Effects of lithiation and wave frequency on the efficiency of lower hybrid current drive on EAST

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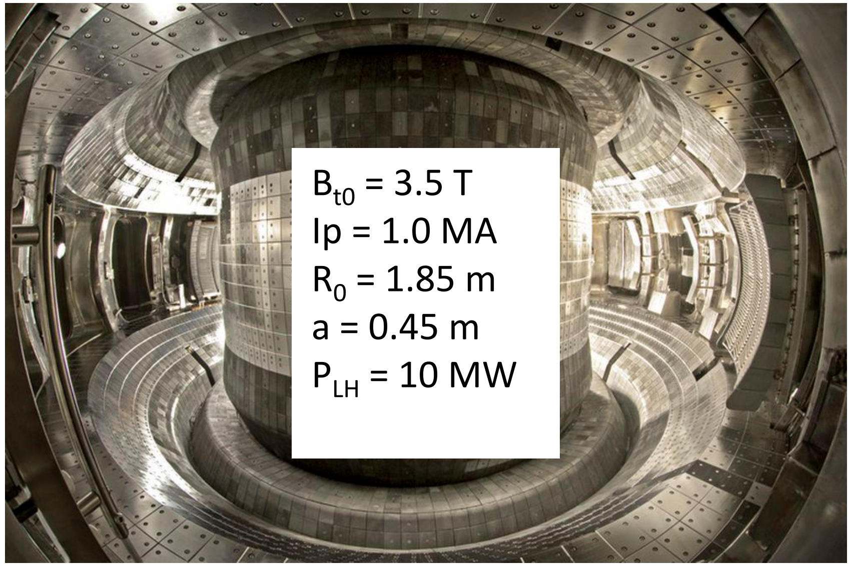


Motivation

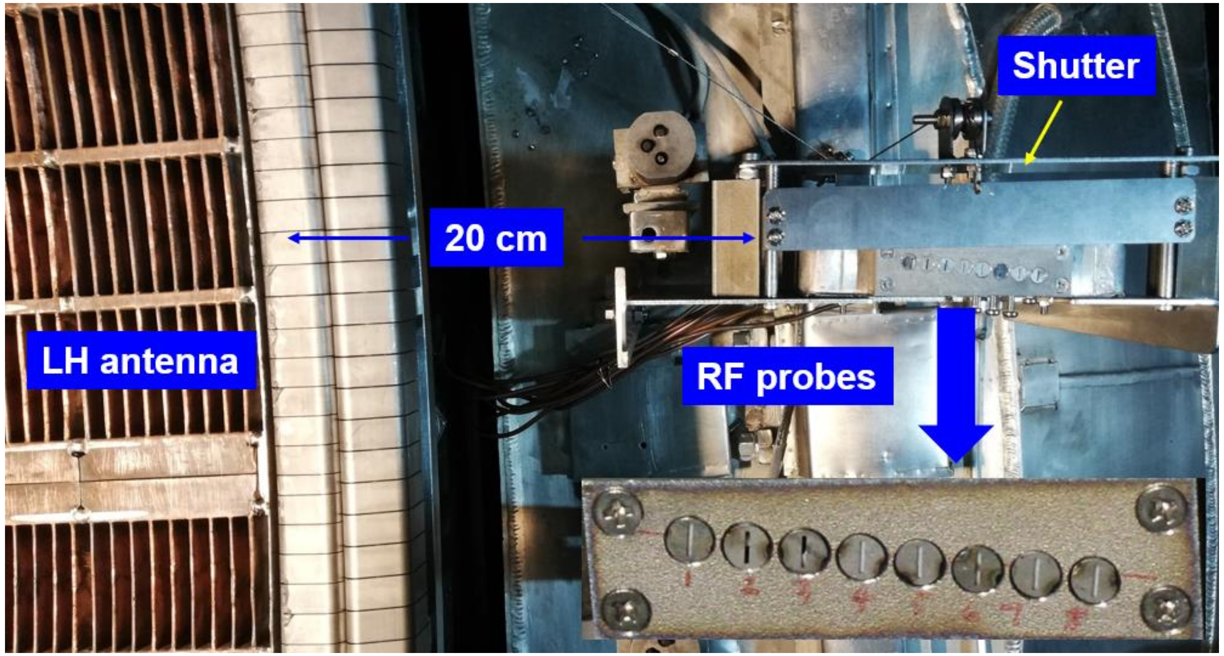
- Lower hybrid current drive (LHCD) is known for its high efficiency for generation of off-axis non-inductive current and for current-profile control.
- Interactions of RF waves with the boundary plasma play a critical role to understand RF physics.
- Anomalous loss of CD efficiency at high density[1,2,3]
  - Identify an approach to mitigate and control parasitic losses at the plasma boundary.

- EAST is equipped with two LHCD systems at 2.45 and 4.6 GHz with availability of lithium wall conditioning.
  - Can we extend effective LHCD with lithiation?
  - Is there a frequency dependence?
  - Can we quantify the amount of wave power absorption?
    - Useful for the construction of the control-level LHCD database

Baek et al, NME 26, 100955 (2021)

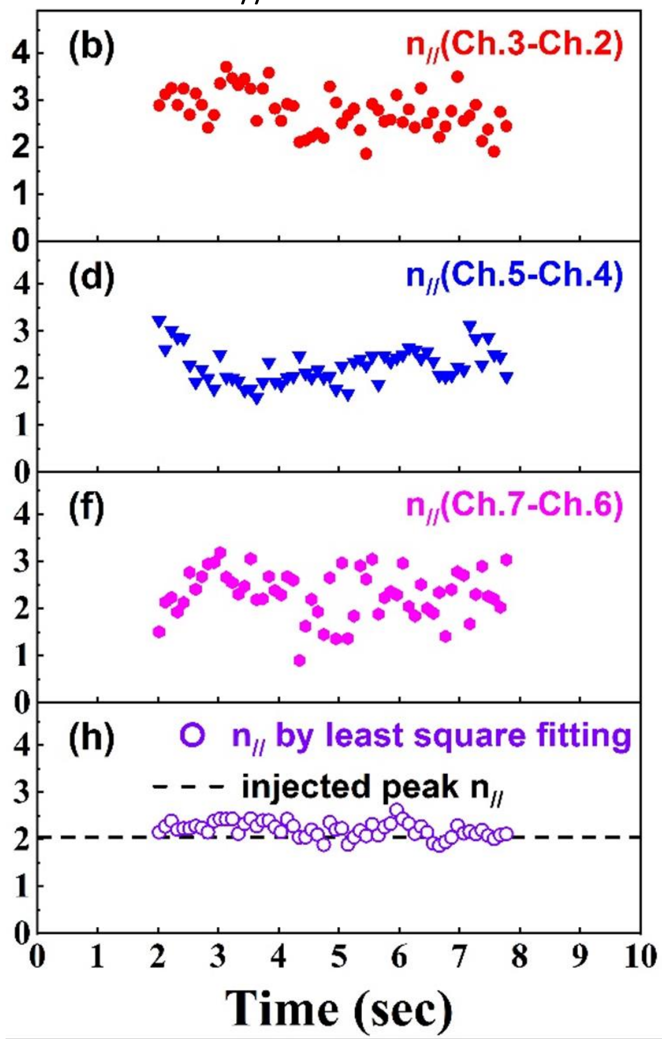
[1]Wallace et al, PoP 17, 082508 (2010)
[2]Cesario et al, Nat. Comm. 1, 55 (2010)
[3]Ding et al, NF 53, 113027 (2013)

MIT is supporting development of an 8 RF B-dot probe array installed next to the 4.6 GHz LH antenna.



- Installation of the 8 probes in a row allow deducing wave $n_{//}$
- The $n_{//}$ identified agrees with the imposed $n_{//}$ at the antenna at low density.
- Wave-SOL interactions on the first-pass will be investigated.

$n_{//}$ vs. Time

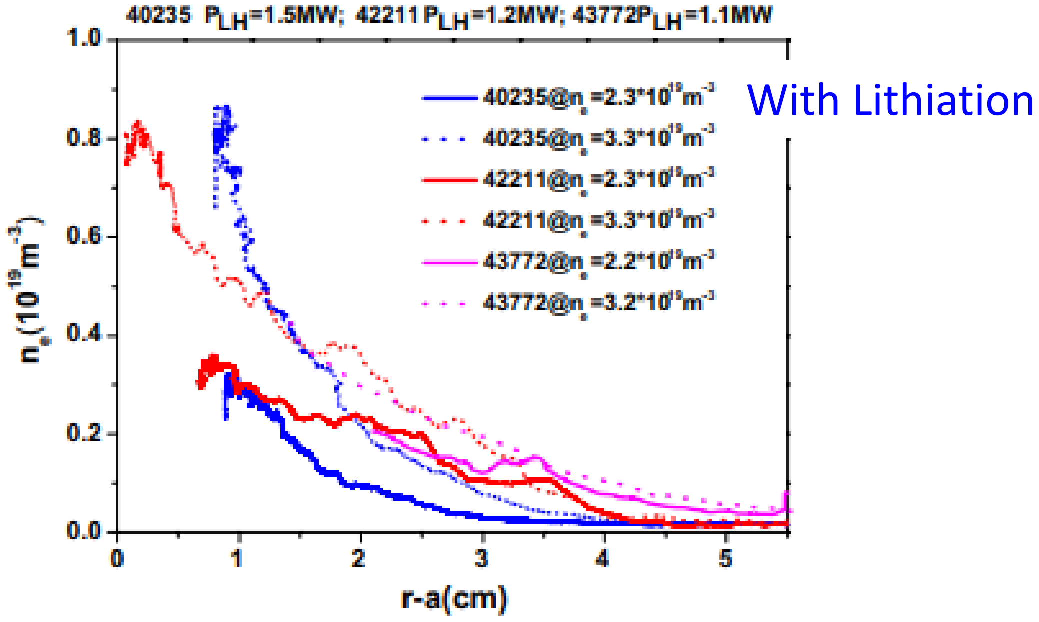


Wang et al, RSI 91, 073502 (2020)

The experiments examined the interactions of LH waves with the boundary plasma under lithium wall conditioning.

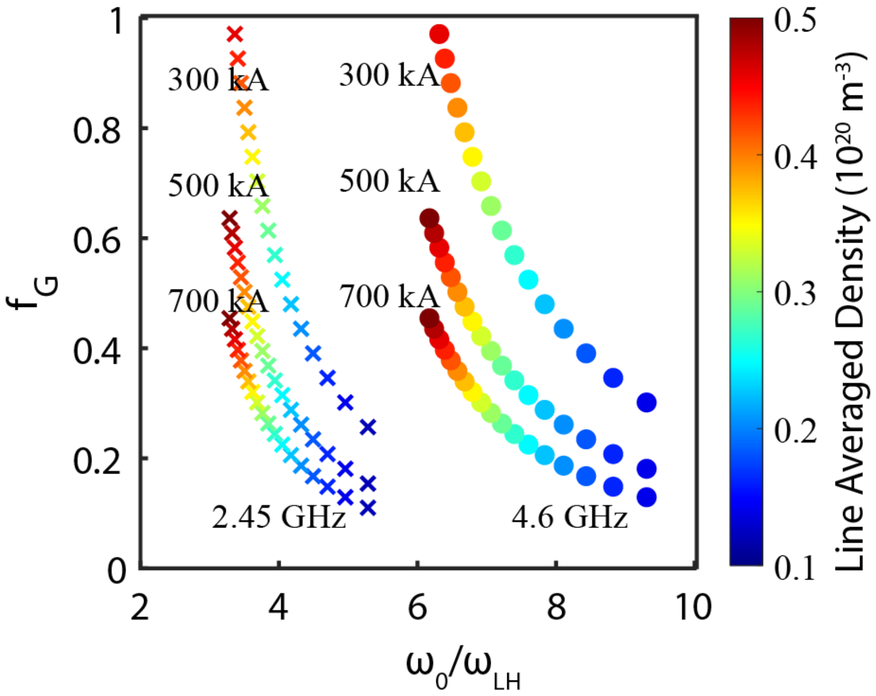
- Lithium wall conditioning on EAST lowers the SOL turbulence and density.
  - Expected to minimize parasitic wave-SOL interactions
- On EAST, two LHCD systems at 2.45 GHz and 4.6 GHz with I_p scan allow accessing a wide range of f_G and ω_0/ω_{LH} (representative of PDI strength)

SOL Density Profile on EAST



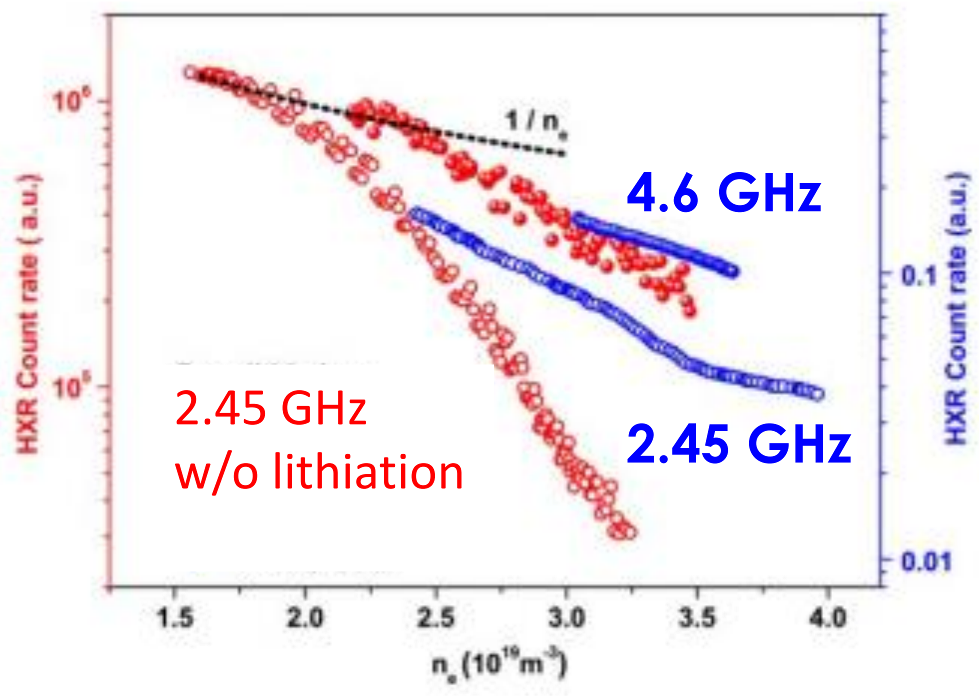
Ding et al, NF 53, 113027 (2013)

Experimental Regime Accessed



Lithiation mitigates the fast fall-off of the hard X-ray emission rates and suppress parasitic losses for 2.45 GHz.

HXR vs. Density

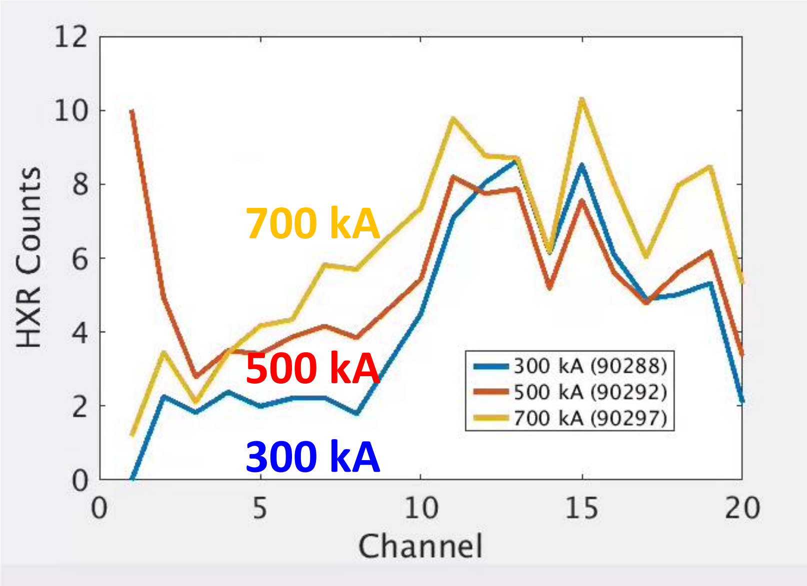


Huang et al, PPCF (2020)

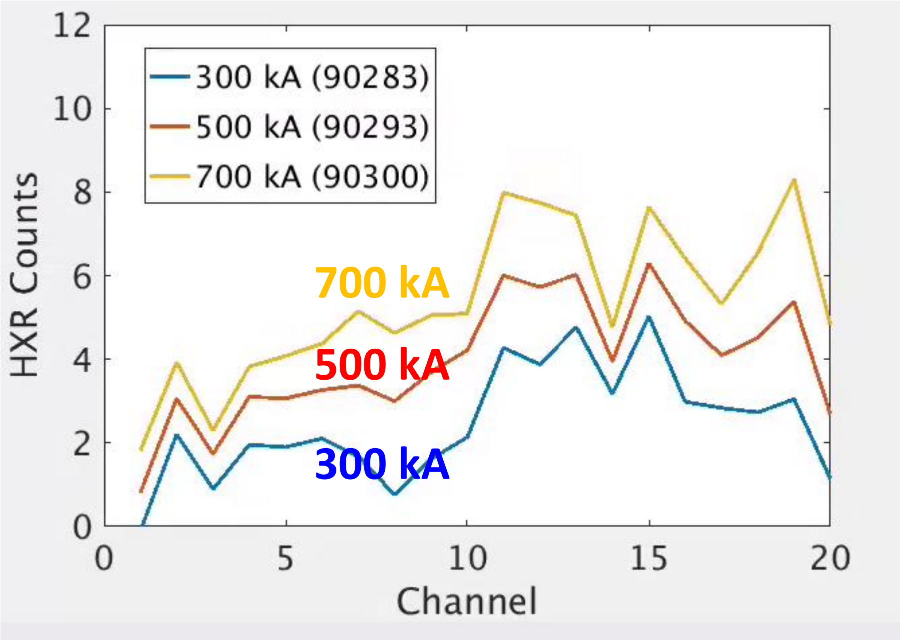
- HXR emission is an indicative of fast electron populations generated by LH waves.
- HXR emission is significantly increased for the 2.45 GHz case with lithiation.
- Experimental indications of parasitic losses are observed for $\bar{n}_e > 3x10^{19}$ m^{-3} (vs. 2x10^{19} m^{-3} without lithiation)

High-density, high-current (700 kA) operation on EAST broadens current profile and increases the off-axis HXR count rates.

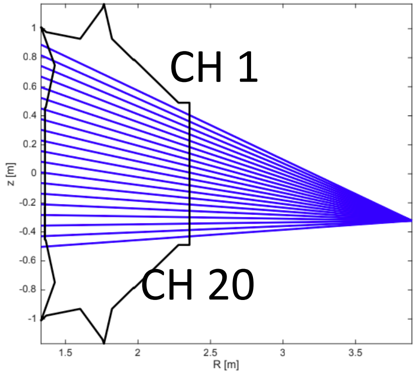
HXR Profile
4.6 GHz, $\bar{n}_e = 3.5\text{x}10^{19}$ m^{-3}



HXR Profile
2.45 GHz, $\bar{n}_e = 2.9\text{x}10^{19}$ m^{-3}



HXR Sightline Channels

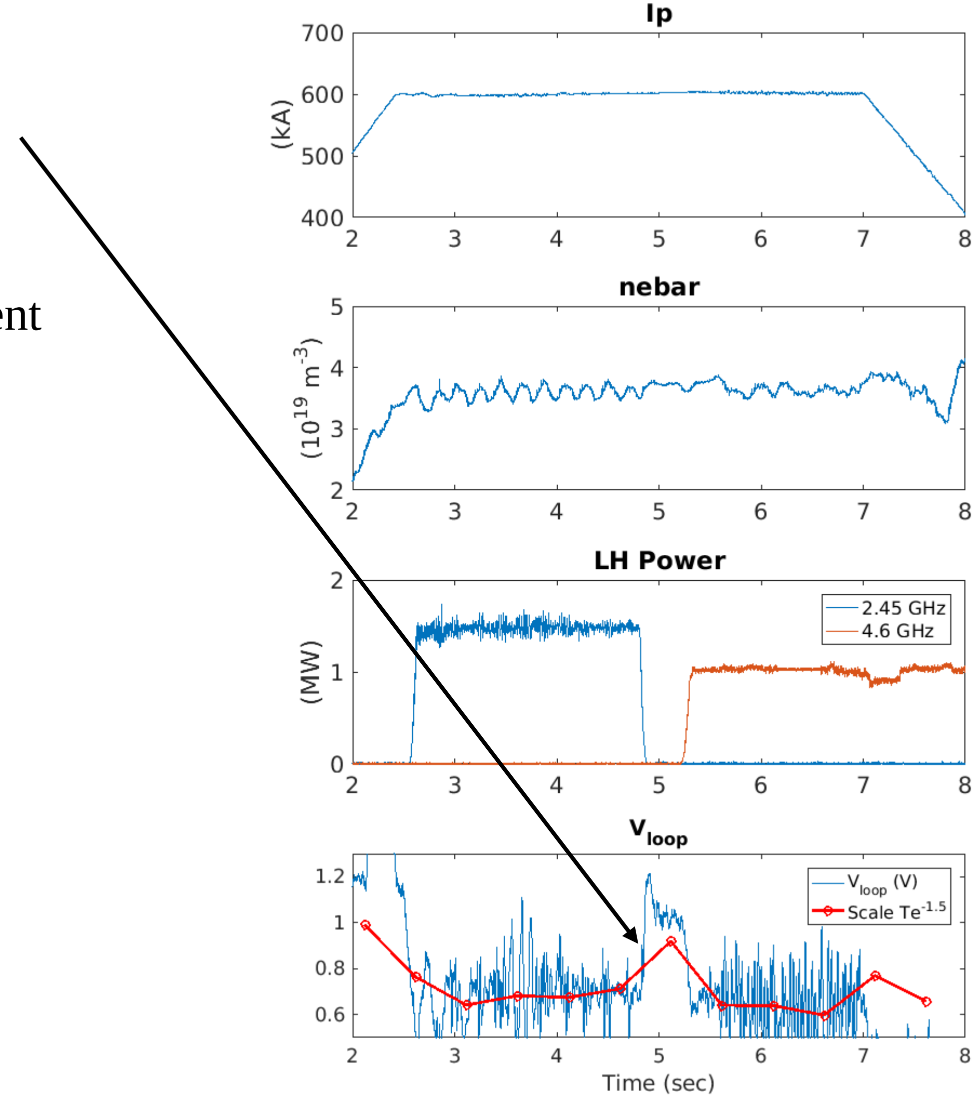


- l_i decreases from 1.5 to 1. (300 kA -> 700 kA)
- May be ideal for developing scenarios with ICRF at high density
- New experiment is proposed to EAST for upcoming campaign

With lithiation, LH heating and current drive are extended to high density.

- A comparable drop of loop voltage by ~ 0.3 V is observed for both 2.45 GHz (1.5 MW) and 4.6 GHz (1.1 MW).
  - LH plasma heating accounts for 70% of the loop voltage change.
  - The remaining change of < 0.1 V (< 60 kA) is from current drive.

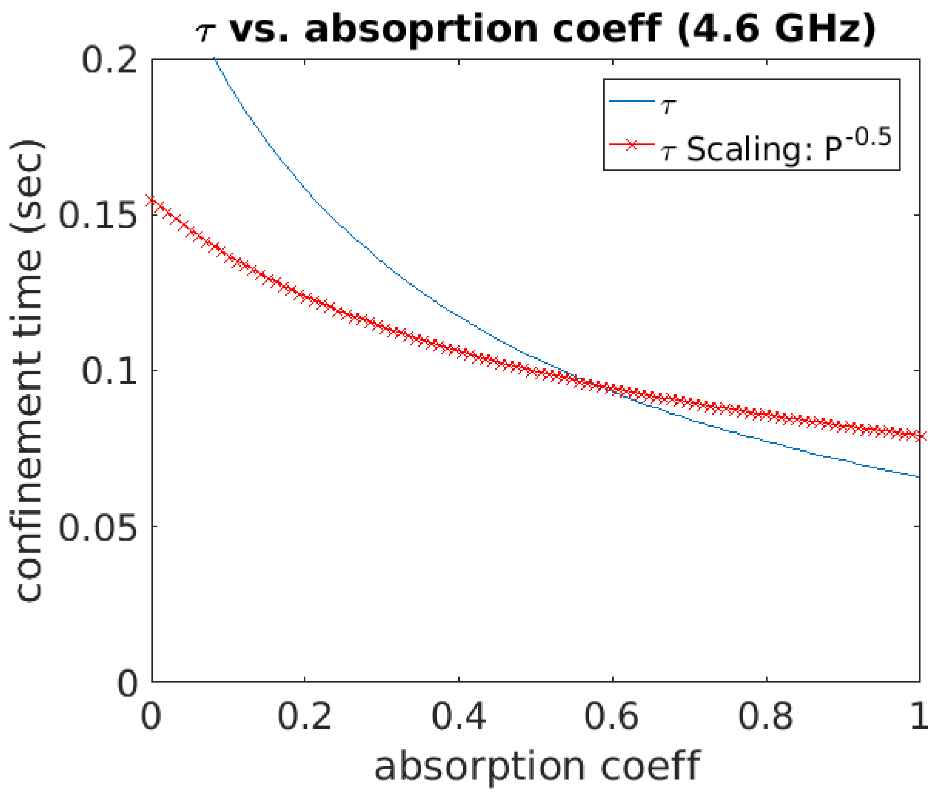
- A typical discharge at a density of ~ 4×10^{19} m^{-3} would exhibit a complete loss of current drive efficiency with a use of 2.45 GHz.



Power absorption to the confined plasma at 2.45 GHz is ~60% of that at 4.6 GHz.

- Wave power absorption coefficient, α, is from two expressions for the confinement time
  - $\tau_{exp} = \frac{W}{P_{tot}}$
    - W: plasma stored energy
    - $P_{tot} = P_{oh} + \alpha P_{LH,injected}$
  - $\tau_{scaling} = \tau_{oh} \times (P_{tot}/P_{oh})^{-0.5}$
    - τ_{oh}: the ohmic reference τ without LH power

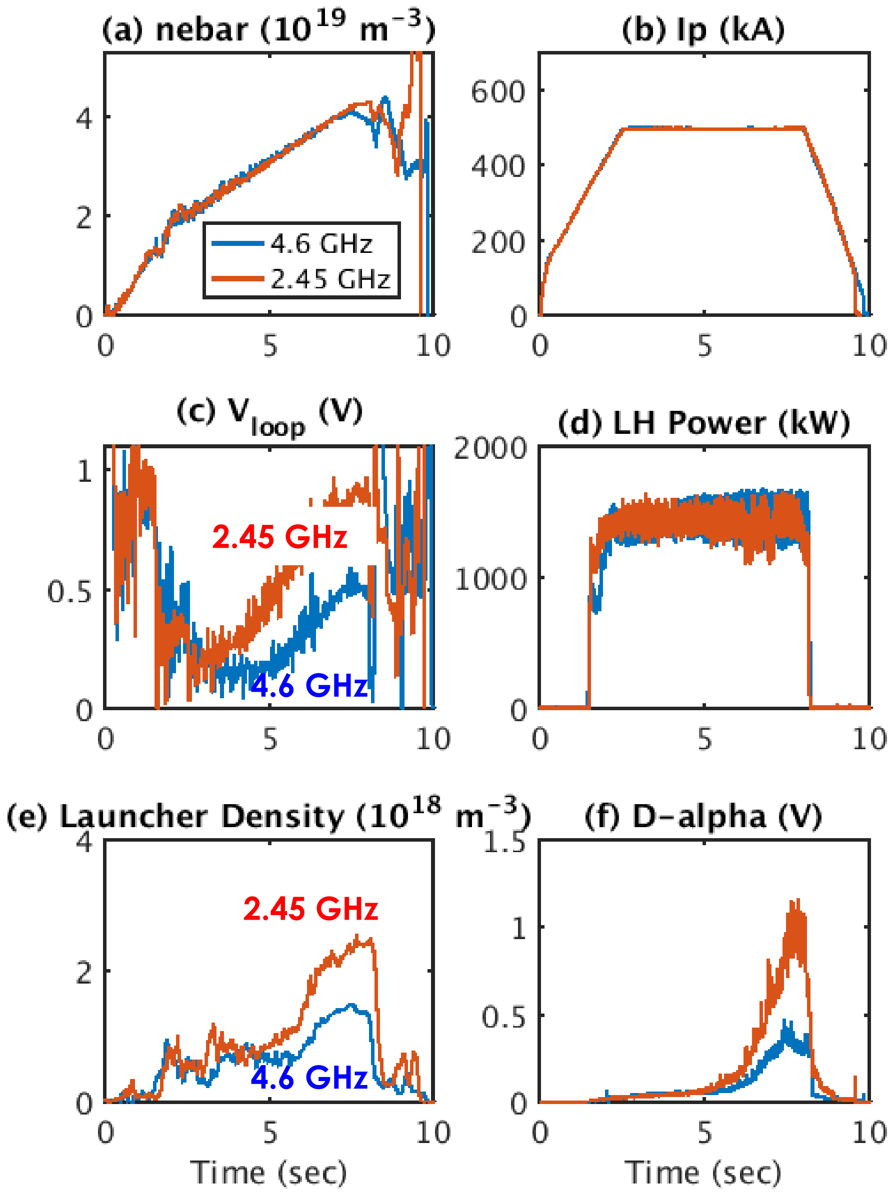
Power Dependence	α (4.6 GHz)	α (2.45 GHz)
$P^{-0.5}$	0.57	0.36



[1] P.N. Yushmanov et al, NF 30, 1999 (1990)

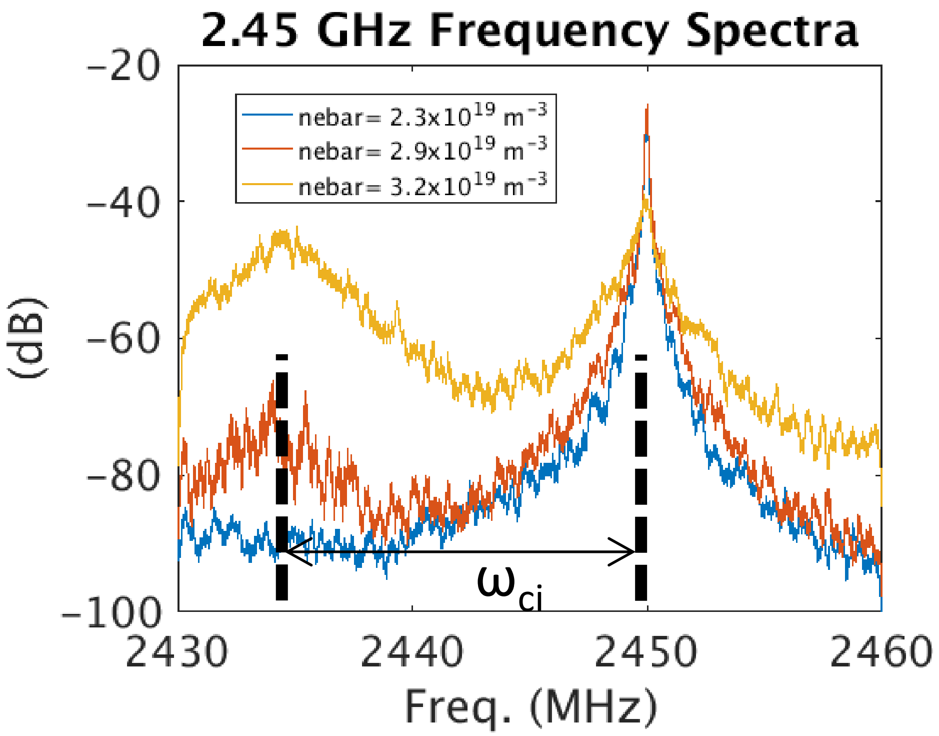
Increased levels of parasitic power damping is observed at 2.45 GHz for $\bar{n}_e > 3\text{x}10^{19}$ m^{-3}.

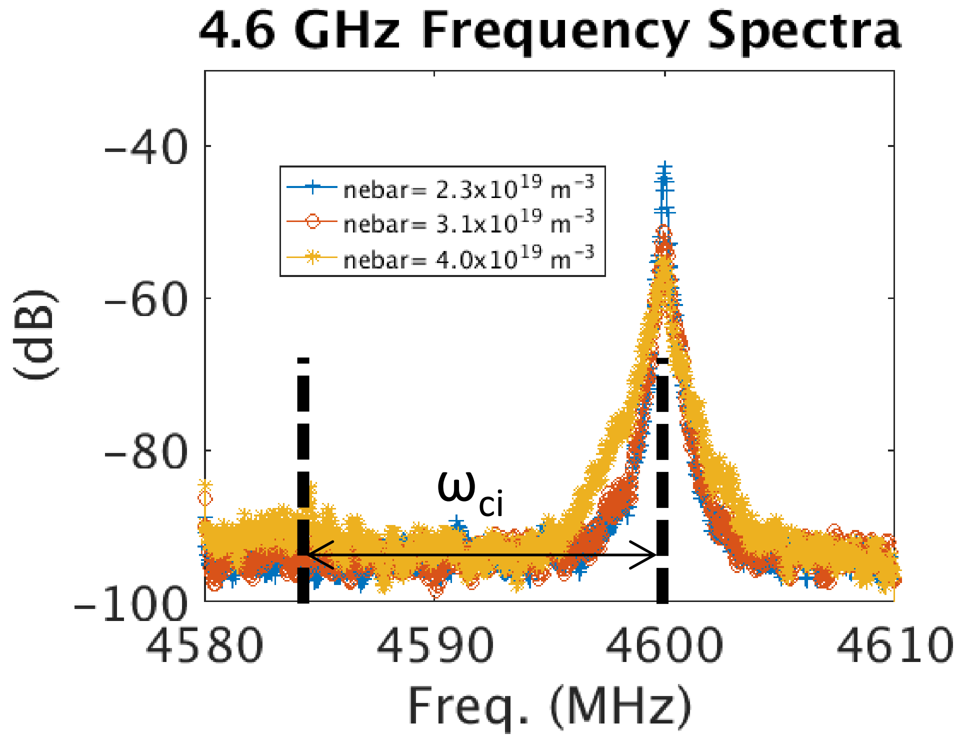
- LHCD at 2.45 GHz loses its efficiency faster than that at 4.6 GHz, as indicated by a higher voltage.
- RF ionizations are observed near and away from the antenna.
  - The electron density measured at the launcher surface increases strongly.
  - Simultaneously, D_α emission near the X-point increases strongly.
- LHRF power at 2.45 GHz may induce an earlier divertor transition[1,2], possibly due to power damping in the plasma periphery
  - Can result in the increased levels of collisional loss



[1]Niemczewski et al, NF 37 151 (1997)
[2]Meng et al, PPCF 62 065008 (2020)

Onset of parametric decay instabilities (PDI) is correlated with the rise in the launcher density.

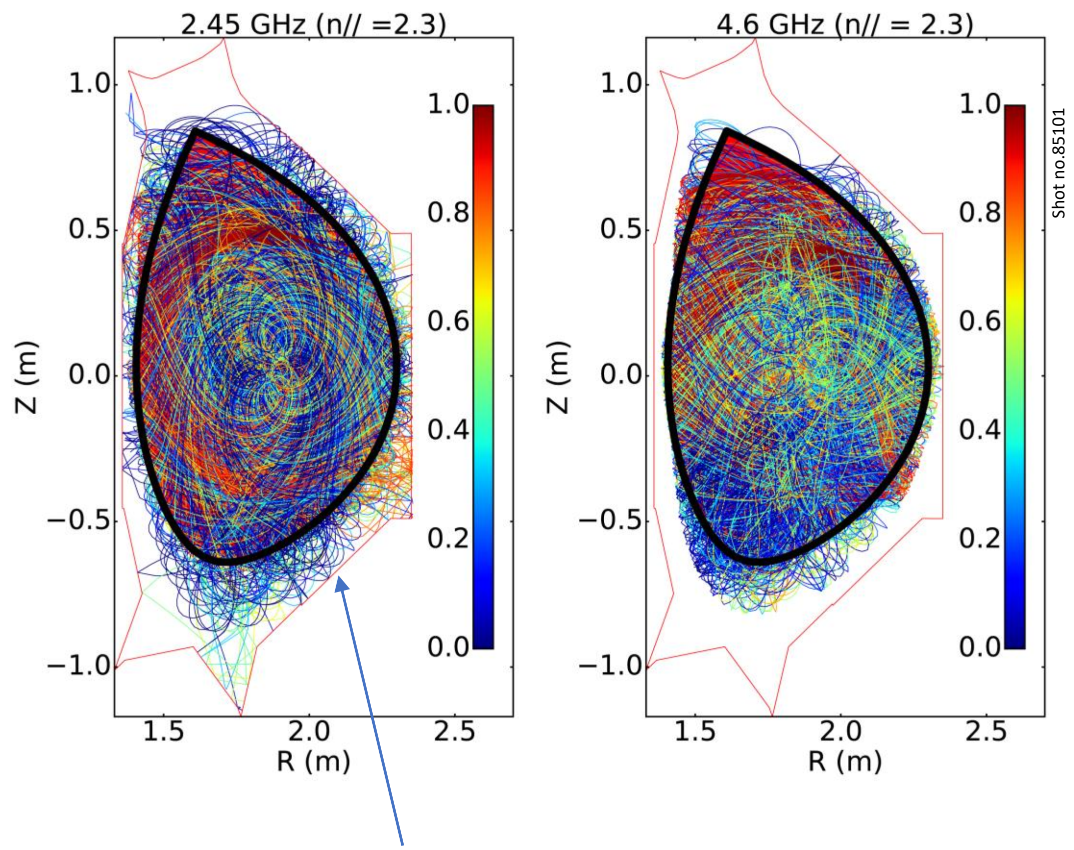




- Ion cyclotron PDIs are excited in the 2.45 GHz case only
- In line with the PDI model that predicts higher growth rates at a lower frequency[1]
- A control of the launcher density is critical to suppress the onset of decay instabilities.

[1]Porkolab, IEEE Tran. on Pla. Sci., 12, 107 (1984)

Inclusion of SOL plasma in the model can match the experimental power absorption coefficient.



Lower cut-off density results in an increased level of collisional power loss.

- GENRAY/CQL3D ray-tracing[1]/Fokker-Planck[2] code
- The scrape-off-layer model assumes the exponential decay outside the LCFS.
  - The SOL decay length is a free parameter.
  - Collision is a only power-loss mechanism.

	α (4.6 GHz)	α (2.45 GHz)
Exp	0.57	0.36
Model	0.63	0.36

- The lower power absorption coefficient at 2.45 GHz is attributed to the lower cut-off density(~ω^2), leading to enhanced collisional power damping.

[1]Smirnov and Harvey, Bull. Amer. Phys. Soc. 40,1837 (1995)
[2]Harvey and McCoy, US DCO NITS Docu. No. DE93002962

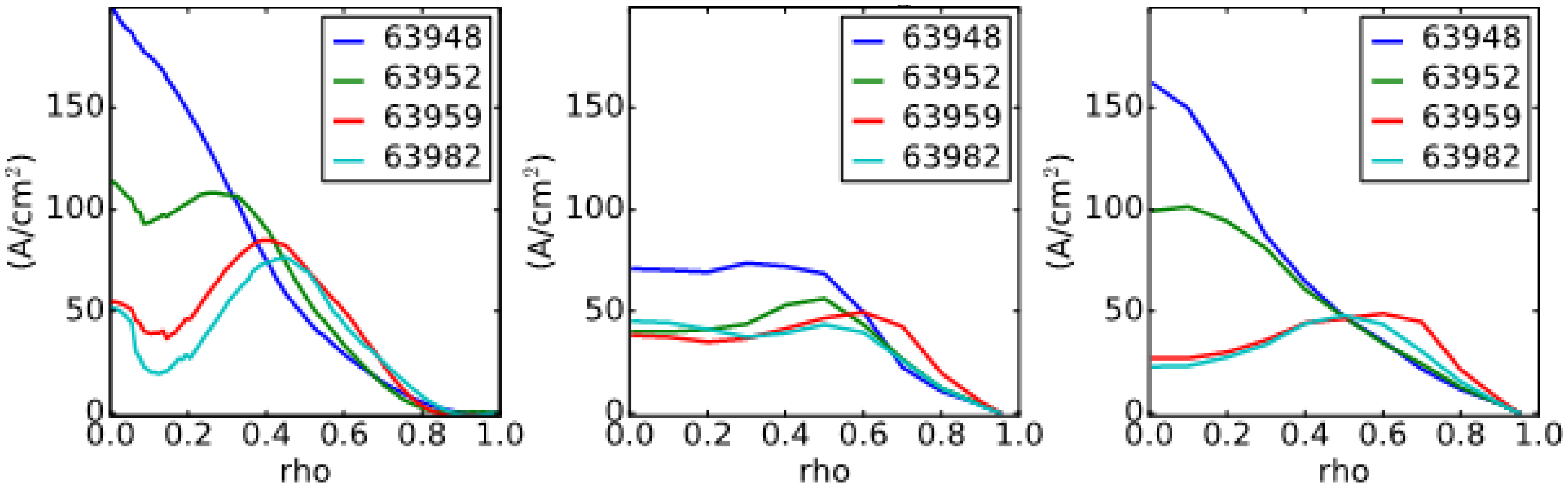
Power absorption coefficient evaluated provides a guidance on effective wave power absorption.

- A potential role of turbulent wave scattering in LHCD is being studied on EAST.
  - Four well-diagnosed non-inductive H-mode discharges by A. Garofalo NF 57, 076037 (2017).
  - Identified an optimum rotation angle (+40 deg) of the perpendicular wave-vector that can reproduce experimental profiles, possibly due to wave scattering
- Results will used to construct a simulation database of LH power deposition and current drive in EAST (Bonoli, Thursday).

Exp. Current Profile

Reference Model

Modified Initial Condition of Perp. Wavevector



Summary

- Highlights
  - Effective LHCD is extended to high density under lithium wall conditioning (lithiation).
  - Experimental evidence of LH power loss in the scrape-off-layer/divertor plasma is characterized.
  - Frequency-dependent wave power absorption is evaluated using the confinement time scaling law.
  - The experimental power absorption coefficient was reproduced in the ray-tracing /Fokker-Planck model.
  - A potential role of turbulent wave scattering in LHCD is investigated on EAST

- Implication
  - Control of neutral and electron densities in front of the launcher may be a key to improve LHCD further.

Extra Slides

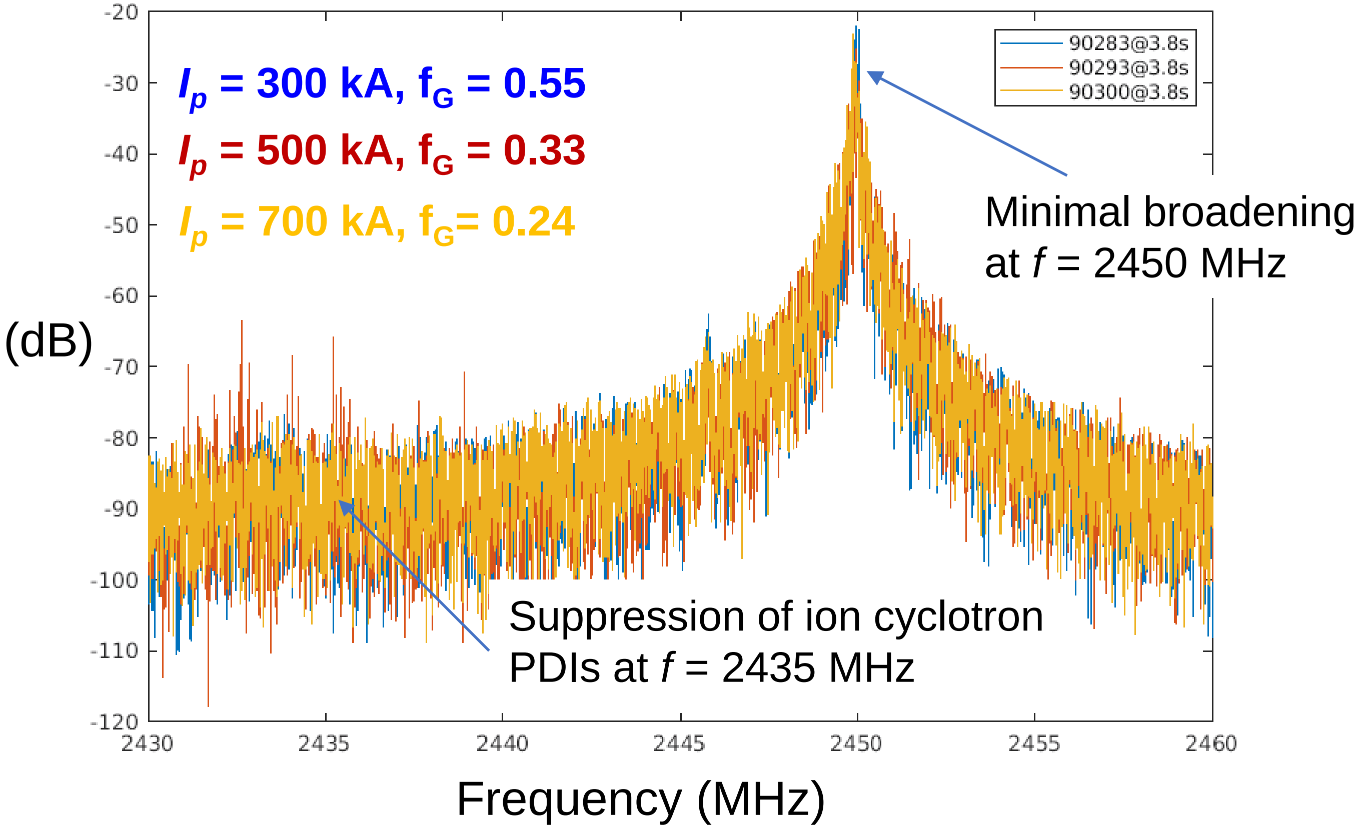
Lithiation is dominant over the change in Greenwald fraction in determining the SOL behavior.

- Frequency spectra at 2.45 GHz are shown here at a density level at which ion cyclotron PDIs are typically observed without wall conditioning ($\bar{n}_e \sim 2\text{x}10^{19}$ m^{-3}).

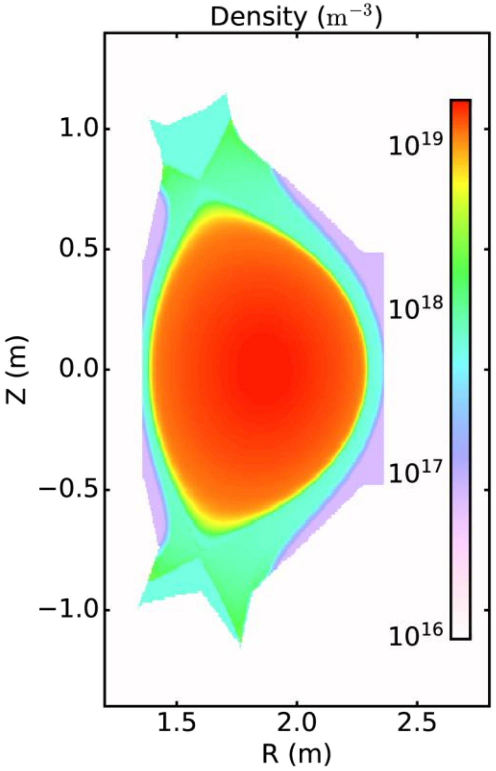
- With lithium wall conditioning, frequency spectra (2.45 GHz) indicate no systematic response to the change in Greenwald fraction, unlike observations made on C-Mod.

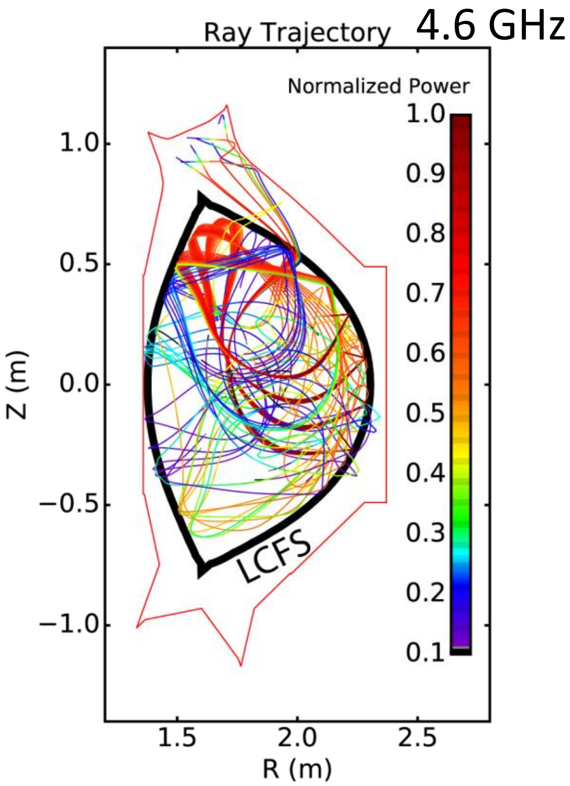
- SOL is expected to be quiescent with lithium wall conditioning

Wave Frequency Spectrum ($\bar{n}_e$ = 2.6x10^{19} m^{-3})



The 2-point SOL model may help accurately describe ray propagation in the divertor region.

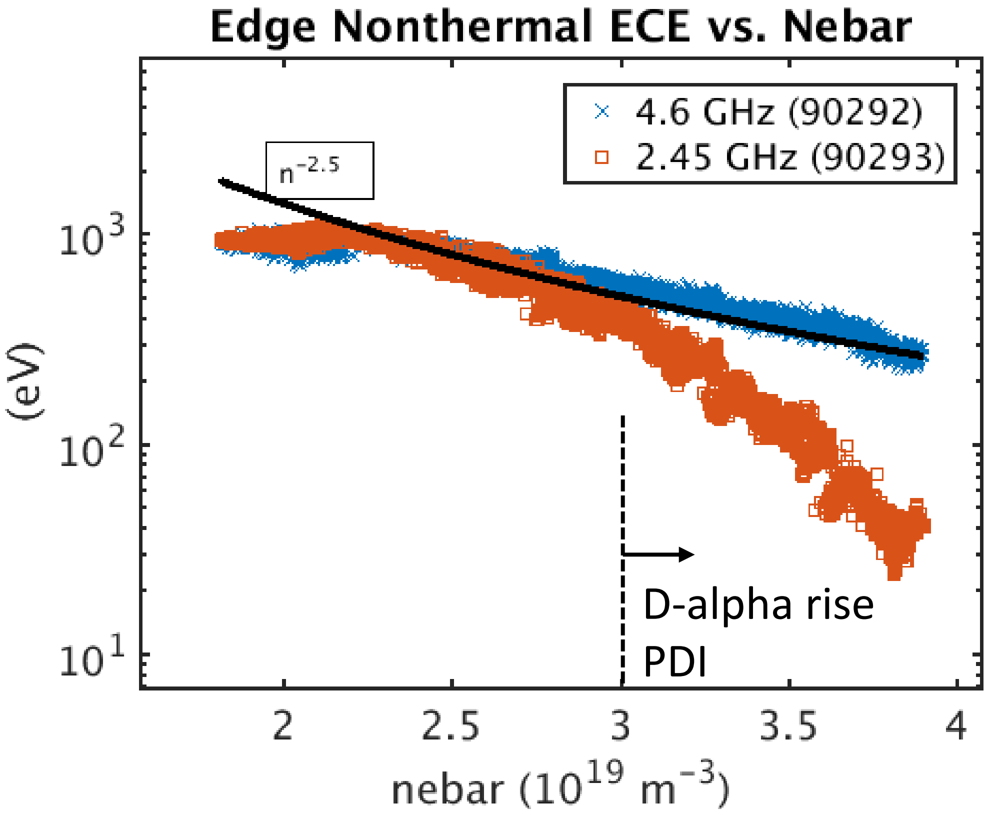


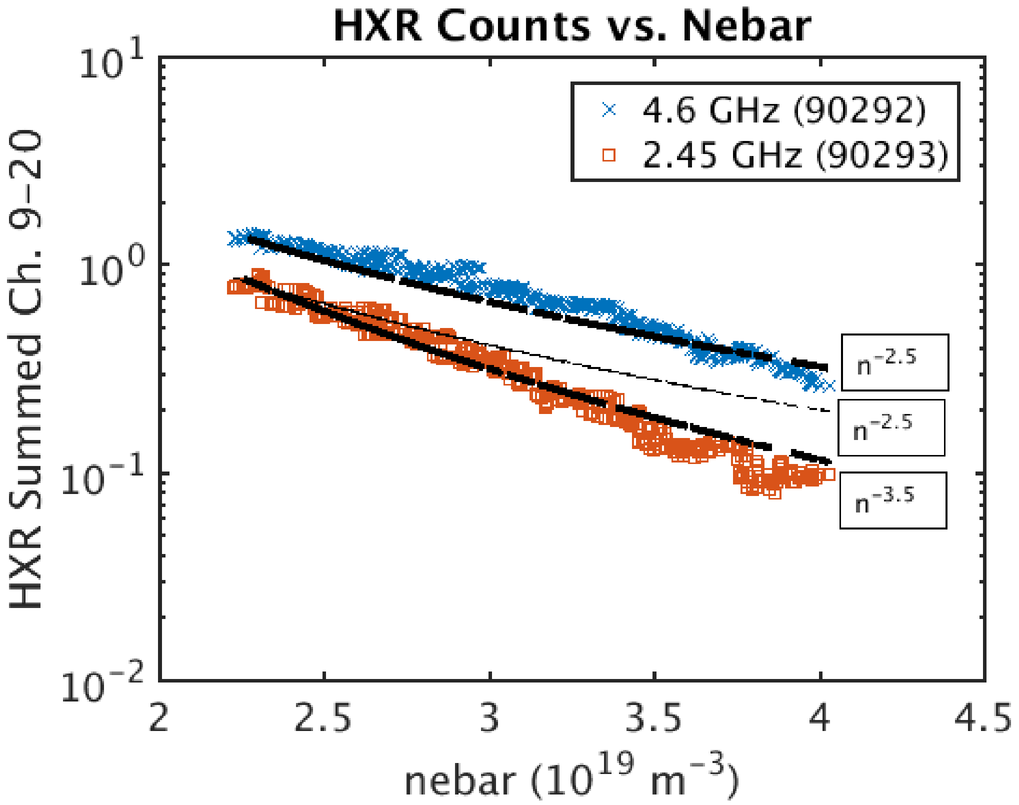


- The model is based on the previous study done on C-Mod[1]
- The model implies that the divertor SOL can provide a path for the rays to propagate to the cold and dense divertor, leading to additional power damping.
- We continue the modeling investigation at high density.

[1]Shiraiwa, RFPPC (2015)

With the increase in the D-alpha signal and the PDI onset, nonthermal electron cyclotron emission (ECE) shows a rapid decrease.





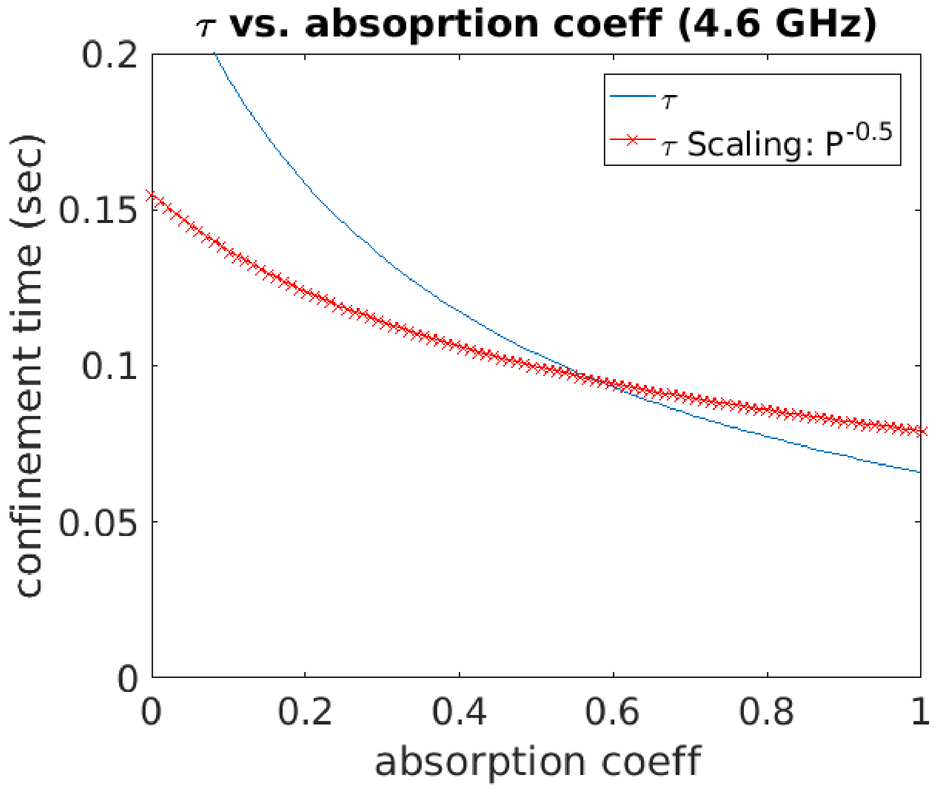
- Effective wave power absorbed within the LCFS could be decreasing as the parasitic wave interactions become evident.
- A further investigation is needed to understand the different trend between the HXR and ECE measurements.

Power absorption to the confined plasma is lower at 2.45 GHz than at 4.6 GHz.

- Wave power absorption coefficient, α, is evaluated by finding α that matches the experimental confinement time (τ_{exp}) to the confinement time scaling law ($\tau_{scaling}$).
  - $\tau_{exp} = \frac{W}{P_{oh}+\alpha P_{LH}}$
    - τ : energy confinement time
    - W: plasma stored energy
  - $\tau_{scaling} = \tau_{oh} \times (P_{tot}/P_{oh})^{-0.5}$
    - τ_{oh}: the ohmic reference τ without LH power
    - $P_{tot} = P_{oh} + \alpha P_{LH}$

Scaling Law	α (4.6 GHz)	α (2.45 GHz)
$P^{-0.5}$	0.57	0.36
$P^{-0.7}$	no solution	0.66

- No α is found for 4.6 GHz with the scaling law of $P^{-0.73}$, implying that the confinement time degradation may be weaker than $P^{-0.73}$ on EAST



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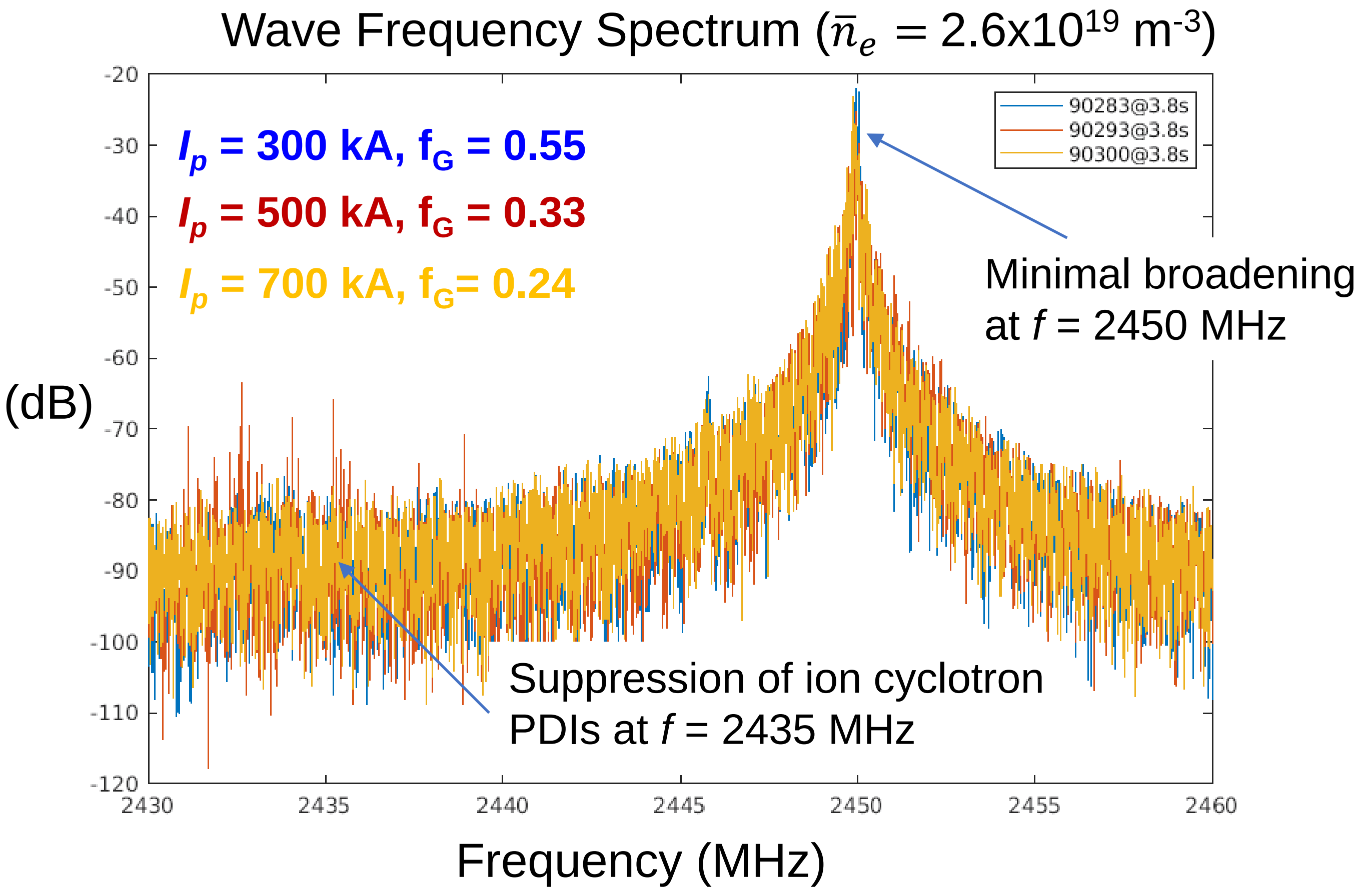

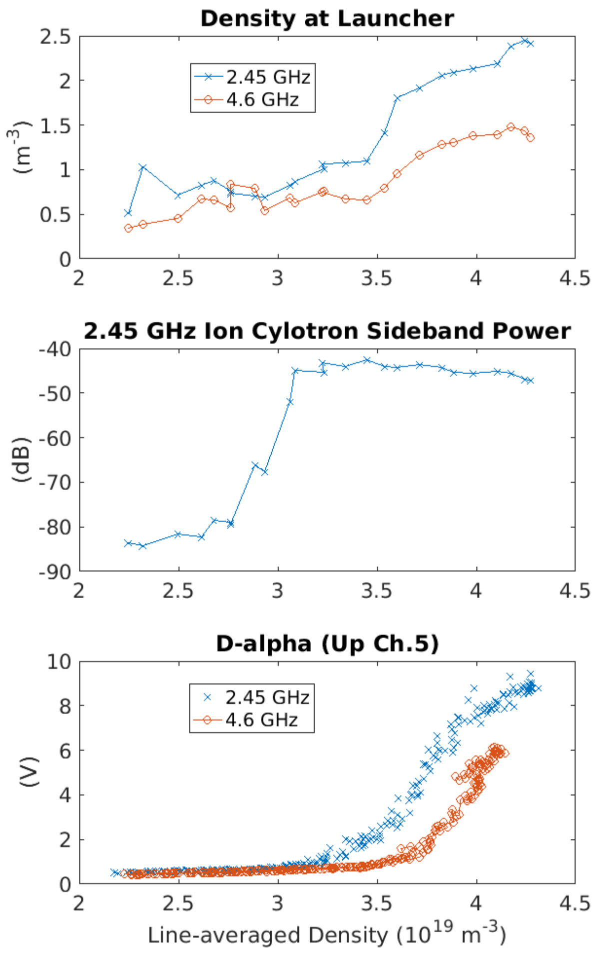

Density at Launcher
2.45 GHz
4.6 GHz
(m-3)
2.45 GHz Ion Cylotron Sideband Power
(dB)
D-alpha (Up Ch.5)
2.45 GHz
4.6 GHz
(V)
Line-averaged Density (10^19 m^-3)