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Overview of Recent Progress on Non-inductive Start-up Experiment in LATE

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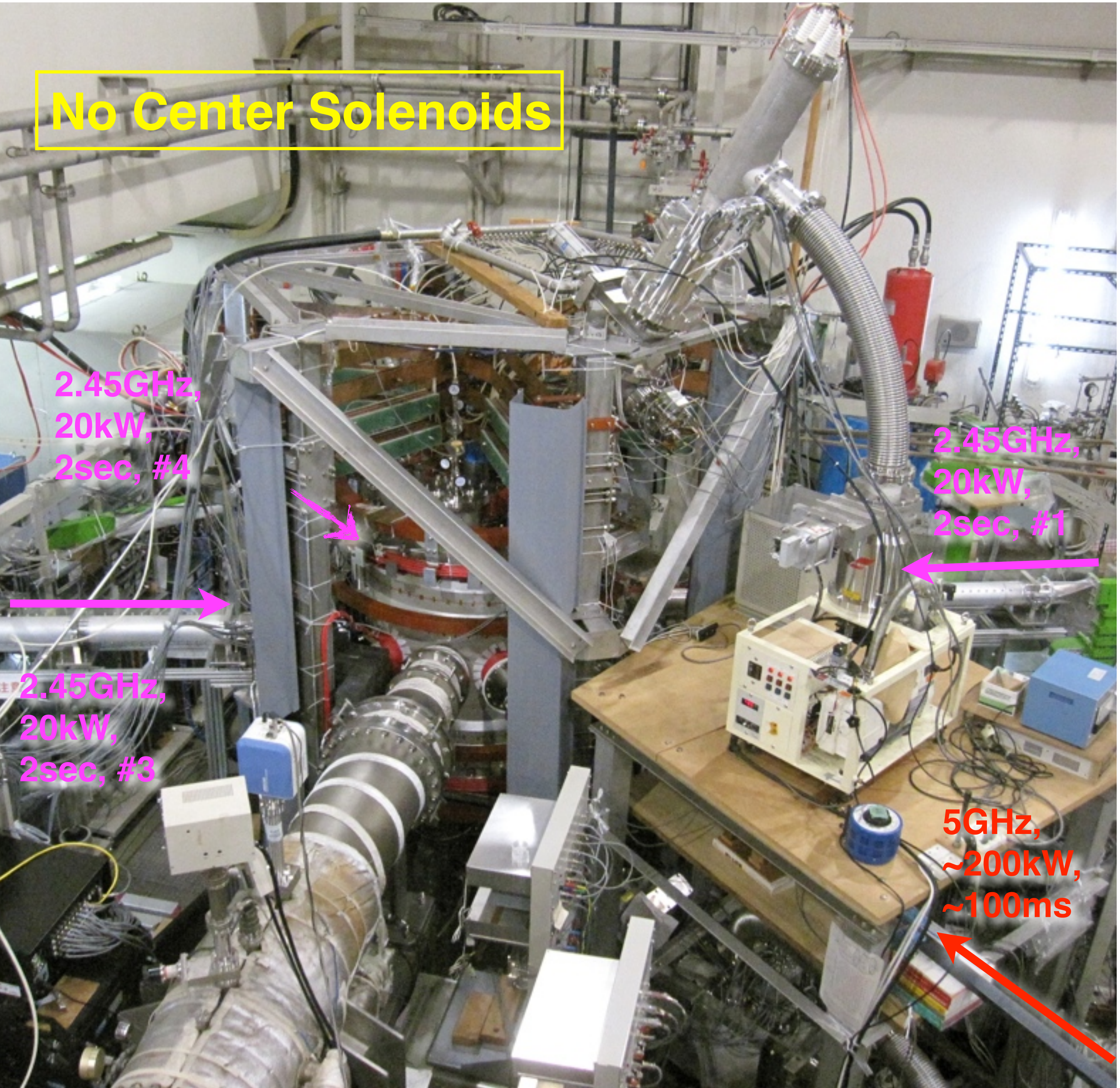
Topics

1. Polarization Adjustment for Non-inductive Production of Highly Overdense ST Plasma by EBW

2. Intermittent Plasma Ejection Events in an Overdense ST Plasma sustained by EBW

3. Electron Beam Injection into EBW-produced plasma (Preliminary Result)

LATE (Low Aspect ratio Torus Experiment)



Cylindrical Vacuum Vessel :
- $R = 5.7 \sim 50$ cm
- $Z = -50 \sim 50$ cm
- $A \geqq 1.24$

Toroidal Field @ R = 25 cm
- $Bt \leqq 1.6$ kG, > 0.13 sec

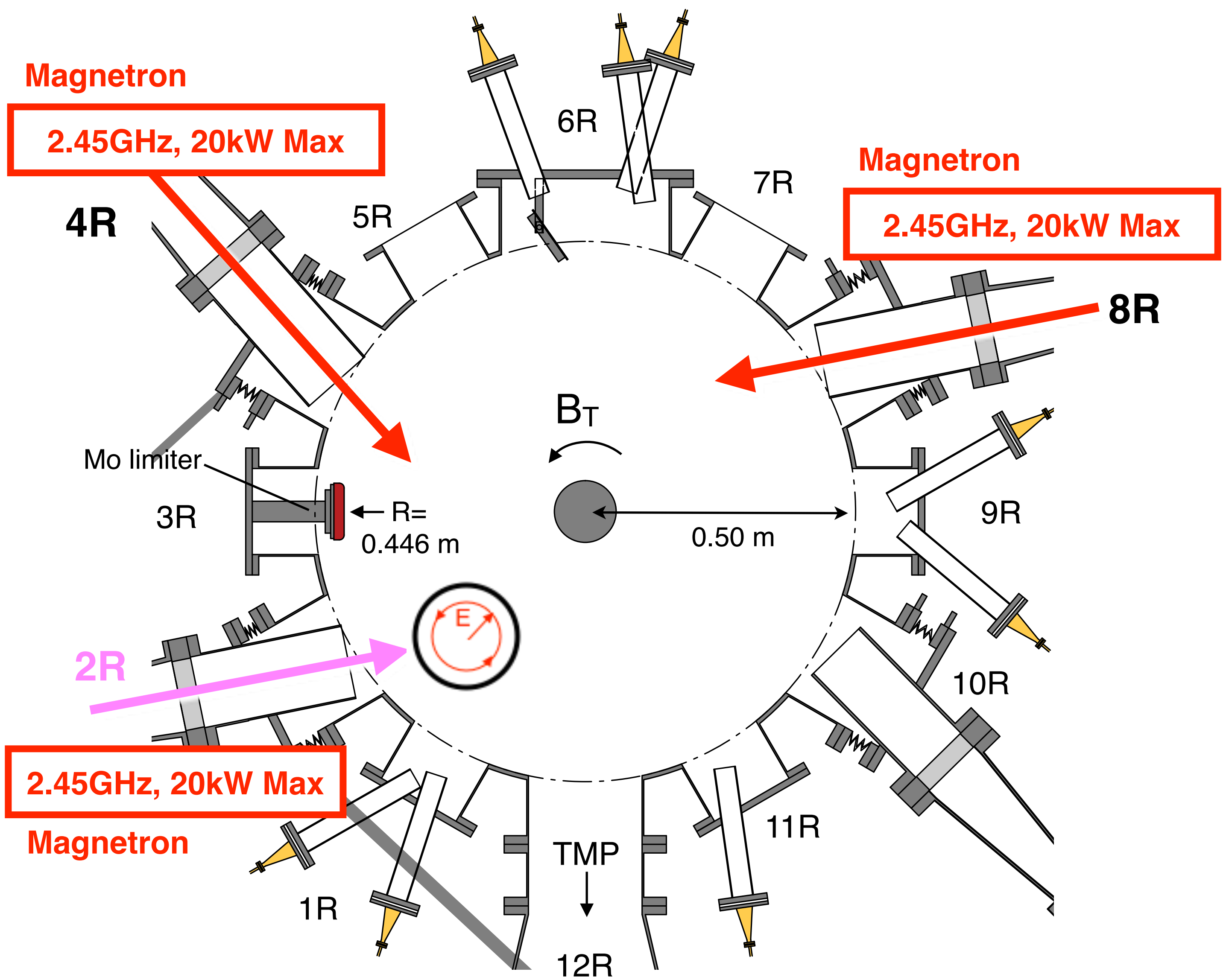
Vertical Field @ R = 25 cm
- $Bv \leqq 250$ G, 2 sec

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

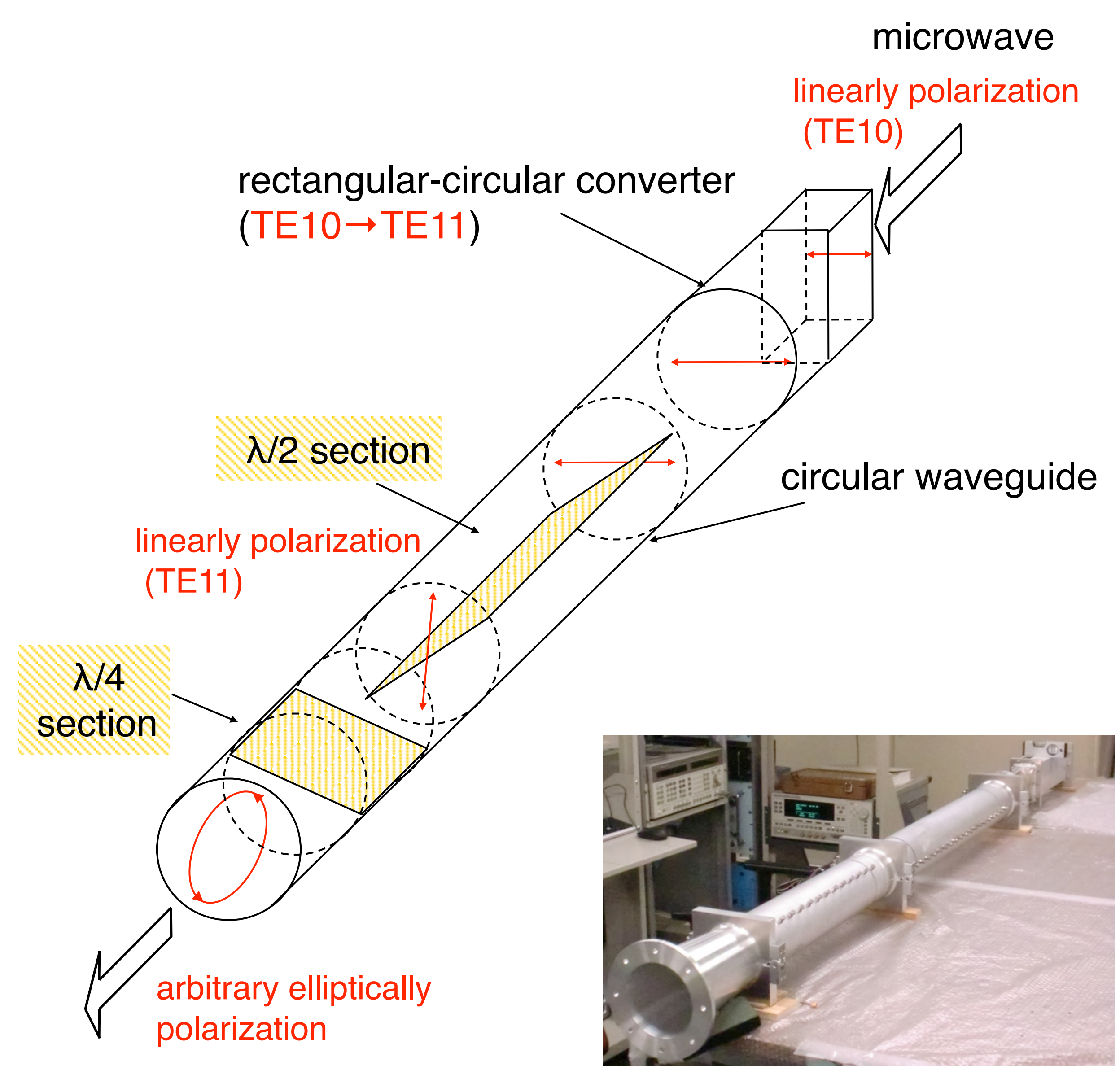
Diagnostics :
- Magnetic Measurement
  - (17 Flux Loops, 14 MPs)
- 4 ch 70 GHz Interferometers
- XUV Cameras (20ch x 3)
- Fast CCD Camera
- Visible Light Spectrometer
- 4 ch HX PHA system
- HX pin-hole camera
- HIBP system (Rb+, 20kV)

2.45GHz Microwave Launching System

LATE (Top View)

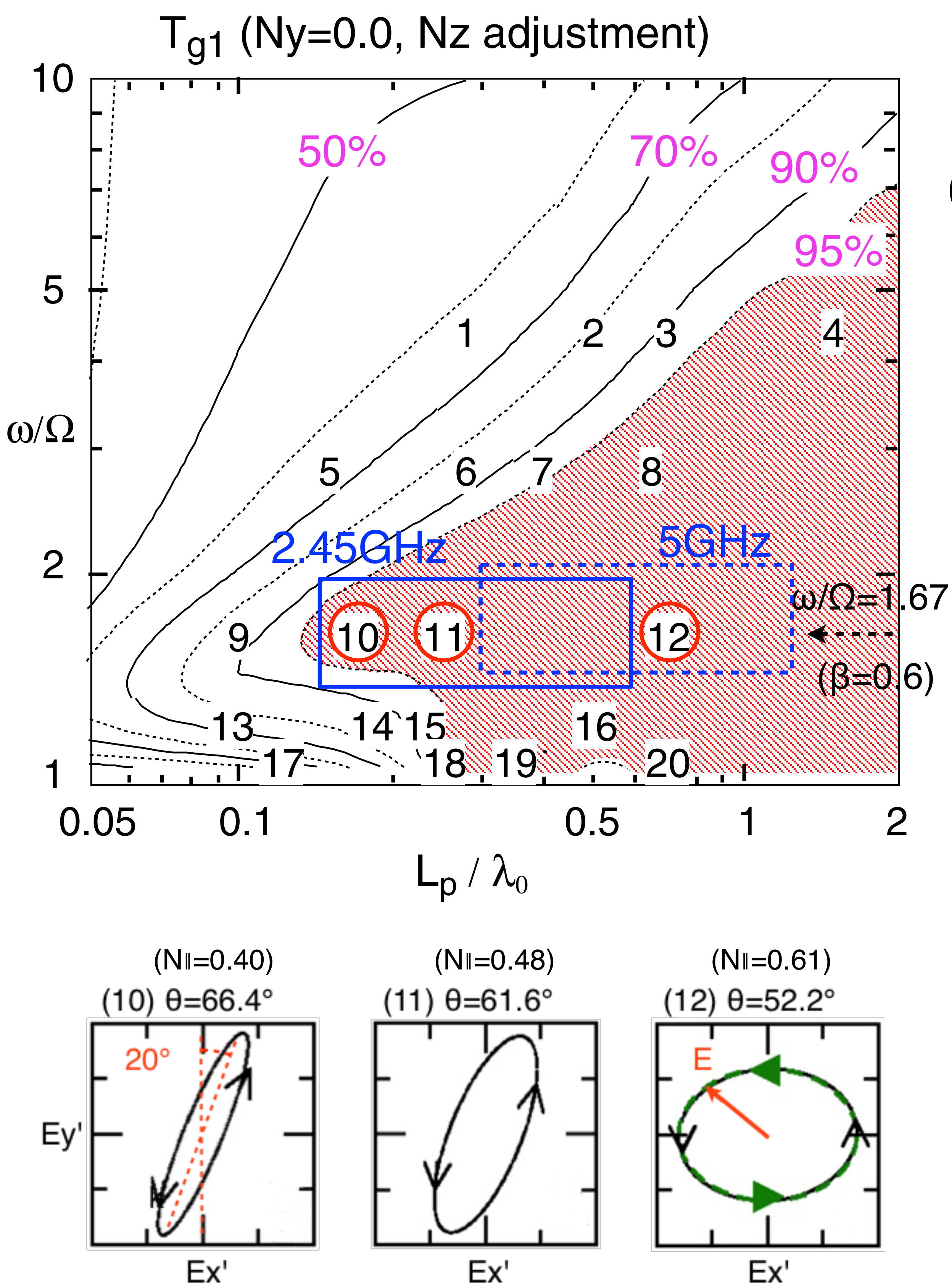


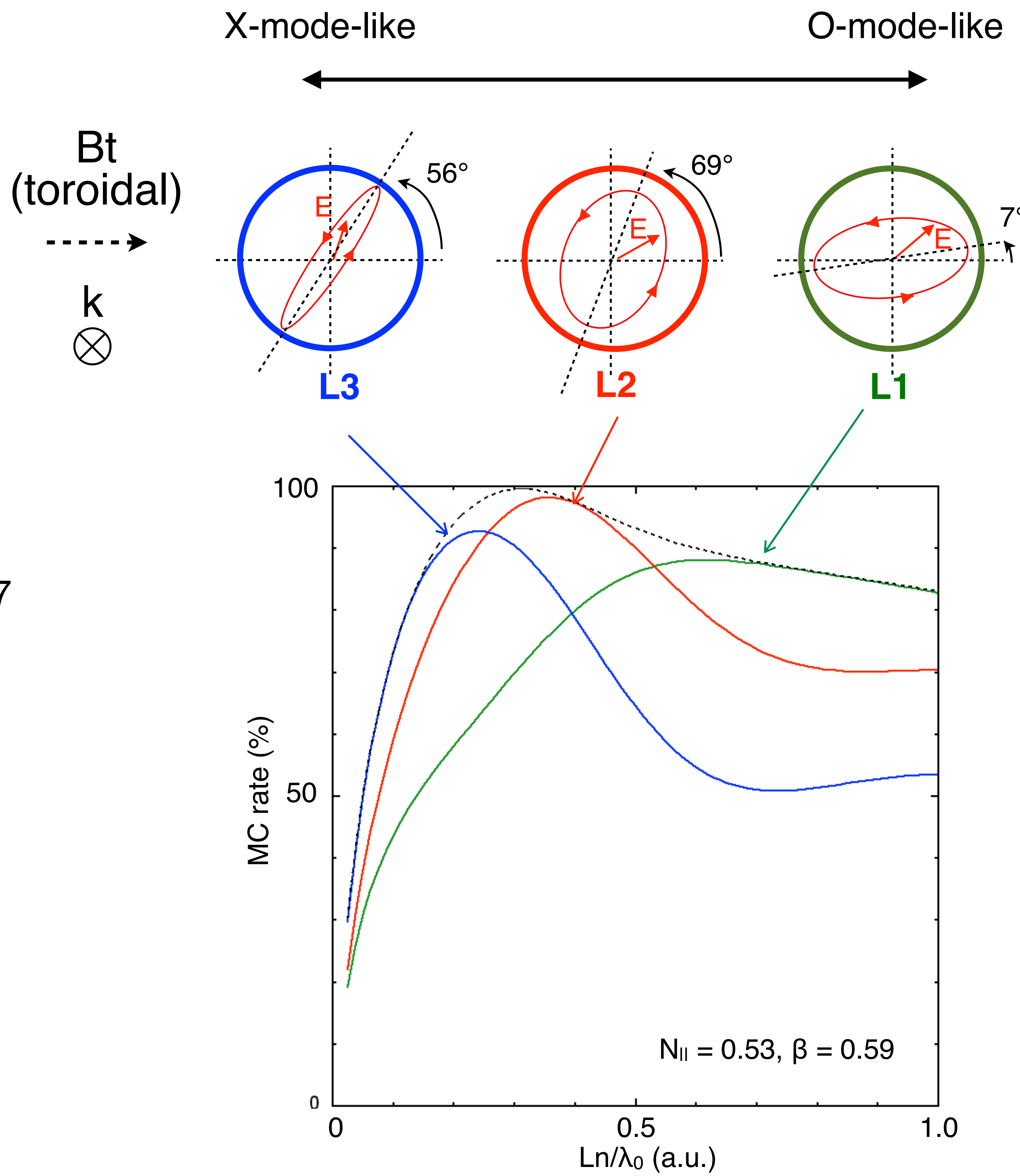
Three Sets of Polarizer



Y. Noguchi, *et al.*, Plasma Phys. Control. Fusion **55**, 125005 (2013)

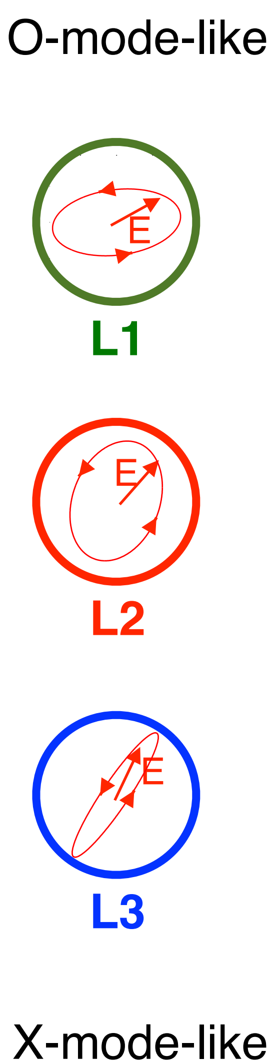
Mode Conversion Rate for Outboard Injection

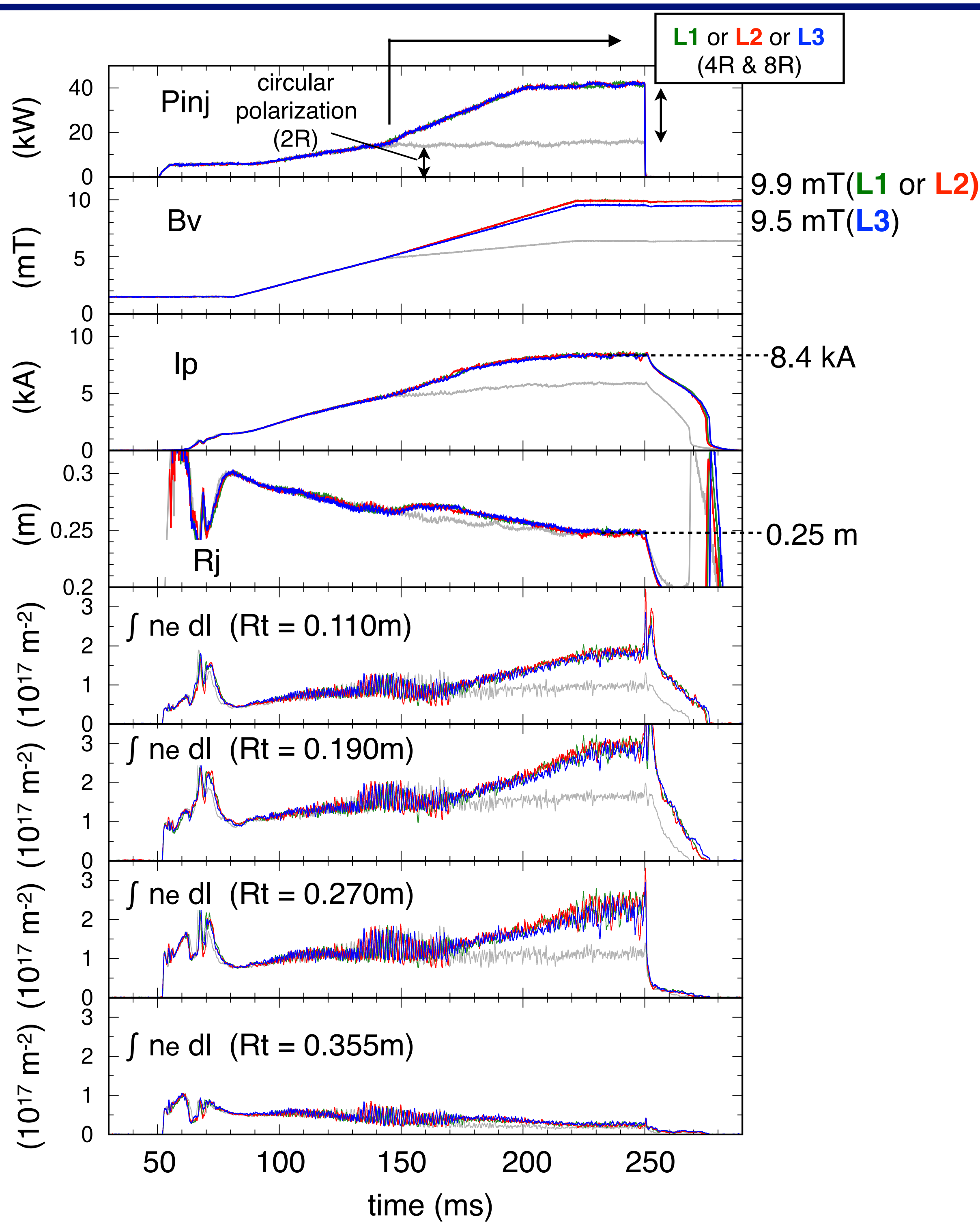


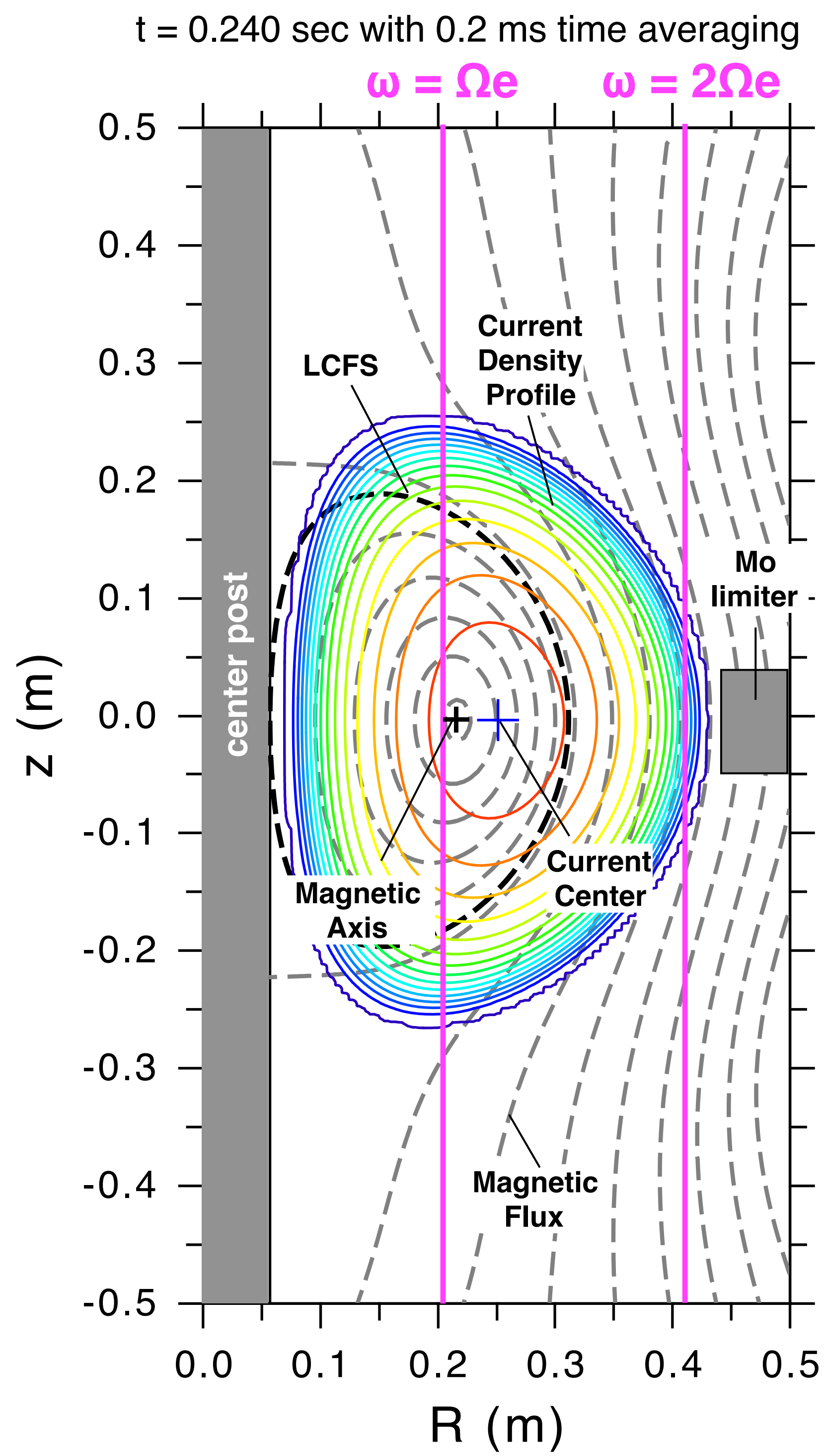


Igami et al., PPCF 48 (2006) 573

Waveforms (L1, L2, L3)



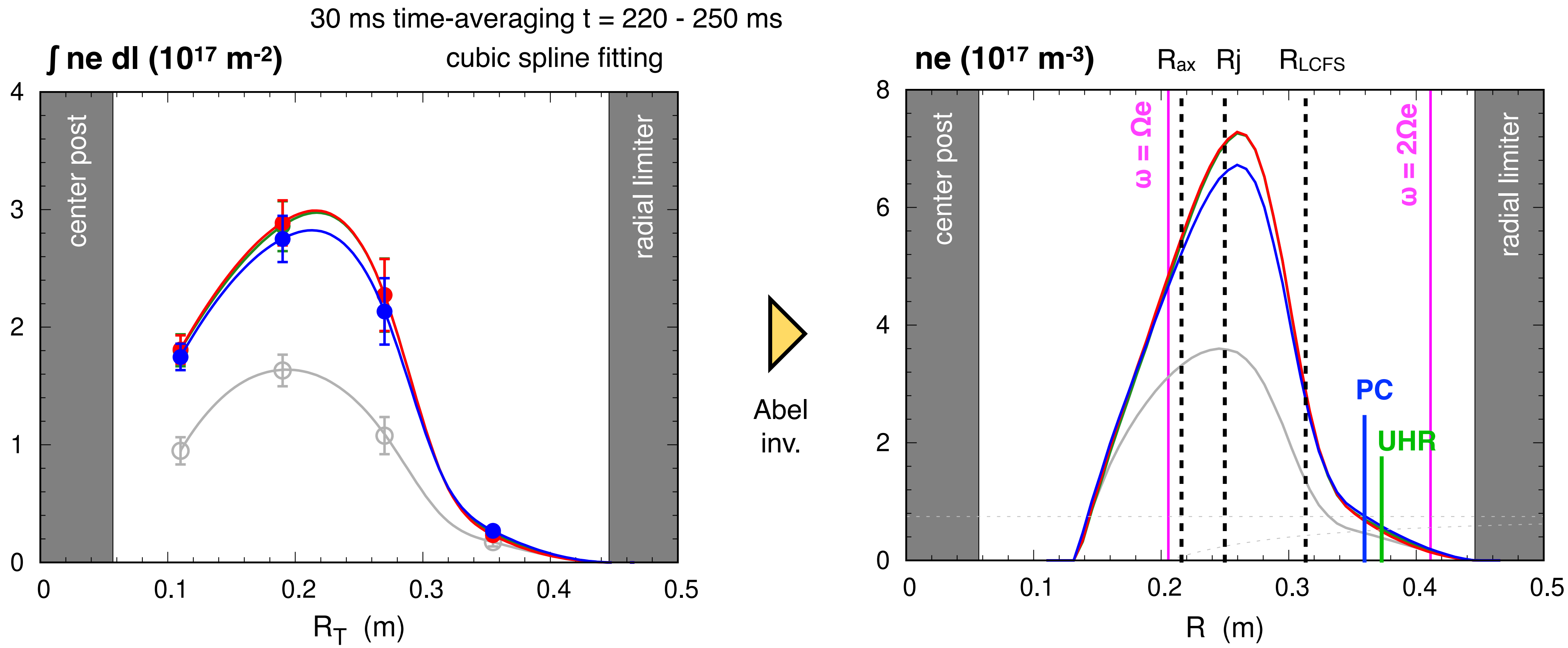




The difference of Ip is very small, suggesting that the produced high energy electrons are nearly the same among the three polarizations. The plasma current may be determined by the equilibrium Bv strength.

Density Profiles on the Mid-Plane (L1, L2, L3)

$R_{\Omega e}$ = 0.206 m
R_{ax} = 0.26 m
R_j = 0.25 m
R_{LCFS} = 0.315 m
R_{PC} = 0.36 m
R_{UHR} = 0.37 m
$R_{2\Omega e}$ = 0.412 m
$R_{Limiter}$ = 0.465 m



peak density value

L2 = L1 > L3

$7.3 \times 10^{17}\ m^{-3}$ = $7.3 \times 10^{17}\ m^{-3}$ > $6.7 \times 10^{17}\ m^{-3}$

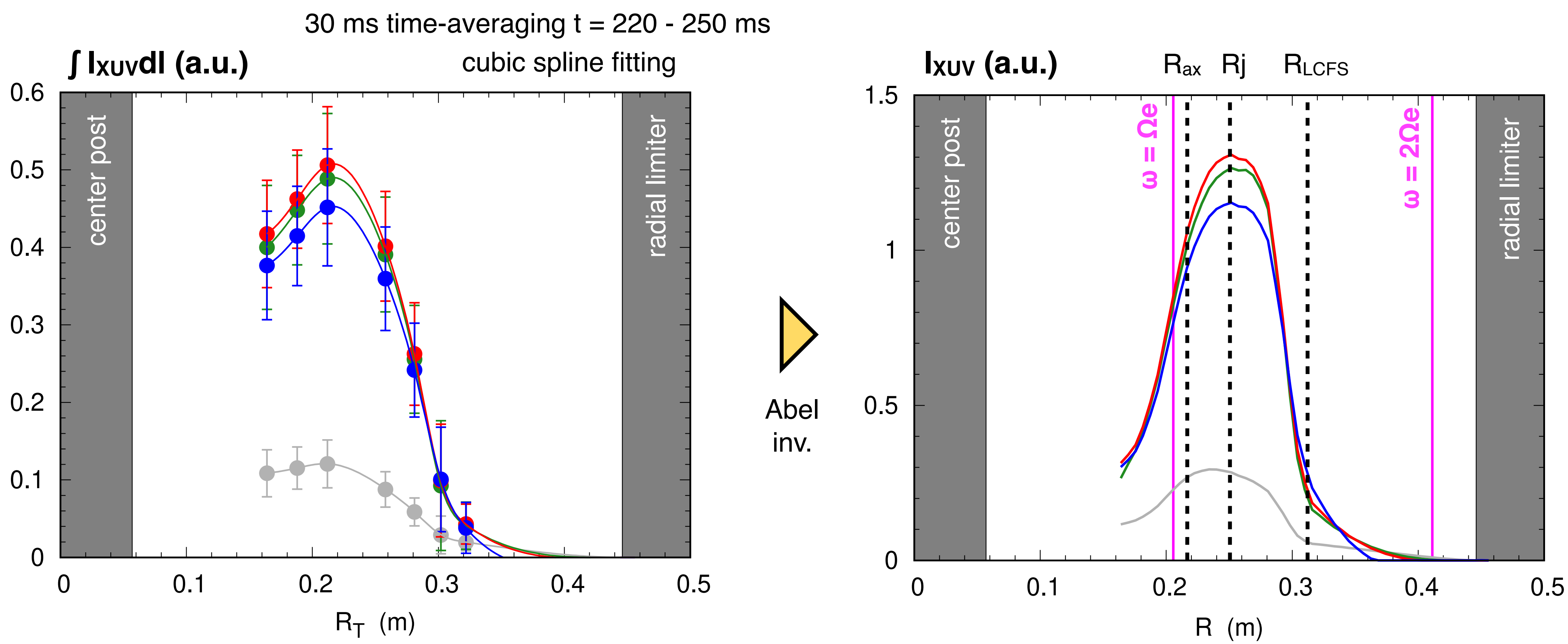
(~10 times the plasma cutoff density)

mode conversion rate (L_n/λ_0 = 0.47, $N_{||}$ = 0.52 and Ω_e/ω = 0.58)

L2 = L1 > L3

91 % > 82 % > 64 %

Soft X-ray Profiles on the Mid-Plane (L1, L2, L3)

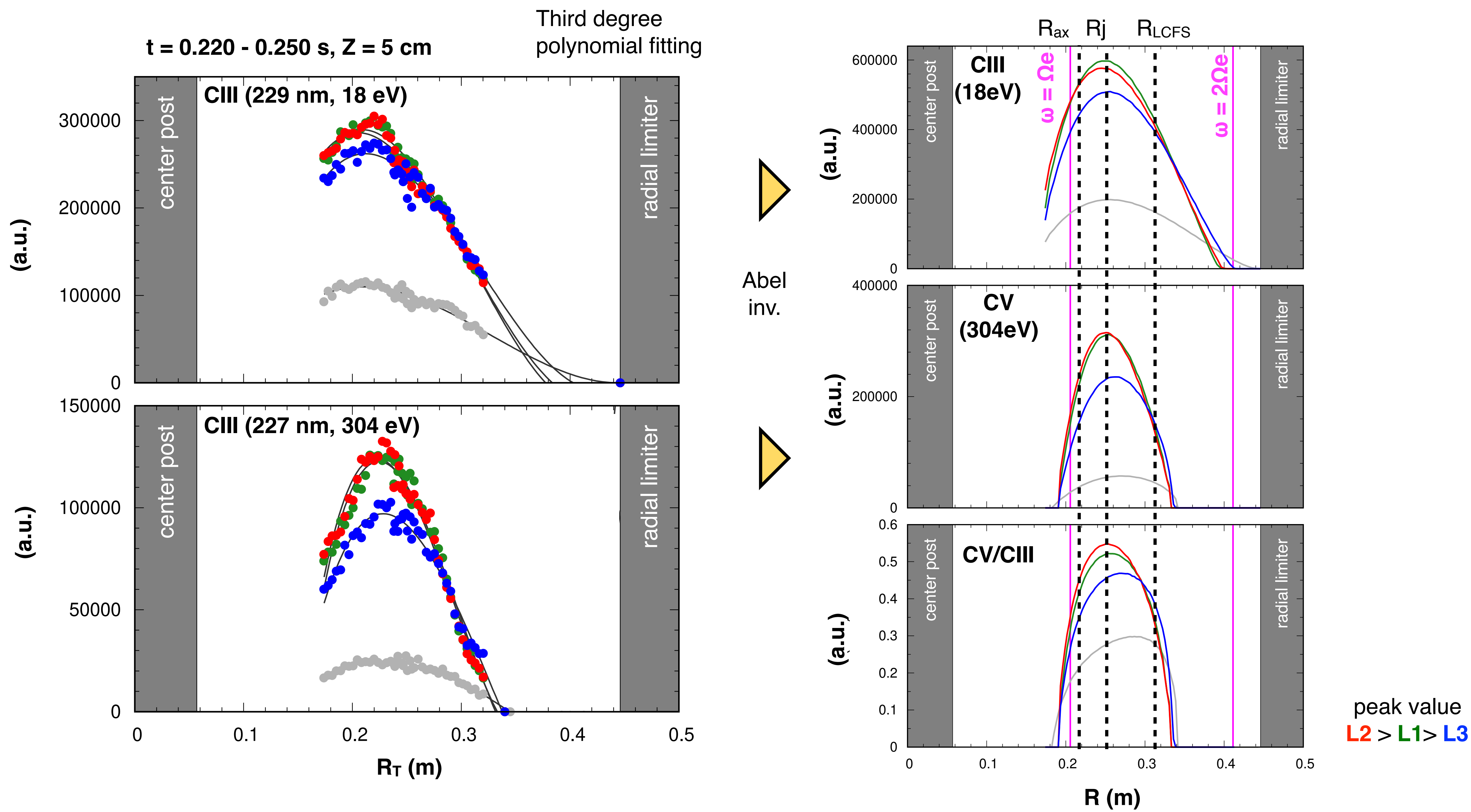


peak I_{SX} value

L2 > L1 > L3

1.31 > 1.21 > 1.15

Impurity Line Radiation Profiles on the Mid-Plane (L1, L2, L3)



peak CV/CIII value

L2 > L1 > L3

0.55 > 0.52 > 0.47

Summary on Polarization Adjustment for EBWH/CD

* Overdense ST plasmas are non-inductively formed by oblique injection of 2.45 GHz microwave on the mid-plane with three left-handed elliptical polarizations (L1, L2 and L3), respectively, at $\Omega e/\omega \sim 0.6$.

* The difference of Ip is very small, suggesting that the produced high energy electrons are nearly the same among the three polarizations.

  The plasma current may be determined by the equilibrium Bv strength.

* The bulk electrons in the plasma core region (~10 times the plasma cutoff density) is effectively heated by EBW when the polarization of incident microwave is L2, whose mode conversion rate is largest among three polarizations.

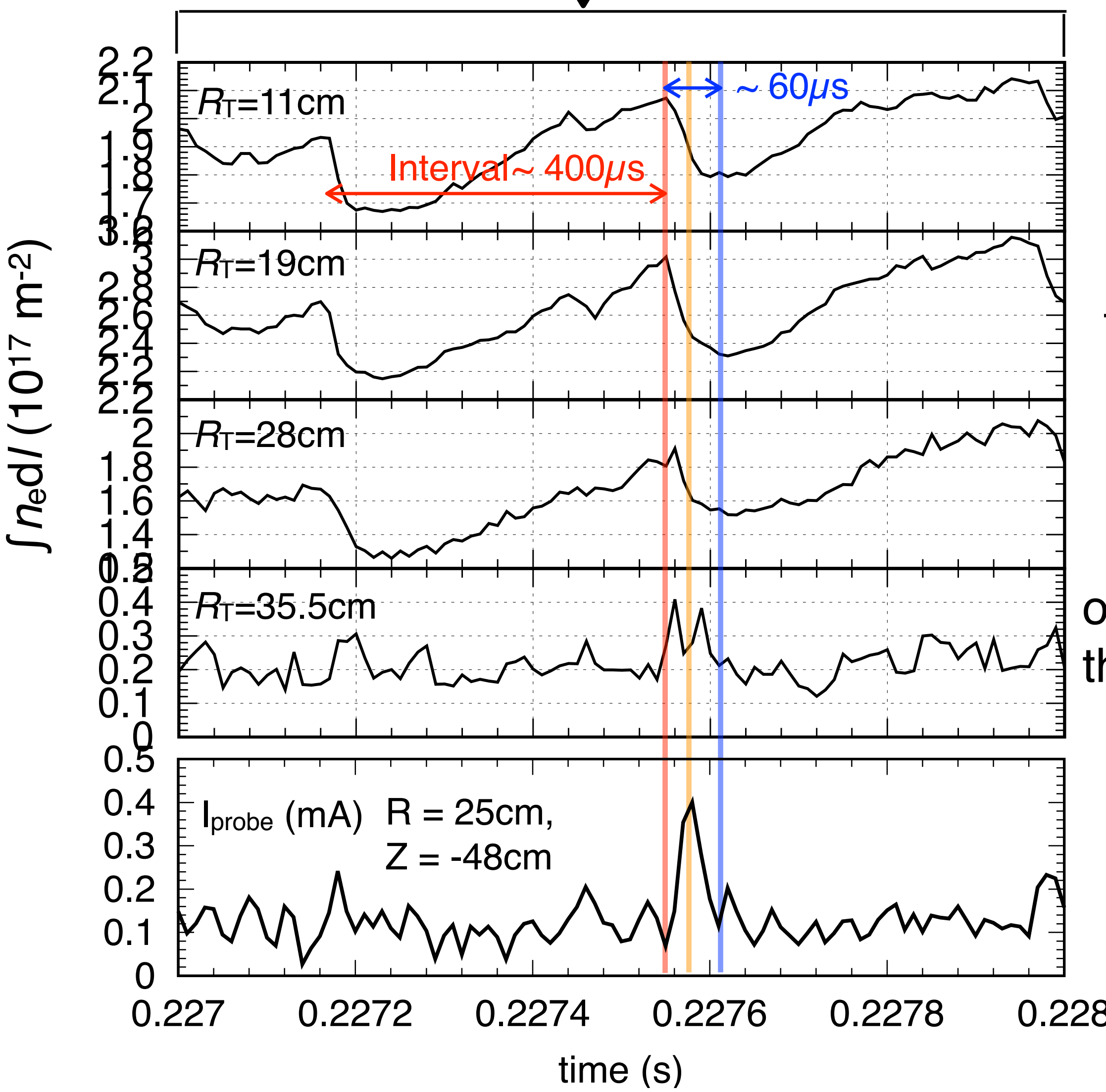
  It is difficult to explain quantitatively, but linear mode-conversion theory well guide the optimal polarization.

1. Polarization Adjustment for Non-inductive Production of Highly Overdense ST Plasma by EBW

2. Intermittent Plasma Ejection Events in an Overdense ST Plasma sustained by EBW

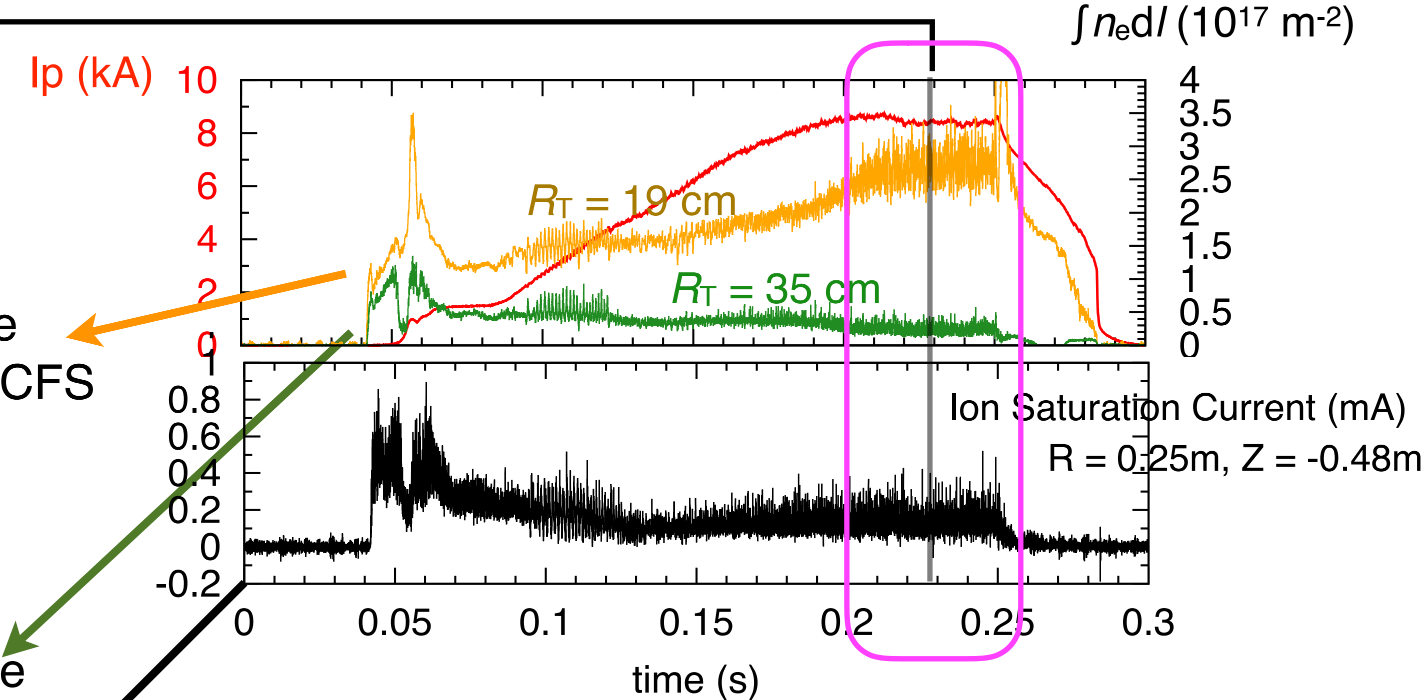
3. Electron Beam Injection into EBW-produced plasma (Preliminary Result)

Variation of Density Profile at Ejection Events



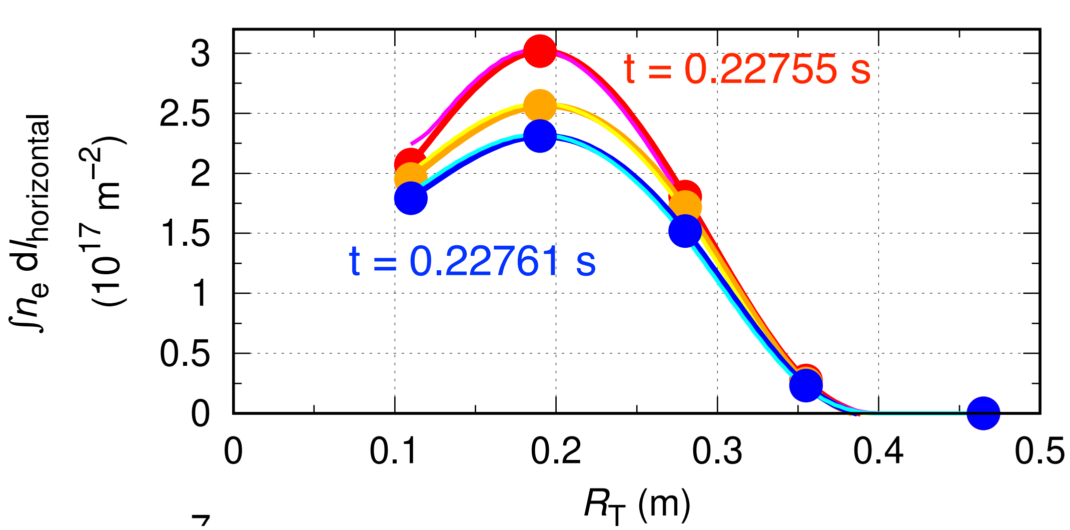
inside the LCFS

outside the LCFS



appearing when Ip and ne are large

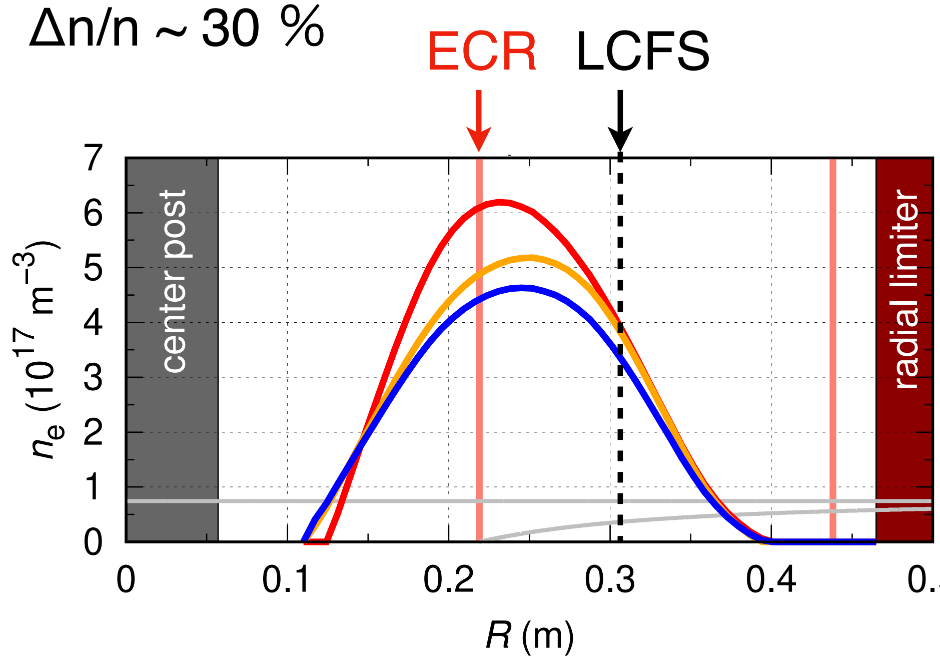
$q_0 \sim 8$, $q_a \sim 60$



Abel Inversion

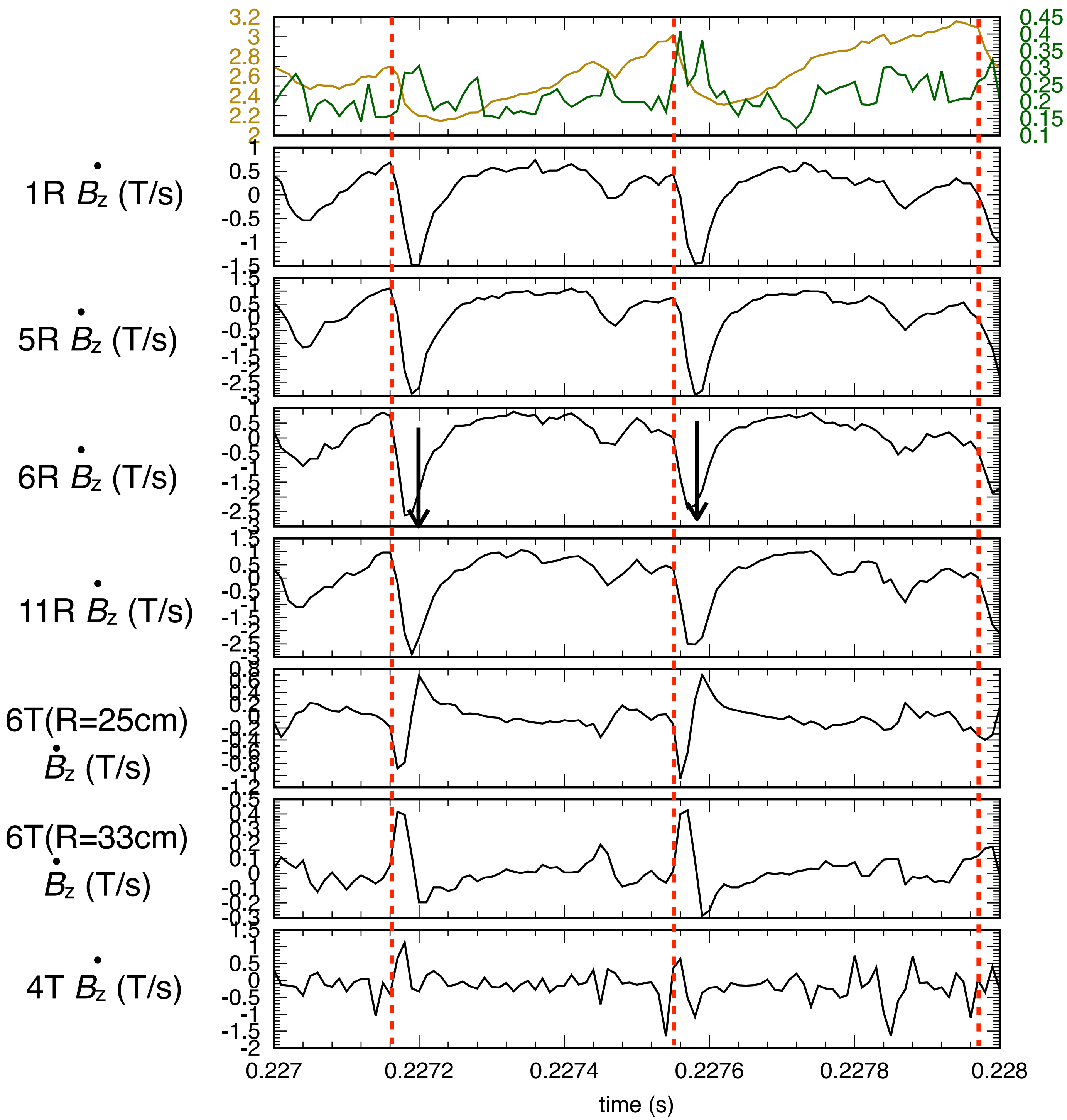
Density reduction for before and after crash

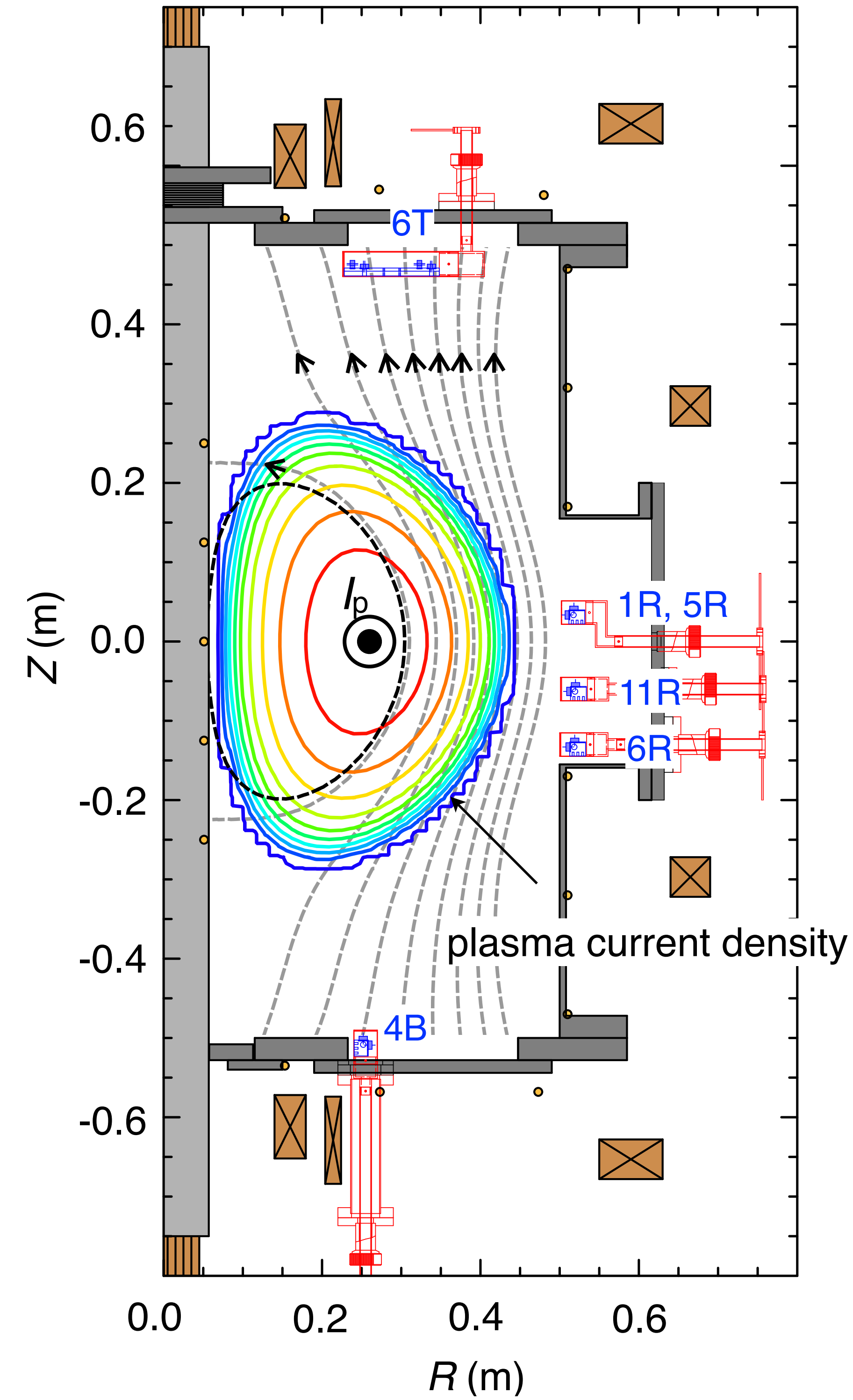
$\Delta n/n \sim 30$ %



Variation of Poloidal Field during Ejection Event

Poloidal field produced by plasma current reduces during the ejection event.

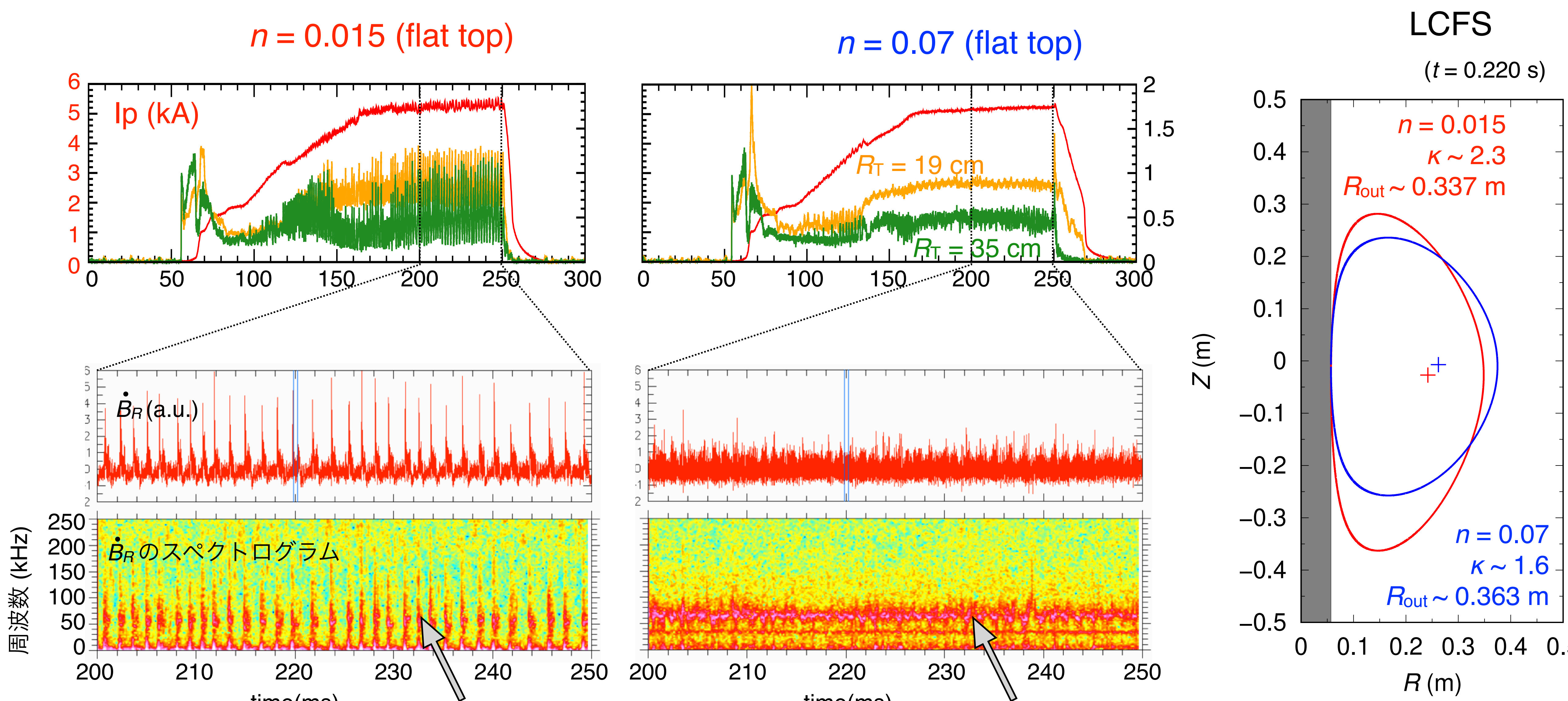




Effect of Plasma Elongation

The peak density value increases as the plasma elongation becomes large.

--> Balooning-type instability?



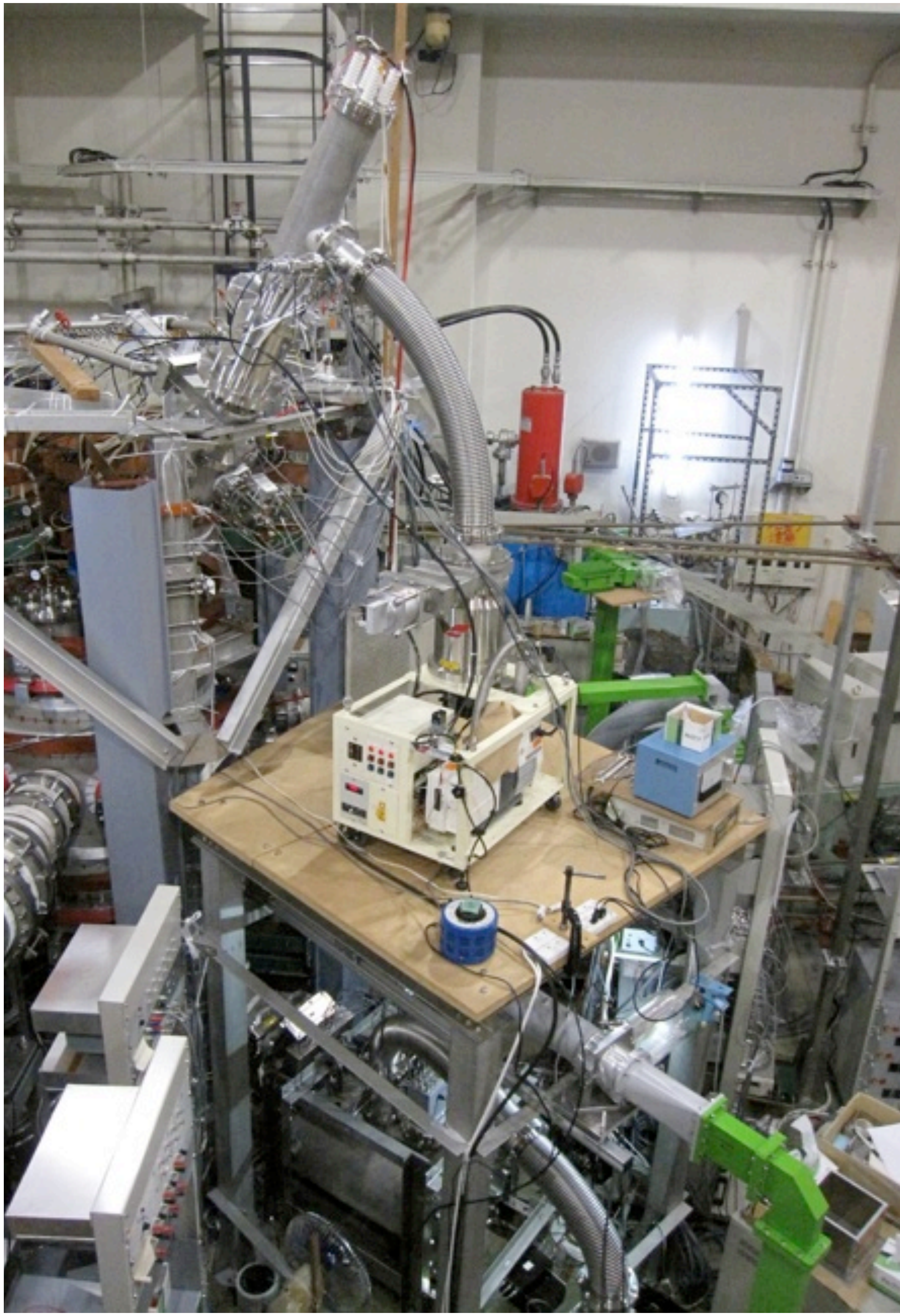
f ~ 80 kHz oscillation appears only during the crash

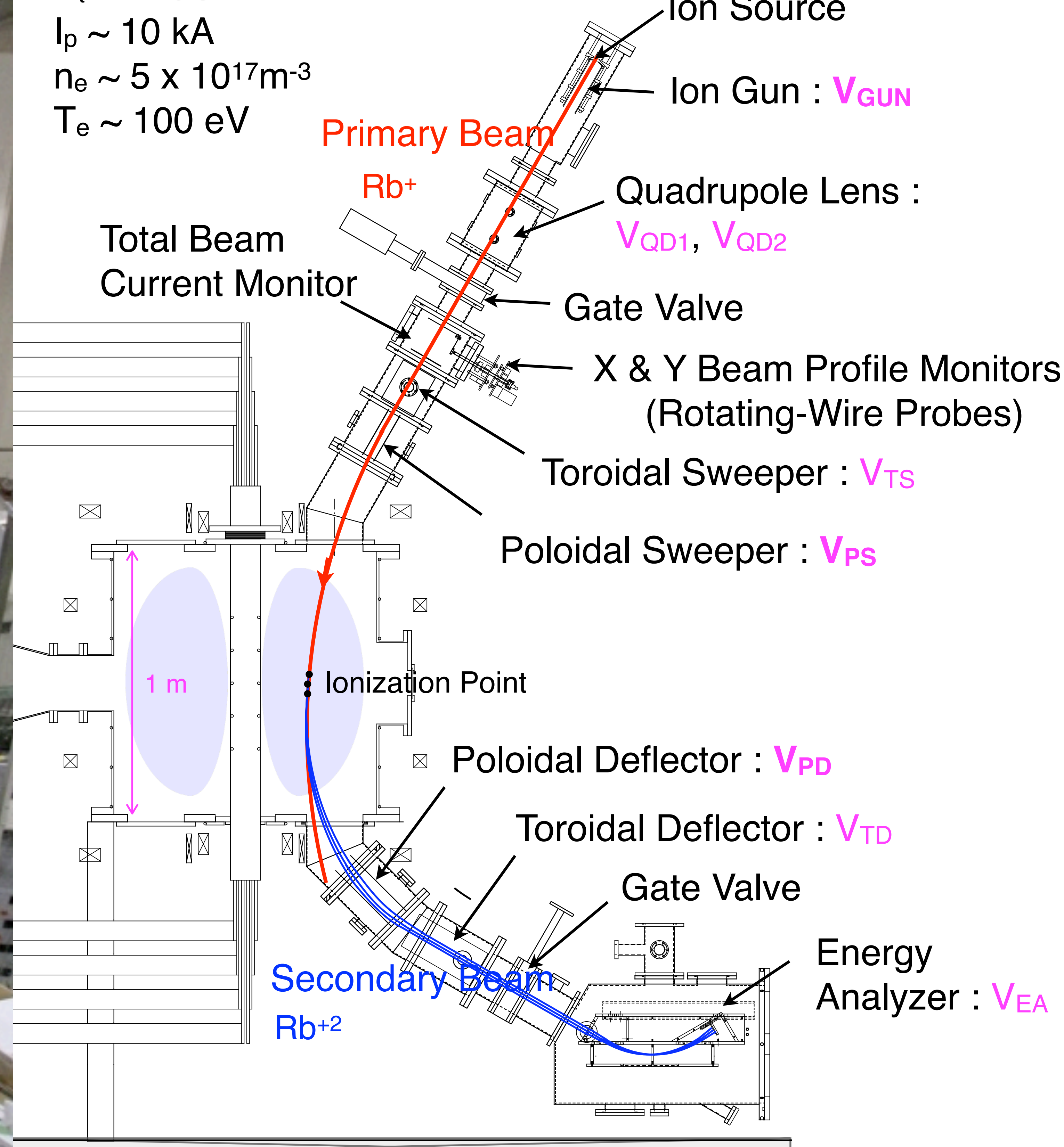
f ~ 80 kHz oscillation

HIBP System

Target Plasma :

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



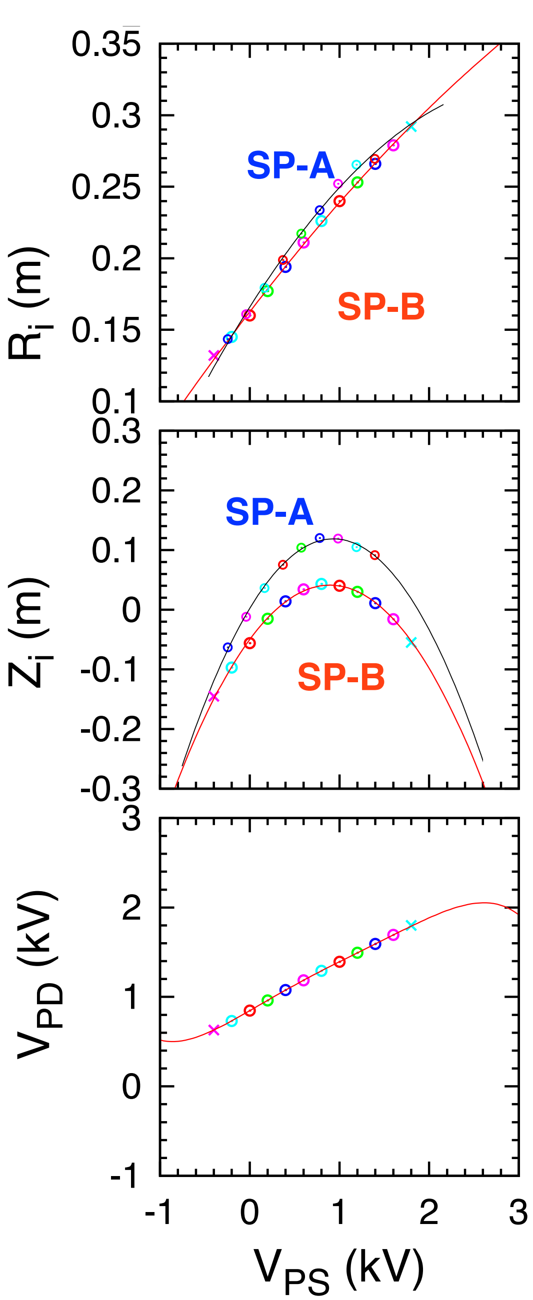


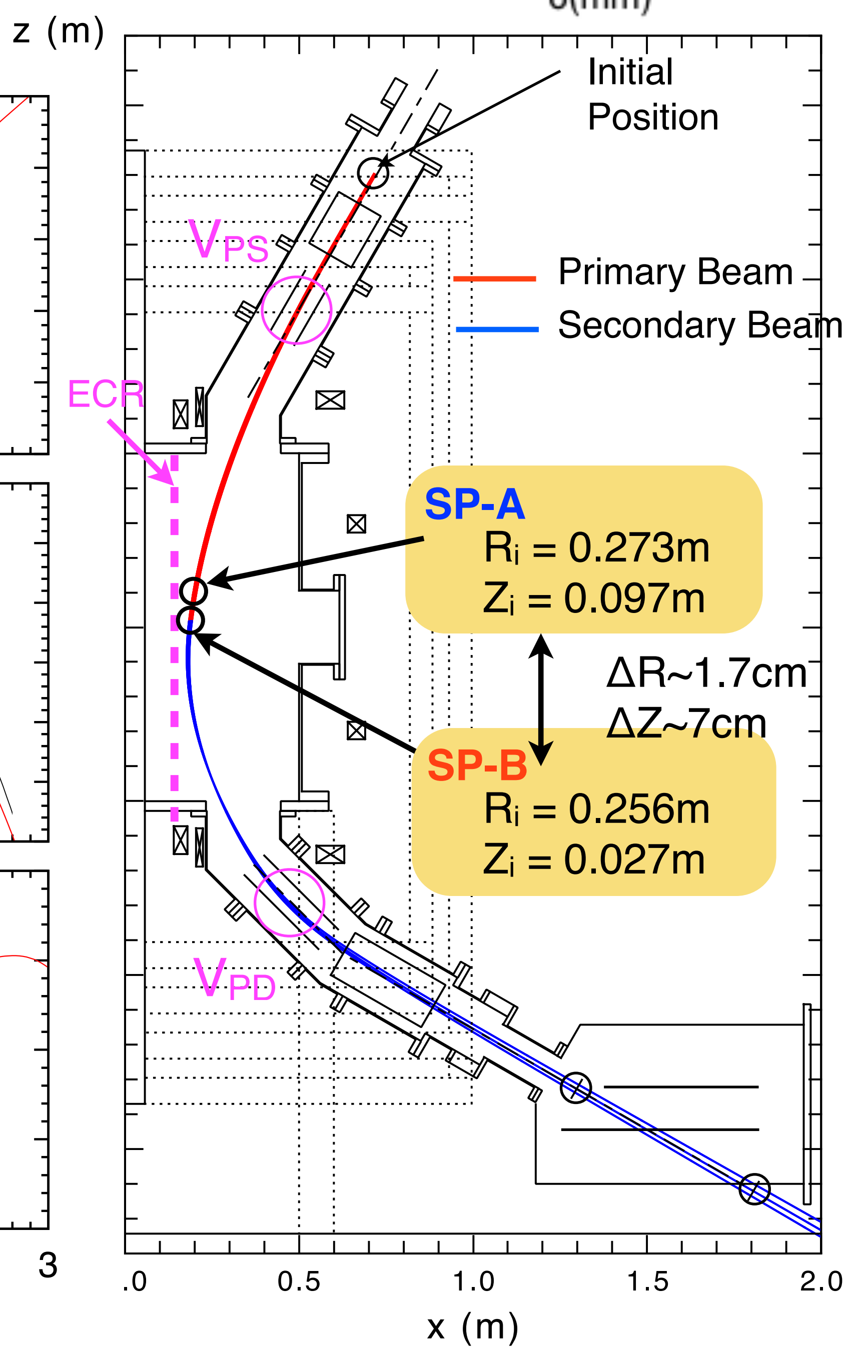
Measurement Positions of Space Potential

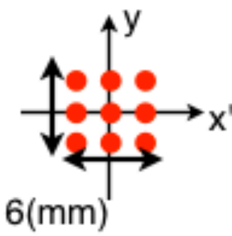
Trajectory Calculation

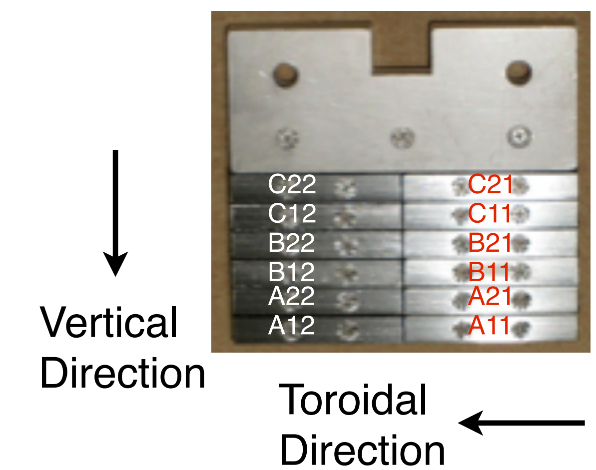
Bt = 720G
Bv = 0G, Ip = 0A
Rb^+, V_{GUN} = 16kV
V_{PS} = 1248V
V_{PD} = 1518V

Measurement positions are changed by adjusting the voltages of V_{GUN}, V_{PS}, V_{PD}.

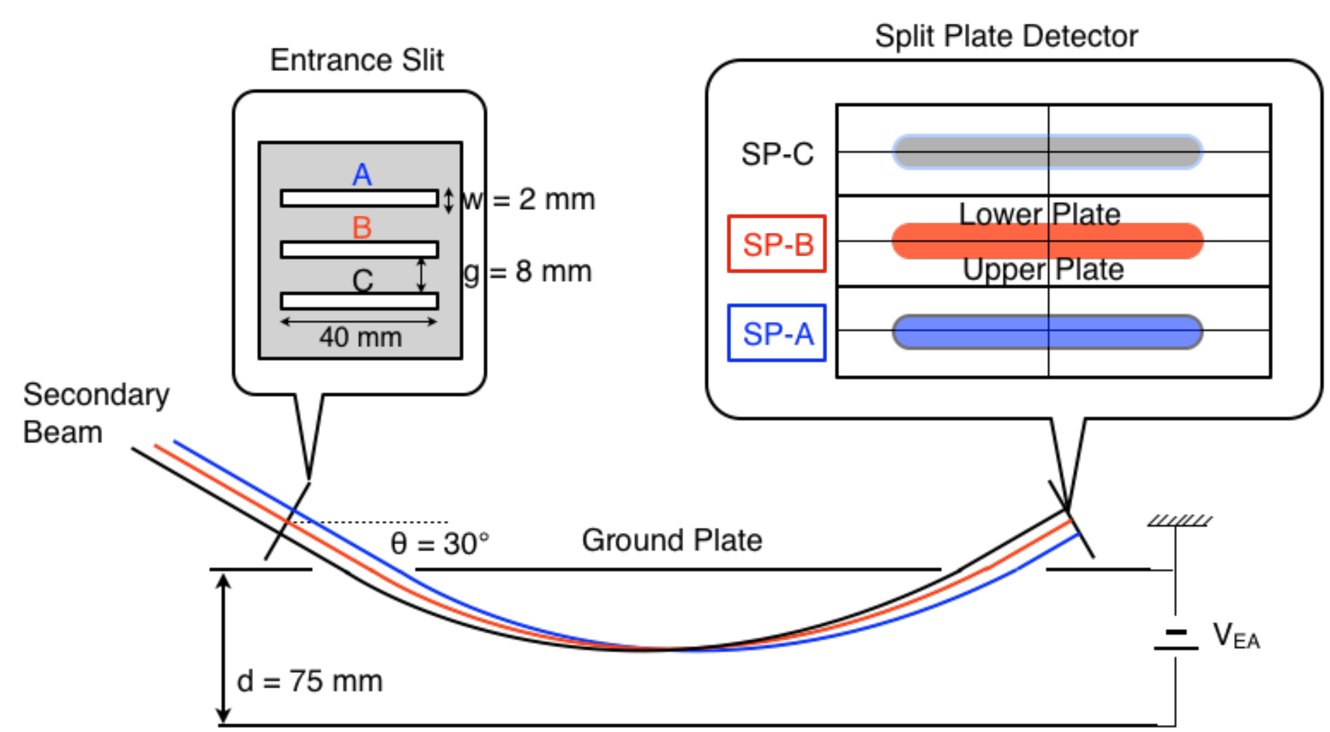






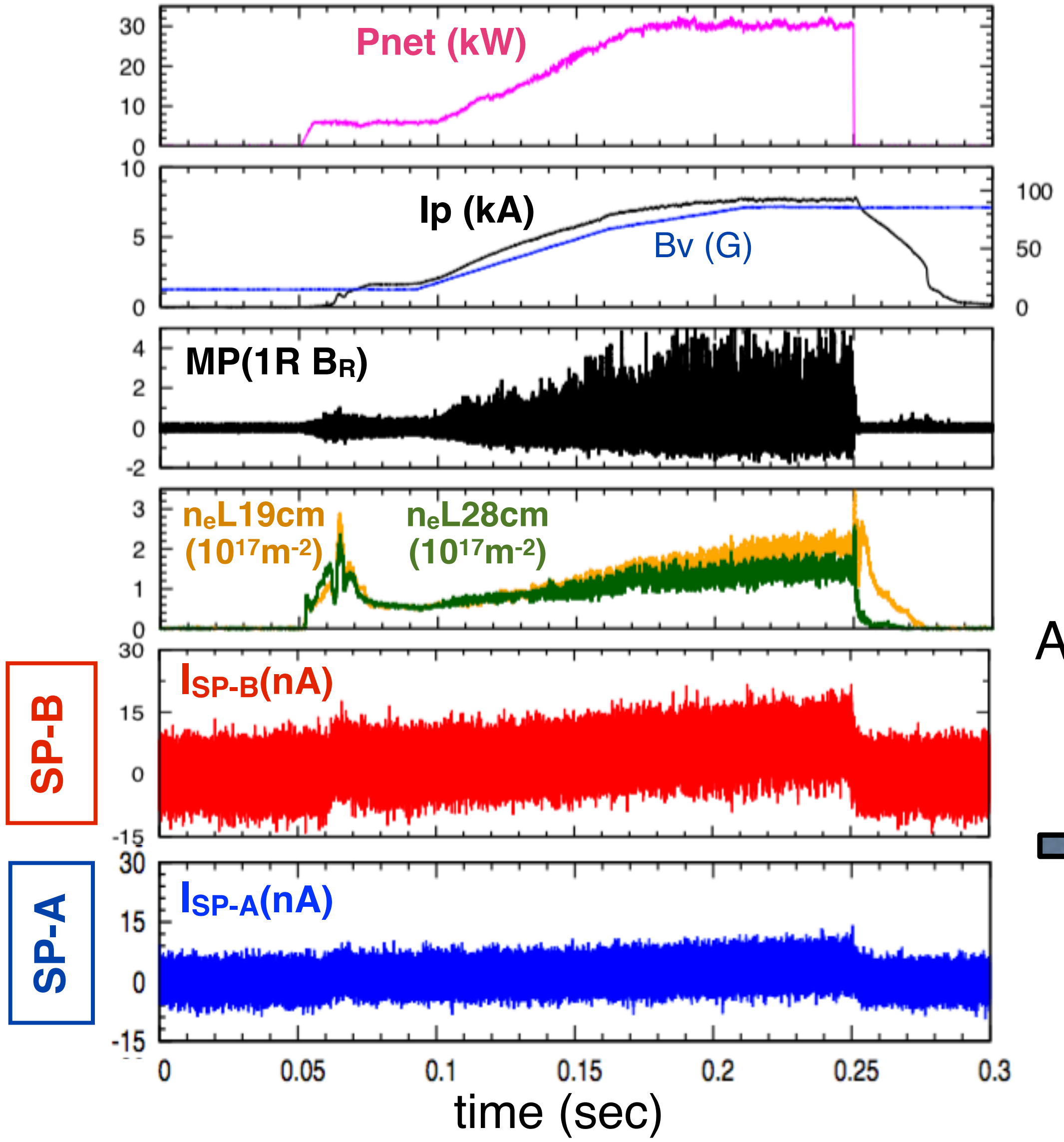


Energy Analyzer



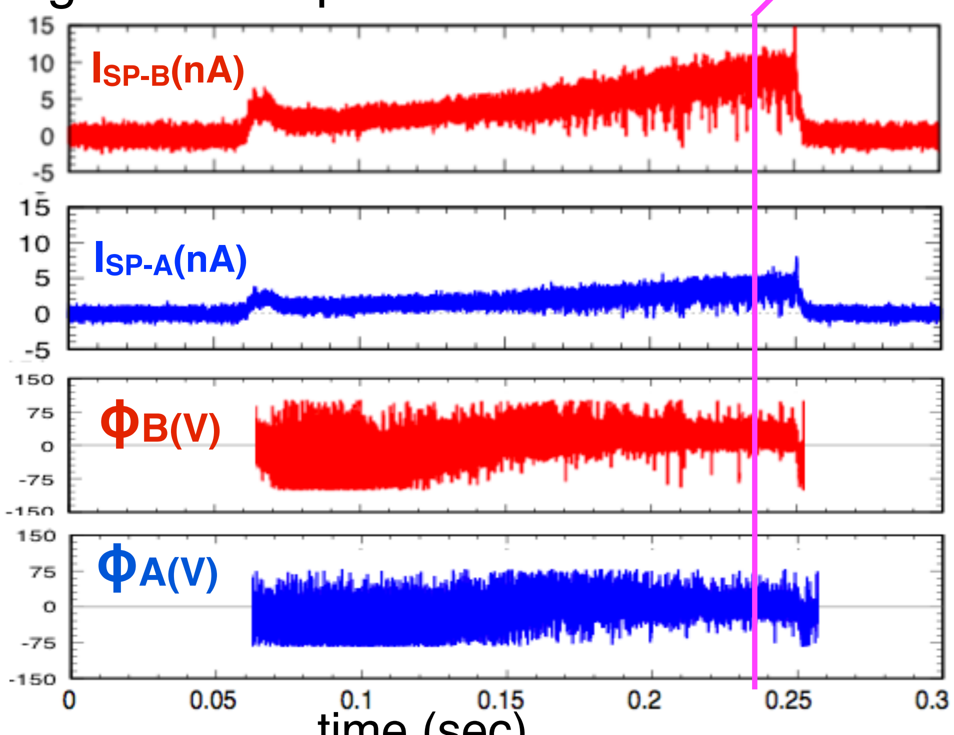
Identifying Events from Waveforms

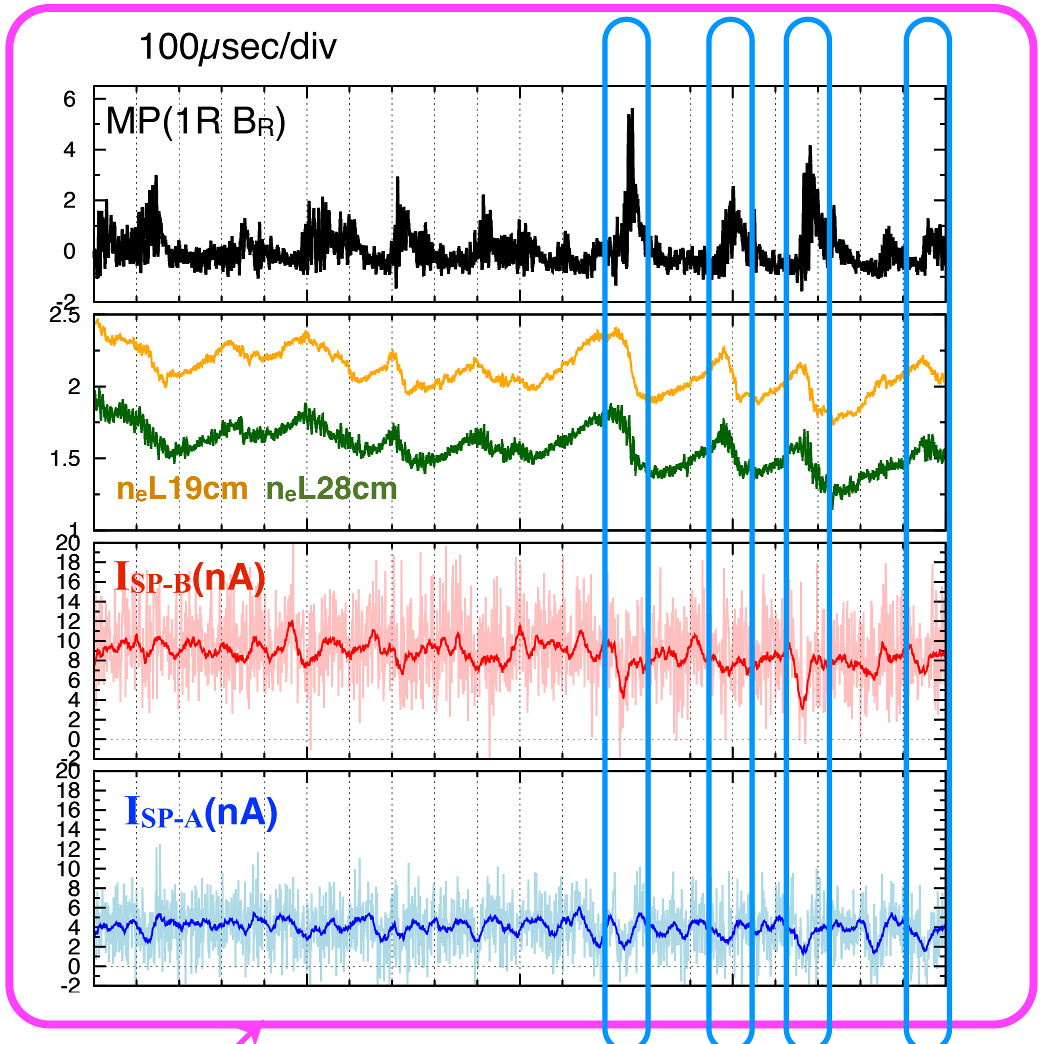
B_T=720 (G)
P_{net} = 31(kW), I_p =7.2 (kA)
B_V = 80(G), n_eL_{19cm}= 2.4($10^{17}m^{-2}$)



sampled data at every 1 µsec

Average over 20 µsec





Select data

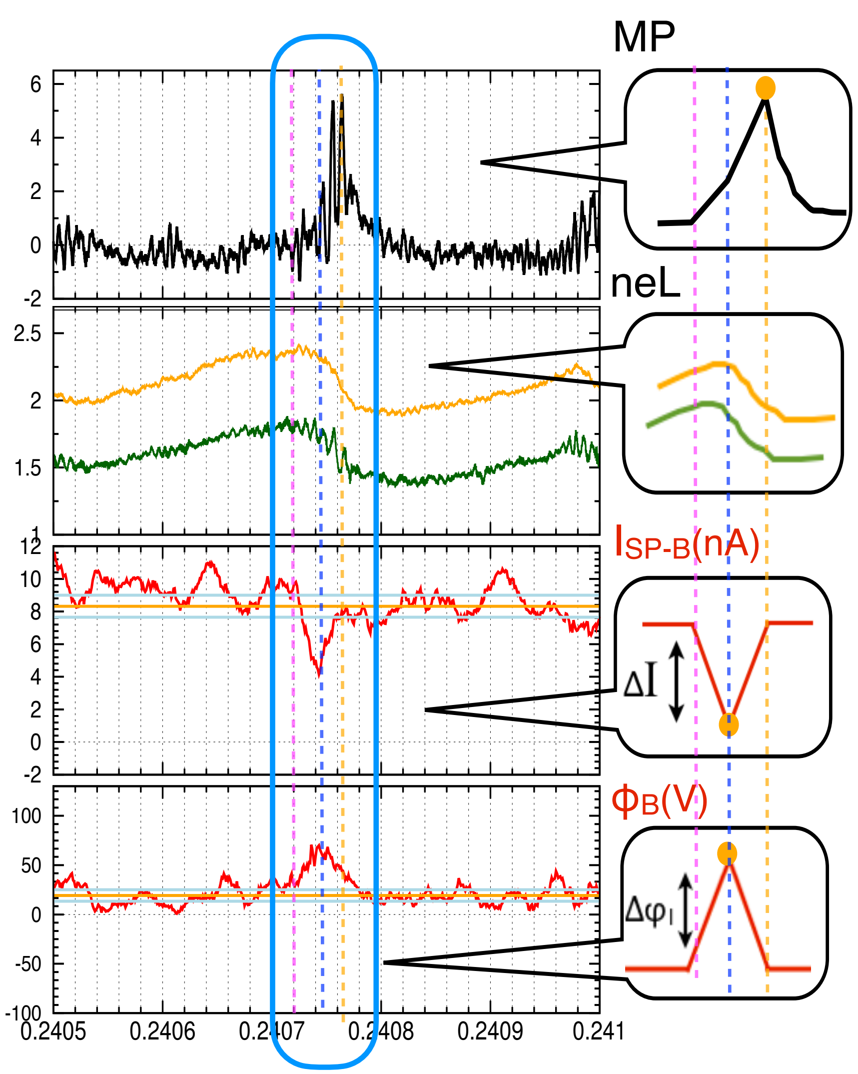
Variation Patterns during Ejection Events

Secondary beam current $I_{SP\text{-}A}$ and $I_{SP\text{-}B}$ decreases syncronized with the ejection events.

Decrease of Electron Density

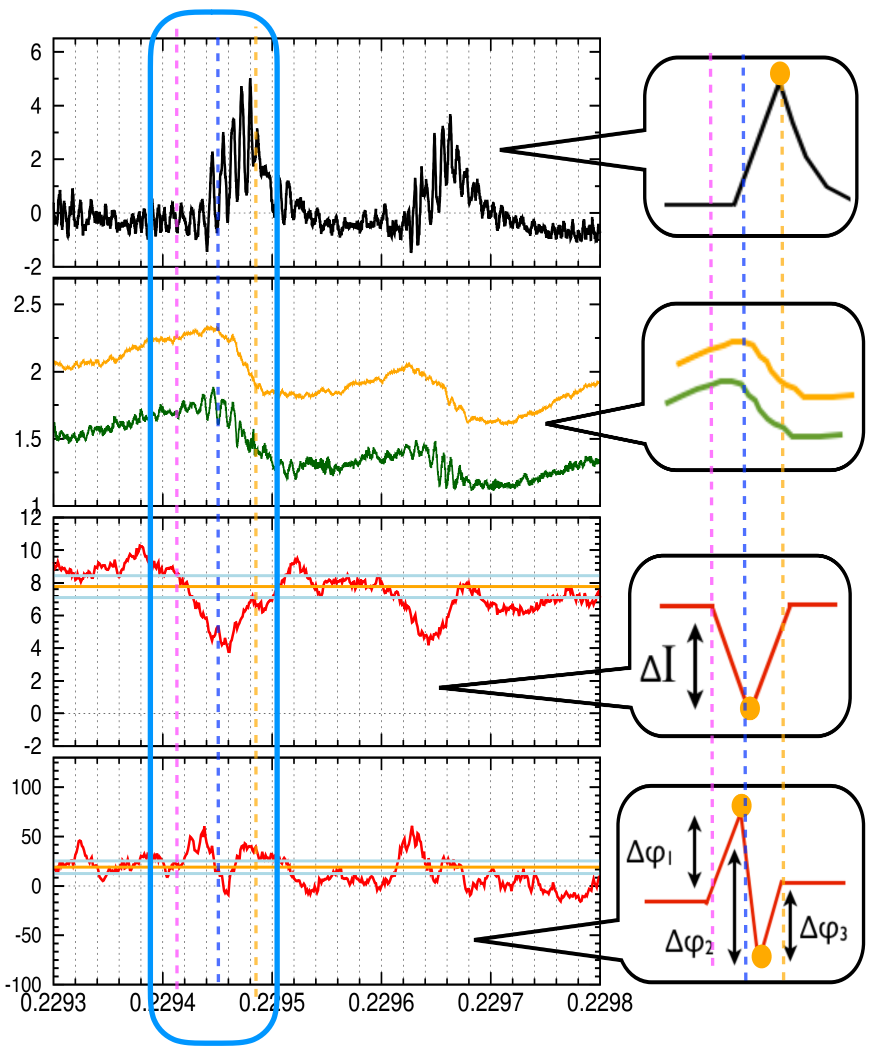
Type 1

Potential increases and recovers



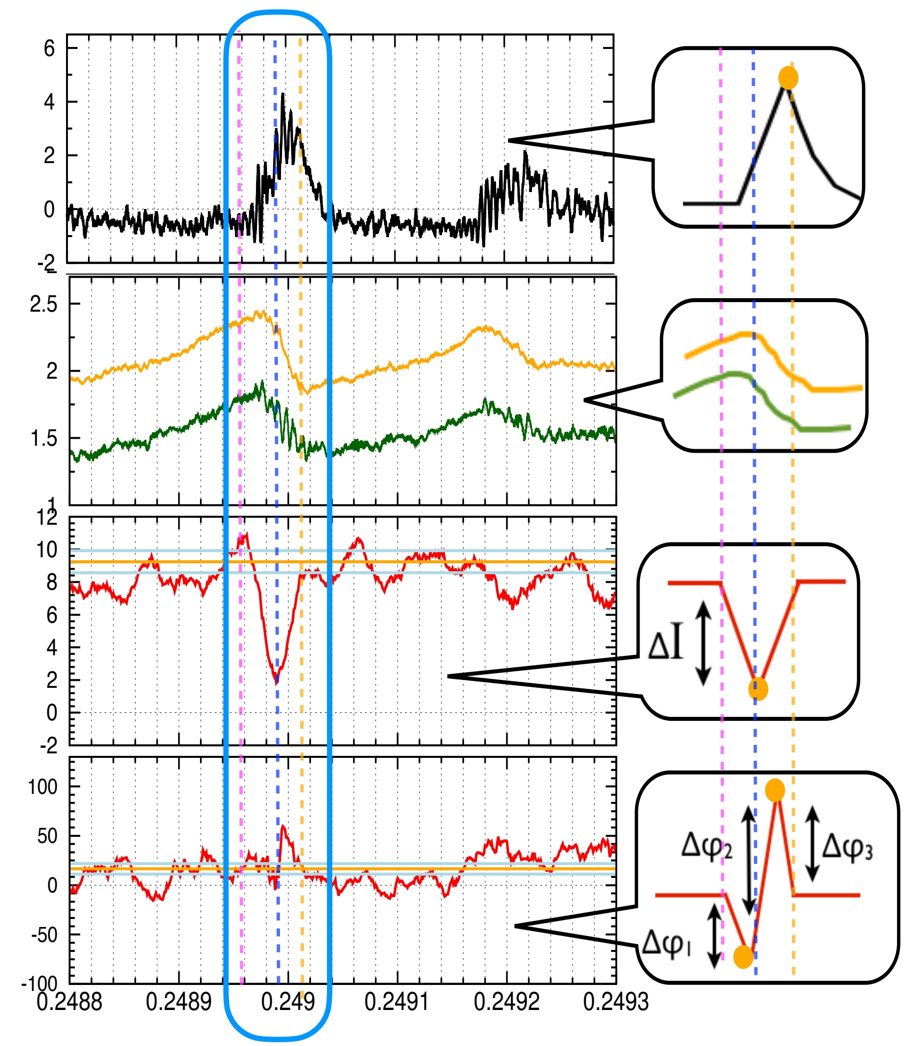
Type 2

Potential increases firstly and decreases below the initial value, then recovers



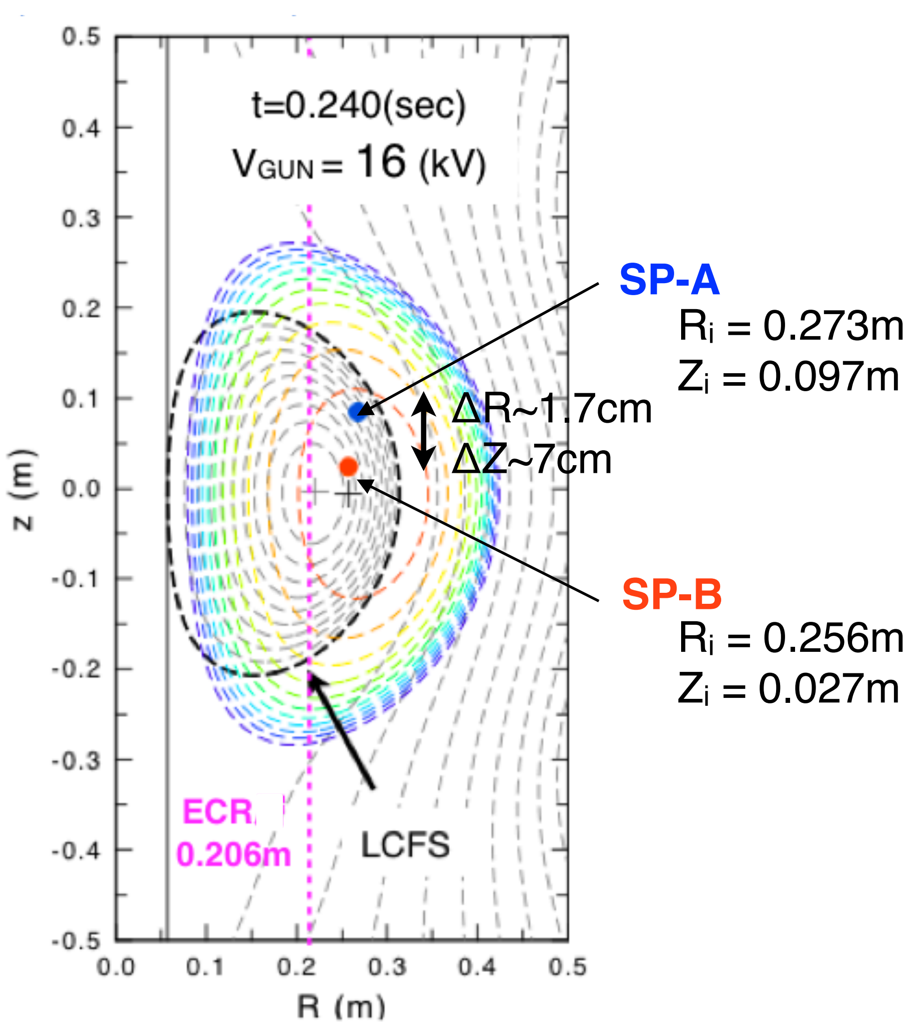
Type3

Potential decreases firstly and increases above the initial value, then recovers



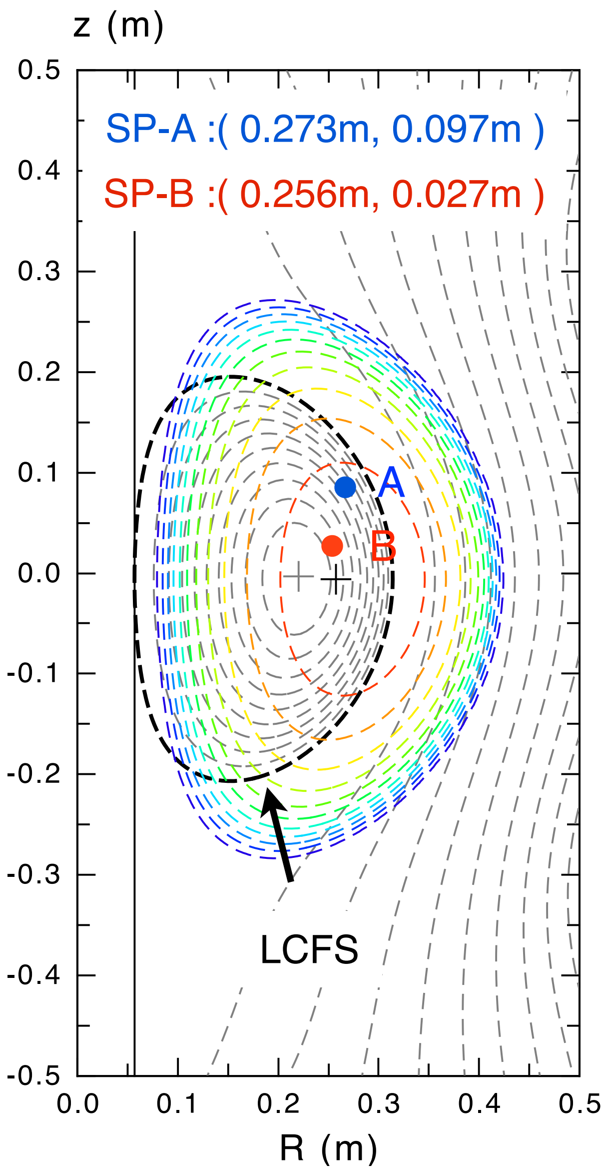
Combination of Variation Patterns in 2 Positions

t = 0.200 ~ 0.250 sec



SP-A \ SP-B	Type 1 ($\Delta\varphi_1$)	Type 2 ($\Delta\varphi_1$, $\Delta\varphi_2$, $\Delta\varphi_3$)	Type 3 ($\Delta\varphi_1$, $\Delta\varphi_2$, $\Delta\varphi_3$)	No Coherent Signals
Type 1 ($\Delta\varphi_1$)	51	28	10	4/93
Type 2 ($\Delta\varphi_1$, $\Delta\varphi_2$, $\Delta\varphi_3$)	24	23	2	2/51
Type 3 ($\Delta\varphi_2$, $\Delta\varphi_3$, $\Delta\varphi_1$)	2	5	4	10/21
No Coherent Signals	6/83	3/59	3/19	Total 177

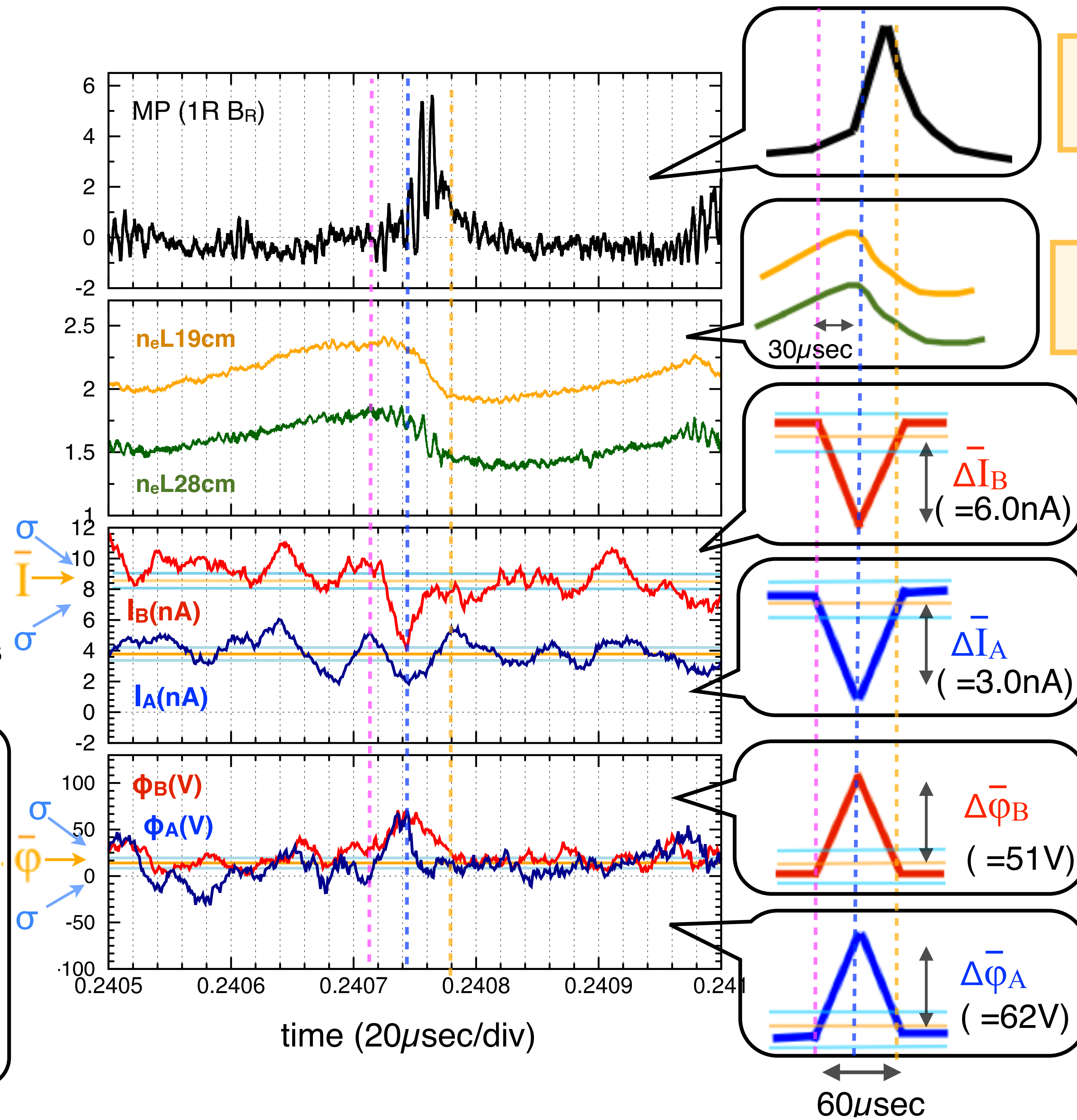
Time Variation of Space Potential : Type 1



t = 0.200～0.250(msec)
averaged value

SP-B $\bar{I}_B = 8.5 \pm 0.6$ nA
$\bar{\varphi}_B = 18 \pm 5$ V

SP-A $\bar{I}_A = 3.9 \pm 0.4$ nA
$\bar{\varphi}_A = 12 \pm 6$ V



Spikey Signal of Magnetic Probes

Decrease of Line-Integraged Density

Decrease of Secondary Beam Current
Decrease of Electron Density

Increase of Space Potential by ~Te
Faster loss of Electrons

Summary on Plasma Ejection Events

* Sawtooth-like density oscillations in the plasma core are observed, which are synchronized with poloidal field decrement, suggesting that the loss of both bulk and high energy electrons. Such ejection events frequently appears when Ip and ne are large (typically, $q_0 \sim 8$, $q_a \sim 60$)

* The peak density value increases as the plasma elongation becomes large.

* HIBP measurement also shows the local electron loss.
  Two position measurement of space potential suggest that some positive and negative potential distributions appear during the ejection events.
  The structure size is more than 7cm and the potential difference is order of Te.

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2. Intermittent Plasma Ejection Events in an Overdense ST Plasma sustained by EBW

3. Electron Beam Injection into EBW-produced plasma (Preliminary Result)

Electron Beam Injection + ECH/ECCD

Background

* Electron Bernstein wave (EBW) is an electrostatic wave and can propagate into the core plasma and heat electrons without density limit. It is effective for non-inductive start-up of over-dense ST plasmas by ECH/ECCD.

* Electron beam injection (EBI) from a cathode can drive plasma current directly and effectively. It has been investigated from the view point of helicity injection for non-inductive start-up of ST plasmas.

Purpose

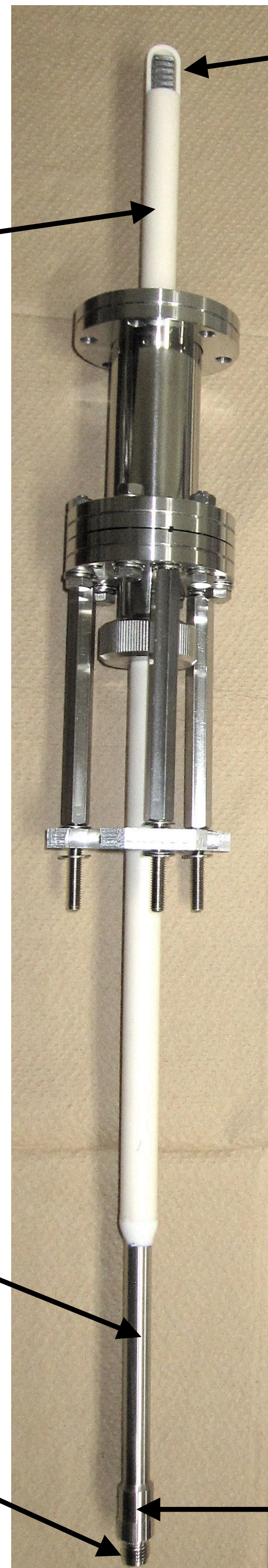
An attempt to drive higher plasma current non-inductively in an over-dense plasma by EBI and EBW, expecting synergy effects such as preferential heating of electrons injected from a cathode by EBW.

==> Combination of ECH/ECCD by EBW and CD by EBI is expected higher current and density via synergy interaction between them.

Cold Cathode for EBI

Mo cathode head

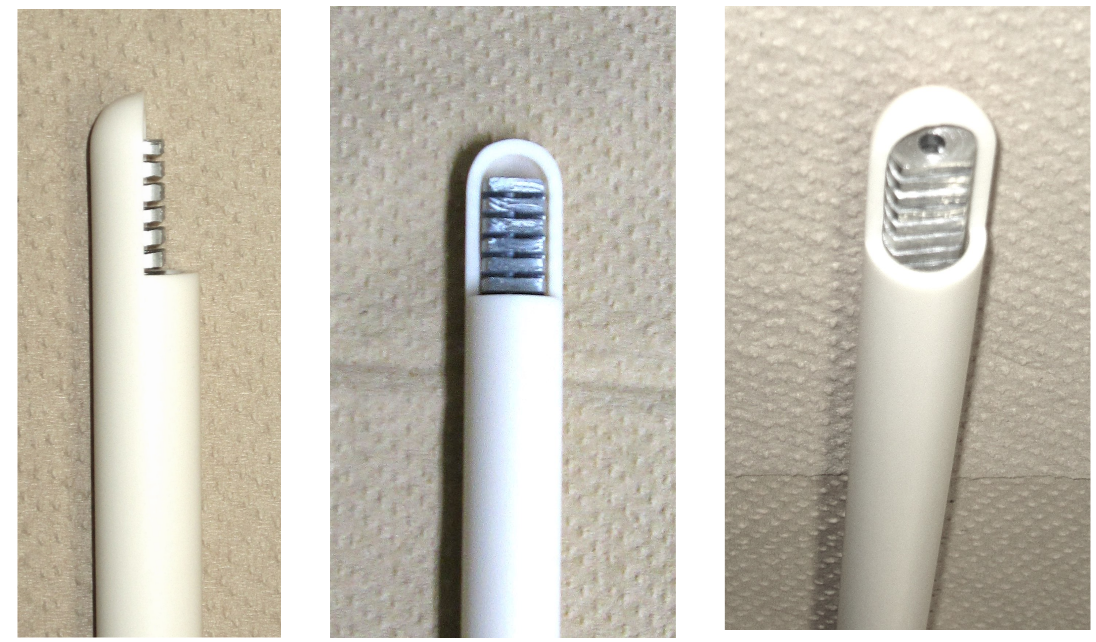
Alumina Ceramics



ϕ15 SUS pipe

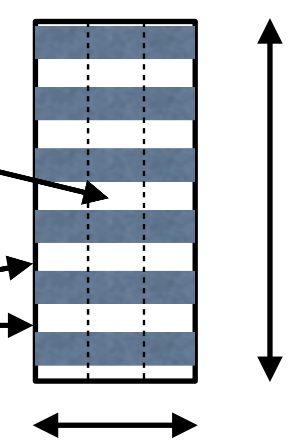
H_2 gas inlet from piezo valve

connection to negative high voltage power supply



H_2 gas outlet

slits

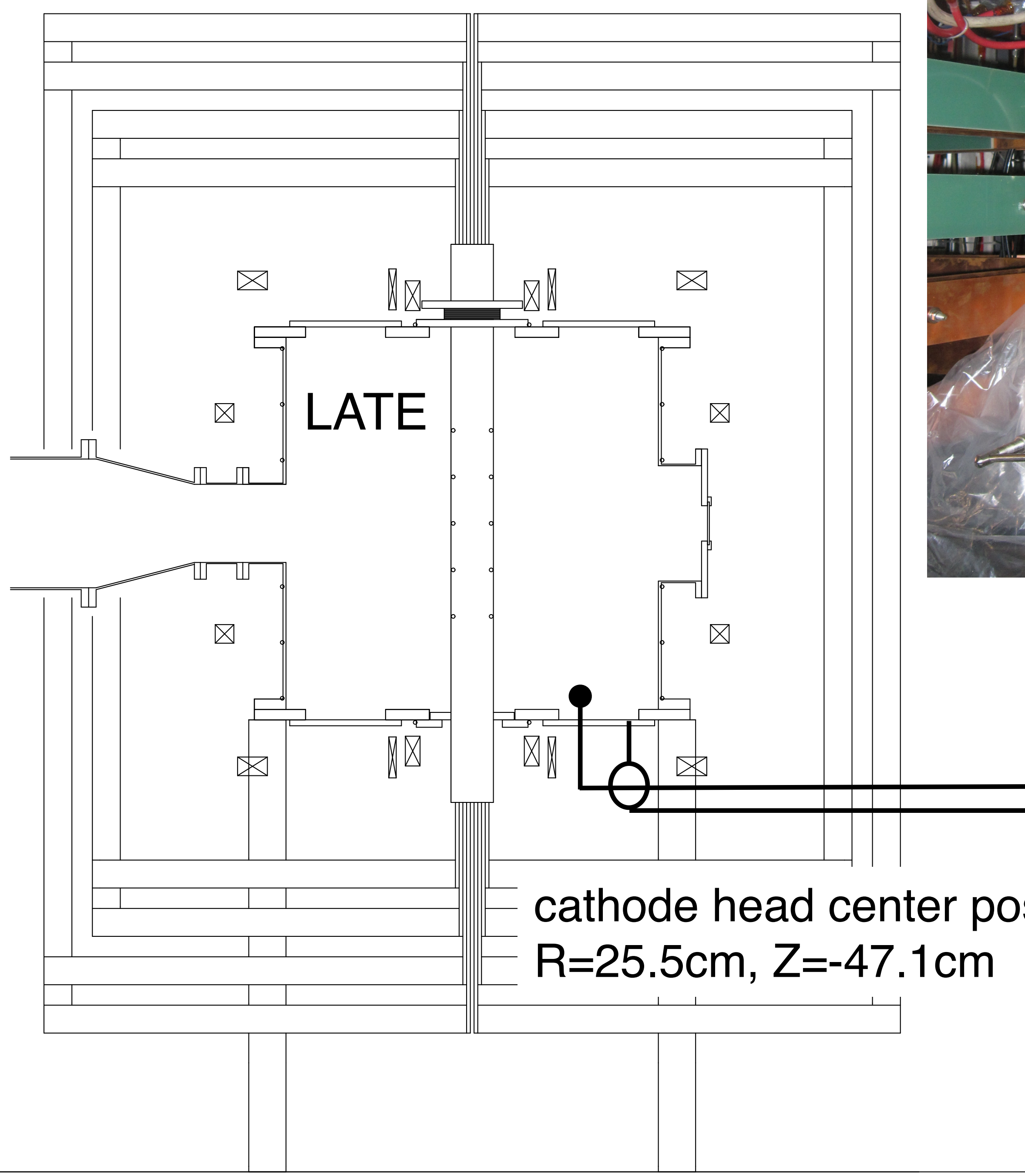


18mm

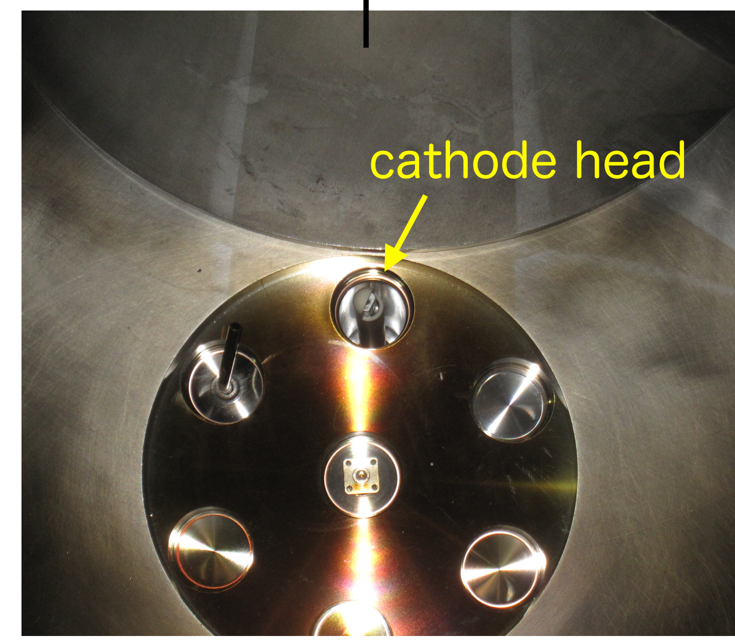
8mm

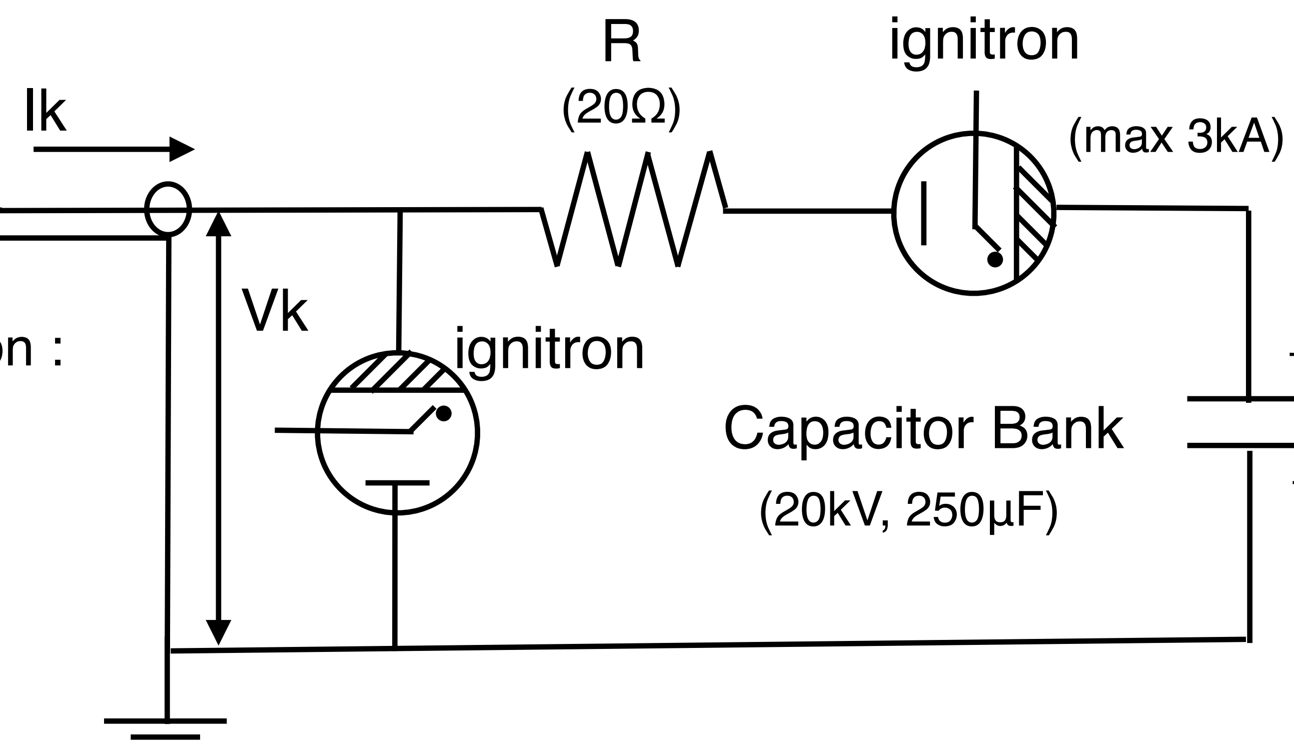
Set-Up of Cathode and Power Supply

EBI via plasma-anode method

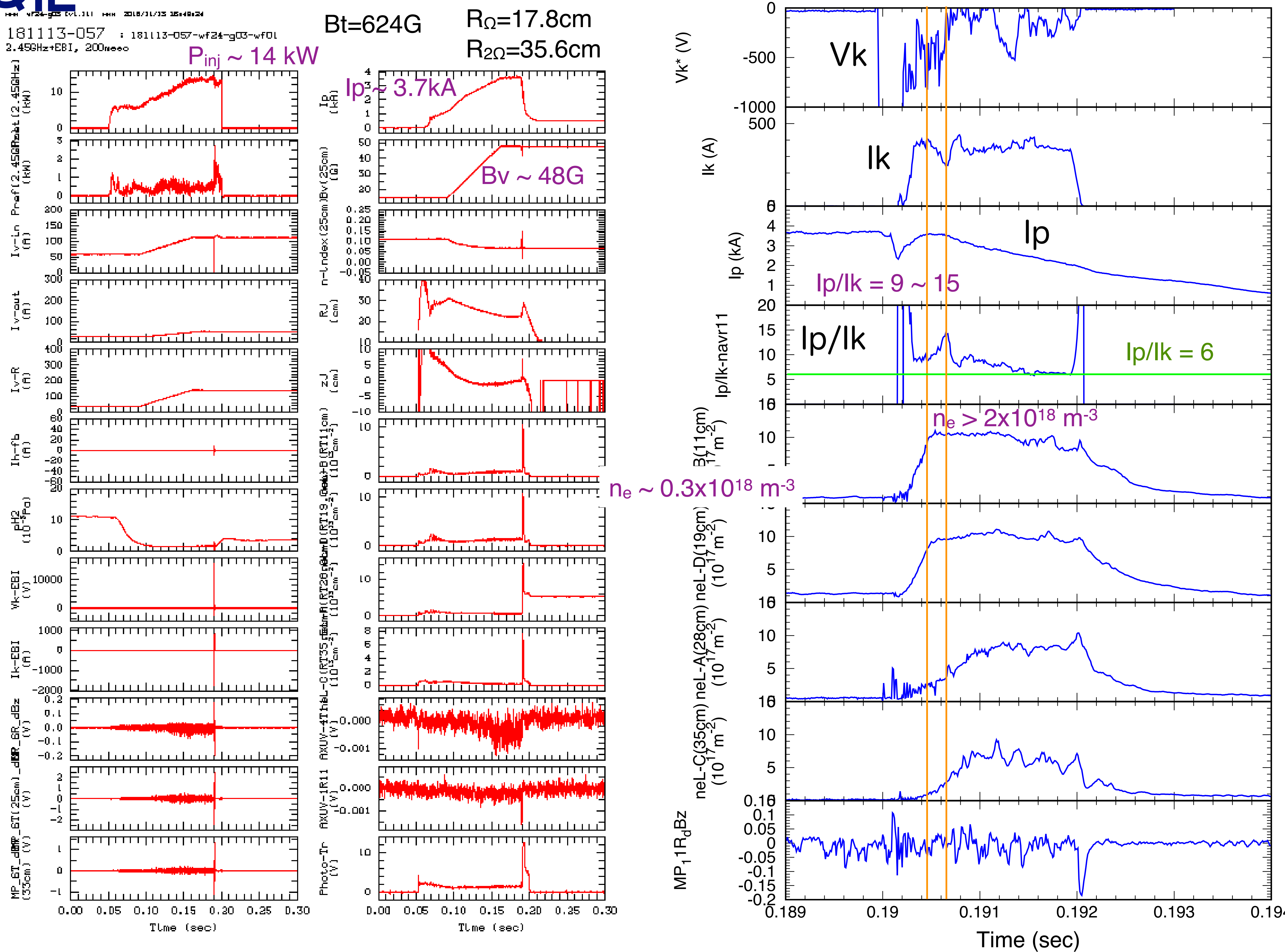


cathode head center position :
R=25.5cm, Z=-47.1cm

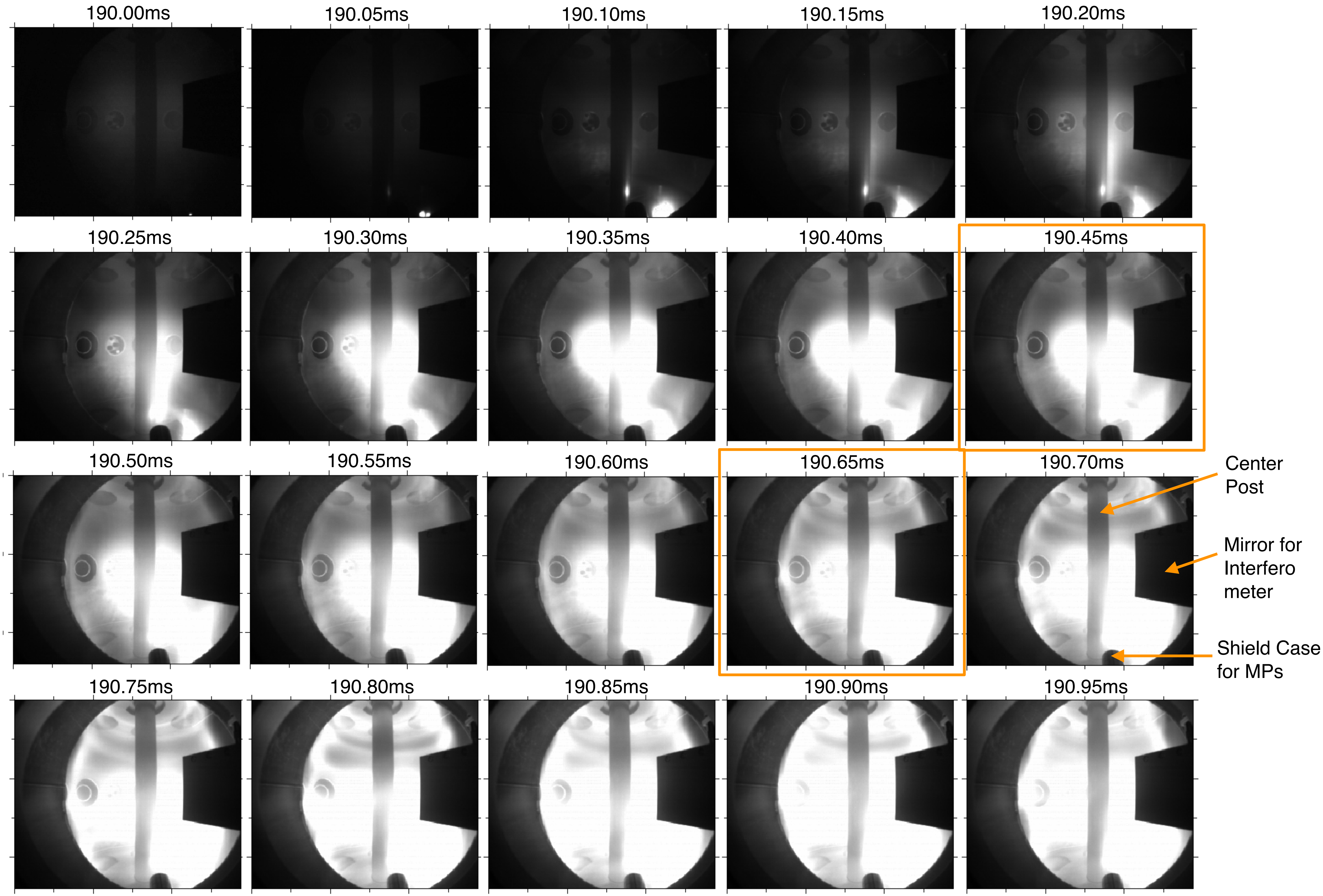




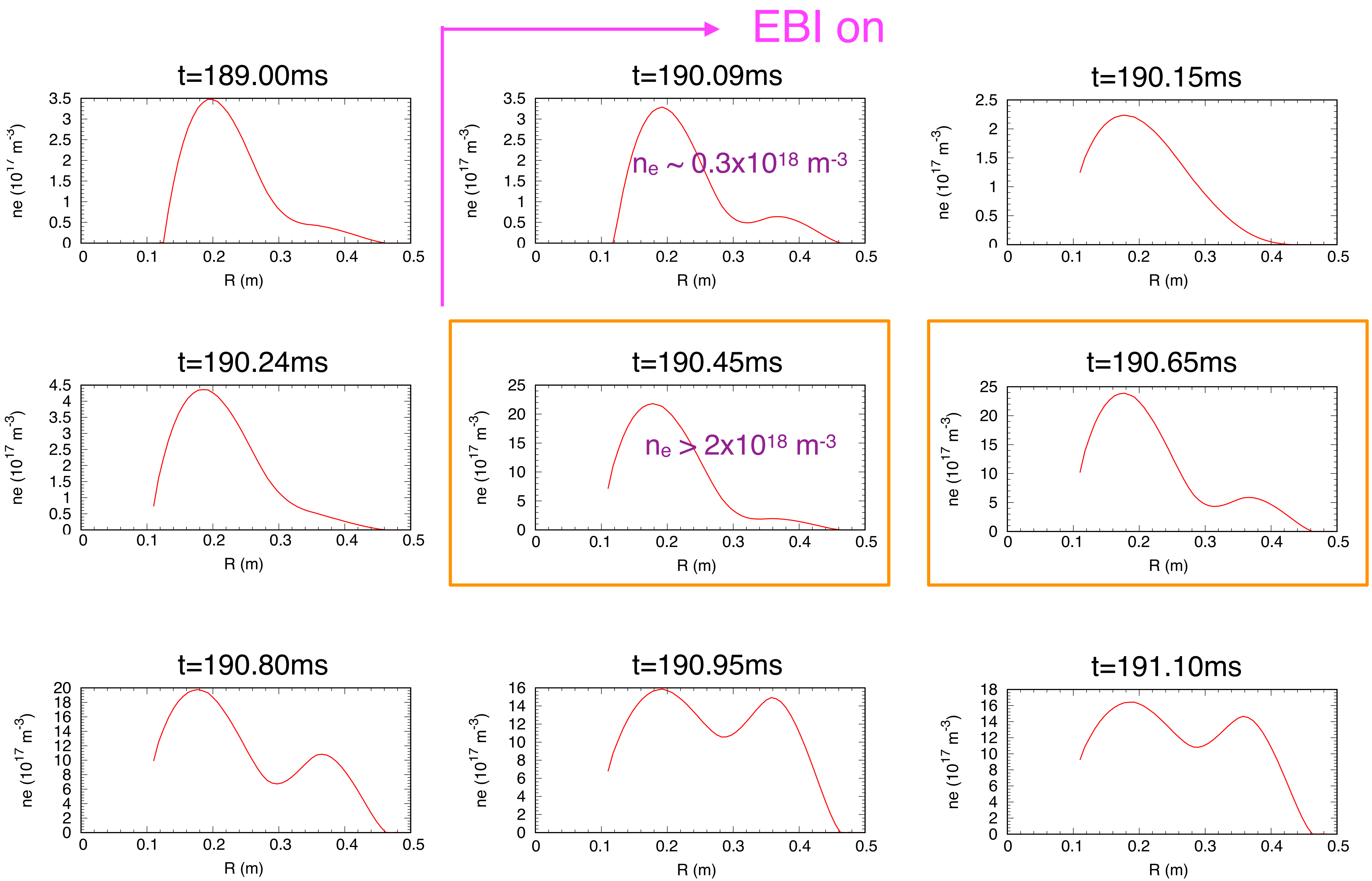
Time Evelution



Fast CCD Camera Images at the Beginning of EBI



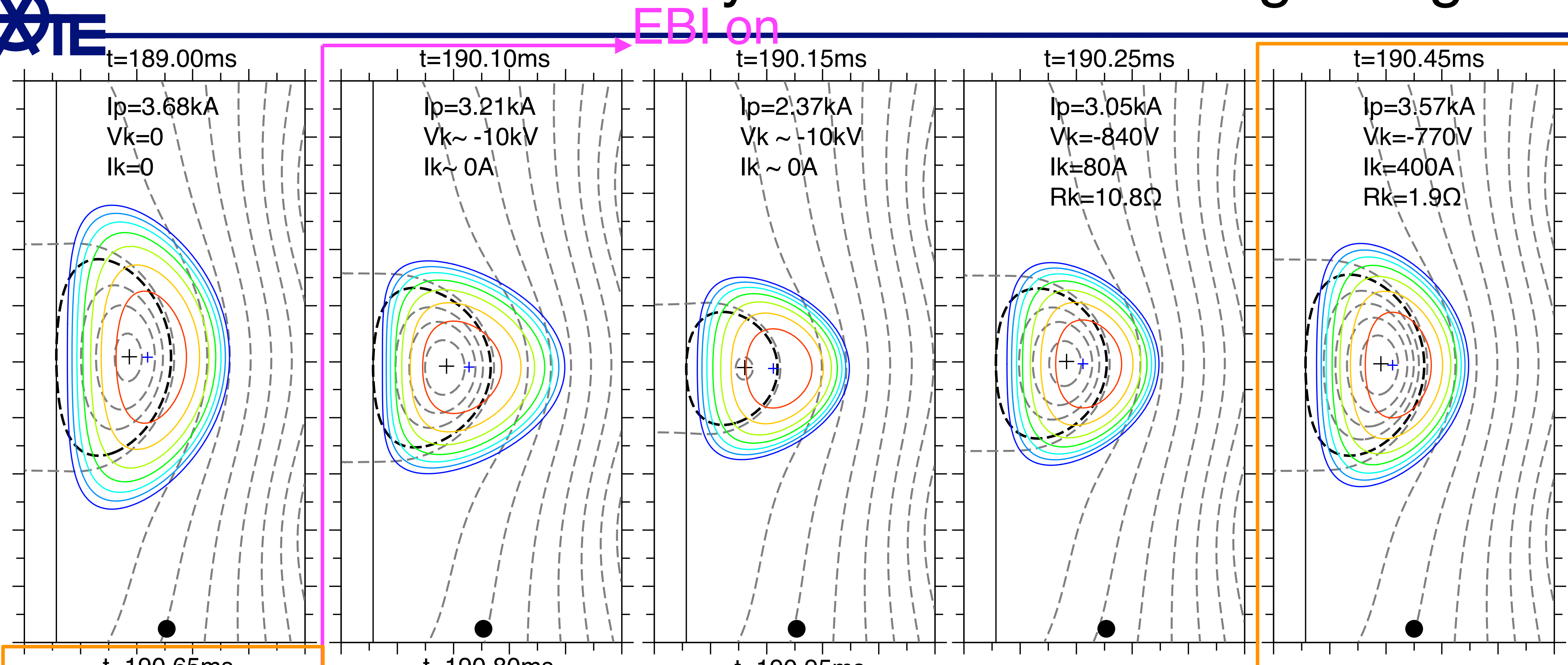
Electron Density Profiles at the Beginning of EBI

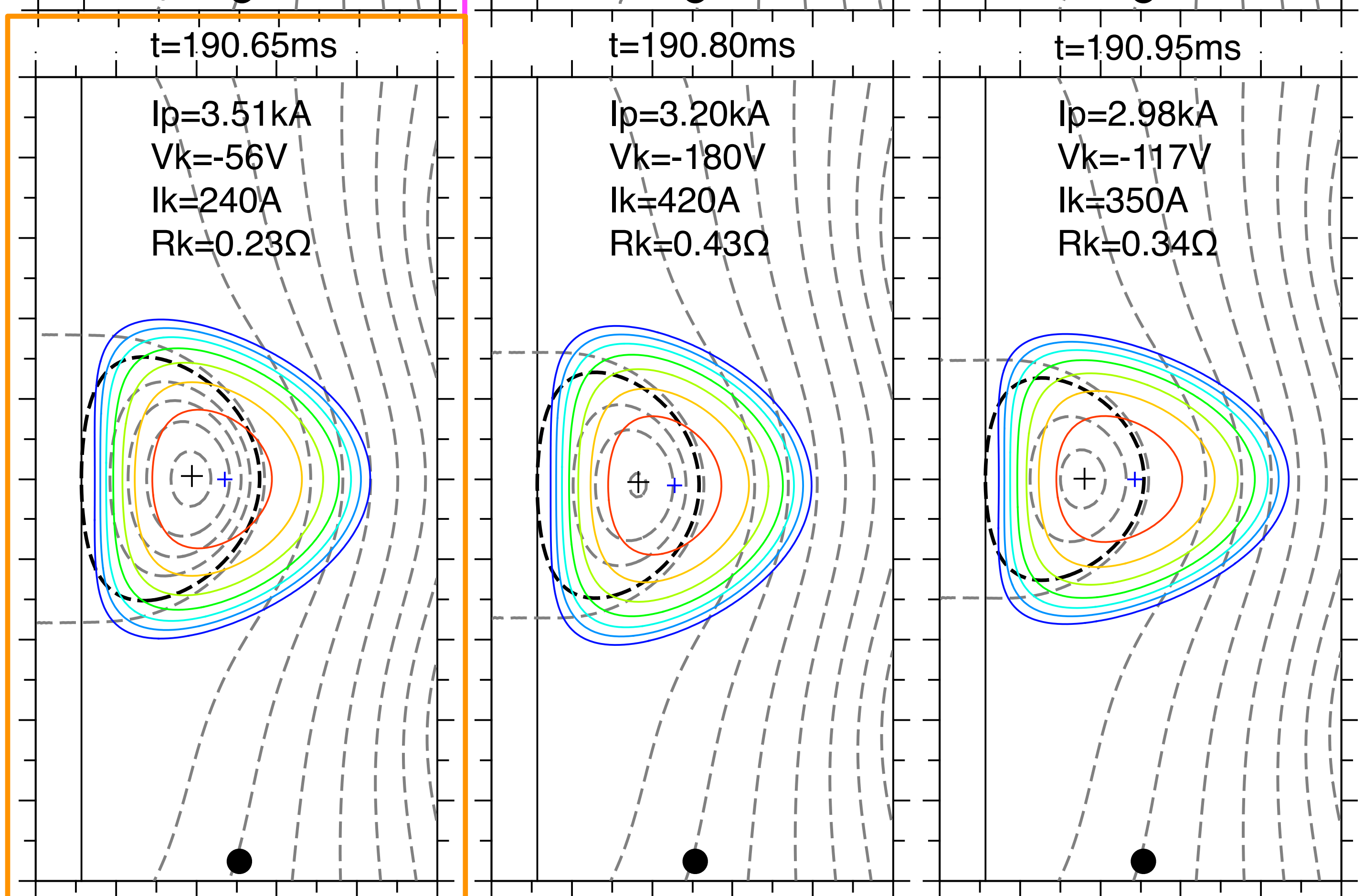


Before application of Vk, $n_{e0} \sim 3.5 \times 10^{17}\ m^{-3}$

==> ~0.65ms after application of Vk, $n_{e0} \sim 2.4 \times 10^{18}\ m^{-3}$ ... ~7 times higher

Plasma Current Density Profiles at the Beginning of EBI





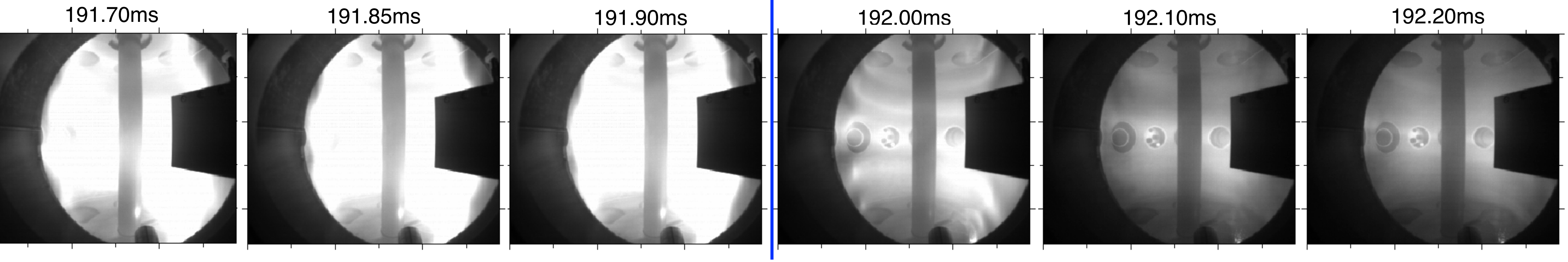
* During ~0.15ms after application of VK, Ik scarcely flows and Ip decreases from ~3.7kA to ~2.4kA .

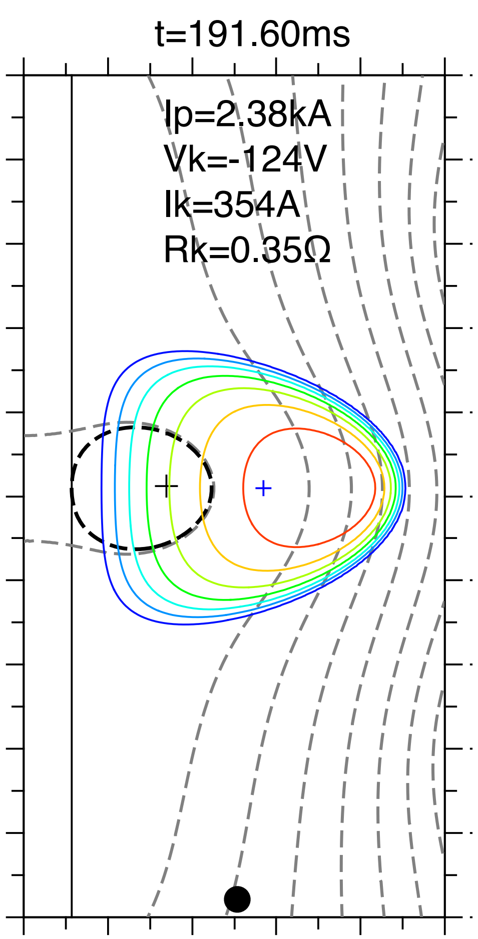
* At ~0.45ms after application of VK, Ip becomes maximum ~ 3.6kA. At ~0.65ms , the ratio Ip/Ik reaches ~ 15 at maximum.

* After that, Rk, Vk and Ip/Ik decrease rapidly.

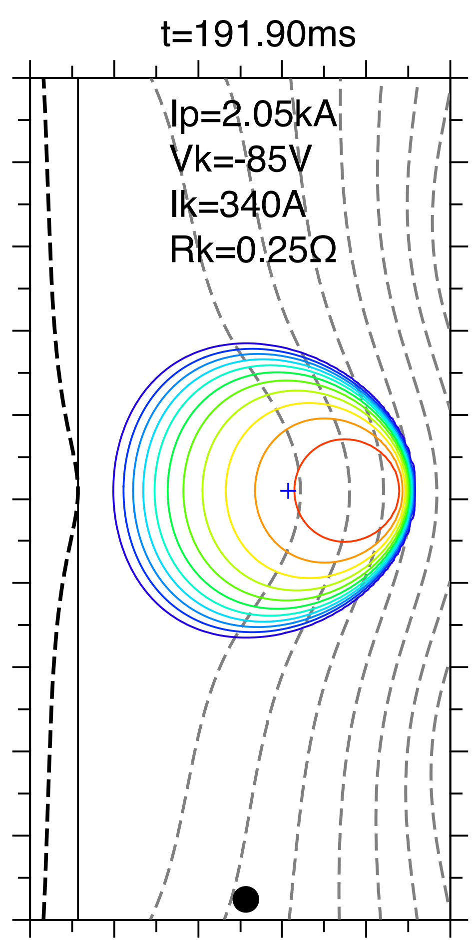
Fast CCD Camera Images and Plasma Current Density Profiles At the End of EBI (~ 2 ms After)

EBI off





閉じた磁気面
の喪失
(Ip ~ 2.2 kA)

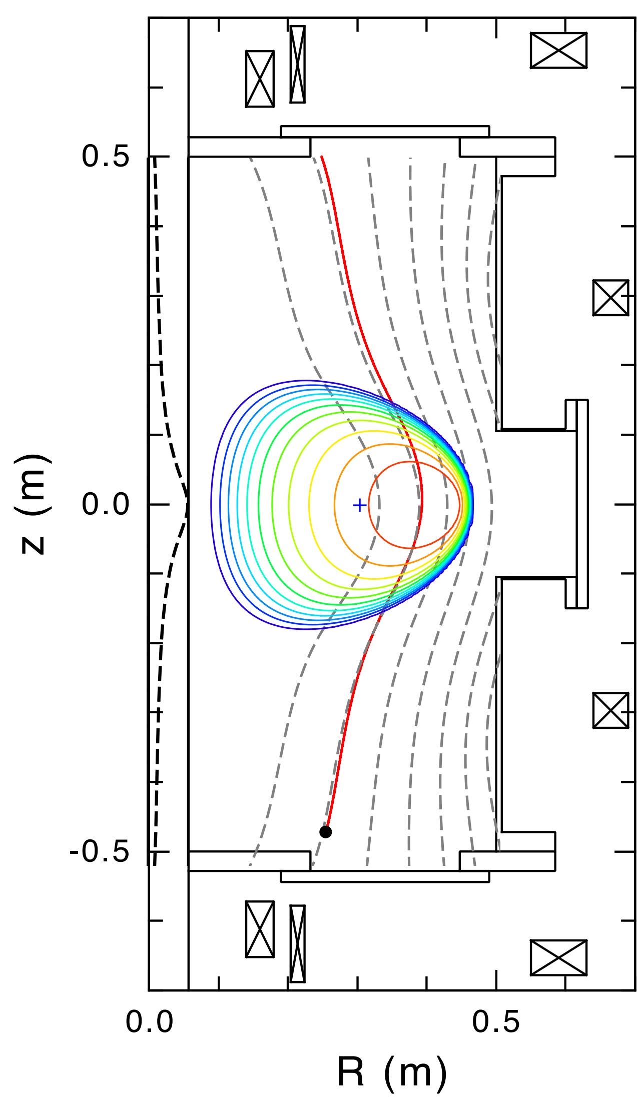


* During ~0.15ms after application of VK, Ik scarcely flows and Ip decreases from ~3.7kA to ~2.4kA .
* At ~0.45ms after application of VK, Ip becomes maximum ~ 3.6kA. At ~0.65ms , the ratio Ip/Ik reaches ~ 15 at maximum.
* After that, Rk, Vk and Ip/Ik decrease rapidly. Ik becomes nearly constant at ~350A , while Ip decreases slowly.
After ~1.7ms after Vk application, when Ip < 2.2 kA and Ip/Ik ~ 6, there is no closed flux surface.

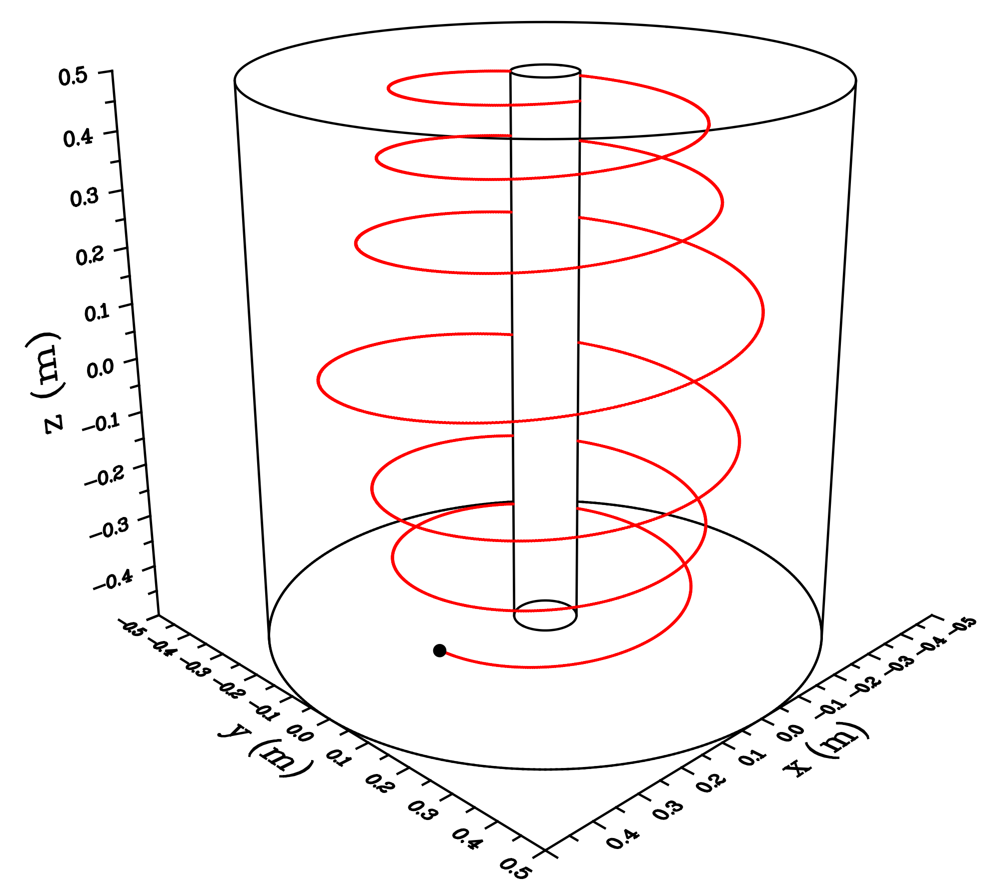
Trajectory of Injected Electrons

Bt=624G

Ip=2.18kA (t=191.80ms)



When Ip < 2.2kA, electrons go round ~6 times along the toroidal direction until they reach the top wall.



EBI Wk=134V θz=20°

R0=25.5cm (thx=-70°)

Z0=-47.1cm

Summary on EBI Experiment

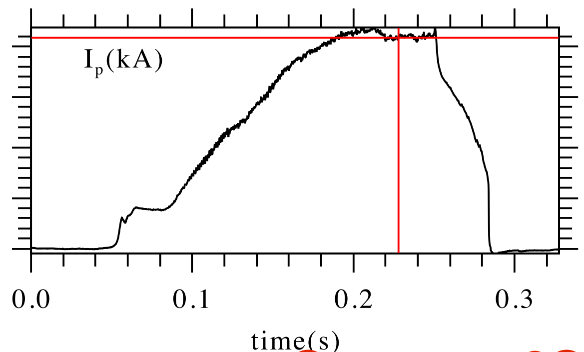
Electron Beam is injected from a cold cathode set at the bottom port into a ST plasma which is produced non-inductively by ECH/ECCD.

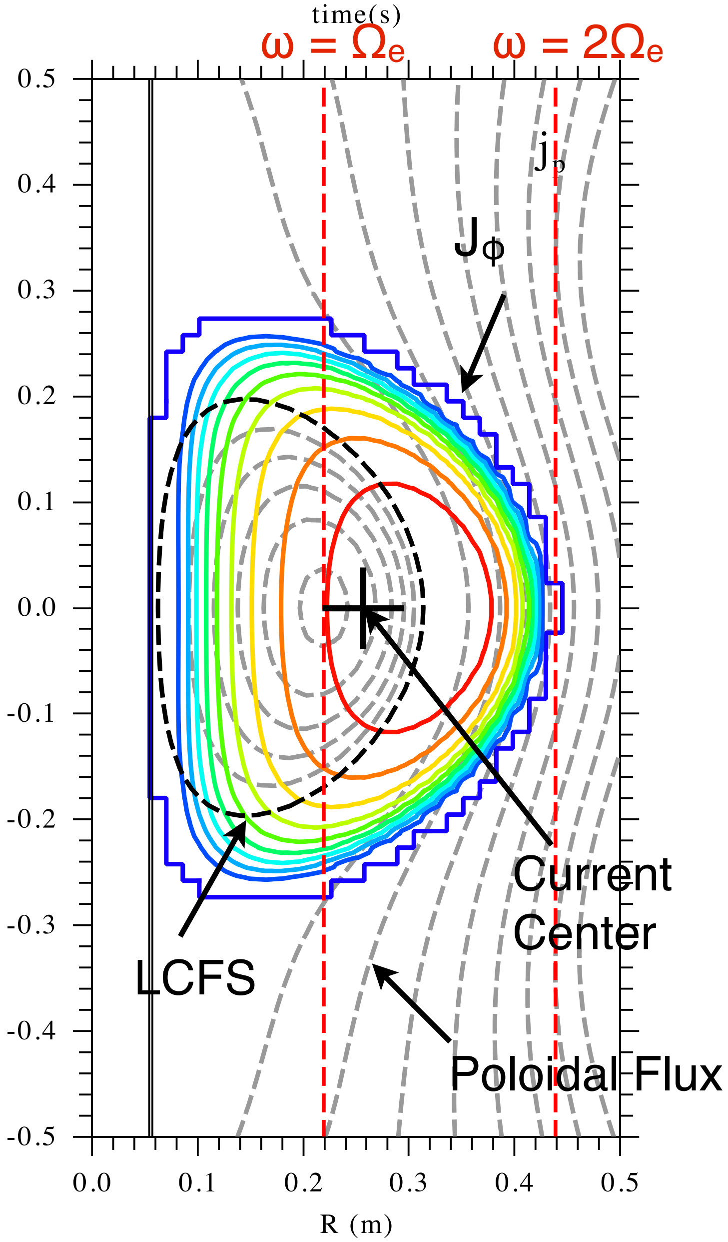
* A cold cathode with Mo head is set at the bottom port. A negative voltage is applied by a high-voltage power supply with capacitor bank (20kV, 250 μF) through 20 Ω resistor.
* An electron beam is injected for ~2 ms into a ST plasma with Ip ~ 3.7kA, ne ~ 0.3 x 1018 m-3 at Bt = 624G and Bv = 48G.
* Plasma current does not exceed the original value and the ratio Ip/Ik is 9 ~ 15. Electron density increased rapidly up to more than 2 x 1018 m-3.
* The density gradient at the plasma cut-off layer and the upper-hybrid resonance layer become very steep (Ln/λ0 < 0.1) and the mode-conversion rate is estimated to be less than 40 %. The reflection of microwave power increases and the EBW driven current may be reduced strongly and the most plasma current may be driven by injected electron beam.
* After ~1.7ms after Vk application, when Ip < 2.2 kA, there is no closed flux surface. Calculation of electron trajectory shows that electrons go 6 times round the toroidal direction until they reach the top wall, which is consistent with the experimental result of Ip/Ik ~ 6.

Back-up

Current & Pressure Profile

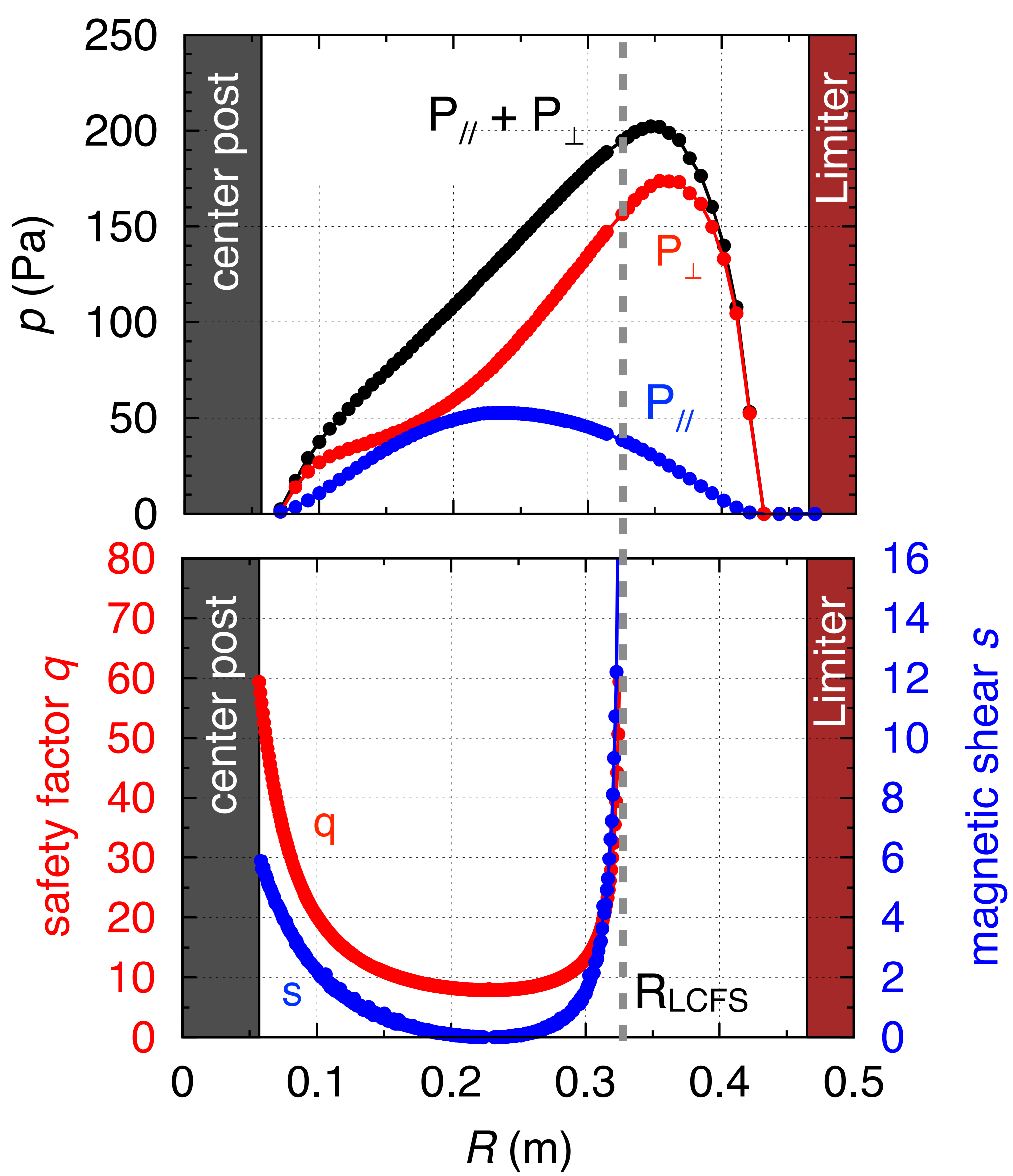
171215-101
Bt=0.0768T
R_{EC}=21.9cm
t=0.228sec
(0.2ms averaged)





Pressure profile is estimated from equilibrium analysis with anisotropic pressure

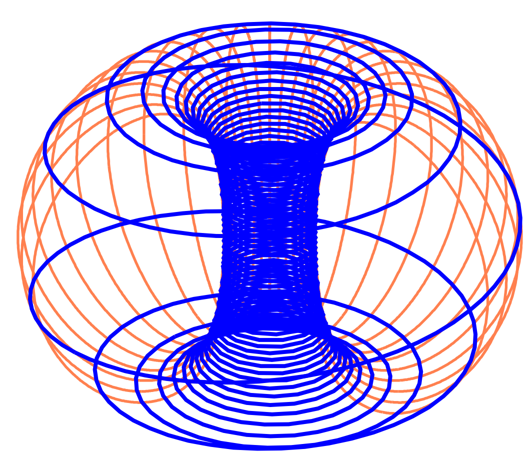
$$j \times B = \nabla \cdot P \qquad (P = P_\perp I + (P_{//} - P_\perp) bb) \text{ and } \nabla \cdot j = 0$$



High q state

$q_0 \sim 8$
$q_a \sim 60$

High magnetic shear near the plasma surface



Fast CCD camera images shows plasma is ejected across LCFS