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.

**This talk**

Direct measurement of RF electric field ➔ calibrate coupling model

**Wave Spectrum**

- Wave Coupling ➔ Power handling, CD efficiency
- Ponderomotive forces ➔ Density depression
- RF sheaths (ICRF) ➔ Hot spots, Impurities
- Electron acceleration (LH) ➔ Hot spots
- Wave scattering, PI ➔ Spectral broadening

**Electric Field**
OUTLINE

- Lower Hybrid wave coupling
- Dynamic Stark effect spectroscopy diagnostic and modeling
- Electric field measurements during LHCD experiments
- Conclusion & Outlook
LOWER HYBRID WAVE COUPLING
Directive (asymmetric) wave launched for Current Drive

Launched Power Spectrum

Parallel wave index \( n// \)

Fourier Transform

P(\( n// \))
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, a **direct estimate of the wave directivity** is obtained.

![Graph showing wave index and directivity](image)
DIAS DIAGNOSTIC ON TORE SUPRA
PASSIVE STARK-EFFECT SPECTROSCOPY DIAGNOSTIC (DIAS) SET-UP ON TORE SUPRA

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

LH Launcher

Sight ranged limited by Inner Wall

DIAS Endoscope

Klepper, RSI14
DYNAMIC STARK EFFECT IS FUNDAMENTALLY DIFFERENT FROM STATIC STARK EFFECT

Dynamic

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

\[ I_{ki}(\bar{\omega}) = I \sum_{s=-\bar{s}}^{\bar{s}} J_{s}^{2}(\alpha_{RF}) \delta(\omega_{ik} - \bar{\omega} - s\omega) \]

\[ \alpha_{RF} \propto E_{RF} \]

Static

\[ E = E_{DC} \]

\[ I_{ki}(\bar{\omega}) = I \delta(\omega_{ik} - \bar{\omega} - \alpha_{DC}) \]

\[ \alpha_{DC} \propto E_{DC} \]

e.g. for \( D_{\beta} \) (n= 4\( \rightarrow \)2)

Martin, PhD Thesis 14
Schrödinger equation encompasses 3 Hamiltonians

\[ i\hbar \frac{\partial \Psi}{\partial t} = \left( H_0 + H_B + H_{Ed} \right) \Psi \]

- **First order** time dependent perturbation (\( E_d < 50\text{kV/cm} \))
- Time averaged emission intensity for the \( i \rightarrow k \) 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.

Martin, submitted to PPCF
Modeling of the spectral data

Full wave electric field modelling

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

Klepper, PRL13

*Fully time-dependent modelling, R.C. Isler and E.H. Martin (ORNL)*
Emission region is bounded by

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

Full-wave LH modelling performed with low $T_e0$ ($\sim 4$eV) and high $T_e0$ ($T_e0 \sim 10$eV)
ELECTRIC FIELD MEASUREMENTS
DURING LHCD EXPERIMENTS
Density profiles from X-mode reflectometer in LHCD launcher

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

With modelled Ponderomotive Forces (PF)

\( \Delta R = 5 \text{mm} \)

With Pond. Forces (\( \Delta R = 5 \text{mm} \))

Expt

w/o Pond. Forces

\( L_n = 1.3 \times 10^{-3} \text{m} \)

\( L_n = 1.6 \times 10^{-3} \text{m} \)

\( 3.09 \), \( 3.1 \), \( 3.11 \), \( 3.12 \), \( 3.13 \)

\( n_e (\text{m}^{-3}) \)
PONDEROMOTIVE FORCES ACT ON A VERY NARROW PLASMA LAYER

**Without** Ponderomotive Forces (Linear ne profile)

- $T_{e0} = 10\text{eV}$
- $T_{e0} = 4\text{eV}$

**With** Ponderomotive Forces (PF)

- $T_{e0} = 10\text{eV}$
- $T_{e0} = 4\text{eV}$

- E\textsubscript{RF} measurements confirm that PF are over-estimated in most cases.
- E\textsubscript{RF} measurements are more consistent with model assuming low Te0 (~4eV).
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 $T_e$, rays from Module 1 do not contribute to $\langle E_{RF} \rangle$.

Significant effect of Mod.1 on $\langle E_{RF} \rangle$ expected on the main $N_\parallel$ 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 - Tungsten (W) Environment in Steady-state Tokamak, at CEA) and MPEX (Material Plasma Exposure eXperiment, at ORNL) facilities.

- Generalization to measure fields near ICRF antennas
NON-LINEAR INTERACTION BETWEEN LH WAVE & SCRAPE-OFF LAYER

Wave scattering on density fluctuations

Parametric Decay

Broadening of the N/\ spectrum

Reduced CD efficiency

Cesario, PRL04

Madi, EPS14, submitted to NF
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 baseline 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)*
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 $T_e$ ($\sim 4$ 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 $n_e$ & $T_e$ are provided when changing the power feeding of the antenna.
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.