Abstract

Numerical modeling of electron Bernstein wave (EBW) propagation and damping on the very-low-aspect ratio PEGASUS Toroidal Experiment has been explored using the GENRAY ray tracing code and CQL3D Fokker-Planck code in support of planned heating and current drive experiments. Calculations were performed for 2.45 GHz waves launched with a 10 cm poloidal extent for a variety of equilibrium configurations. Poloidal launch scans show that driven current is a maximum when the poloidal launch angle is between 10 and 25 degrees, supporting a launcher placed near the midplane. Calculations predict that 400 kW of coupled EBW power will drive 10 kA of plasma current in plasmas with an $I_{tf}$ of 90-150 kA. RF-driven current densities reached 20-100 kA/cm² between a normalized minor radius of 0 to 0.2 where the central density and temperature are $4.5 \times 10^{19}$ m⁻³ and 310 eV, respectively. Current drive was primarily via the Fisch-Boozer mechanism. Initial results of O-X-B mode coupling calculations will also be presented.

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Motivation

• Next generation ST experiments will require non-inductive heating and current drive (CD)

• ECRH and ECCD are standard but O- and X-modes will not propagate in overdense plasmas
  – STs, RFPs and spheromaks typically have low B-fields and high densities which cut off cold plasma waves

• PEGASUS provides an economic way to test non-inductive heating and CD methods in support of larger devices
  – Modest scale university project
  – Upgrade has added significant plasma control capabilities
PEGASUS provides an overdense plasma

- EC waves can provide localized heating and CD
  - Tailor j and p profiles; suppress tearing modes
- EC localized emission can be used to measure radial $T_e$ profile
- EC waves are cutoff for overdense plasmas:
  \[ \omega_{pe} > n\Omega_e \]

Model of EC resonances & cutoffs in PEGASUS

First three EC harmonics are overdense through most of the plasma in PEGASUS

Electron Bernstein waves (EBWs) may supply the heating and CD required
EBWs damp at EC harmonics

- EBWs are purely perpendicularly propagating, electrostatic, hot plasma waves that damp on electron cyclotron harmonics in an ST

\[
1 - 2 \frac{\omega_e^2}{\Omega_e^2} \left( \frac{1}{\lambda_e^2} \right) \sum_{n=1}^{\infty} e^{-\lambda_e} I_n(\lambda_e) \frac{n^2}{Q^2 - n^2} = 0
\]

where: \( Q = \frac{\omega}{\Omega_e} \) and \( \lambda = \frac{k_{\perp} \kappa T_{\perp}}{m \Omega_e^2} \)

- Resonant when \( \omega = n \Omega_e \)
- EBWs do not experience a density cutoff in the plasma
- Cannot propagate in vacuum \( \Rightarrow \) must launch O- or X-modes to mode couple to EBW
Coupling EC to the EBW

**X-B**
- Normal incidence of wave
- X-mode tunnels from R cutoff to UHR to couple to EBW
- Cutoffs and UHR must be close for optimal coupling (steep $\nabla n_e$)

**O-X-B**
- Tangential incidence of wave
- O converts to SX to EBW
- Requires shallow $\nabla n_e$
EBWs provides heating and CD

- **Heating**
  - EBWs damp at the EC resonance
  - Absorption is preferentially on particles with large $v_{\parallel}$ in the same direction as $n_{\parallel}$
  - Electron heating is thus achieved by excitation of an electron tail

- **Two methods of CD**
  - Fisch-Boozer
    - An asymmetric resistivity is developed by selective heating of electrons with one sign of $v_{\parallel}$ which drives current
  - Ohkawa
    - Achieved by increasing the $v_{\perp}$ of negative passing particles, trapping them and increasing current in the positive direction
  - Fisch-Boozer and Ohkawa CD drive current in opposite directions
2.45 GHz System well suited for PEGASUS

- Low toroidal field allows use of low frequency klystrons
  - 2.45 GHz fundamental is resonant with 880 G on axis
  - Existing 2.45 GHz equipment will be used for the planned 0.9 MW system

- System must be robust to variety of profiles:
  - Density
  - Temperature
  - Magnetic field

Modeling Goal ➡ find optimal antenna location with highest heating/CD for a variety of plasmas
  - Varying poloidal launch angle changes resonance location due to Doppler broadening
Numerical codes model EBW propagation & damping

**GENRAY**
- General ray tracing code which calculates EM wave propagation
- Assumptions used:
  - antenna 10 cm high
  - $n_{\parallel}$ is -0.45 to -0.55
  - 2.45 GHz with 200 kW of power distributed among 48 rays
  - Direct launch of EBW into plasma at $\rho=0.95$
- GENRAY just recently added the ability to model OXB coupling
  - Consider O-X-B coupling in support of NSTX

**CQL3D**
- Fokker-Planck code that calculates heating and CD profiles
- Uses ray tracing results from GENRAY
B_T scan performed to check robustness of EBW

- **Scan in toroidal field**
  - Rod currents of 90, 120 and 150 kA studied
  - I_p = 148 kA, \( \kappa \sim 2 \), li-0.45, R_0 = 0.39 m, \( \beta \sim 40\% \)
  - Increasing B moves EC resonance location toward low-field-side of plasma edge

Red lines show the location of the fundamental 2.45 GHz resonance for I_{tf} = 90, 120, 150, 180, 210 and 240 kA.
Increase in poloidal launch angle changes resonance location

- EBW rays launched close to midplane damp near axis
- Rays launched at higher poloidal angles damp on Doppler broadened resonances:
  - $n_\parallel$ increases
  \[
  \omega - k_\parallel v_\parallel - n\Omega = 0
  \]

Doppler broadening due to $n_\parallel \sim 4$ near damping

$I_{tf}=120$ kA
Near midplane launch gives optimal heating

- EBWs damping near axis results in localized heating
  - Energy damped in smaller plasma volume leads to maximized heating

![Graph showing peak power density vs. poloidal angle and power density vs. \( \rho \)]
Near midplane launch maximizes current drive efficiency

- EBWs can be used to tailor current profile
  - Can be used to affect tearing mode stability
  - Maximize pressure driven current ($I_{BS}$)
\( \ell_i \) scan performed to check effectiveness of EBWs for varying current profiles

- \( \ell_i = 0.3, 0.5, \) and 0.6 → the current profiles were extremely different for each case
- \( T_e \) and \( n_e \) profiles constant, \( I_p = I_{tf} = 150 \) kA, \( \kappa \approx 2, \) \( \beta \approx 20\% \), and \( R_o = 40 \) cm
Increase in poloidal launch angle increases Doppler shift & radius of damping location

- Increase in poloidal launch angle leads to increase in Doppler broadening
  - Damping location moves out in $\rho$
  - At higher values of $\rho$, damping region spreads

$\ell_i=0.6$

Error bars show FWHM of damping region

<table>
<thead>
<tr>
<th>Poloidal Angle</th>
<th>$\ell_i=0.6$</th>
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</thead>
<tbody>
<tr>
<td>$10^\circ$</td>
<td>0.1</td>
</tr>
<tr>
<td>$45^\circ$</td>
<td>0.2</td>
</tr>
<tr>
<td>$75^\circ$</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Radius [m]  

$Z$ [m]
Heating is peaked for near midplane launch at all $\ell_i$ values

- At lowest possible $\ell_i$, current still peaks near axis

- $\ell_i$ scan reveals sign of current is sensitive to profiles
  - A more extensive scan will be performed in the future to investigate this sensitivity
Fisch-Boozer CD is dominant CD mechanism for near-midplane launch

- Quasilinear diffusion coefficient peaks in passing particle region
- Preferential heating of electrons with negative $v_{\parallel}$ is seen

These are characteristics of Fisch-Boozer CD and are observed for all cases with positive driven current.

120 kA at 15 degrees, $\rho = 0.1$ near the CD region
Ohkawa CD dominant at high $I_{tf}$ and large poloidal launch angle

- For $I_{tf}=150\text{kA}$ with poloidal launch angles $> 55^\circ$, Ohkawa CD is dominant
- Ohkawa CD experiments will support the planned high power EBW system for NSTX

Distribution function shows no Fisch-Boozer characteristic shift at $\rho=0.575$. 
Ohkawa CD dominant at high $I_{tf}$ and large poloidal launch angle

- Quasilinear diffusion coefficient is peaked near the trapped-passing boundary indicating Ohkawa CD

Electron flows in velocity space at $\rho=0.575$

- Electron flows are into the trapped particle region
Modeling of OXB coupling has begun

- Initial OXB coupling calculations from OPTIPOL by M. Carter, ORNL
- Two cases considered:
  1. Mode conversion well outside LCFS with a shallow density gradient
  2. Antenna within the LCFS with a local limiter to force mode conversion in front of the antenna
- Future modeling will include GENRAY calculations

O-X-B dominant, $L_n=2.9$ cm

X-B dominant, $L_n=0.4$ cm
Near midplane X-mode launch experiments possible on PEGASUS

**X-mode**
- \( I_{tf} = 150 \text{ kA} \)
- 15° launch angle
- \( n_{||} = -0.05 \) to 0.05

**O-mode**
- \( I_{tf} = 150 \text{ kA} \)
- 15° launch angle
- \( n_{||} = -0.55 \) to -0.45
Near midplane X-mode launch provides Fisch-Boozer current drive

**X-mode launch**
- CD = 3.2 kA
- Fisch-Boozer CD

**O-mode launch**
- CD = 4.7 kA
- Fisch-Boozer CD
Conclusions

• Power launched 15 degrees above midplane provides maximum heating and CD
  – 2-15 W/cm\(^3\) of heating
  – 20-25 kA/MW of CD
• Existing 2.45 GHz hardware and source from PPPL and Oak Ridge can be used (see RP1.00055)
• Future work
  – Modeling calculations of coupling from O-mode to EBW
  – Include a greater variation of plasma parameters
  – Investigate the dependence of \(l_1\) on the sign of the driven current
  – Perform more modeling to optimize Ohkawa CD in support of NSTX