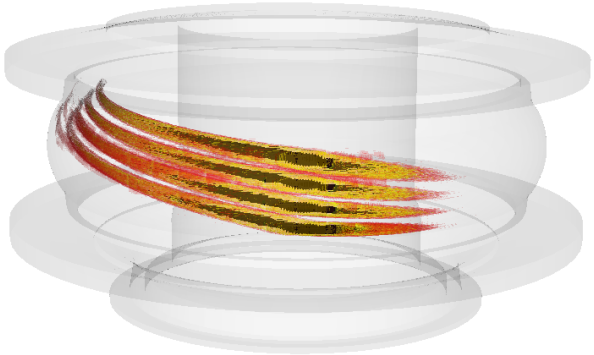
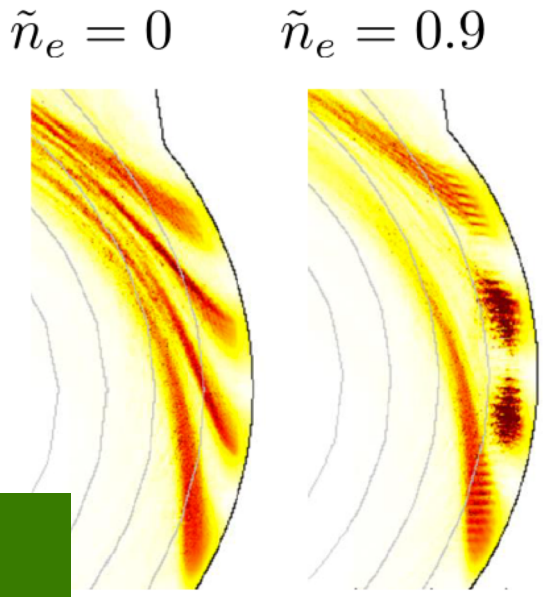
Experimental Evidence of Lower Hybrid Wave Scattering in Alcator C-Mod due to Scrape Off Layer Density Fluctuations





Elijah H. Martin

Fusion and Materials for Nuclear Systems Division, ORNL

Presented by:

Gregory M. Wallace

Plasma Science and Fusion Center, MIT

27th IAEA FEC | Gandhinagar, India | October 26th, 2018

COLLABORATORS

Cornwall Lau (ORNL, FMNSD) → leader of the simulation effort

Greg Wallace (MIT, PSFC)

Bob Mumgaard (MIT, PSFC)

Syunichi Shiraiwa (MIT, PSFC)

Paul Bonoli (MIT, PSFC)

John Wright (MIT, PSFC)

David Green (ORNL, FMNSD)

Maxim Umansky (LLNL, FES)

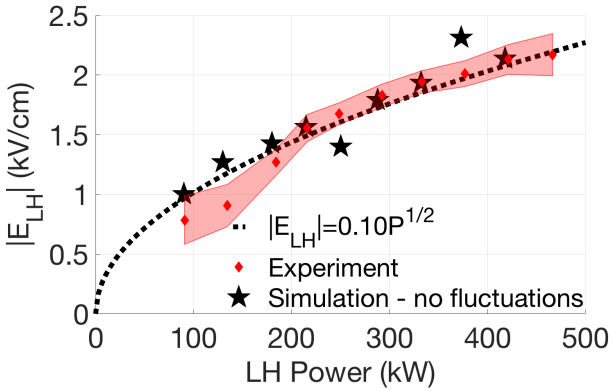
Andris Dimits (LLNL, FES)

Ilon Joseph (LLNL, FES)

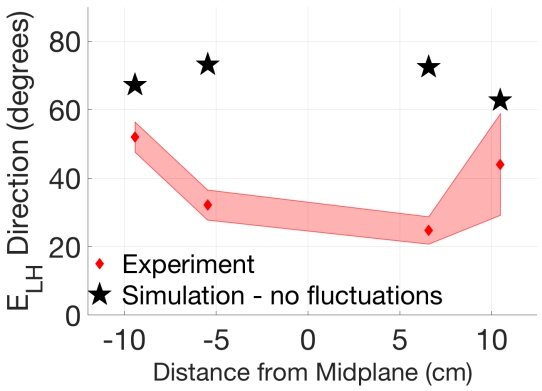
Edge Turbulence Alters Lower Hybrid Wave Propagation

Direct Experimental Measurement ⇉ E_{LH} = Lower hybrid wave electric field vector

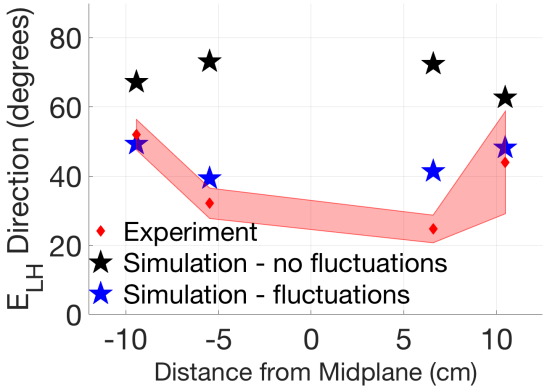
LH wave absorption negligible in SOL near the launcher



Strong LH wave scattering is occurring in the SOL



SOL density fluctuations predict LH wave scattering



Lower Hybrid Current Drive Provides Off-Axis Current at High Efficiency

- External current drive is necessary for the steady state reactor.

LHCD Provides:
- off-axis current
- high efficiency

- Lower hybrid current drive has been successfully demonstrated in the low density regime.

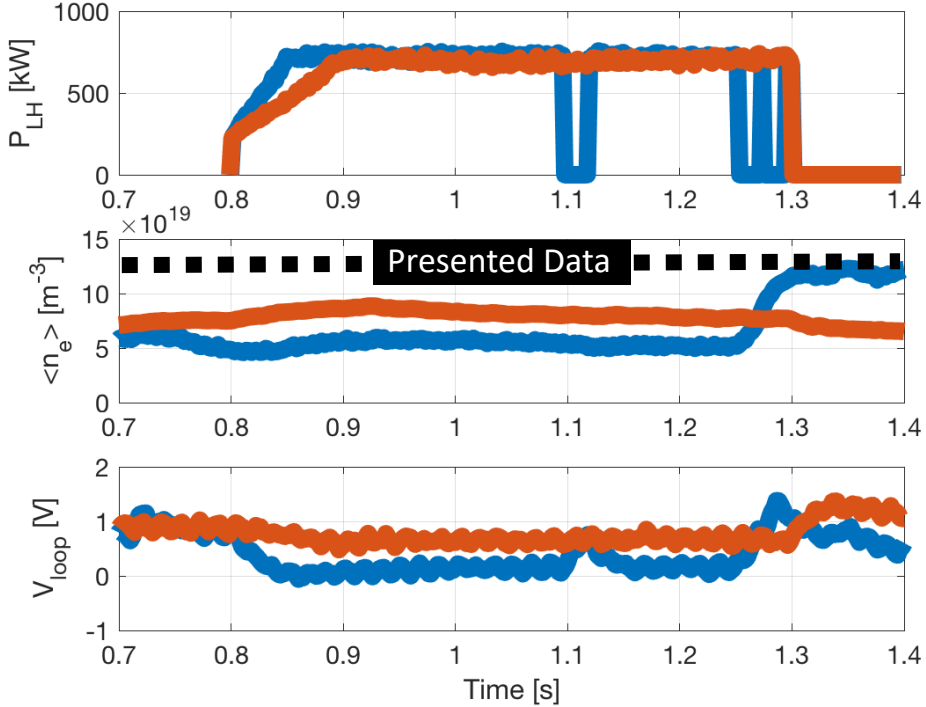
High density plasmas

↓

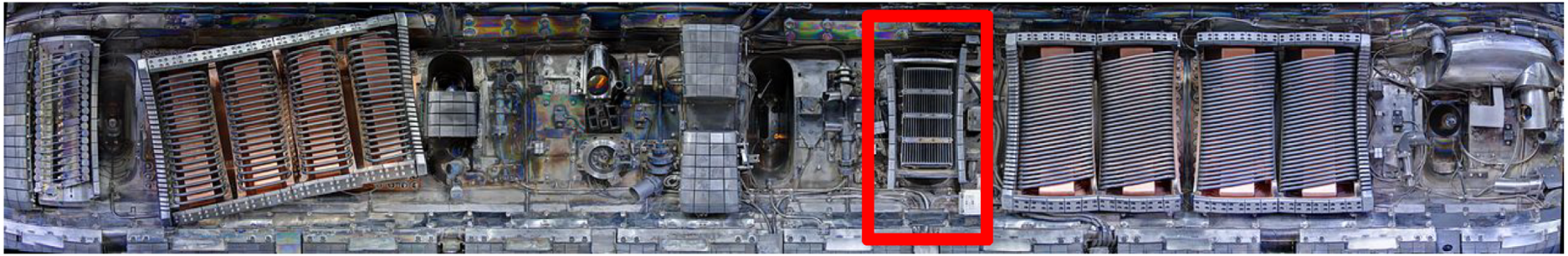
Loss of efficiency at high density ($n_e > 10^{20}$ m^{-3})

↓

WHY and will a measurement of E_{LH} help?



Lower Hybrid Current Drive on C-Mod



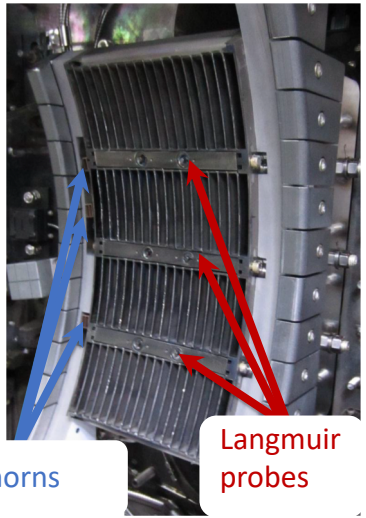
Lower Hybrid Antenna

PRESENTED DATA

	C-Mod	Reactor
Field	5.4 T	5 T
Density	13 $\cdot 10^{19}$ m^{-3}	5-10$\cdot 10^{19}$ m^{-3}
Frequency	4.6 GHz	5.0 GHz
Shape	Diverted	Diverted
Launched $n_{\parallel}$	1.9	2

local n_e profile

REQUIRED FOR ACCURATE SIMULATIONS OF $|E_{LH}|$



Outline

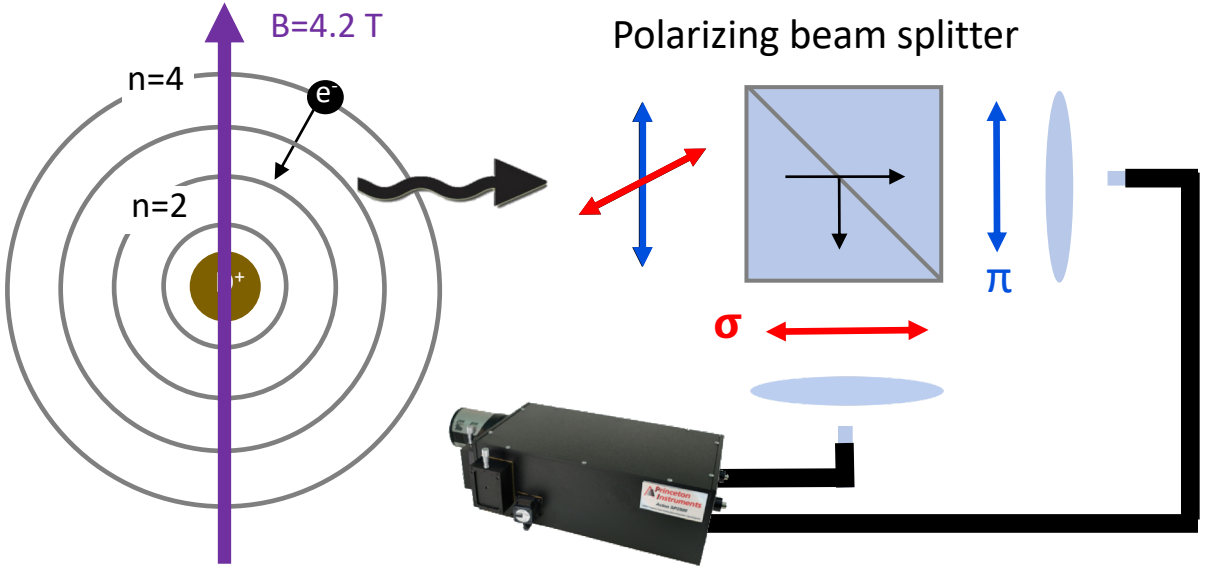
The Diagnostic and Implementation on Alcator C-Mod

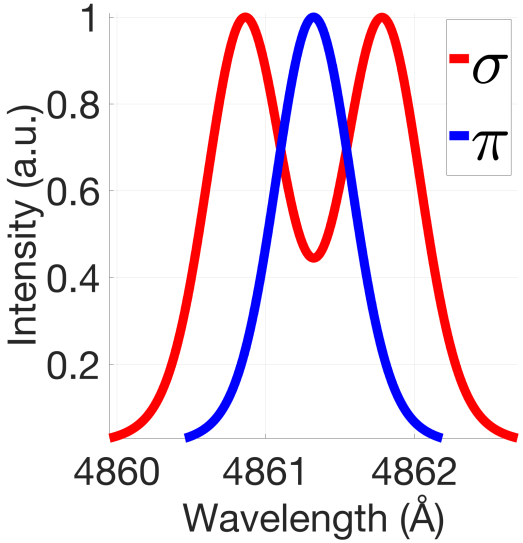
COMSOL Full-Wave 3D Simulations

Comparison of Experimental and Simulation Results

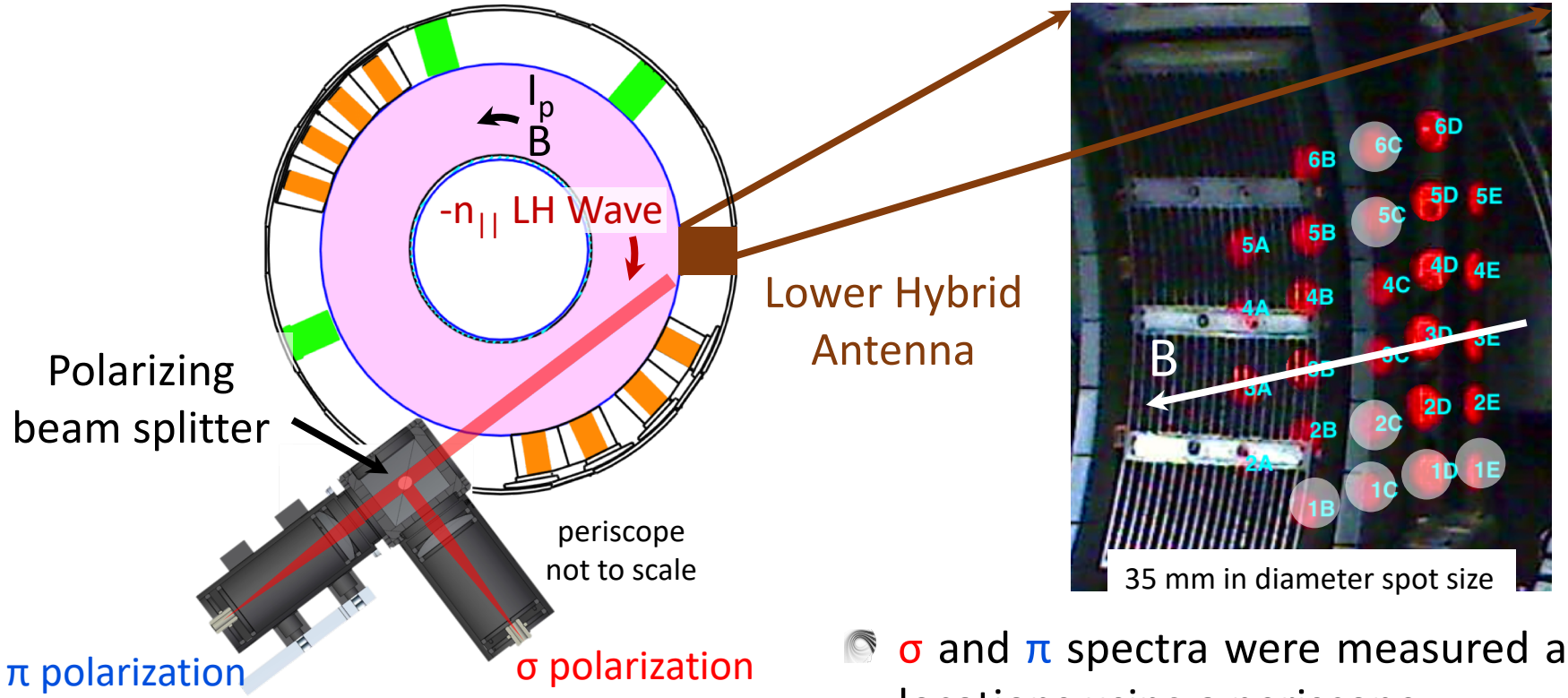
Polarized Optical Emission Spectroscopy

- Polarized ⟶ measurement of optical emission having a specific polarization.
- Optical emission spectroscopy ⟶ passive measurement of the D_β spectrum.
- E_{LH} is determined from a systematic fit to the shape of the spectral line profiles.





Diagnostic Implementation on C-Mod



- σ and π spectra were measured at 7 locations using a periscope.

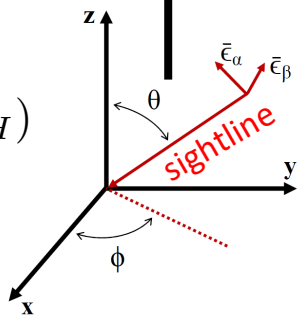
Determining E_{LH} From the σ and π Spectra

- The time dependent Schrodinger equation is fit to the experimentally measured σ and π spectra.

$$i\hbar\frac{\partial\Psi}{\partial t} = \left[H + H^B + H^E(t) + \hat{H}\right]\Psi$$

unperturbed Hamiltonian $\quad f(\mathbf{B}) \quad f(\mathbf{E}_{LH})$

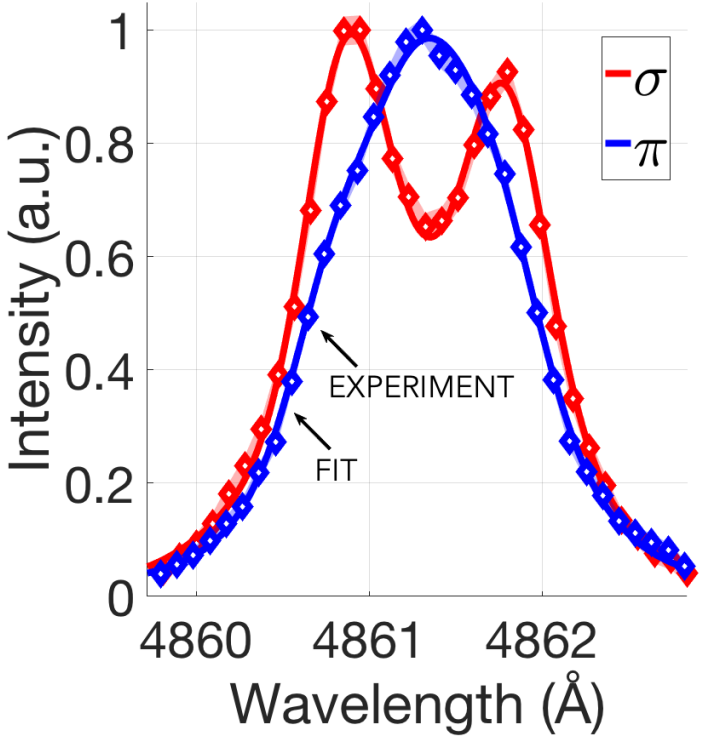
FIT



$E_{||} = 0.0 + 0.2$ kV/cm

$E_{\perp r} = 1.8 \pm 0.1$ kV/cm

$E_{\perp p} = 1.7 \pm 0.2$ kV/cm



Outline

The Diagnostic and Implementation on Alcator C-Mod

COMSOL Full-Wave 3D Simulations

Comparison of Experimental and Simulation Results

3D FULL-WAVE COMSOL MODELING

- 3D simulations of E_{LH} are required because LH resonance cone is strongly localized.
- Assumed axisymmetry in n_e and reduced problem to Fourier sum of toroidal modes.

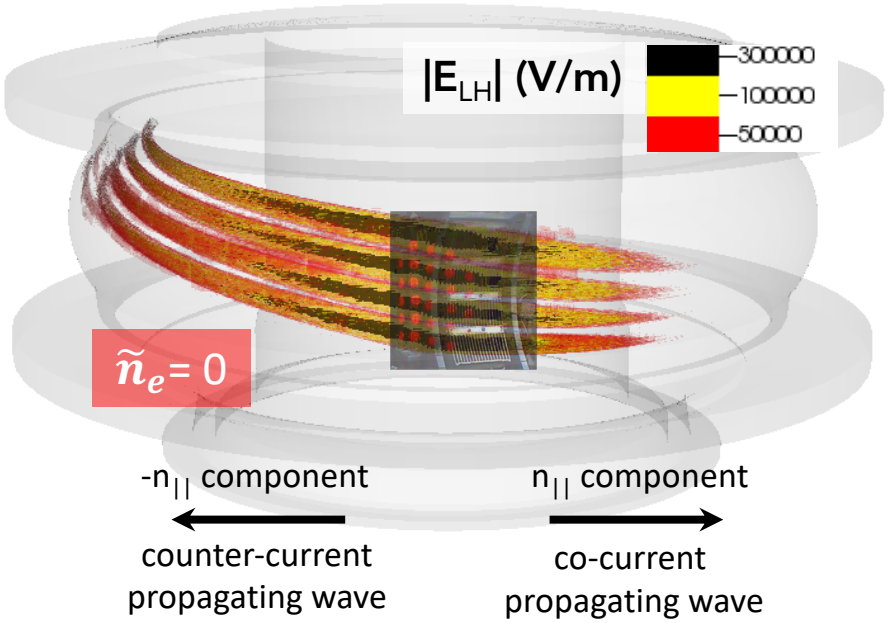
$$\mathbf{E}_{LH}(r,z,\theta) = \sum_{m=1}^{N_m} A_m \mathbf{E}_m(r,z) e^{im\theta}$$

- The n_e profile is set by reflectometry measurements and a synthetic turbulence model.

$$n_e = n_{eo}\left[\left(1 + \tilde{n}_e\, e^{-\frac{(r-r_c)^2}{r_w}} \sin\left(\frac{2\pi p}{\lambda_{ne}}\right) - \frac{(p-p_c)^2}{p_w^2}\right)\right]$$

REFLECTOMETRY MEASURED

STATIC SYNTHETIC TURBULENCE MODEL



E_{LH} Definitions

$$\mathbf{E}_{LH} = E_{||}\hat{e}_{||} + E_{\perp r}\hat{e}_{\perp r} + E_{\perp p}\hat{e}_{\perp p}$$

Parallel to B

<

x10

radial

poloidal

Perpendicular to B

direction of $\mathbf{E}_{LH}$ $\approx tan^{-1}\left(\frac{E_{\perp r}}{E_{\perp p}}\right)$

magnitude of $\mathbf{E}_{LH}$ $= |\mathbf{E}_{LH}|$

Outline

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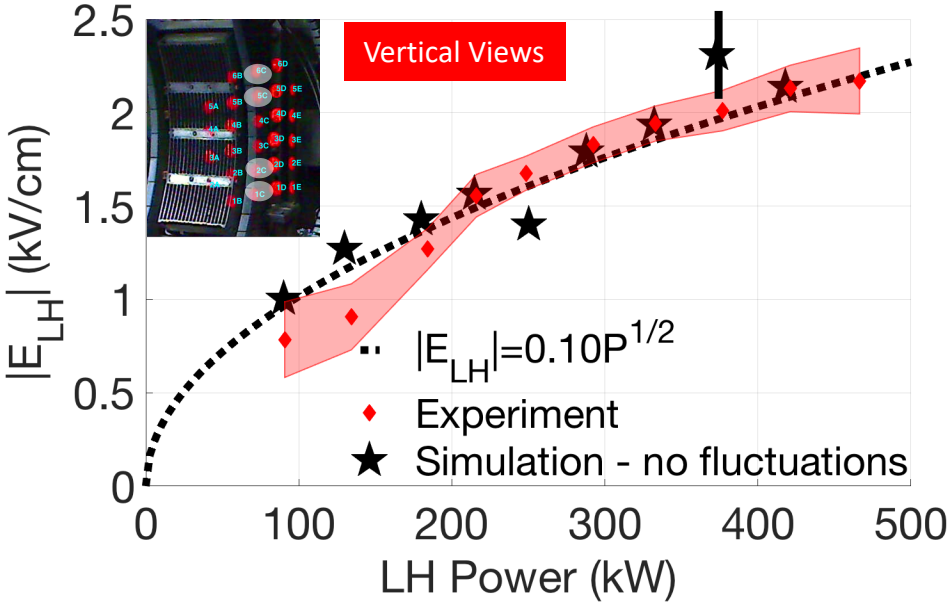
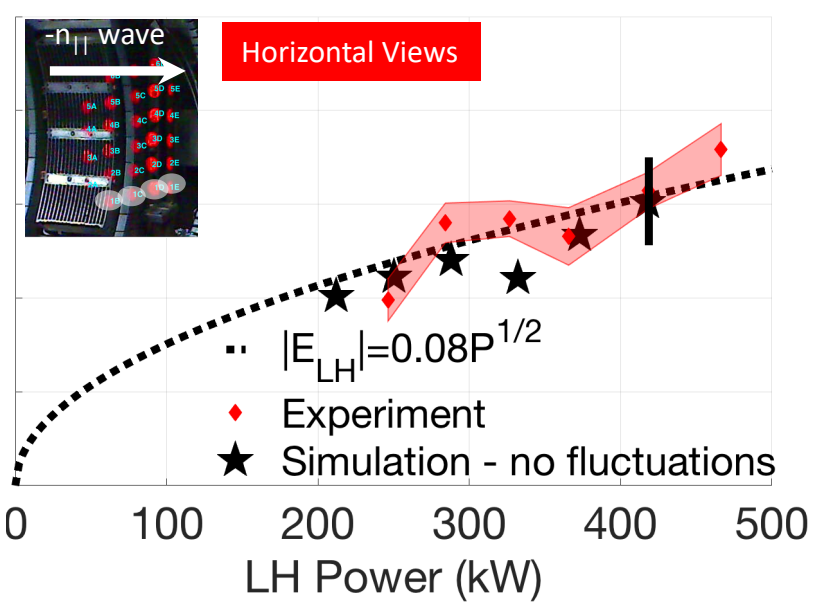
$$n_e = n_{eo}\left[\left(1 + \tilde{n}_e\, e^{-\frac{(r-r_c)^2}{r_w}} \sin\left(\frac{2\pi p}{\lambda_{ne}}\right)\right) e^{-\frac{(p-p_c)^2}{p_w^2}}\right] = 0$$

WITHOUT DENSITY FLUCTUATIONS

Globally $|E_{LH}|$ Scales as $P_{LH}^{1/2}$ as Predicted

- $|E_{LH}|$ was averaged over the vertical and horizontal measurement locations to study power distribution between $-n_{||}$ and $n_{||}$ waves.

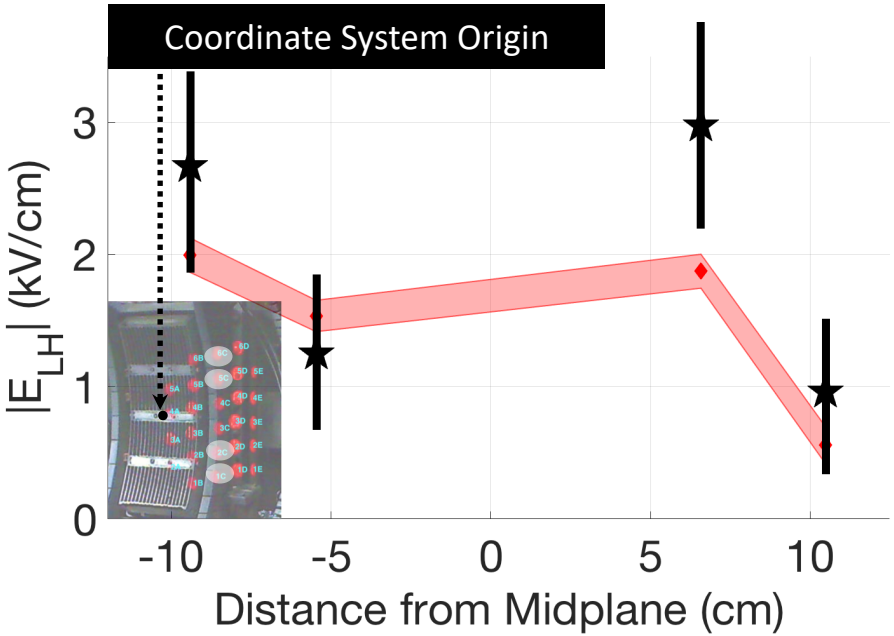


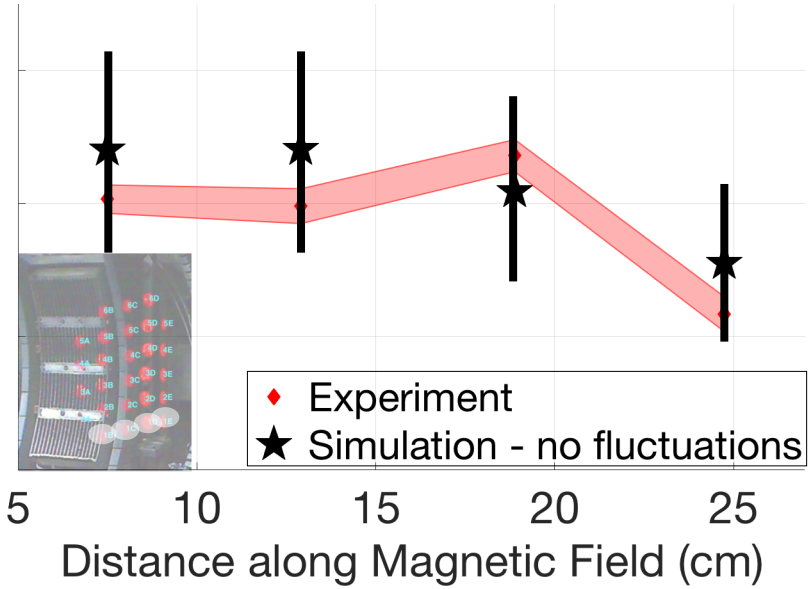


- Averaged $|E_{LH}|$ results indicated a majority of the power is being distributed to $-n_{||}$ wave.

Spatial Variation of $|E_{LH}|$ is Predicted

- The spatially variation of $|E_{LH}|$ is in good agreement with the simulation.

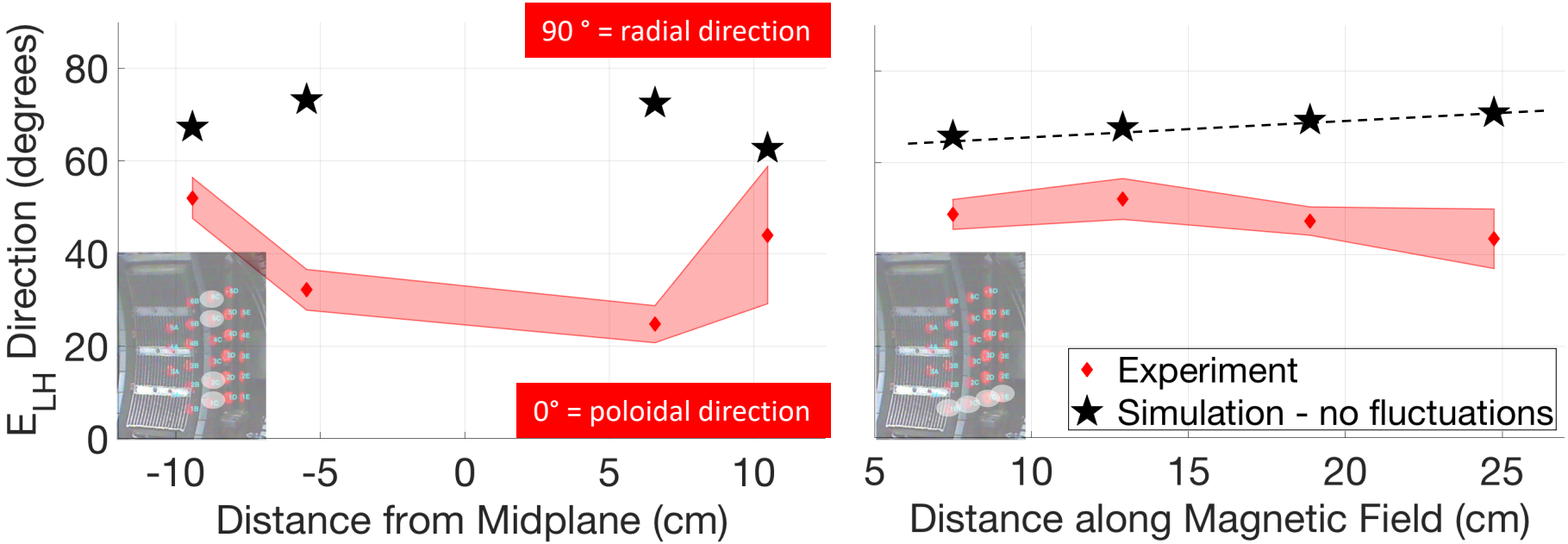




- LH wave power is not being strongly absorbed in SOL near the launcher.

LH Wave Scattering Directly Measured by E_{LH}

- LH wave scattering was found to increase as the midplane is approached.



- Strong disagreement was found between simulation and experiment, not sensitive to the n_e profile.

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$$n_e = n_{eo}\left[(1 + \tilde{n}_e\, e^{-\frac{(r-r_c)^2}{r_w}} \sin\left(\frac{2\pi p}{\lambda_{ne}}\right) - \frac{(p-p_c)^2}{p_w^2}\right]$$

WITH DENSITY FLUCTUATIONS

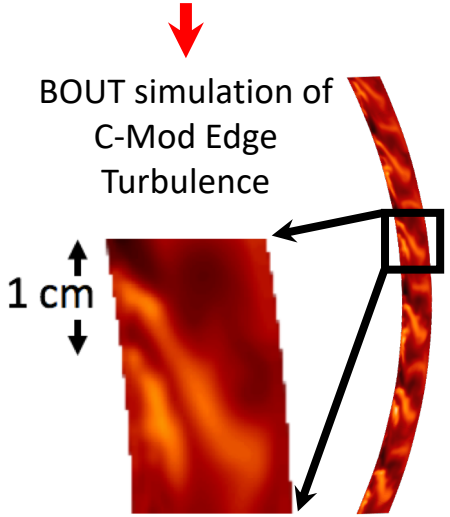
Synthetic Turbulence has Large Effect on E_{LH}

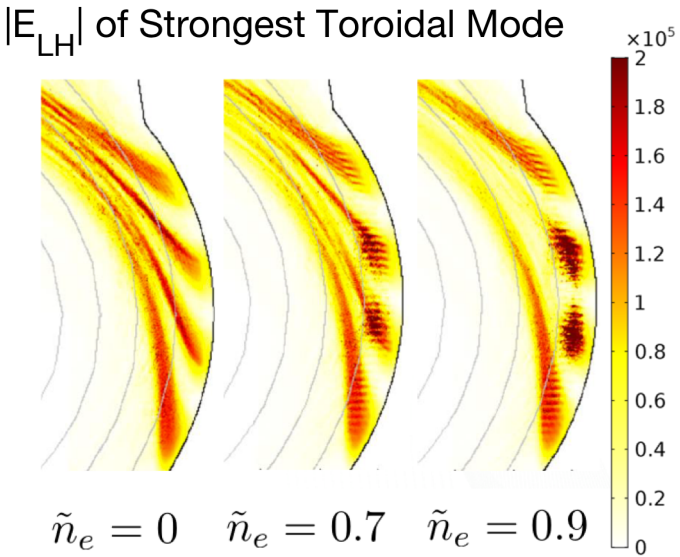
- Synthetic turbulence model is based on experimental observations [1] and a BOUT simulation [2].

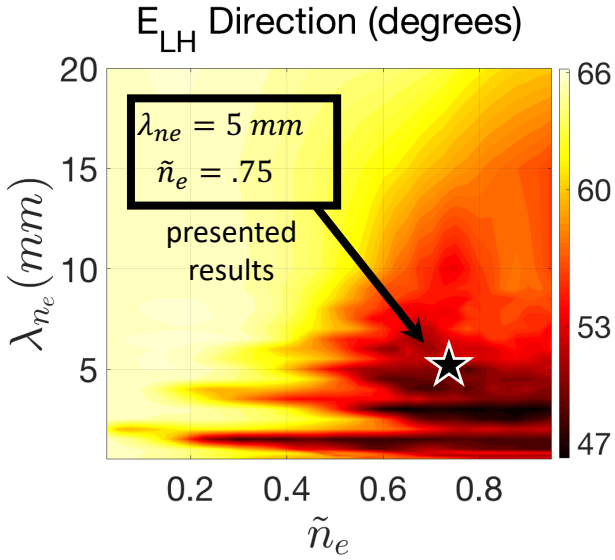
Density fluctuations peak at midplane [1]

Density fluctuation scale length ≅ 1 cm [2]

$$n_e = n_{eo}\left[\left(1 + \tilde{n}_e\, e^{-\frac{(r-r_c)^2}{r_w}} \sin\left(\frac{2\pi p}{\lambda_{ne}}\right)\right)^{-\frac{(p-p_c)^2}{p_w^2}}\right]$$







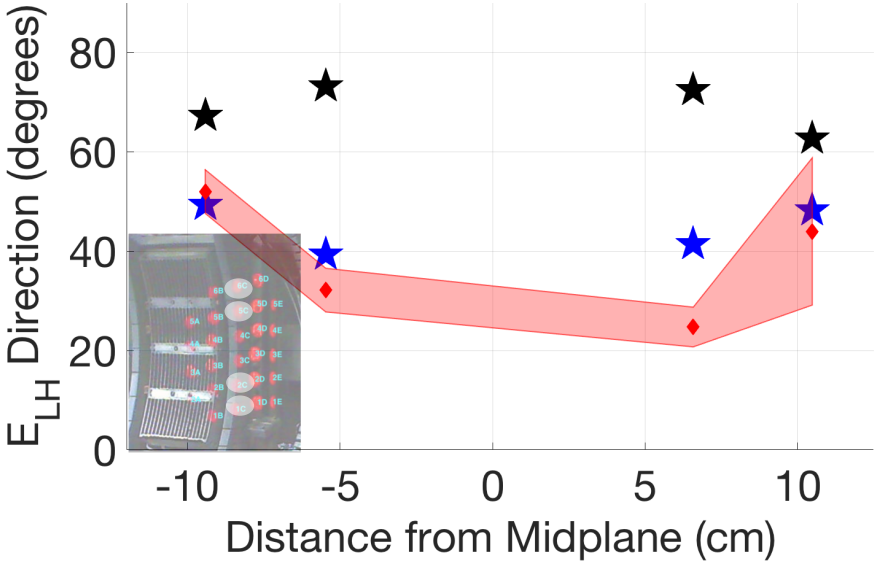
[1] SMICK N. et al., Nucl. Fusion 53 (2013) 023001.

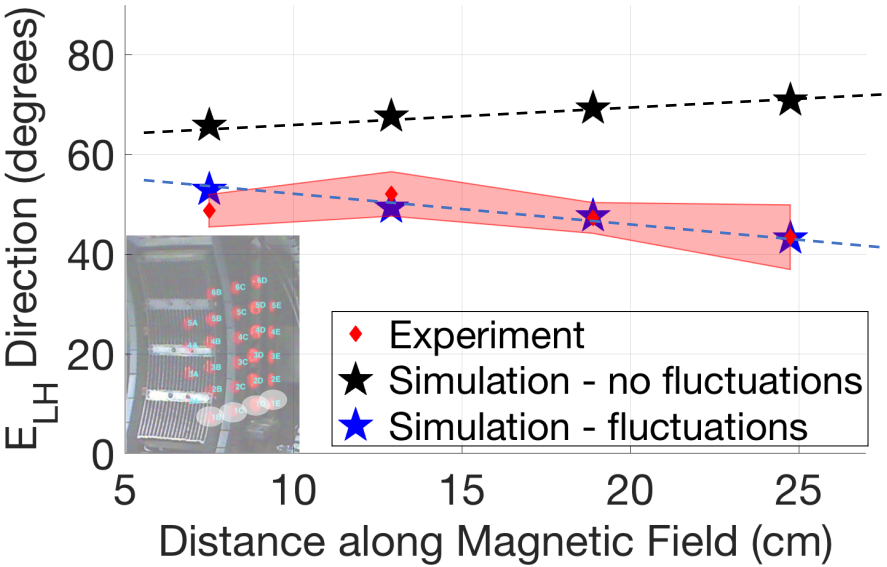
[2] UMANSKY M.V. et al., J. Nucl. Mater. 337 (2005) 266.

Synthetic Turbulence Predicts LH Wave Scattering

- Synthetic turbulence having $\lambda_{ne} = 5\ mm$ and $\tilde{n}_e = .75$ can be used to explain experimental and simulation discrepancy in both vertical and horizontal sets of measurements.

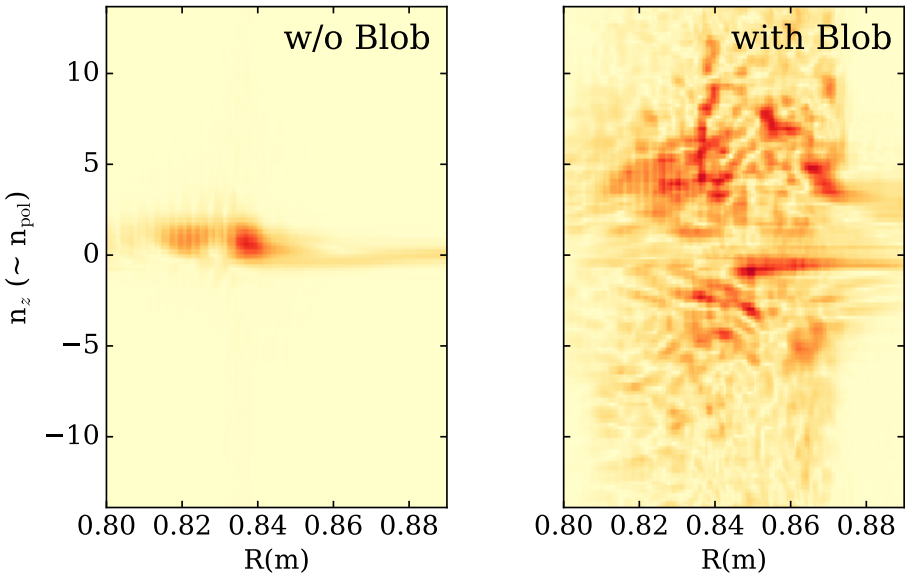
WIDE RANGE OF λ_{ne} AND $\tilde{n}_e$ VALUES YIELD SIMILAR RESULTS

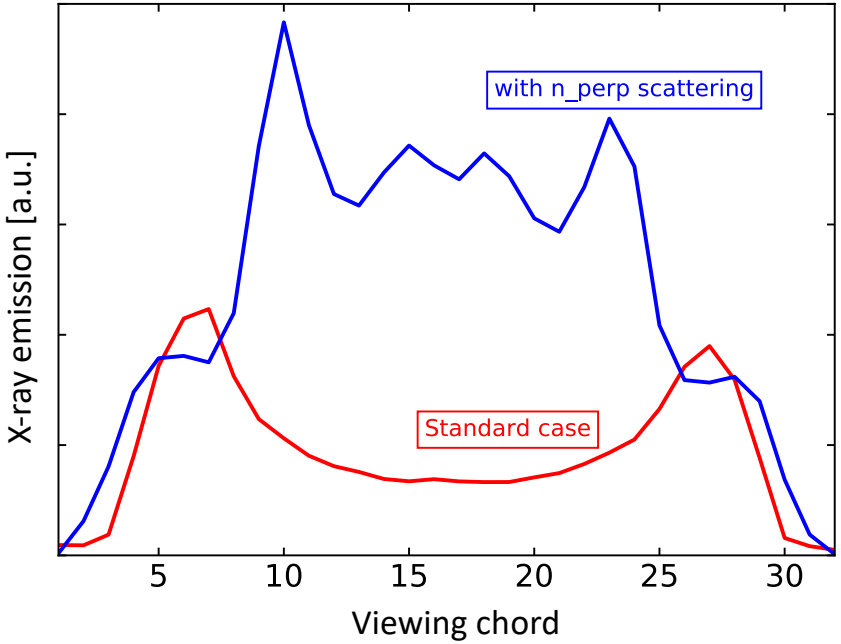




Scattering of $k_\perp$ has Significant Impact on Core Wave Propagation/Absorption

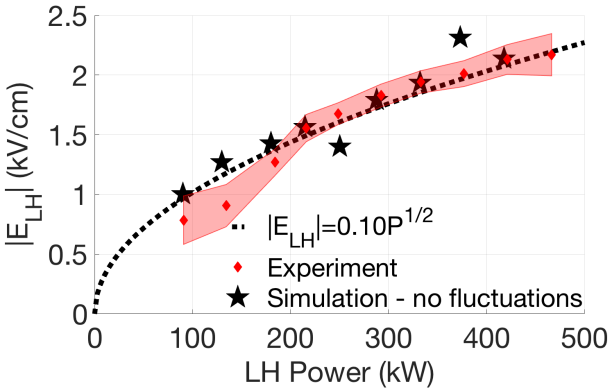
- Scattering of $k_\perp$ by density blobs can change evolution of $k_{||}$ along the ray ➔ different damping profile



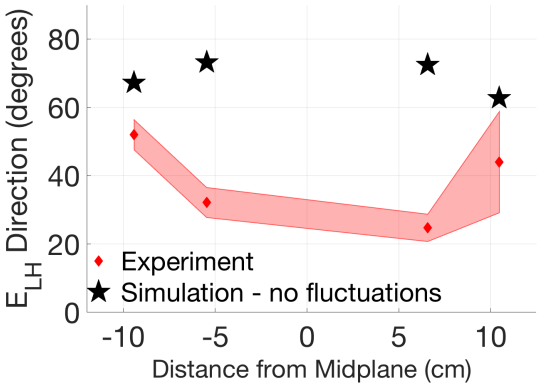


Conclusions

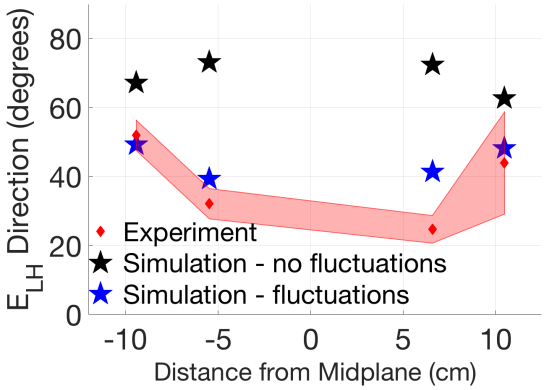
LH wave absorption negligible in SOL near the launcher



Strong LH wave scattering is occurring in the SOL



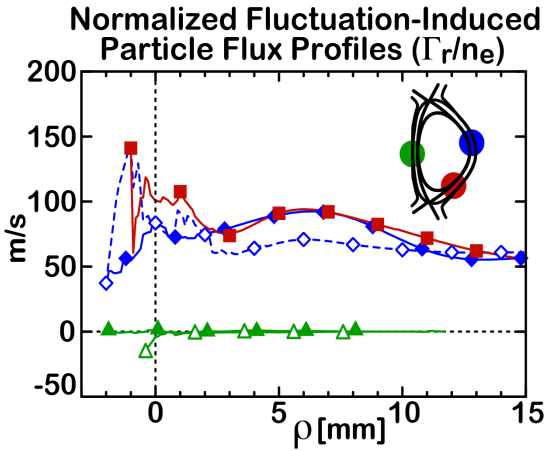
SOL density fluctuations predict LH wave scattering



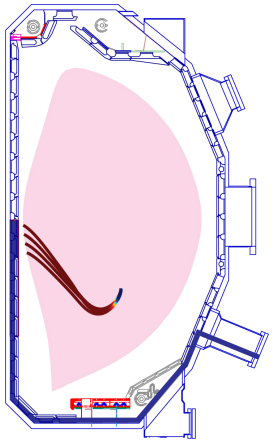
Future Measurements of E_{LH}

DIII-D High Field Side Launch

HFS SOL is quiescent - density fluctuations seem to be absent!

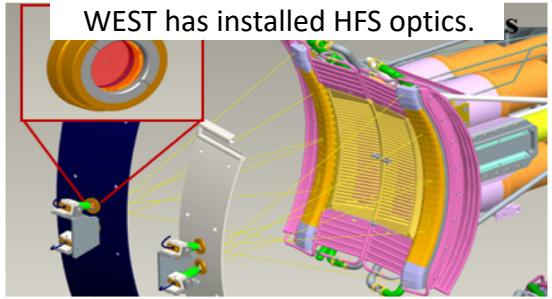


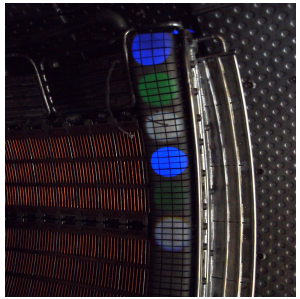
N. Smick NF (2013)



HFS LHCD simulation of DIII-D discharge 147634 using GENRAY-CQL3D shows excellent wave penetration and single pass damping.

WEST

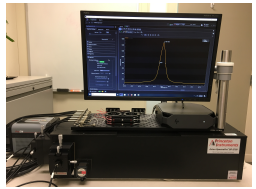




Polarizers will be installed early next year, yielding 12 sightlines.

Your Machine?

Have spectrometer… Will travel…

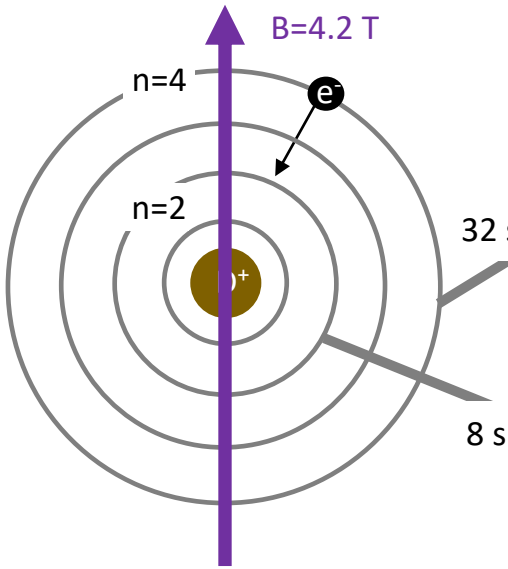


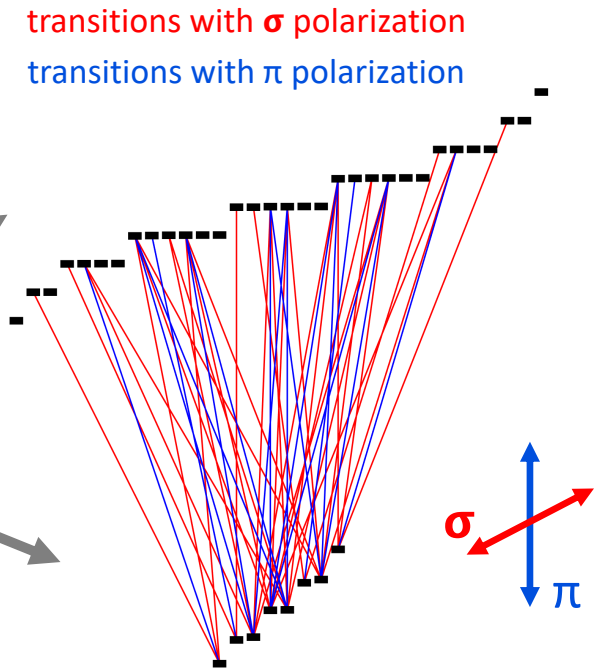
FWHM = 0.007 nm

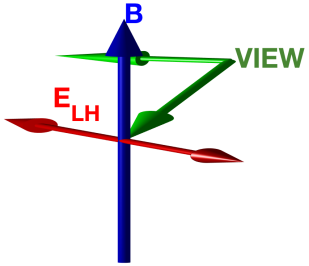
QUESTIONS

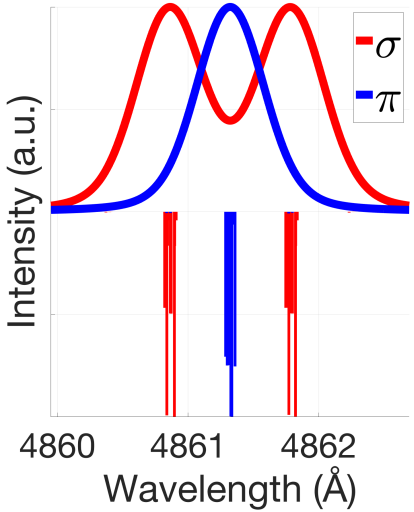
Spectral Line Profile Sensitivity to E_{LH}

- The spectral line profile is uniquely sensitive to all components of the E_{LH} vector.



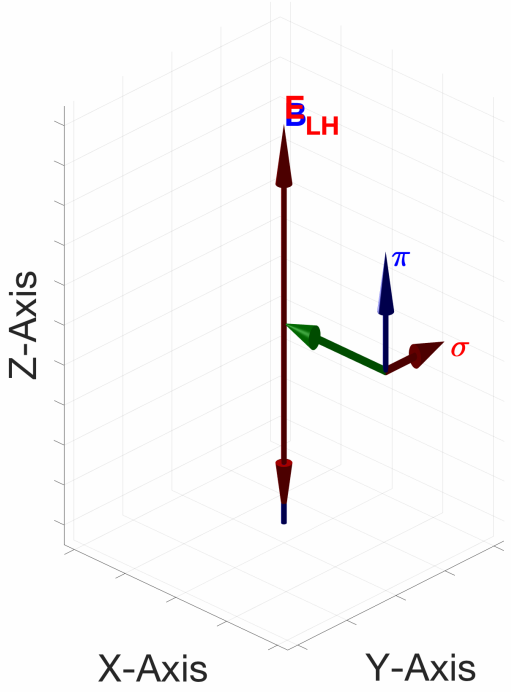


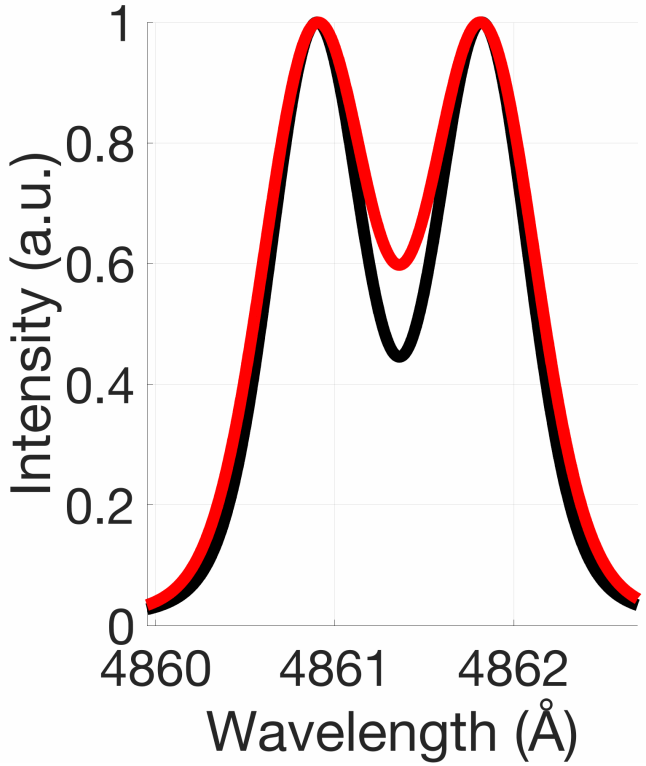


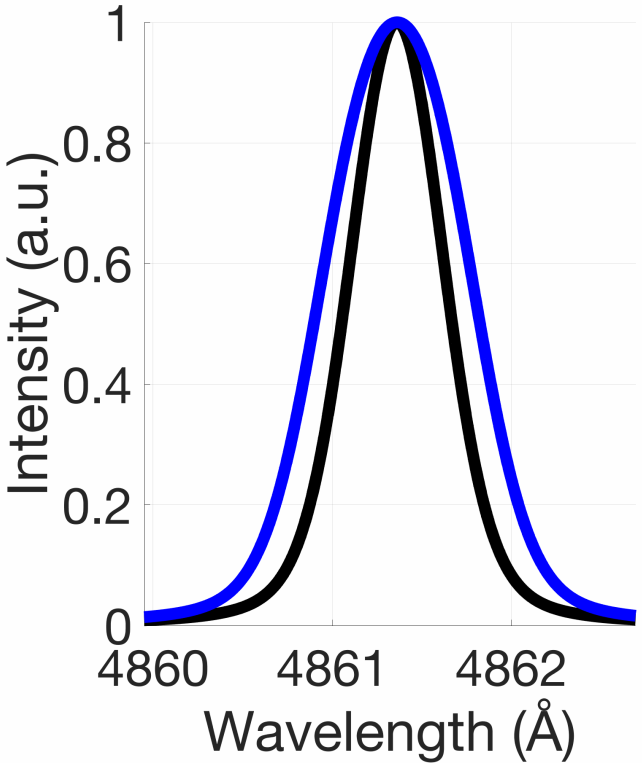


Spectral Line Profile Sensitivity to E_{LH}

$$E_{LH} = 0.0\ \hat{x} + 0.0\ \hat{y} + 2.5\ \hat{z}\ \mathrm{kV/cm}$$

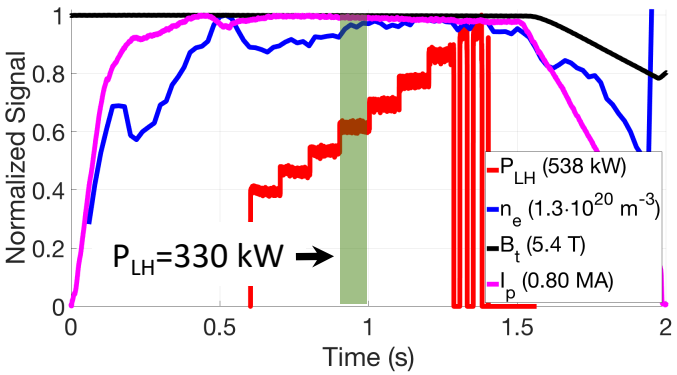


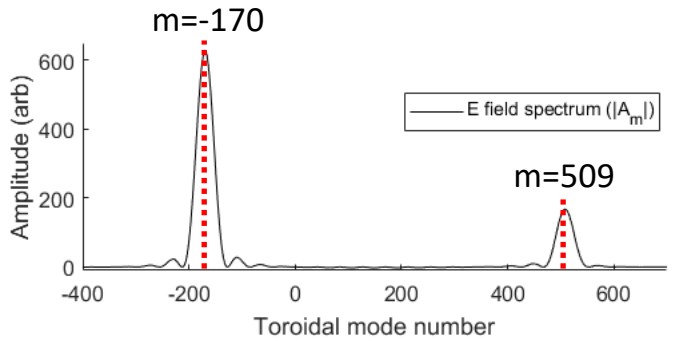


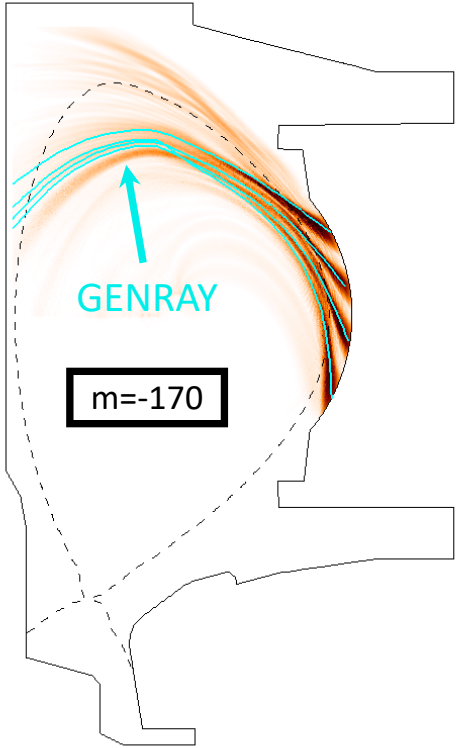


GENRAY Validation of COMSOL Simulations

- COMSOL model was validated using GENRAY.







counter-current propagating wave

co-current propagating wave

Vertical Position Scan of $|E_{LH}|$ vs. P_{LH}