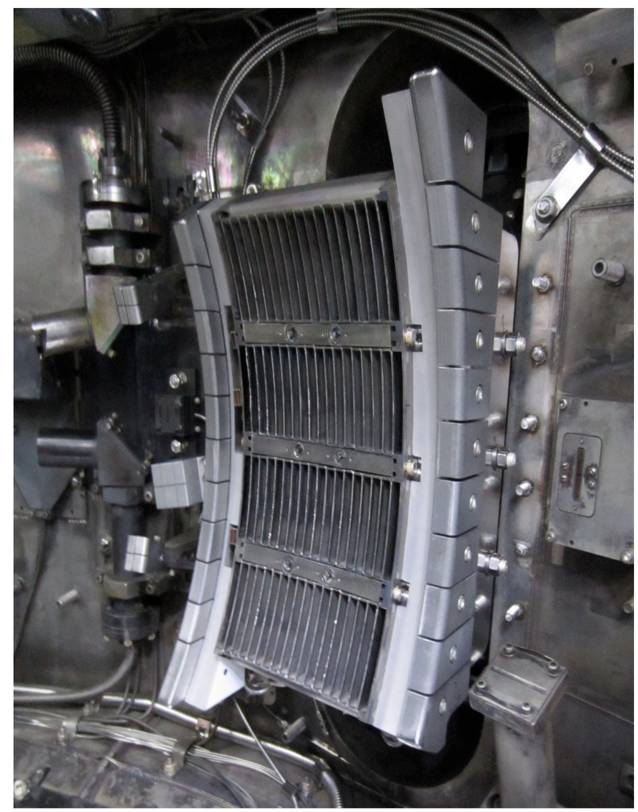
Progress in LHCD modeling and experiments towards AT regime on Alcator C-Mod*

S. Shiraiwa

Acknowledgment
MIT PSFC: S.G. Baek, P.T Bonoli, I.C. Faust, A.E. Hubbard, O.Meneghini, R.R. Parker, G.M. Wallace, J.W. Hughes, B.L. LaBombard, Y. Ma, R. Mumgaard, M.L. Reinke, J.L. Terry, D.G. Whyte, J.C. Wright, S.J. Wukitch

CompX: R.W. Harvey, A.P. Smirnov

PPPL: J.R. Wilson, S. Scott

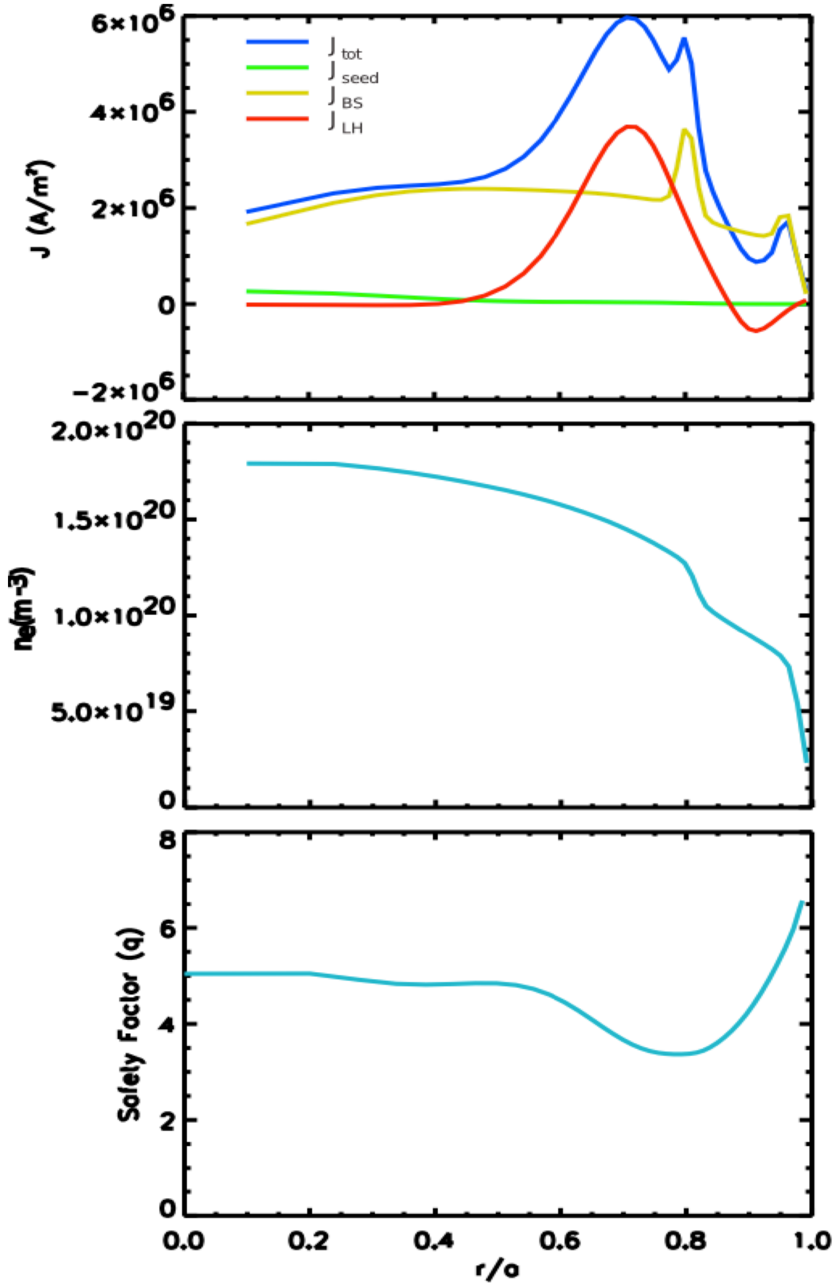


LH2 in Alcator C-Mod

2011. 11. 28 ITC-21 at Toki conf.

*Supported by US DOE Awards DE-FC02-99ER54512 and DE-AC02-09CH11466

LHCD is a knob to control current profile on AT experiments on Alcator C-Mod



P. Bonoli et. al., NF, (2000)

envisioned parameters

P_{LHCD} = 2.5-3 MW@4.6GHz (< 1.2MW)

B_t = 4 - 6 T

$n_e = 1.5 \bullet 10^{20} m^{-3}$

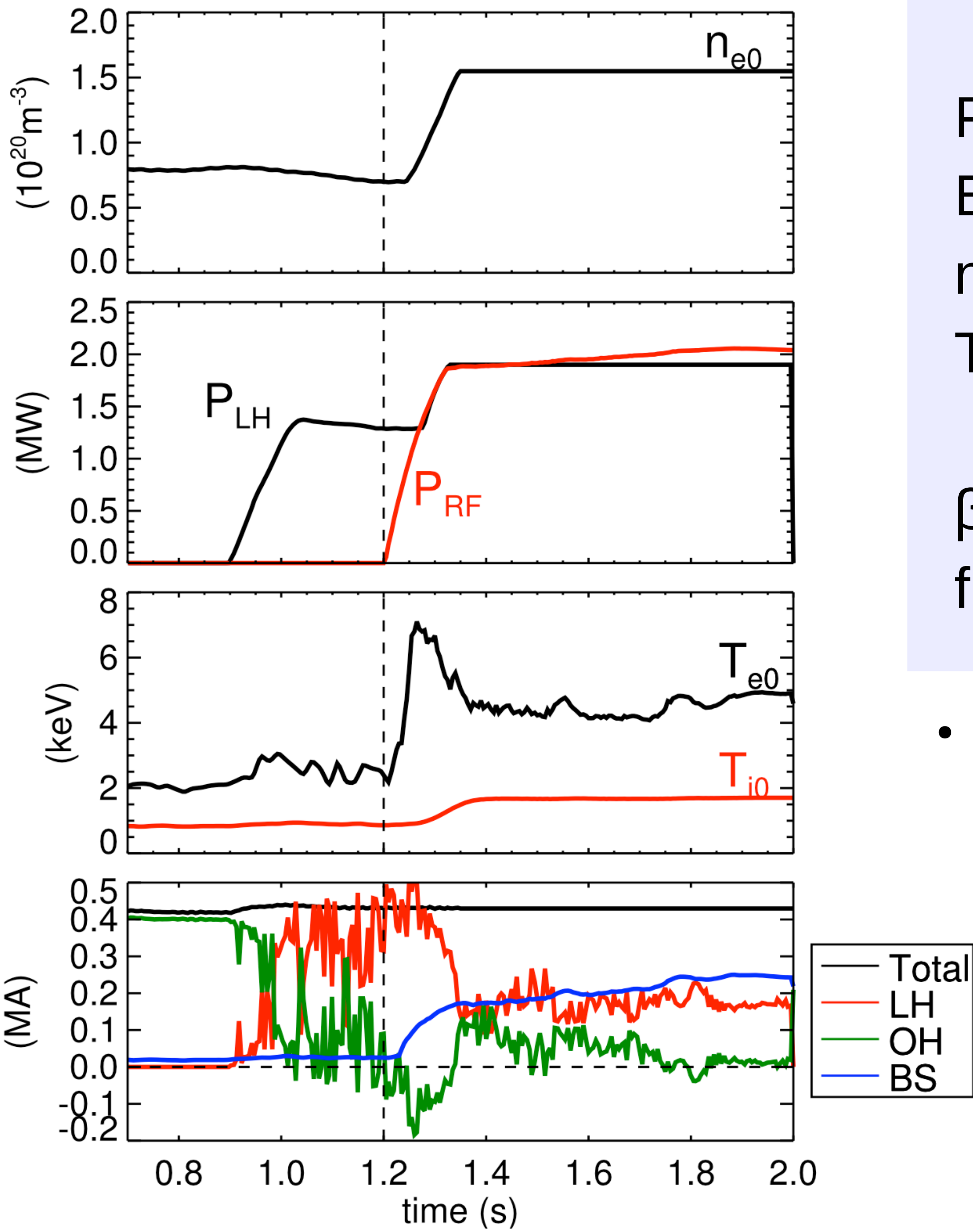
T_{e0} = 5 - 7 keV

(~10 keV @ $n_e = 1.5 \bullet 10^{20} m^{-3}$)

β_N = 2.5 ~ 3

f_{BS} = 50 - 70 %

LHCD is a knob to control current profile on AT experiments on Alcator C-Mod



envisioned parameters

P_{LHCD} = 2.5-3 MW@4.6GHz (< 1.2MW)

B_t = 4 - 6 T

$n_e = 1.5 \cdot 10^{20} m^{-3}$

T_{e0} = 5 - 7 keV

(~10 keV @ $n_e = 1.5 \cdot 10^{20} m^{-3}$)

β_N = 2.5 ~ 3

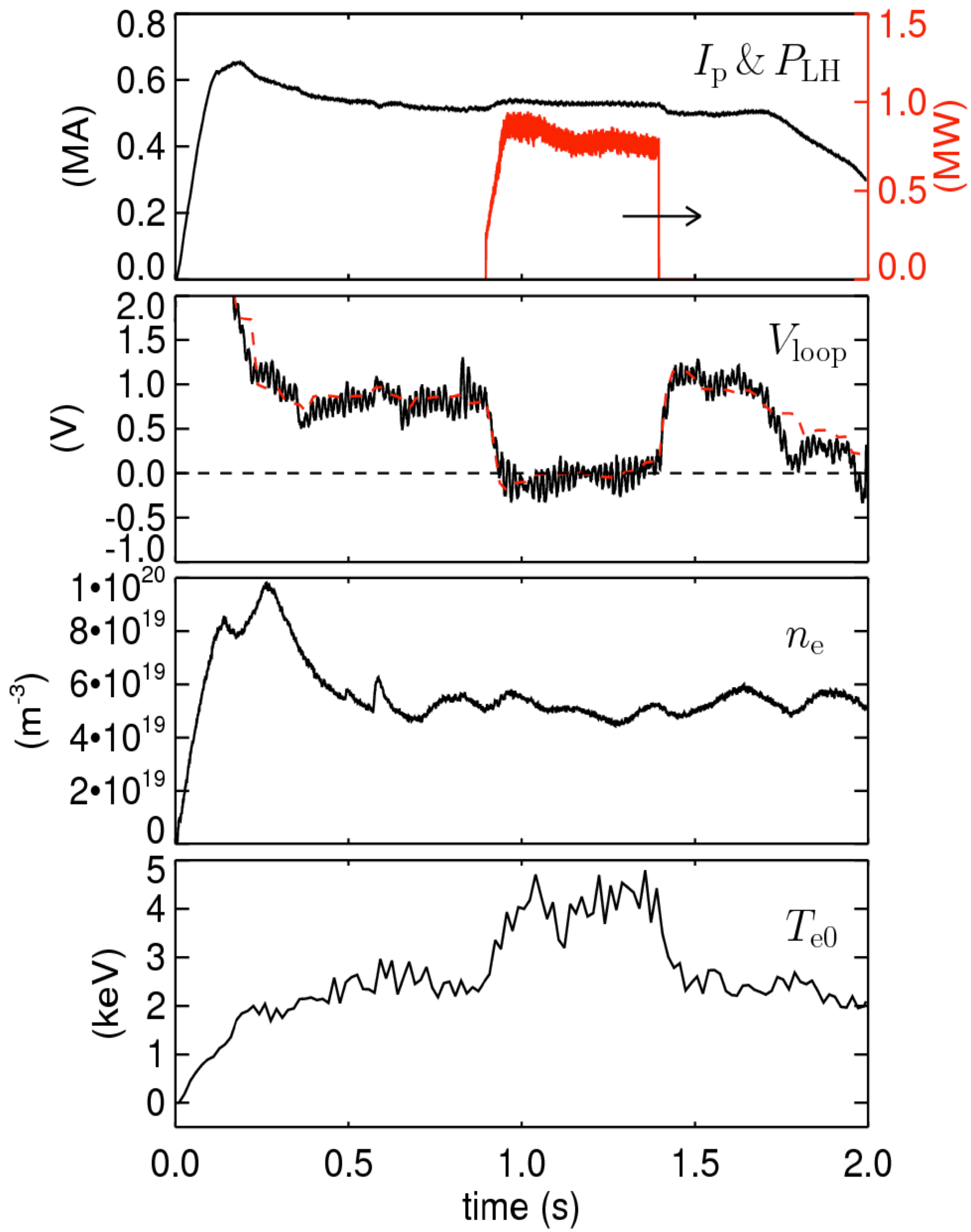
f_{BS} = 50 - 70 %

- Integration is a key
  - Off-axis LHCD → ICRF heating
  - shear reversal
  - confinement improvement
  - broad pressure profile
  - high f_{BS}

Outline

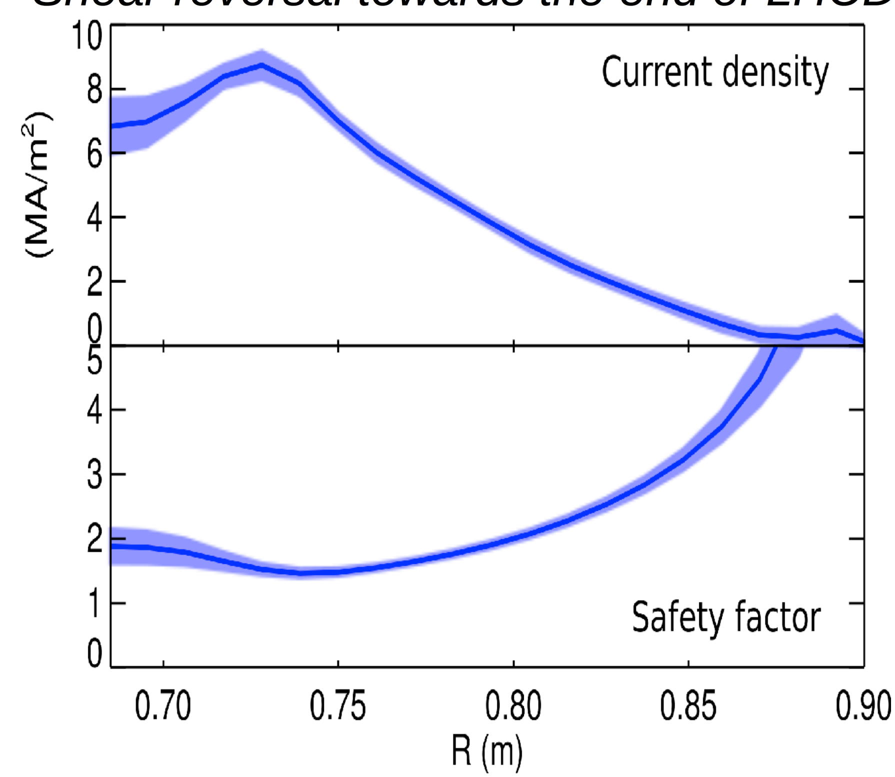
- Demonstration of fully non-inductive RS plasmas by off-axis LHCD at moderate density.
- Advanced wave simulations to better understand how the LH wave behaves at higher density
- Plan for next experiment with doubled net LHCD power

Fully non-inductive LHCD was demonstrated at the density close to ITER SS scenario for a few current relaxation time

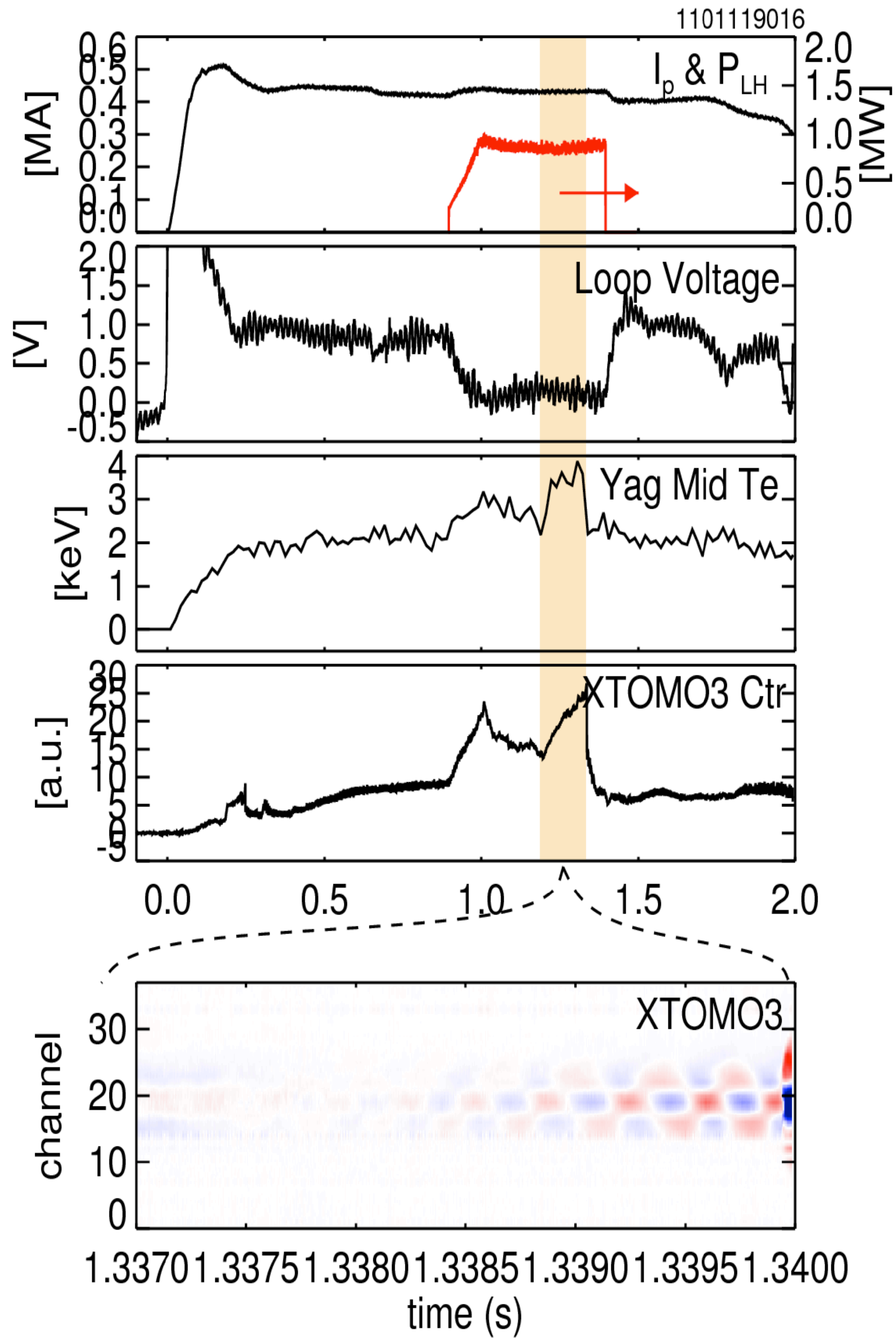


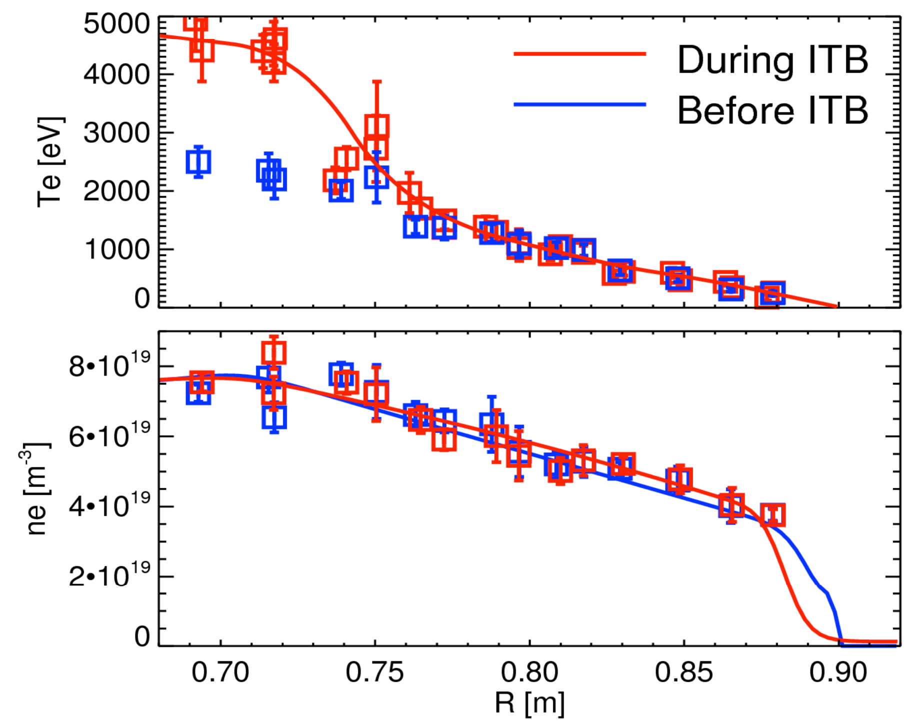
n_e~0.55x10^{20} m^{-3}, I_p ~ 500 kA,
f_{LH}=4.6GHz, B_φ=5.4 T
CD efficiency :η (≡$n_e I_{LH} R_0 / P_{LH}$)
= 2.0 – 2.5x10^{19} AW^{-1}m^{-2})
(ITER : η=2.3x10^{19} AW^{-1}m^{-2})

Shear reversal towards the end of LHCD



With more off-axis LHCD, ITB formation in T_e profile was observed during RS phase



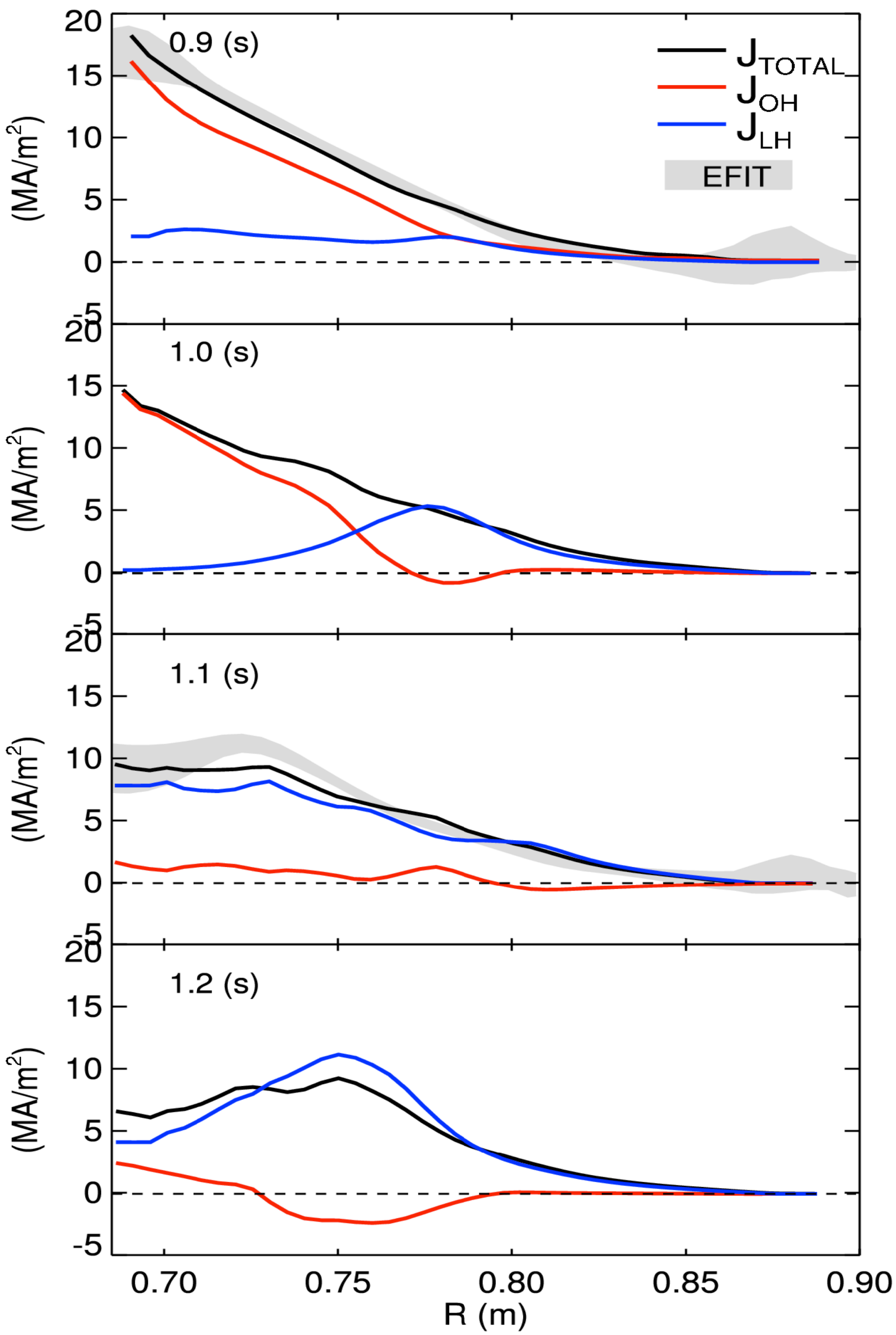


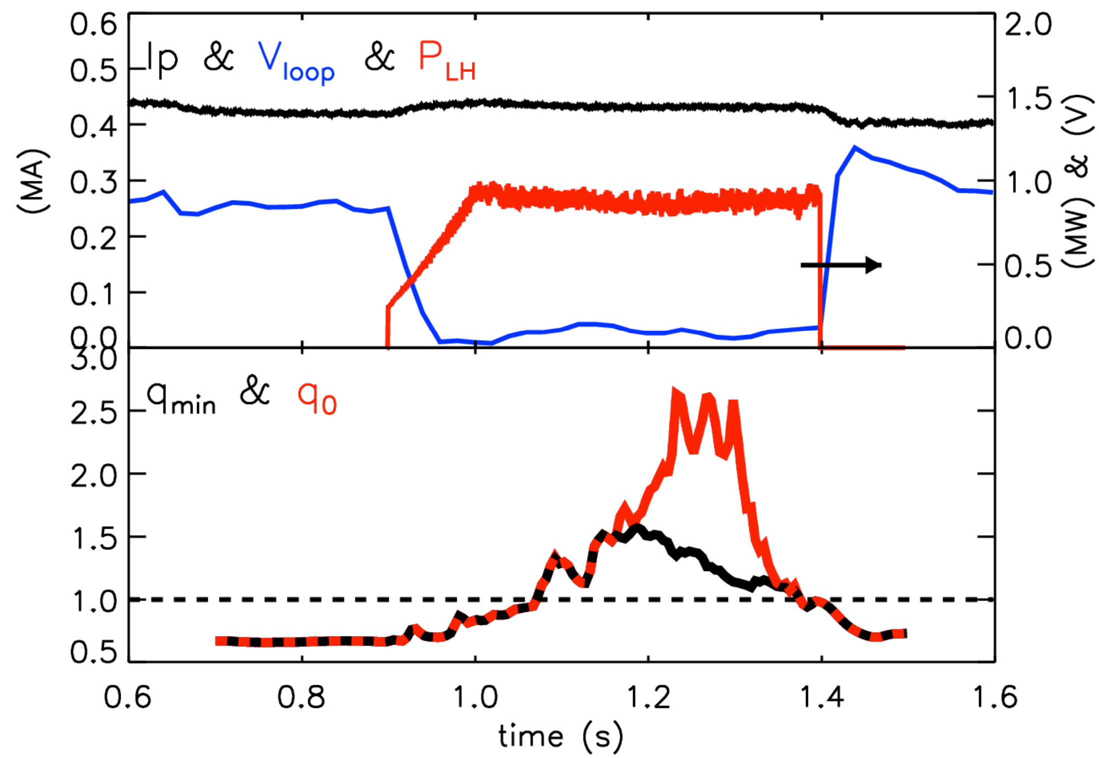
Higher $N_{//}$ (1.9) was used to move the power deposition outward.

ITB transition after J_{tor}(r) evolved in T_e(r) but neither in T_i(r) nor in n_e(r)

m=2/n=1 MHD activities leads the ITB collapse. Will be studied in detail by using 5th SX diode array.

TRANSP/LCS predicts current profile evolution well





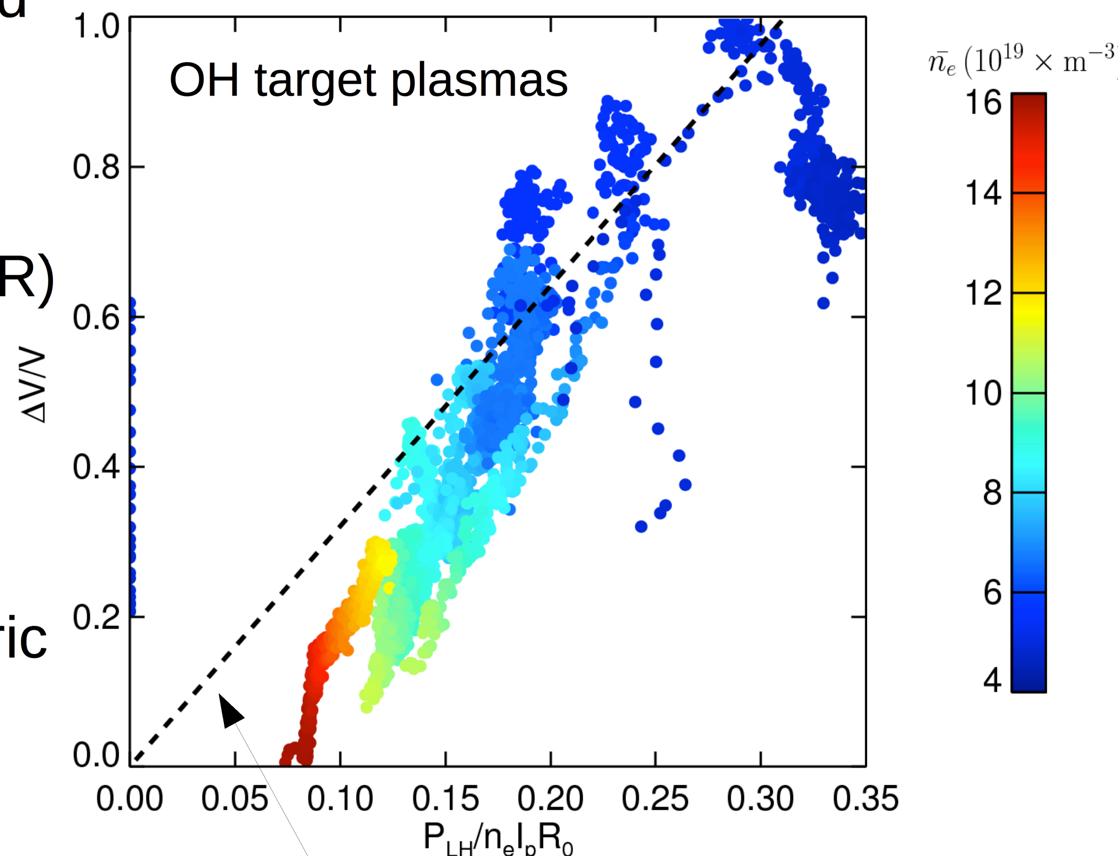
TRANSP/LSC (ray tracing + 1D FP model) was used to calculate the current profile evolution.

Comparison with EFIT reconstruction constrained by MSE/pressure measurements show good agreement.

Shear reversal after 1.2 s when ITB developed

Approaching AT regime needs LHCD efficiency at higher density, $n_e > 10^{20} m^{-3}$, but.....

- LHCD decreases strongly at high density (the line averaged density of $n_e > 10^{20} m^{-3}$)
  - Loop voltage
  - Hard X ray emissions (HXR)
  - non-thermal ECE
- Not caused by accessibility
- Happens below the traditional "density limit" due to parametric decay instability

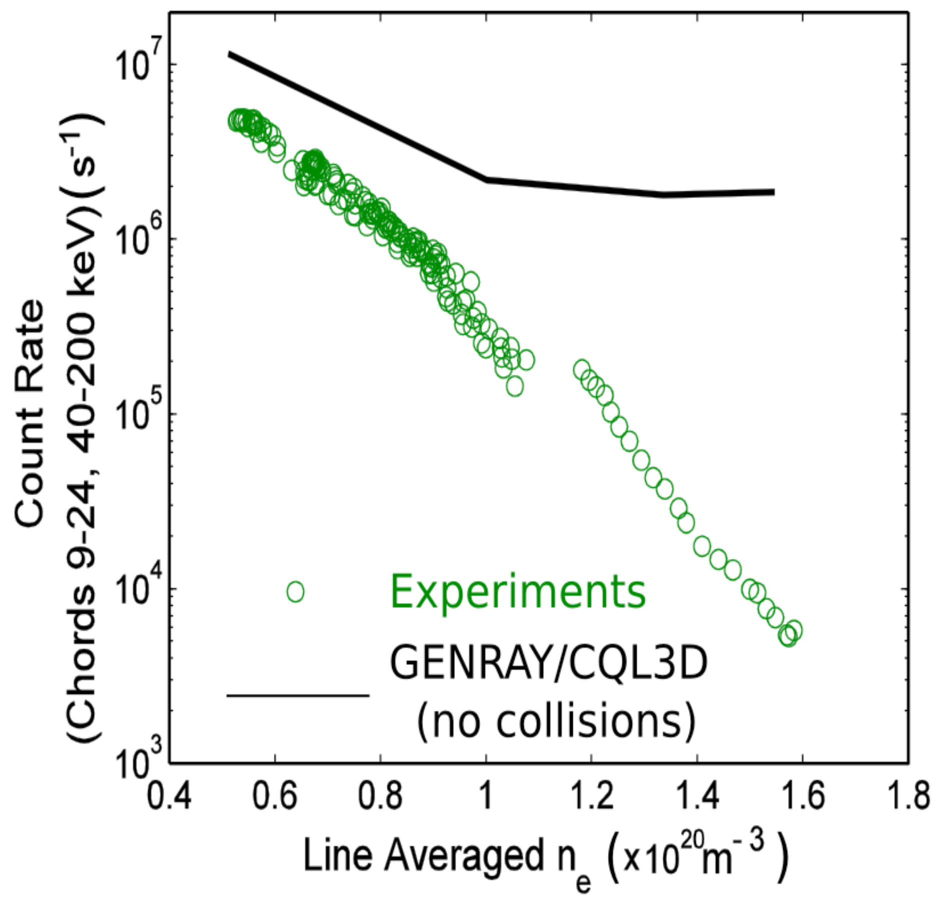


Power scan at low density
(P. Bonoli, et. al., PoP, 2008)

A standard ray tracing + FP does not predict the observation

- HXR count rate
  - Drops as the density increase
  - GENRAY[1]/CQL3D[2] disagrees significantly in $n_e > 10^{20} m^{-3}$

line integrated hard X-ray count rate



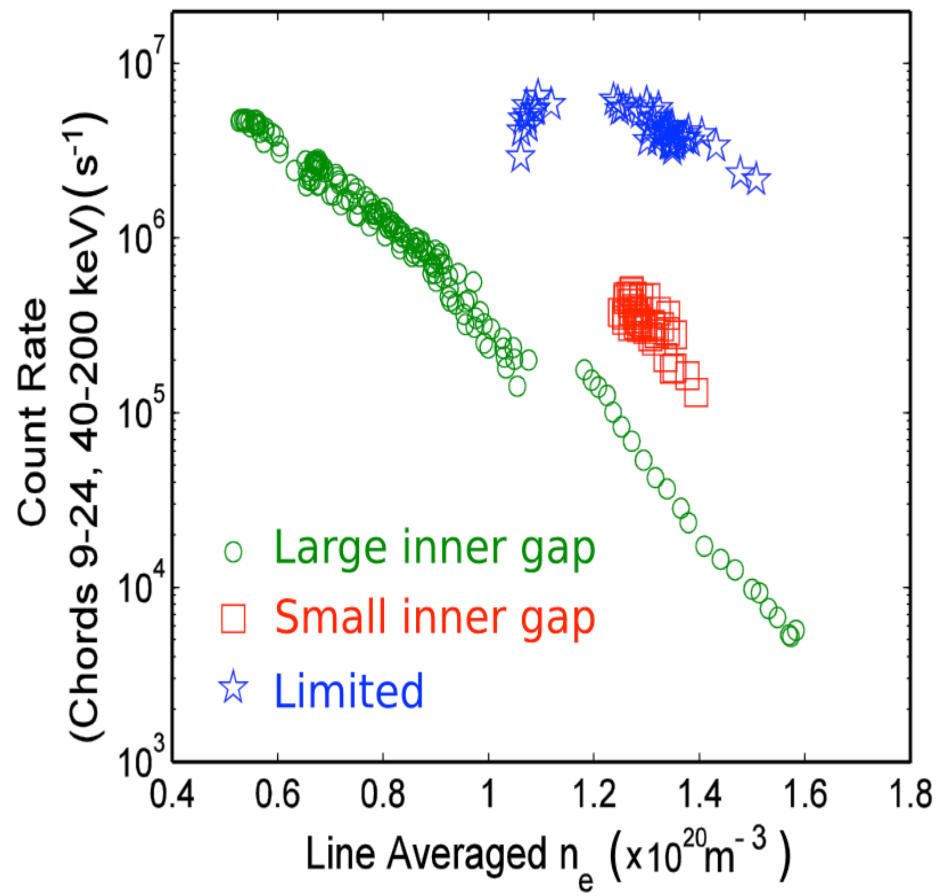
(Wallace, et al., NF, 2011)

1. A. P. Smirnov, et. al., Bull. Amer. Phys. Soc. (1994)
2. R. W. Harvey, et. al., IAEA-TCM, Monreal (1992)

A standard ray tracing + FP does not predict the observation

- HXR count rate
  - Drops as the density increase
  - GENRAY[1]/CQL3D[2] disagrees significantly in $n_e > 10^{20} m^{-3}$
- Recovery of LHCD was observed by changing the plasma configuration
  - Limited shape shows better LHCD
- Observations suggested power dissipation in edge plasmas
- Important for C-Mod AT and ITER LHCD

line integrated hard X-ray count rate



(Wallace, et al., NF, 2011)

1. A. P. Smirnov, et. al., Bull. Amer. Phys. Soc. (1994)
2. R. W. Harvey, et. al., IAEA-TCM, Monreal (1992)

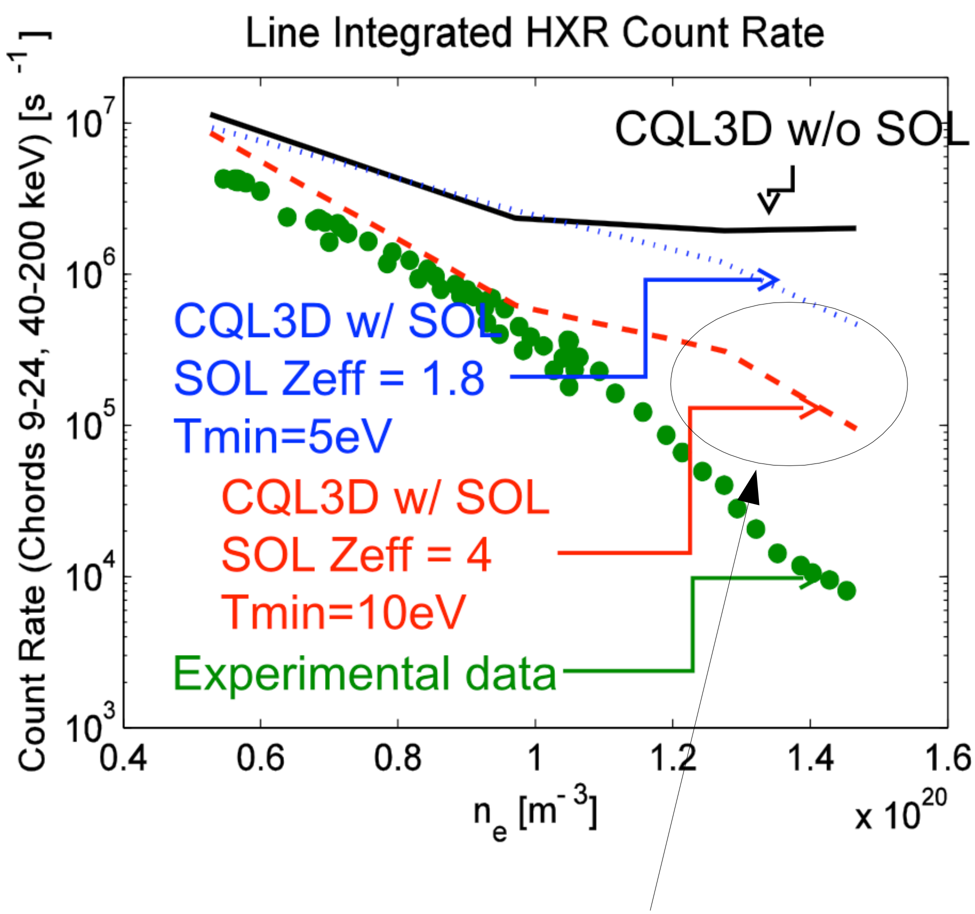
Experiment/modeling efforts have been made to better understand and solve the degradation

Alcator C-Mod

- Expand existing codes to include SOL
  - GENRAY/CQL3D (ray tracing + FP)
    - SOL models
  - LHEAF/VERD (full wave + FP)
    - a physics based SOL model (SOIL)
    - code optimizations to simulate high density experiments
    - See O. Meneghini et. al., in this conference (P2-237)
  - Improved codes both reproduce the experimental trends, but suggest different potential mechanisms.
- Examine PDI/fluctuation induced wave scattering
  - LH reflectometer and edge Langmuir probes
  - See S.G. Baek et. al., in this conference (P1-56)
- Study the density effect using ICRF heated high T_e plasmas

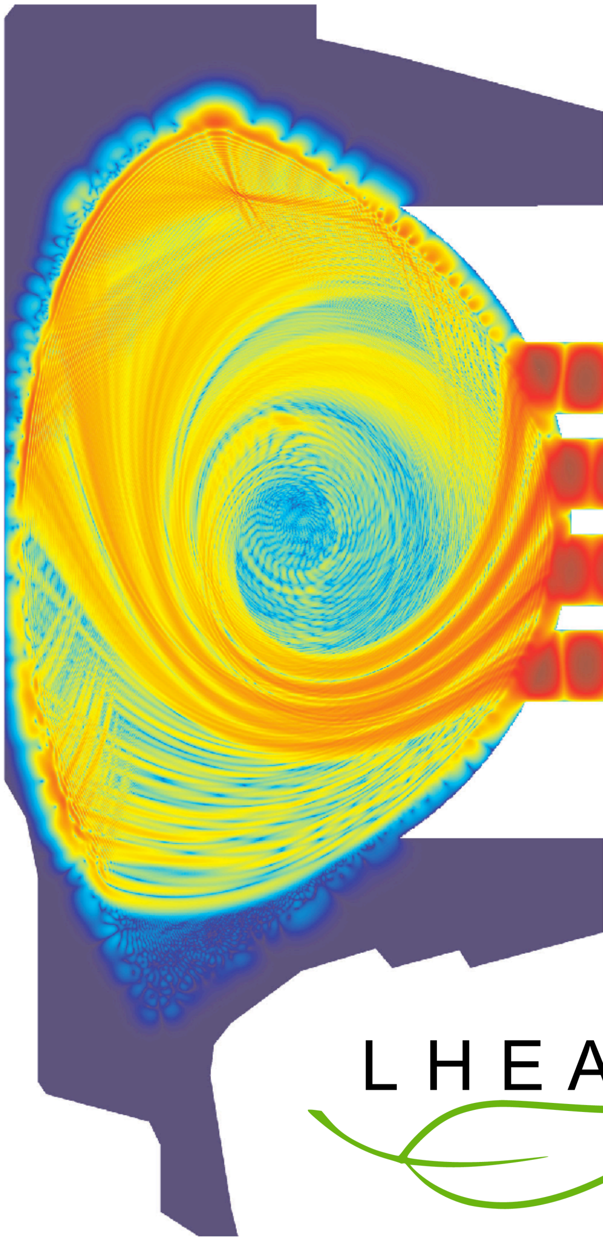
GENRAY/CQL3D with SOL predicts lower HXR, as observed in experiments

- As n_e increases, more and more LH power tends to be absorbed in SOL
  - Lower T_e and wave propagate in large r/a region → weaker Core ELD
  - SOL → more collisional
- Results are sensitive to SOL profiles (e.g. Z_{eff}), and other physics can contribute such as
  - Ionization effect.
  - Full wave effects is not considered.



> 50 % is lost is SOL by collisions !

LHEAF/VERD was used to investigate the effects which may be overlooked in the eikonal approximation



LHEAF : Lower Hybrid wavE Analysis by FEM[1]

- Finite Element Method (FEM)
  - seamless handling of SOL
  - efficient calculation.
- cold plasma + ELD (electron Landau damping)
- very high spacial resolution
  - typical mesh size ~ 0.25 mm)
  - resolves the low phase velocity waves (~ 3·v_{th}) close to the edge.

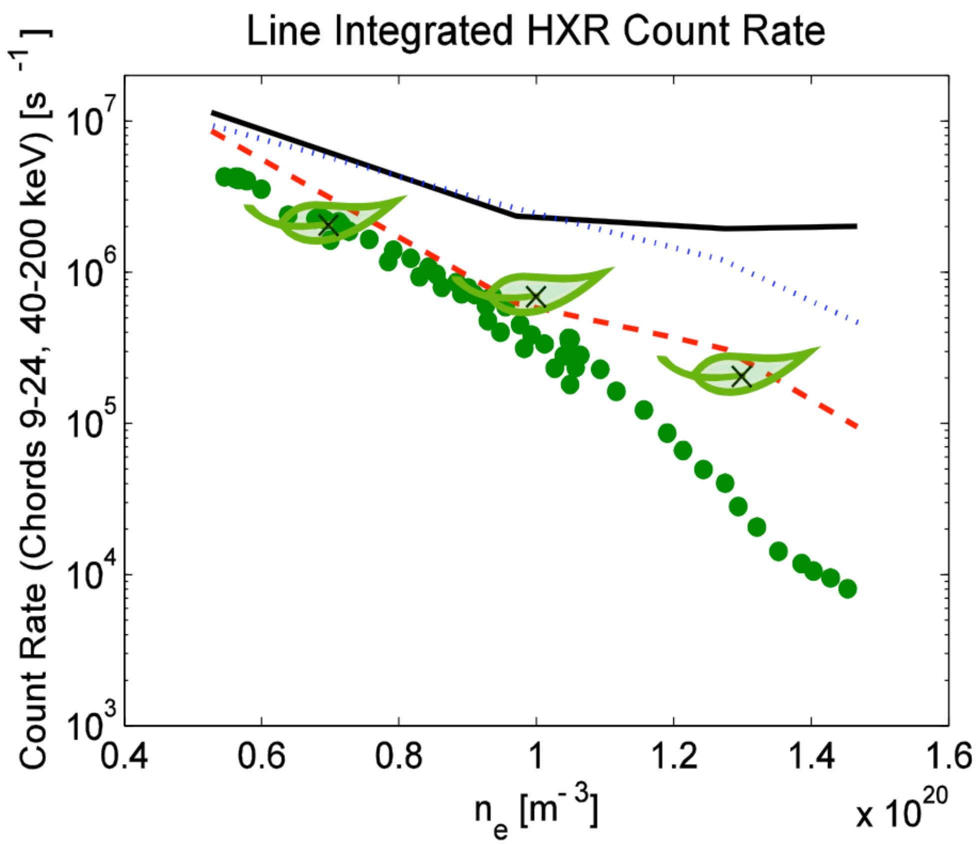
VERD : VElocity Radial Diffusion

- Bounce averaged Fokker-Planck based on zero banana width approx.
- Radial diffusion
- D_{ql} evaluation based on the transit time acceleration.

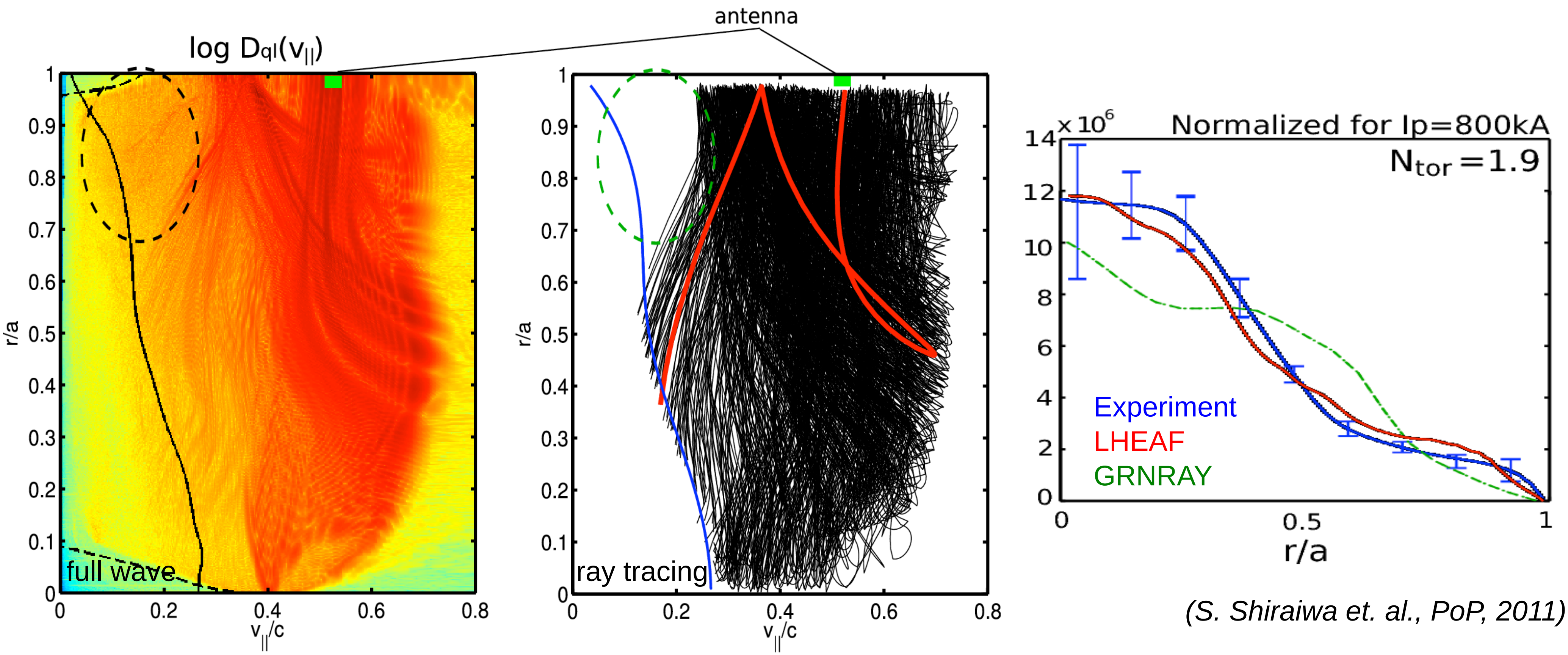
1. O. Meneghini, et. al., PoP, 2009

LHEAF also reproduced the experimental trend. but the collisional loss has relatively small importance

- LHEAF and ray tracing (red case) agree. The collisional loss does not dominate as ray tracing.
  - $P_{loss} < 10\%$
  - $Z_{eff} \sim 1$ is used
- The difference is mostly due to the different collision frequency used in the simulations. With the same collision frequency, the power loss by collisions is similar.
- LHEAF does not need high collision frequency to reproduce the experimental results. Why?



LHEAF consistently predicts larger spectrum broadening than the one predicted by the ray tracing (1)

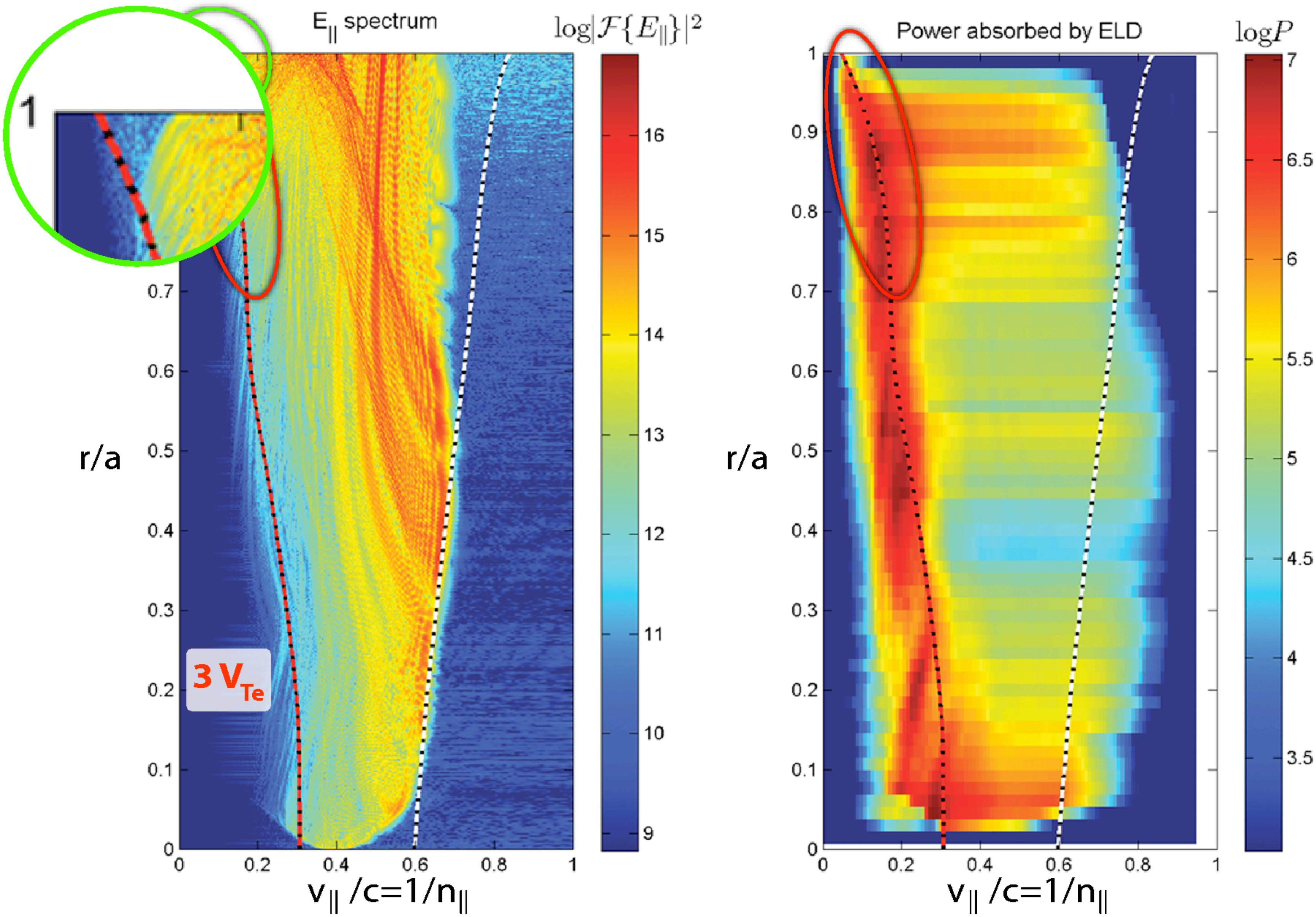


(S. Shiraiwa et. al., PoP, 2011)

Comparison of ray tracing and LHEAF at n_e ~ $0.5 \cdot 10^{20} m^{-3}$

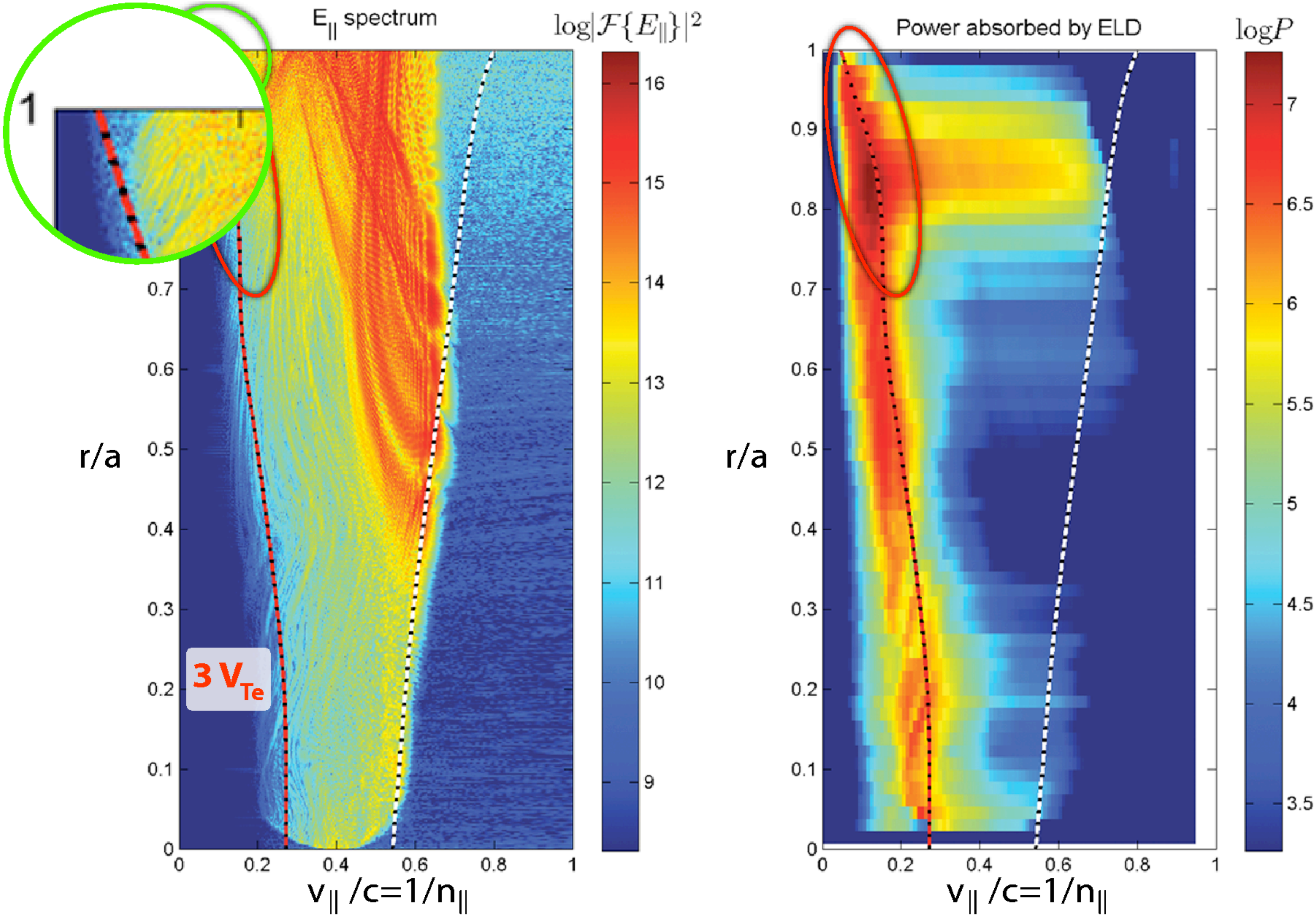
Overall spread of wave spectrum are similar between two codes
Close to the edge, LHEAF predicts a finite wave spectrum while no rays pass thorough the area
→ results in broader power deposition profile and better agreement of the current profile with experiment.
Such a difference was not observed in strong single pass absorption cases.

LHEAF consistently predicts larger spectrum broadening than the one predicted by the ray tracing (2)



$n_e = 0.7 \cdot 10^{20} m^{-3}$

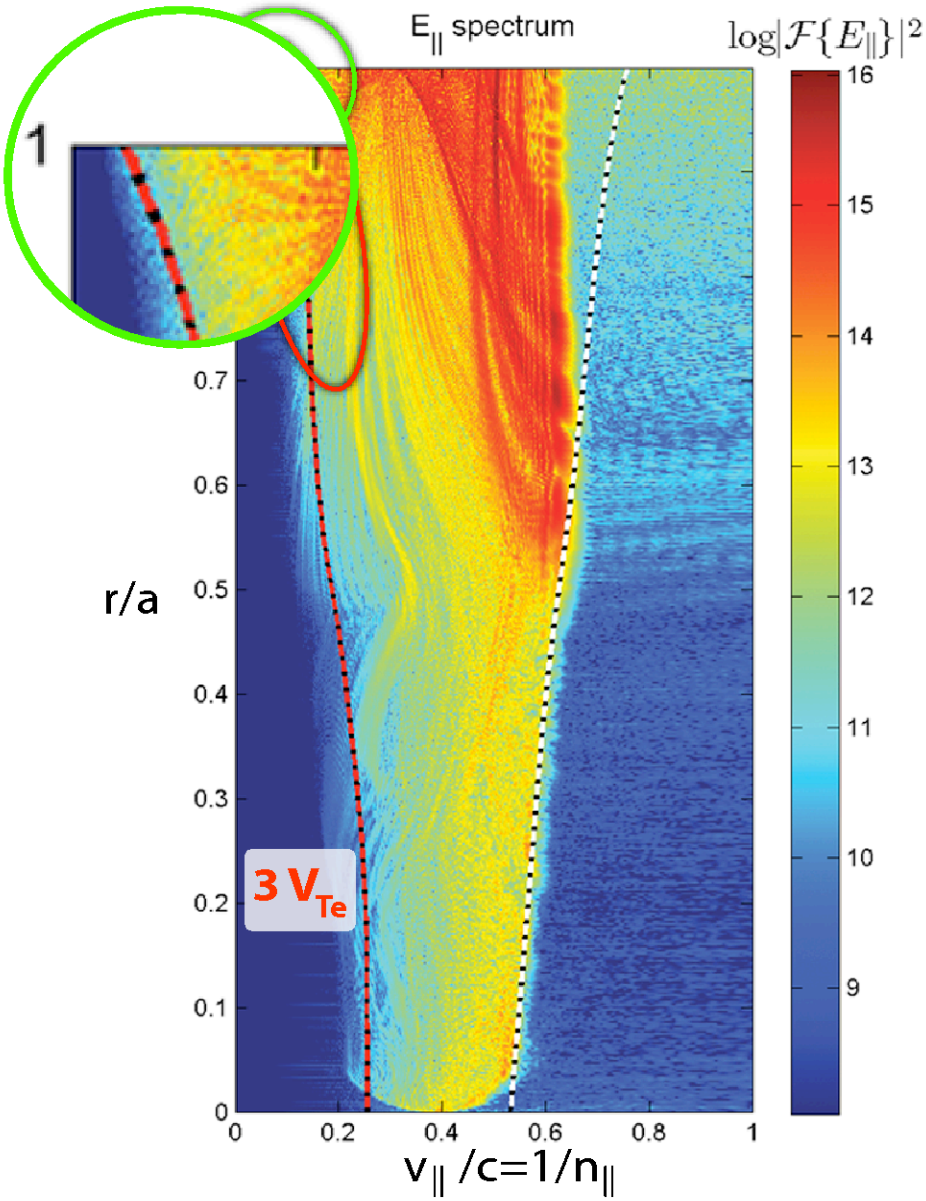
LHEAF consistently predicts larger spectrum broadening than the one predicted by the ray tracing (2)

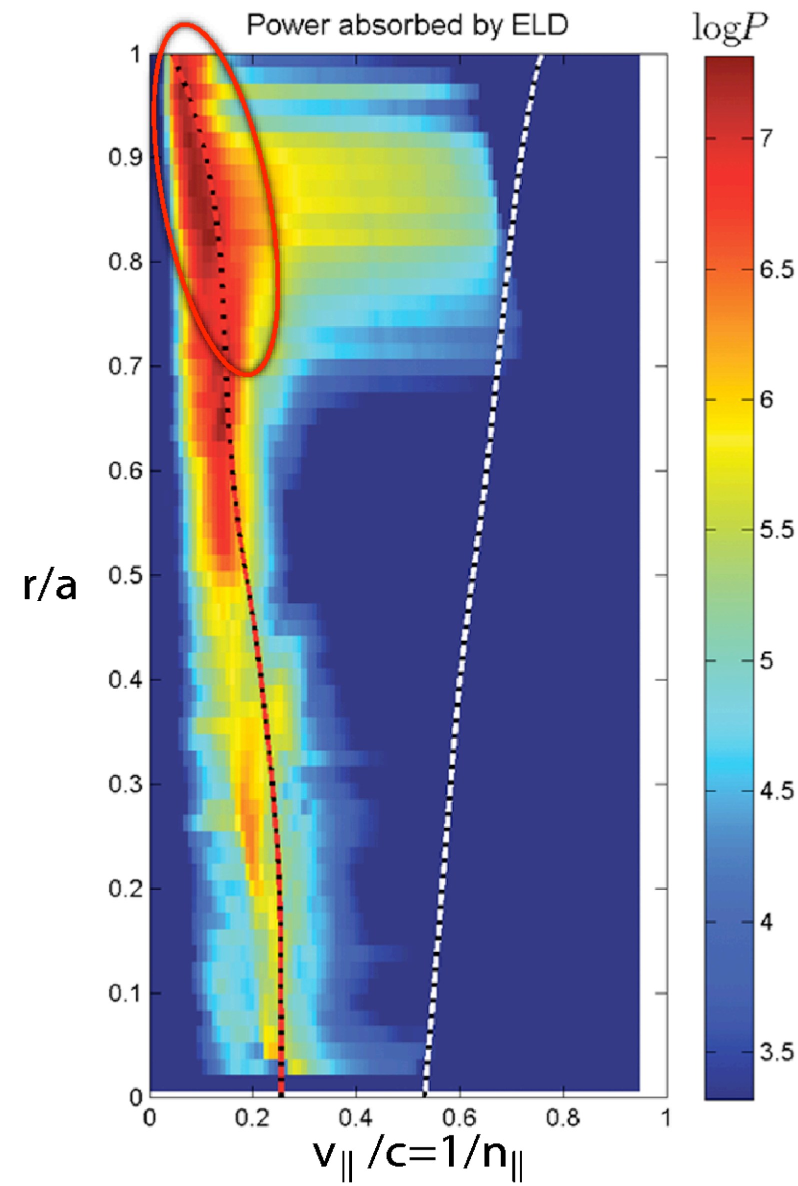


$n_e = 1.0 \cdot 10^{20} m^{-3}$

LHEAF consistently predicts larger spectrum broadening than the one predicted by the ray tracing (2)

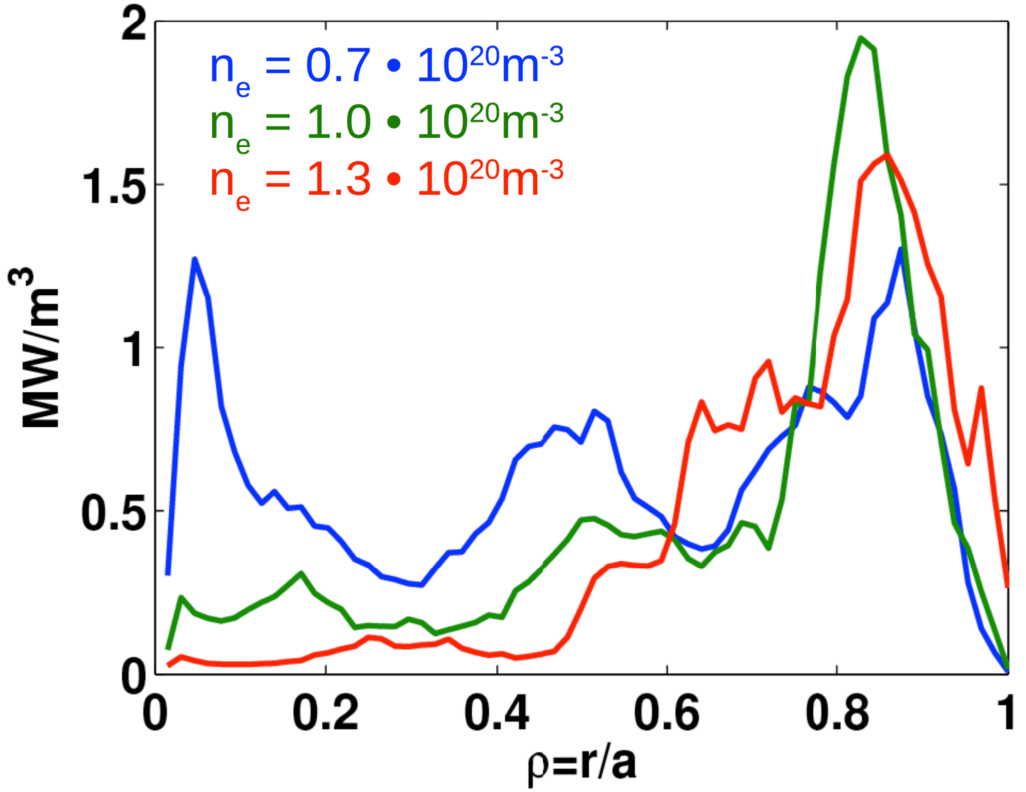
Alcator C-Mod

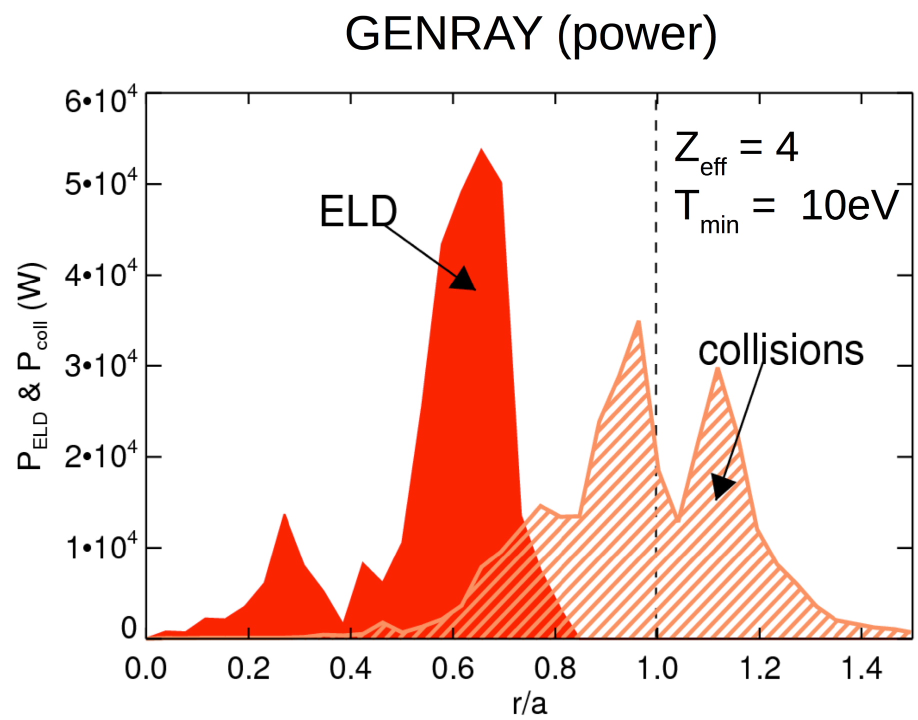




$n_e = 1.3 \bullet 10^{20} m^{-3}$

At high density, the power deposition profile becomes strongly off-axis in LHEAF/VERD

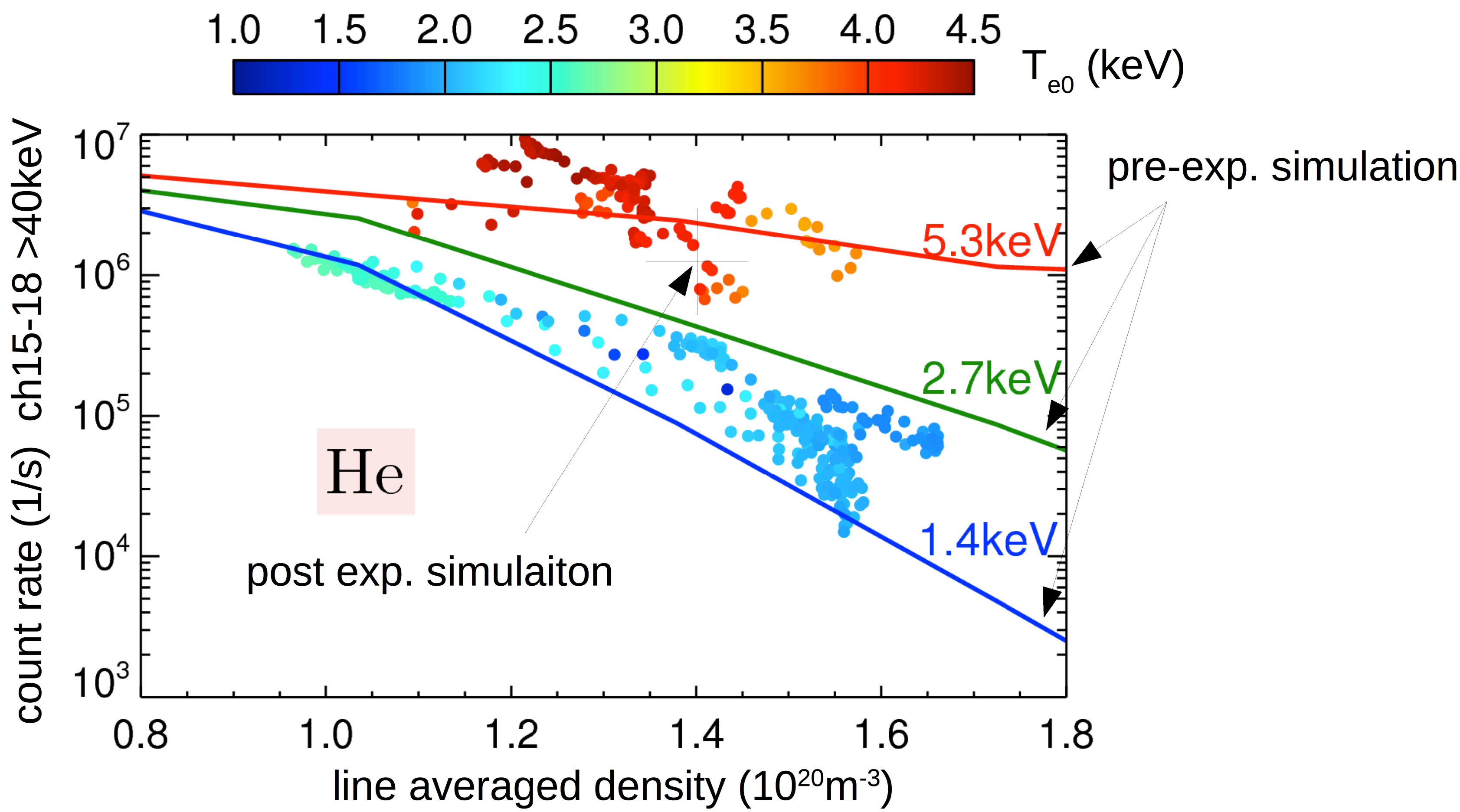




The power deposition profile in ray tracing at high density is centered around 0.8-0.9, while in ray tracing the power deposited via ELD in r/a < 0.8.
Strong off-axis power deposition profiles also occurs in ray tracing too, but at much higher density, typically H-mode case.
Although different mechanisms (collisions, full wave effects) have stronger effect...

- The power deposited inside (r/a < 0.7) is very small
- Both processes become more significant as rays propagate long distance in the plasma.
- Improving single pass absorption may work as a universal solution

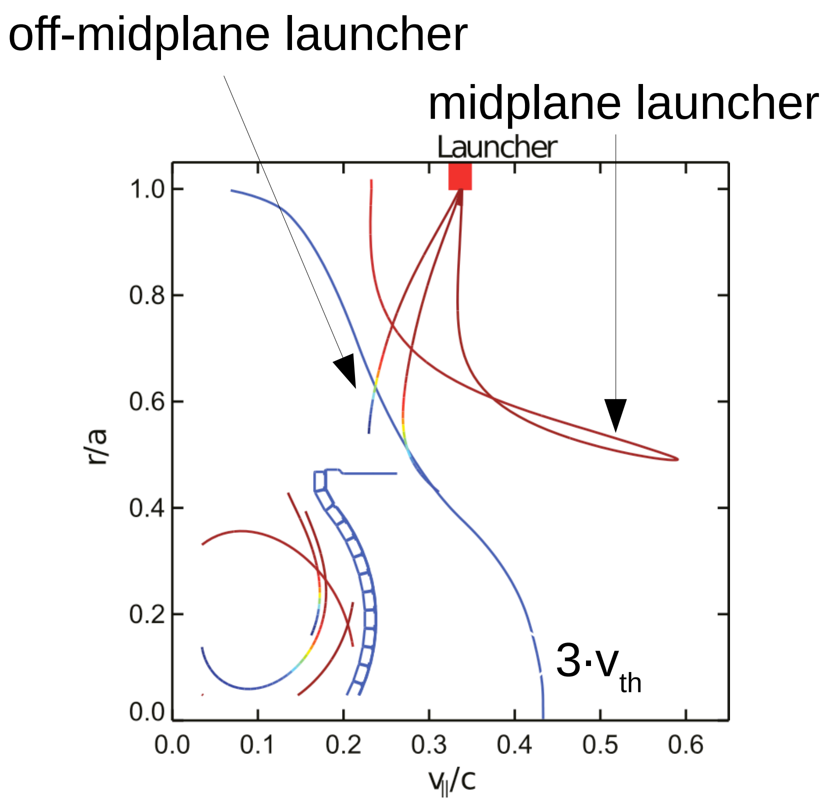
Ray tracing model predicted higher HXR emission for high T_e target plasmas and confirmed by experiments

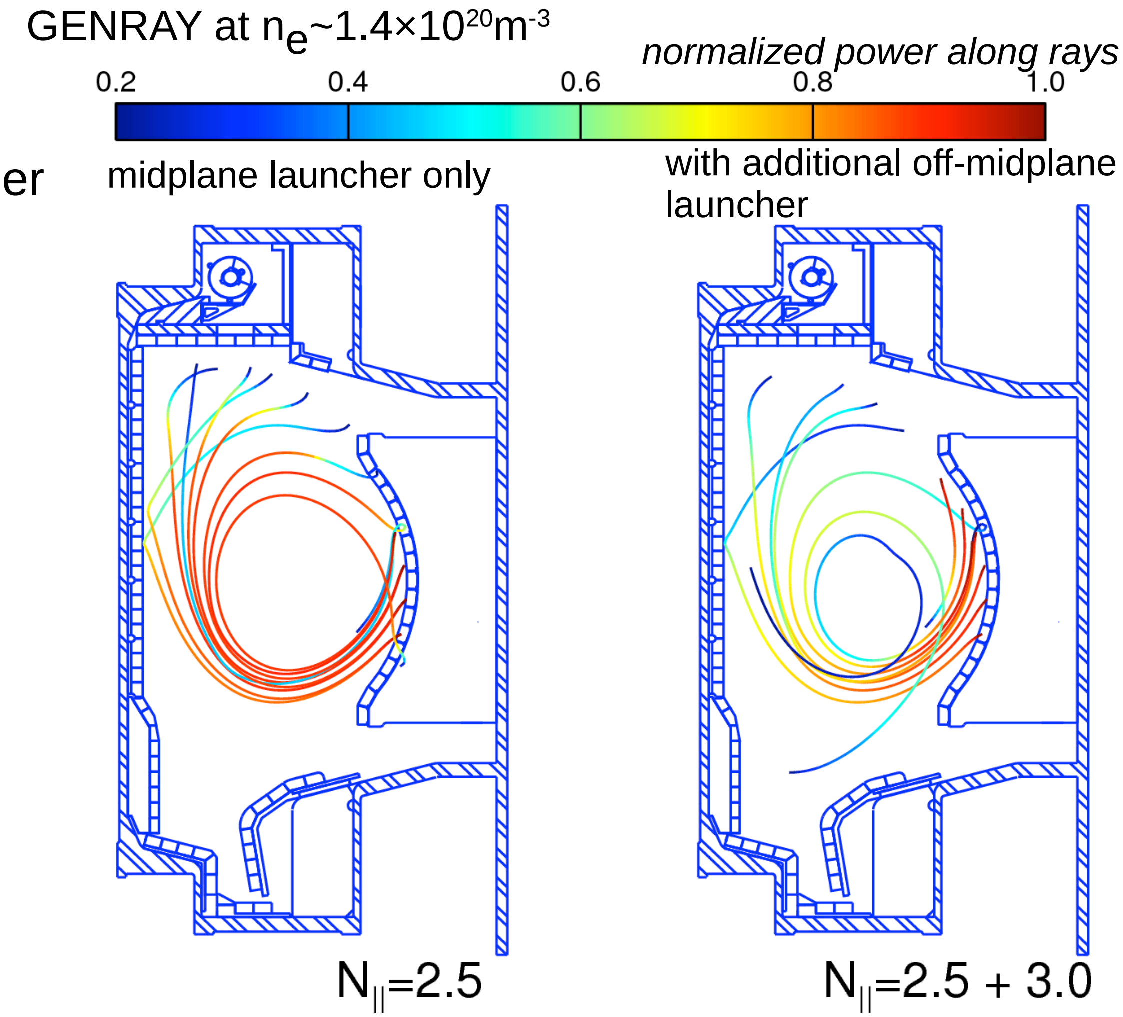


Hot L-mode He discharges with strong electron heating by the mode-conversion ICRF heating show improved HXR emission as compared to cold D discharges.

However, the LH power still deposited far off-axis.

Combination of midplane launcher and off-midplane launcher create velocity space synergy

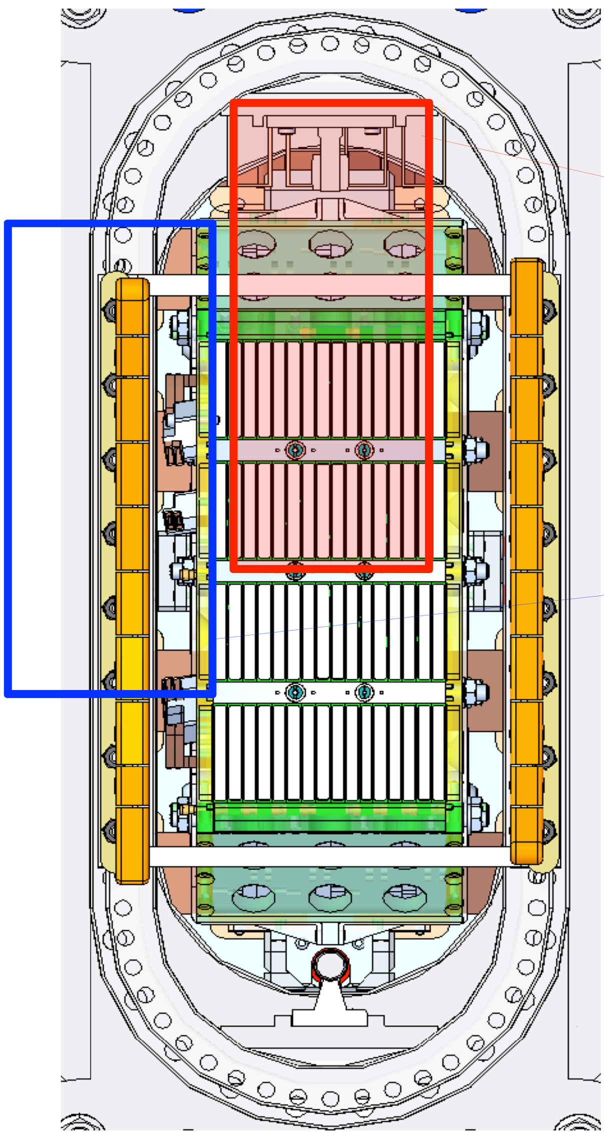


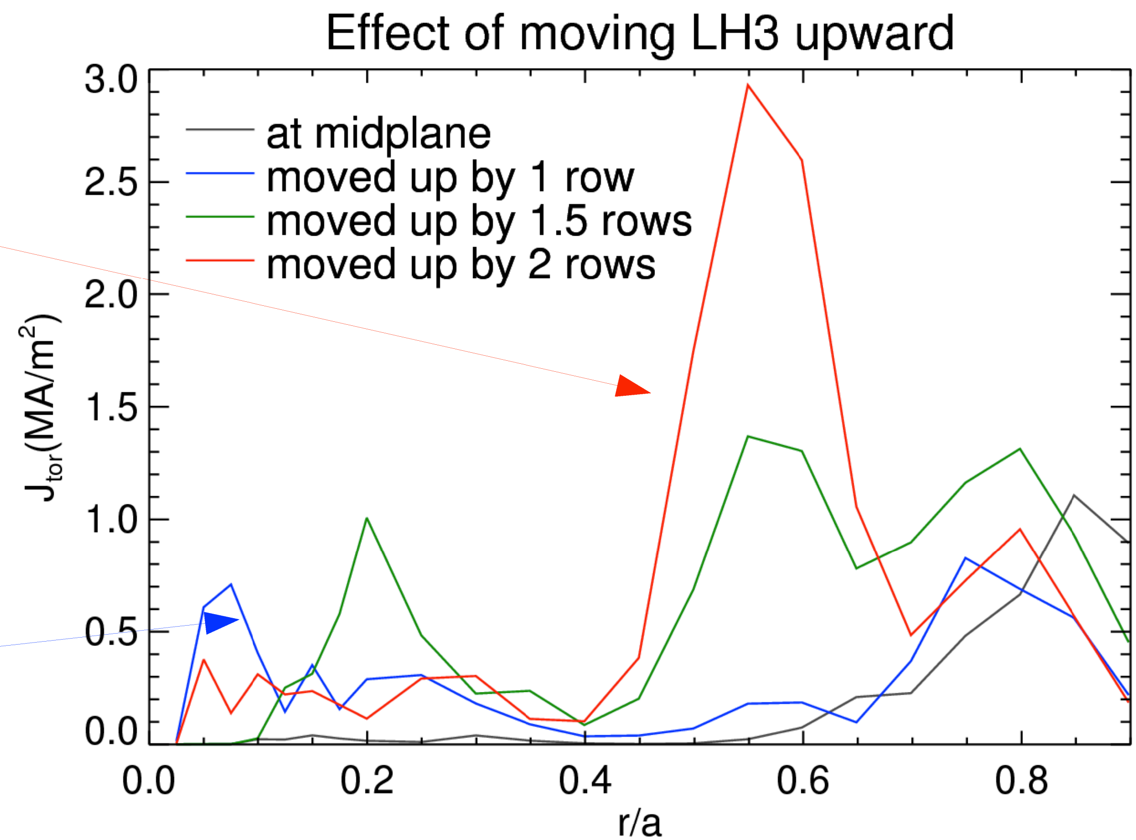


- The LH waves launched from off-midplane experience strong up-shift and are absorbed by ELD during the first pass to the core, thus generating seed electrons.
- These seeds are accelerated by the LH waves launched from midplane, enhancing overall single pass absorption.
- Previous experiments on PLT[1] and JT-60[2], not yet tested at high density

1, S. BERNABEI, NF, 1986 2, S. IDE, NF, 1996

Additional LH launcher shifted by two rows upward is under consideration





Together with the current midplane launcher, the additional off-midplane launcher allows for good LHCD at n_e~$1.4\times10^{20}m^{-3}$

Summary/Conclusions

Demonstration of fully non-inductive RS plasmas by off-axis LHCD at moderate density

- n_e~0.55x10^{20} m^{-3}, Ip ~ 500 kA, B_φ=5.4 T
- CD efficiency :η ($\equiv n_e I_{LH} R_0/P_{LH}$) =2.0 – 2.5x$10^{19}$ $AW^{-1}m^{-2}$
- ITB development in T_e

Advanced wave simulations to better understand how the LH wave behaves at higher density

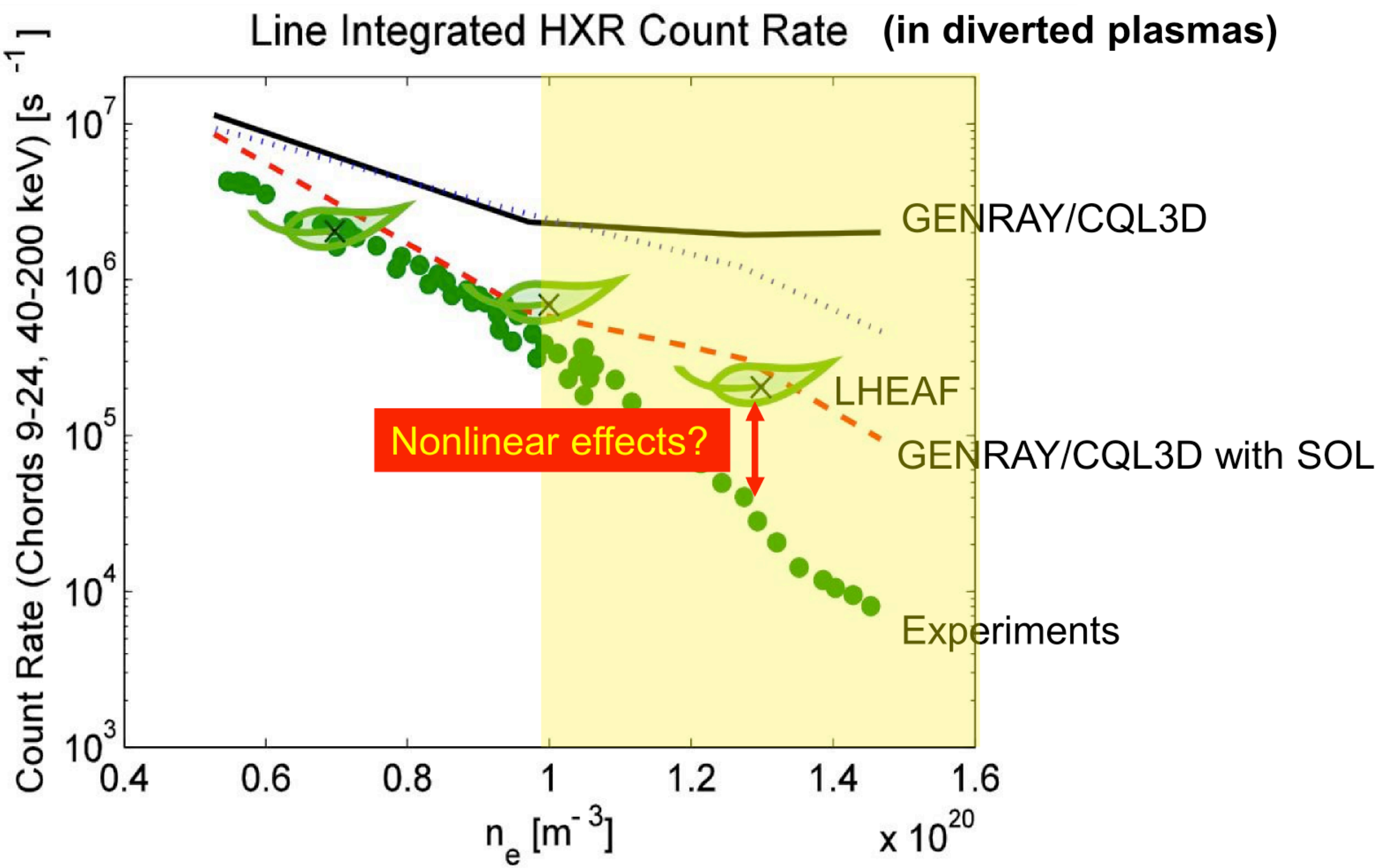
- Absorption close to the edge becomes more significant as the density increases
- LHEAF/VERD predicts that full wave effects spread the spectrum even wider than what is expected from ray-tracing
- Both models suggest the observed degradation is intrinsic to the multi-pass absorption regime.
- ITER is in the strong single pass absorption regime, although the prompt loss in front of launcher may be still an issue.

Additional off-midplane launcher planned in 2012-13

- Double the LHCD power
- Velocity space synergy improves single pass absorption and deposits the power in the region suitable for AT scenarios

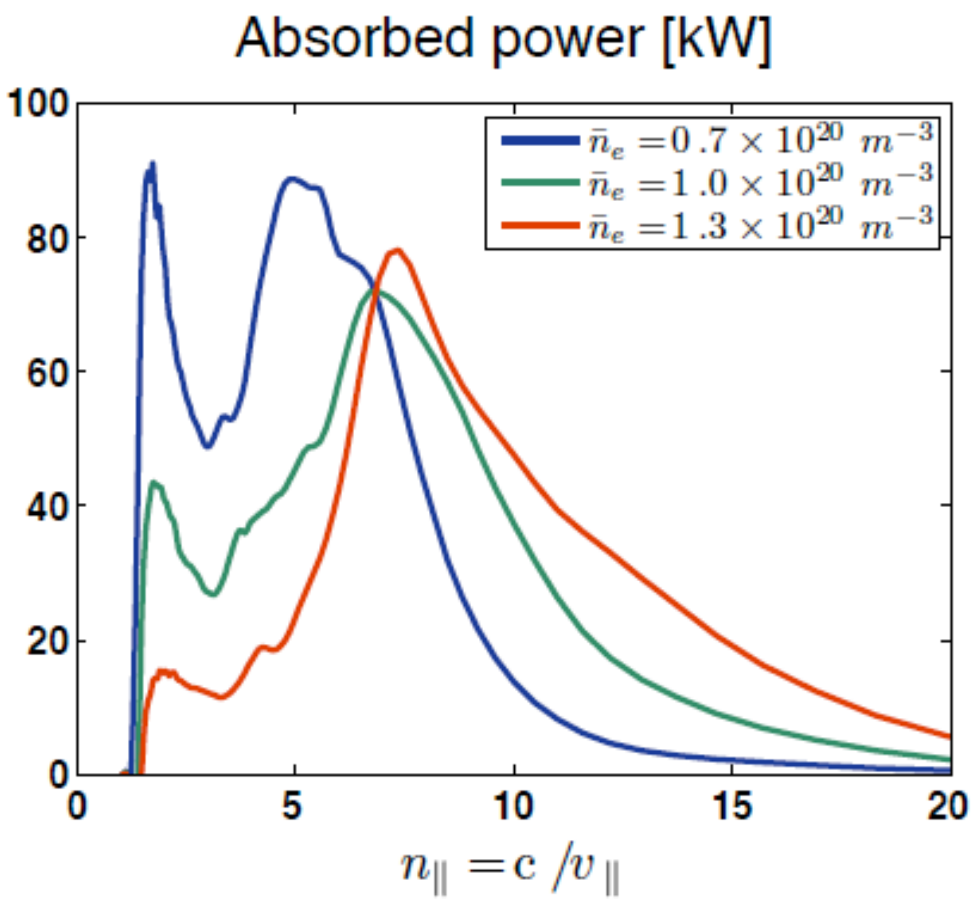
Extra slides

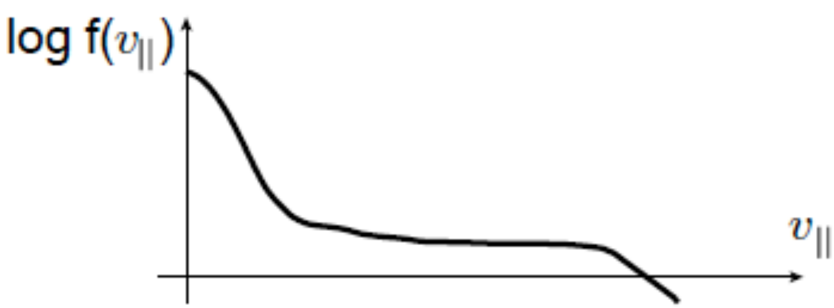
Nonlinear effects may play an additional role at higher density, given that there exists a discrepancy between experiments and simulations.



P1-56

Strong spectral upshift lowers LHCD efficiency





When evaluating LHCD efficiency one can not assume flat plateau from $n_{\parallel\,3Th} < n_{\parallel} < n_{\parallel \text{launched}}$

$$\eta_{LH} = \frac{j}{P} \propto \frac{1}{n_e n_{\parallel}^2}$$

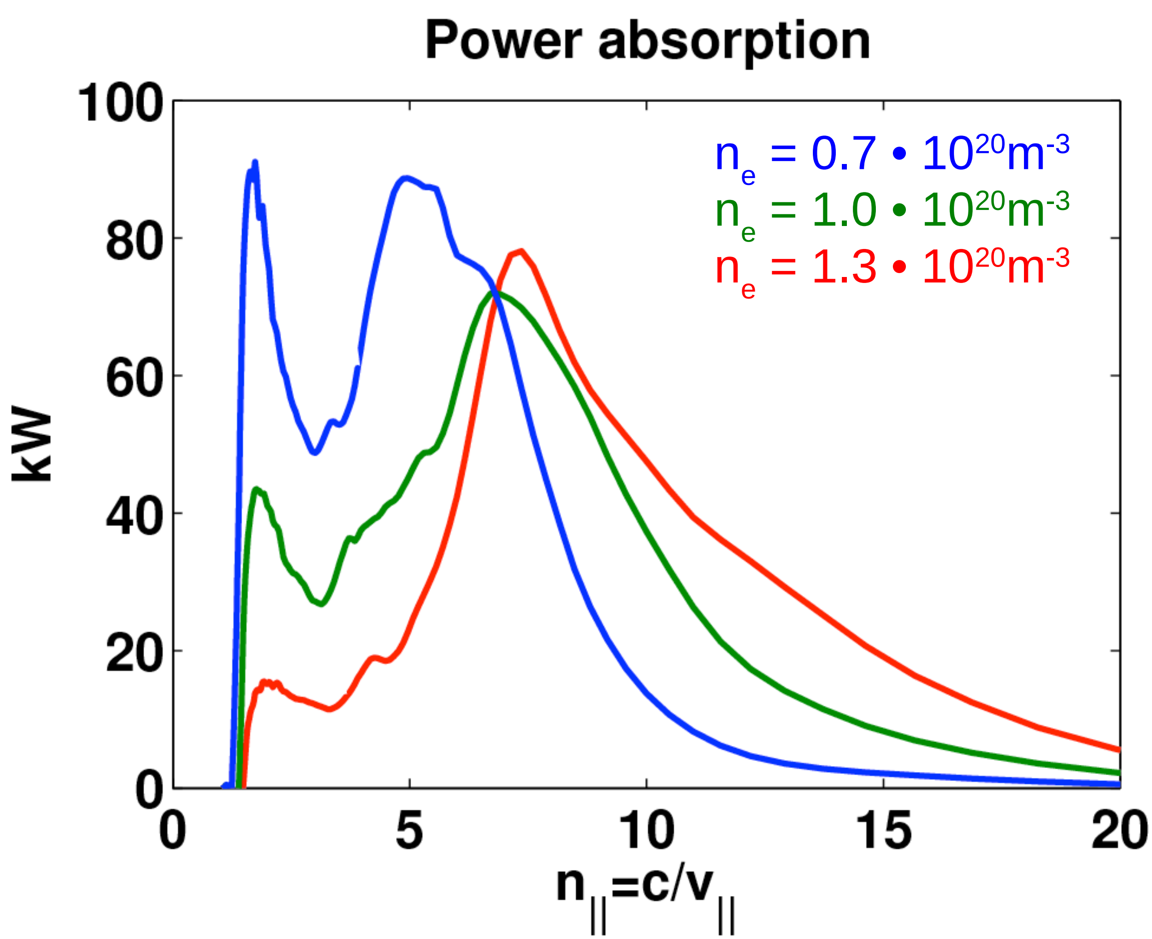
- At larger radii the power density is lower, and plateau is not fully developped
- The $n_{\parallel}$ at which waves interact increases for higher densities

Solutions:

- Move damping more in the core
- Shoot more power

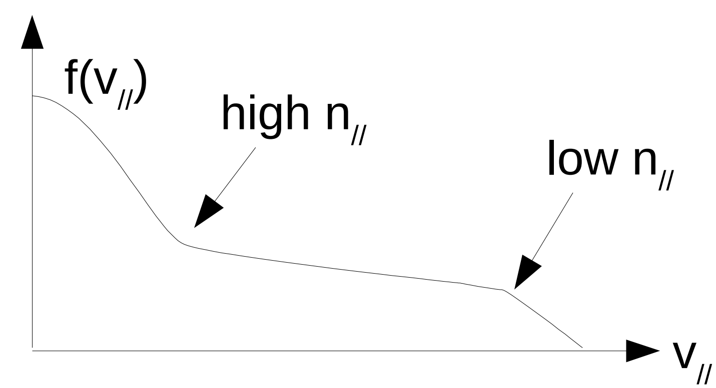
P2-237

Absorption profile in the velocity space suggests approaches to improve the LHCD at high density



As the density increases...

- High $n_{//}$ peaks moves to higher $n_{//}$
- Low $n_{//}$ peaks drops



Potential approach

- Need to increase LH power
  - however,
- Move the power deposition inward
  - improve single pass absorption