The Unsolved Problem of the Ubiquitous Spectral Gap in Lower Hybrid Current Drive

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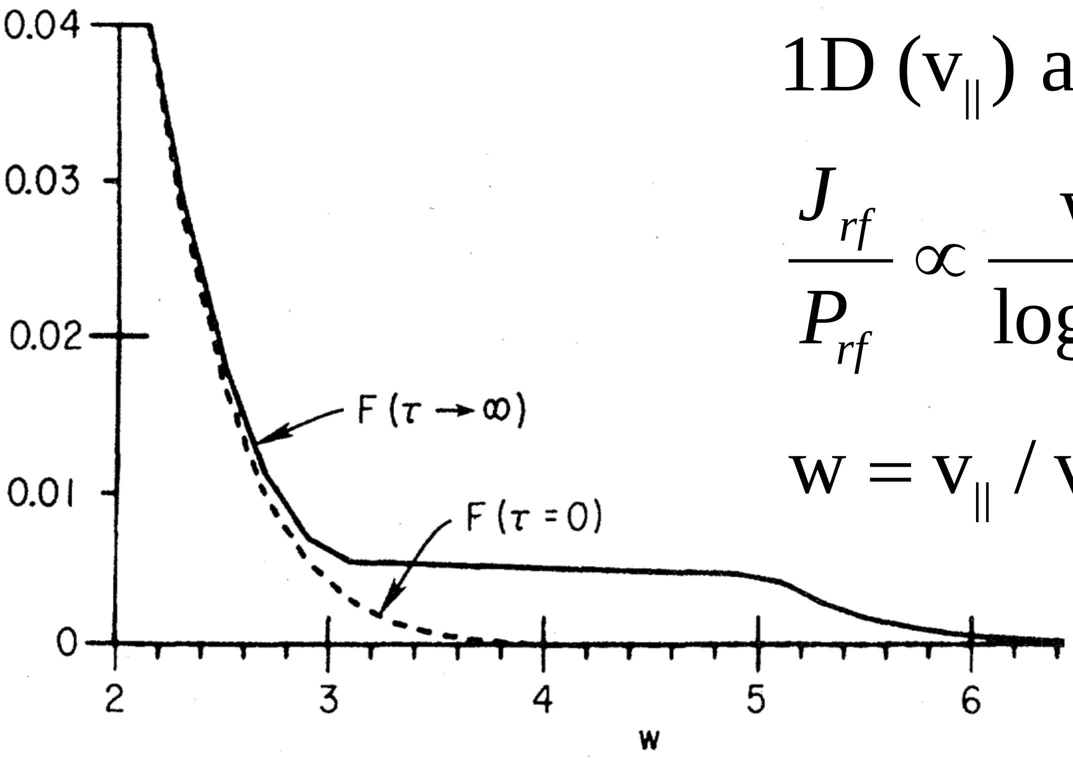
Alcator C-Mod

Outline

- **Early theoretical investigations of the current drive effect with LH waves**
- **Success of early LHCD experiments**
- **Puzzle of the “spectral-gap” and its importance**
- **Theoretical and computational investigations of the spectral-gap**
- **Density limit observed in LHCD experiments and its possible relationship to the spectral-gap.**
- **Summary and suggestions for future work**

Early theoretical work identified RF current drive using driven lower hybrid (LH) waves as especially promising

- **LH waves damp on "tail" electrons at $v_{//} \geq 3v_{te}$ which are relatively collisionless [$\nu \propto 1/(v_{//})^3$].**



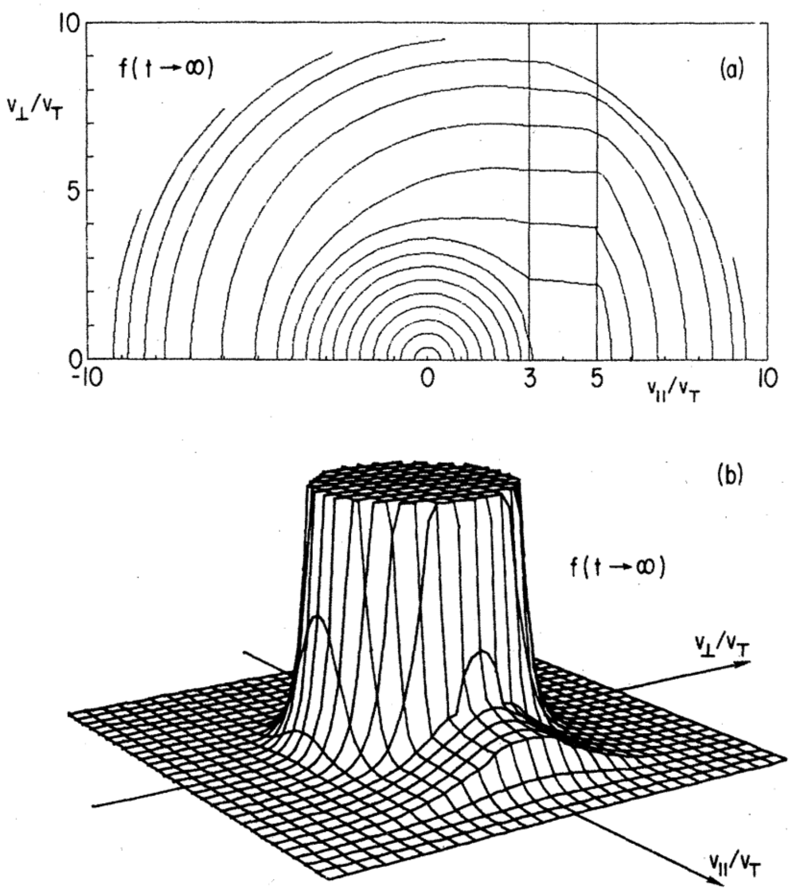
1D ($v_{||}$) analysis:

$$\frac{J_{rf}}{P_{rf}} \propto \frac{w_2^2 - w_1^2}{\log(w_2 / w_1)},$$

$$w = v_{||} / v_{te}, \quad v_{te} = \sqrt{2T_e / m_e}$$

Fisch, PRL (1978)

Subsequent numerical and theoretical analyses revealed 2D ($v_\perp$, $v_{//}$) velocity space effects result in a significantly higher LHCD efficiency (× 1.7)



- **Just as efficient to push electrons in the perpendicular direction as in the parallel direction**

$$\frac{J_{rf}}{P_{rf}} = \left(\frac{1}{5+Z_{eff}}\right)\frac{\mathbf{s}_w \cdot \partial/\partial\mathbf{u}(\mathrm{w}u^3)}{\mathbf{s}_w \cdot (\partial/\partial u)(u^2/2)},$$

$$u^2 = (x^2 + \mathrm{w}^2), \qquad \mathrm{w} = \mathrm{v}_{||}/\mathrm{v}_{te},$$

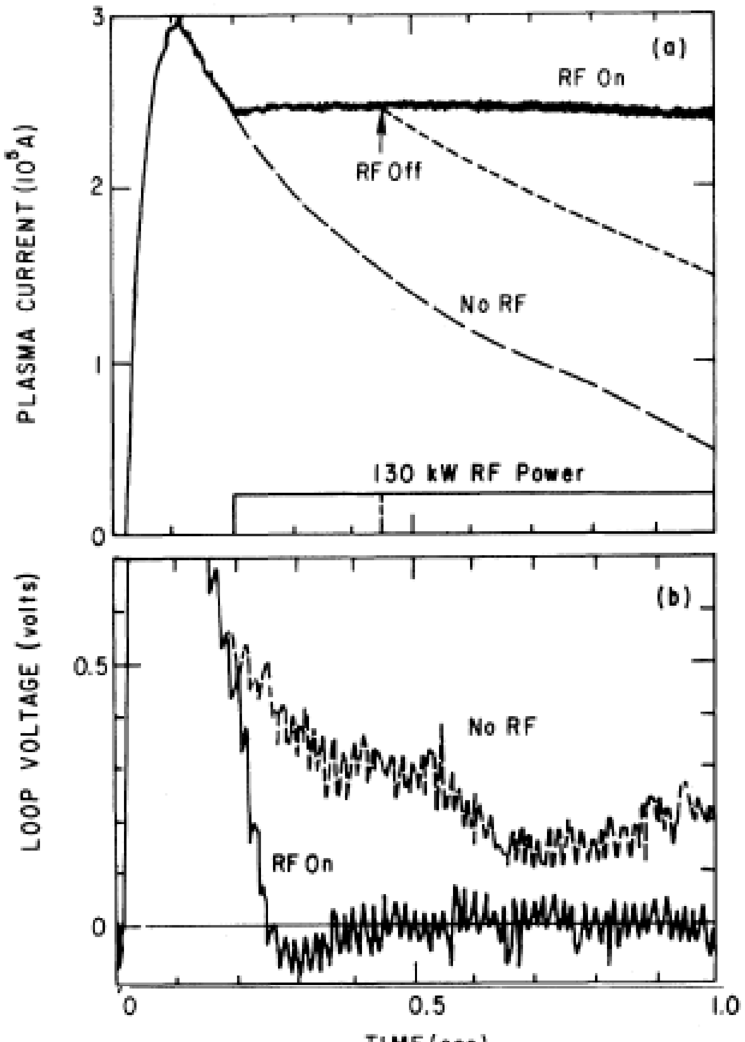
$$x = \mathrm{v}_\perp/\mathrm{v}_{te}$$

Karney & Fisch, PoP (1979)

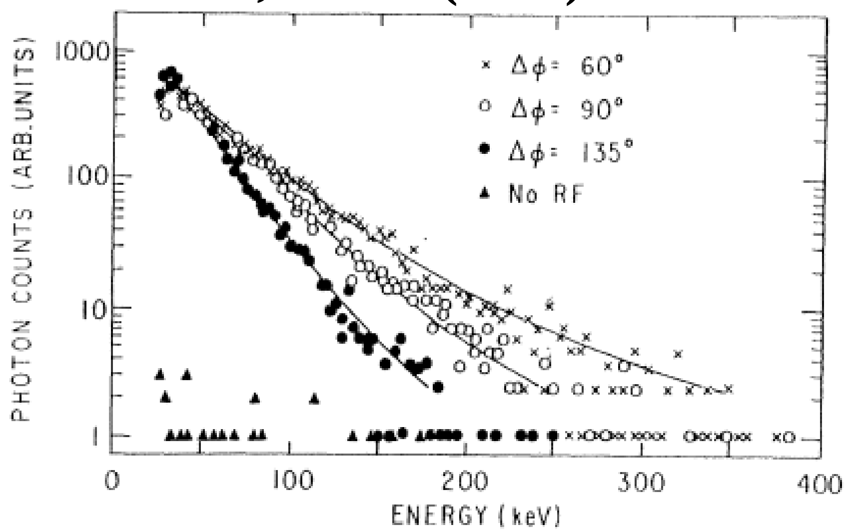
Fisch & Boozer, PRL (1980)

Early experiments motivated by these theoretical predictions were carried out in tokamaks including the PLT device (circular and limited)

Bernabei, PRL (1982)



Hooke, IAEA (1982)



$\bar{n}_e \approx 3.5 \times 10^{18}$ m^{-3}

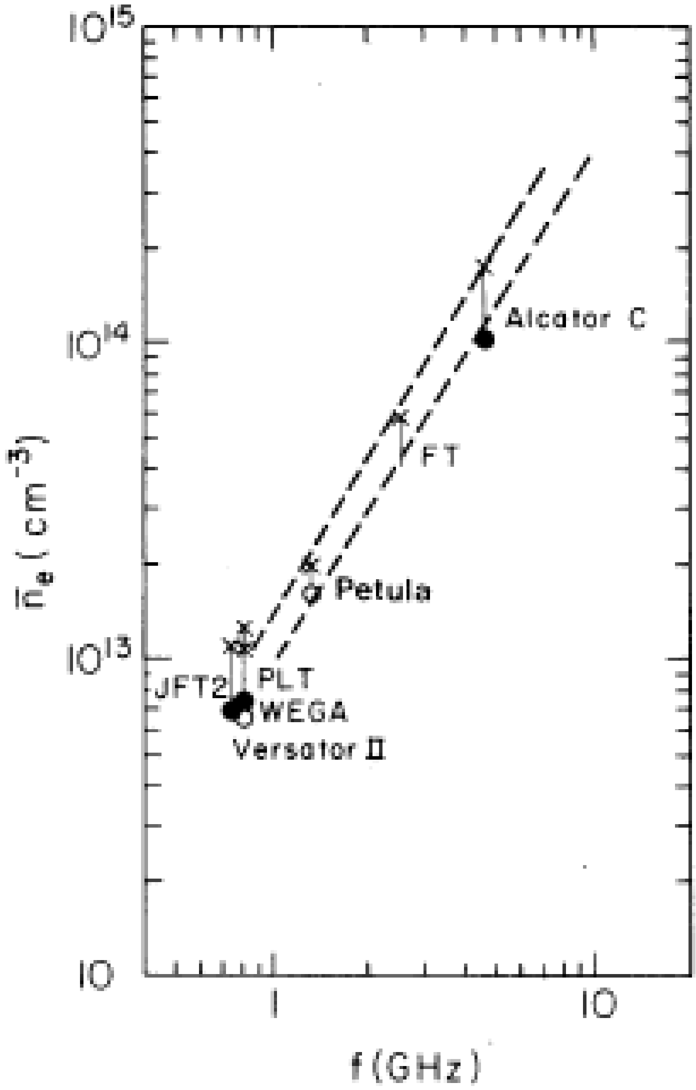
$T_e(0) \sim 1$ keV

$f_0 = 800$ MHz, $n_{//} = 1.5$

$\eta_{CD} \equiv \bar{n}_e \, I_{CD}(A) \, R_0(m) \,/\, P_{RF}(W)$

$\approx 0.85 \times 10^{19}$ (A/W/m^2)

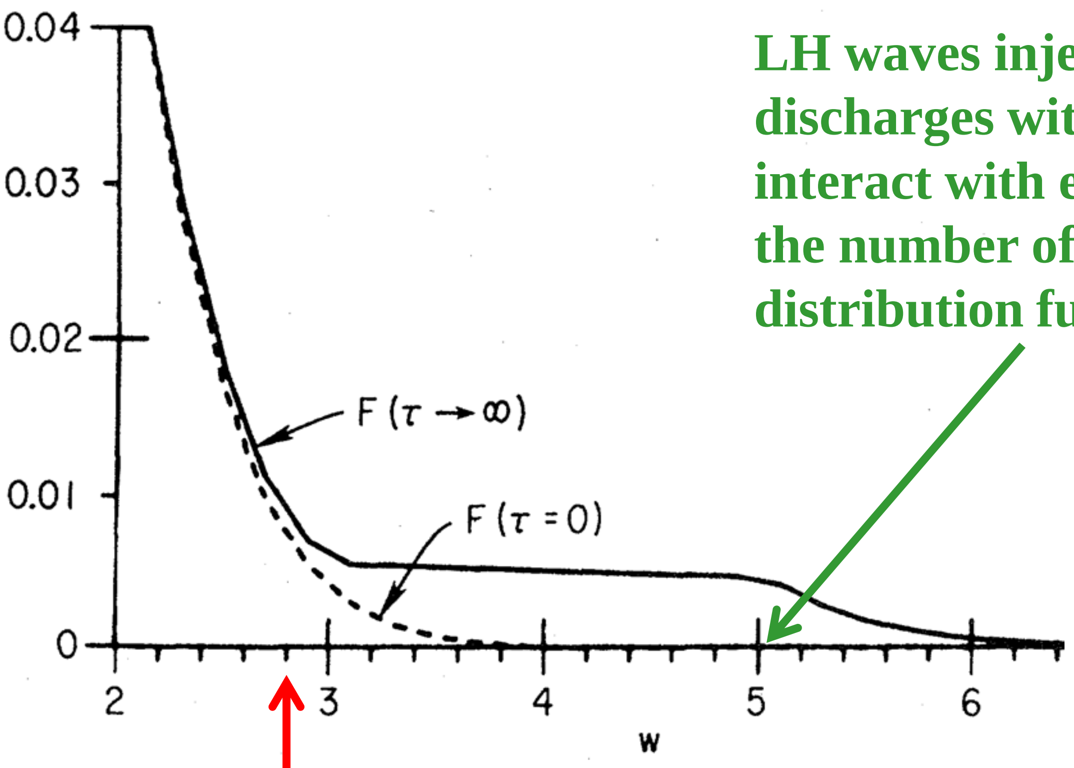
LHCD experiments universally exhibit a "density limit" that scales with source frequency and can be understood in terms of the parametric decay instability (PDI)



Density limit correlates with the onset condition for PDI → $\omega \approx 2 \times \omega_{LH}$ [Porkolab, PoF (1978)].

Porkolab, IEEE Transactions on Plasma Science (1984)

Calculations of the LHCD efficiency (J_{rf} / P_{rf}) are quite accurate, but what about the dissipated LHRF power ?



LH waves injected at $n_{//}$ ~ 1.5 – 1.6 into discharges with $T_e(0)$ ~ 1-2.5 keV should only interact with electrons at $v_{//} \geq 5 \times V_{te}$, where the number of tail electrons in the target distribution function is exponentially small.

But from quasilinear damping theory we know that LH waves damp strong at $v_{//} \approx$ (2.5-3) $\times V_{te}$. Thus there exists a gap in velocity space (the "spectral-gap") between the injected LH wave phase velocity and the phase speeds at which LH waves damp.

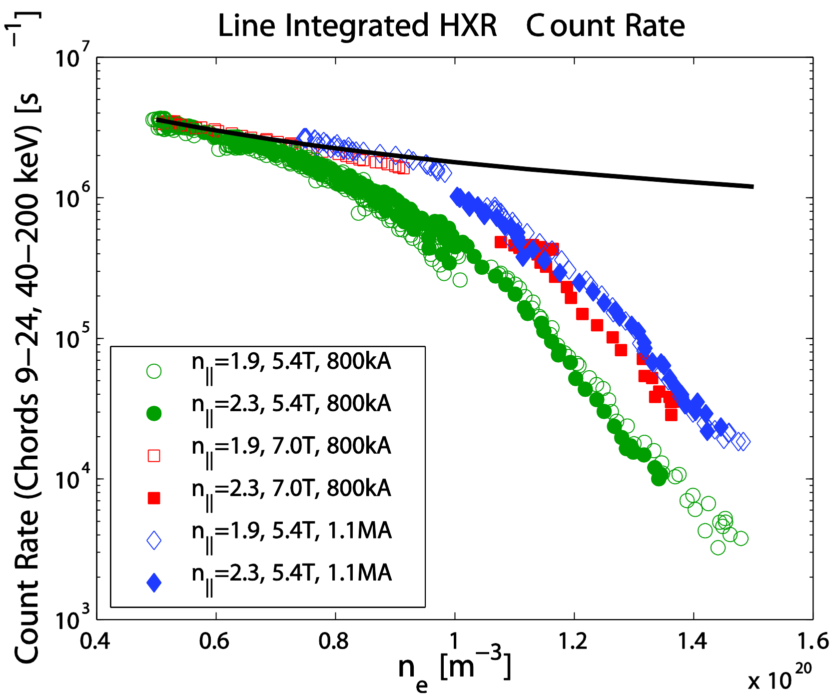
Although the spectral-gap will not exist in burning plasmas such as ITER there are still important reasons to understand the physical mechanism(s) responsible for bridging this gap

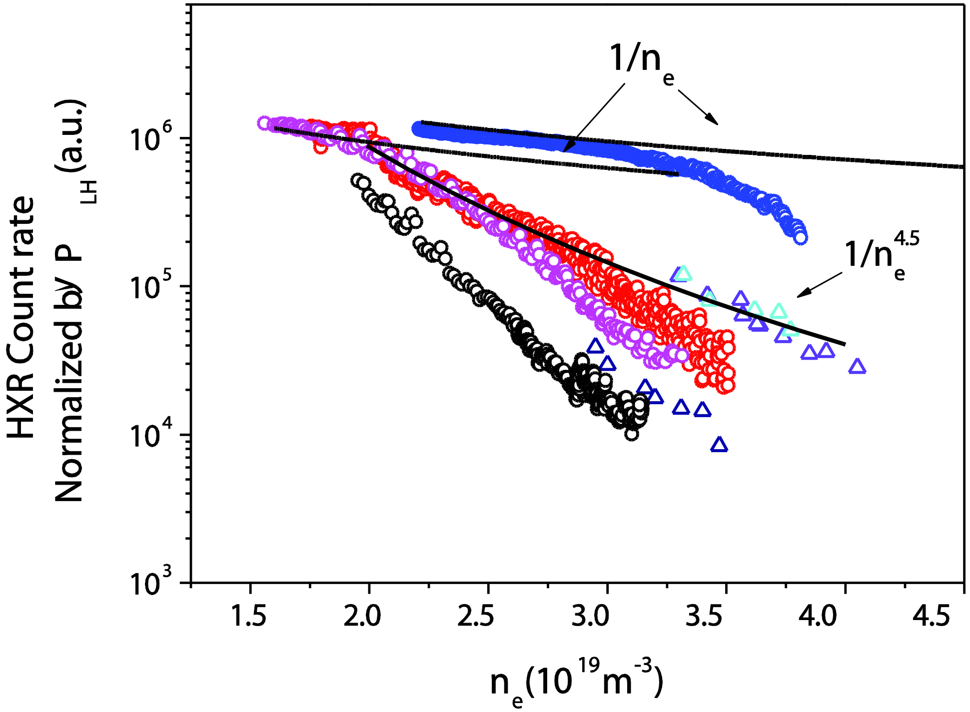
- **If proposed mechanisms for spectral broadening in present day devices are also operative in a burning plasma this may result in wave absorption too near to the edge.**
- **There is some evidence that the presence of the spectral-gap may be responsible for an observed density limit [Wallace, PoP 2010] occurring lower than the "classical" limit corresponding to the onset of PDI** [$\omega \approx 2 \times \omega_{LH}$].

Discharges with lower than expected density limits also suffer from weaker single pass damping as the density is raised → increasing spectral-gap

Alcator C-Mod [Wallace – PoP (2011)]

EAST [Ding – NF (2013)]





Leading candidates for closing the spectral-gap span the breath of linear and nonlinear LH wave theory

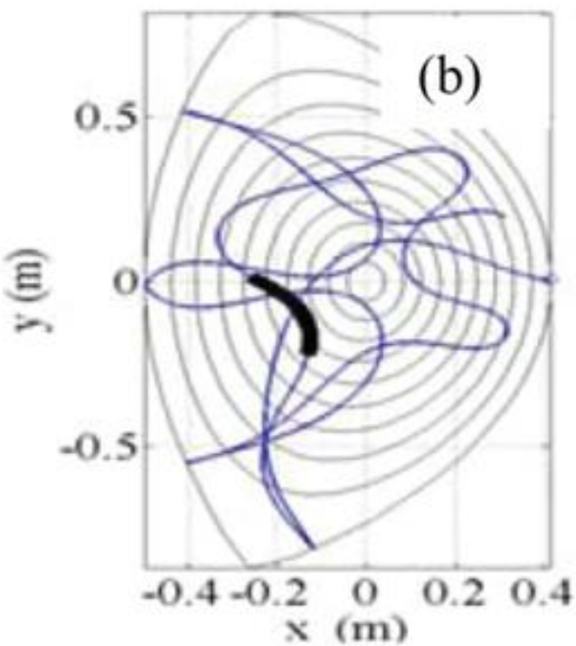
- Toroidally induced increases in the parallel wave number
- Scattering of LH waves from density fluctuations
- Spectral broadening of the LH pump wave from parametric instability
- Full-wave effects such as focusing and diffraction
- NOTE: all of the mechanisms above rely on interactions of the LH wave with the scrape-off layer !
  - This aspect of the problem will be covered by Professor Ron Parker on Wednesday:

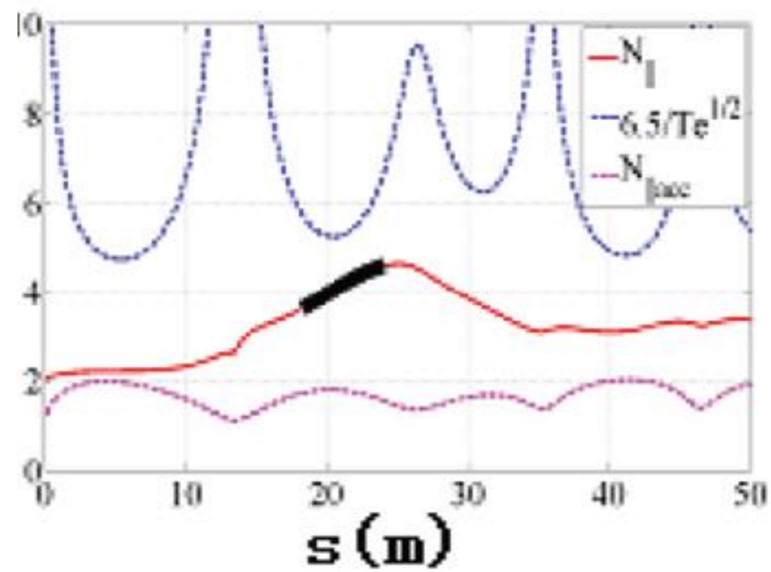
    "Mechanisms for loss of LHCD efficiency at high density"

Toroidally-induced increases in the parallel wavenumber ($k_{//}$) have long been proposed as plausible mechanism for closing the spectral-gap

Variations of the poloidal mode number (m) in toroidal geometry are converted to changes in $k_{//}$ through the poloidal field [Bonoli & Ott, PoF (1982)]

$$k_{\parallel} = \boldsymbol{k} \cdot \boldsymbol{B} / B = \left(\frac{m}{r} \frac{B_\theta}{B} + \frac{n_\phi}{R} \frac{B_\phi}{B} \right)$$

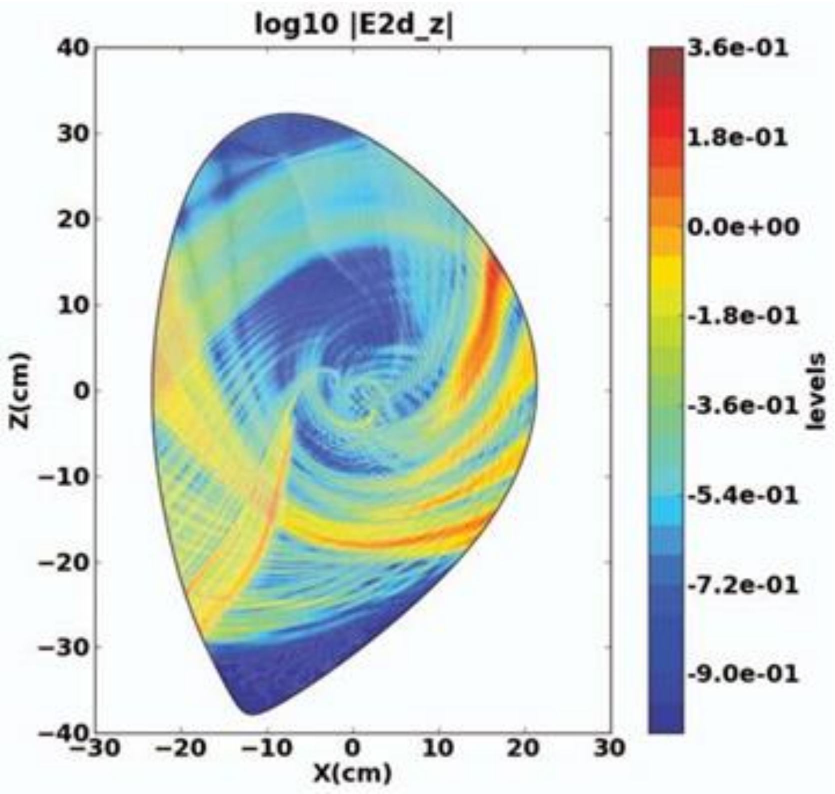


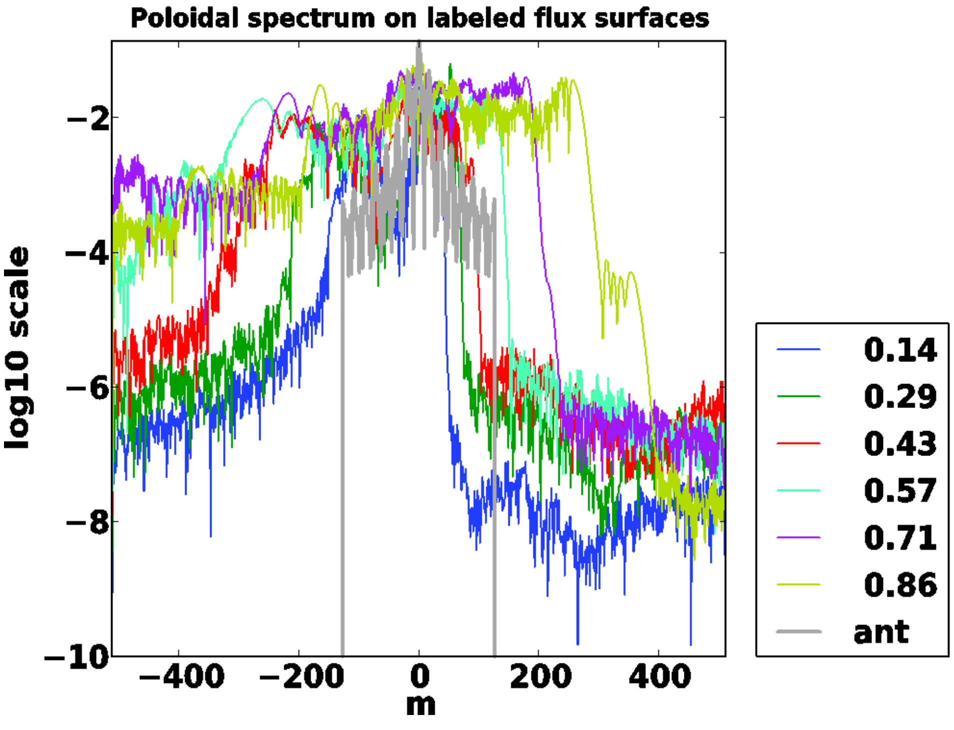


Ray trajectories computed using the C3PO ray tracing code for EAST parameters [Ding, PoP (2011)]

Full-wave LH electromagnetic field simulations have confirmed toroidally induced upshifts in $k_{//}$ seen in ray tracing

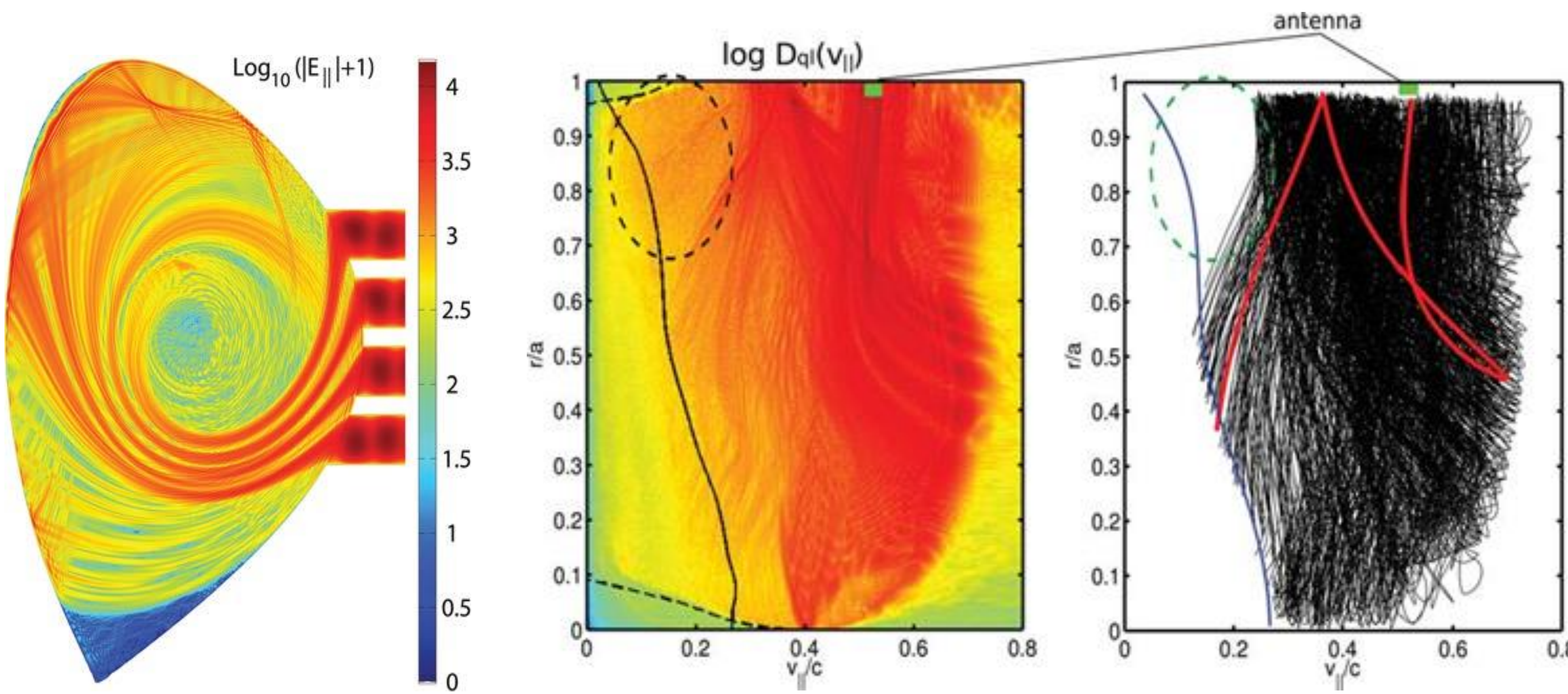
- Results shown for Alcator C-Mod device using a semi-spectral full-wave / Fokker Planck model - TorLH / CQL3D [Wright, PoP (2009)]:
  - Asymmetry in poloidal mode spectrum reflects wave accessibility (left) and electron Landau damping (right).





Full-wave electromagnetic field simulations have also confirmed the existence of large $k_{//}$ upshifts at the plasma edge

- **Results shown for Alcator C-Mod device using the finite element method (FEM) code LHEAF [Shiraiwa, PoP (2011)]:**
  - **Presence of RF power being Landau damped near the plasma edge is not observed in ray tracing and may be a new (full-wave) effect.**



D_{QL} from full-wave **Ray phase space**

Scattering of LH waves from density fluctuations in Alcator C-Mod has been treated by solving a wave kinetic equation using a Monte Carlo wave scattering technique in GENRAY-CQL3D

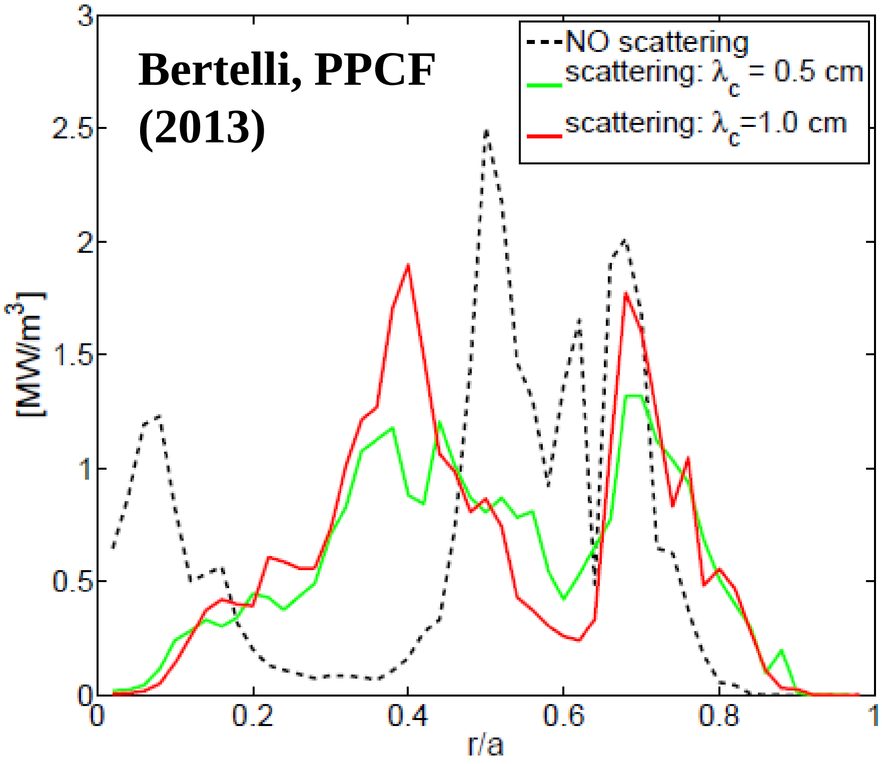
- **Although scattering effect was found to be important it is difficult to separate from the effects of ray stochasticity**

- **Scattering is treated as a three-wave process [Bonoli & Ott, PRL (1981)]:**

$$\omega_0 = \omega_0{}' + \omega_{Fluct} \approx \omega_0{}',$$

$$k_{||} = k_{||}{}' + k_{||}^{Fluct} \approx k_{||}{}',$$

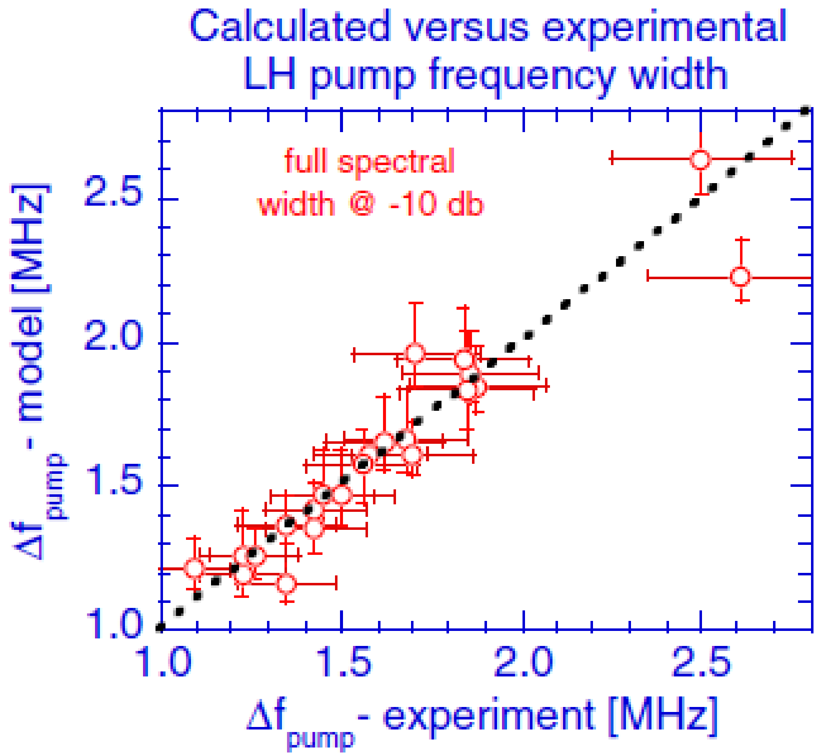
$$\boldsymbol{k}_\perp = \boldsymbol{k}_\perp{}' + \boldsymbol{k}_\perp^{Fluct}$$



$n_e = 0.53 \times 10^{20}$ m^{-3}

Extensive work has also been done to interpret the FTU results in terms of LH wave scattering from density fluctuations in the SOL

- **Calculated an optical thickness (τ_{OPT}) of the plasma SOL due to LH wave scattering from density fluctuations (following Andrews and Perkins, PF, 1983).**
- **Spectral broadening of LH pump wave simulated by scattering effect found to be consistent with experimental measurement.**

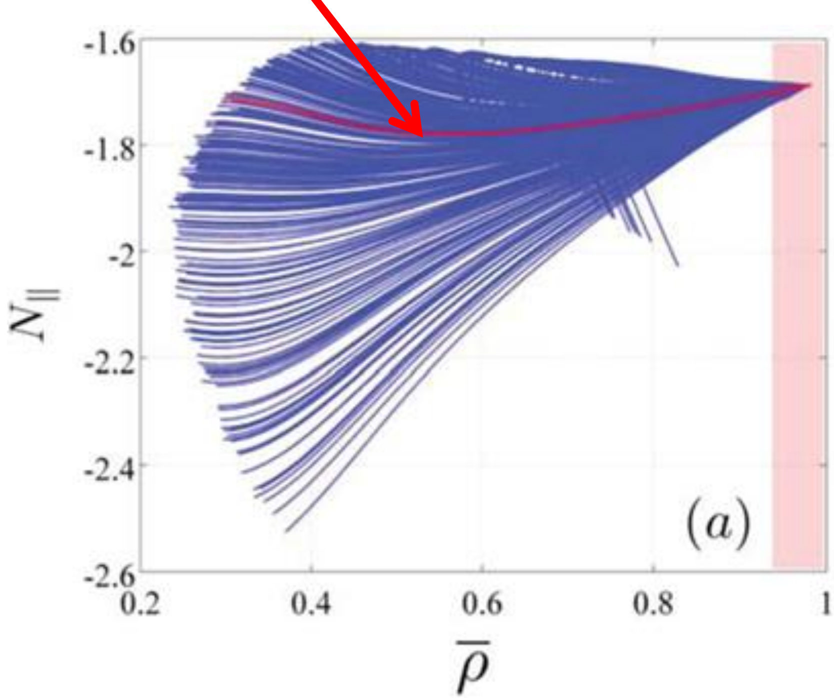


Pericoli-Ridolfini, NF (2011)

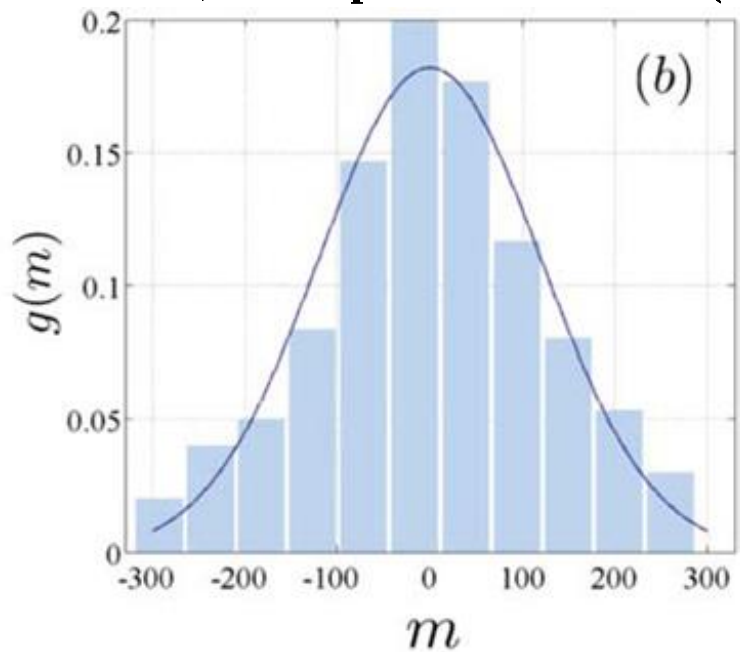
Scattering of LH waves from density fluctuations found to be sufficient to bridge the spectral-gap in Tore Supra

- **Modified ray-tracing formalism in the C3PO ray tracing code that takes into account time-dependent perturbations of the density due to turbulent fluctuations, while iterating with the Fokker–Planck solver LUKE.**

Ray with no scattering

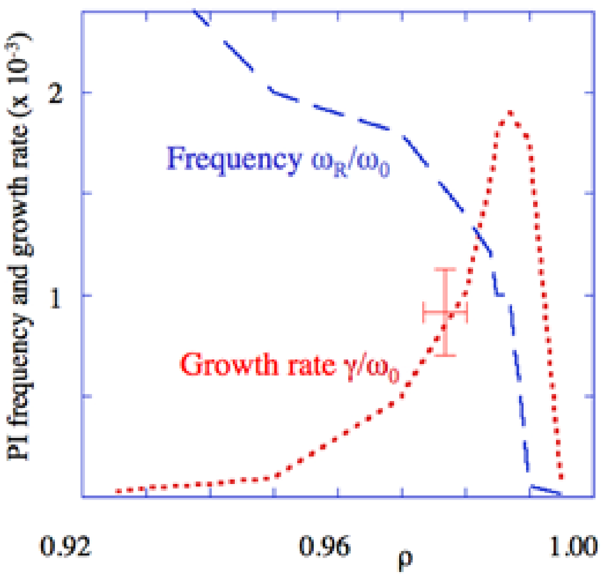


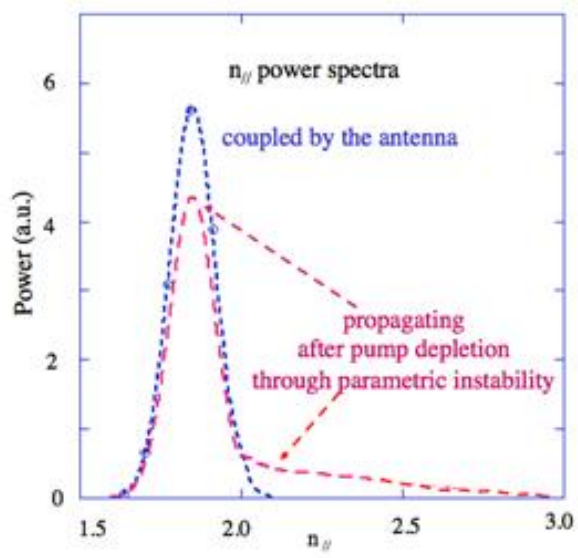
Peysson, PPCF (2011)
Decker, RF Topical Conference (2013)

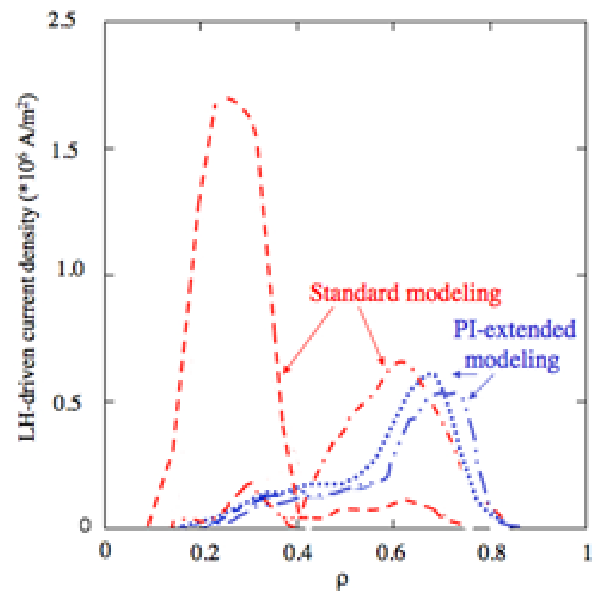


Analysis of discharges in JET with LHCD has revealed that nonlinear broadening of the pump wave due to parametric instability (PI) can bridge the spectral gap

- **Simulations using the LH^{star} code [Cesario, PRL (2004)] first solve the parametric dispersion relation:**
  - **High $n_{//}$ component from broadened pump wave is following using ray tracing**
  - **Resulting power deposition is completely off-axis, consistent with results for ITB formation in JET discharges with LHCD.**





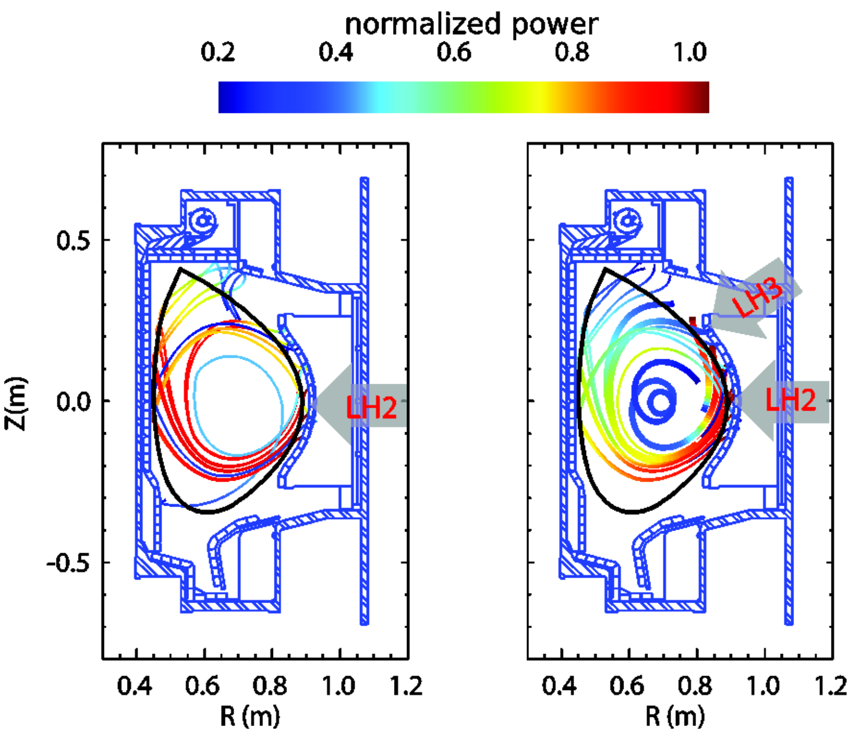


Summary

- Original work by Fisch on RF current drive using LH waves provided the theoretical motivation for highly successful LHCD experiments.
  - Theoretical and numerical predictions for the current drive efficiency have generally been quite accurate
- Calculations of the RF wave – induced flux have continued to be a challenge (and unsolved mystery) because of the large gap that exists in velocity space between injected LH waves and the phase speeds necessary for strong Landau damping.
- Multiple plausible explanations for filling the spectral gap have been proposed over the years:
  - Toroidal effects, wave scattering from density fluctuations, full-wave effects, and nonlinear pump broadening
  - No single explanation has been shown definitively to work

Future Work

- **More experiments are needed in order to completely validate combined wave propagation / Fokker Planck models:**
  - **The interaction of LH waves with SOL must be clarified in existing experiments (see talk by R. Parker)**
  - **Experiments should be conducted with higher single pass damping – either raise T_e or use "compound" LH launchers (phase space engineering)**



Shiraiwa, NF (2013)