Lower Hybrid Coupling Experiments on Alcator C-Mod*

G.M. Wallace,¹ P.T. Bonoli,¹ A.E. Hubbard,¹ Y. Lin,¹ R.R. Parker,¹ A.E. Schmidt,¹ C.E. Kessel,² and J.R. Wilson²

¹MIT Plasma Science and Fusion Center, Cambridge USA
²Princeton Plasma Physics Laboratory, Princeton USA

*Work supported by US DOE awards DE-FC02-99ER54512 and DE-AC02-76CH03073.
Abstract

The Alcator C-Mod Lower Hybrid launcher couples RF waves at 4.6 GHz via 4 rows of 22 phased waveguides. Directional couplers in the launcher structure measure forward and reflected power in each waveguide, while six Langmuir probes mounted to the front of the antenna grill monitor density at the plasma edge and act as RF probes for the observation of parametric decay. Parametric decay spectra grow exponentially with line averaged electron density in the regime $\omega = 3 - 6 \omega_{lh}$. Measurements of the coupling of lower hybrid waves have been performed at power levels approaching 1 MW. Edge density, launched $n_\| \|$ spectrum, and plasma shape have been adjusted to optimize coupling in Ohmic and ICRF heated L- and H-mode plasmas. Preliminary results show that deleterious effects of ICRF on LH coupling are reduced following boronization, particularly in H-mode. Experimentally observed coupling results will be compared to simulations from several coupling codes.
LH System Overview

- $f_0 = 4.6$ GHz
- 4X22 waveguide phased array
- Molybdenum protection limiters
- Langmuir probes measure plasma density in front of LH antenna
Forward and Rear Waveguide Detail

- Power measurements made on transmitter side of final 3 dB splitter
- No direct measurement of forward or reflected power possible in B or C waveguide rows
LH System Overview - Single Channel

Signals used in calculation of net power and reflection coefficient

Signals used in ratio based arc protection system
Coupling in Slab Geometry

- For $n_{\parallel}^2 > 1$, wave is evanescent if $n_e < n_c = 2.6 \times 10^{17} \text{m}^{-3}$
- Analytic solution in form of Airy functions for a linear density gradient

$$\nabla \times \nabla \times \vec{E} - \frac{\omega^2}{c^2} \epsilon \cdot \vec{E} = 0$$

$$\frac{\partial^2 E_z}{\partial x^2} - \frac{\omega^2}{c^2} \epsilon_{\parallel} (n_{\parallel}^2 - 1) E_z = 0$$

$$n_c = \frac{(2\pi \cdot f)^2 m_e \epsilon_0}{q^2}$$

Fast and slow wave $n_{\perp}^2$, $B=5.4\text{T}$
Measured Probe Density ↔ Code Density Profiles

Probe measures average density in region from grill to probe tip

\[
n_{\text{probe}} = \frac{1}{x_{\text{probe}} - x_{\text{grill}}} \int_{x_{\text{grill}}}^{x_{\text{probe}}} n(x)dx
\]

Density Profiles Compatible with “Grill” Code

- No vacuum gap
- Density gradient variable
- Small edge density

\[
n(x) = n_0 + x \frac{dn}{dx} \approx x \frac{dn}{dx}
\]

- Vacuum gap
- Constant density gradient
- Step density variable

\[
n(x) = \begin{cases} 
0 & x < x_{\text{gap}} \\
 n_0 + (x - x_{\text{gap}}) \frac{dn}{dx} & x_{\text{gap}} \leq x
\end{cases}
\]

Exponential density profiles are more realistic given close proximity to limiters
Slab Model

- 1-D infinite slab geometry
- Calculates wave reflection and transmission at each surface
- Weighted average over launched $n_{\parallel}$ spectrum
- Evanescent region at low density
- Impedance mismatch at high density
- Minimum reflections $\sim 20\%$
**“Grill” Coupling Code**

- No vacuum gap
- Density gradient variable
- Small edge density

\[ n(x) = n_0 + x \frac{dn}{dx} \approx x \frac{dn}{dx} \]

- Vacuum gap
- Constant density gradient
- Step density variable

\[ n(x) = \begin{cases} 
0 & x < x_{gap} \\
 n_0 + (x - x_{gap}) \frac{dn}{dx} & x_{gap} \leq x 
\end{cases} \]

- Coupling code calculates reflection coefficients of launched waves based on Airy function solution[1]
- Poloidal variations in density and gradient not included in model
- Linear density profile yields minimum reflections ~5%
- Experimental observations of reflections ~20% more consistent with vacuum gap [2] or constant edge density profiles
  - Best fit with \( x_{gap} = 0.5 \text{ mm} \) and \( \frac{dn}{dx} = 1 \times 10^{20} \text{ m}^{-4} \) for vacuum gap model
  - Best fit with \( n_0 = 4.0 \times 10^{17} \text{ m}^{-3} \)
**TOPLHA Coupling Code**

- Under development at Politecnico di Torino and MIT
- Based on TOPICA code for ICRF antennas[3]
- 3-D model of antenna coupled to plasma response function from FELICE
- Calculates full S-parameter matrix
Finite Element Models

• CST and COMSOL
  – Commercial 3-D RF packages
  – Calculate S-parameter matrix
  – Require small mesh size
    • Very computationally intensive for large problems
  – CST
    • Cold plasma model included as part of simulation package
    • Homogenous slabs only
  – COMSOL Multiphysics
    • Arbitrary dielectric tensor defined as a function of space
Experimental Results: L-Mode

- Low power (~200kW), 10ms pulses to prevent perturbing the plasma
- High power (500+kW), long (100+ms) pulses show spread in reflection coefficients, possibly due to modification of density profile by LH waves
- Reflections are high at low line averaged densities, thus low edge densities, desirable for efficient current drive
Long Pulse Coupling

- $n_{\text{edge}}$ data not directly comparable from ’06 to ‘07
  - Langmuir probes shortened from 3mm to 1.5mm
- Launcher proud of limiter by $\sim 1$mm during 2006 run campaign
  - Loss of Langmuir probes due to melting
- Launcher kept $>1.5$mm behind limiter during 2007 run campaign
- Higher line average density required to achieve best coupling with launcher pulled back 1.5mm
  - Lower current drive efficiency at high density
$n_\parallel$ Spectrum Flexibility

Launched $n_\parallel$ varied throughout single shot

Peak $n_\parallel$ varied from 1.5 to 3 without losing directivity
Parametric Decay

- PDI level increases logarithmically with line average density up to $1.5 \times 10^{20}$ m$^{-3}$
- $\omega / \omega_{lh} = 3 - 6$ and $T_e \sim T_i$ indicates decay into cold LH wave and ion cyclotron wave or ion cyclotron quasi-mode[4]

\[
\frac{\omega}{\omega_{lh}} = 6 \quad 5 \quad 4 \quad 3
\]

Symmetric sidebands observed at 78MHz from fundamental during ICRF
Parametric Decay

- PDI level grows exponentially with density then saturates above $2 \times 10^{20}$ m$^{-3}$
  - Local density determined from frequency shift
- Distance between peaks in high frequency sweep matches maxima of low frequency sweep

$\Delta f = 32$ MHz
Scanning Probe Measurement

- Reciprocating RF probe located ~10cm above midplane on A-Port
- One electrode connected through 4.6 GHz bandpass filter to RF diode
- Localization of RF electric field in scrape off layer near R=91cm
Improving Performance

• Poor coupling often caused by too little density at the antenna during shots with low core density
• Other tokamaks (JET[5], ASDEX[6]) improve coupling by injecting gas through capillaries magnetically connected to LH antenna to raise the edge density
• Rerouted two spare NINJA capillaries to C-Port for upcoming run campaign
• Details about the mechanism of gas ionization near LH couplers or how to best increase electron density locally near antenna without increasing global plasma density still unclear
Coupling with ICRF and H-Mode

- LH operation with D-Port ICRF antenna unreliable
- E- and J-Port ICRF antennas causes fewer problems
- Langmuir probe data difficult to interpret when D and E antennas are operating due to voltage sheaths produced by ICRF
- Coupling with ICRF better during H-modes
Conclusions and Future Work

• LHCD system successfully operated during ‘07 campaign with ICRF and H-mode
• Parametric Decay observed
  – Have not reached “density limit”
• Several codes under development to simulate coupling in complex geometry with arbitrary density profiles
• Simple gas injection system installed for upcoming ’08 campaign
• New antenna for FY09
  – X-mode reflectometer
    • Measures density profile
    • Not affected by ICRF sheaths
  – 2nd generation gas injection system
References and Poster Download

[3] TP8.00138, TO4.00006, BP8.00068

To download a copy of this poster, go to:
or
http://www.mit.edu/~wallaceg/wallace_aps_07.pdf