Abstract

The PEGASUS Toroidal Experiment provides an attractive opportunity for investigating the physics and implementation of electron Bernstein wave (EBW) heating and current drive in an overdense ST plasma. The toroidal field of 0.07-0.15 T on axis provides fundamental resonant absorption of 2.45 GHz waves. The new plasma control system will provide a stable plasma edge to support resilient EBW coupling; initial tests will focus on the O-X-B mode conversion scenario. Experiments with up to 1 MW of rf power will address fundamental issues concerning EBWs in ST experiments. These include edge coupling, nonlinear effects (such as parametric instabilities) at the edge, ray propagation, deposition locations, and current drive efficiency, which may be as large as 60 kA/MW at high $T_e$. The proposed hardware is made up in large part of pieces from the PLT lower hybrid system. These include two 450 kW klystrons and associated systems, recirculators, and power transmission equipment.

Work supported by U.S. D.O.E. Grant DE-FG02-96ER54375 and U.S. D.O.E. Contract DE-AC02-76CH03073.
PEGASUS provides an attractive opportunity to study EBW physics

• Electron Bernstein waves potentially useful for heating and current drive
  - propagate in overdense plasmas where EC waves cutoff
    ♦ useful in STs, RFPs, stellarators, etc.
  - larger devices pursuing research (NSTX & MAST particularly)

• Moderate size ⇒ high-power experiments tractable
  - Magnetic field good match for existing 2.45 GHz hardware
  - 1 MW rf power = ohmic input power
  - relatively simple hardware can be used (antennas, waveguide, etc.)
  - machine is highly accessible for intensive campaigns

• Flexibility/controllability ⇒ interesting and useful experiments can be done
  - robust, high-beta plasmas available as targets
  - plasma control system will provide stable edge (Bongard et al., this session)
  - advanced diagnostics coming online
    ♦ Thomson scattering (Battaglia et al., this session)
    ♦ SXR q-profile measurements
    ♦ 2D HXR imaging

• Experiments to be pursued in support of larger NSTX effort
  - significant scientific and engineering involvement from PPPL
  - loan of 2.45 GHz hardware and sources from PLT
The planned experiments address several issues

• Coupling
  - validation of predicted coupling window
  - studies of nonlinear instabilities
  - demonstration of mode conversion at significant power via O-X-B and X-B

• Propagation and damping
  - validation of raytracing models
  - demonstration of local heating
  - study synergism between heating and current drive
  - measurements of Fisch-Boozer current drive efficiency
  - possible investigation of Ohkawa current drive

• ECH-only pressure-driven startup
  - form plasma by ECH in mirror field
  - similar to work on CDX, TST-2
Mode conversion layer located well outside last closed flux surface

- Low rf frequency puts UH layer in low density region
  - 2.45 GHz $\Rightarrow n_e < 7.4 \times 10^{16}$ m$^{-3}$

- SOL density profile not measured yet
  - strongly pumping walls may have significant effect on edge density & EBW coupling
  - will study scrape-off $n_e$ with multi-tipped probe

- Local limiters likely required around antenna

Model edge densities

Flux Plot & Resonances

2.45 GHz Resonances
- Cyclotron
- UH Layer Case 1
- UH Layer Case 2

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47th APS-DPP Denver
October 27, 2005
Mode conversion window modeled to guide system design

- Fiducial equilibrium established for modeling
- Two points chosen to reflect possible conditions
  - A: well into SOL, shallow $\nabla n$, $T_e = 5$ eV
    + using only machine limiters
  - B: at LCFS, steep $\nabla n$, $T_e = 10$ eV
    + with local antenna limiters
- Further modeling with measured density profiles and realistic neutral profiles required
Conversion window strongly dependent on local $L_n$

**OPTIPOL calculations of coupling window (M. Carter, ORNL)**

**Location A:**
O-X-B dominant
$L_n = 2.9$ cm

**Location B:**
X-B dominant
$L_n = 0.4$ cm
Resonance locations exist over entire minor radius

- 2.45 GHz S-band radiation a good match to Pegasus magnetic fields

- Controllable deposition location provides tools for experiments:
  - testing of ray propagation calculations
  - current drive tests
  - modification of mode conversion location

- Toroidal field variable on 4 ms timescale
  - shorter than projected 10 ms rf pulse
Ray propagation changes as $B_\phi/B_\theta$ is varied

- Similar equilibria generated with varying $I_{tf}$
  - $I_p = 150$ kA; shape, $W$, $\ell_i$, profiles held constant

- As $I_p/I_{tf}$ varied, $n_\parallel$ variations more pronounced
  - $n_\parallel$ upshift can be large (>10)
  - implications for directional CD?

- Wave damping observed at Doppler-broadened cyclotron resonances

\[ \rho \]

![Power Deposition (CQL3D)]

Flux Plot & Ray Propagation (GENRAY)

Launched Rays (Color code matches graph)
Nonlinear effects will be important

- Ponderomotive and parametric effects can be observed
  - oscillatory velocity of electrons in rf field: $v_o \equiv eE_{\text{max}}/m_e\omega$
  - ponderomotive effect reduces density in beam
    - destabilized if $v_o \gtrsim v_{t,e}$
  - parametric instability couples power at UHR to LH waves
    - destabilized if $(v_o/v_{t,e})^2 \gtrsim 0.1$
    - recently observed on MAST

- At high power, instability thresholds easily exceeded
  - model $T_e$ profile
  - WR340 waveguide antenna
  - even 100 kW excites both instabilities

- Raises interesting physics issues
  - modification of density at UHR
  - changes in ray propagation
  - power losses to LH waves
  - will address as part of physics campaign

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Pegasus Toroidal Experiment
University of Wisconsin-Madison
Antenna placement optimization

- Need optimal placement of launch antenna
  - maximize driven current
    - requires deposition near axis
  - flexibility in deposition location
  - far-off-axis antenna required?
    - new vacuum port would be needed

- Scans of poloidal launch angle conducted:
  - $I_p = 150$ kA
  - $I_{tf} = 90 - 150$ kA
  - $A = 1.13$, $R = 0.4$ m
  - Poloidal launch angle = $10^\circ - 75^\circ$
Heating and CD maximized around 15-25 degrees poloidal launch angle

- This angle results in near-axis deposition
  - low n$_{||}$
    - higher n$_{||}$ at larger $\theta$ results in larger Doppler broadening
  - maximized CD due to higher $T_e$

- Midplane port can be used for launcher
Current drive efficiency dependent on deposition location

- Efficiency highest when deposition near magnetic axis
  - $T_e$ largest on axis
  - as expected from Fisch-Boozer

- Dimensionless CD efficiency shows reduced efficacy of off-axis CD
  - Defined as (Luce et al.):
    \[
    \xi_{EBW} = 3.27 \frac{I_{EBWCD}(A)R(m)n_e (10^{19} m^{-3})}{T_e(keV)P(W)}
    \]
  - effects of trapped particles visible in dimensionless scaling
  - some evidence of Ohkawa CD at large $\rho$

- For optimal current drive, deposition must be near axis
Auxiliary heating may increase current drive efficiency

- Current drive efficiency nominally proportional to $T_e/n_e$
  - Modeling confirms for Fisch-Boozer CD in PEGASUS

- Multiple auxiliary heating systems are available
  - 1 MW HHFW system
    - provides bulk electron heating
    - up to 200 kW injected to date
    - improved edge position control will allow coupling to full 1 MW
  - EBW also heats electrons locally
    - heating not included in current drive calculations
    - 500 kA coupled power is comparable to ohmic heating
Conceptual heating system design

- Most components are parts of PLT lower hybrid system
- Klystron power supplies available from ORNL and LANL

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Conceptual antenna design requires single waveguide

- Bellows feedthrough gives 15° steerability toroidally and poloidally
  - radial positioning also possible

- Local limiters will be required to control $n_e$ and $L_n$
  - keep plasma out of waveguide to minimize impaction

- Further modeling and measurements required to refine the design
Hardware to be shipped from PPPL to UW

Dummy Load

500 kW Klystron

Klystron Cabinet

Recirculator and Waveguide

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Pegasus Toroidal Experiment
University of Wisconsin-Madison
### Proposed implementation schedule

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Summary

• Pegasus is a good testbed for high-power EBW experiments
  - frequency match with available 2.45 GHz heating system
  - PCS and advanced diagnostics for sophisticated experiments
  - moderate size and plentiful runtime

• Research is a collaborative effort in support of NSTX
  - formal agreement with PPPL Spring 2005
  - additional help from ORNL, LANL

• Modeling has begun to frame relevant issues
  - coupling
    ♦ OXB coupling likely requires local limiters to set L_n
    ♦ significant ponderomotive & parametric effects likely
  - propagation and damping
    ♦ midplane antenna acceptable
    ♦ deposition locations available across minor radius
    ♦ dominant CD mechanism is Fisch-Boozer

• Implementation begins soon (pending funding)
  - modeling continues
  - PLT lower hybrid system dismantling & shipping late 2005/early 2006
  - edge plasma characterization next year
  - first heating experiments 2008
### Abstract

Why EBW on Peg?

Issues to address

### MC Layer

MC Setup

Optipol

### TF Match

TF Scan

Nonlinear Effects

### Angle Scan Raytracing

Angle Scan Results

CD Fisch-Boozer

### System Schematic

Antenna Concept

Heating increases CD

### Photos

Schedule

Summary

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**Titlestrip**