Mechanisms for loss of Lower Hybrid Current Drive at high density

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Solved and Unsolved Problems in Plasma Physics

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Background

Non-inductive current drive is required to create steady state operation of a tokamak.

Of the available methods, injecting RF waves near the lower hybrid frequency is the most attractive:

- Efficient steady-state sources and related technology are readily available
- Waveguide grill launching structure is compatible with low density and temperature scrape-off-layer plasma
- Efficiency (Amps/Watt) is the highest of any RF method.

Yet, despite decades of experiments, theory and simulations on LHCD, mysteries remain.

It is important to resolve these “unsolved problems”, not only to elaborate the underlying physics, but also to establish LHCD as a viable technique for producing steady-state regimes in a tokamak reactor.

A lower Hybrid Current Drive Primer:

The theoretical basis for driving current in toroidal plasmas by lower hybrid waves was established in a 1978 seminal paper by N. Fisch (1978 *PRL* **41** 873), which was based on his PhD thesis. Nat showed that QL RF diffusion would flatten the electron distribution function in the neighborhood of the wave parallel phase velocity, $c/n_{\|}$, producing a current density given by

$$J_n \cong \frac{c^2}{v_{th}^2} \frac{1}{n_{\|}^2} P_n$$

where $J_n = J/nev_{th}$ and $P_n = P/mnv_{th}^2 \nu_0$ are normalized current and power densities. (Multiplying the RHS by the factor 1.4 gives exact agreement with numerical calculation.)

This calculation was subsequently refined in an elegant calculation by N. Fisch and A. Boozer (1980 *PRL* **45** 720) yielding the result

$$J_n = \frac{2}{3} \frac{\hat{s} \cdot \nabla(v_{\|} v^3)}{v_{th}^2 \hat{s} \cdot \nabla(v^2)} P_n$$

and thus the answer to the question: Why does pushing particles perpendicular to the field yield parallel current? Here $\hat{s}$ is a unit vector in the direction that the particles are pushed. This result yields the factor 1.33 in the upper expression for "parallel" pushing.

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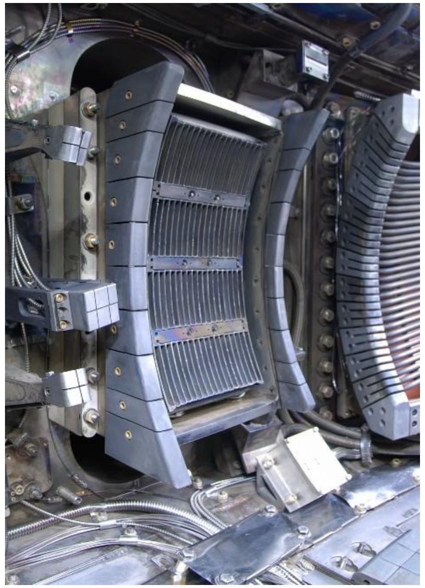
Nat's result $J_n \cong \frac{c^2}{v_{th}^2}\frac{1}{n_\parallel^2}P_n$ is disarmingly simple. But what is $n_\parallel$, $P_n(n_\parallel, f(\vec{r},\vec{v}))$?

Lower Hybrid waves are typically launched at a fairly well defined $n_\parallel$ by a waveguide grill as in the case of Alcator C-Mod.

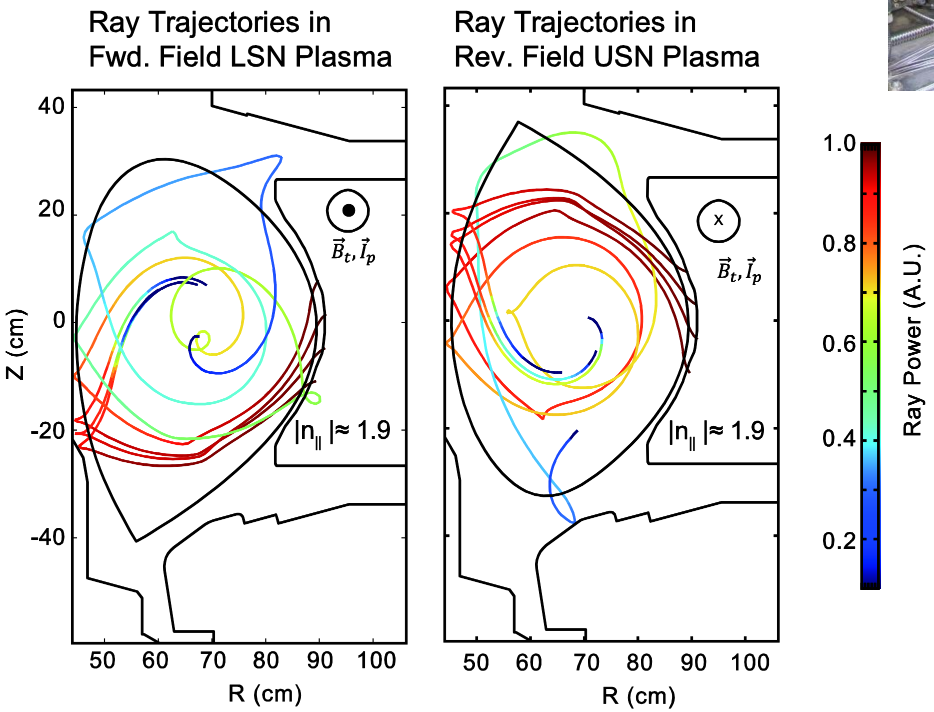


The frequency is above that of the lower hybrid frequency everywhere in the plasma, typically in the range of 2.5 – 5 GHz.

For typical tokamak plasmas, the wavelength is much smaller than the density and temperature scale lengths. Hence ray tracing is often used to represent the propagation of LH waves:

$$\frac{d\vec{r}}{dt} = \nabla_k \omega(\vec{r},\vec{k}) = \vec{v}_g$$

$$\frac{d\vec{k}}{dt} = -\nabla_r \omega(\vec{r},\vec{k})$$



These eqs are combined with an F-P equation with a QL RF diffusion coefficient to evolve the distribution function.

Bottom Line: The evolution of $n_\parallel$ is unintuitive, complex, involves multiple bounces by wall or SOL.

What can be measured to verify theory and simulation and is there agreement?

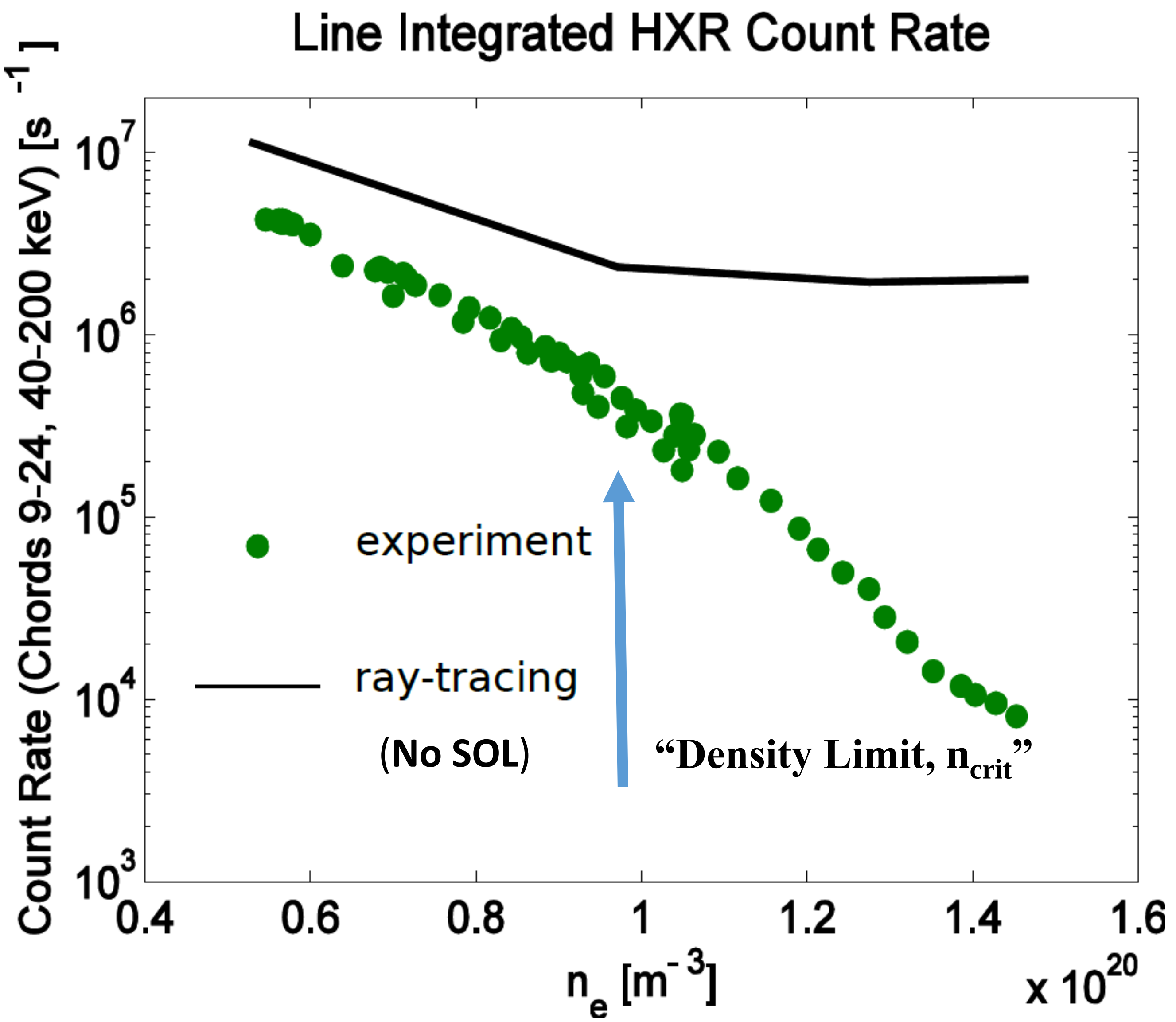
Measurement	Result
Total Current	Surprisingly good agreement with engineering efficiency (follows from J_n/P_n) $\eta = \frac{n_{20} I R}{P} \cong 0.2 - 0.3$ A·m/W . But η often doesn't scale with $1/n_{\parallel,launch}^2$. (See Paul Bonoli talk.) Also, η strongly degrades as density approaches accessibility limit $n_{\parallel} > \frac{\omega_{pe}}{\omega_{ce}} + \sqrt{1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2}}$.
Hard x-ray flux	Poor agreement with rigid boundary model. Better with SOL absorption included, but diverges as density approaches accessibility limit.
Hard x-ray profile	Poor agreement with either rigid or collisional SOL. Improved with ad hoc spatial diffusion and addition of higher $n_{\parallel}$ components in launched spectrum.
Current Profile	Poor agreement with either rigid or collisional SOL. Somewhat improved with ad hoc spatial diffusion and addition of higher $n_{\parallel}$ components but still inadequate.

Hard x-rays, viewed and energy-resolved by a poloidally viewing x-ray camera reveal a shortfall in emission

The ray-tracing, F-P codes GENRAY & CQL3D have a module which calculates the x-ray emission due to fast electrons produced by wave-particle interactions.

Comparing the simulation results without a SOL model (essentially specular reflection at the separatrix) as a function of density shows large discrepancy between simulation and experiment.

Above the "density limit", essentially no change in core parameters is observed.

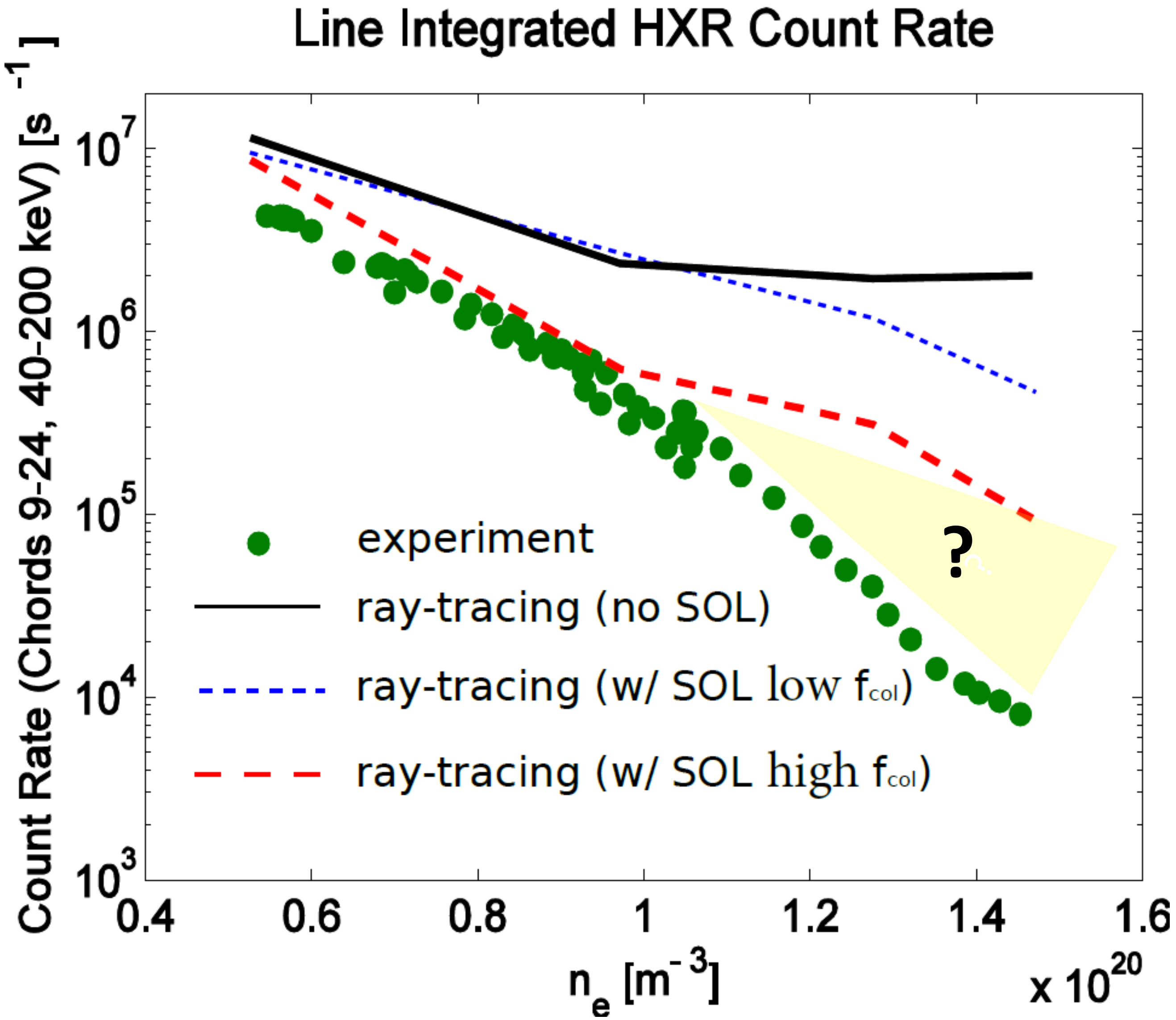


The disparity between simulation and measurement can be reduced by incorporating a model of the scrape-off layer

Adding a scrape-off-layer (SOL) model results in collisional absorption in the SOL and reduces disparity between experiment and simulation[1]

The SOL model is largely empirical and it is necessary to assume a high Zeff = 4 to get agreement up to $n = 10^{20}\ m^{-3}$. Measurements of Zeff in the SOL are not available

Beyond $n = 10^{20}\ m^{-3}$, a systematic divergence still appears. Result of deficiencies in ray-tracing model?

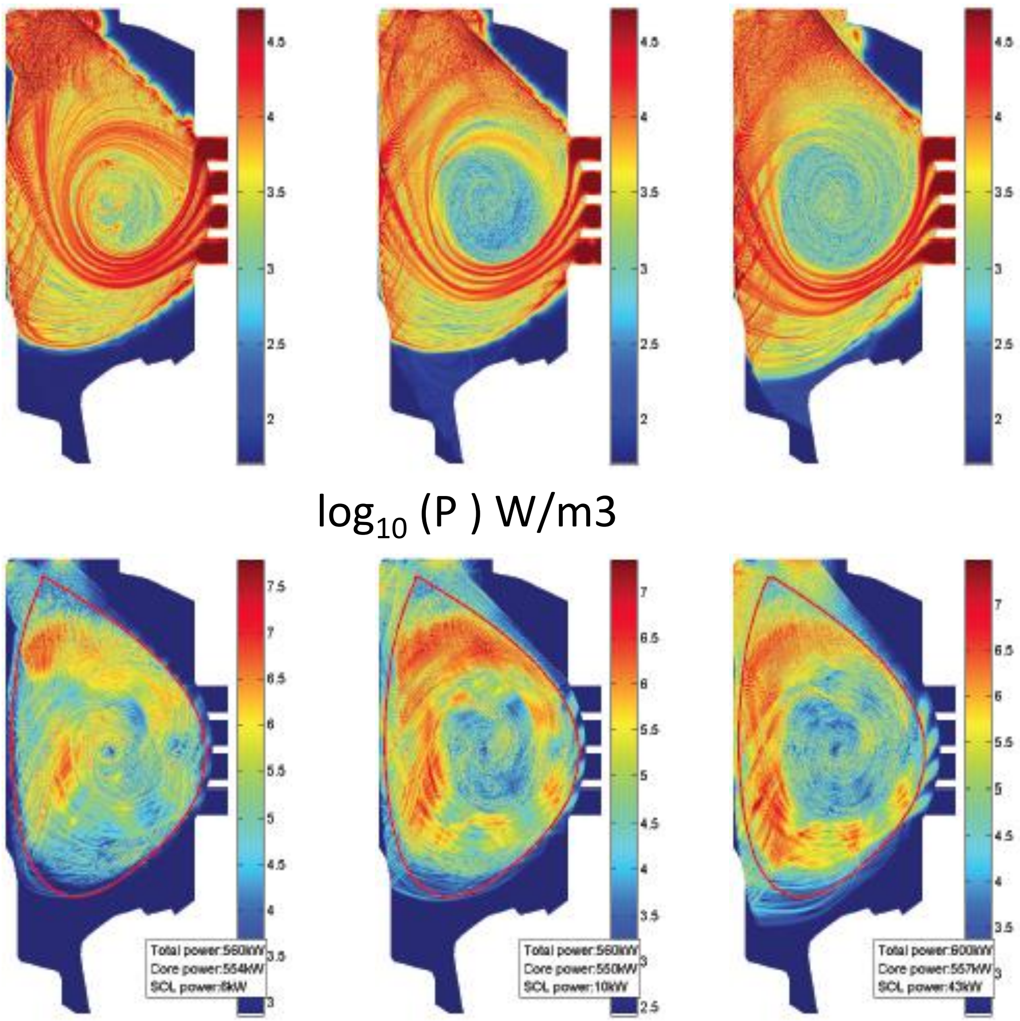


[1]G. M. Wallace *et al* 2012 *Phys. Plasmas* 19 062505

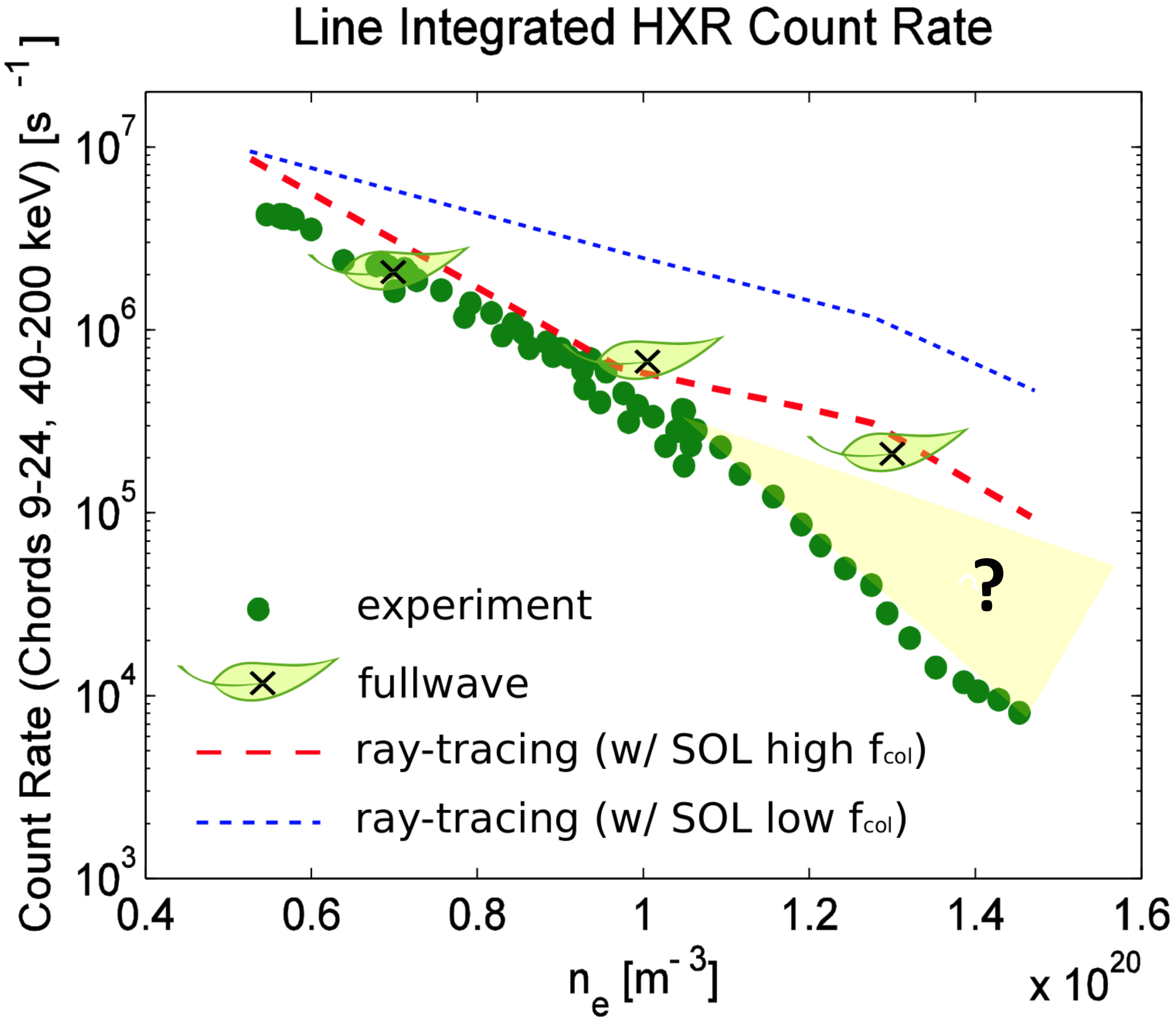
Full wave FEM simulation shows similar trend with lower collisionality in SOL but with higher $n_\parallel$-upshifts resulting in Landau absorption closer to separatrix

$\log_{10}(|E_\parallel|)$ V/m

$\log_{10}(P)$ W/m3



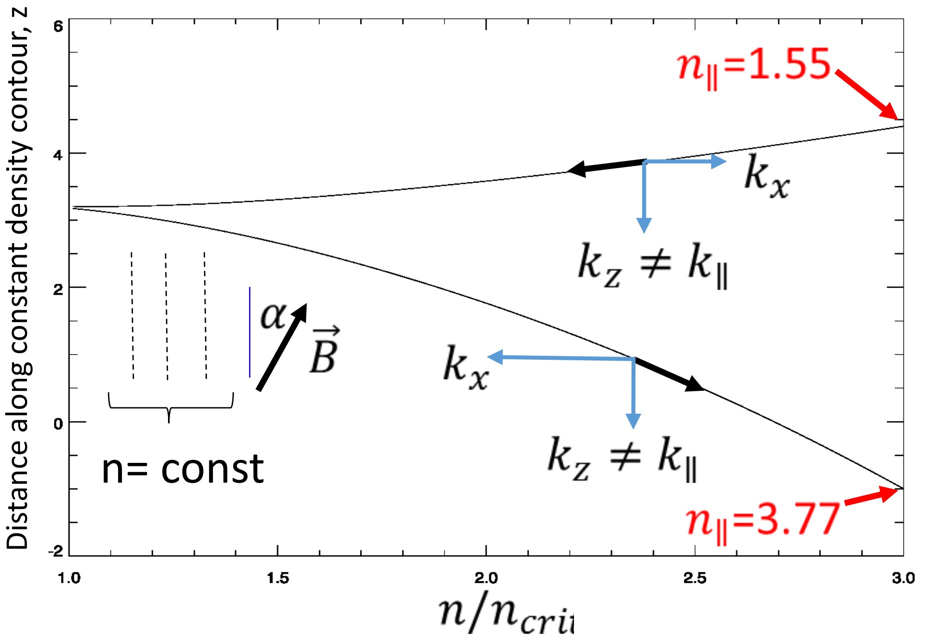
$n_{20} = 0.7$ $n_{20}=1.0$ $n_{20}=1.3$



O. Meneghini 2011 PhD Thesis MIT; S. Shiraiwa *et al* 2010 *Phys. Plasmas* 17 056119

Reflections from boundary can be non-specular, resulting in up- or down-shift in $n_\parallel$

$\vec{B} \cdot \nabla n \neq 0$

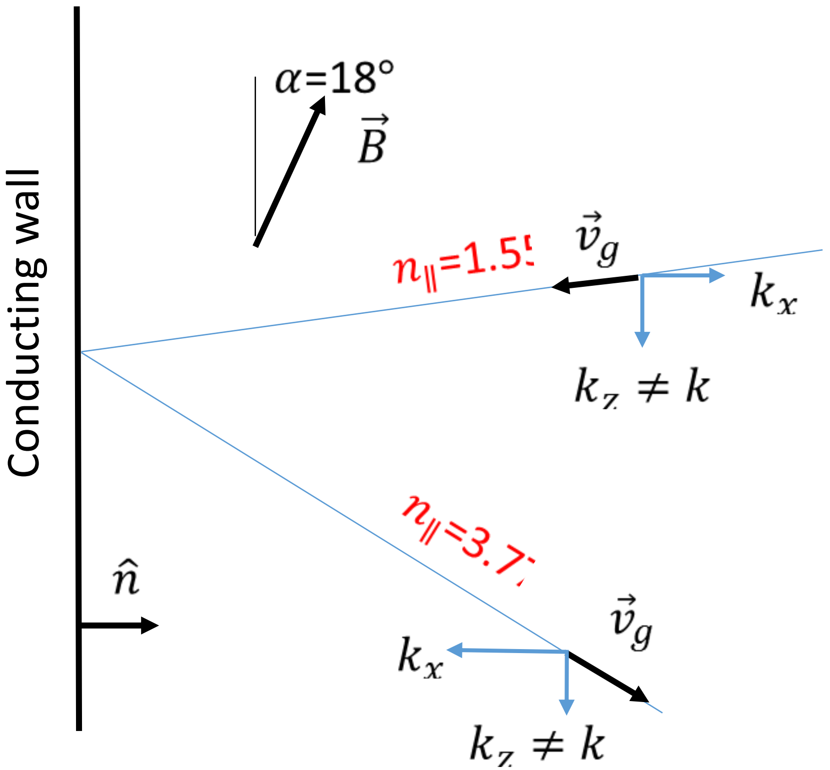


$$k_x^2 + 2k_x k_z \frac{K_{xz}}{K_{xx}} + k_z^2 \frac{K_{zz}}{K_{xx}} - k_0^2 \frac{K_\parallel K_\perp}{K_{xx}} = 0$$

$$K_\perp \cong 1, K_\parallel = 1 - \omega_p^2/\omega^2$$
$$K_{xx} = 1 - \omega_p^2 \, sin^2\alpha/\omega^2$$
$$K_{xz} = -\omega_p^2 \cdot sin\alpha \cdot cos\alpha/\omega^2$$
$$K_{zz} = 1 - \omega_p^2 cos^2\alpha/\omega^2.$$

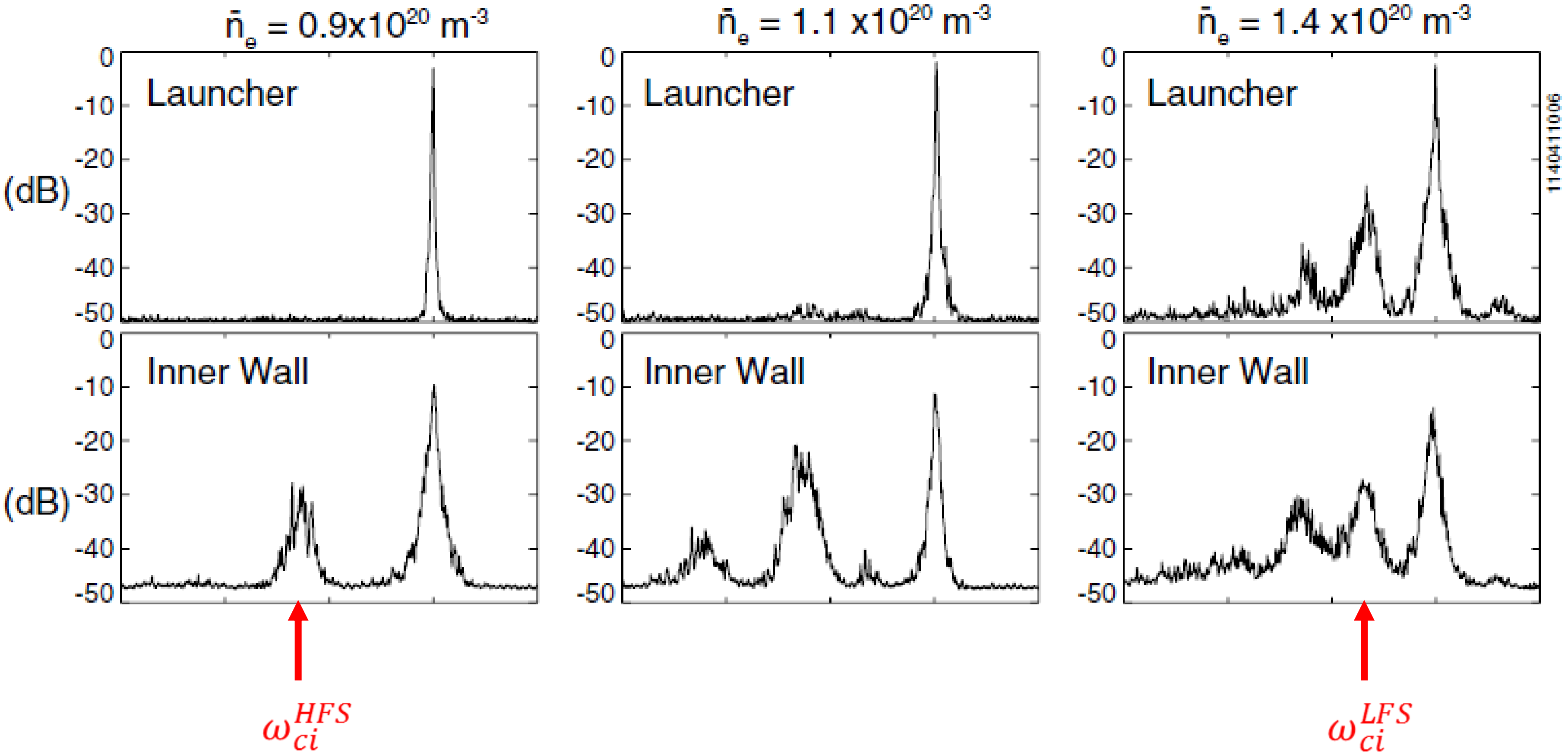
$\vec{B} \cdot \hat{n} \neq 0$

$n/n_{crit} = 3$



Violation of Fresnel's Law!

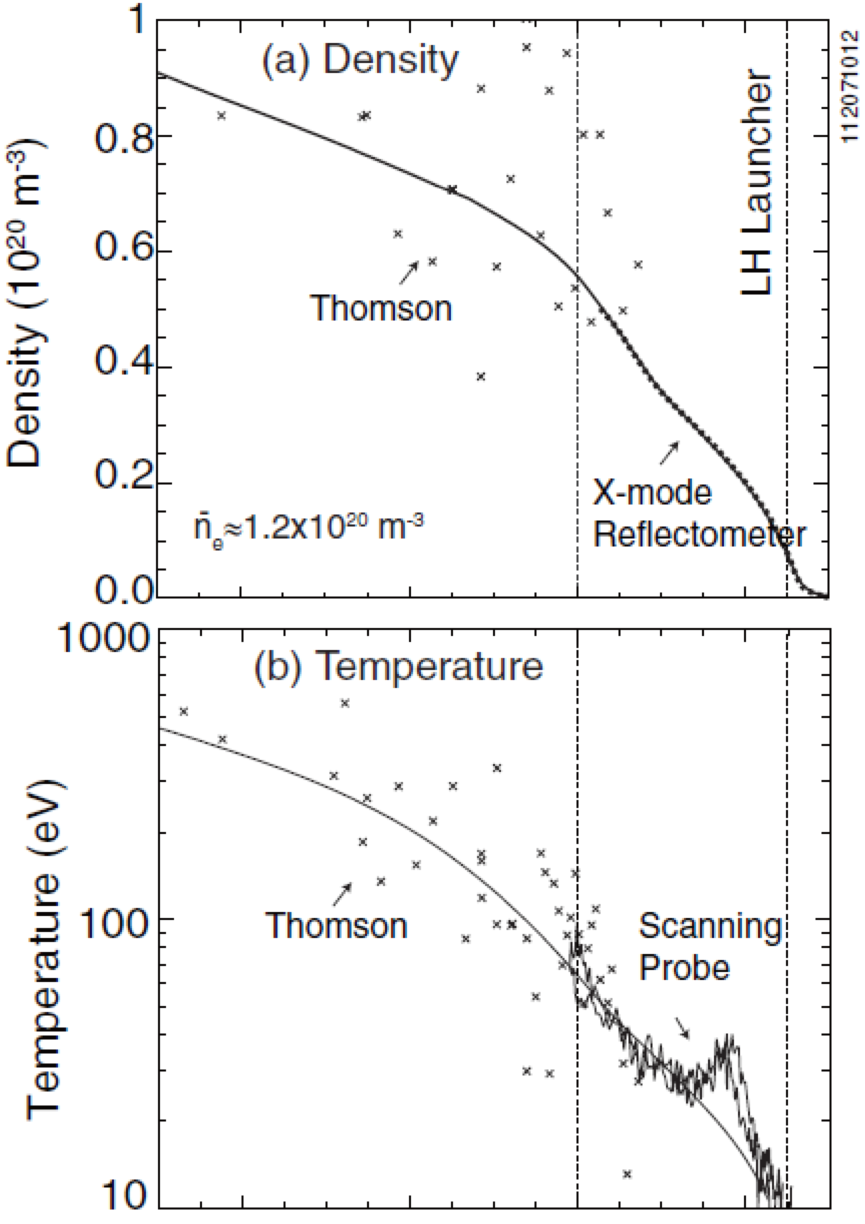
As the density is increased above n_{crit}, strong parametric decay instabilities develop in the SOL/edge plasma at multiples of the local ion cyclotron frequency



Whether the PDI initiate at the outer or inner wall depends on the magnetic topology. With $\vec{B} \times \nabla B$ toward (away from) the X-point, PDI initiates at the inner (outer) wall. This is understood in terms of the plasma conditions in the SOL for the two cases.

S-G Baek *et al* 2015 *Nucl. Fusion* **55** 043009

The calculated growth rate and real frequency qualitatively agree with observation



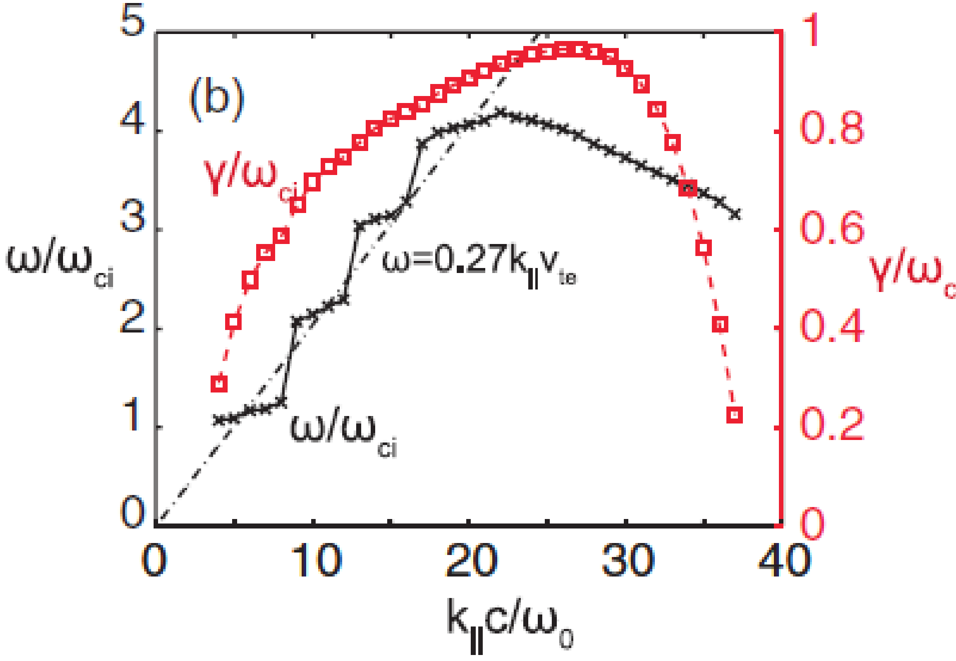
Measured SOL/Edge Profiles

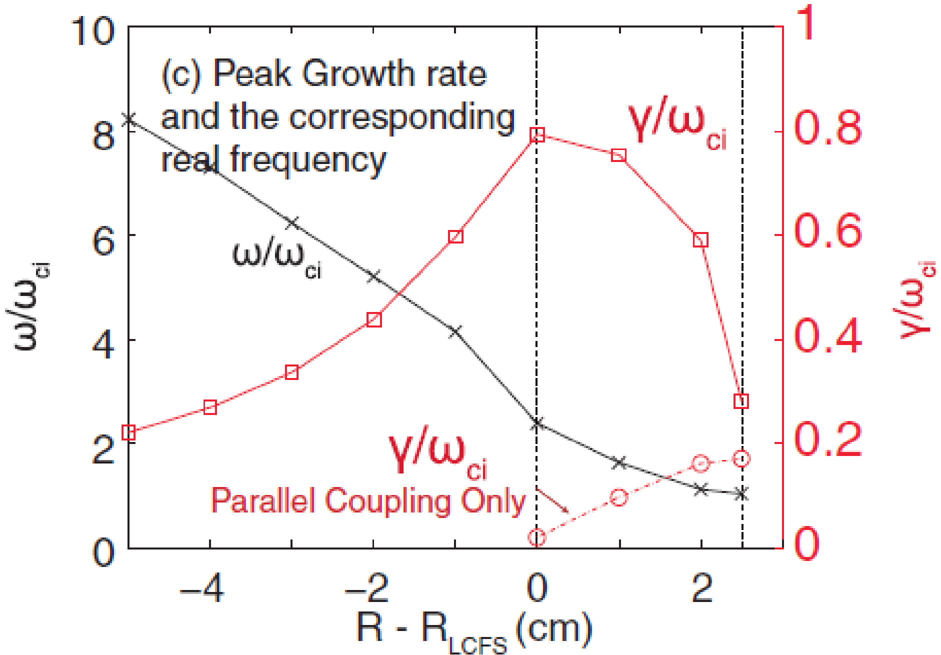
With local values of the SOL density and temperature profiles, the calculated growth rate is found to maximize at ion cyclotron harmonics with relatively high $n_\parallel$

However, inside the separatrix the temperature rises rapidly and the growth rate falls. The observed PDI are therefore expected to be localized to the SOL/edge plasma

Speculation: high $n_\parallel$ daughter LH waves may lead to absorption of the primary launched wave by creating an epithermal electron population near the edge.

S-G Baek *et al* 2015 *Nucl. Fusion* **55** 043009





The mechanisms that cause the loss of current drive efficiency all point to power absorption near the edge or SOL, preventing current drive in the core. Is there experimental evidence?

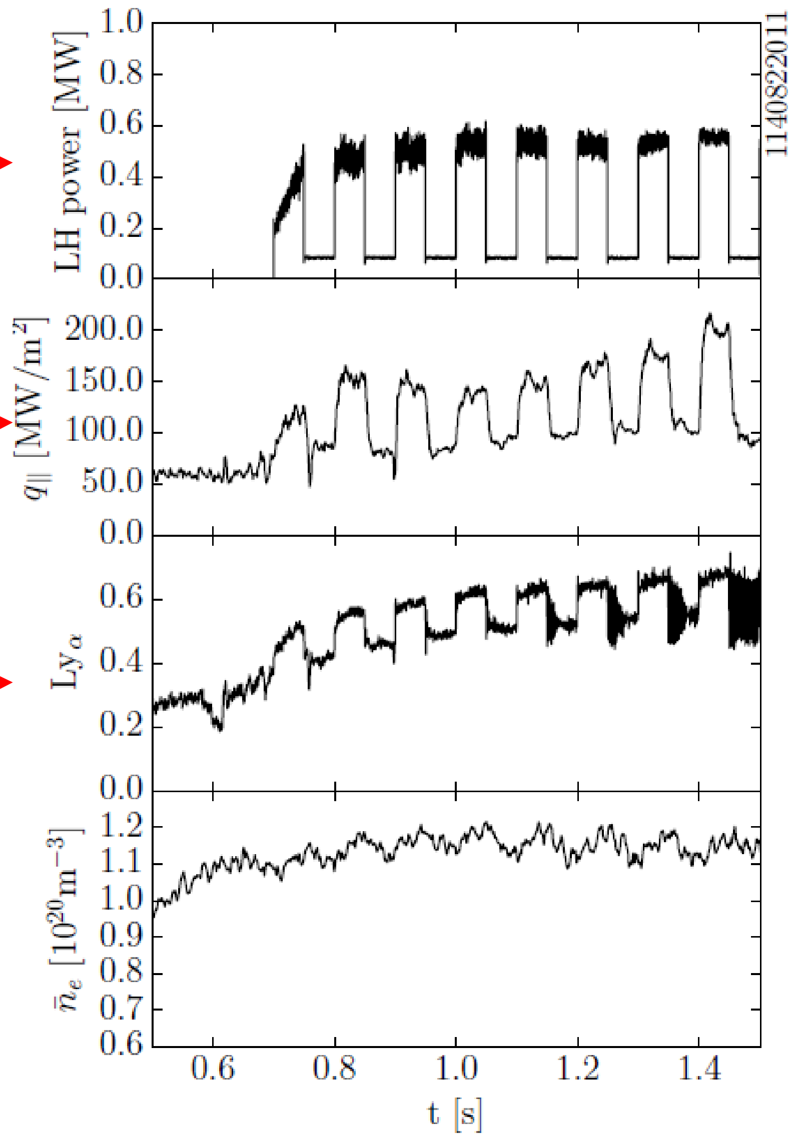
Answer is YES ! [1]

Recent measurements with modulated LH power confirm that substantial power is absorbed near the edge or in the SOL for $n > n_{crit}$.

The power conducted to the divertor (measured with fast thermocouples imbedded in the divertor plates) is transported to the SOL in a time much shorter than the energy confinement time

There is also significant power lost to ionization in the SOL as indicated by a Lyman alpha camera viewing the plasma poloidal cross section

Quantitatively, nearly 80% of the applied LH power is accounted for at high density by fast power deposition in the edge/SOL plasma



[1]I. Faust *et al* 2016 *Phys Plasmas* (Submitted)

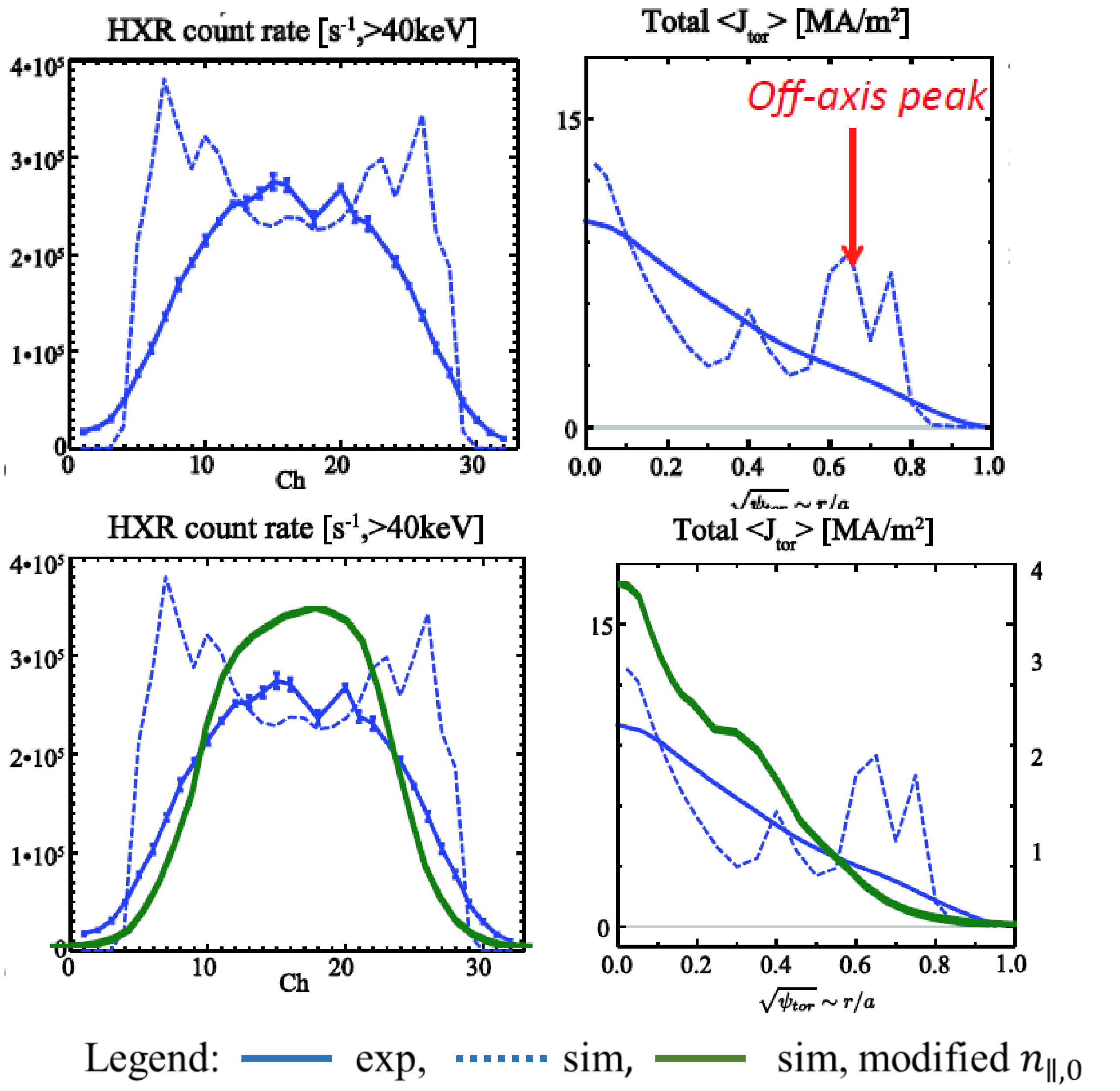
Ray-tracing models do not do a good job regarding x-ray and current profiles

Both x-ray and current profiles predicted by ray-tracing-FP simulations are jagged, and have off-axis peaks which are at variance with measurements

Although jaggedness can be smoothed by spatial diffusion, shape still does not conform to measurement.

Somewhat better agreement is reached by incorporating peaks in the actual applied $n_\parallel$ spectrum, and by adding a modest amount of diffusion[1]. (Green curves in figures)

Other mechanisms are available for modifying the wave $n_\parallel$-spectrum, including turbulent scattering, PDI and reflections at the wall or cutoff layer.



[1]S. Shiraiwa et al 2015 APS DPP Meeting, Savannah, GA

Another problem, recently partially resolved: Which way does the core plasma rotate when LH waves are injected?

Obvious answer: In the direction of the injected waves, i.e., counter current since rate of wave momentum input is in that direction!

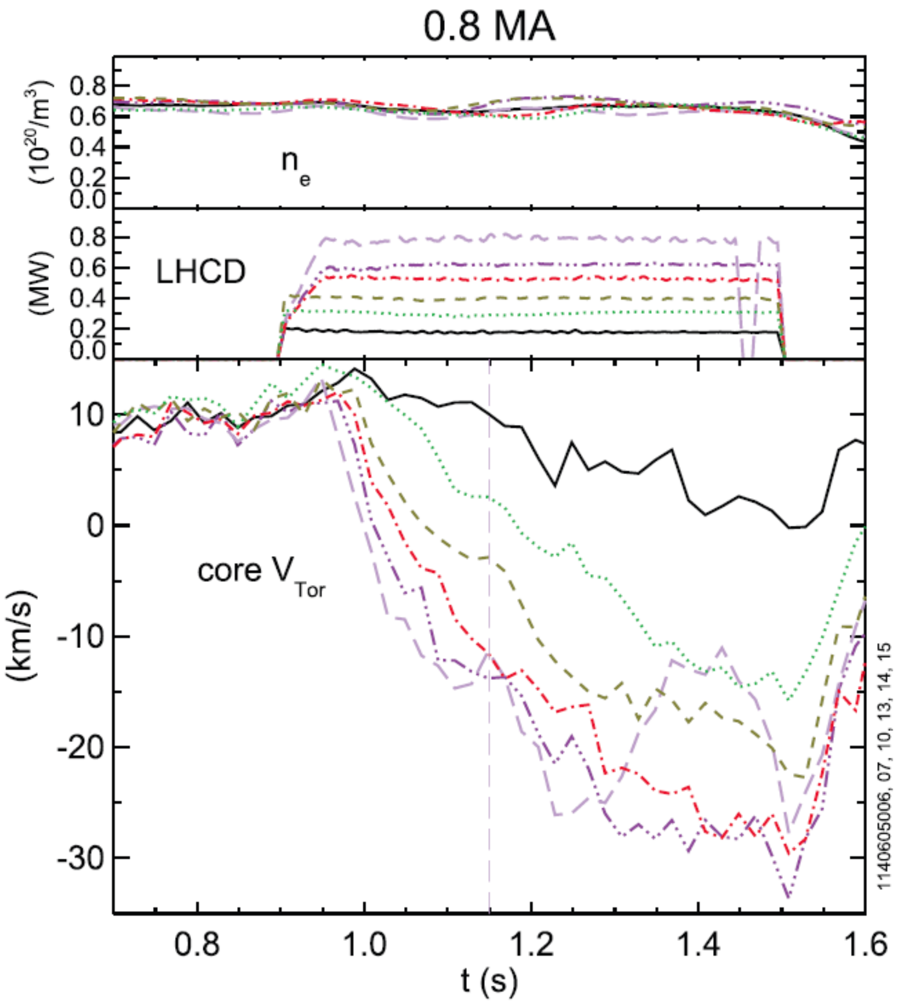
$$\dot{P}_\varphi = \int d\vec{A} \cdot \frac{1}{\omega} \vec{v}_g \langle W \rangle \vec{k}_\varphi \cdot \vec{\varphi} = \frac{n_\varphi}{c} \times Power$$

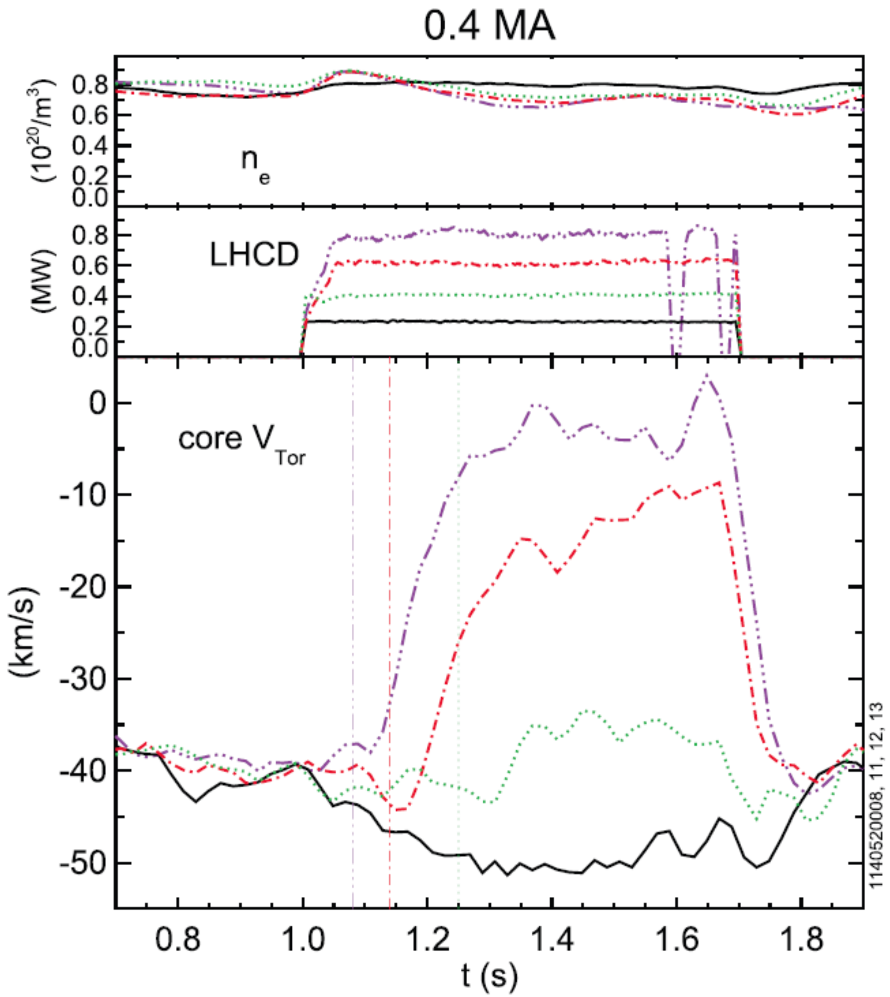
In Alcator C-Mod the corresponding torque is 0.001 – 0.002 Nm, enough to spin up the core to 30 – 40 km/s in the *counter* direction.

But many papers claim that that plasma rotates in the co-direction due to application of LHCD! Why?

When LH waves are injected, which way does the plasma rotate?

The answer is that the core can rotate in *either* direction, depending on the evolution of the equilibrium due to the application of LHCD power[1]





Rotation reverses (from counter to co) when q(0) $\gtrsim$ 1. LH torque initiates rotation but also modifies equilibrium by increasing q(0) above 1. Residual stress determines final rotation state.

[1]Rice, J.E. *et al* 2016 *Nucl. Fusion* **56** 036015

Summary and Conclusions

Nat's ground braking work established the basis for Current Drive by LH waves and spawned many successful LHCD experiments

But the devil is in the details, in particular the effect of the scrape-off layer, especially in the "multipass" regime.

Collisional absorption, full wave effects, up/down $n_{\|}$ shifts and parametric instability all occur near the SOL as the density approaches the accessibility limit. Their effect is to eliminate useful current drive. A PIC simulation of PDI would be helpful in assessing saturation levels, localization and relative importance.

Ray-tracing plus F-P fails in predicting x-ray and current profiles -- an important problem! Validated simulations are lacking!

An integrated full wave/boundary simulation is foreseen, which should address more fully the limitations of ray-tracing (see John Wright poster)

The question of LHCD-induced rotation has been clarified, or at least relegated to the problem of calculating residual stress!

The best way to avoid SOL effects is to ensure single-pass absorption via a high temperature (~ 10 keV) plasma core with optimized coupler location! See Dennis Whyte's talk.

Nat, congratulations, not so much on reaching 65 (it’s not so uncommon these days) but on remaining curious, creative, and productive, and for the enormous esteem with which your colleagues and students hold you!