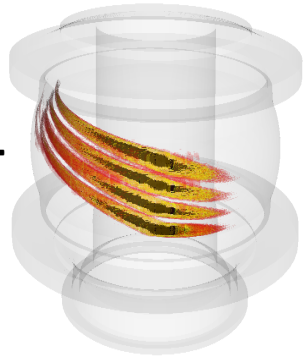


EXPERIMENTAL EVIDENCE OF LOWER HYBRID WAVE SCATTERING IN ALCATOR C- MOD DUE TO SCRAPE OFF LAYER DENSITY FLUCTUATIONS



$$\tilde{n}_e = 0 \quad \tilde{n}_e = 0.9$$

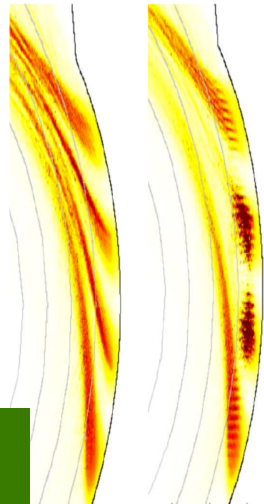
Elijah H. Martin

Fusion and Materials for Nuclear Systems Division, ORNL

PRESENTED BY:

Gregory M. Wallace

Plasma Science and Fusion Center, MIT



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



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Syunichi Shiraiwa	(MIT, PSFC)	Maxim Umansky	(LLNL, FES)
Paul Bonoli	(MIT, PSFC)	Andris Dimits	(LLNL, FES)
John Wright	(MIT, PSFC)	Ilon Joseph	(LLNL, FES)

EDGE TURBULENCE ALTERS LOWER HYBRID WAVE PROPAGATION

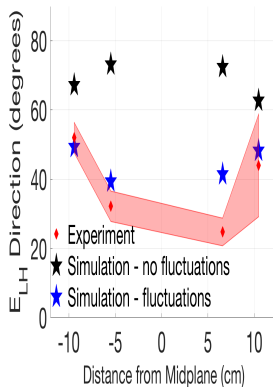
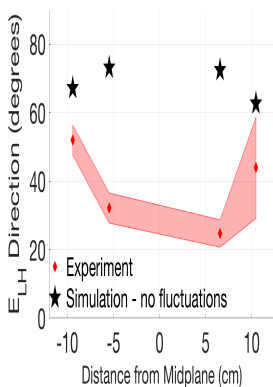
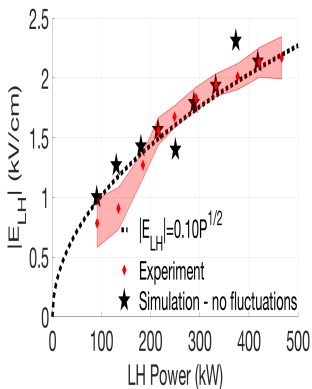
1

DIRECT
EXPERIMENTAL MEASUREMENT $\Rightarrow E_{\text{LH}}$ = 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

2

- 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.

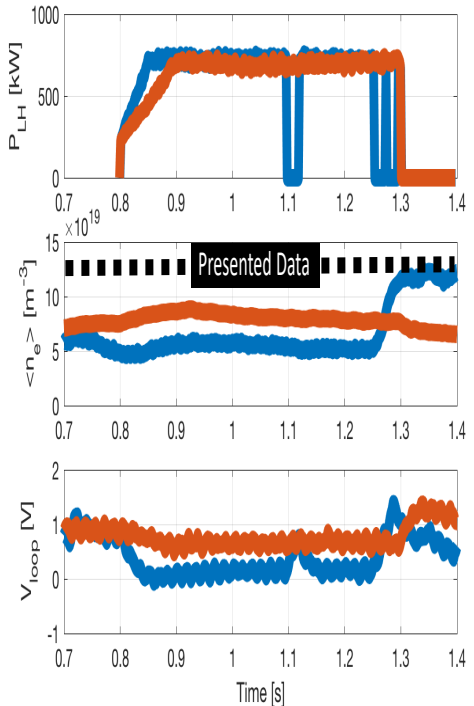
High density plasmas

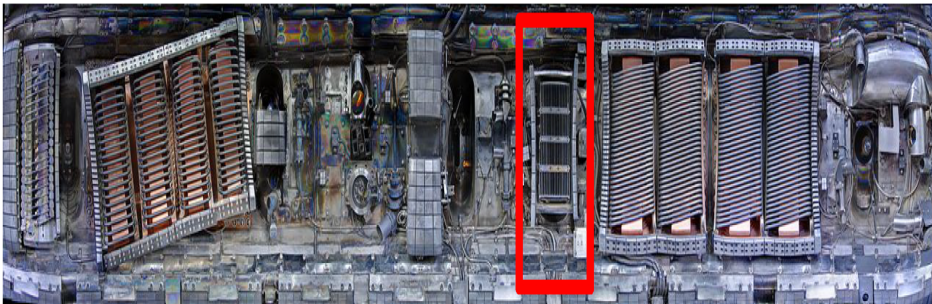


Loss of efficiency at high density ($n_e > 10^{20} \text{ m}^{-3}$)



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





Lower Hybrid Antenna

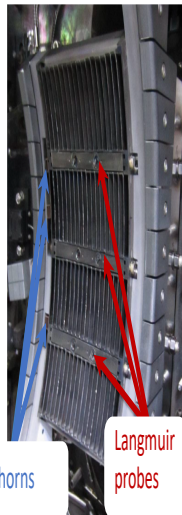
PRESENTED DATA

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

local n_e profile



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



X-mode reflectometer horns

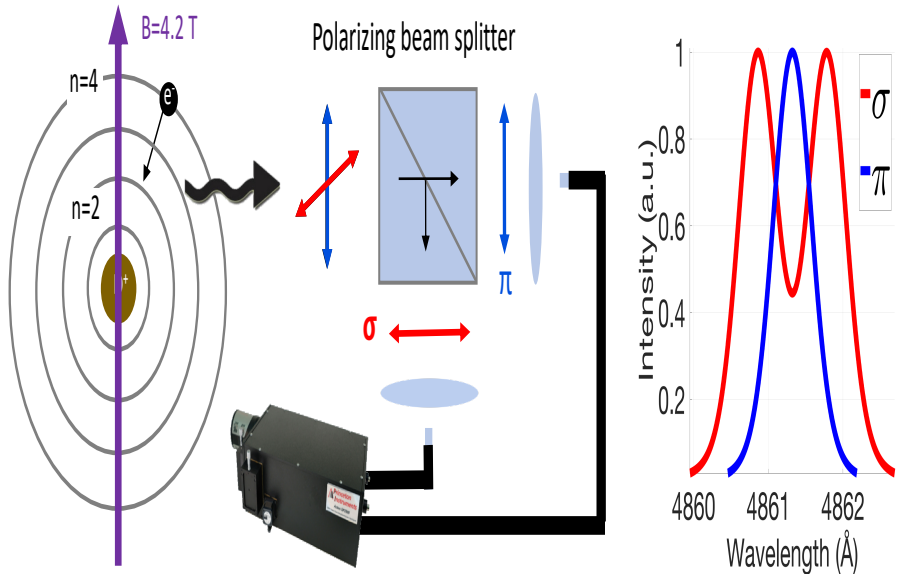
Langmuir
probes

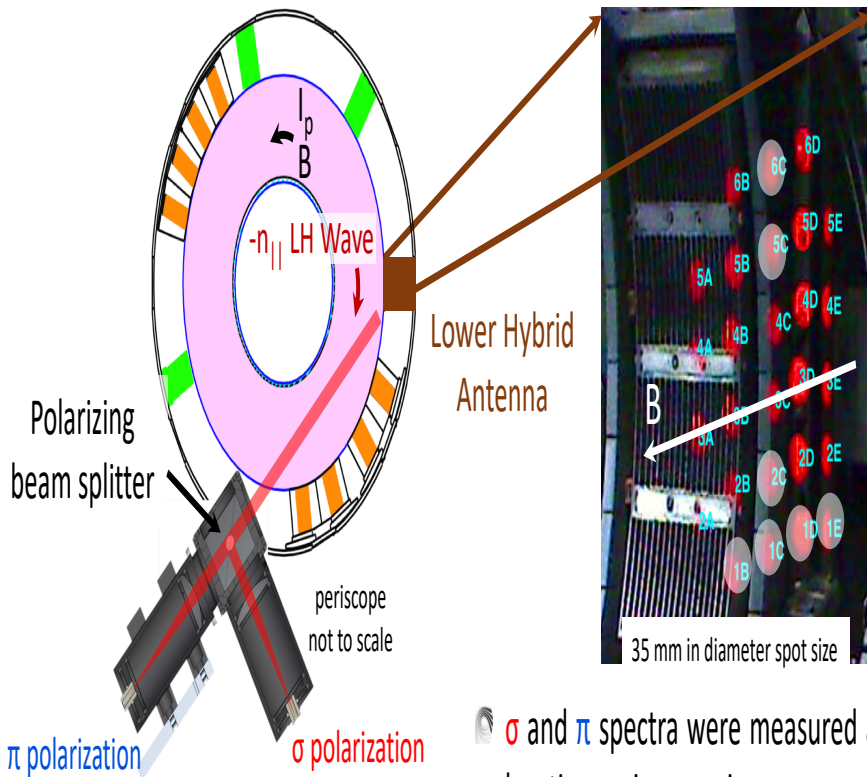
THE DIAGNOSTIC AND IMPLEMENTATION ON ALCATOR C-MOD

COMSOL FULL-WAVE 3D SIMULATIONS

COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

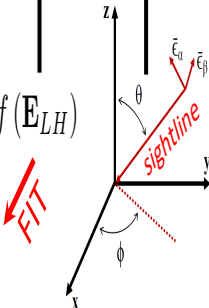
- Polarized \rightarrow measurement of optical emission having a specific polarization.
- Optical emission spectroscopy \rightarrow passive measurement of the D_{β} spectrum.
- E_{LH} is determined from a systematic fit to the shape of the spectral line profiles.





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

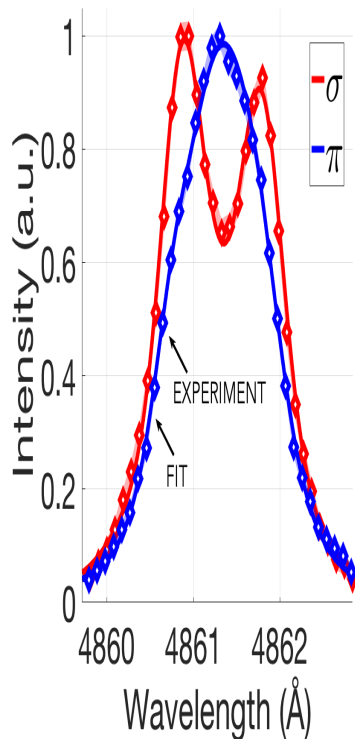
The time dependent Schrodinger equation is fit to the experimentally measured σ and π spectra.

$$i\hbar \frac{\partial \Psi}{\partial t} = \left[\underset{\substack{\uparrow \\ \text{unperturbed Hamiltonian}}}{H} + \underset{\substack{\uparrow \\ f(B)}}{H^B} + \underset{\substack{\uparrow \\ f(E_{LH})}}{H^E(t)} + \underset{\substack{\uparrow \\ \theta, \phi}}{\hat{H}} \right] \Psi$$


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

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

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



THE DIAGNOSTIC AND IMPLEMENTATION ON ALCATOR C-MOD

COMSOL FULL-WAVE 3D SIMULATIONS

COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

- 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.

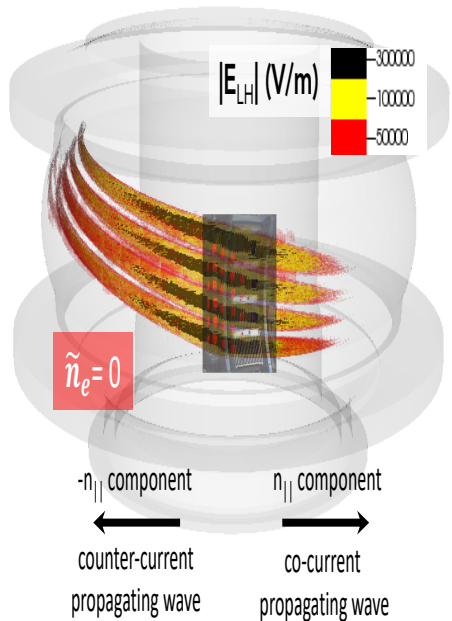
$$E_{LH}(r, z, \theta) = \sum_{m=1}^{N_m} A_m E_m(r, z) e^{im\theta}$$

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

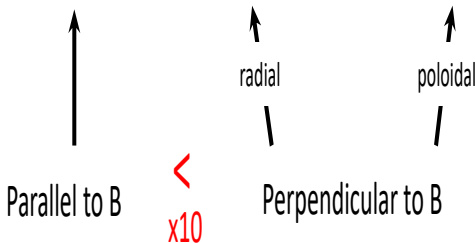
$$n_e = n_{e0} \left[\left(1 + \tilde{n}_e e^{-\frac{(r-r_c)^2}{r_w}} \sin\left(\frac{2\pi p}{\lambda_{ne}}\right) - \frac{(p-p_c)^2}{p_w^2} \right) \right]$$

REFLECTOMETRY
MEASURED

STATIC SYNTHETIC
TURBULENCE MODEL



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



direction of \mathbf{E}_{LH}

$$\approx \tan^{-1} \left(\frac{E_{\perp r}}{E_{\perp p}} \right)$$

magnitude of \mathbf{E}_{LH}

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


THE DIAGNOSTIC AND IMPLEMENTATION ON ALCATOR C-MOD

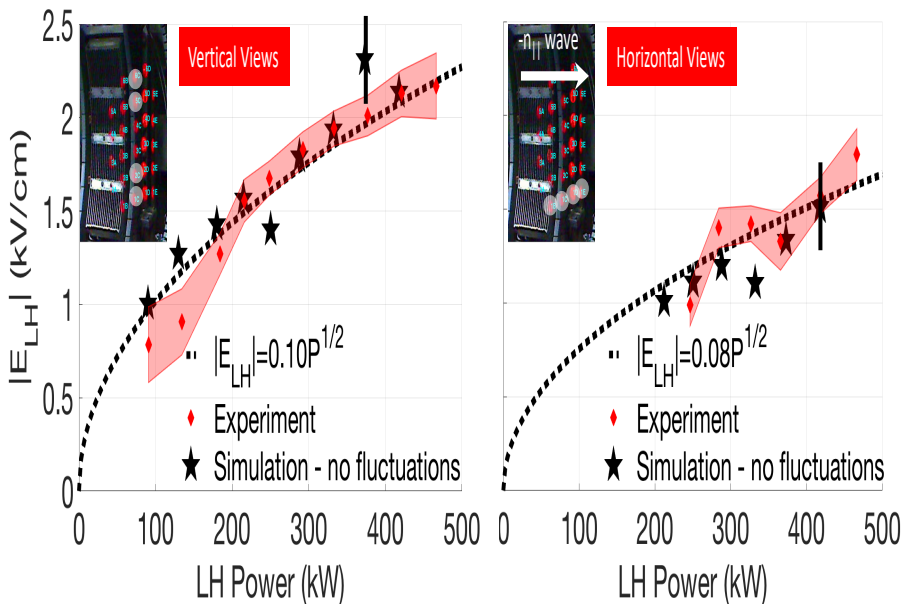
COMSOL FULL-WAVE 3D SIMULATIONS

COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

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

WITHOUT DENSITY FLUCTUATIONS

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

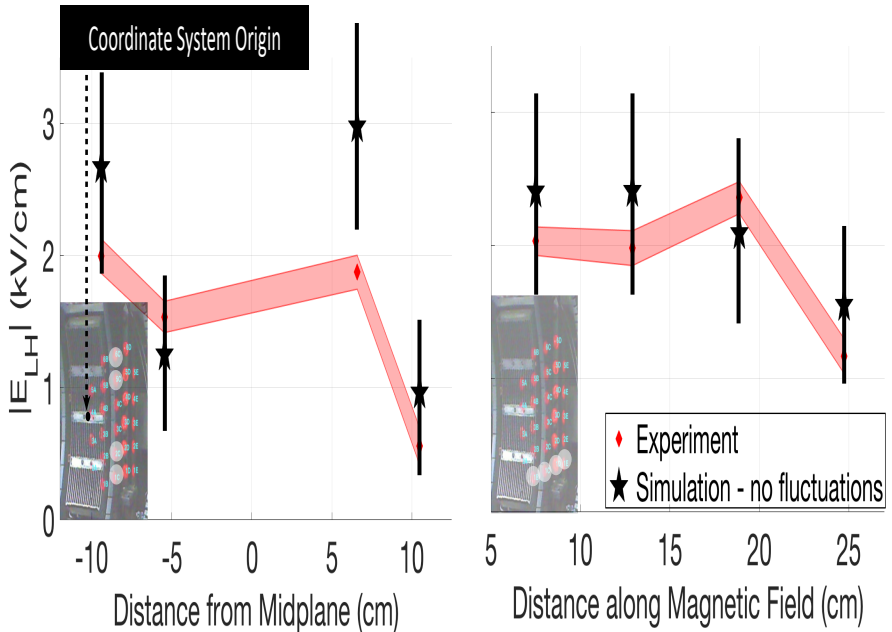


-  Averaged $|E_{LH}|$ results indicated a majority of the power is being distributed to $-n_{||}$ wave.

SPATIAL VARIATION OF $|E_{LH}|$ IS PREDICTED

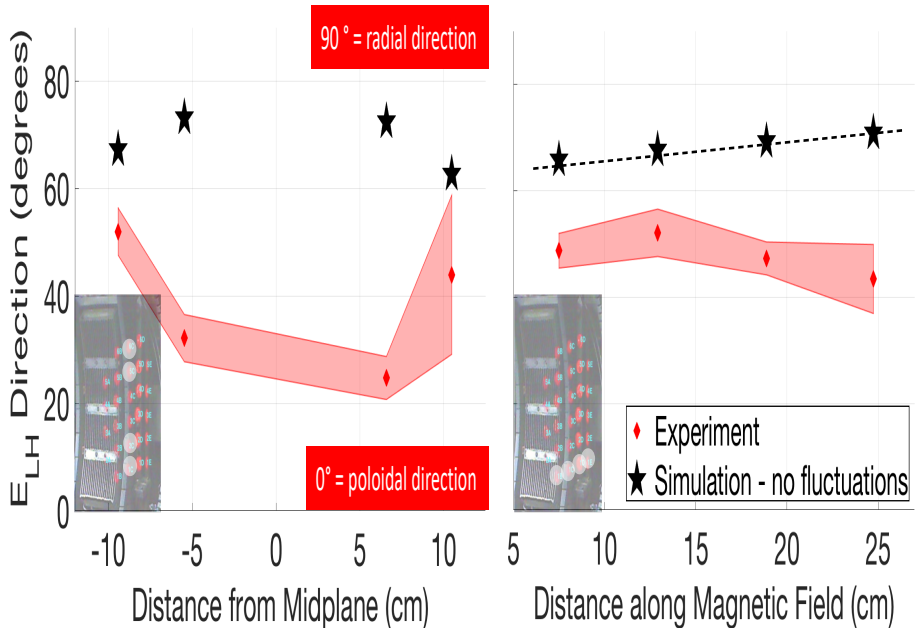
10

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 was found to increase as the midplane is approached.



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

THE DIAGNOSTIC AND IMPLEMENTATION ON ALCATOR C-MOD

COMSOL FULL-WAVE 3D SIMULATIONS

COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

$$n_e = n_{e0} \left[1 + \tilde{n}_e e^{-\frac{(r-r_c)^2}{r_w}} \sin\left(\frac{2\pi p}{\lambda_{ne}}\right) - \frac{(p-p_c)^2}{p_w^2} \right]$$



WITH DENSITY FLUCTUATIONS

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

Density fluctuations peak at midplane [1]

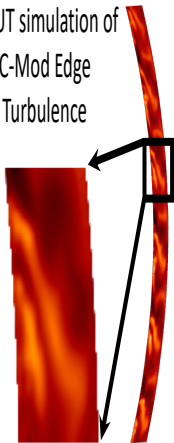
Density fluctuation scale length $\cong 1$ cm [2]

$$n_e = n_{e0} \left[1 + \tilde{n}_e e^{-\frac{(r-r_c)^2}{r_w}} \sin\left(\frac{2\pi p}{\lambda_{ne}}\right) - \frac{(p-p_c)^2}{p_w^2} \right]$$

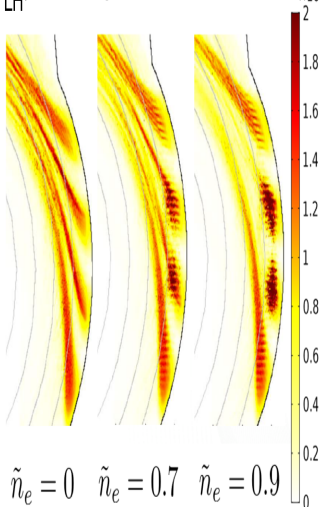


BOUT simulation of
C-Mod Edge
Turbulence

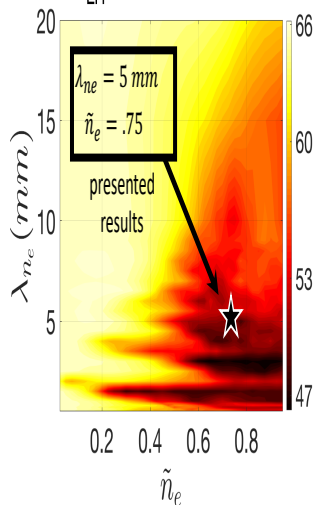
1 cm
↑
↓



$|E_{LH}|$ of Strongest Toroidal Mode



E_{LH} Direction (degrees)




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

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

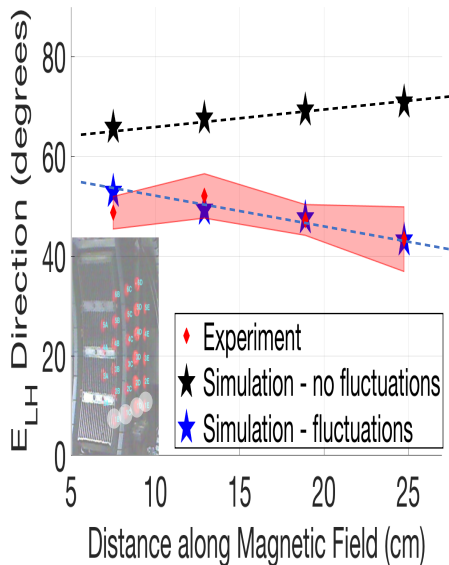
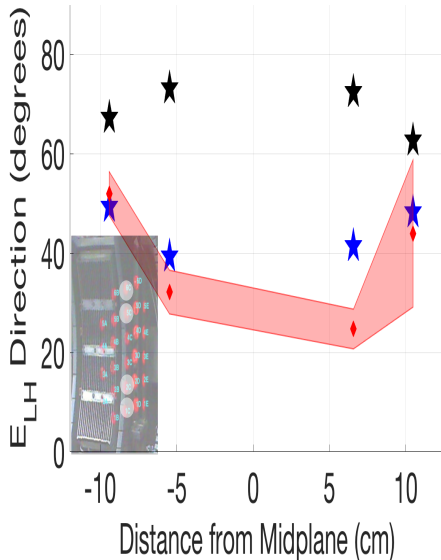
SYNTHETIC TURBULENCE PREDICTS LH

WAVE SCATTERING

13

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

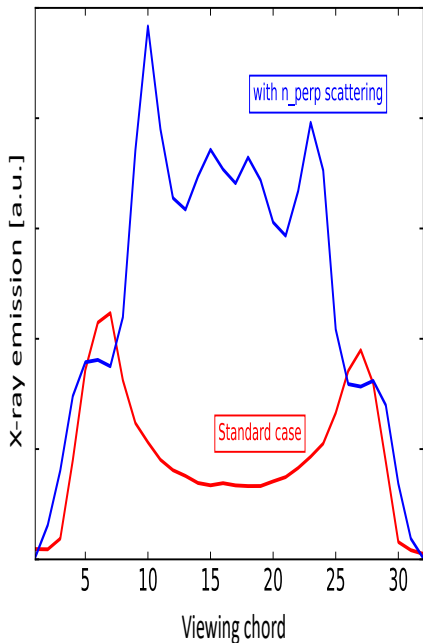
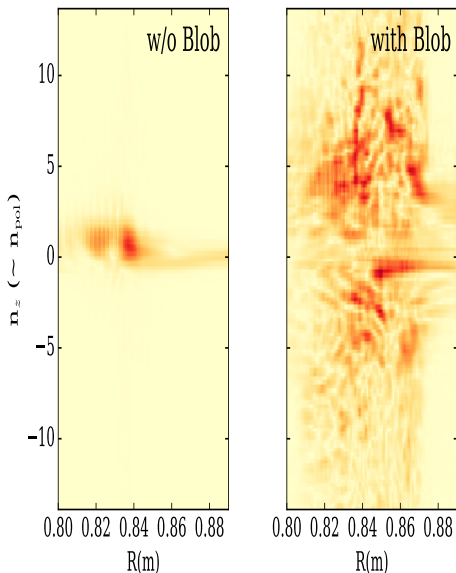
WIDE RANGE OF λ_{ne} AND \tilde{n}_e VALUES YIELD SIMILAR RESULTS



SCATTERING OF k_{\perp} HAS SIGNIFICANT IMPACT ON CORE WAVE PROPAGATION/ABSORPTION

14

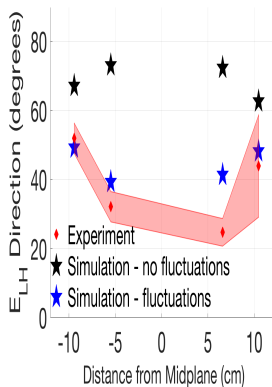
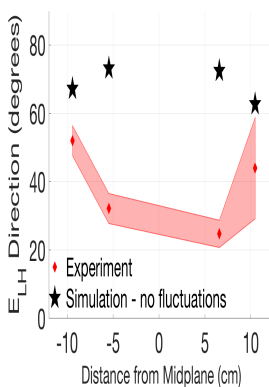
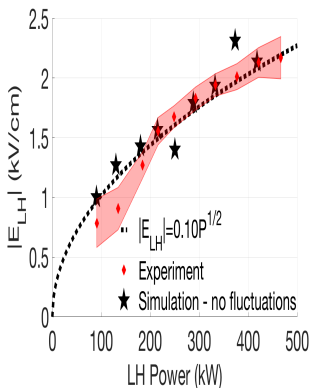
Scattering of k_{\perp} by density blobs can change evolution of k_{\parallel} along the ray \rightarrow different damping profile



LH wave absorption negligible in SOL near the launcher

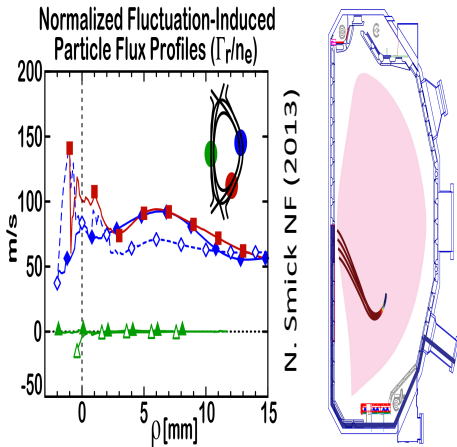
Strong LH wave scattering is occurring in the SOL

SOL density fluctuations predict LH wave scattering



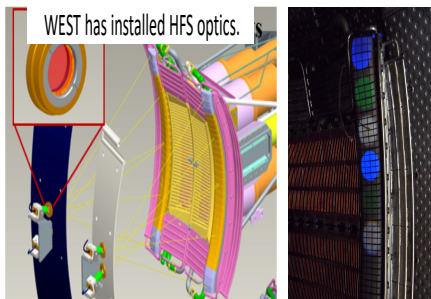
DIII-D High Field Side Launch

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



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

WEST

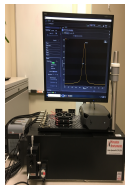


Polarizers will be installed early next year, yielding 12 sightlines.

Your Machine?

Have spectrometer... Will travel...

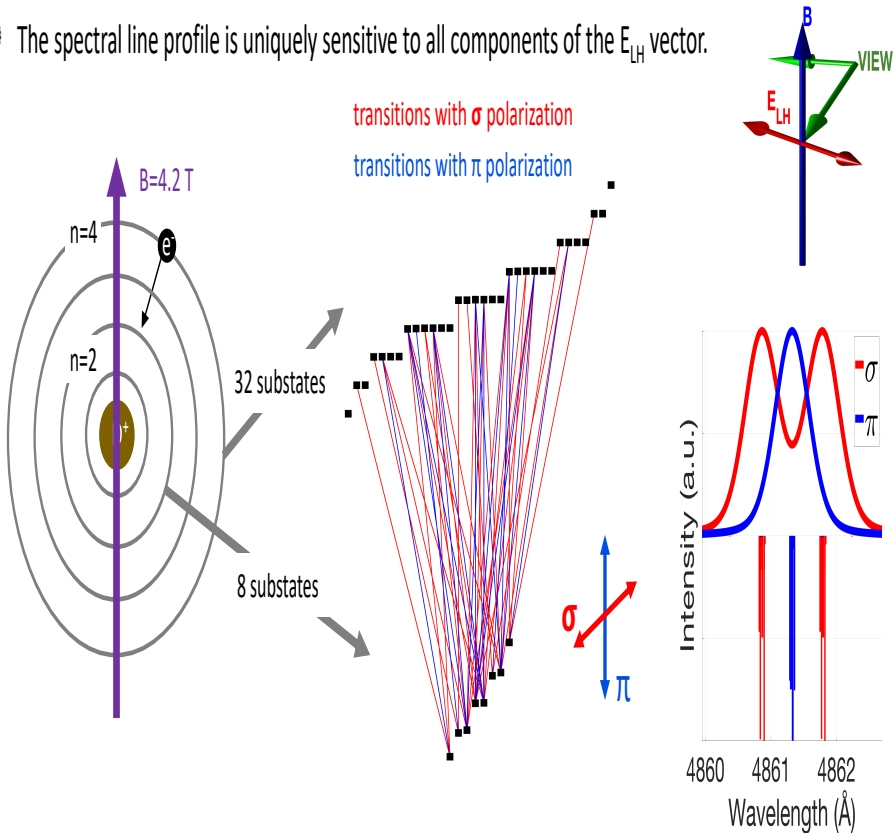
FWHM = 0.007 nm



QUESTIONS

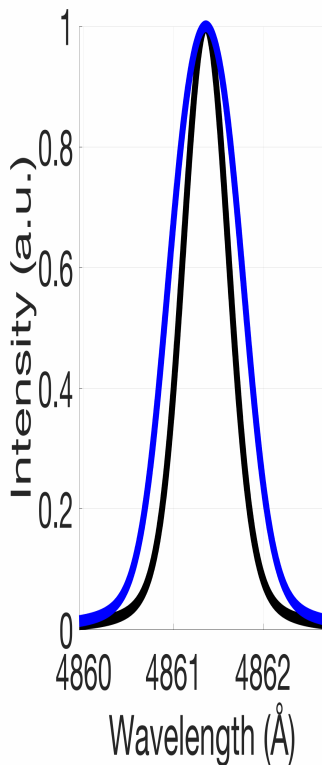
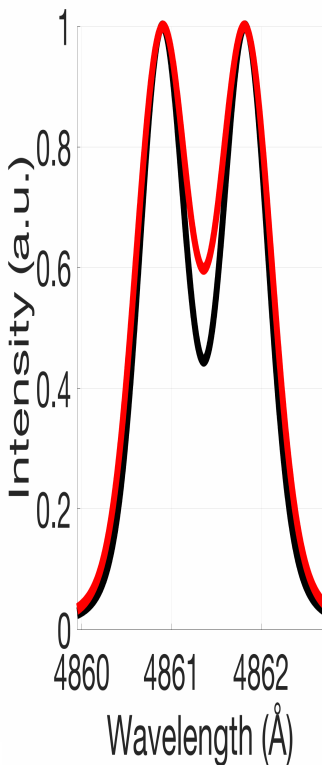
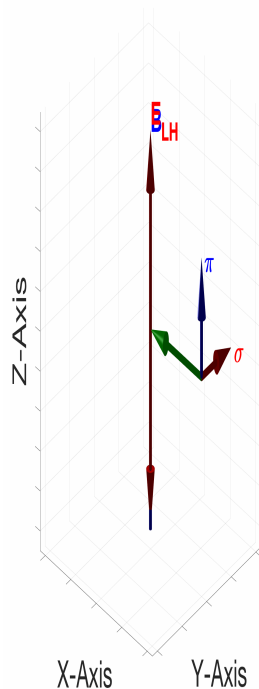
SPECTRAL LINE PROFILE SENSITIVITY TO E_{LH}

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

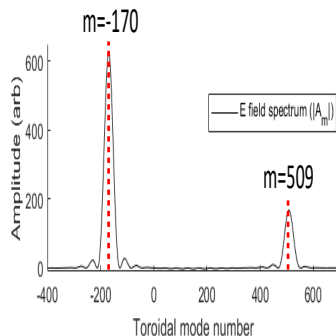
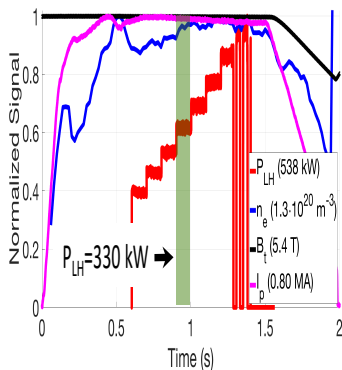


SPECTRAL LINE PROFILE SENSITIVITY TO E_{LH}

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



COMSOL model was validated using GENRAY.

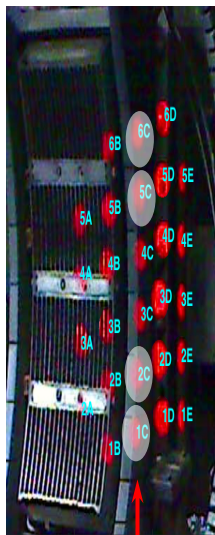


counter-current propagating wave



co-current propagating wave

VERTICAL POSITION SCAN OF $|E_{LH}|$ VS. P_{LH}



Vertical Views

