Modification of Current Profile, Toroidal Rotation and Pedestal by Lower Hybrid Waves in Alcator C-Mod


18th Topical Conference on RF Power in Plasmas

Gent, Belgium

June 24-27 2009
Lower Hybrid waves are injected into Alcator C-Mod plasmas at 4.6 GHz via an 88-waveguide grill.

Probes used to Measure edge density

4X22 Waveguide grill

5.5X60 mm² waveguides, stainless steel

1.5 < n || < 3.5, continuously and dynamically variable

12 klystrons, 250 kW each, CW

Maximum coupled power = 1.2 MW
Motivation

- Use LHCD as actuator to broaden current profile for access to low shear, high performance, near-steady-state regimes relevant to ITER.

  Similar field – $B_T = 5.4$

  Similar shape – Diverted

  Similar density – $\bar{n} = 5 \times 10^{19} - 2 \times 10^{20} \text{ m}^{-3}$

  Similar frequency – $f = 4.6 \text{ GHz}$

- Develop understanding of LH physics for confident extrapolation to ITER
Outline

- Modification of current profile by LHCD
- Observation of LHCD-induced counter-rotation, comparison with injected wave momentum
- Pedestal, rotation modification in H-Mode
- Development of new FEM simulation tool
- New coupler design and future plans
- Summary
Modification of current profile by LHCD

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MSE signals show clear response to LHCD pulse

MSE traces at various major radii for discharge with MHD. Onset of tearing mode activity modifies current profile.
MSE-constrained EFIT reconstructions show broadened $j_\varphi$ profiles

For EFIT reconstruction $P'$ and $FF'$ are modeled by 2- and 3- term polynomials, respectively, and poloidal field on mid-plane is constrained by MSE measurements. Any structure in $j_\varphi(R)$ is smoothed by this approach.

Behavior of central $q$ and internal Inductance (from EFIT) are consistent with broadening of $j_\varphi$ profile.
Direct reconstruction from MSE data yields current profiles with some structure—but is it real?

- Analytic formula developed by Petty et al. (PPCF 47 (2005) 1077) is also used to directly derive $J_\phi$ profiles.

- Analysis is limited to two $n_\parallel$ cases that have multiple shots for the same $n_\parallel$ for better statistics ($d(\Delta B_V)/dR$ is involved).

For $n_\parallel = 1.56$ there appears to be more structure than in EFIT reconstructions.

For $n_\parallel = 1.95$, no noticeable structure. Good agreement with the EFIT $J_\phi$ profile.
Both EFIT and direct reconstructions show broadening of $J_\phi$ profile

LHCD causes a redistribution of current from “center” ($r/a < 0.44$) to “off-axis” ($r/a > 0.44$) – strongest for lowest $n_\parallel$

$n_\parallel = 1.56$

$n_\parallel = 1.95$

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MSE + EFIT

- MSE + Petty et al.
Raw MSE signals & reconstructed profiles show inverse $n_{\parallel}$ dependence of efficiency.

- Reference Ohmic phase taken from 0.6 to 0.7 sec.
Simulations using GENRAY/CQL3D show qualitative agreement with experiment but with discrepancies.

Fokker Planck modeling using GENRAY/CQL3D

- Small spatially uniform diffusion coefficient with a linear velocity dependence is used.

Plans to resolve discrepancies:

- Higher resolution $j(r)$ measurements with MSE upgrade and polarimetry (new)
- Direct detection of wave fields with reflectometer, possibly PCI detection of LH wave density
- Incorporate pinch and diffusion from dynamic X-ray measurements into CQL3D
- Improve simulations using full wave plus FP codes
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LHCD generates counter rotation and negative radial electric field - cause or effect?

The rotation generally develops on the resistive time scale and is largely confined to the core.

A. Ince-Cushman, PRL 102, 035002 (2009)
J. Rice, Nucl. Fusion 49, 025004(2009)
Rate of injected wave and particle momentum is sufficient to explain plasma momentum buildup

Rate of toroidal momentum buildup in plasma:

\[ \dot{P}_\phi = m_i n v \phi \cdot Vol = 4.2 \times 10^{-3} \text{ N} \]

Rate of momentum injected by wave\(^1\):

\[ \dot{P}_\phi = \int dA \cdot \frac{1}{\omega} k S \cdot \phi = \frac{n \phi}{c} \int dA \langle W \rangle v_g \cdot \phi = \frac{n \phi}{c} \text{ Power} \]

\[ = 6.7 \times 10^{-3} \text{ N} \]

Rate at which fast current carrying electrons lose momentum:

\[ \dot{P}_\phi = \frac{2\pi R \int dA m_e (nv)_{fast}}{\tau_{SD}} = \frac{2\pi R m_e I}{e \tau_{SD}} = 5.7 \times 10^{-3} \text{ N} \]

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Wave momentum transferred to trapped electrons also results in inward pinch

\[
\frac{d}{dt}(mR^2 \dot{\phi} - e \psi) = eRE_\phi
\]

\[
\Delta \psi \approx \delta r \frac{\partial \psi}{\partial r} = -\oint RE_\phi dt' \approx \frac{TR}{e} \left\langle \frac{dp_\phi}{dt} \right\rangle
\]

\[
v_r \approx \frac{1}{en_r B_p} \left\langle \frac{dP_\phi}{dt} \right\rangle
\]

Numerically, \( v_r \approx 0.7 \text{ m/s (inward)} \)
LH pulse is square-wave modulated and Bremsstrahlung is sorted into time and energy bins.

By analyzing buildup and decay with a diffusion-pinch model, a pinch velocity is obtained:

Scan across plasma vertical cross-section
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At high densities, evidence for fast electrons and current drive diminishes – an issue for C-Mod H-modes

- Hard X-Ray emission falls rapidly above $n \sim 1 \times 10^{20} \text{ m}^{-3}$
- Weak PDI (decay to IC harmonics) routinely observed at all densities
- Density “limit” is well below that expected for decay to two LH waves ($\omega \sim 2\omega_{\text{LH}}$)
- Possible explanation: Propagation, damping in SOL

Greg Wallace B 60
However in high density H-modes, LH Waves modify pedestal and rotation

- Pedestal density decreases, profile broadens
- Pedestal temperature increases, leading to increased temperature and stored energy
In this H-Mode, LH induces substantial change in rotation-additive to ICRF induced rotation.
In H-mode discharge LHCD modifies pedestal density and edge rotation

Pedestal rotation change occurs before change in core rotation

LH also increases SOL density, decreases density in pedestal and core

SOL density profile broadens

These H-modes will be a focus for LHCD studies in the next campaign!
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A new, finite element full-wave code for LH waves has been developed (1)

Uses commercial FEM software package COMSOL Multiphysics to iteratively solve for fields in spatial domain:

\[
\nabla \times (\nabla \times \vec{E}(\vec{r})) - k_0^2 \vec{\varepsilon}(\vec{r}) \cdot \vec{E}(\vec{r}) = 0
\]

\[
\vec{\varepsilon}^n = \vec{\varepsilon}_{\text{cold}} + \frac{-i}{E_z} \frac{\hat{2\pi}}{\sqrt{2\pi}} \int dz' \varepsilon_L(z - z') E_z(z')
\]

\[
\varepsilon_L(z) = FT^{-1} \text{Im} \varepsilon_{zz}(k_z)
\]

(z is coordinate along field line)

Nth iteration:

\[
\vec{\varepsilon}^N = \vec{\varepsilon}_{\text{cold}} + \frac{-i}{E_z^{N-1}} \frac{\hat{2\pi}}{\sqrt{2\pi}} \int dz' \varepsilon_L(z - z') E_z^{N-1}(z')
\]

Syun'ichi Shiraiwa B 58
A new, finite element full-wave code for LH waves has been developed (2)

The code agrees with ray-tracing in the case of strong single pass damping.

An attractive feature is that it seamlessly treats fields from source to dissipative sink in plasma, including propagation through waveguides, grill, SOL and pedestal.

Adaptable to quasi-linear Fokker-Planck treatment of $f(\vec{v})$. 
Field profiles for Maxwellian and 1-D Fokker-Planck $f(\mathbf{v})$ show significant differences.

Alcator C-Mod plasma: $n_0 = 5 \times 10^{19} \text{m}^{-3}, T_{e0} = 2.5 \text{ keV}$, $n|| = 2.5$. An 800 kA, $B_T = 5.4$ T EFIT equilibrium was used.
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A new coupler designed for more efficient coupling and higher power handling capacity is being fabricated.

Design is based on 4-way, H-plane splitter – load tolerant

Fed by standard C-Band waveguides, matched with step transformer

Design was carried out with integrated simulation based on CST Microwave Studio and coupling code TOPLHA

Orso Meneghini A 57
Future Plans

Hardware:
- Install new coupler this summer
- Expect to increase maximum coupled power to ~ 1.5 MW
- Construct additional coupler and install in 2011
- Add 7-8 more klystrons to bring total source power to 4 MW, ~ 3 MW to plasma in 2011

Main research topics:
- Operation at high density, H-mode density limit
- Physics of rotation
- Further development of full wave codes\(^1\,\^2\) and experimental validation

\(^1\)Syun’ichi Shiraiwa B 58
\(^2\)John Wright I 16
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Summary
Lower hybrid current drive has been shown to broaden the current profile in Alcator C-Mod plasmas – useful tool to explore AT operation

Spatial deposition of $j_\phi$ measured with MSE, in qualitative agreement with ray tracing, Fokker-Planck simulations, but detailed questions remain

Strong counter current rotation accompanies LH wave injection – wave momentum input sufficient, but details need further exploration

Current drive efficiency falls off rapidly with density, well below the $2\omega_{\text{LH}}$ limit – why?

A new full wave FEM simulation has been developed:

- Seamless treatment from source to sink
- Good agreement with ray-tracing in single pass regime, discrepancies in multi-pass case