Lower Hybrid: Progress and Plans

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Lower Hybrid waves are injected into Alcator C-Mod Plasmas at 4.6 GHz via an 88-waveguide grill.

Stainless steel grill used to inject LH waves into Alcator C-Mod plasmas. Nearly 1 MW was coupled in 2006 campaign, up to 700 kW in 2007– system restored to (at least) 900 kW in present campaign.
Objectives are two-fold:

1. Produce and study high performance tokamak regimes in Alcator C-Mod which are steady-state on the resistive time-scale. Performance metrics: $\beta_n$, $f_{BS}$, $\tau_E/\tau_H$, $\tau_{\text{pulse}}/\tau_{\text{res}}$.

2. Support the scientific and technological basis for a decision to install an LHCD system on ITER for day 1 operation, and ensure its success.

Clearly, maintaining tight connections between theory, simulation and experiment will be crucial to successfully achieving these goals. See talk by Paul Bonoli!
The ITER STAC has recommended development of a plan for a 20 MW LHCD system for day 1 operation on ITER

The objectives of an ITER LHCD system would include:

Reducing the startup volt-sec consumption (30 % appears feasible)

Reducing $l_i$ during startup

Extending the pulse length in all modes of operation

Facilitating entry into hybrid and advanced modes of operation

Response to the STAC recommendation is being led by the European Party (Alain Becoulet). Alcator C-Mod personnel (Bonoli and Parker) are actively involved, both through C-Mod experiment R&D and development and application of simulation tools.

Regarding the ITER LHCD, note that $\omega$, $\omega_{pe}$, $\omega_{ce}$ and grill power density are essentially identical to those in Alcator C-Mod LHCD scenarios!
Significant progress has been made on the following:

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

- Compare in detail X-Ray and ECE emissions with GENRAY/CQL3D, and DKE/FP simulations

- Measure current profile modification – MSE and/or Polarimetry

- Optimize coupling in L-Mode, ICRF-heated and H-mode plasmas and develop improved coupling model
Power limitations have delayed reaching these goals:

- Achieve $V_{\text{loop}} = 0$ for $\sim 0.5$ s (several resistive diffusion times). Demonstrate $\frac{dl}{dt} > 0$ with $\frac{d\Phi_{\text{trans}}}{dt}=0$ and evaluate efficiency of transformerless startup.

- Operate at high power and drive significant current in H-Mode target discharge

We have restored RF power to 2006 level ($\sim 900$ kW), and anticipate exceeding it during present campaign, which would permit further progress toward these goals.

- Simulate alpha particle absorption of LH waves on ICRF generated proton tail

This experiment will be scheduled in the present campaign.
Recent Research Highlights
The Current Drive Efficiency $\eta = n_{19} I(A) R(m)/P(W) \approx 3$

Using method of Giruzzi\(^1\):

1. $I_p = I_{\text{Ohmic}} + I_{\text{LH}} + I_{\text{hot}}$
2. $I_{\text{Ohmic}} = V/R_{\text{Ohmic}}$
3. $I_{\text{LH}} = n_0 P_{\text{LH}}/n_{e19} R_0$
4. $I_{\text{hot}} = V/R_{\text{hot}}$
5. Fit: $y = (\eta_0 + \eta_1)x/(1 + \eta_1 x)$
6. $\eta_0 = n_{19} I R/P = 3.1 \pm 0.1$
7. $\eta_1 = 0.25 \pm 0.25$


Note: $n_e = \text{density} @ T_e = 2.2 \text{ keV}$

R. Wilson
The effective $n_{\parallel}$ deduced from Fisch-Karney theory$^1$ indicates absorbed $n_{\parallel}$ is upshifted from launched value.

Absorption predicted to occur where $T_e (keV) \approx 30 / n_{\parallel}^2$

Spread in data results from density and temperature variations in different shots.

$n_{\parallel}$ absorbed = $n_{\parallel}$ launched

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X-Ray Profiles and ECE Spectra Compare Favorably with CQL3D/GENRAY Simulations

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

X-Rays have broader profile – spatial diffusion? Or broader wave-particle interaction?

A. Schmidt
Bremsstrahlung profiles broaden as $n_\parallel$ is increased

Dynamic development of Bremsstrahlung profiles obtained by square wave modulating RF with 25 ms period.

Spectra averaged over ~ 100 pulses.  

A. Schmidt

Buildup and decay of 40-60 keV photon emission profiles in 2.5 ms intervals

Little evidence for significant diffusion of fast electrons (but see talk by P. Bonoli)
First MSE measurements of $\tan^{-1}(B_\theta/B_\phi)$ with LHCD have been made.
The inferred current density is consistent with off-axis drive as predicted by GENRAY/CQL3D Simulations.

MSE-based measurements of $j(r)$ will be a focus of LH studies during the remainder of the present campaign.

J.-S. Ko
S. Scott
P. Bonoli
In general, coupling is good (~20% reflection) provided $\omega_{p,\text{grill}} > \omega_{RF}$.

However, coupling and performance is poor with magnetically connected D-Port ICRF antenna. Although good coupling can be maintained in H-Modes, no current has been driven due to high H-mode density.

G. Wallace
LHCD has produced both expected and unexpected results

- Stabilization of sawteeth by shrinking inversion radius and raising $q_0$
- Both stabilization and destabilization of tearing modes
- Excitation of electron driven TAE modes during startup
- Development of counter rotation and formation of apparent ITB
LHCD has both stabilized and destabilized classical tearing modes. The same $\Delta'$ modification with LHCD should carry over directly to NTM stabilization.

Destabilization
$n_\parallel = 2.3$

Stabilization
$n_\parallel = 1.6$

R. Granetz
J. Snipes
S. Wolfe
Fast Electron Driven TAEs with LHCD in the Current Rise

- Mode frequencies fit well $f_{TAE} = v_A/(4\pi q R)$ for intermediate $q$ values and bursts occur at integer and half-integer $q$ values from 11 down to 5.5
- Three frequency bands scale roughly as $n=2, 3, 4$ within a broad TAE gap
LHCD induces counter rotation and drop in $l_i$
LHCD-induced counter rotation profiles are localized to core
Future Plans
The basic goal of the LH program in the next 5 years is to achieve the motivating objectives

1. Produce and study high performance tokamak regimes in Alcator C-Mod which are steady-state on the resistive time-scale.

   Performance metrics: $\beta_n$, $f_{BS}$, $T_E/T_H$, $T_{pulse}/T_{res}$.

2. Support the scientific and technological basis for a decision to install an LHCD system on ITER for day 1 operation, and ensure its success.

Our experience with the LHCD system to date indicates that the overall performance is in-line with expectations based on simulations and understanding of the physics.

However, in order to use LHCD as a tool to explore high performance “steady-state” regimes, a considerable upgrade of the available RF power will be required.

Thus, our strategy for the 5-year plan for LH is mainly centered on increasing the LHCD power.
The strategy for the 5-year plan for LH is based on increasing the available RF power.

The RF power available for launching LH waves will be increased by:

- Adding a second launcher, optimized to reduce transmission losses and prevent RF breakdown in the transmission system;
- Rebuilding 4-5 of the original 16 Alcator C klystrons to restore them to their original 250 kW capability;
- Procuring 3-4 new klystrons, essentially of the same design as the Alcator C klystrons.
- Replacing the first coupler with one based on the new launcher design.

By implementing this plan we expect to have 4 MW of source power, of which ~ 3 MW should be available for launching LH waves. This is a factor of 3 increase over present capability and, based on measured efficiency, should be sufficient to drive 300 kA in advanced tokamak regimes.
The new launcher design is simplified to maximize power.

4-way split based on H-plane Tee junction
Assembly view of new launcher design
The timetable calls for a new launcher and sufficient klystrons to power both it and the present launcher to be available for FY 09 campaign.

Replacing the present launcher with one based on the new design is scheduled to occur near the end of 2010.
Several scientific issues need further study and resolution

Further characterization of plasma-grill interactions, particularly with ICRH, at high LH power and in H-modes.

Possibility to couple long distances (measured in terms of perpendicular wavelength) to separatrix – effect of gas puffing near grill.

Propagation through H-mode pedestals.

Validation of both ray-tracing and full wave codes, coupled with Fokker-Planck codes.

To assist in these studies, new diagnostics are being considered:

- Vertical view of downshifted electron cyclotron harmonic emission
- Reflectometer to accurately characterize edge density profile
- CO2 scattering and/or reflectometer to measure LH-wave induced density fluctuations