Abstract

The electron Bernstein wave (EBW) is being studied for use in a wide variety of high-beta confinement devices where the plasma is overdense. The EBW is of particular interest in spherical torus (ST) experiments, where it could be used both as an electron temperature diagnostic and as a technique for heating and current drive. The PEGASUS Toroidal Experiment provides an attractive opportunity for investigating the physics and implementation of EBW heating and for developing scenarios for larger experiments such as the National Spherical Torus Experiment (NSTX). It operates at low toroidal field ($B_t < 0.15$ T), allowing the utilization of abundant, low-cost 2.45 GHz hardware and sources. Recent upgrades to the experiment provide for programmable position control which is essential coupling of the electromagnetic waves to the EBW. Planning has begun for a 0.5-MW heating and current drive experiment on PEGASUS. Raytracing calculations, accessibility considerations, diagnostic requirements and experimental possibilities are presented.

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Motivation

• Next-generation ST experiments will require non-inductive heating and current drive
  - Upcoming phase of PEGASUS ops to explore some of these techniques

• Electrostatic electron Bernstein waves may fulfill this function
  - ECH is a standard tool, but X&O modes will not propagate in overdense STs

• PEGASUS may provide a useful test bed for high-power EBW studies
  - Significant plasma control capabilities
  - Low cyclotron frequencies
  - Modest scale

• Must determine suitability of PEGASUS for these experiments
  - Mode conversion of EBW at plasma edge
  - Propagation in plasma
  - Availability of heating system
Electron cyclotron waves cannot access “overdense” plasmas

- Electron cyclotron waves (ECW) have significant uses
  - Localized heating and current drive
    - \( J \) and \( p \) tailoring, NTM suppression
  - Localized emission
    - \( ECE \) is standard \( T_e(R) \) diagnostic

- EC waves are cutoff if \( \omega_R > \omega \) along path of propagation
  - low-field devices with \( \omega_{pe} > n\omega_{ce} \) (approximately!) overdense for harmonic \( n \)
    - \( STs, RFPs, \) spheronaks, etc.
  - Only first 2-3 harmonics strongly emit/absorb

First three EC harmonics are cut off over most of the plasma
EBW can propagate where EC waves are cutoff

- EBW is electrostatic ⇒ evanescent in vacuum
  - Direct launch requires close-fitting antenna
  - EC waves can mode-convert to EBW at edge

- Mode conversion occurs near UHR
  - ECW propagate in vacuum
  - ECW readily launched outside plasma

- O- and X-mode convert differently:
  - X-mode
    = normal incidence \((n_\parallel=0)\)
    = cutoffs & UHR must be in close proximity
      \((i.e.\ steep\ \nabla n_e)\)
    = tunnels from R cutoff to UHR
  - O-mode
    = tangential incidence
    = optimal \(n_\parallel^2=\omega_{ce}/(\omega_{pe}+\omega_{ce})\)
    = requires shallow \(\nabla n_e\)
    = O converts to SX to EBW

(After S. Shiraiwa)
**PEGASUS is a mid-sized, ultra-low A ST**

**Centerstack:**
Exposing Ohmic Heating Solenoid (NHMFL)

**Experimental Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>Phase II Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.5-1.3</td>
<td>1.2-1.3</td>
</tr>
<tr>
<td>R (m)</td>
<td>0.2-0.38</td>
<td>0.2-0.45</td>
</tr>
<tr>
<td>$I_p$ (MA)</td>
<td>≤ 0.16</td>
<td>≤ 0.30</td>
</tr>
<tr>
<td>$I_N$ (MA/m-T)</td>
<td>6-8</td>
<td>15-20</td>
</tr>
<tr>
<td>$RB_t$ (T-m)</td>
<td>≤ 0.03</td>
<td>≤ 0.1</td>
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<tr>
<td>$\kappa$</td>
<td>1.4–3.7</td>
<td>1.4–3.7</td>
</tr>
<tr>
<td>$\tau_{\text{shot}}$ (s)</td>
<td>≤ 0.02</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>$n_e$ ($10^{19}$ m$^{-3}$)</td>
<td>1-5</td>
<td>≤ 10</td>
</tr>
<tr>
<td>$\beta_t$ (%)</td>
<td>≤ 20</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>$P_{\text{HHFW}}$ (MW)</td>
<td>0.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Equilibrium Field Coils**

**Vacuum Vessel**

**RF Heating Antenna**

**Toroidal Field Coils**

**Ohmic Trim Coils**

**Plasma Limiters**
PEGASUS may offer a unique test bed for EBW experiments

- Current and position control allow quasi-steady edge conditions
- Low toroidal field allows use of low-frequency klystrons
  - Frequencies 2-10 GHz can be considered
- University scale allows effective experiments at modest power
- Long-term PEGASUS goals include non-inductive CD
2.45 GHz - good frequency match

- 2.45 GHz (S-band) fundamental is resonant with 880 G
  - Vacuum TF = 400 - 1500 G at R=0.4 m

- Significant hardware exists to handle this frequency
  - PLT lower hybrid system operated here
    (see later in the poster)
  - Diagnostic hardware readily available

- Cutoff for 2.45 GHz is at $7.5 \times 10^{16} \text{ m}^3$
  - Local limiter likely needed
  - Need measurements of edge density

- Remainder of this poster assumes 2.45 GHz for PEGASUS
Equilibrium used for preliminary raytracing calculations

- Raytracing calculations shown in next 8 pages
- GENRAY used for ray propagation
- CQL3D used for power deposition
- All runs are PRELIMINARY and not optimized

Equilibrium Parameters

I_p: 194 KA
R: 0.39 m
A: 1.15
κ: 2.1
RB_{t, vac}: 0.04 T-m
I_p/I_{tf}: 0.92
β_t: 20%
Oblique O-Mode Launch
200 kW
n_\parallel = 0.45 - 0.55

48 Rays
Launch \theta = 25^\circ
Antenna Length = 10 cm
Case I - Heating and Current Drive

- Power deposited in inner 20% of plasma
- +1 KA, -2 KA driven near axis
Case II - Raytracing

Oblique O-Mode Launch
200 kW
\( n_{||} = -0.45 \) - \(-0.55 \)

48 Rays
Launch \( \theta = 25^\circ \)
Antenna Length = 10 cm
Case II - Heating and Current Drive

- Power deposited in inner third of plasma
- Drives +/− 1 KA near axis
Case III - Raytracing

Oblique O-Mode Launch
200 kW
n_|| = 0.45 - 0.55

48 Rays
Launch \( \theta = 0^{\circ} \)
Antenna Length = 10 cm
Case III - Heating and Current Drive

- Power deposited strongly at resonance
- 5 KA driven
Case IV - Raytracing

Normal X-Mode Launch
200 kW
$\eta_\parallel = -0.05 - 0.05$

48 Rays
Launch $\theta = 0^\circ$
Antenna Length = 10 cm
Case IV - Heating and Current Drive

- Power deposited strongly at resonance
- 500 A driven
EBW implementation on Pegasus is accelerating

• Detailed raytracing calculations beginning 12/2004
  - Studies to focus on realistic profiles & equilibria
  - Target discharges will be identified

• Plasma control is advancing
  - Pre-programmed PF coils already give some position control
  - Full ohmic power supply online 12/2004
  - Feedback control systems being investigated
  - Divertor coils online

• Detailed plasma diagnosis beginning
  - Several diagnostics coming online (*=working):
    = \( n_e \): 1 mm IF*, VB
    = \( T_e \): Ross filters, PHA
    = Impurities: bolometers*, SPRED*
  - Use CDX-U EBW diagnostic for edge characterization

• High-power heating components have been identified
Stage 1 - Plasma measurements & modelling

• Edge density and stability must be assessed
  - Proper MC requires knowledge of resonance locations
  - Stable edge required for good coupling
  - Focus on OXB scenario
    = *Elliptically polarized O-mode*
    = good transmission over a range of $L_n$
    = *H. Igami et al., PPCF 46, 2004*

• Use CDX-U combined EBW diagnostic
  - Radial Langmuir probe array
  - Quad-ridged horn antenna
    = *Use 2.45 GHz horn*
    = *Build radiometer for $T_{rad}$ measurement*
  - Movable local limiters

• Coincidentally conduct detailed raytracing studies
  - Study effects of profiles, resonance locations, etc.
Stage 2 - Plasma heating system

- Significant advantage of EBW tests on PEGASUS $\Rightarrow$ 2.45 GHz hardware abundant
- Most of the parts of a conceptual system are available
  - Many pieces of PLT LH system still exist at PPPL & ORNL
  - 2.45 GHz hardware widely used in communications & industry
    $= New\ components\ less\ expensive\ than\ for\ other\ bands$
- Implementation of heating system depends on results of Stage 1
2.45 GHz hardware from PLT

- Recirculator & Waveguide
- Recirculator Dummy Load
- Antenna
- Phase Shifter Output
- Klystron Output
- Klystron Cabinet
Summary

• Next-generation ST experiments will require non-inductive current drive
  - Several candidate techniques are being studied
  - Next phase of PEGASUS work will focus on non-ohmic studies

• Electron Bernstein waves may play a valuable role in ST experiments
  - Electron cyclotron waves cannot propagate in overdense plasmas
  - EBW can propagate, but coupling and propagation more complicated
  - May provide a useful technique for heating, CD, and $T_e$ diagnosis

• Work has begun to study the feasibility of high-power EBW experiments on the PEGASUS Toroidal Experiment
  - Commonly-used 2.45 GHz will work with low toroidal field
  - Raytracing has begun, but requires much more study
  - Need to study edge emission and density profile
  - Parts of a 0.5 MW heating system have been identified