Ray Tracing and Full-wave Simulation of KSTAR LH Wave

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Outline

- LH wave accessibility and Landau damping
- Off-midplane and inside launching
- Ray tracing study of outside midplane launcher
- Full-wave simulation for wave coupling and propagation
- Summary
Understanding of LH wave accessibility condition and Landau damping is important for desirable launcher design

- The wave propagation is proved to closely depend on the LH wave accessibility condition, by which maximum wave phase velocity parallel to magnetic field in the plasma is determined
- And wave is absorbed through the Landau damping

\[ n_{\parallel,acc} = \sqrt{1 - \frac{\omega_p^2}{\omega^2} + \frac{\omega_{pe}^2}{\omega_{ce}^2} + \frac{\omega_{pe}}{\omega_{ce}}} \]

\[ v_{ph} = v_{\parallel} = 3\sim5 \ v_{th} \]

\[ n_{LD} = 5.4/\sqrt{T_e} \]

\[ n_{\parallel,acc} < n_{\parallel} < n_{LD} \]
Wave accessibility and Landau damping for H-mode density profile

"Inside launch": higher field increases the window for accessibility and strong LD allowing lower $n_{||}$ to penetrate, which improves efficiency since $\eta \sim 1/n_{||}^2$
The off-midplane launch has a benefit of significant upshift on the evolution $n_{//}$

- **Off-midplane launch**

  Robust accessibility and off-axis current drive avoiding wave interactions in SOL region (PDI, power spectrum splitting, collisional damping, etc)

Y.S. Bae et al, PPCF 58 (2016) 075003
Outside midplane launcher in KSTAR 5 GHz LHCD

- Conventional grill waveguide launcher
- To be replaced by steady state launcher (PAM)
Ray tracing and Fokker Planck calculation for KSTAR outside midplane LH launcher using GENRAY/CQL3D code

Plasma density and temperature profile
- Theoretical H-mode pedestal profile near rho = 0.9

For simplicity, only main forward peak is considered in GENRAY/CQL3D simulations
- total launched power of 1.5 MW loaded to forward power
Multiple reflections in 2 T case even with high $n_{//} = 2.5$

$2T$

$2.5T$

$ne=3e19/m3, Te=5keV$
LH-drive current profile is strongly dependent upon temperature and density profiles both for $n_{//} = 2.0$ and 2.5

$B_0 = 2.5 \text{ T, } n_{//} = 2.0$

$B_0 = 2.5 \text{ T, } n_{//} = 2.5$
Current drive efficiency for Bt = 2.0 T

- Current drive dependency on the density for various Te(0) and $n_\parallel/(2.0, 2.2, 2.5)$
  - for $n_e(0)=7\times10^{19}/m^3$, 80~150kA/MW and $\eta = 1\sim2.8\times10^{19}$ Am^{-2}W^{-1} for Te(0)=3-10keV

\[ \eta = n_e R I_{cd}/P_{abs} \]
Current drive efficiency for Bt = 2.5 T

- ~20% enhancement than Bt=2T
- Current drive dependency upon density for various Te(0) and n//
  - 100~250kA/MW and η = 1.5~2.7x10^{19} Am^{-2}W^{-1} for ne(0)=7x10^{19}/m^3
Current drive efficiency for Bt = 3.0 T

- Similar CD efficiency as Bt=2.5T
- Current drive dependency upon density for various Te(0) and n//
  - 120~200kW/MW and $\eta = 1.5\sim3.0 \times 10^{19}$ Am$^{-2}$W$^{-1}$ for ne(0)=7x10$^{19}$/m$^3$
Confinement time of fast electron
\[ \frac{\tau_F}{\tau_E} \sim \gamma^\alpha \]
\[ \alpha = 3 \sim 4 \]
In Cylindrical geometry,
\[ \chi_F \approx \frac{a^2}{6 \tau_F} \]

If 100 keV, \( \gamma = 1.1956 \);
For KSTAR,
\[ \tau_F = \tau_E \gamma^\alpha \approx 0.1 \text{ s} \times 1.1956^3 \sim 0.2 \text{ s} \]
\[ \chi_F \sim 0.2 \text{ m}^2/\text{s} \]

\( I_{\text{CD}} \) decreases by \( \sim 20\% \)
Reversed spectrum from the launcher with forward to reverse power loading, 70:30% results in reduced current drive by ~ 40%

\[ n_{//} = \frac{\Delta \phi}{k_0 p} + \frac{2\pi m}{N k_0 p}, m = lN, l = 0, \pm 1, \pm 2, \ldots \]

\( p \) is period
\( N \) is number of active waveguide in each PAM module

\( \Delta \phi = 270\text{deg} \)
\( l=0, n_{//}=-2.5 \) (main lobe)
\( l=-2, n_{//}=4.2 \) (opposite lobe)

With reversed spectrum
\( l_{\text{CD}} = 180 \text{ kA} \)

With only main peak
\( l_{\text{CD}} = 320 \text{ kA} \)
Multiple side lobes results in much smoother spectral gap “filling”

Multiple high $n_{\text{tor}}$ side lobes are predicted by theoretical calculation of power spectrum from the grill launcher

- 3 high $n_{\text{tor}}$ peaks are included for $n_0 = 2.5$
- Different from customary approach with the only main peak, which tends to result in poorer spectral phase space “filling”
Proposed configuration of KSTAR 3 MW PAM launcher using 8 x 0.5 MW klystrons

2 way x 4 way x 4 active x 8 klys = 256 active wgs (32 toroidal x 8 poloidal)

\[ n// = \frac{\Delta \phi}{k_{0p}} + \frac{\delta \phi - 180^\circ}{N_{wg} k_{0p} \times 180/\pi} = 2.5 \]

Power flux

\[
\frac{3\text{MW}}{256/(58\text{mmx7mm})} = 28.8\text{MW/m}^2
\]

ITER design: 33 MW/m^2
Tore Supra: 25 MW/m^2 (2.7 MW during 78 s) to be increased to > 30 MW/m^2
RF power reflection calculation in PAM launcher from the edge plasma using FEM-based full-wave simulation

Perfect Matched Layer (PML)

Wave equation

\[ k \times k \times E - k_0^2 \left( \varepsilon_r - i \frac{\sigma}{\omega \varepsilon_0} \right) E = 0 \]

Plasma model: Dielectric tensor in Stix’s frame

\[ \varepsilon_r = \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix} \]

COMSOL Multiphysics® model
16 active and 17 passive waveguides
With bA = 7 mm, bP = 7 mm (5 mm), e = 3mm (2mm)
Wave propagation from the PAM grill waveguides shows two main lobes of the radiation spectrum

\(N_{wg} = 16\)
\(n_{\text{main}} = -2.5; \ n_{\text{opp}} = 4.1\)

Directivity = 55 %

Fourier Transform of Ex near the launcher
Power reflection as a function of edge density ($n_{e\_edge}$) and density gradient ($n_e/\nabla n_e$)

- Reflection changes significantly with density gradient at the low density regime, but less effect at high density regime.

$bA=7\text{mm}, bP=7\text{ mm}, e=2\text{ mm}$

$bA=7\text{mm}, bP=5\text{mm}, e=3\text{ mm}$
LH wave propagation inside tokamak using FEM-based full-wave simulation  
Collaboration with MIT

- In the wavenumber domain
  \[
  \vec{k} \times (\vec{k} \times \vec{E}(\vec{k})) + \frac{\omega}{c^2} \vec{\varepsilon}_{\text{LH}}(\vec{k}) \cdot \vec{E}(\vec{k}) = 0
  \]
  - LH dielectric tensor: cold plasma + electron Landau damping
  \[
  \vec{\varepsilon}_{\text{LH}} = \vec{\varepsilon}_{\text{cold}} - i\vec{\varepsilon}_L = \begin{pmatrix}
  S & -iD & 0 \\
  iD & S & 0 \\
  0 & 0 & P
  \end{pmatrix}
  - i \begin{pmatrix}
  0 & 0 & 0 \\
  0 & 0 & 0 \\
  0 & 0 & \varepsilon_L(k_z)
  \end{pmatrix}
  \]

- An integro differential equation in real space
  \[
  \nabla \times (\nabla \times \vec{E}(\vec{x})) + \frac{\omega}{c^2} \left( \vec{\varepsilon}_{\text{cold}} \cdot \vec{E}(\vec{x}) - i \frac{\hat{z}}{\sqrt{2\pi}} \int \varepsilon_L(z-z')E_z(z')dz' \right) = 0
  \]
  \[
  \varepsilon_L(z) = \frac{1}{\sqrt{2\pi}} \int \varepsilon_L(k_z)e^{-ikz}dk_z
  \]
  Convolution integral

Conventional PDE solved by COMSOL
Convolution integral done in LiveLink® Matlab
Stix’s dielectric tensor should be rotated with two angles defined by 3D equilibrium magnetic field data (Bx, By, Bz)

- Dielectric tensor in Stix’s frame
  \[
  \tilde{\varepsilon} = \begin{pmatrix}
  S & -iD & 0 \\
  iD & S & 0 \\
  0 & 0 & P - i\varepsilon_{ELD}
  \end{pmatrix}
  \]

- Rotation of dielectric tensor
  \[
  R(\theta, \phi) \bullet \varepsilon \bullet R(-\theta, -\phi)
  \]
  \[
  \theta \text{ and } \phi \text{ is defined with Bx, By, Bz} \]
Summary

- Using GENRAY/CQL3D code, the wave ray tracing and its current drive are studied for KSTAR outside midplane launcher.

- The simulation results show that high toroidal magnetic field or high launched $n_{\parallel}$ is recommended according to accessibility condition and strong Landau damping.

- A significant LH wave current drive could be obtained for the wave spectrum with peak value $n_{\parallel} = 2.5$ if a toroidal magnetic field $B_t = 2.5 \sim 3.0$ T is applied.

- Further studies in full wave simulation is planned for the investigation of the of LH wave non-linear interaction in SOL region and edge region.

- Proposed off-midplane (top launcher) for strong single pass absorption hence high CD efficiency in KSTAR LHCD is being considered for future upgrade.
Next time, I hope to see you again in Hokkaido (?) with another topic of top launcher of ECH
Lower hybrid wave penetration and absorption

- **Lower hybrid wave frequency in tokamak**
  \[
  \omega_L H = \frac{\omega_{pi}}{\sqrt{1 + \frac{\omega_{pe}^2}{\omega_{ce}^2}}}^{1/2}
  \]
  \[
  n_{||1} = \sqrt{1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} \left(1 - \frac{\omega_{ce} \omega_{ci}}{\omega^2}\right) + \frac{\omega_{pe}}{\omega_{ce}}}
  \]
  \[
  \omega_{GM}^2 = \omega_{ce} \omega_{ci}
  \]
  - **Accessibility**
    \[
    n_{||2} = \sqrt{\frac{30}{T_e(keV)}} \quad \leftrightarrow \quad v_{ph} = v_{||} = 3v_{th}
    \]
    \[
    n_{||2} = \sqrt{\frac{49}{T_e(keV)}} \quad \leftrightarrow \quad v_{ph} = v_{||} = 2.3v_{th}
    \]
  - **Landau damping**
  \[
  \omega_{GM}^2 = \omega_{ce} \omega_{ci}
  \]
  \[
  \omega_{GM}(0) = 1 \times 10^{20}/m^3, \ B_t = 2 \ T
  \]

**Accessibility**

**Landau damping**