Effect of Electron Cyclotron Waves on Plasma with Runaway Electrons

Pavel Aleynikov, Alexander Battey, Carlos Paz-Soldan, Eric Hollmann,
Andrey Lvovskiy, Jayson Barr, Claudio Marini, Daisuke Shirake, Charles Lasnier

EC for RE motivation

The “free space” O- and X-mode EC waves are used routinely for plasma heating and current drive.

O and X modes do not interact directly with relativistic electrons due to their high parallel phase velocity.

They have a relatively low cutoff. Their application to RE plateau may be problematic due to complete reflection.

A possible workaround is the **O-sX-B** mode conversion in overdense plasma. It allows lower frequency gyrotrons to be used in high density plasma (above the O-mode cutoff).

EC wave interaction with runaway electrons is a possible mechanism of their control.

Outline

Theoretical background

DIII-D experiment

Interpretation

Theoretical background

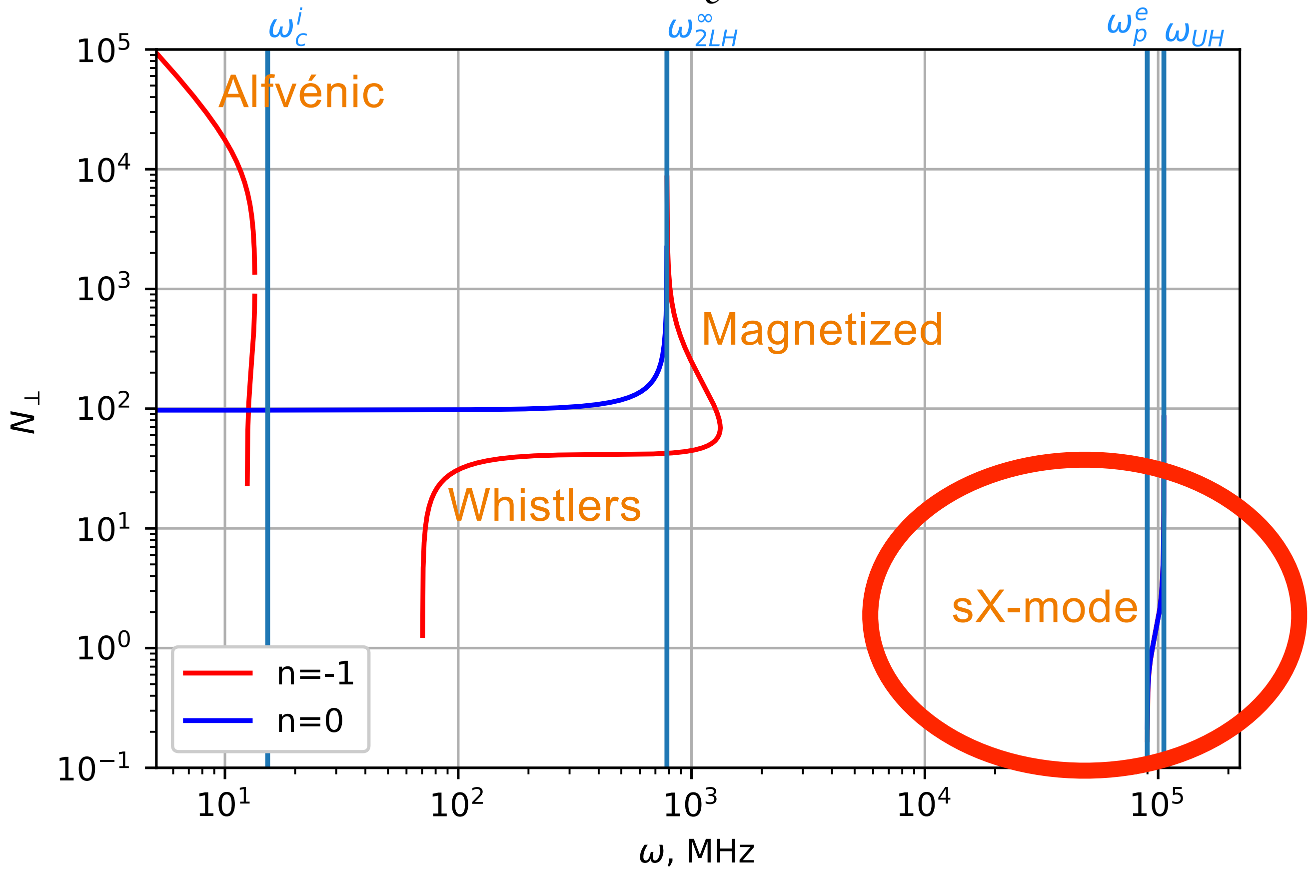
Theoretical background: RE resonances

Resonance condition:

$$1 - N_{||}\beta\cos\theta - \frac{n\omega_c}{\gamma\omega} = 0$$

Note that when γ is large, only resonances with $N_{||} \sim 1$ are effective in $\omega \sim \omega_c$ range

Waves resonant with $\gamma = 20; \theta = 0$ electrons in $B = 2T$, $n_e = 10^{20} m^{-3}$



Theoretical background: O-,X-,sX-modes

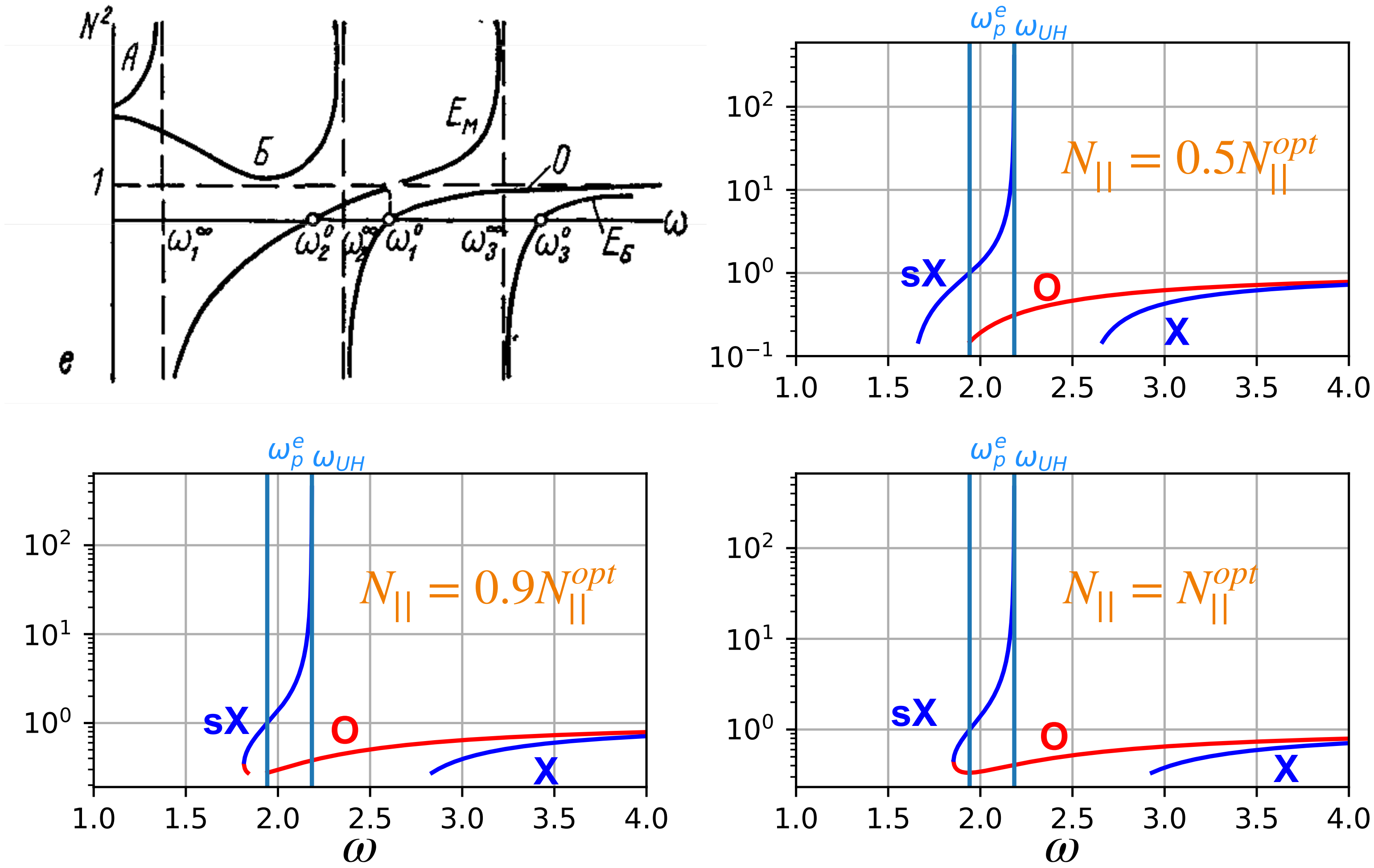
Two branches of the dispersion relation (O and sX) merge if

$$\omega = \omega_p$$

$$N_{||}^2 = 1 - \frac{\omega_p^2}{\omega(\omega + \omega_c)}$$

i.e. $N_{||}^{opt} \approx 0.57$ or 55° to $\overrightarrow{B}$.

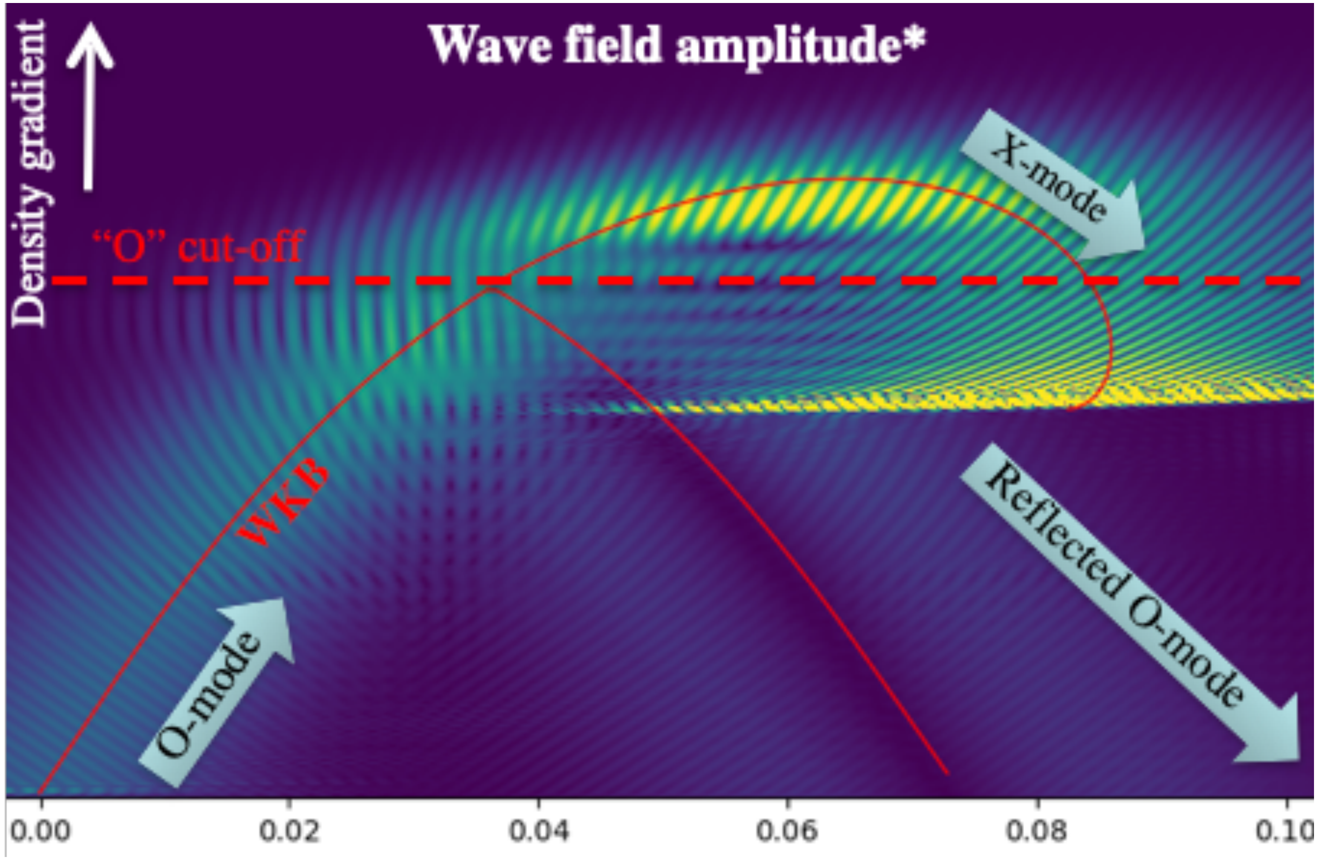
Cold plasma dispersion relation [*]



[*] V.D. Shafranov, Reviews of Plasma Physics vol. 3, 1967.

Theoretical background: Mode conversion (Full Wave)

The corresponding Full Wave calculations [*] predict ≈70% conversion efficiency



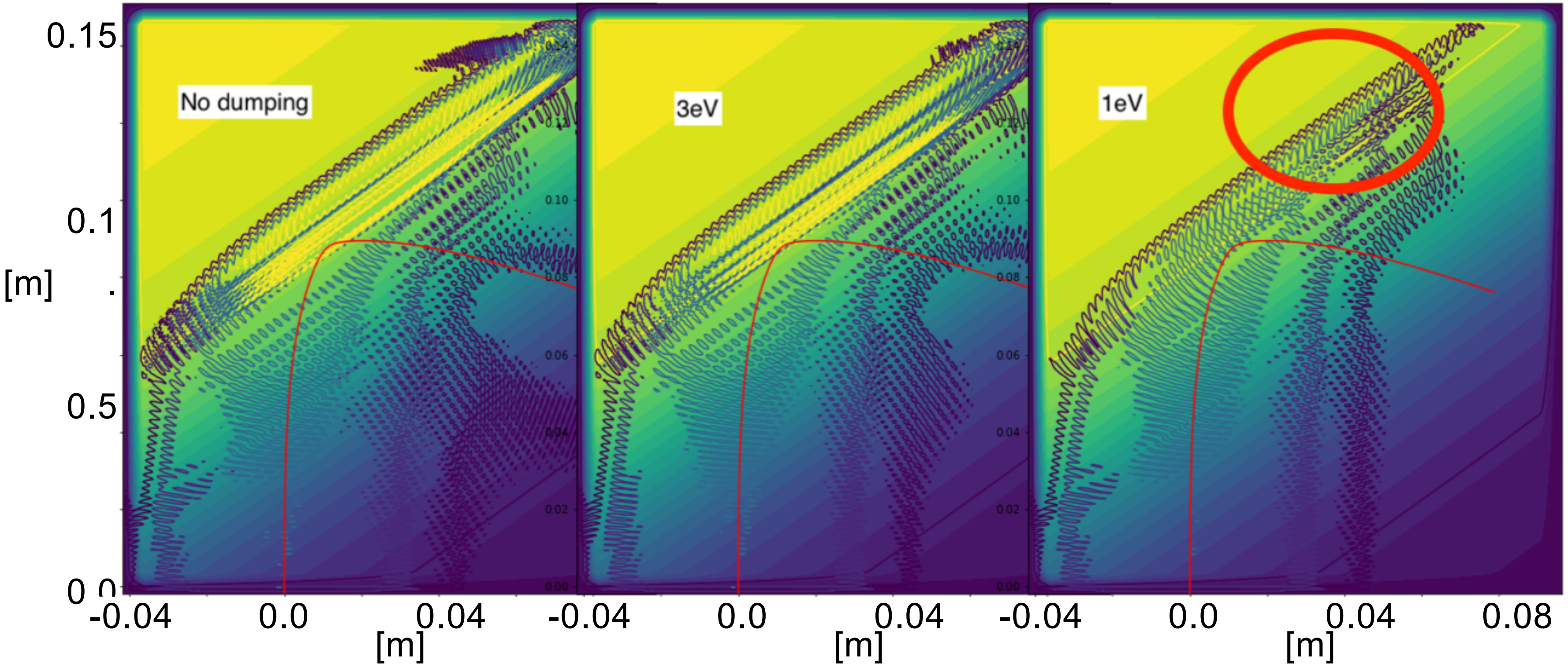
[*] Pavel Aleynikov, Nikolai B. Marushchenko, CPC 241 (2019) 40–47

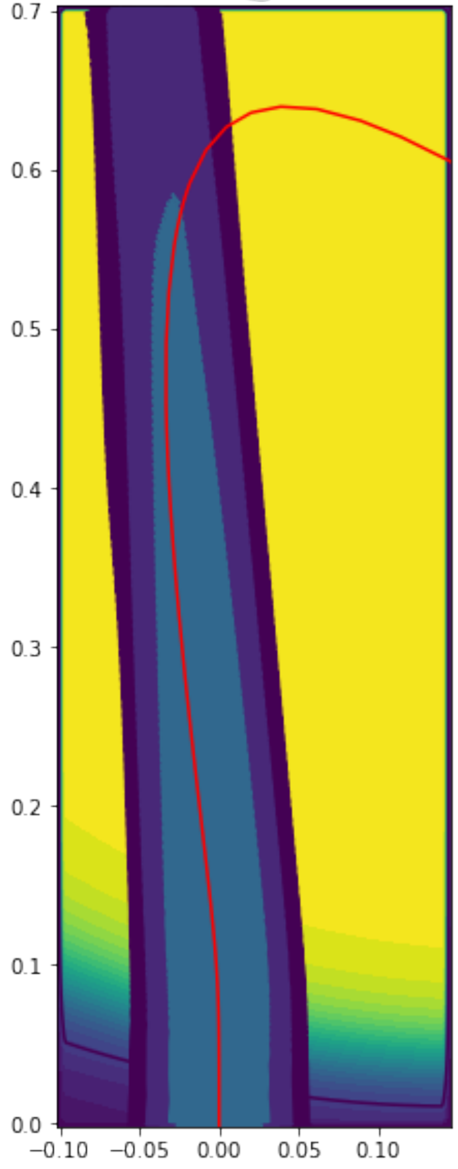
Theoretical background: Collisional damping

"Standart" quasilinear ECRH theory does not apply to 1 eV plasma.

Collisional damping dominates.

Damping length is of order of 1m in 1eV plasma.



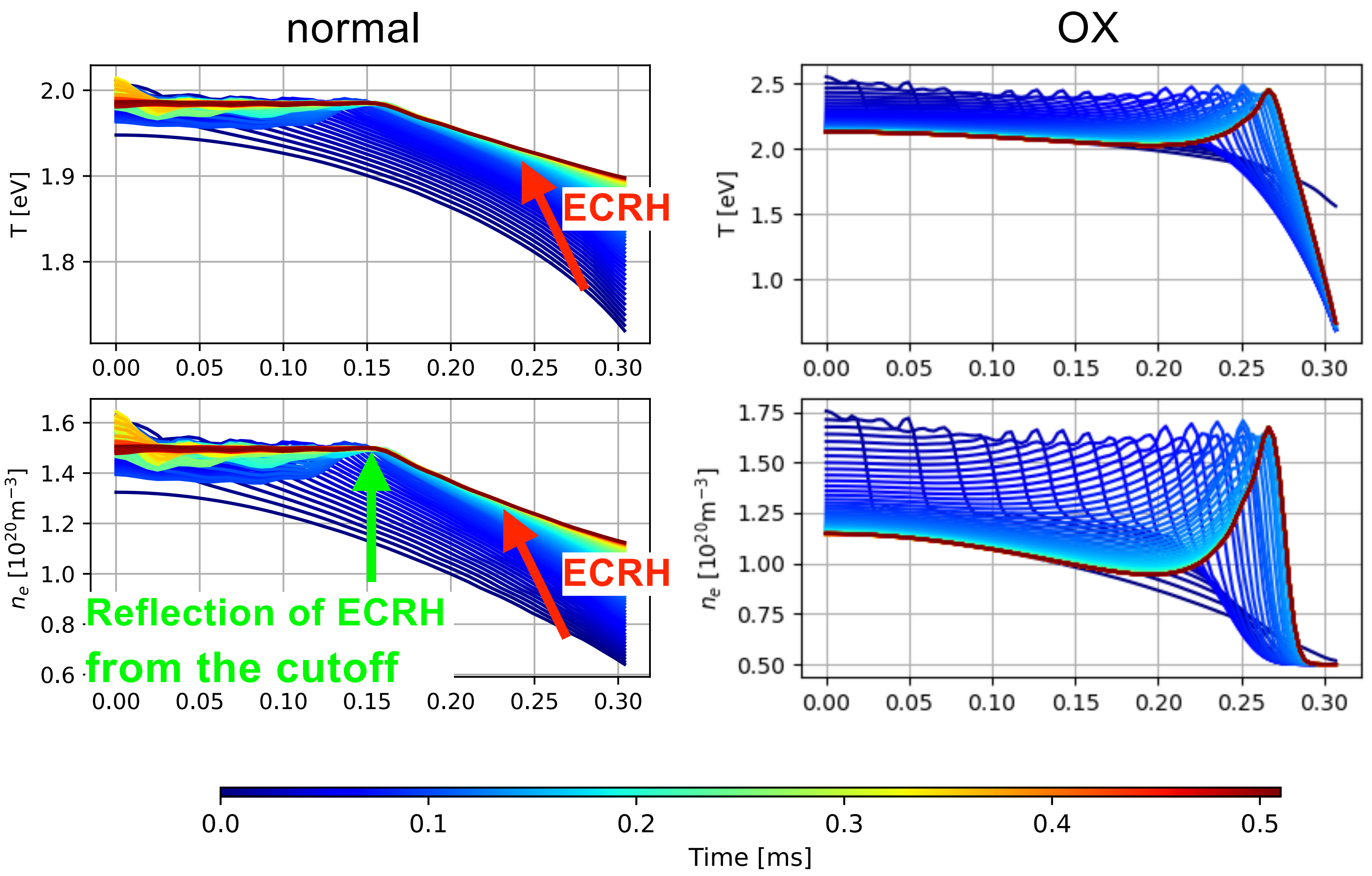


Theoretical background: Raising density using ECRH

Profile modelling suggests:

- **Flat profile** at cutoff for normal heating

- **Peaking at the edge** for OX



Experiment

Experimental setup

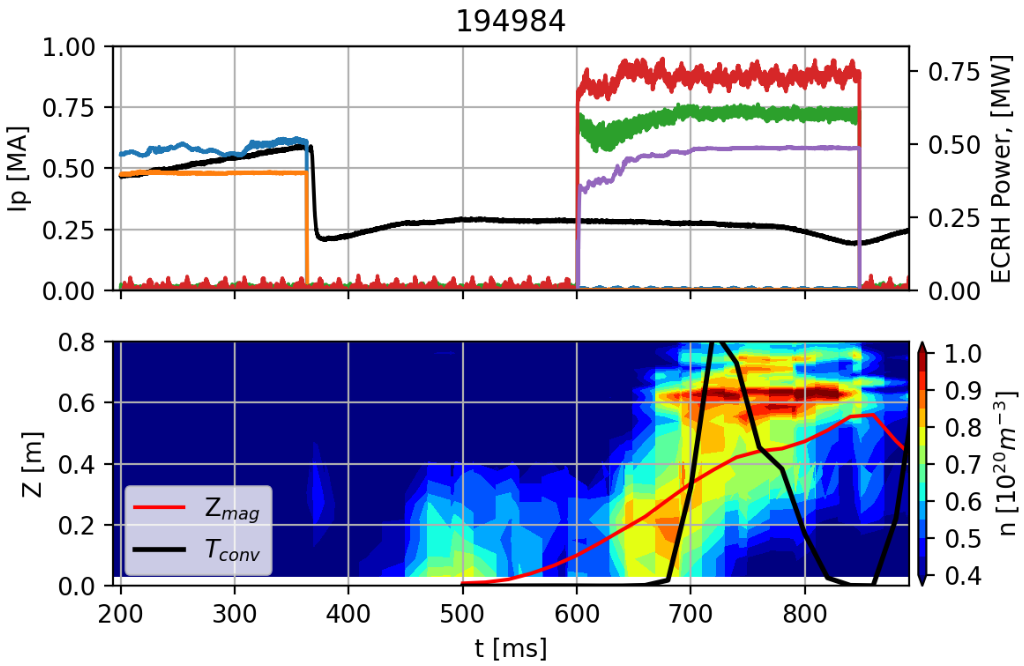
A runaway plateau is generated by disrupting plasma using Ar pellet injection

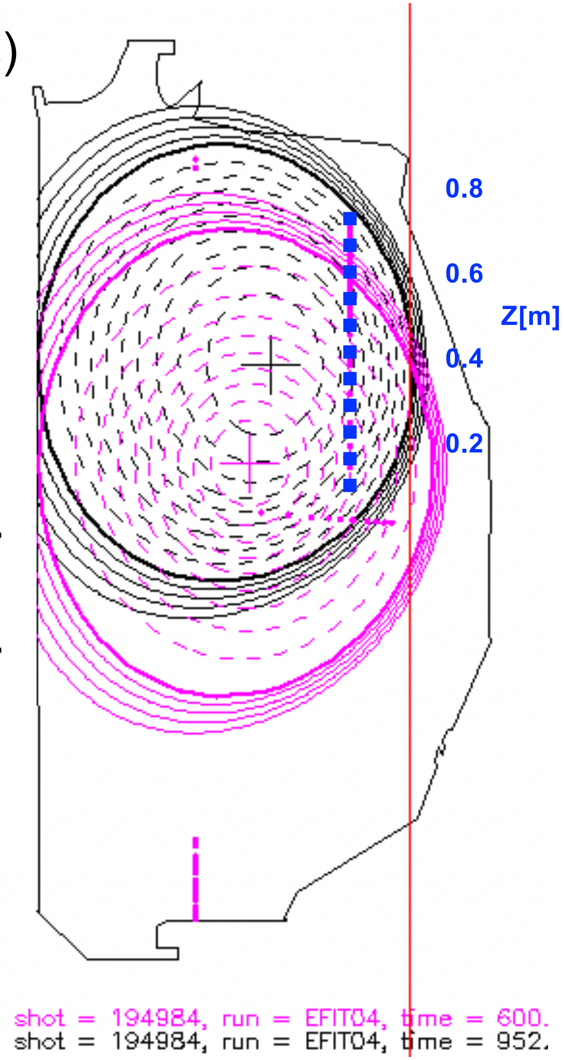
Helium MGI

The plasma configuration is manipulated to give access to optimal OX launching angles

The ECRH launching angles are pre-set before the shot

Plasma moved upward ($Z_0 = 0.0m \rightarrow 0.4m$)





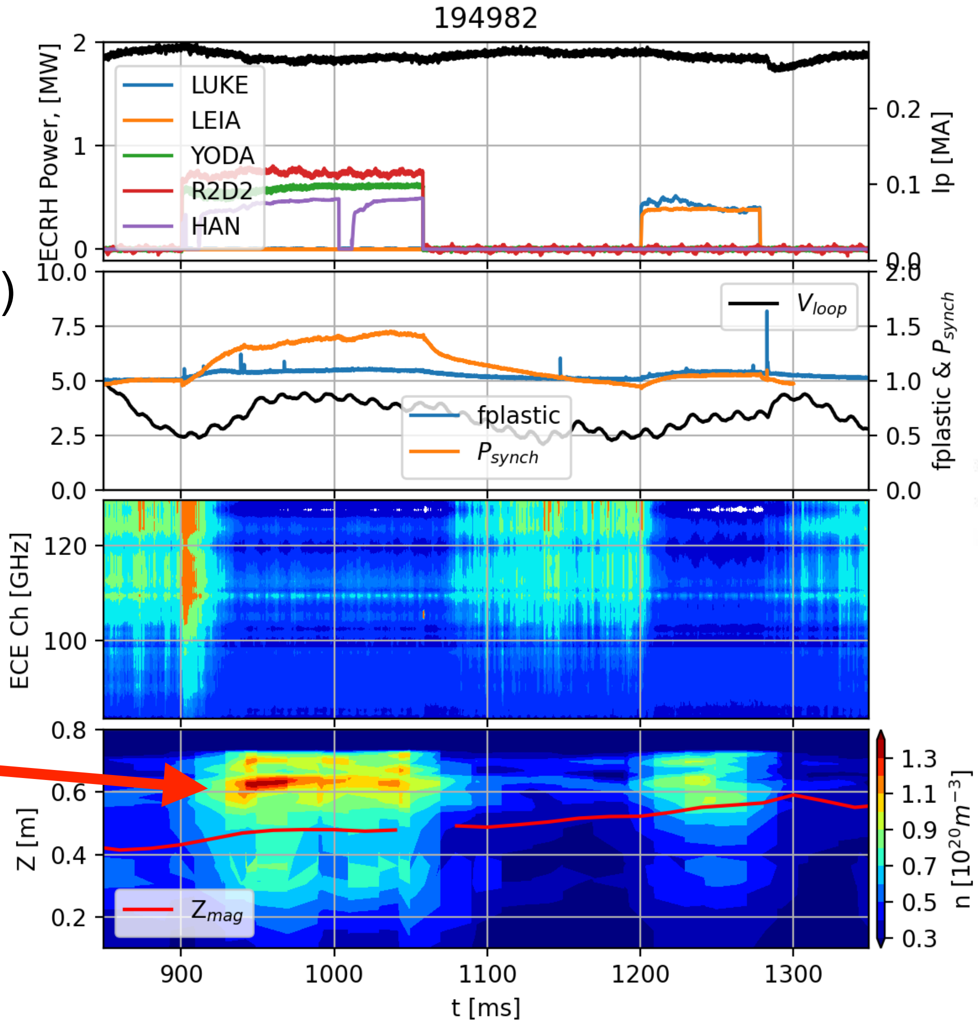
Experimental observations I (#194982): formation of the density peak and synchrotron increase

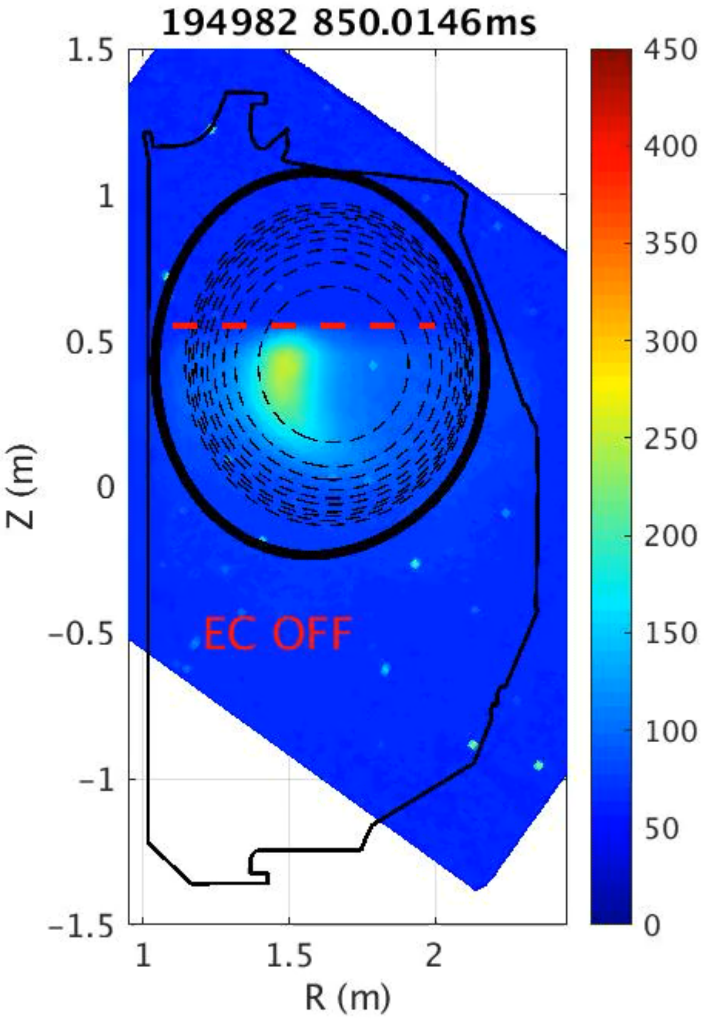
EC power applied at OXB conversion angle in DIII-D discharge

- 1.8 MW of power (3 gyrotrons)
- 160ms application

Measurements indicated successful mode conversion

Density peaking observed significantly off-axis



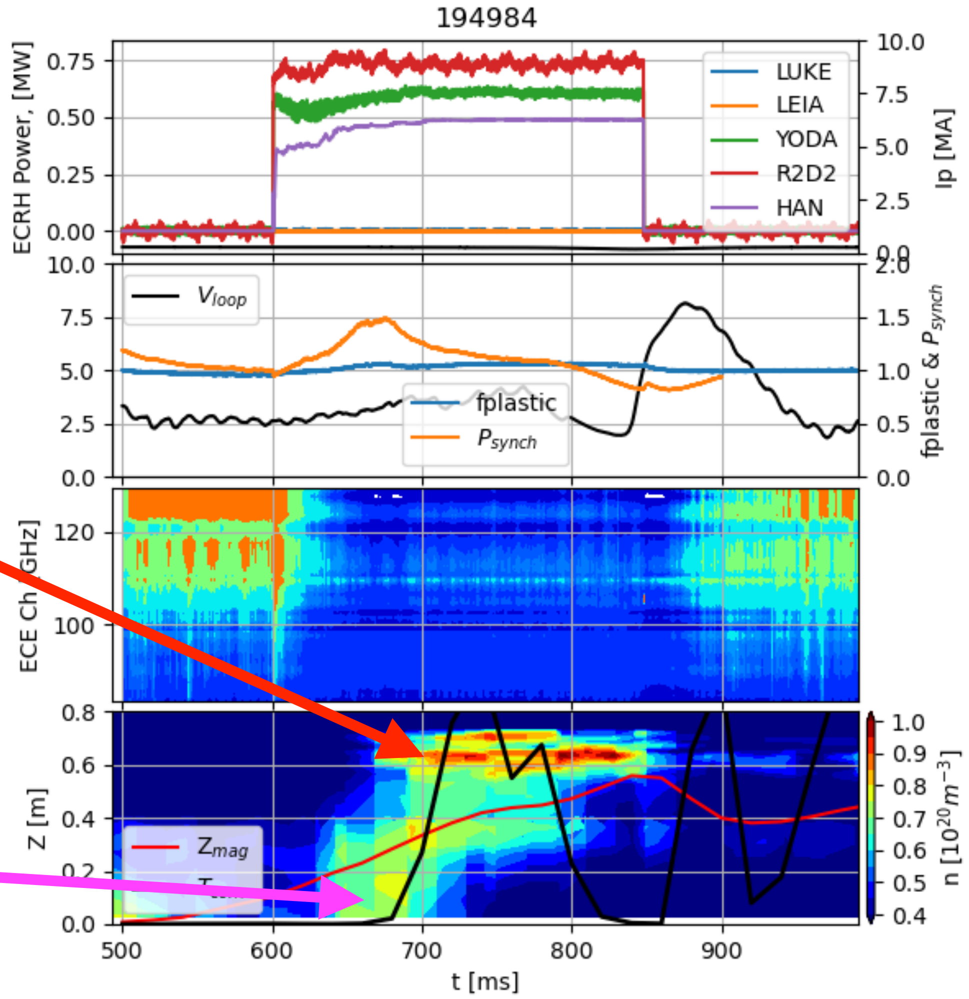


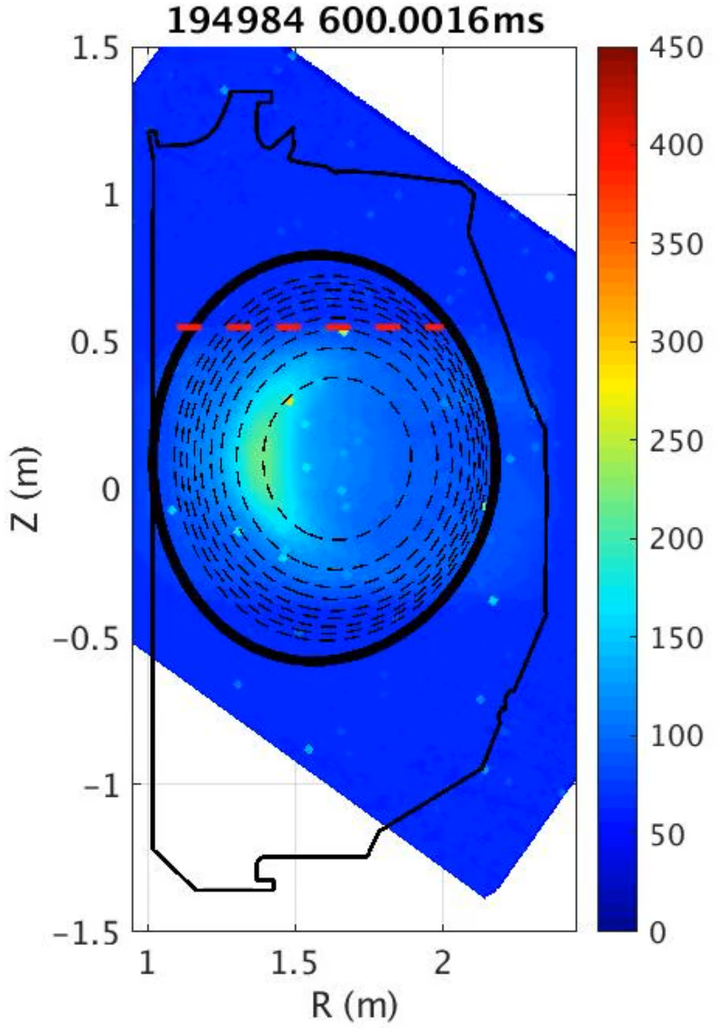
Experimental observations II (#194984): density peak formation only for optimal angles

Vertical plasma position was scanned to compare OXB and standard O-mode effects

Indicates mode conversion window:

- **Off-axis peaking** in electron density observed at vertical positions corresponding to nonzero mode conversion efficiency
- Away from optimal angles **broad density profile** observed well below cutoff value





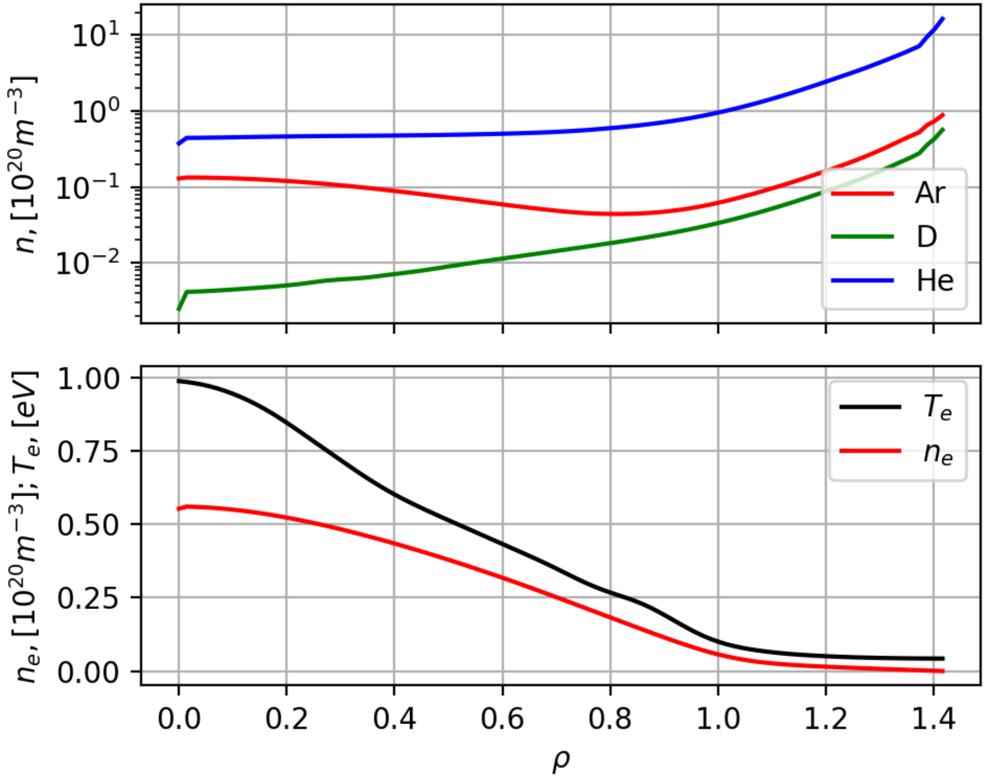
Interpretation

The near-threshold RE regime

- In RE plateau regime, the loop voltage is expected to settle at the E_{crit} level (or a few times that).
- ~200 Torr-L He is injected
- 1D transport modelling (including neutrals) [Hollmann] provides He and Argon densities before ECH

- The near-threshold RE theory [Aleynikov] gives corresponding $V_{crit}^{free+bound+synch} \approx 2.8V$ in agreement with the experimental $V_{loop}^{exp} \approx 2.5V$

Pre-ECH profiles modelling

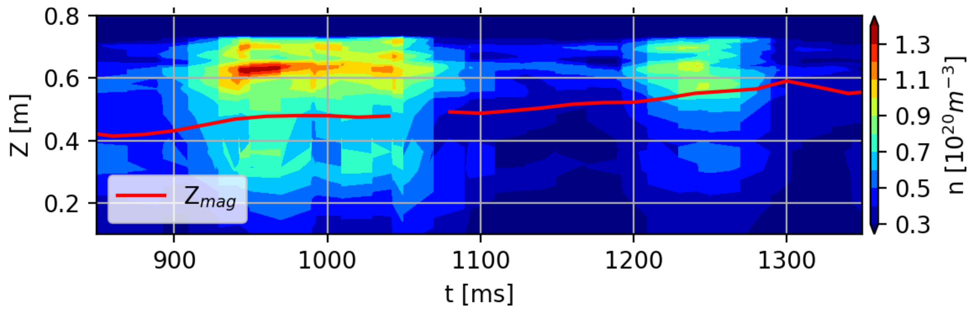


[Hollmann E.M. et al 2019 Nucl. Fusion ***59*** *106014]*

[Aleynikov Breizman PRL 114, 155001 (2015)]

1D transport modelling with ECH

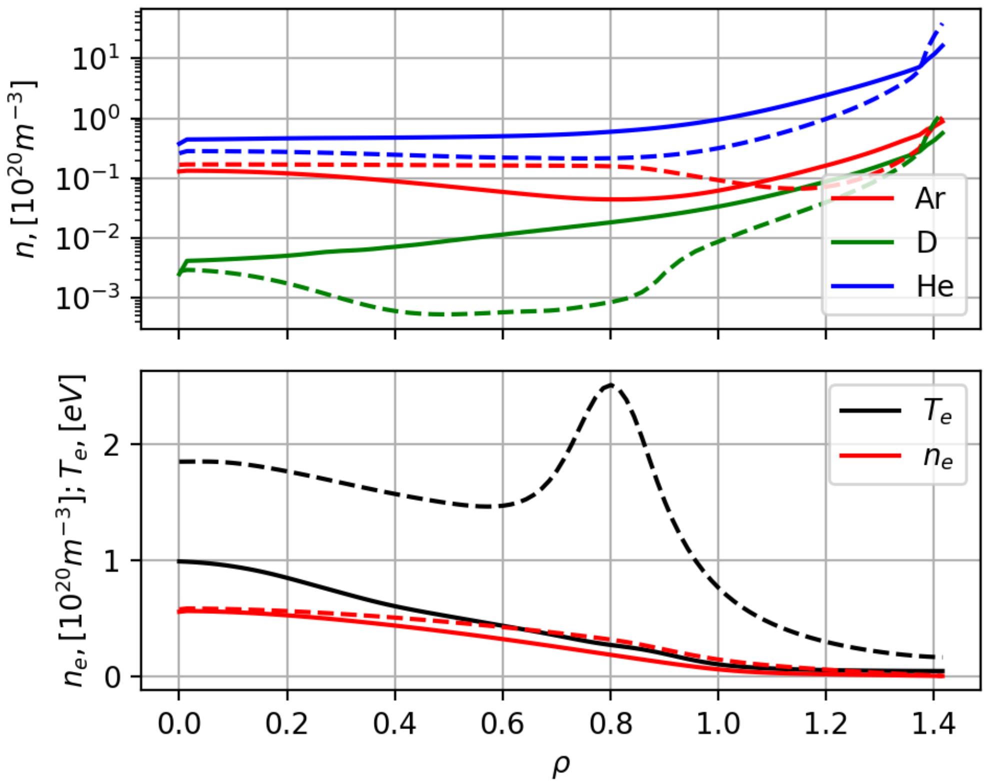
- Application of a localised ECH in 1D transport modelling does not actually lead to the formation of a strong density peak
- The flux-surface averaged ECH power is not strong enough to overcome line radiation and neutral heat transport
- But:



Why do we see much higher densities in experiment?

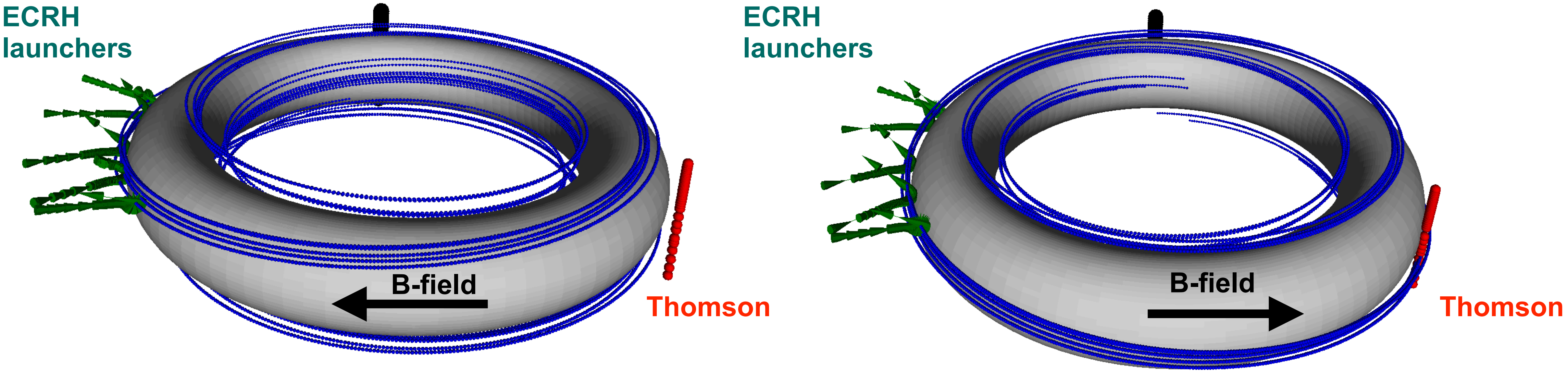
- Possibly due to 3D structure of the ionised plasma.

Pre- and post-ECH profiles modelling



3D plasma structure. Effect of the B-field direction

Apparently ECH does not lead to a complete ionisation of a heated flux surface, but only a “tube” of filed lines. Thus the connection length from the ECH to Thomson has an effect on the measurements.



This does not prevent OX conversion, but complicates the analysis

The near-threshold RE regime with the heating

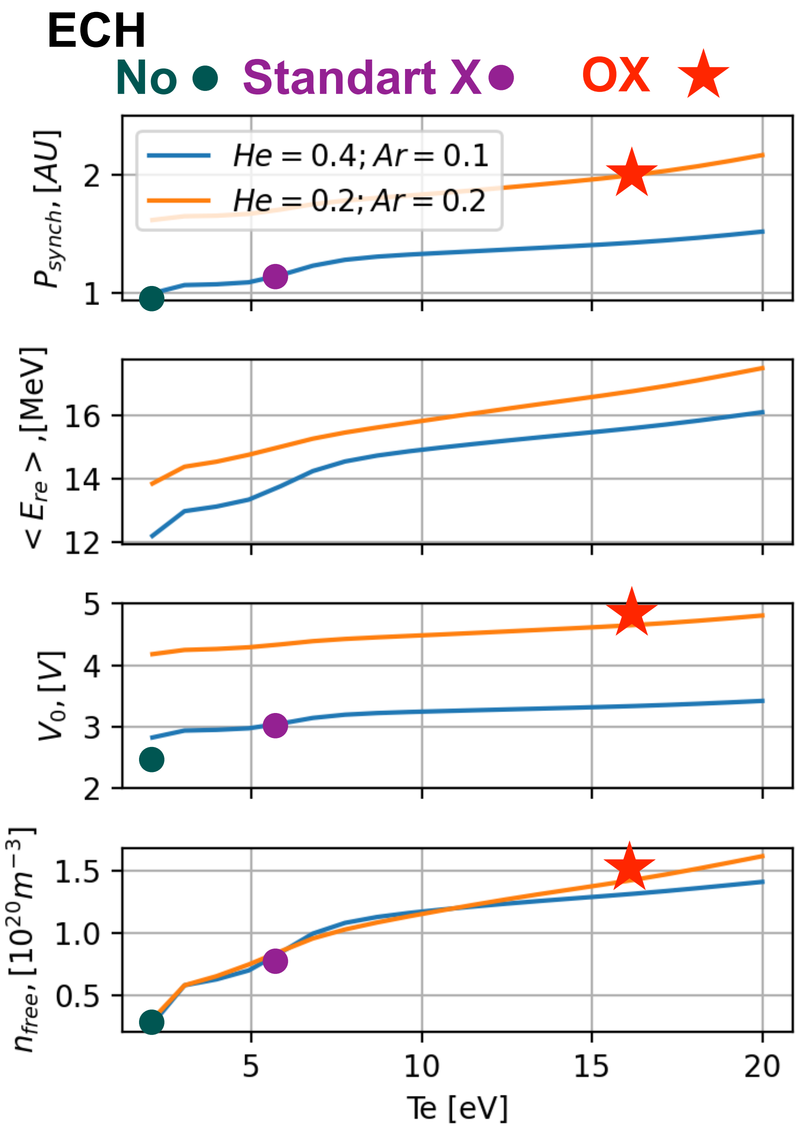
Increasing the **ionisation fraction** via ECRH with a fixed He and Ar profiles increases P_{synch} and V_{loop} by **only about 30%**.

If Argon density increases by ECH → increase of P_{synch} and V_{loop} are in the experimental range.

ECRH is a reliable control of the mitigation rate!

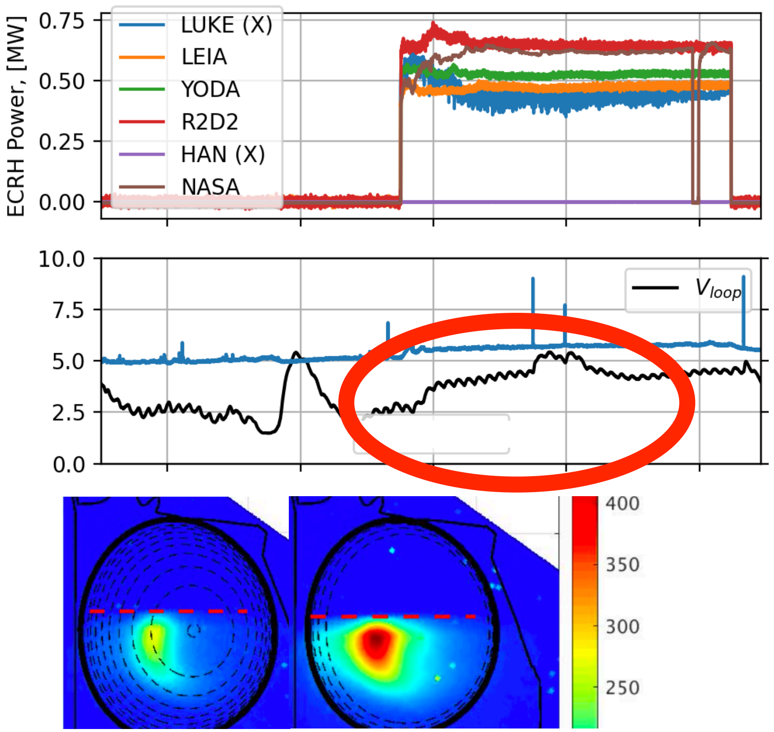
n.b! profiles after heating are not in agreement with measurements

Not possible to rule out wave-RE effects

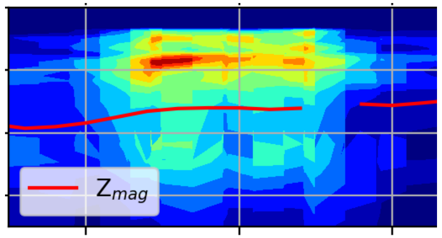


Summary

- **EC heating can control the RE mitigation rate**
  - 2x loop voltage with the ECH observed in DIII-D
  - 2x synchrotron radiation power
  - Likely due to ionisation and accumulation of Ar



- **O-sX modes conversion is tested at DIII-D**
  - Possible to heat an over-dense plasma



Outline/Conclusions

Theoretical background →

slow-X mode can be generated and can interact with RE

DIII-D experiment →

x2 sustainment V_{loop} with ECH

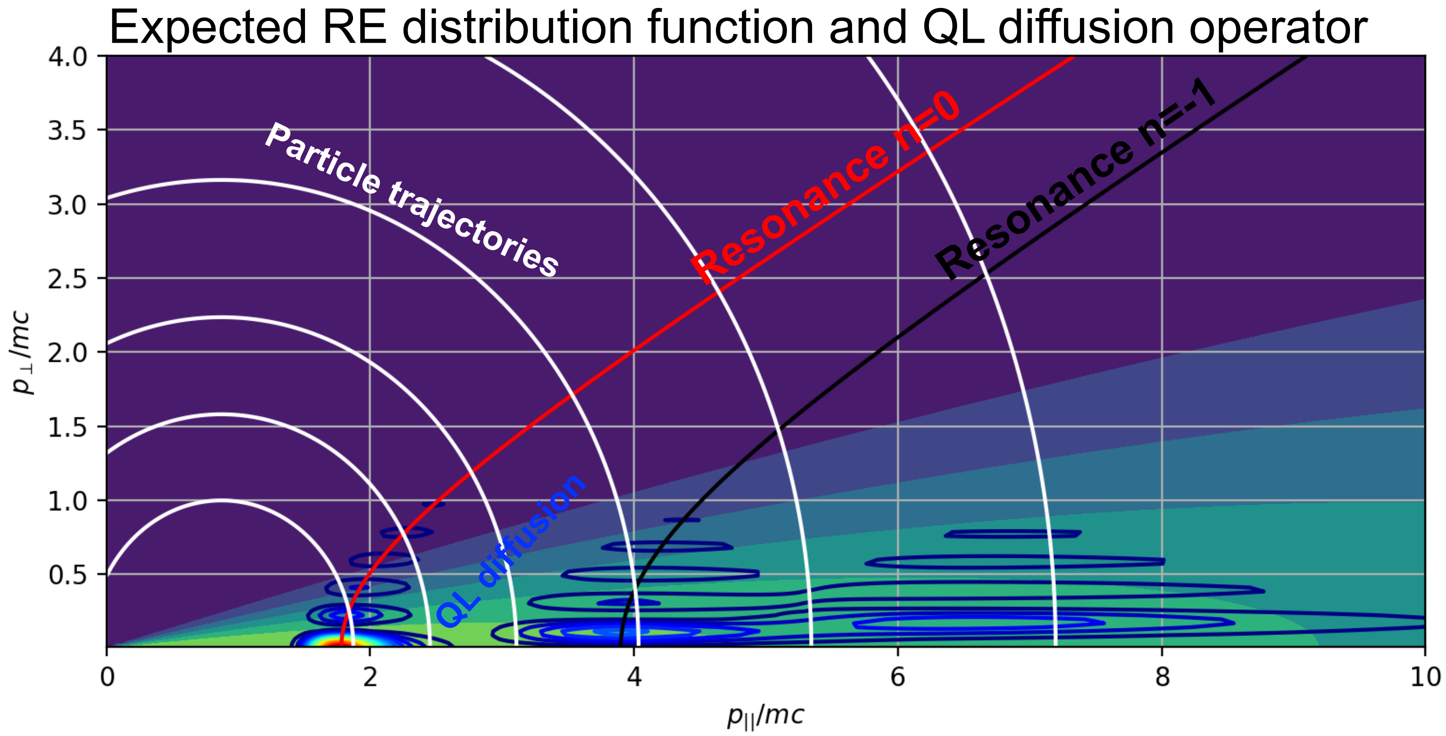
Interpretation →

Probably increased scattering from stripped Argon. Wave-RE interaction(?)

Backup

Theoretical background: Effect on RE

RE can be scattered by this wave



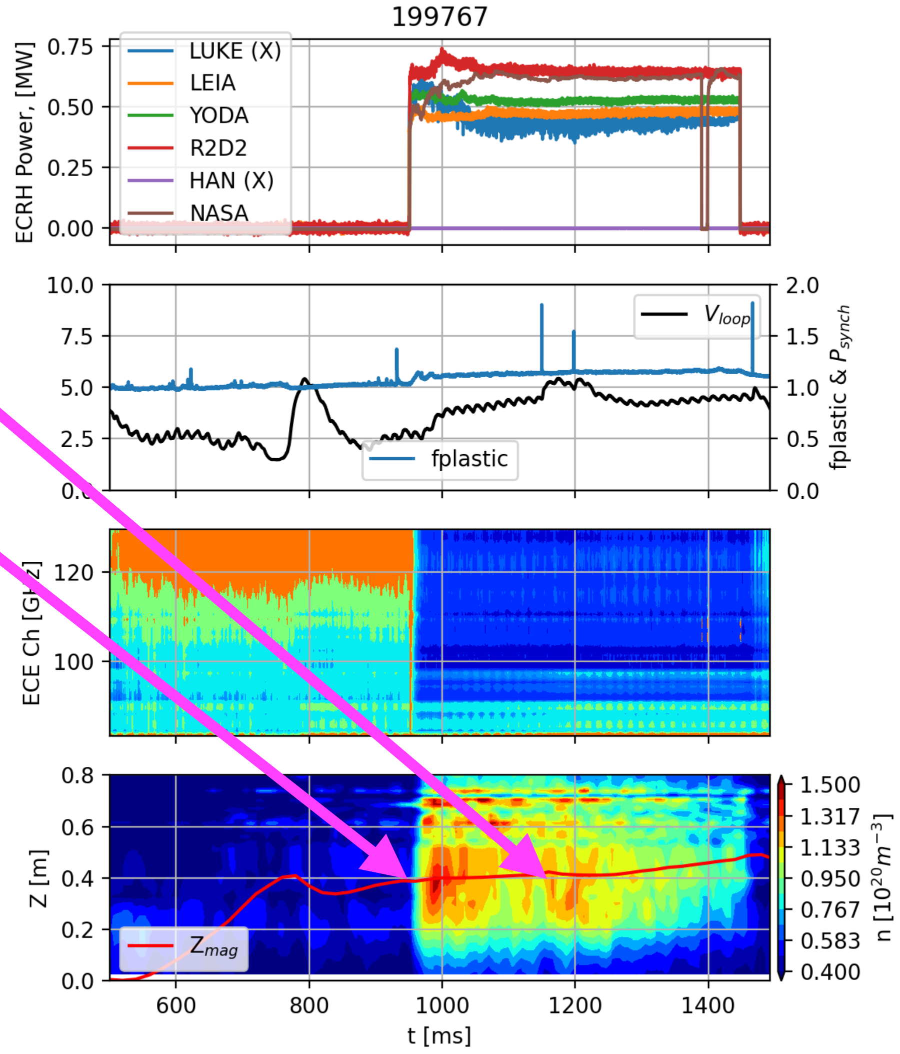
$$\left(N_{||} = 1.14, \frac{\omega}{\omega_c} = 2.238, \frac{\omega_p}{\omega_c} = 2.01\right)$$

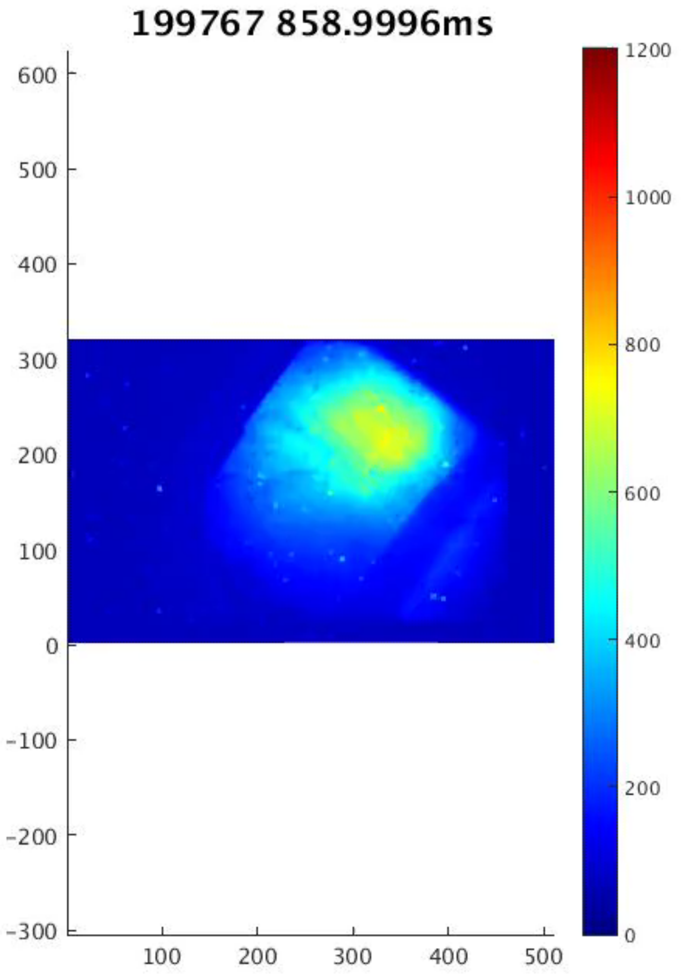
Experimental observations III (#199767): ECH mirrors steering and the change of the B-field

Density profiles evolve during ECH steering

Density peaks when ECH is at optimal angles (1000 and 1200 ms)

The density profile is now broad without an obvious “peak”



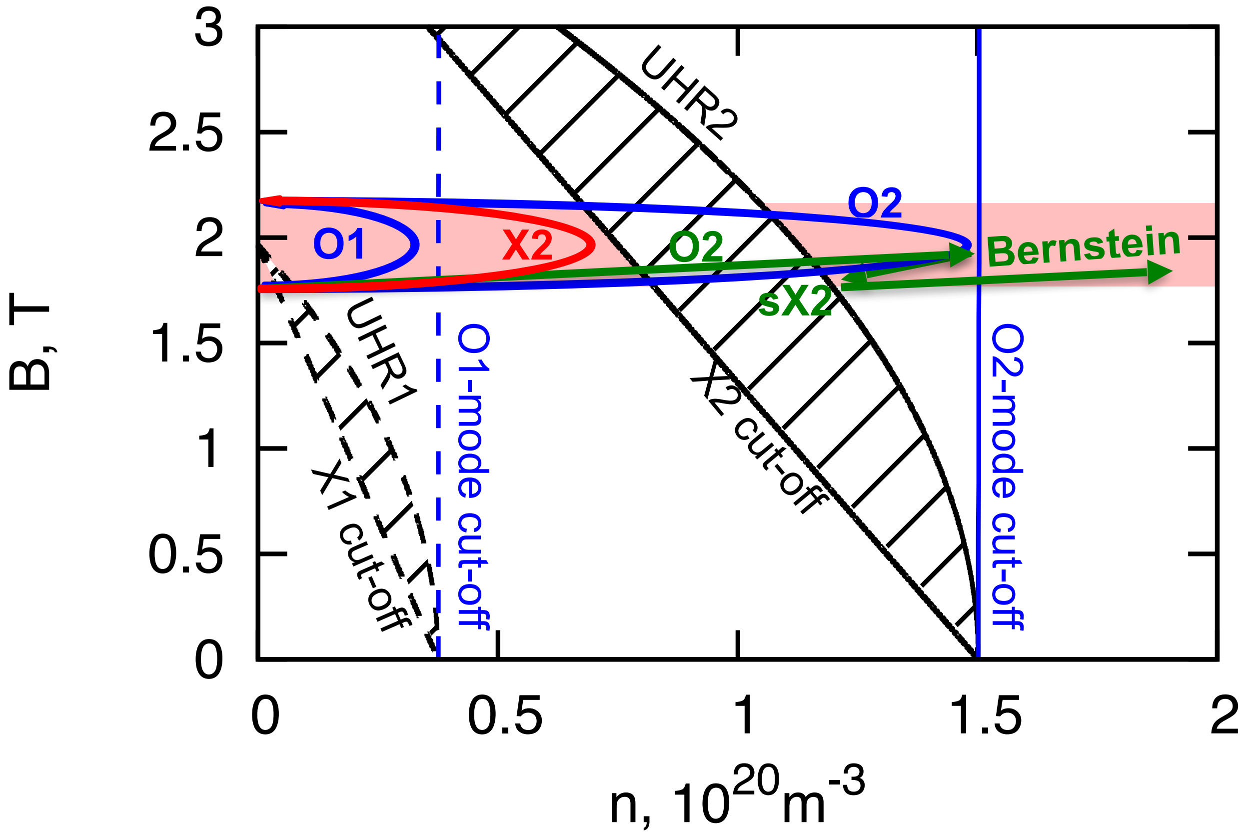


Theoretical background II: O-,X-,sX-modes

Injection capabilities

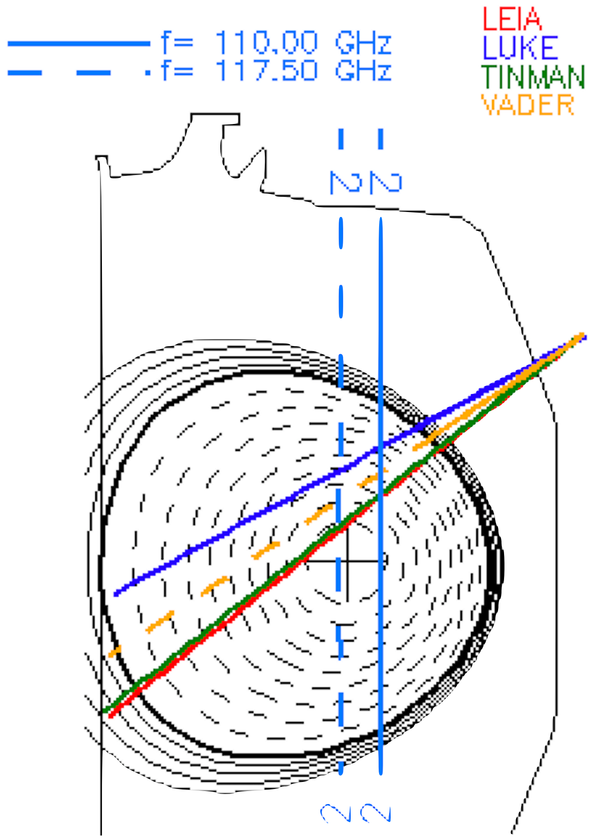
O- and X-modes are injected routinely. O2 has a cutoff $\omega = \omega_p$, i.e. $1.5 \cdot 10^{20} m^{-3}$ for 110 GHz

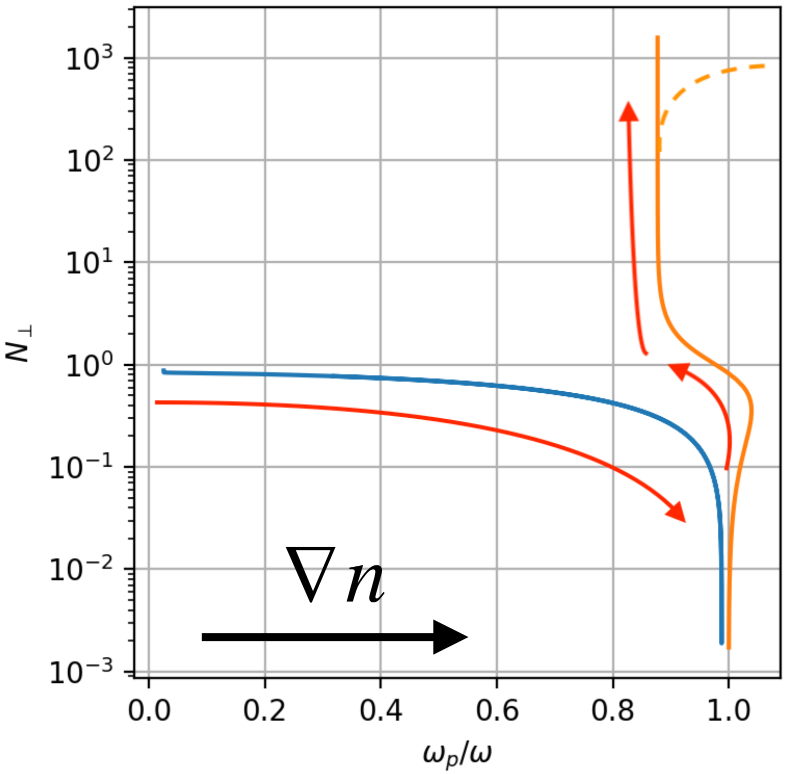
Injection of O2 into cutoff under special "optimal" angle to $\vec{B}$ leads to a mode conversion.

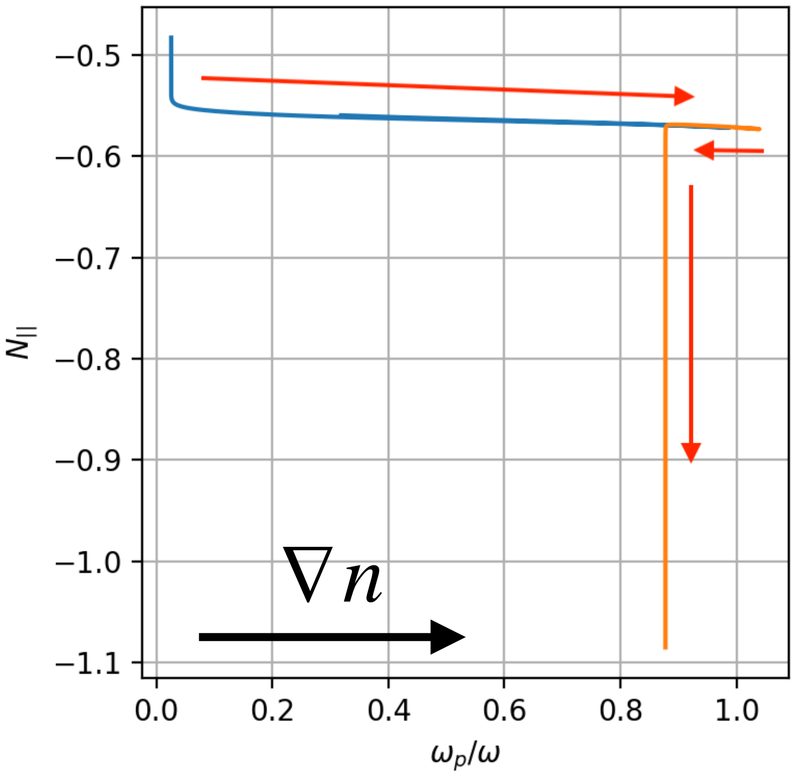


Theoretical background III: mode conversion (WKB)

Ray-tracing calculations for RE-plateau equilibria in DIII-D determine the optimal aiming angles







Experimental setup

A runaway plateau is generated by disrupting plasma using Ar pellet injection

The plasma configuration is manipulated to give access to optimal OX launching angles

The ECRH launching angles are pre-set before the shot

Plasma moved upward ($Z_0 = 0.0m \rightarrow 0.4m$)