DE LA RECHERCHE À L'INDUSTRIE

NEAR-FIELD PHYSICS OF LOWER-HYBRID WAVE COUPLING TO LONG-PULSE, HIGH TEMPERATURE PLASMAS IN TORE SUPRA

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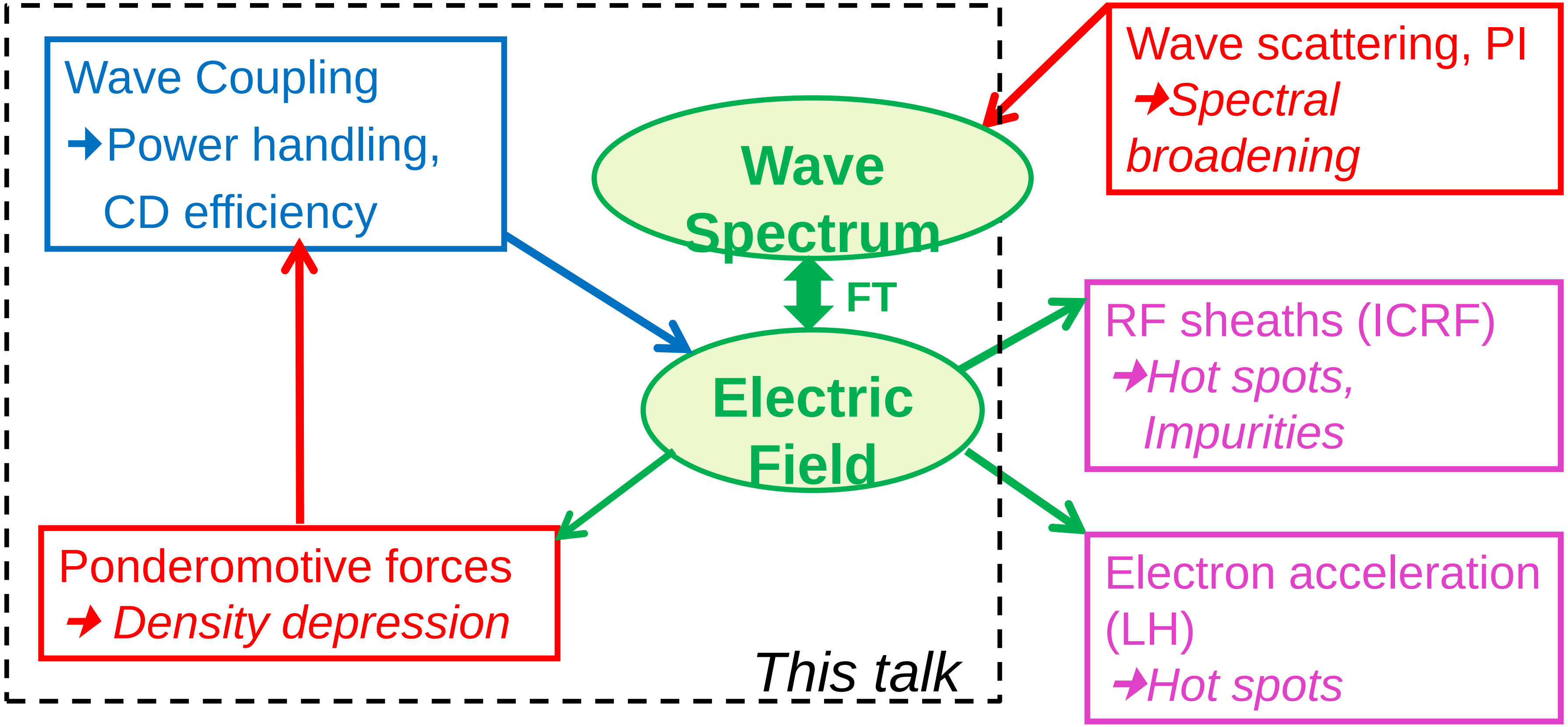
Waves have to channel **efficiently and reliably** through the edge plasma from the antenna to the plasma core



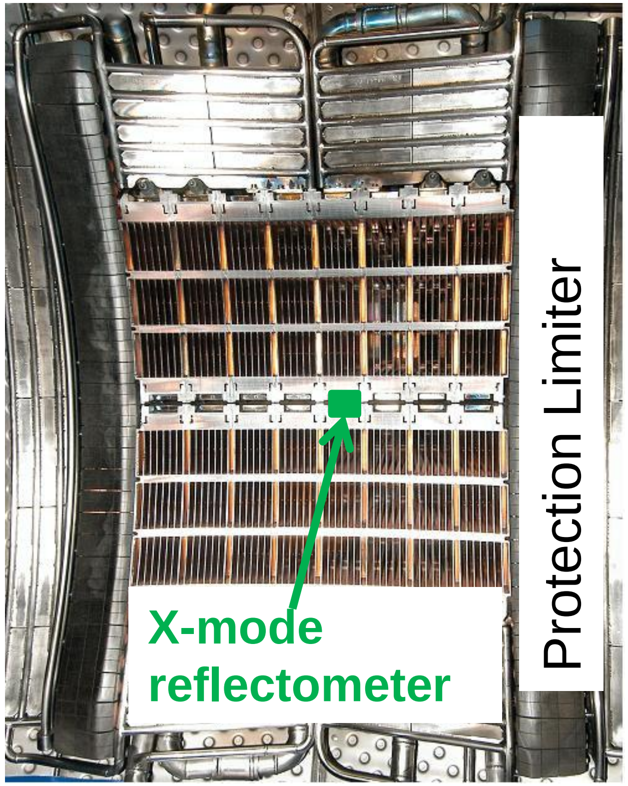
Direct measurement of RF electric field ⇨ calibrate coupling model

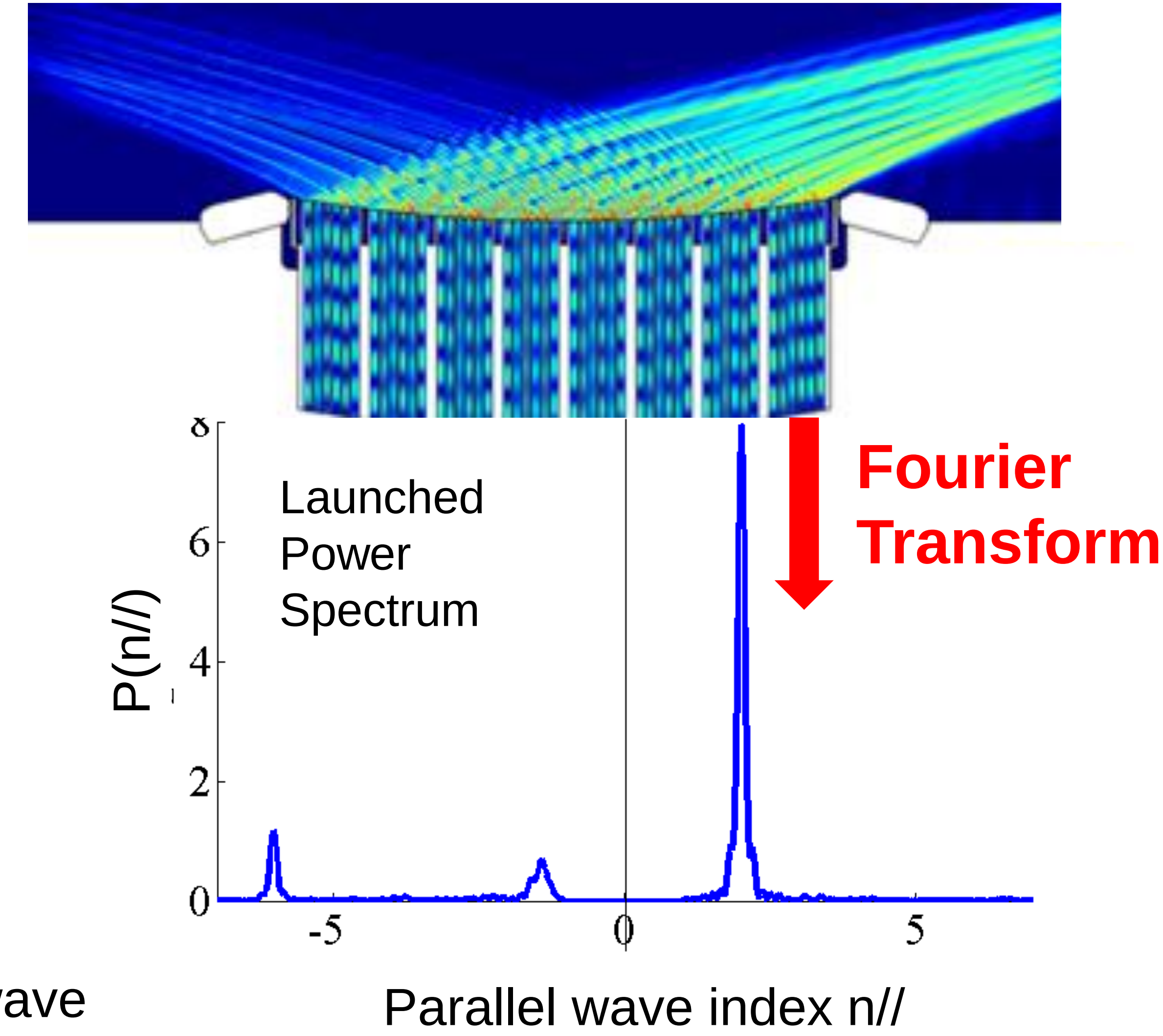
OUTLINE

- Lower Hybrid wave coupling
- Dynamic Stark effect spectroscopy diagnostic and modeling
- Electric field measurements during LHCD experiments
- Conclusion & Outlook

LOWER HYBRID WAVE COUPLING

LOWER HYBRID ANTENNA FOR CURRENT DRIVE

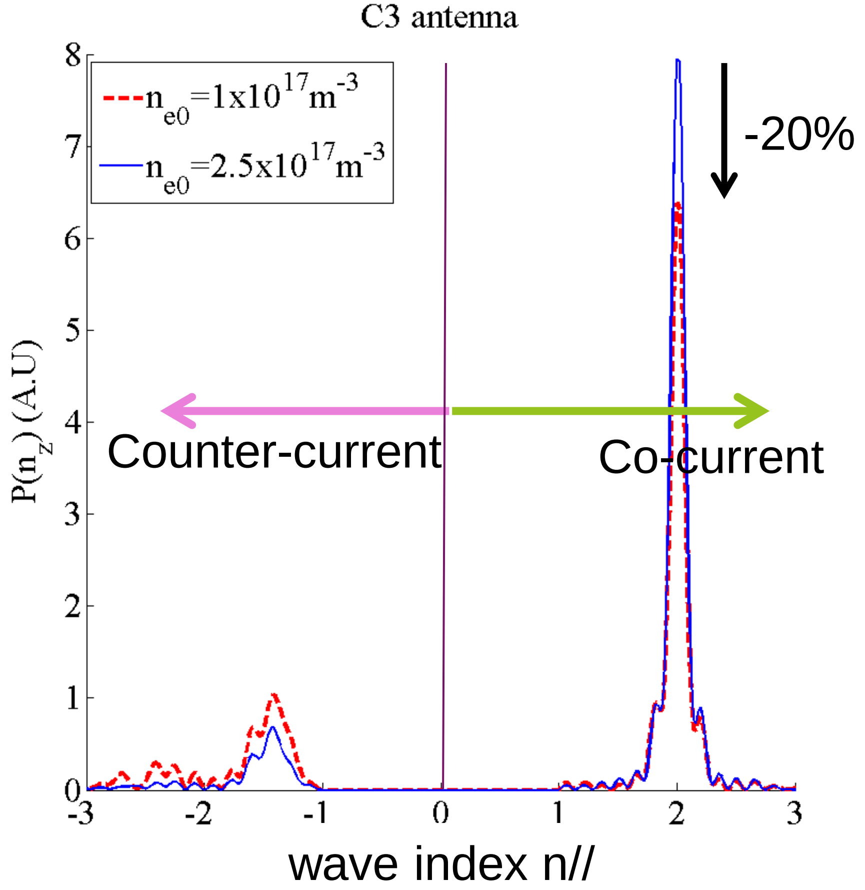




- Directive (asymmetric) wave launched for Current Drive

DIRECTIVITY OF THE WAVE AFFECTS CD EFFICIENCY

- Depending on **RF coupling** conditions, wave **directivity** can change significantly
- **Directivity** is not measured , but derived from coupling codes

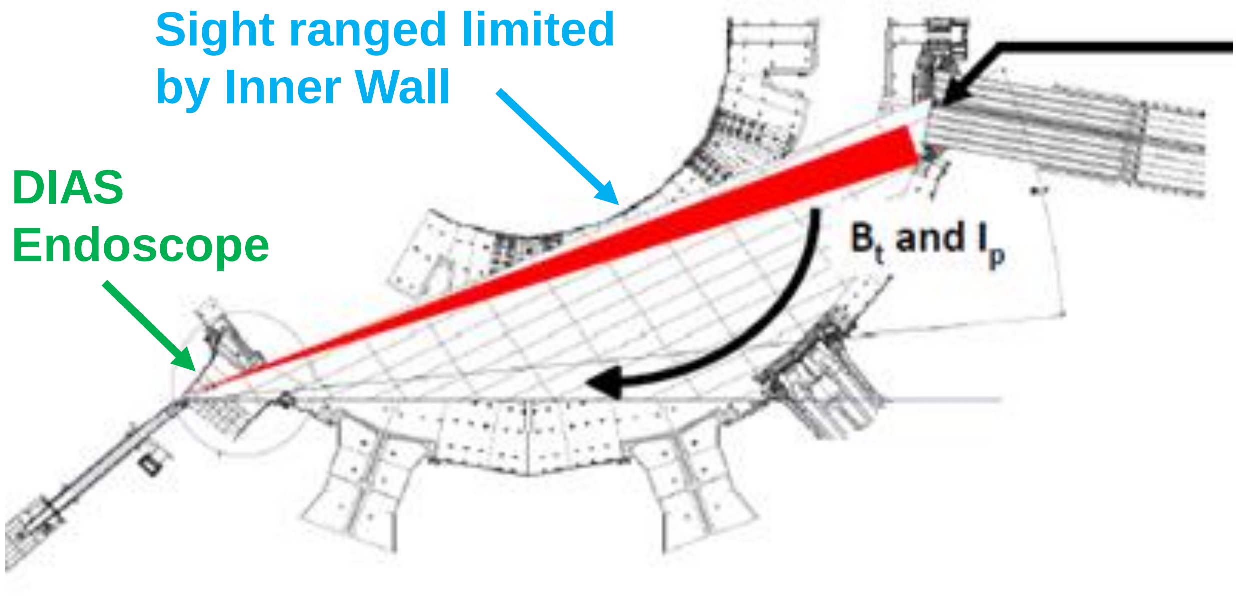


⇨ From an in-situ measurement of the electric field

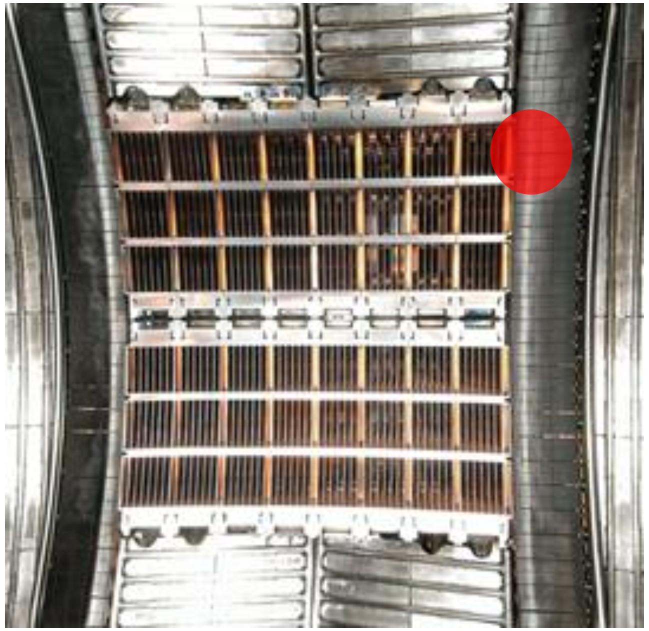
direct estimate of the wave directivity

DIAS DIAGNOSTIC ON TORE SUPRA

PASSIVE STARK-EFFECT SPECTROSCOPY DIAGNOTIC (DIAS) SET-UP ON TORE SUPRA



LH Launcher



Klepper, RSI14

- B (Zeeman effect)
- Plasma/neutrals toroidal rotation (Döppler effect)
- **E (Stark effect)**

Dynamic

$$E = E_{RF}\cos(\omega t)$$

$$I_{ki}(\tilde{\omega}) = I\sum_{s=-\tilde{s}}^{\tilde{s}} J_s^2(\alpha_{RF})\delta(\omega_{ik} - \tilde{\omega} - s\omega)$$

$$\alpha_{RF} \propto E_{RF}$$

Static

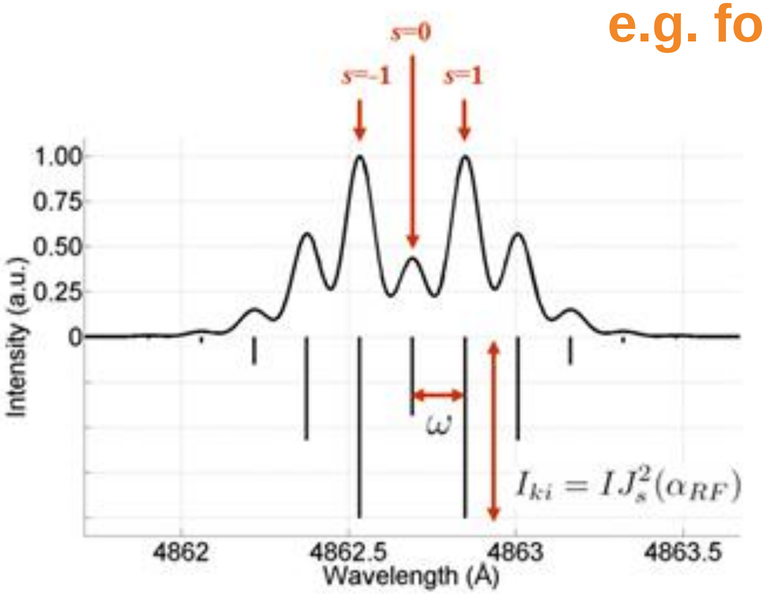
$$E = E_{DC}$$

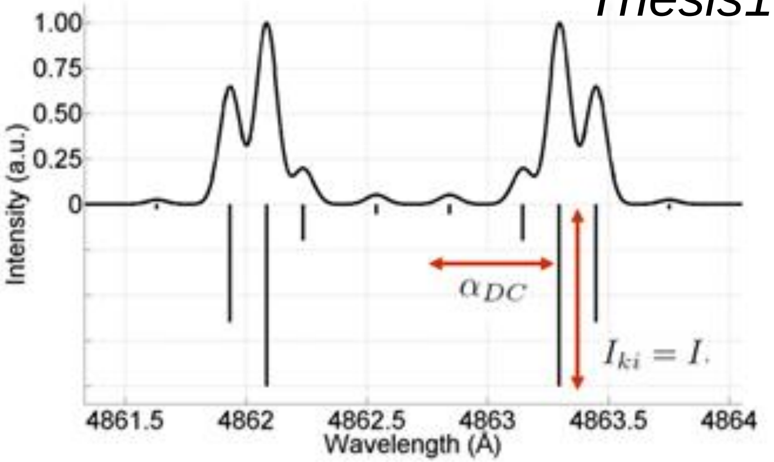
$$I_{ki}(\tilde{\omega}) = I\delta(\omega_{ik} - \tilde{\omega} - \alpha_{DC})$$

$$\alpha_{DC} \propto E_{DC}$$

e.g. for D_β (n= 4→2)

Martin, PhD Thesis14





Schrödinger equation encompasses 3 Hamiltonians

$$i\hbar \frac{\partial \Psi}{\partial t} = (H_0 + H_B + H_{Ed})\Psi$$

Martin, submitted to PPCF

Unperturbed Hamiltonian

Hamiltonian associated with static B0

Hamiltonian associated with dynamic E

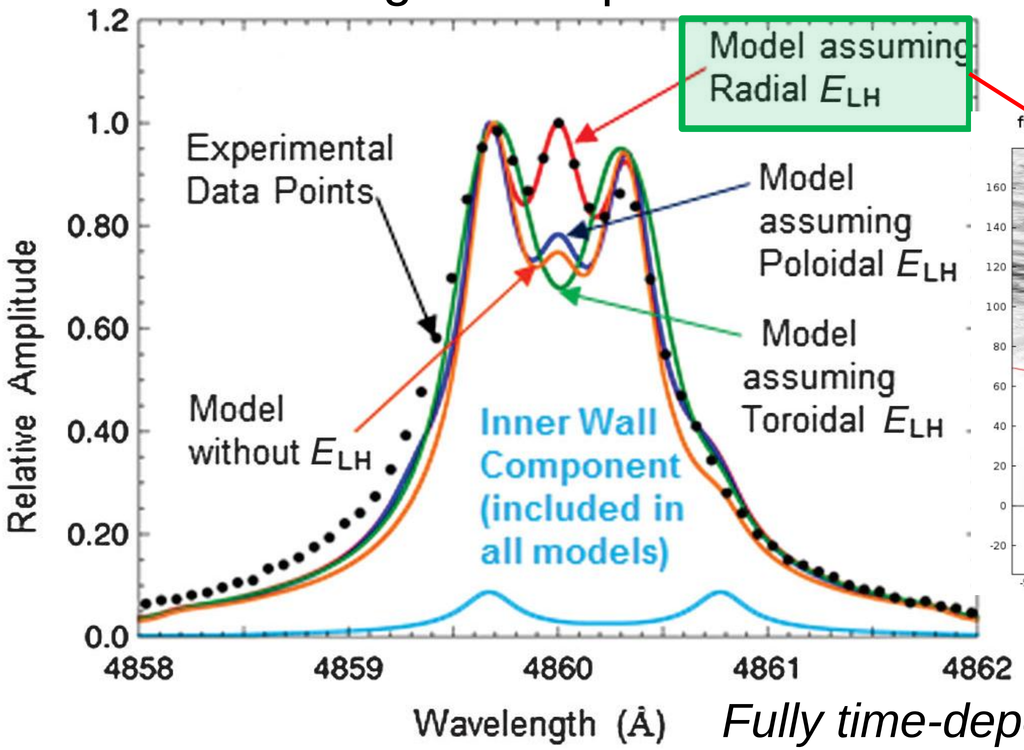
$$H_{Ed} = E_d \cos \omega t$$

- **First order** time dependent perturbation (E_d <50kV/cm)
- Time averaged emission intensity for the **i ➜ k transition** determined
- **Discrete spectral line profile** obtained by summing over both the i and k ind.
- **Convolution** with the instrument and radiator distribution functions

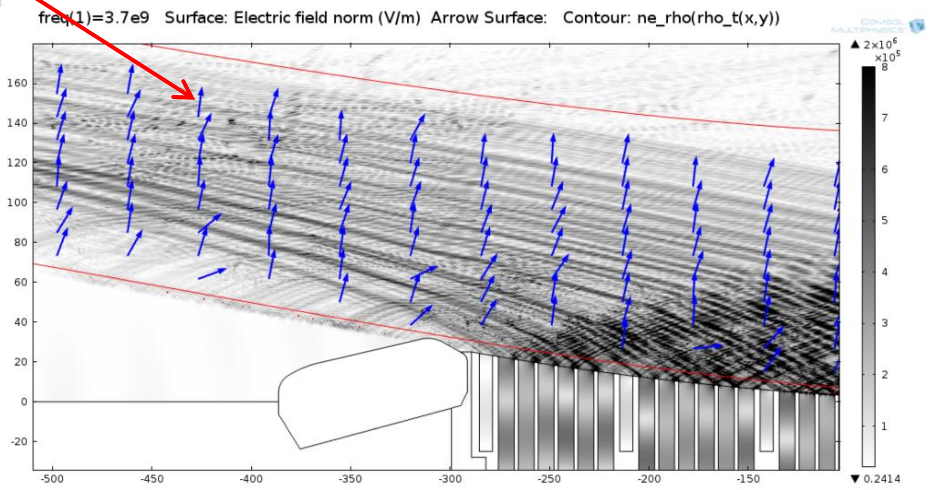
⇨The obtained continuous spectral line profile is directly compared with the experimental measurements.

PASSIVE STARK-EFFECT SPECTROSCOPY MODELLING VS. EXPERIMENT

Modeling of the spectral data



Full wave electric field modelling



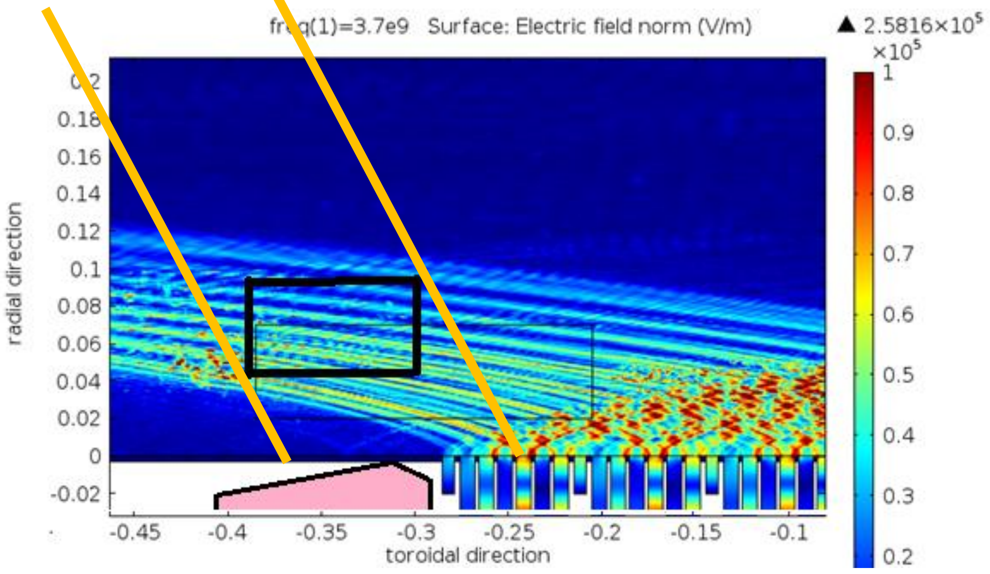
Klepper, PRL13

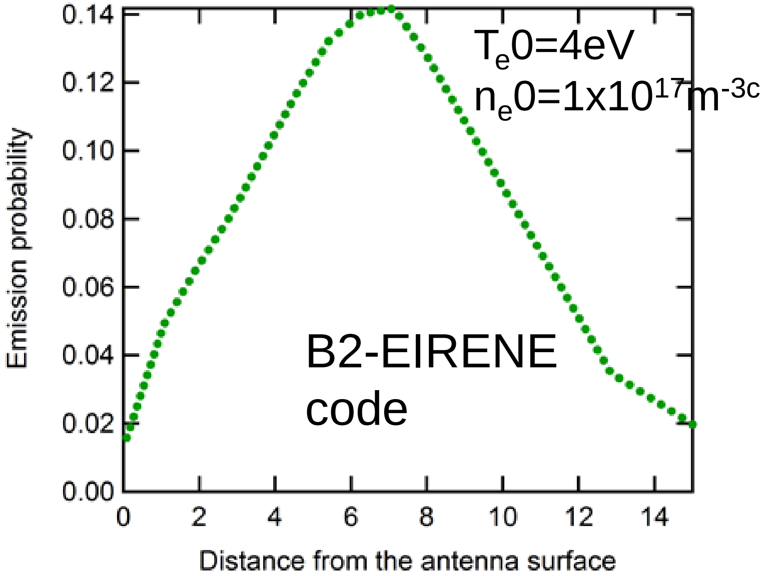
Fully time-dependent modelling,
R.C. Isler and E.H. Martin (ORNL)

- **Data fits the model with Radial E_{LH} as expected from full wave electric modelling when $n_e/n_{cut\text{-}off} \gg 1$**

Emission region is bounded by

Line-of-sight (Toroidal) | Atomic physics (Radial)



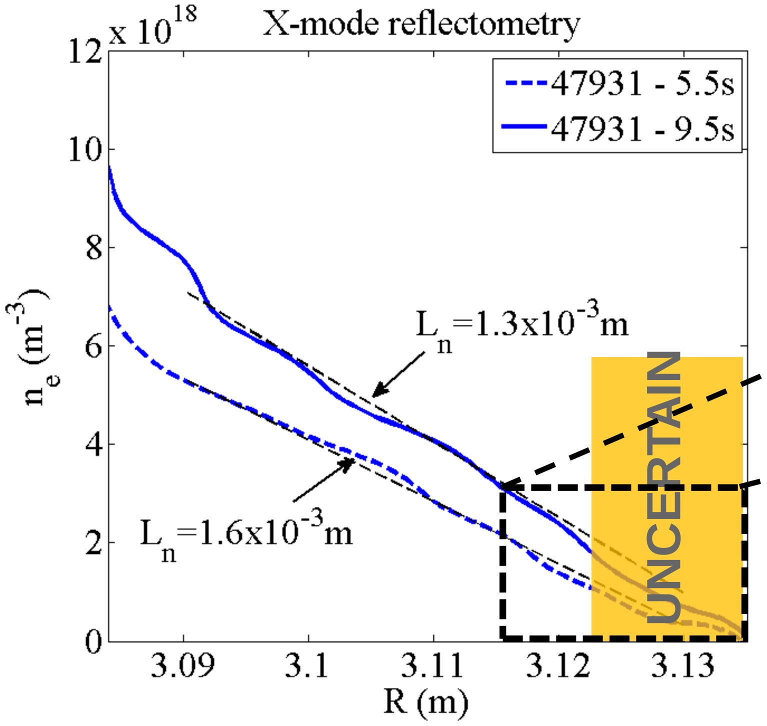


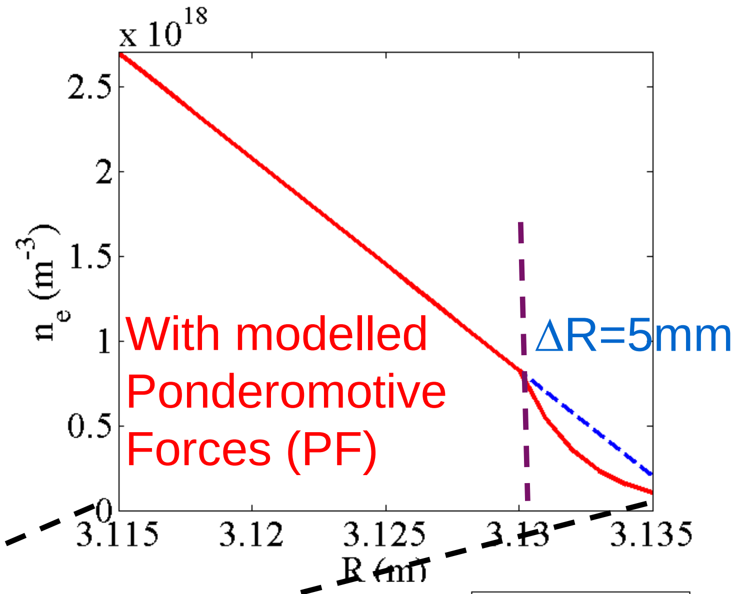
- Full-wave LH modelling performed with low T_e0 (~4eV) and high Te0 (T_e0~ 10eV)

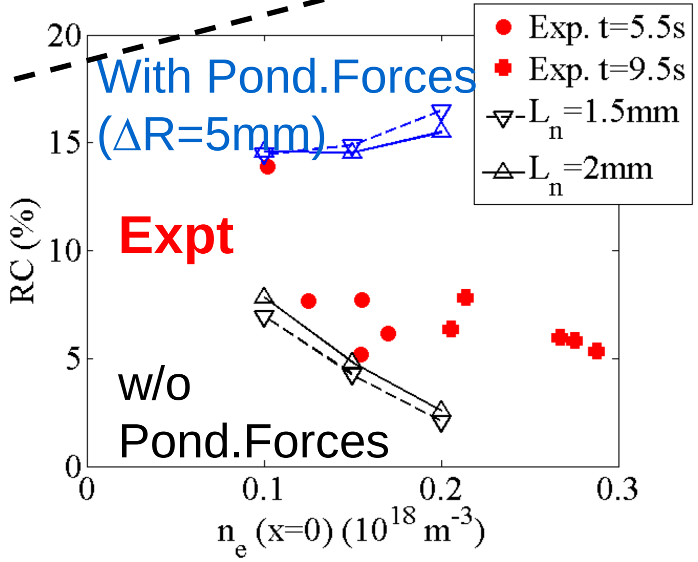
ELECTRIC FIELD MEASUREMENTS DURING LHCD EXPERIMENTS

DENSITY PROFILES IN FRONT OF THE LHCD ANTENNA

Density profiles from X-mode reflectometer in LHCD launcher



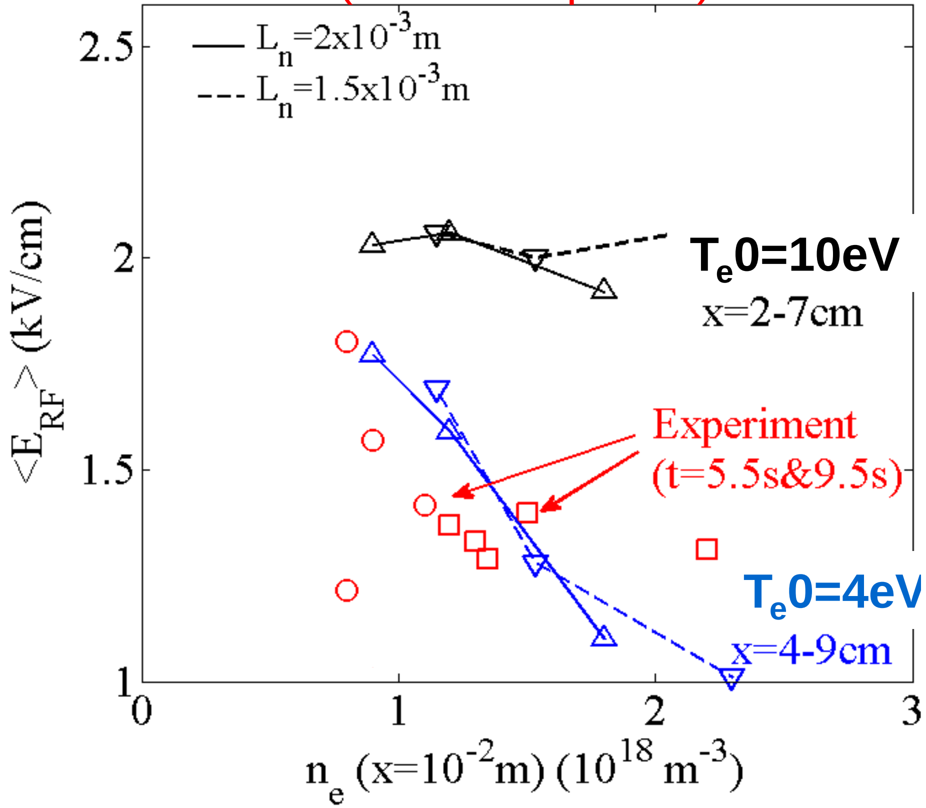




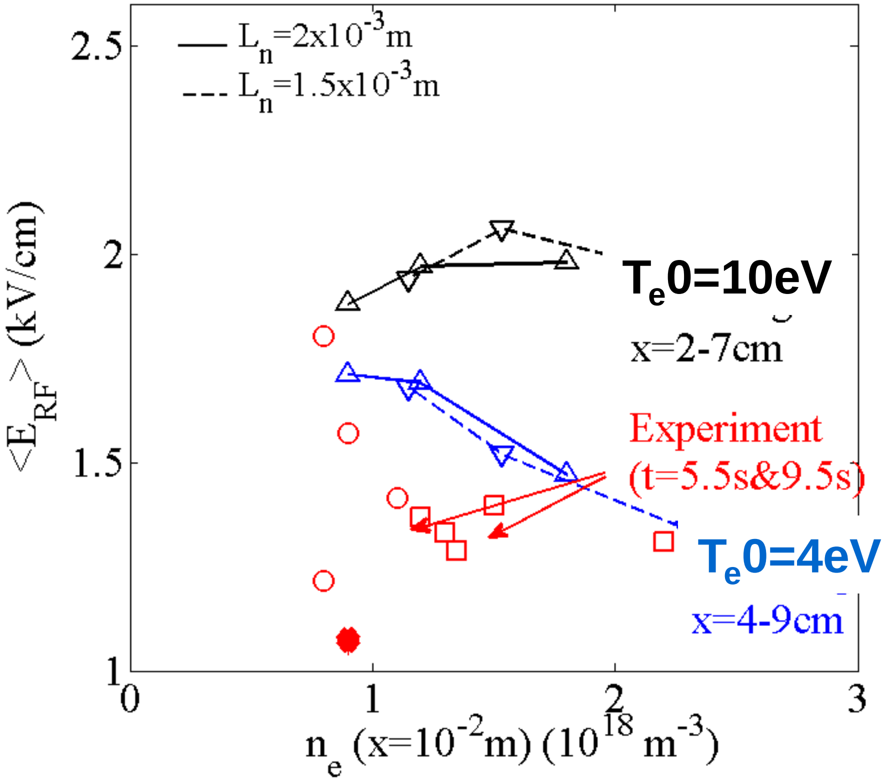
- RC measurements indicate that PF are over-estimated in most cases

PONDEROMOTIVE FORCES ACT ON A VERY NARROW PLASMA LAYER

Without Ponderomotive Forces
(Linear ne profile)

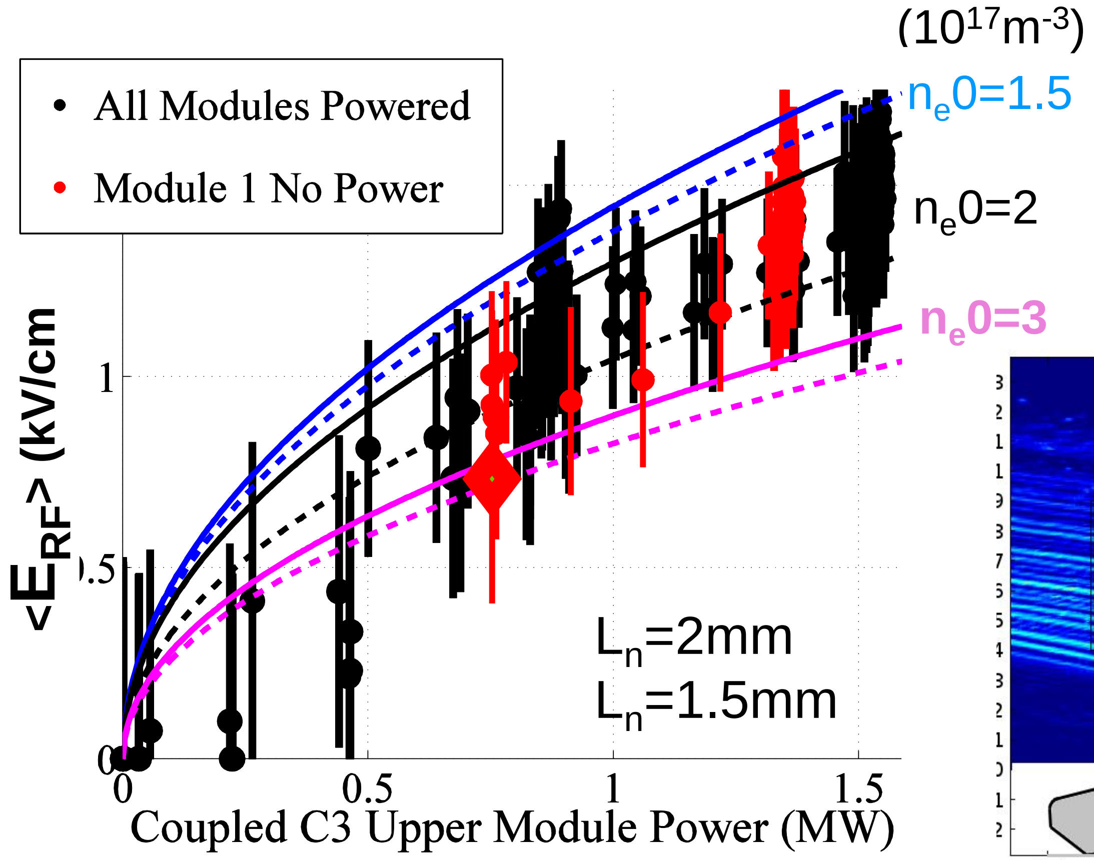


With Ponderomotive Forces (PF)

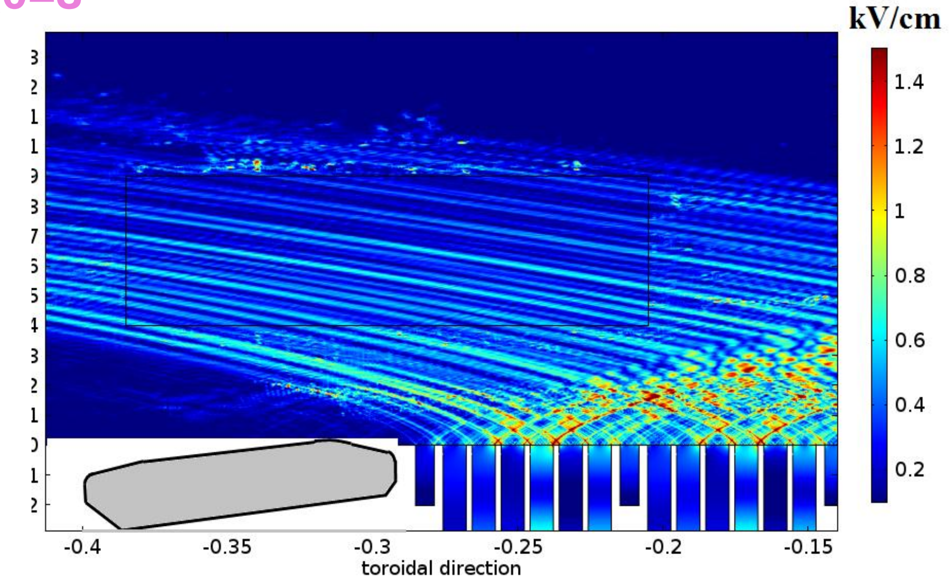


- E_{RF} measurements are more consistent with model assuming low Te0 (~4eV)
- E_{RF} measurements confirm that PF are over-estimated in most cases

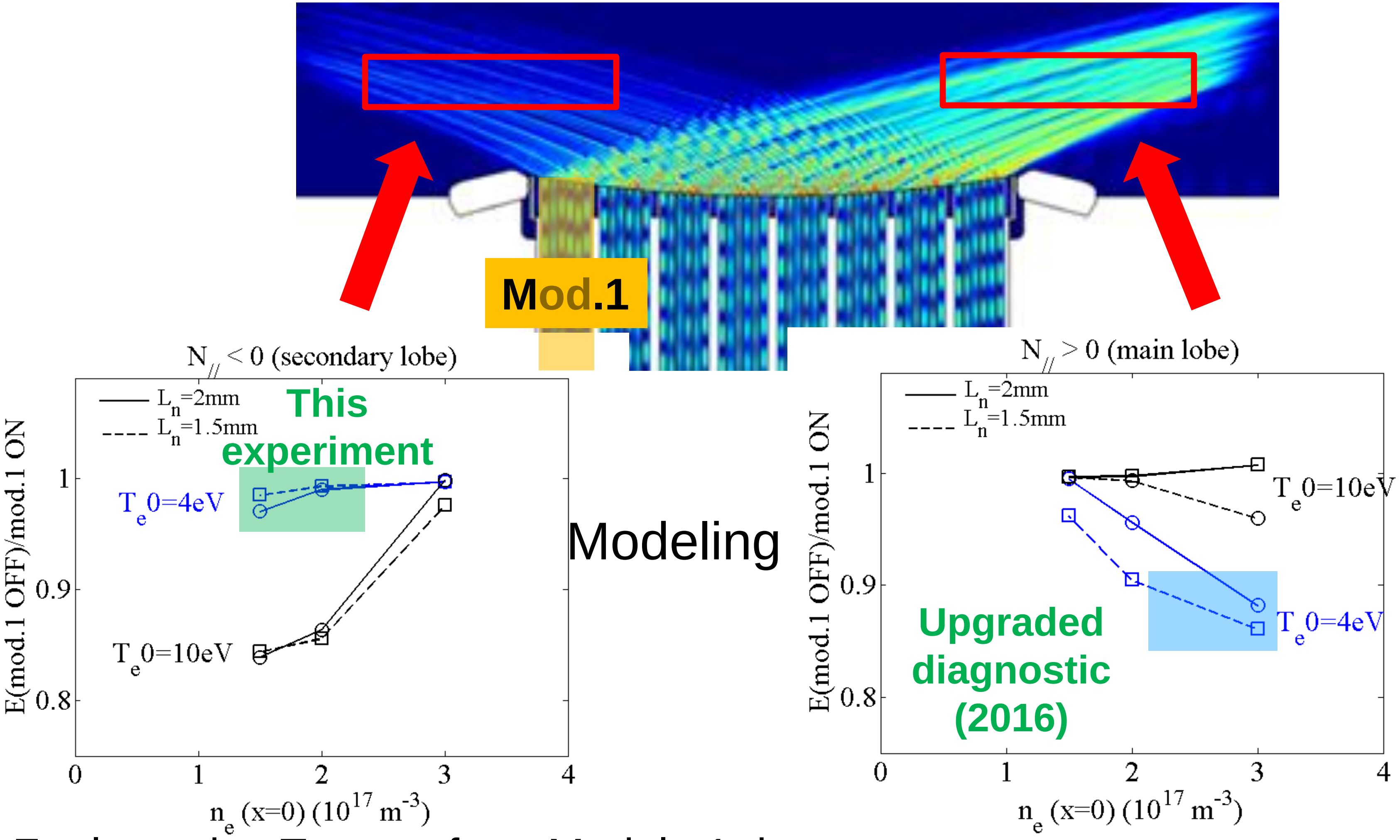
ELECTRIC FIELD MEASUREMENT POWER SCALING



Electric field map



- Expected scaling of E_{RF} with P_{LH} ($\rightarrow P_{LH}^{1/2}$)
- No effect of the power launched by the edge waveguides (Mod.1) on $<E_{RF}>$



- For low edge Te, rays from Module 1 do not contribute to $<E_{RF}$
- Significant effect of Mod.1 on $<E_{RF}>$ expected on the main $N_{//}$ lobe side

CONCLUSION & OUTLOOK

- RF electric field near an LHCD antenna is measured by Stark effect spectroscopy in Tore Supra successfully.
  - Wave polarization unambiguously identified from physics-based modeling of the spectral lines.
  - Amplitude consistent with density profile measurements.
  - Good quantitative agreement with full wave modeling.
  - Ponderomotive forces do not act on a radial distance > 2-3mm

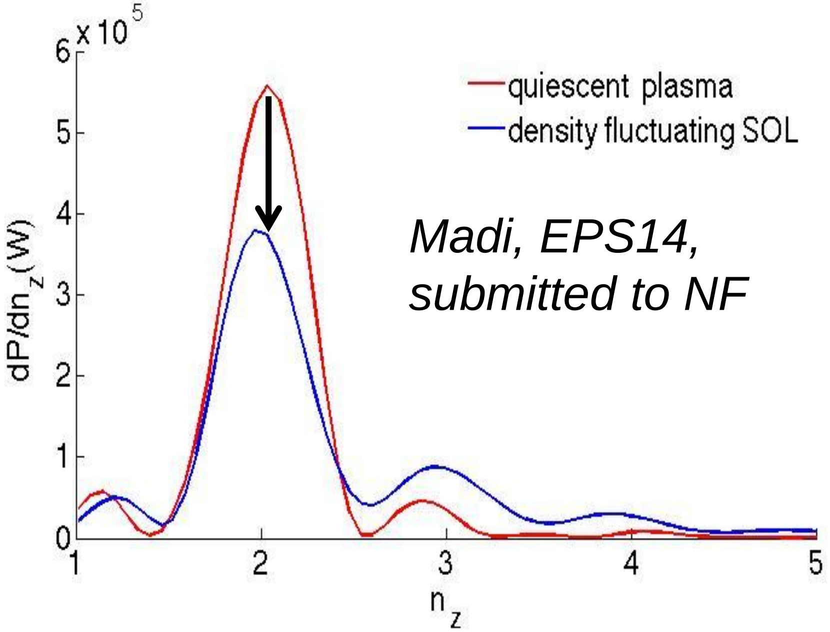
- Improved diagnostic (with He injection) will be implemented in WEST (WEST - **T**ungsten (W) **E**nvironment in **S**teady-state **T**okamak, at CEA) and MPEX (**M**aterial **P**lasma **E**xposure e**X**periment, at ORNL) facilities.
- Generalization to measure fields near ICRF antennas

EXTRA SLIDES

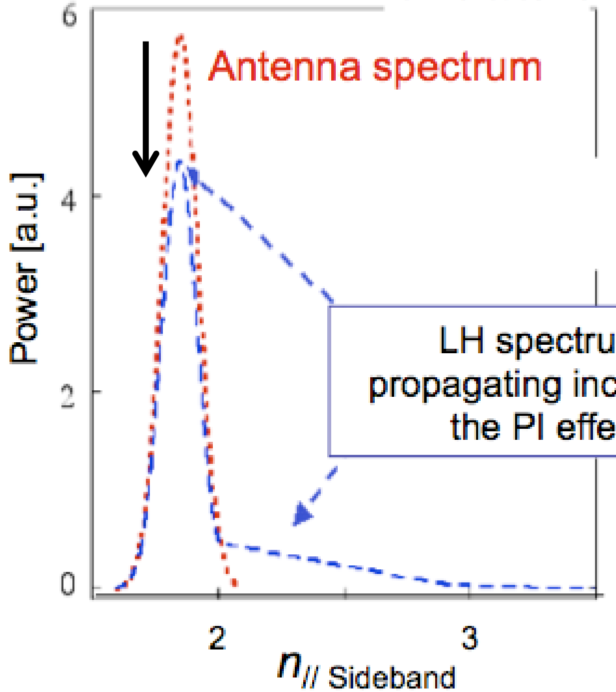
NON-LINEAR INTERACTION BETWEEN LH WAVE & SCRAPE-OFF LAYER

OAK RIDGE National Laboratory
NC STATE UNIVERSITY

Cesario, PRL04



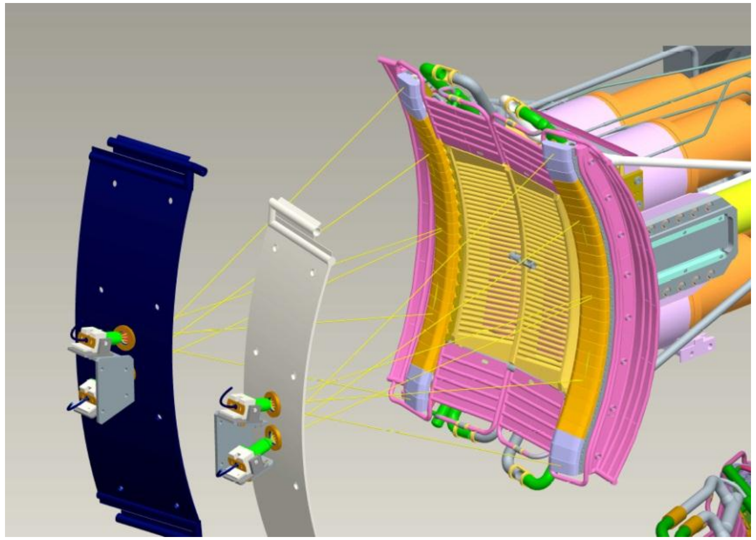
Madi, EPS14, submitted to NF



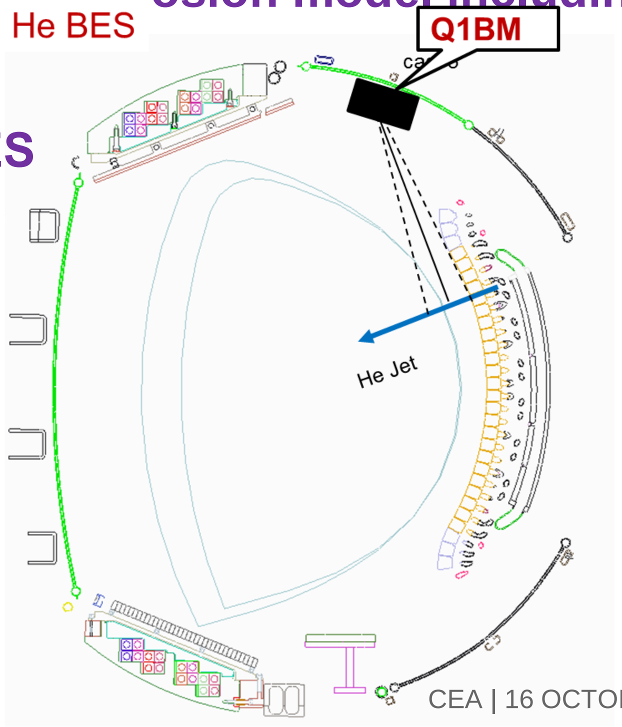
- Wave scattering on density fluctuations
- ParametrIc Decay

- Broadening of the N// spectrum
- Reduced CD efficiency

WEST'S RELEVANT SPECTROSCOPIC TOOLS



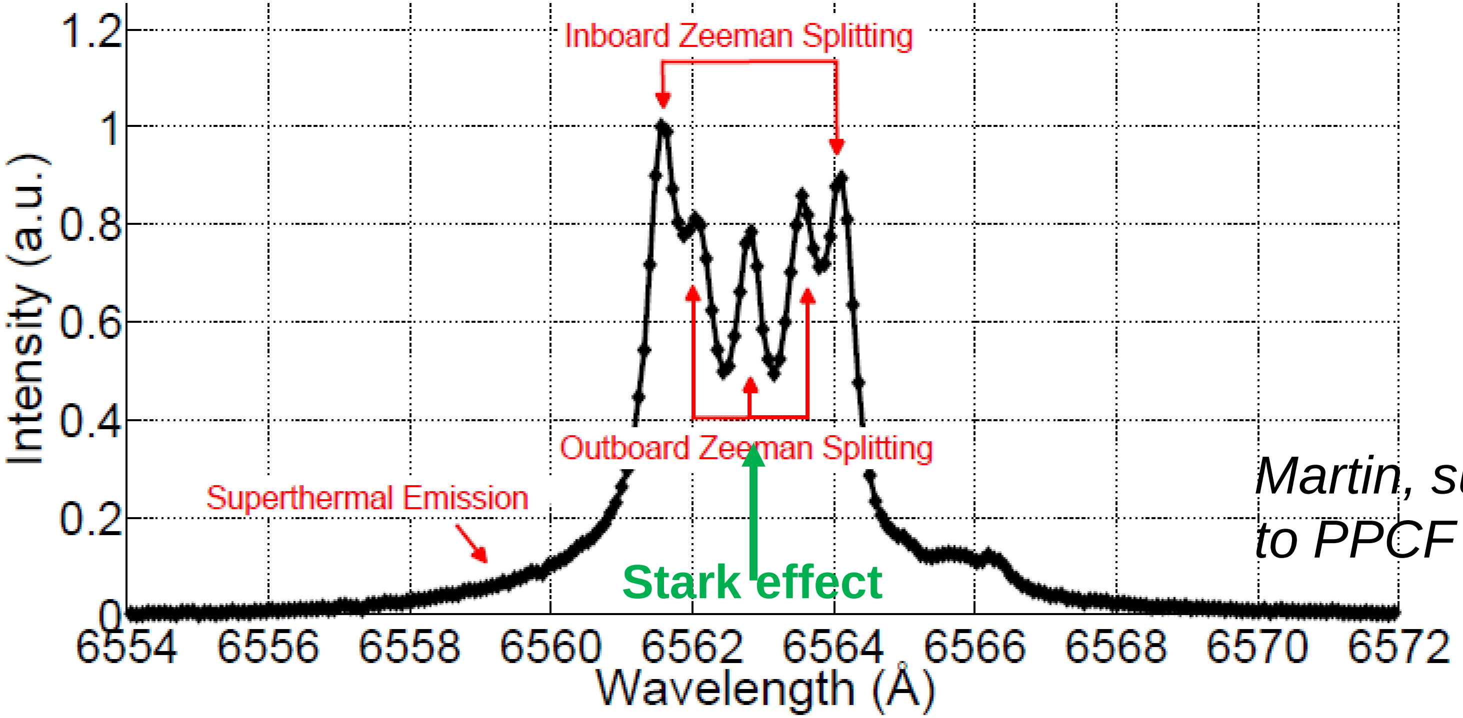
- **WILL HAVE: Optical access (from high-field side !) of antenna structures**
  - **Optics optimized for W I lines**
  - **All part of beseline diagnostic set**
- **SHOULD HAVE:**
  - **Experimental plans to relate measurements to rf-sheath interactions**
  - **Erosion model including rf sheaths**



- **PROPOSING TO HAVE: "Thermal" BES**
  - **Ne, Te profiles (SOL→Pedestal)**
  - **X-point and Upstream**
- **SHOULD ALSO HAVE:**
  - **Extra system at antenna PFC**
    - ➢ **Ne(r) , Te(r) at antenna**
    - ➢ **SOL modification studies**
    - ➢ **Tie in with E_{RF} studies**
    - **(*DIAS project* extension)**

PASSIVE STARK-EFFECT SPECTROSCOPY

Raw Dα Spectral Line Profile



Martin, submitted to PPCF

- Inboard (High B) and Outboard (Low B) Zeeman splitting can be discriminated
- **Stark effect** superimposed to Zeeman central line => modelling needed

CONCLUSION

- The RF electric field near a LHCD antenna has been measured by Stark effect spectroscopy. Wave polarization is unambiguously found from physics-based modeling of the spectral lines.
- Amplitude of E_{RF} is consistent with density profile measurements.
- E_{RF} data are in better agreement with full wave modeling of the electric field when a low Te (~4 eV) near the antenna is considered.
- E_{RF} data indicates that ponderomotive forces do not act on a radial distance exceeding 2-3mm consistently with LH coupling (and PF modeling).
- Further constraints on edge ne & Te are provided when changing the power feeding of the antenna.

OUTLOOK

- Diagnostic will be re-directed on WEST with improved spatial resolution to view the main lobe of the N// spectrum
  - Higher Electric Field => More accurate measurement.
  - Direct measurement of the wave directivity (=> CD efficiency).
- Active Stark-effect spectroscopy (with He injection) is also envisaged to further improve the diagnostic.
- R & D is planned on the MPEX facility (ORNL) to assess the feasibility of measuring the rectified potential in front of an ICRH antenna.