Electron Bernstein wave core deposition via O-X-B double mode conversion in TCV


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Context

• Electron cyclotron (EC) waves accessibility limitation in medium to low $B$ field tokamaks
  \[ n_{e,\text{cut-off}} \propto B^2 \]

• Solutions:
  – Higher harmonics
  – Electron Bernstein waves (EBW)

• In TCV (H-mode, $I_p = 0.5$ MA, $a = 0.2$ m)

<table>
<thead>
<tr>
<th>Waves</th>
<th>Max $n_e/\langle n_{eG} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-mode 2nd harm.</td>
<td>~12%</td>
</tr>
<tr>
<td>O-mode 2nd harm.</td>
<td>~23%</td>
</tr>
<tr>
<td>X-mode 3rd harm.</td>
<td>~35%</td>
</tr>
<tr>
<td>EBW via O-X-B</td>
<td>100%, no upper limit</td>
</tr>
</tbody>
</table>

Tokamak empirical density limit

\[
\langle n_{eG} \rangle [\text{m}^{-3}] = 10^{20} \cdot \frac{I_p [\text{MA}]}{\pi \cdot (a [\text{m}])^2}
\]
Bernstein waves are electrostatic
⇒ need a conversion from externally launched e.m. waves in O-mode

- **O-mode to X-mode** conversion at the O-mode cutoff: angular window for the wave injection angles ($\pi$ and $\tau$) of width $T_{O-X}$

$$T_{O-X} \propto \exp(-\pi k_0 L_n); L_n = \left(\frac{dn}{dR} \frac{1}{n}\right)^{-1}$$

⇒ needs a small normalized density scale length $k_0 L_n$ (steep $\nabla n$)

- **X-mode to B-mode** conversion at the upper-hybrid resonance: needs $k_0 L_n > 1$
O-X-B EBH plasma target in TCV

- High-confinement mode provides the adequate $\nabla n$ conditions ($k_0 L_n \sim 10$ at the edge)
  - Medium $\delta_{95} \sim 0.4$
  - High $\kappa_{95} \sim 1.5$
  - Low $q_{95} \sim 2.2$
  - Thus high $I_p \sim 400$ kA

- Strong central sawtooth activity

- EC power
  - ON/OFF modulation
  - 181 Hz
  - 50% duty cycle
From off-axis to core EBW deposition

ART non-relativistic ray-tracing:
• Oblique launch: $\rho_{\psi_{dep}} \sim 0.76$
• Equatorial launch: $\rho_{\psi_{dep}} \sim 0.17$ (~73% of power)
Duplex Multiwire Proportional soft X-ray detector (DMPX)

- High spatial resolution (64 vertical lines of sight)
- High time resolution (200 kHz)
Off-axis deposition: FFT analysis

- $Z_{axis} \sim 20$ cm, UL launchers
- Off-axis deposition to avoid the strong central sawteeth
- Total energy from Diamagnetic Loop (DML) shows up to 60% global absorption
- Clear perturbation on edge soft X-ray channels (DMPX) for each EC power pulse
- Fast Fourier Transform (FFT) analysis can be used
  - FFT $\rightarrow \rho_{\psi,dep} \sim 0.71$
  - ART $\rightarrow \rho_{\psi,dep} \sim 0.76$
- Successful EBW deposition demonstrated
Core deposition: FFT analysis

- $Z_{axis} \sim 0$ cm, equatorial launchers
- DML shows up to 60% global absorption
- Slight but visible perturbation on soft X-ray channels (DMPX)
- Strong sawtooth activity hampers FFT analysis for $\rho_{\psi_{dep}} < 0.7$
Break-in-slope (BIS) analysis

- Method for the power deposition localization excluding the time of the fast sawtooth crash perturbation
  ⇒ Quantify the break in the slope of soft X-ray traces due to EC power modulation

- Automatic detection of sawtooth crashes
- Select the EC power modulations excluding the sawtooth crashes and their propagation
- Linear fit of soft X-ray traces before/after EC switch-ONs
- Calculate the change in slope for each DMPX channel
  ⇒ Break-in-slope profile

Advantages:
- BIS analysis provides information for each EC power switch-ON non-perturbed by the sawtooth
- Can be used where FFT is dominated by the sawtooth perturbation
Test BIS analysis on off-axis case

- BIS $\rightarrow \rho_{\psi_{dep}} \sim 0.70$
- FFT $\rightarrow \rho_{\psi_{dep}} \sim 0.71$
- ART $\rightarrow \rho_{\psi_{dep}} \sim 0.76$

EBW deposition profile from BIS
EBW deposition profile from FFT

BIS agrees with FFT and ART

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BIS deposition location in $B_\phi$-scan

- $B_\phi$ scan to change the radial position of the resonance
- Power deposition location determined with BIS method applied on the DMPX channels
- Small database
  - 5 shots
  - 4 values of $B_\phi$
- Optimum $B_\phi \sim 1.42$ T found for central heat deposition
- ART agrees on the trend and on typical $B_{\phi,\text{opt}}$ but significant radial discrepancies
Conclusions

• Successful assessment of a break-in-slope method for the detection of power deposition location in presence of strong sawteeth perturbation.

• This method now allows central power deposition measurements, not accessible with FFT.

• From yet a small database, initial experimental trend and field for a central EBH optimization was determined.

• Work in progress
  – Take into account the heat pulse propagation delay in the break-in-slope method
  – Use of a Drift-kinetic-equation solver and a fully-relativistic ray-tracing simulation (collaboration with J. Decker, CEA Cadarache) for evaluation of relativistic effects on the power deposition location.
Spare slides
O-X-B double mode conversion

- O-X conversion angular window for the wave injection directions

\[
T_{O-X} = \exp \left\{ -\pi k_0 L_n \sqrt{Y/2} \left[ 2(Y + 1)(N_z - N_{z,\text{opt}})^2 + N_y^2 \right] \right\}
\]
\[
L_n = \left( \frac{dn}{dR n} \right)^{-1}
\]
\[
Y = \frac{\omega_{ce}}{\omega}
\]
\[
N_{z,\text{opt}}^2 = \frac{Y}{Y + 1} = \cos^2(\theta_c)
\]

- X-B conversion transmission function (neglecting non-linear effects)

\[
T_{X-B} = 1 - \exp \left\{ -\pi k_0 L_n Y^2 \sqrt{(\omega_{UH} / \omega_c - 1)/X} \right\}
\]
\[
X = \frac{\omega_{pe}^2}{\omega^2}
\]

- Thus, required normalized density scale length is typically \( k_0 L_n \sim 10 \) in TCV
Test ray propagation sensitivity to $Z_{axis}$

- Difficulty for the power localization could come from the presence of a double absorption location

$\Delta Z_{axis} = -1, -2 \text{ cm}$

$\Delta Z_{axis} = 0$

$\Delta Z_{axis} = +1, +2 \text{ cm}$
Power deposition sensitivity to $Z_{axis}$

- The more the plasma moves away from $Z_{inj} \sim -2.1$ cm ($Z_{axis} \sim 2.3$ cm, $\Delta Z_{axis} > 0$), the more power is absorbed at the outer location.