Theory and simulation analysis of lower hybrid current drive experiments on the EAST tokamak

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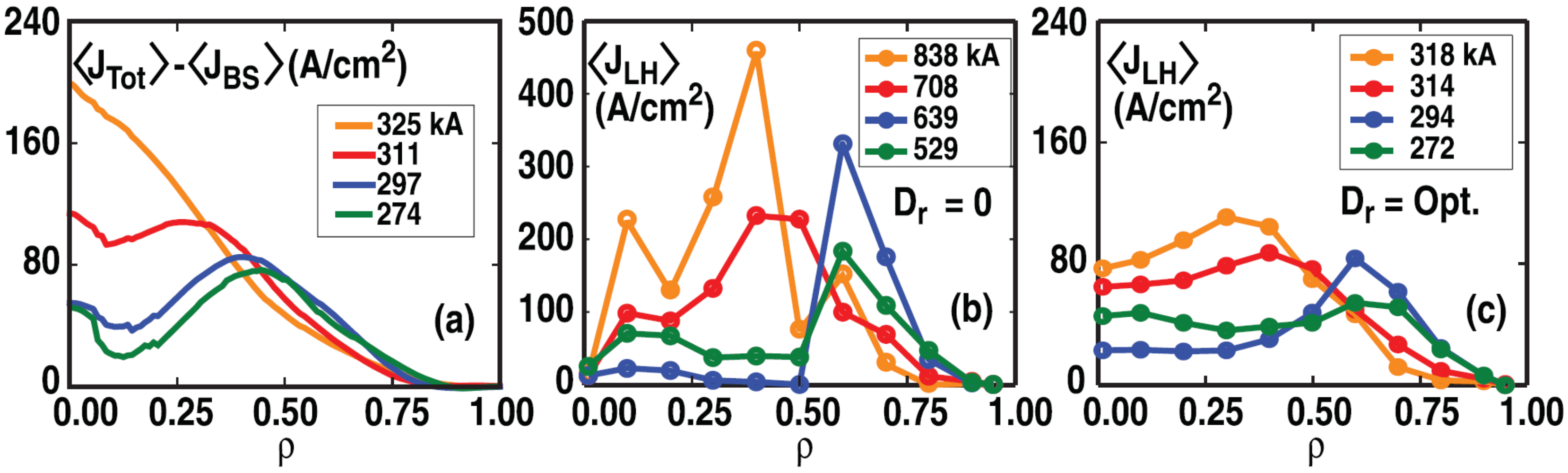
Modeling efforts on lower hybrid current drive (LHCD) on EAST have focused on three questions motivated by experimental observations

1. The ubiquitous spectral gap problem of how LH waves that are coupled into EAST plasmas at suprathermal phase speeds are able to damp at 2-3 × v_{te}, which is a necessary condition for efficient Landau damping of LH waves.
2. Why simulation results from ray tracing / Fokker-Planck models tend to be much more sensitive to changes in plasma parameters than what is observed is experiment.
3. Why simulated LH power deposition profiles in EAST plasmas, especially at 4.6 GHz, tend to be peaked off-axis whereas experimental measurements of hard x-ray emissivity indicate the wave damping is more centrally peaked.

- Review ongoing improvements in the physics of the LH current drive models aimed at answering these three questions that include:
  - Incorporation of scattering of LH waves from turbulent density fluctuations.
  - Inclusion of full-wave effects on LH wave propagation and absorption.
- **End goal is to produce a reliable control level LHRF actuator model**

Analysis of EAST discharges with LHCD elucidated the role of magnetic shear in broadening of the LH current profile [X. Zhai et al, PPCF 61, 045002 (2019)]

- Analysis by J. Chen & X. Zhai of four well-diagnosed non-inductive L-mode discharges with increasing density [see A. Garofalo NF **57**, 076037 (2017)] showed qualitative agreement between LH current density profiles and measured profiles:
  - Employed both GENRAY-CQL3D simulations and phase space analysis techniques.
  - Included both LH source frequencies (2.45 GHz + 4.6 GHz) and compared results for $D_r = 0$ (no fast electron diffusion) and for an optimized diffusion coefficient for fast electrons.



Effect of LH wave scattering has been found to be important in both EAST and Alcator C-Mod in a number of studies

- Introduction of a fluctuating density $\delta n_e(\rho, \theta, \phi)$ into GENRAY simulations was found to produce qualitative changes in LHRF power deposition (more peaked profiles) but still not in quantitative agreement with experiment [C. Yang et al, Physics of Plasmas **25**, 082516 (2018)].

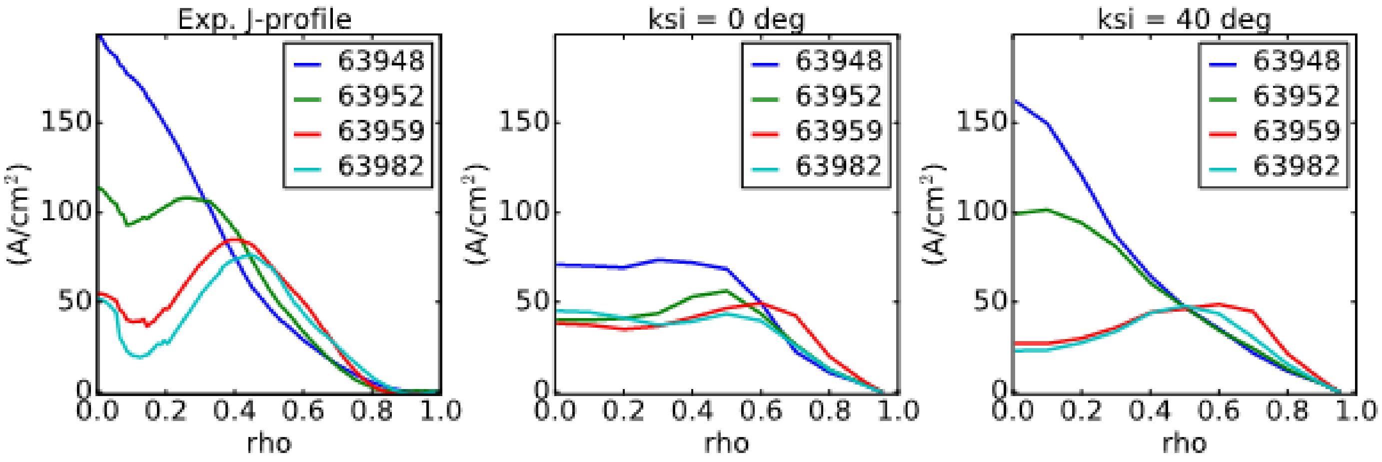
- Refraction of LH waves from field aligned blob-like turbulence in Alcator C-Mod was found to greatly reduce sensitivity to variations in background density and also to result in some peaking of LHRF power deposition profiles [B. Biswas et al, PPCF **62**, 115006 (2020)].

- Effect of $E \times B$ drifts has been found to significantly broaden the probability distribution of scattering angles ($k_{||}$ and k_θ) at the LCFS [C. Wu (doctoral thesis); also being submitted for publication].

- **Application of an initial rotation angle in the LH wave $k_\perp$ vector has identified an optimum rotation angle that results in quantitative agreement with measured current profiles in EAST [S. G. Baek this meeting].**

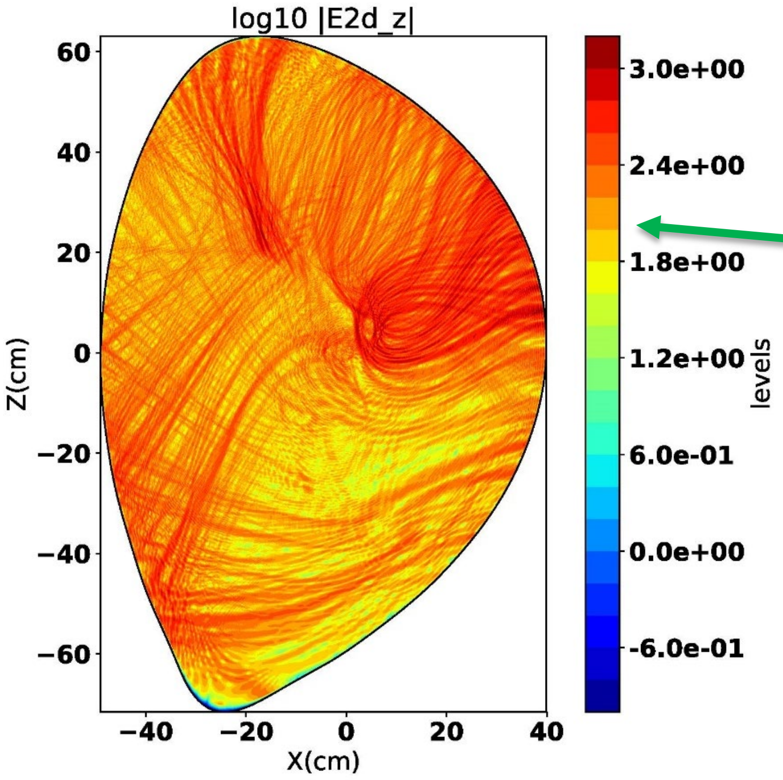
Wider study performed to assess the potential role of turbulent scattering on LHCD in EAST [S. G. Baek – 2020 & 2021]

- Revisited non-inductive L-mode discharges [see A. Garofalo NF **57**, 076037 (2017)] and identified an **optimum rotation angle (+40 deg.) of the perpendicular wave-vector in GENRAY, possibly due to wave scattering which reproduces experimental profiles:**



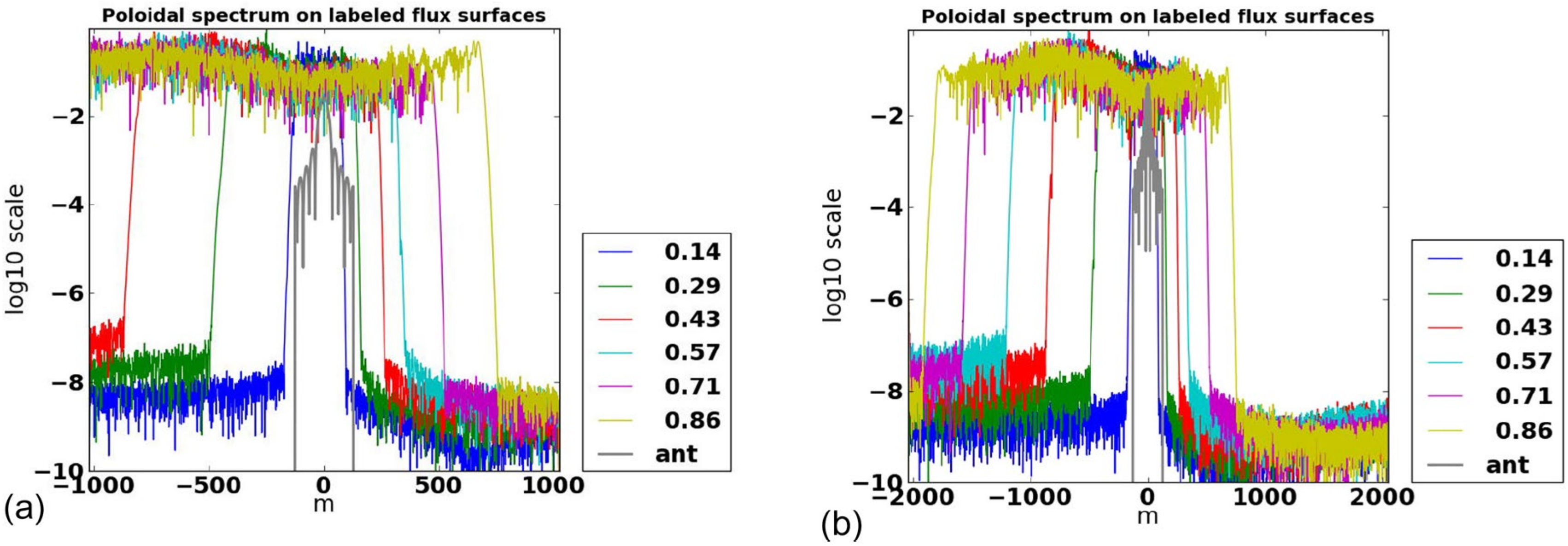
- Rotation of $\mathbf{k}_\perp$ vector applied to both 2.45 GHz and 4.6 GHz power.
- Results assumed 55% of LH power was absorbed with optimized fast electron diffusion coefficients from Chen and Zhai ($D_r \sim 1\ m^2/s$).

We have used HPC and advanced RF simulation models to study LHCD physics in EAST



- **Goal is to establish validity of ray tracing in weak LH damping regimes.**
- **EAST simulations have been very challenging:**
  - **Field solver (TorLH) required 4095 poloidal modes and 480 radial elements**
  - Largest problem ever done with TorLH
  - Recent work (S. Frank) suggests that more radial finite elements will be needed for complete convergence (~2000)
- **S. Frank (GS), P. Bonoli, J. C. Wright (MIT); J.-P. Lee (Hanyang Univ.); C. Yang (IPP-CAS)**

Collaboration between CAS-IPP (C. Yang) and MIT (S. Frank) motivated first converged full-wave field solutions for LH waves in EAST



- **2047 poloidal mode case run on Shenma (left) is not converged. Required 4095 poloidal modes to converge solution (right) – case used ~32,000 compute cores on Cori for ~2/3 hour of wall clock time.**
- **C. Yang**, P. T. Bonoli, S. Shiraiwa, B. Ding, M. H. Li, **S. Frank**, and X. Zhai, Physics of Plasmas **25**, 082516 (2018).

Workflow for TorLH-CQL3D iteration is manged by the Integrated Plasma Simulator (IPS) (Python – based)

TorLH
(Wave Solver)

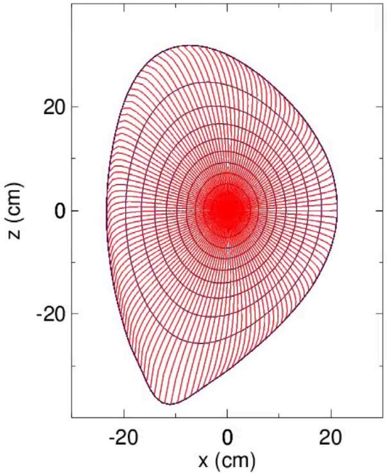
Solves Wave Eqn. for ϵ_{plasma} in LH Limit:

$$\Omega_i \ll \omega \ll \Omega_e$$

Uses Semi-Spectral Discretization:

$$E = \sum_m E(r) e^{im\theta + in\phi}$$

E-Field solution creates Kennel-Engelmann D_{ql} (Kennel, Engelmann, 1966 PoF)



D_{ql} →

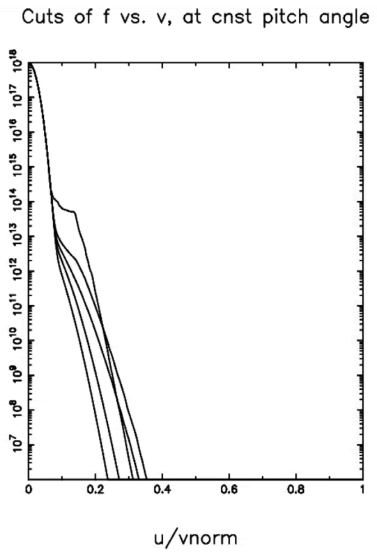
← $f(r,v)$

CQL3D
(Fokker Planck Solver)

D_{ql} generated by TORLH used in FP equation:

$$\frac{df}{dt} = \frac{\partial}{\partial v_{||}} D_{ql} \frac{\partial f}{\partial v_{||}} + C(f)$$

Non-Maxwellian Distribution passed back to TORLH and used to recalculate wave fields

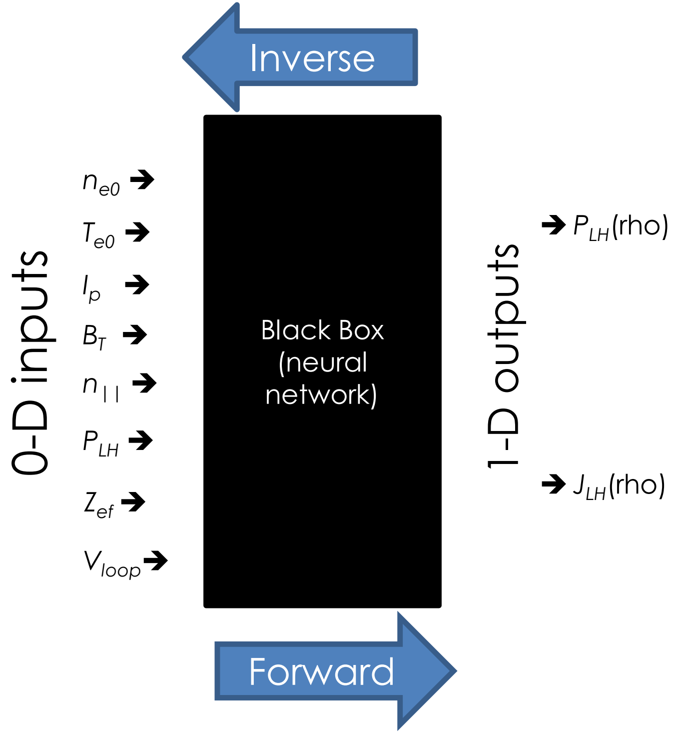


Iterate Until Solution Converges ~ 400,000 CPU hours on Cori

S. Frank et al, 62nd APS-DPP Meeting (Nov. 2020), Paper BO11.00006

Development of a fast surrogate model for LHCD on EAST will include the effect of LH wave scattering in the scrape-off layer

- **Current database consists of:**
  - 4374 simulations on structured grid of input parameters → f_0, Z_{eff}, n_{e0}, T_{e0}, $n_{\|}$, P_{LHRF}, B_T, I_p
  - And 3800 simulations at unstructured random points → n_{e0}, T_{e0}, $n_{\|}$, P_{LHRF}, B_T, I_p
  - Collaboration with AI experts at LBNL to train fast surrogate model (neural network)
    - Preliminary results show that approach is successful within range of parameters scanned so far
- **Future work will incorporate +40 $k_\perp$ rotation due to LH wave scattering in second simulation database**



Summary

- We reviewed ongoing improvements in the physics of the LH current drive models aimed at improving their agreement with experiments in EAST:
  - Incorporation of scattering of LH waves from turbulent density fluctuations leads to robustness in LHRF power deposition profiles and increased peaking of profiles, in better agreement with experiment.
  - Inclusion of full-wave effects on LH wave propagation and absorption will help to establish regions of validity for the geometrical optics approximation, especially in weaker damping regimes.

- We are now ready to construct a simulation database for EAST LHCD from which a control level LHRF actuator model can be developed.