Lower Hybrid: Progress and Plans

Ron Parker

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Motivation for Applying Lower Hybrid Current Drive in Alcator C-Mod is to
Produce and Study Fully Steady-state High Performance Regimes

\[ I_p = 0.98 \text{ MA}, \ I_{BS} = 0.7 \text{ MA}, \ I_{LH} = 0.28 \text{ MA} \]
\[ \beta_n = 2.9, \ H_{ITER-89} = 2.5 \text{ (assumed)} \]

\[ P_{LH} = 2.4 \text{ MW}, \ \eta_{LHCD} = 0.1, \ n_{||} = 2.75 \]
\[ P_{ICRF} = 4 \text{ MW} \]

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The Original 96 Waveguide Grill (Ti) was Replaced with Grill Fabricated From Stainless Steel

Ti grill as installed in January 2005
This grill quickly deteriorated due to rapid formation of titanium hydride.
Formation of TiH could be problematic for ITER – Needs further study

Stainless steel grill installed in January 2006 as it looked at the end of Alcator C-Mod campaign in July 2006.
(close inspection shows only 88 waveguides!)
LHCD Experiments Made Good Progress in 2006 Run Campaign

Highlights:

- ~ 1 MW net coupled, $\Gamma^2 \sim 15\%$
- Reasonable agreement with Brambilla coupling code with vacuum gap
- Nearly 1 MA driven, $n_{19}\text{IR/P} \sim 3$
- Sawtooth stabilization, central heating observed
- Generally good agreement with GENRAY/CQL3D model regarding total current, hard X-Ray and cyclotron emission synthetic diagnostics. X-Ray profiles broader than code prediction
- Experimental results so far are in-line with requirements for high performance SS operation.
Comparison of Measured Reflection Coefficient With Brambilla Coupling Code

- 0.08 cm Vacuum Gap $dn/dx = 6 \times 10^{12} \text{ cm}^{-4}$
- Variable Density Gradient with No Vacuum Gap

**Graphs:**
- Probe Density cm$^{-3}$ vs. Fraction Power Reflected
- Density Profile with Gap
- Density Profile No Gap

**Equations:**
- $dn/dx = 6 \times 10^{12} \text{ cm}^{-4}$

**Variables:**
- Probe Density cm$^{-3}$
- Distance from Grill cm
- Cutoff Density

G. Wallace
Increasing Lower Hybrid Power Decreases the Voltage Required to Maintain Constant Current
Example of Discharge in Which Sawteeth Were Stabilized and $T_{e0}$ Increased

Shot 106072029
Two Shots Have Been Modeled with GENRAY and CQL3D

<table>
<thead>
<tr>
<th>Parameter</th>
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<td>$I_p$ (MA)</td>
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<td><img src="image2" alt="Plot" /></td>
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<tr>
<td>$V_{loop}$ (V)</td>
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<td><img src="image4" alt="Plot" /></td>
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<tr>
<td>$n_e$ ($10^{19}$ m$^{-3}$)</td>
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<tr>
<td>$T_{eo}$ (keV)</td>
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<tr>
<td>$P_{LH}$ (kW)</td>
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Good Agreement Between Measured and Modeled Current and Voltage

CQL3D Power Deposition Profiles

CQL3D Modeled Current Profiles

<table>
<thead>
<tr>
<th>Shot/Time</th>
<th>V_{loop}</th>
<th>I_P(MA)</th>
<th>V_{loop}</th>
<th>I_P(MA)</th>
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<tr>
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<td>0.1</td>
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<tr>
<td>t = 1000 ms</td>
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</tbody>
</table>

A. Schmidt
CQL3D/GENRAY profiles are narrow, consistent with narrow current deposition.

X-Rays suggest a broader current profile – spatial diffusion?

A. Schmidt
The Current Drive Efficiency $\eta = n_{19}I(A)R(m)/P(W) \approx 3$

Using method of Giruzzi\(^1\):

\[ I_p = I_{\text{Ohmic}} + I_{\text{lh}} + I_{\text{hot}} \]
\[ I_{\text{Ohmic}} = \frac{V}{R_{\text{Ohmic}}} \]
\[ I_{\text{LH}} = \frac{n_0 P_{\text{lh}}}{n_{e19}R_0} \]
\[ I_{\text{hot}} = \frac{V}{R_{\text{hot}}} \]

Fit: $y = (\eta_0 + \eta_1)x/(1 + \eta_1x)$

$\eta_0 = n_{19}IR/P = 3.1 \pm 0.1$

$\eta_1 = 0.25 \pm 0.25$

$= R_{\text{Ohmic}}n_e I_p R_0/R_{\text{hot}} P_{\text{lh}}$

\(^1\)Giruzzi, G., et al., Nuclear Fusion, 37 (1997) 673

Note: $n_e = $ density @ $T_e = 2.2$ keV

R. Wilson
Motivation for Applying Lower Hybrid Current Drive in Alcator C-Mod is to produce and study fully steady-state high performance regimes.

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\[ \beta_n = 2.9, \quad H_{\text{ITER-89}} = 2.5 \text{ (assumed)} \]

\[ P_{LH} = 2.4 \text{ MW}, \quad \eta_{LHCD} = 0.1, \quad n_\parallel = 2.75 \]

\[ P_{\text{ICRF}} = 4 \text{ MW} \]

New LH Capability for FY 07-08 Campaigns

Increased Source Power Capability: from 1.8 to 2.7 MW (FY07 Campaign)

New couplers: Restoring 24 waveguides (original design) permits ~11% increase in coupled power for same power density (FY08 Campaign*)

Present couplers: 22 waveguides in toroidal direction. Power from klystrons 1 and 12 split, half to waveguide, half to dummy load.

New Couplers: 24 waveguides in toroidal direction. Each klystron feeds two waveguide columns. (Four being fabricated, delivery Mid-February.)

*In 2007 Campaign if vacuum opening
The overall goal for next campaigns is to develop LHCD into a tool that can be used to control and optimize plasma performance. Specific objectives include:

- Achieve $V_{\text{loop}} = 0$ for $\sim 0.5$ s (several resistive diffusion times). Demonstrate $dI/dt > 0$ with $d\Phi_{\text{trans}}/dt=0$ and evaluate efficiency of transformerless startup, compare with Fisch-Karney theory.

- Explore parametric dependence ($n$, $T$, $n_{||}$, $B_T$, $Z_{\text{eff}}$) of efficiency and compare with theory (Fisch-Karney) and modeling (CQL3D and GENRAY)

- Compare in detail X-Ray and ECE emissions with GENRAY and CQL3D and DKE FP models
Lower Hybrid Experimental Objectives for FY 07-08 Campaigns
(Cont’d)

- Optimize coupling in L-Mode, ICRF-heated and H-mode plasmas and develop improved coupling model
- Operate at high power and drive significant current in H-Mode target discharge
- Simulate alpha particle absorption of LH waves on ICRF generated proton tail
- Measure current profile modification – MSE and/or Polarimetry
- Begin using LHCD as tool to access AT modes – see Amanda’s talk.

Results from the FY07-08 campaigns will be invaluable in informing the LHCD decision for ITER
Looking beyond 2007, we plan to upgrade the RF power available for LHCD experiments. This will be done by installing an additional launcher and adding more source power.

1. Fabricate and Install 2\textsuperscript{nd} Launcher (end FY 2008)

- 16 vs. 24 waveguides to reduce waveguide losses, increase power density and total power
- Eliminate internal 3 dB splitter
- E-plane cut to reduce losses relative to H-plane cut in present launcher:

- H-Plane Cut: Current crosses gaps capacitively
- E-Plane Cut: No current crosses gaps
E-Plane Launcher (4x16 WG’s) is Fabricated From Five Sheets with Milled Slots

A ~ 2 m long single WG E-plane cut (0.030” gap) prototype has been fabricated and successfully tested to 190 kW, 0.5 s. (130 kW with 0.010” misalignment)

Sufficient for > 8 MW in 64 WG coupler (with no reflection)

Cavity measurements confirm losses lower for E-plane cut as expected ➔ 0.122 vs. 0.52 dB/m
Longer Term Plans (Cont’d)

2. Add more source power:

Reference plan:

- Regun 4 remaining klystrons from Alcator C experiment and restore to 250 kW CW nominal operation (2007-2008)

- Refurbish 4th cart (filament and magnet power supplies, vacuum pumps, circulators, controls, etc.) and install in C-Mod cell (2008)

- Design and Fabricate splitter network (2007-2008)

- Replumb waveguides – 8 klystrons (2 MW) feeding each launcher (2009)

- Begin LH experiments with 2 launchers and 4 MW source power (2009)
2. Add more source power:

**Aggressive plan (requiring incremental funding):**

Same as reference plan (except for replumbing waveguides), but in addition:

- Purchase 4 new klystrons (2008-2009)
- Fabricate 5th cart and install in C-Mod Cell (2010)
- Begin LH experiments with 2 launchers and 5 MW source power (2010)

The incremental cost of the aggressive plan is ～ $3M$
Summary and Conclusions (1)

Lower Hybrid Current Drive has been implemented on Alcator C-Mod:

Goal is to use LHCD as a tool to supplement bootstrap current and enable performance optimization studies leading to attractive steady-state regimes.

Results will inform LHCD decision for ITER

Nearly 1 MW has been coupled and current drive approaching 1 MA at \( n \sim 5 \times 10^{19} \text{ m}^{-3} \) has been achieved.

First results indicate current drive efficiency is in line with expectations based on models and sufficient to achieve target regimes, although higher \( n_{\|} \) (lower efficiency) for accessibility and additional power will be required at higher density.

Good general agreement achieved between experiment and both X-Ray and ECE CQL3D/GENRAY synthetic diagnostics. There are indications that \( j(r) \) is broader than code predicts – supported by TRANSP modeling.
In next Alcator C-Mod campaigns, emphasis will be on raising absorbed power toward 1.5 MW, increasing density above $n_e = 1e20 \text{ m}^{-3}$, exploring interactions with ICRH antenna, coupling into H-Mode plasmas and using as tool to access AT regimes.

Meanwhile, a second phase incorporating a second launcher and upgrading the source power to 4 MW is underway – operation scheduled for 2009.

In a more aggressive plan requiring incremental funding, the source power would increased to 5 MW in 2010 – this would provide margin for optimizing steady-state AT modes.