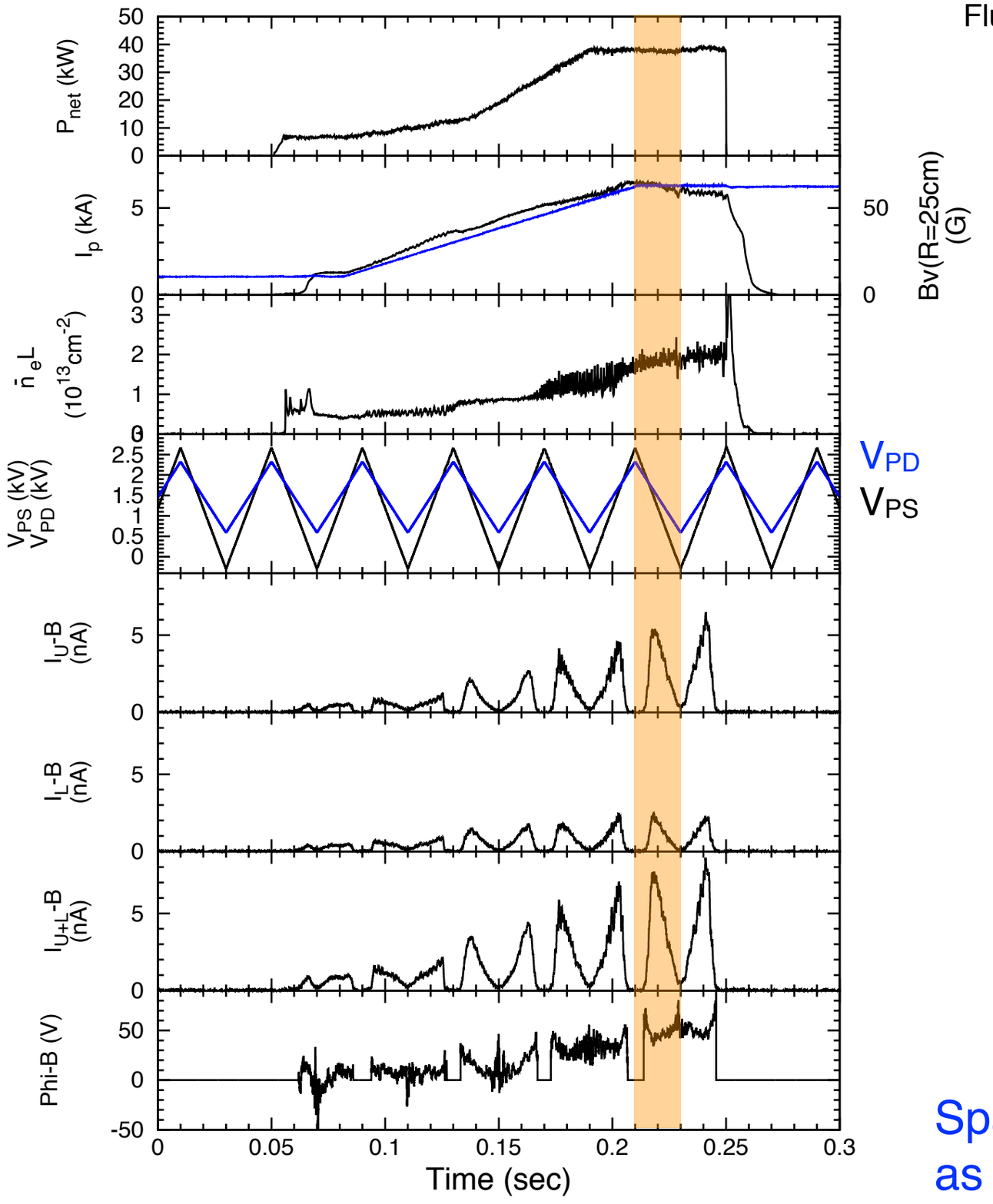


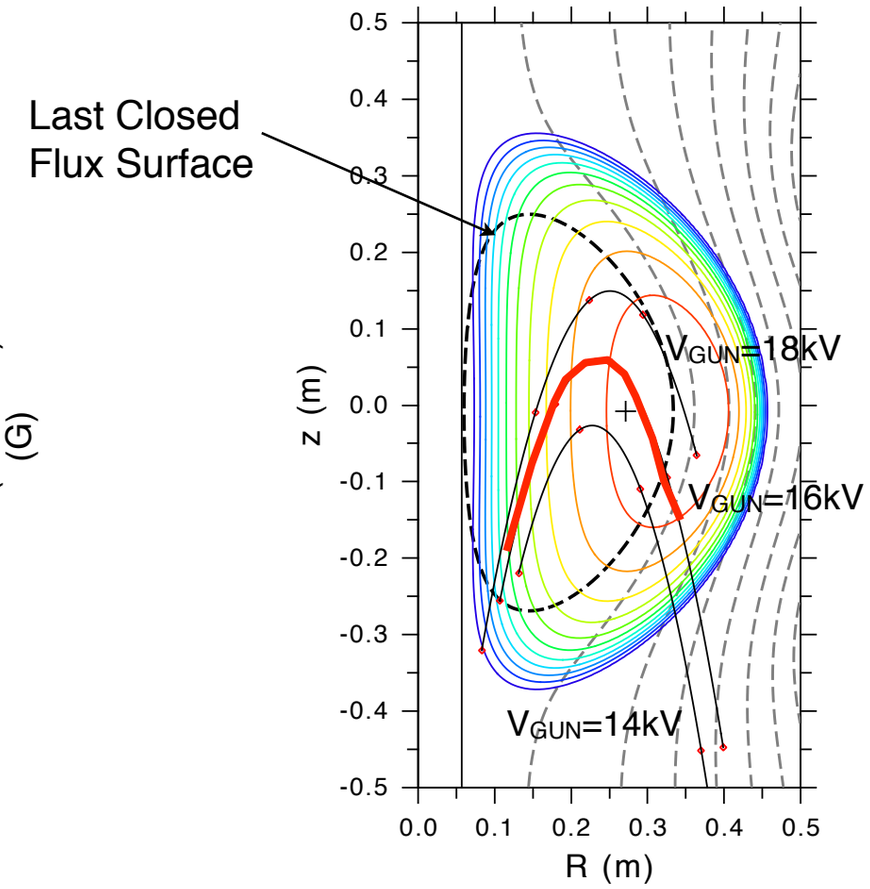
# Measurement Position is Determined by Two Voltages $V_{PS}$ & $V_{PD}$



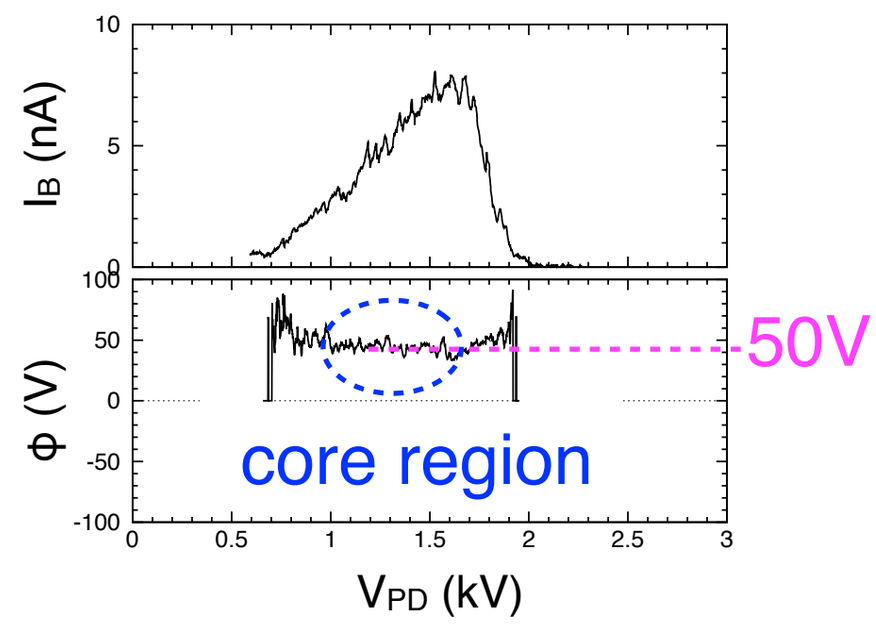
# Detection of Secondary Beam

$I_{TF}$ = 90kA, Bt = 720G, 150115-036
Ip ~ 6.5kA, $n_eL$ ~ 2 x $10^{17}$ $m^{-2}$
$V_{GUN}$ = 16kV




t = 0.210 ~ 0.230sec




Space potential is positive and increases as the density increases.

# Summary

* By injecting 2.45 GHz microwave, non-inductive formation of high density ST plasma with 7 times the plasma cutoff density is achieved when EBW is excited in the 1st propagation band.

* When the microwave power in the X-mode-like polarization is increased at the last stage, the plasma current is increased while the density is nearly the same.

* By injecting 5 GHz microwave in the similar ECR conditions to those with 2.45GHz microwave, a high density plasma with ~5.5 times the cutoff density is transiently obtained. It is necessary to mitigate the hot spots which may be due to the loss of high energy electrons produced by EBW.

* The space potential in a ST plasma produced by EBW alone is measured by HIBP. The space potential is positive (~50V) in the core and increases as the density increases.