Simulation study of LH waves in KSTAR

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POSTECH

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Motivation and physics issues

- **ITER R&D issues (Why LHCD)**
  - Emergence of an improved H-mode
  - Limited capability and flexibility of the ITER poloidal system

- **ITER LHCD system**
  - 5 GHz/20 MW/PAM launcher

- **LHCD physics issues**
  - Coupling
  - Propagation and absorption
  - Current drive
  - Magnetic flux-saving

<table>
<thead>
<tr>
<th>Device</th>
<th>$\eta_{CD}$ ($10^{19}$ Am$^{-1}$W$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBI</td>
<td>0.5*</td>
</tr>
<tr>
<td>ICRF</td>
<td>0.4**</td>
</tr>
<tr>
<td>ECCD</td>
<td>0.4*</td>
</tr>
<tr>
<td>LHCD</td>
<td>2.3*</td>
</tr>
</tbody>
</table>

R=1.8 m, $n_{e0}=10 \times 10^{19}$ m$^{-3}$

* C. Gormezano, et al., Nucl. Fusion 47 S285
** ITER physics basis, Nucl. Fusion 39 2495

G. T. Hoang et al., Nucl. Fusion 49 (2009) 075001
Contents

- Introduction

- LHCD in integrated modeling
  - Spectral properties (ALOHA)
  - LH wave-plasma coupling (ALOHA)
  - Propagating and absorption (C3PO/LUKE)
  - Current drive (C3PO/LUKE)
  - Magnetic flux-saving (METIS/C3PO/LUKE)

- Summary
Introduction

- Layout of KSTAR initial LHCD system
LHCD in integrated modeling

Experiment
- $B_T, I_P$
- Stored energy
- Plasma pressure
- Flux

Initial equilibrium
- $q, \beta_p, \kappa, \delta, l_i$

Evolve in time solving
- MHD eq.
- Thermal transport eq.
- Density transport eq.

Transport
- $J_{LH}, P_{LH}$
- $\eta_{CD}, \eta_{\parallel}$

Predictive results
- $l_{LH}, n, T, \text{flux}, V_{\text{loop}}$
- $q, b_p, \text{and} \ l_p \text{profiles}$

LH wave propagation
- $n_{\parallel}, P_{LH}$

Launcher
- Coupling efficiency
- $n_{\text{edge}}, \lambda_{\text{SOL}}$

Plasma edge

ALOHA

Limitation of initial LHCD system

LH-assisted scenario

LH-assisted experiment results
Spectral properties

- Initial LH launcher for KSTAR

  ![Diagram of LH launcher](image)

  - Fully active waveguide coupler (grill)
  - 8 waveguides
  - 4 waveguides

- Radiated power spectrum

  $$P(k_\parallel) = \frac{\sin^2(k_\parallel b/2) \sin^2[N(\Delta\phi - k_\parallel b - k_\parallel d)/2]}{k_\parallel^2 \sin^2[\Delta\phi - k_\parallel b - k_\parallel d/2]}$$

  ![Plot of power spectrum](image)

- 2D power spectrum (real part)

  ![2D power spectrum](image)

- RF Characteristics

<table>
<thead>
<tr>
<th>Phase difference</th>
<th>60°</th>
<th>90°</th>
<th>120°</th>
<th>150°</th>
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<tbody>
<tr>
<td>Directivity (%)</td>
<td>95</td>
<td>90</td>
<td>80</td>
<td>67</td>
</tr>
<tr>
<td>$N_{\parallel}$ peak</td>
<td>1.4</td>
<td>2.1</td>
<td>2.8</td>
<td>3.6</td>
</tr>
</tbody>
</table>
**LH wave-plasma coupling**

- **Advanced LOwer Hybrid Antenna (ALOHA)**
- Depend on: geometry of launcher and the edge plasma characteristic
- Assumption
  - Plasma: Cold plasma
  - Under WKB condition
  - Two density gradients in front of the launcher
  - LH wave: Slow wave

- **Electron density profile for ALOHA**
  - Measured profile (#6099)
  - Estimated profile (ALOHA)

- **Assumption**
  - Plasma: Cold plasma
  - Under WKB condition
  - Two density gradients in front of the launcher
  - LH wave: Slow wave

**Parameters**

- \( n_{e,\text{LCFS}} = 2.4 \times 10^{18} \text{ m}^{-3} \)
- \( n_{e,\text{grill}} = 4 \times 10^{17} \text{ m}^{-3} \)
- \( d_{\text{SOL}} = 3.5 \text{ cm} \)
- \( d_{\text{grill}} = 2 \text{ mm} \)
LH wave-plasma coupling results

![Graphs showing coupling efficiency vs. ne,grill and ne,LCFS for different Δp values.](image-url)
Reference data

- Reference shot data (#5952, #6184)
- Measured temperature profile (ECE data)
- Plasma equilibrium (E-fit)
- Assumed density profile

### Reference shot data (#5952, #6184)

#### Flux (Wb)

#### Ip (kA)

#### V_loop (V)

#### ne (x10^19 m^-2)

<table>
<thead>
<tr>
<th></th>
<th>#5952</th>
<th>#6184</th>
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</thead>
<tbody>
<tr>
<td>B_T</td>
<td>2 T</td>
<td>3 T</td>
</tr>
<tr>
<td>R</td>
<td>1.706 m</td>
<td>1.775 m</td>
</tr>
<tr>
<td>r</td>
<td>0.44 m</td>
<td>0.51 m</td>
</tr>
<tr>
<td>κ</td>
<td>1.478</td>
<td>1.414</td>
</tr>
<tr>
<td>li</td>
<td>2.084</td>
<td>1.002</td>
</tr>
<tr>
<td>β_p</td>
<td>0.542</td>
<td>0.339</td>
</tr>
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</table>
LH wave propagation

- Ray-tracing code, C3PO

- Toloidal trajectories

- Poloidal trajectories

-Ray trajectories

-High absorption
Current and power absorption

- Fokker-Planck solver, LUKE

![Graphs showing current and power absorption for different electron densities (n_e=1x10^18 m^-3 and n_e=5x10^18 m^-3).]
Integrated transport: METIS

- Minute Embedded Tokamak Integrated Simulator (METIS)

- Comparison of experiment and METIS calculation
METIS output: LH induced current

- Application of LH power
- LH-induced current

LH power: 300 kW
LH pulse length: 2 s
Variation: LH injection time

(a) all cases of injection time for #5952
(b) 0 to 2 s of injection for #5952
(c) 0.5 to 2.5 s of injection for #6184
METIS output: Magnetic flux-saving

- Saving flux of varying LH injection time

![Graph showing flux saving percentage against injection time for #5952 and #6184.]

- Time trace of internal inductance and plasma resistivity for #5952

![Graphs showing time traces of internal inductance and plasma resistivity with different LH injection times.]

- Level of contribution

![Bar chart showing the level of contribution for resistive and inductive components for #6184 (81%) and #5952 (80.5%).]

- Profiles for early LH application

![Profiles for early LH application showing plasma current and temperature.]

(a) Plasma current
(b) Plasma temperature
When the 1 MW of LH is injected, the flux-saving is about 32%.

Contribution to the rate of the inductive and the resistive terms are almost the same.
A suite of codes specifically coupled and optimized for LHCD modeling was used. The simulated coupling efficiency (ALOHA) was 63.58% with the relative phasing of 90 degree for normal condition of KSTAR plasma (shot #6099). Plasma propagation and power deposition profile were calculated by C3PO for shots #5952 and #6184. Driven current and current drive efficiency were calculated by LUKE. METIS was used to observe the LH wave effect by calculating the time evolution of the magnetic flux and the plasma profile at the plasma current ramp-up regime using the KSTAR experiment data for shots #5952 and #6184. The earlier LH application is more effective for flux-saving.

- 13.7% for #5952 and 14% for #6184
- For #6184, inductive portion ~ 0.08 Wb (19%), resistive portion ~ 0.39 Wb (81%).
- When the 1 MW of LH application, the flux-saving is about 32% and the contribution to the rate of the inductive and the resistive terms are almost the same.