Subject: Lower hybrid resonance cone measurements using the SELHF diagnostic

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Group: LH

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1. Purpose of Experiments
Include immediate goal of the experiments, scientific importance and/or programmatic relevance. Refer to any relevant program milestones.

The primary purpose of the experiment is to investigate the lower hybrid (LH) density limit and LH launcher/SOL interactions by spatially mapping the LH resonance cone structure at high densities near the LH launcher as a function of power and launched $n_\parallel$. This will be achieved through measurement of the LH wave electric field by use of polarized passive optical emission spectroscopy. This new technique will be qualified in the process enabling future measurements on other RF systems. The variable phase and high power LH system on C-Mod, the density range accessible, the reflectometry diagnostic and the newly developed SELHF diagnostic make C-Mod a unique facility in the world to conduct this research.

2. Background
Discuss Physics Basis of the proposed research. Prior results at Alcator or elsewhere, and any related work being carried out separately.

In the low-density limit it has been shown previously on Tore Supra [1,2] that the LH wave electric field is primarily in the radial direction and that it scales with the square root of the absorbed power. Figure 1 presents the magnitude of the LH wave electric field as a function of absorbed power as measured in front of the C3 launcher on Tore Supra. Unpolarized spectroscopic measurements of $D_\parallel$ were obtained near the edge of the launcher corresponding to the negative $n_\parallel$ component of the LH wave. These experimental measurements are in agreement with cold plasma full-wave modeling conducted in COMSOL. This result indicates that non-linear interactions are not significant in the low-density regime. However, at high densities the LH current drive efficiency is severely inhibited and is thought to be due to various parasitic loss mechanics such as the ponderomotive force, high wavenumber harmonic generation, and
the parametric decay instability. These mechanisms may impact LH electric field and propagation/absorption through the SOL.

Figure 1. Measured LH wave electric field on Tore Supra as a function of injected C3 upper module power. Modeled electric field is drawn with a solid line for three densities having a linear profile in the edge: \( n_{e0} = 1.5 \) (blue) \( 2.0 \) (black) and \( 3.0 \times 10^{17} \) (magenta).

The SELHF diagnostic builds upon the previous work by probing the high-density regime using polarized optical emission spectroscopy (OES). Unlike previous work which was not polarization filtered this technique separates the emission into two orthogonally polarized components. This results in an increased accuracy in the direction and magnitude of the electric field vector when compared to unpolarized OES. A fully quantum mechanical code, the Explicit Zeeman Stark Spectral Simulator (EZSSS), is used to simulate the data. Unlike the previous work, the C-Mod SELHF diagnostic has 27 different views of the LH launch as shown by Fig. 2.

Figure 2. Image of the LH launcher with the 27 SELHF views superimposed.
This enables the resonance cones to be mapped as they propagate from the launcher for higher fidelity code validation. The radial location of the measurement is determined by the emitting layer of neutrals in the edge. C-Mod’s LH reflectometer provides an accurate measurement of the density profile in front of the LH launcher with poloidal spatial resolution and the spectroscopy system can be used to localize the neutral emission.

Preliminary work has been conducted to estimate the resolution of the electric field the diagnostic can provide and to localize the measurement location. This led to the design of the diagnostic, which was installed for the FY16 campaign as a collaborative effort between MIT and ORNL. Fig. 3 presents a COMSOL simulation of the expected resonance cone structure. The Dβ emission region was simulated using KN1D and is expected to be about 2 cm in width. The overlap of the simulated emission region and SELHF view 2D (see Fig. 2) is indicated by the black box drawn in Fig. 3.

Figure 3. COMSOL simulation of the resonance cone structure expected for the proposed experiment. The overlap of the emission region simulated by KN1D and the SELHF view 2D is indicated by the black box. This is in forward field. Reversed field flips the resonance cones.
Using parameters determined from piggyback experiments the two orthogonally polarized D_β spectra were simulated having an electric field in the radial (y-axis) and parallel (z-axis) directions. Fig. 4 presents simulated spectra experiencing 0, 1, 2, and 3 kV/cm electric field in the radial direction. The blue dashed lines indicate the wavelength boundaries encompassing the data used when fitting the experimental SELHF spectra. The wings of the line profile are not fit because the electric field has a negligible influence for the magnitudes expected (<3 kV/cm). Electric field in the radial direction primarily affects polarization 2 and increases the intensity at the line center.

![Simulated D_β spectra](image)

**Figure 4.** Simulated D_β spectra using the SELHF observed parameters from a piggyback experiment (see Fig. 6) experiencing an electric field having a magnitude of 0, 1, 2, and 3 kV/cm in the radial direction.

Fig. 5 presents spectra experiencing 0, 1, 2, and 3 kV/cm electric field parallel to the magnetic field. Electric field in the parallel direction affects both polarization 1 and 2. The intensity of the line center of polarization 1 is effectively decreased. This is observed because the dynamic Stark splitting is becoming prominent. Polarization 2 has a similar effect as seen for the radial electric field, where the intensity associated with the line center was increased. The spectra is insensitive to vertical electric field (x-axis), therefore the SELHF diagnostic is constrained to electric field measurements in the radial-parallel (yz) plane. Through simulations of synthetic spectral it looks to be possible to measure the electric field with accuracy approaching 0.2 kV/cm in the Y and Z directions using this technique.
Figure 5. Simulated Dβ spectra using the SELHF observed parameters from a piggyback experiment (see Fig. 6) experiencing an electric field having a magnitude of 0, 1, 2, and 3 kV/cm in the parallel direction.

During a piggyback experiment, the LH wave electric field was measured at SELHF view 2D (see Fig. 2). An electric field having a magnitude of 1.5 kV/cm was measured for 200 kW of LH power, the direction of the vector was perpendicular to B in the radial direction (y-axis). Fig. 5 presents the two orthogonally polarized Dβ spectra fitted to a model that includes emission originating from two outboard locations. The first emission region is associated with the LH launcher and has the y and z components of the electric field vector as fit variables. The second emission region is also on the outboard side of the machine and is located directly in front of the periscope. The neutral temperature is set to 0.85 eV [3] and the magnetic field is set to that at the LCFS for both regions.

Over a series of four shots during the piggyback experiment, a crude scan of the LH wave electric field as a function of inject power was obtained and is presented in Fig. 7. The LH wave electric field was found to be completely radial (y-direction) and proportional to the square root of the LH injected power. The black curve of Fig. 7 represents the fit to the experimental data.
Figure 6. Experimental spectra obtained for shot 1160720014. The raw data and corresponding fit is presented by the markers and solid line respectively. The spectra in the fourth frame were averaged over the LH pulse having 200 kW of power. All other spectra are averaged over times in which no LH power was injected. The spectra are presented in chronological order.

Figure 7. Measured radial (y-component) LH wave electric field on C-Mod at SELHF view 2D as a function of injected LH power. The parallel (z-component) LH wave electric field was found to be zero for this data set. The black solid line is a fit to the experimentally measured ERFy data assuming that it is proportional to the square root of the injected power.
3. Approach
Describe the methodology to be employed; explain the rationale for the choice of parameters, etc. Describe the analysis techniques to be employed in interpreting the data, if applicable. If the approach is standard or otherwise self-evident, this section may be absorbed into the Experimental Plan.

Our goal is to carefully document the LH electric field and density profiles in front of the LH launcher for LH discharges using a subset of the available views, different densities and different launched $n_{||}$. The experimental electric field results will be compared against 2-D and 3-D cold plasma simulations. The density profile is a critical input knob for these simulations thus the reflectometer is required. While piggybacking is possible and has been conducted, dedicated, repeated discharges are necessary due to diagnostic limitations. For a statistically significant number of spectral counts in the piggyback discharges so far, SELHF requires an estimated 200-400 ms steady state LH pulses and high densities (line averaged density > $1.3 \times 10^{20}$ m$^{-3}$) for one measurement. SELHF is limited to two views per discharge. Cell access is required to change the SELHF views to other locations. LH phasing to accommodate reversed field is also preferred so that the SELHF view measures the positive $n_{||}$ direction.

The reflectometer and CHROMEX spectroscopy system viewing through the toroidal outer midplane edge CXRS fibers will be used to provide density and emission profiles respectfully for the simulations.

4. Resources

4.1 Machine and Plasma Parameters
Give values or range for:

- Toroidal Field: 5.4 T
- Plasma Current: 800 kA
- Working Gas Species: D$_2$
- Density: (line averaged density of 0.9-1.5 x $10^{20}$ m$^{-3}$)
- Boronization Requested (if yes, specify whether overnight or between-shot, how recently needed, and any special conditions.): no
- Equilibrium configuration (if possible, refer to database equilibria): recent LSN reversed field discharge

4.2 Auxiliary Systems

- ICRF Power, pulse length, phasing: no
- LHCD Power, pulse length, phasing: max possible, up to 800 ms, phasing at 75°, 90°, 105°
- Pellet Injection (species): no
- Impurity blow-off injection: no
- Diagnostic Neutral Beam: no, cannot operate due to possible interference with SELHF.
- Special gas puffing: NINJA for D$_2$, nothing else.
- Cryopump: Yes, if necessary for density control.
- Non-axisymmetric Coils (Connections, Current): standard.
- Other: none
4.3 Diagnostics
List required diagnostics, and any special setup or configuration, e.g. non-standard digitization rate.

Required: SELHF, SOL reflectometer (C-port), edge Thomson, LH camera, CHROMEX configured to measure outer midplane $D_\beta$ profiles via CXRS chords. NINJA for puffing $D_2$ via LH adjacent points and for GPI CXRS.

Desired: hard x-rays, GPI CXRS.

5. Experimental Plan
Both sections must be filled in.

5.1 Run sequence Plan
Specify total number of runs required, and any special requirements, such as consecutive days, no Monday runs, extended run period – 10 hours maximum – etc.

½ day (16 possible shots)

Scans of power, position on the launcher, density, launched $n_\parallel$ and current if possible in this priority order. LH on from 0.7 to 1.5s to enable the most signal collection. LH reflectometer at the center position.

5.2 Shot sequence plan
For each run day, give detailed specification for proposed shot sequence: number of shots at each condition, specific parameters and auxiliary systems requirements, etc. Include contingency plans, if appropriate.

Part 1, Power scan: Condition LH to highest possible power at 90deg at constant density (1.3 line average) at SELHF 1D/5D. (4 shots)

Part 2, Position scan: Scan of SELHF position at constant density, 90deg and constant power. 1E/5E, 1D/5D, 1C/5C, 1B/5B, 2C/6C. Requires cell access between shots (5 shots)

Part 3, Density scan: Pick best SELHF location and change density shot-to-shot, at 1.0 and 1.5 line average at constant power. (2 shots)

Part 4, $n_\parallel$ scan: At best SELHF location, 1.3 line average at 75, 105deg phasing (2 shots)

Total of 13 shots

If more time:
Part 5, Ip scan: At best SELHF location, 1.3 line average, 90deg, shot to shot current scan at 600kA and 1MA (2 shots)
Revisit Part 2 at 3E and 3A

If signal level is appropriately high at these densities and powers, may do scans in density and $n_\parallel$ within shot to save a few shots.
6. Anticipated Results
Discuss possible experimental outcomes and implications. Indicate if the program may be expected to lead to publications, milestone completions, improved operating techniques, etc. Indicate if the experiments are intended to contribute to a joint research effort, an ITER request, or an external database.

This MP will help characterize LH current drive in high density plasmas as well as SELHF diagnostic capabilities. It will contribute to presentations at APS and future conferences on diagnostic technique and RF power. It is hoped that the development of the SELHF technique will lead to a more standard diagnostic for investigating RF fields in edge plasmas in both LH and ICRF systems including future devices such as WEST and ADX.

7. References
Include references both to external and internal literature or communications which bear on this proposal. See Section 2.