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

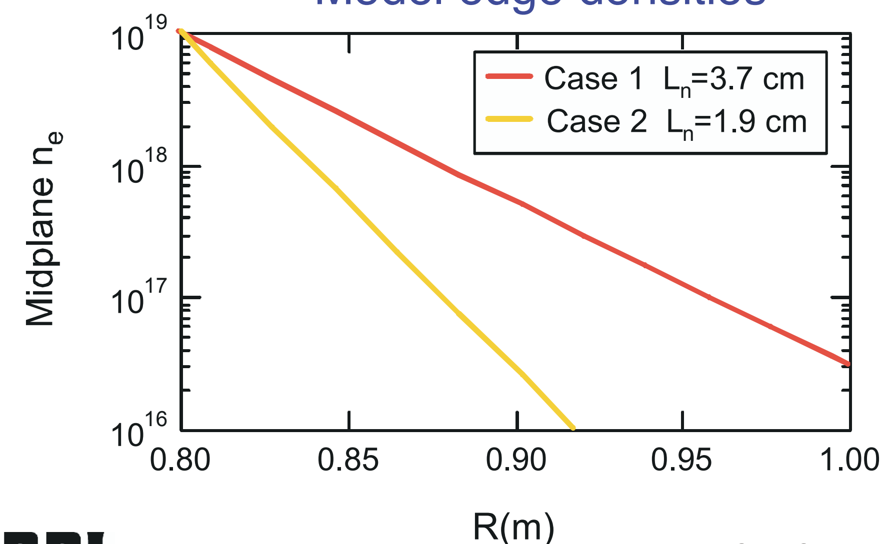
Mode conversion layer located well outside last closed flux surface

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

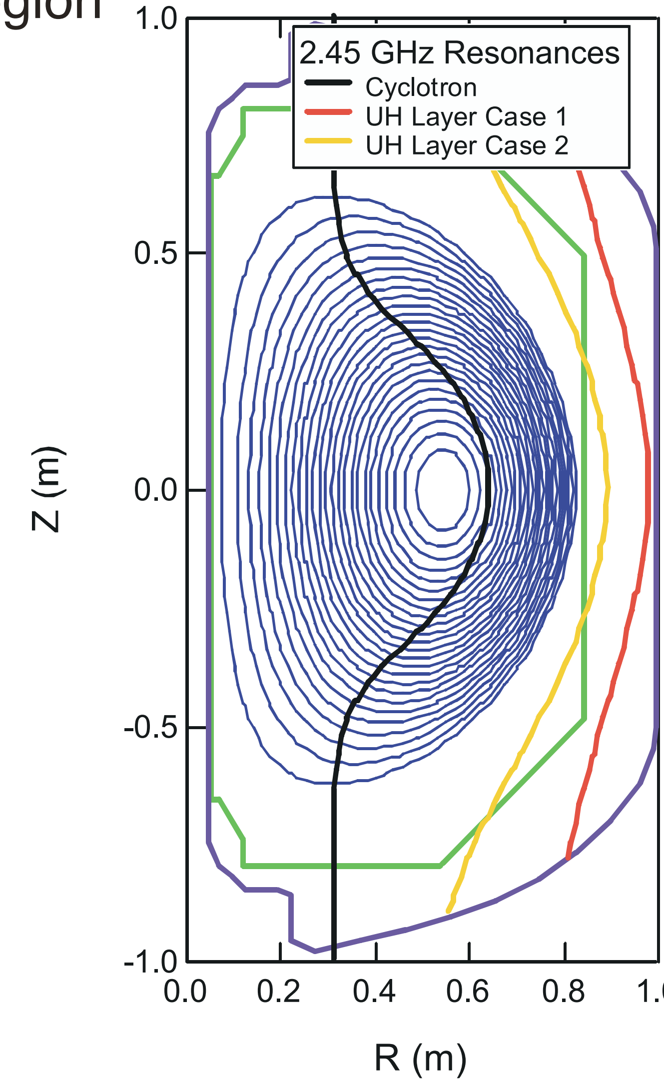
- SOL density profile not measured yet
  - strongly pumping walls may have significant effect on edge density & EBW coupling
  - will study scrape-off n_e with multi-tipped probe

- Local limiters likely required around antenna

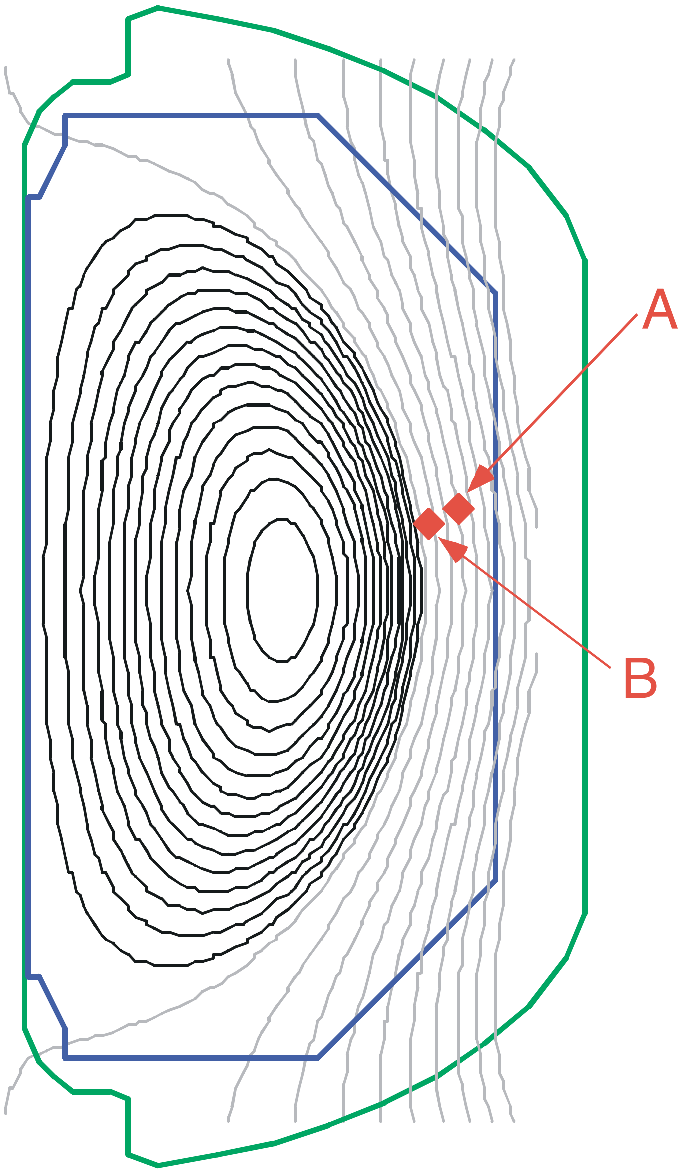
Model edge densities



Flux Plot & Resonances



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 ∇n, T_e=5 eV
    + *using only machine limiters*

  - B: at LCFS, steep ∇n, T_e = 10 eV
    + *with local antenna limiters*

- Further modeling with measured density profiles and realistic neutral profiles required

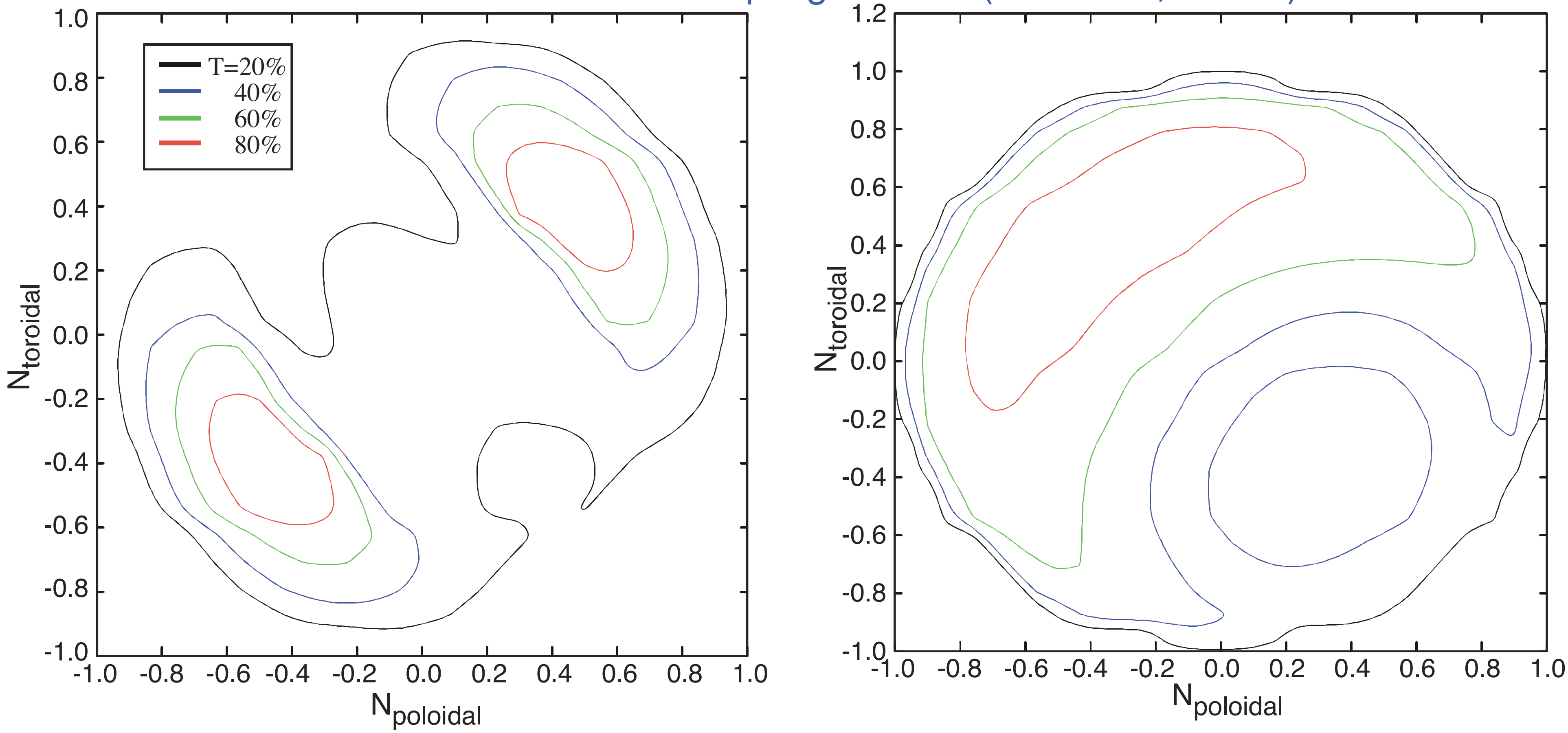
PPPL PRINCETON PLASMA PHYSICS LABORATORY

G.D. Garstka
47th APS-DPP Denver
October 27, 2005

Pegasus Toroidal Experiment
University of Wisconsin-Madison

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

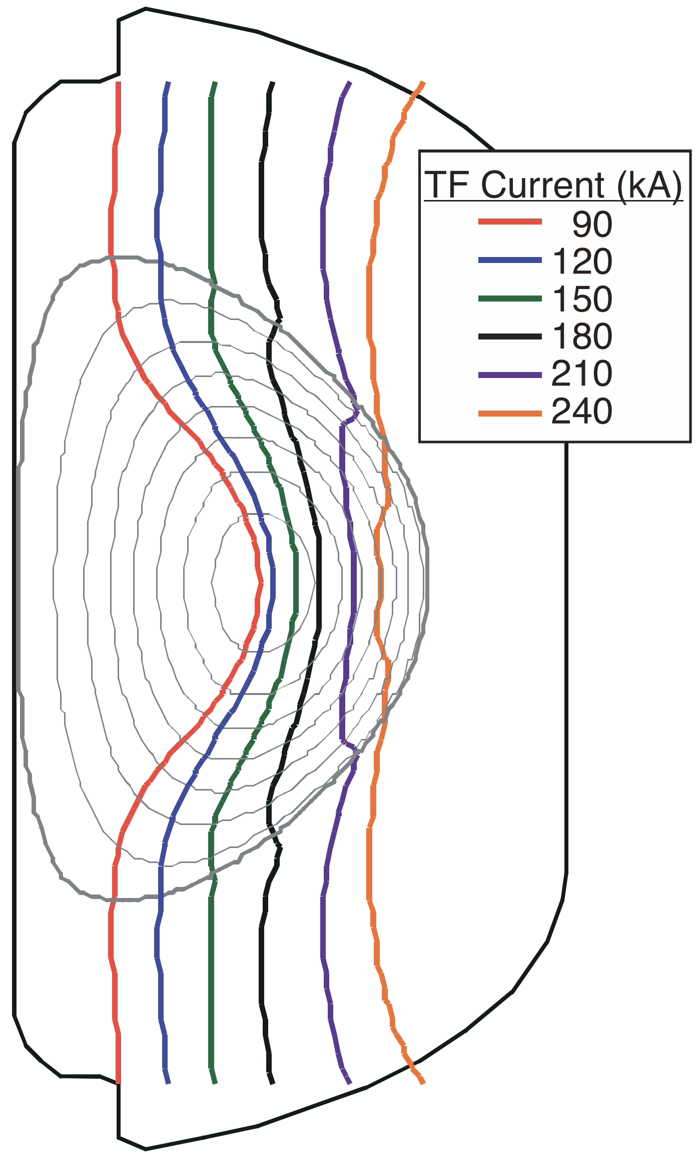
Resonance locations exist over entire minor radius

- 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

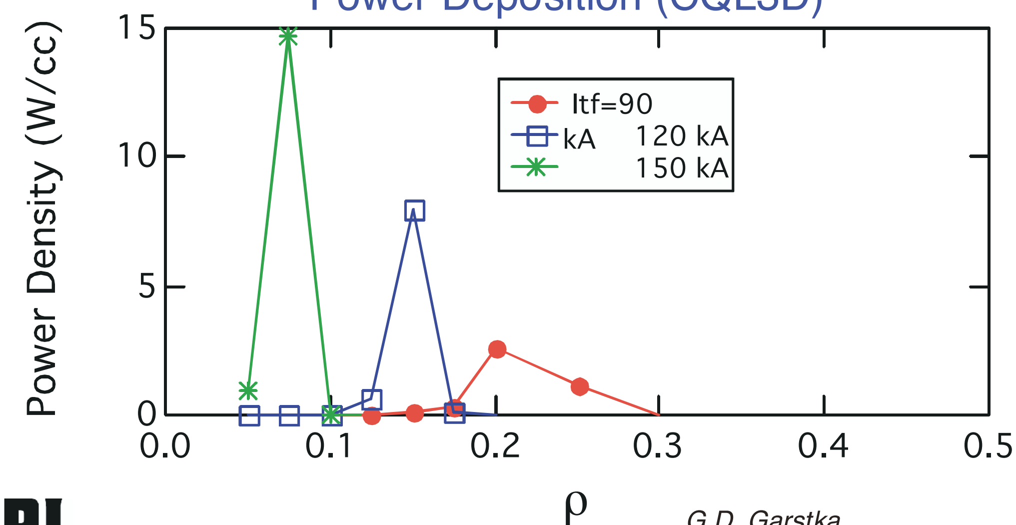
Fundamental Cyclotron Resonances



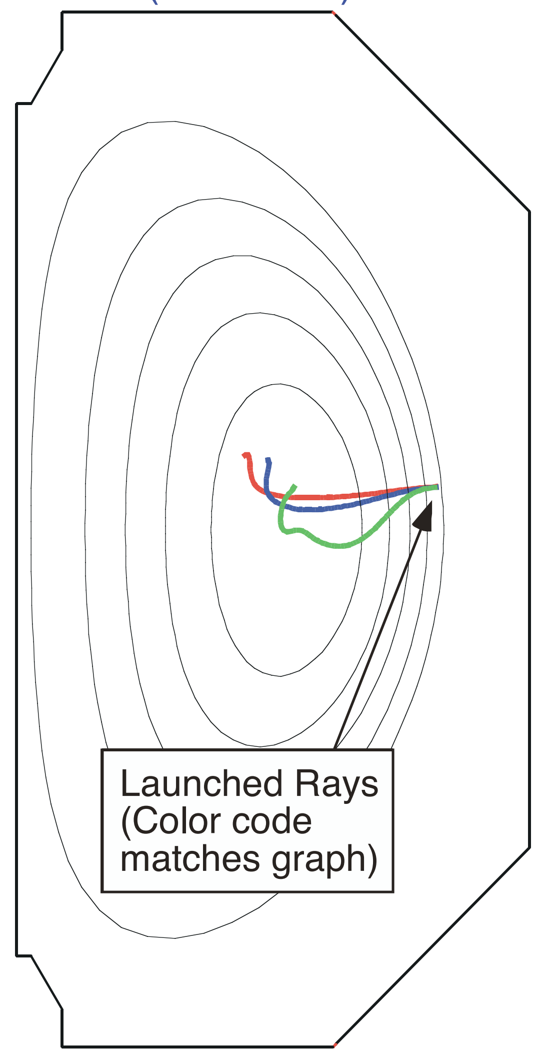
Ray propagation changes as B_ϕ/B_θ is varied

- Similar equilibria generated with varying I_{tf}
  - I_p = 150 kA; shape, W, ℓ_i, profiles held constant
- As I_p/I_{tf} varied, $n_{||}$ variations more pronounced
  - $n_{||}$ upshift can be large (>10)
  - implications for directional CD?
- Wave damping observed at Doppler-broadened cyclotron resonances

Power Deposition (CQL3D)



Flux Plot & Ray Propagation (GENRAY)



G.D. Garstka
47th APS-DPP Denver
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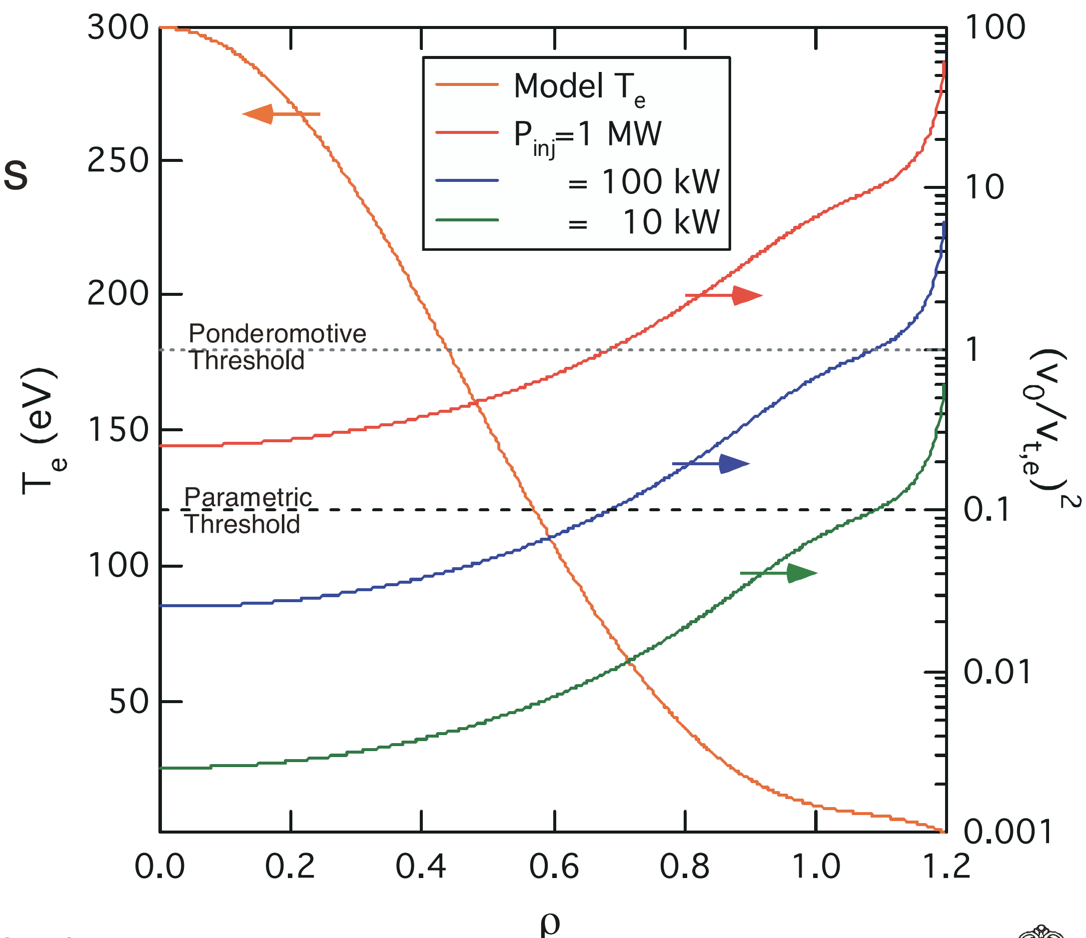
Nonlinear effects will be important

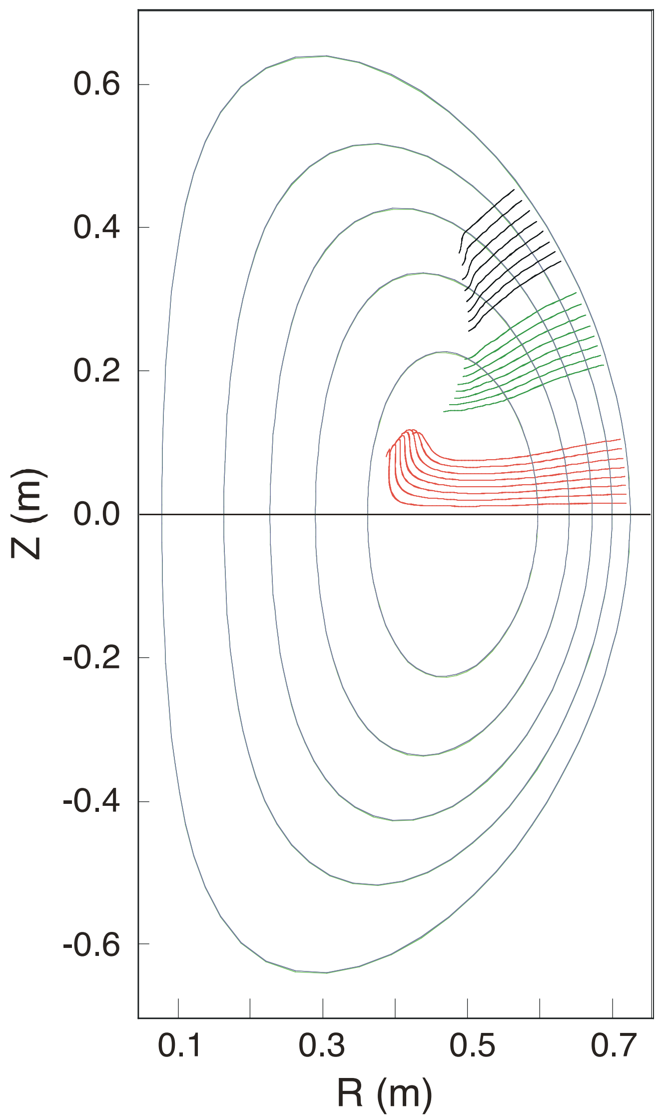
- Ponderomotive and parametric effects can be observed
  - oscillatory velocity of electrons in rf field: $v_o \equiv eE_{max}/m_e\omega$
  - ponderomotive effect reduces density in beam
    - *destabilized if $v_o \gtrsim v_{t,e}$*
  - parametric instability couples power at UHR to LH waves
    - *destabilized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



Antenna placement optimization

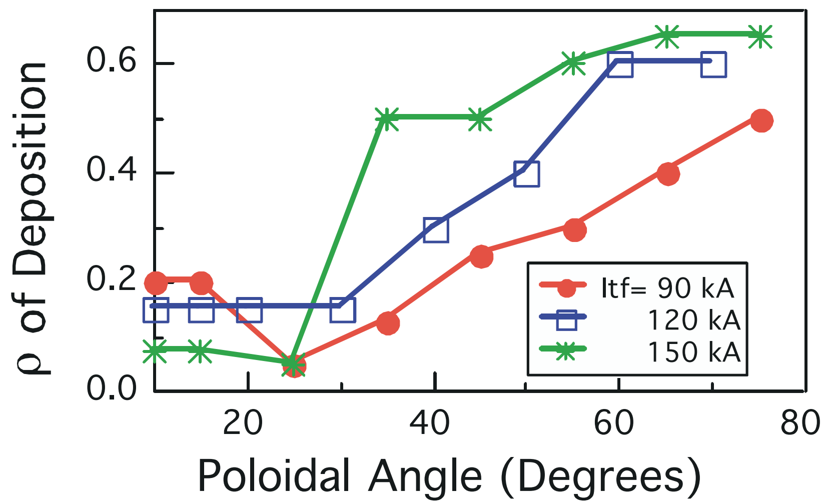


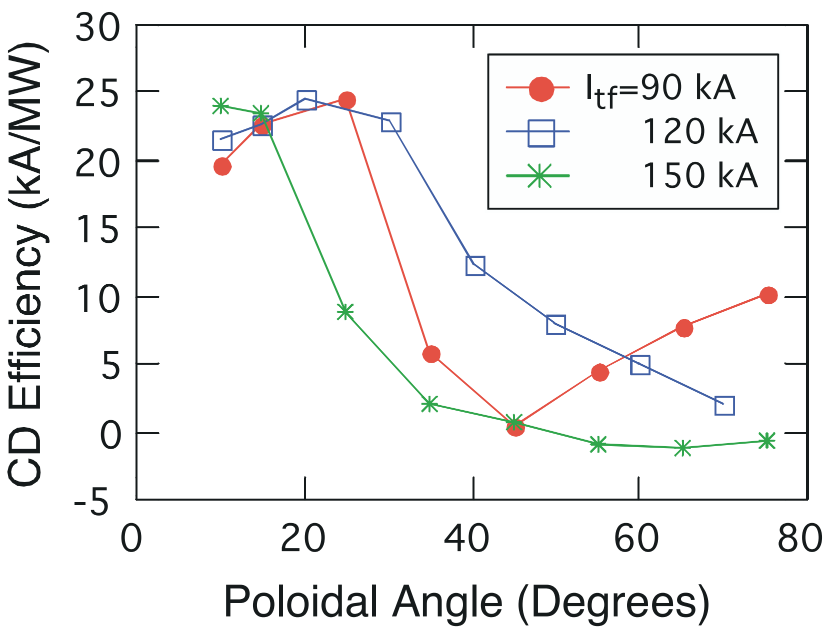
- Need optimal placement of launch antenna
  - maximize driven current
    - *requires deposition near axis*
  - flexibility in deposition location
  - far-off-axis antenna required?
    - *new vacuum port would be needed*

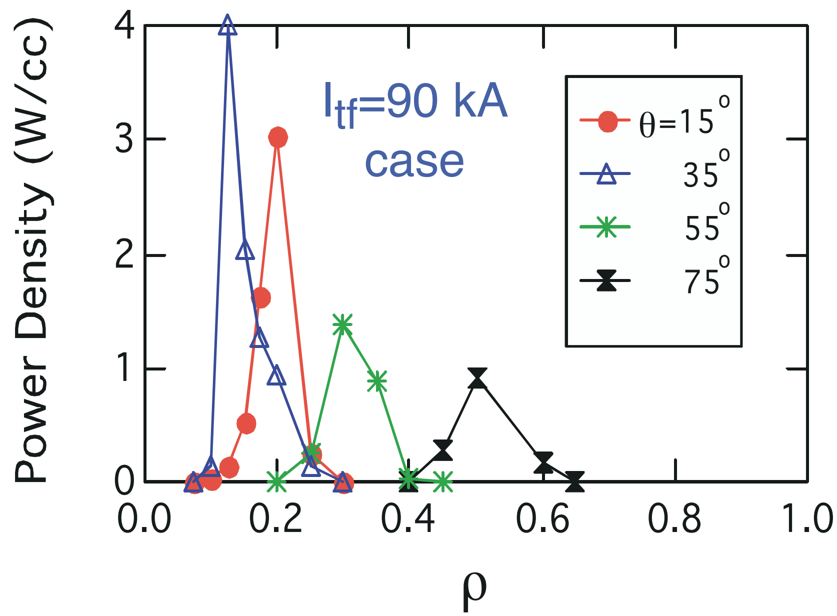
- Scans of poloidal launch angle conducted:
  - $I_p = 150$ kA
  - $I_{tf} = 90 - 150$ kA
  - $A = 1.13$, $R = 0.4$ m
  - Poloidal launch angle = 10° - 75°

Heating and CD maximized around 15-25 degrees poloidal launch angle

- This angle results in near-axis deposition
  - low $n_{||}$
    - *higher $n_{||}$ at larger θ 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

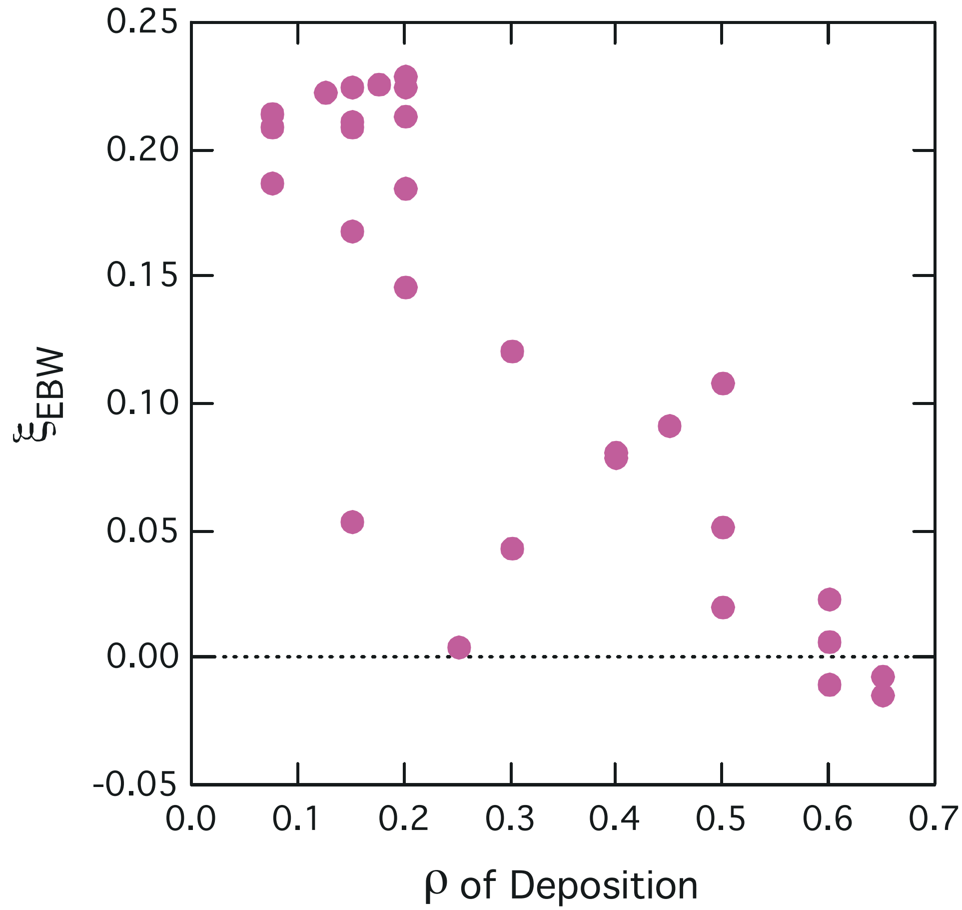
- Efficiency highest when deposition near magnetic axis
  - T_e largest on axis
  - as expected from Fisch-Boozer

- Dimensionless CD efficiency shows reduced efficacy of off-axis CD
  - Defined as (Luce *et al.*):

$$\xi_{EBW} = 3.27\frac{I_{EBWCD}(\mathrm{A})R(\mathrm{m})n_e(10^{19}\mathrm{m}^{-3})}{T_e(\mathrm{keV})P(\mathrm{W})}$$

  - effects of trapped particles visible in dimensionless scaling
  - some evidence of Ohkawa CD at large ρ

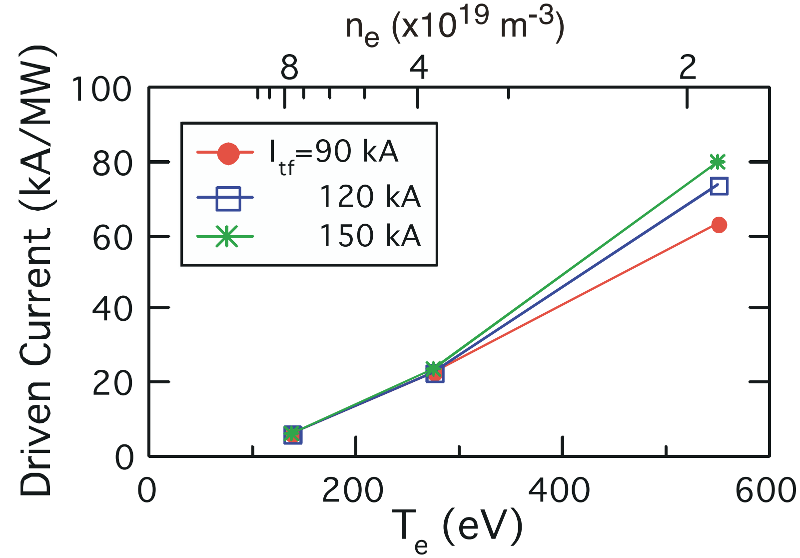
- For optimal current drive, deposition must be near axis



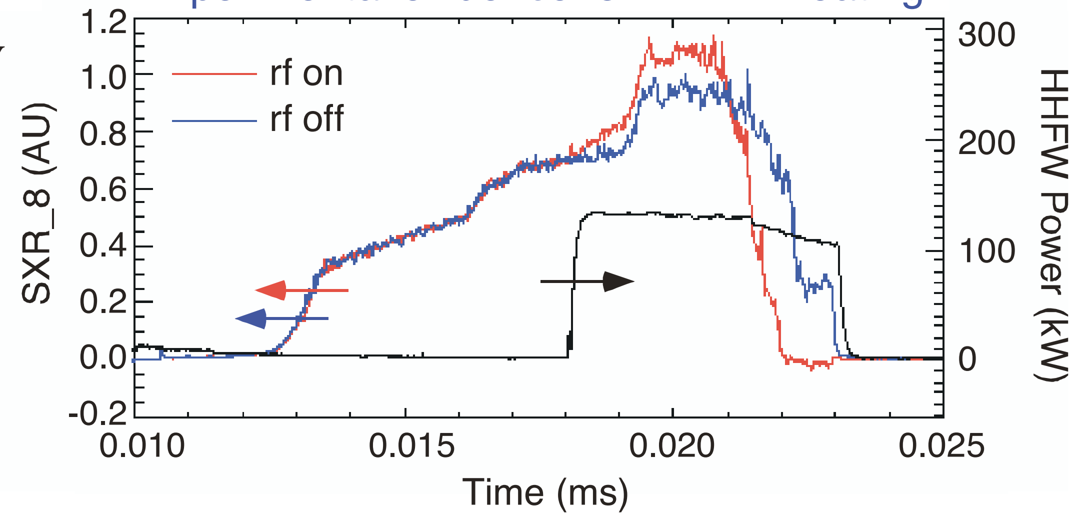
Auxiliary heating may increase current drive efficiency

- 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*

Constant Pressure CD Scan

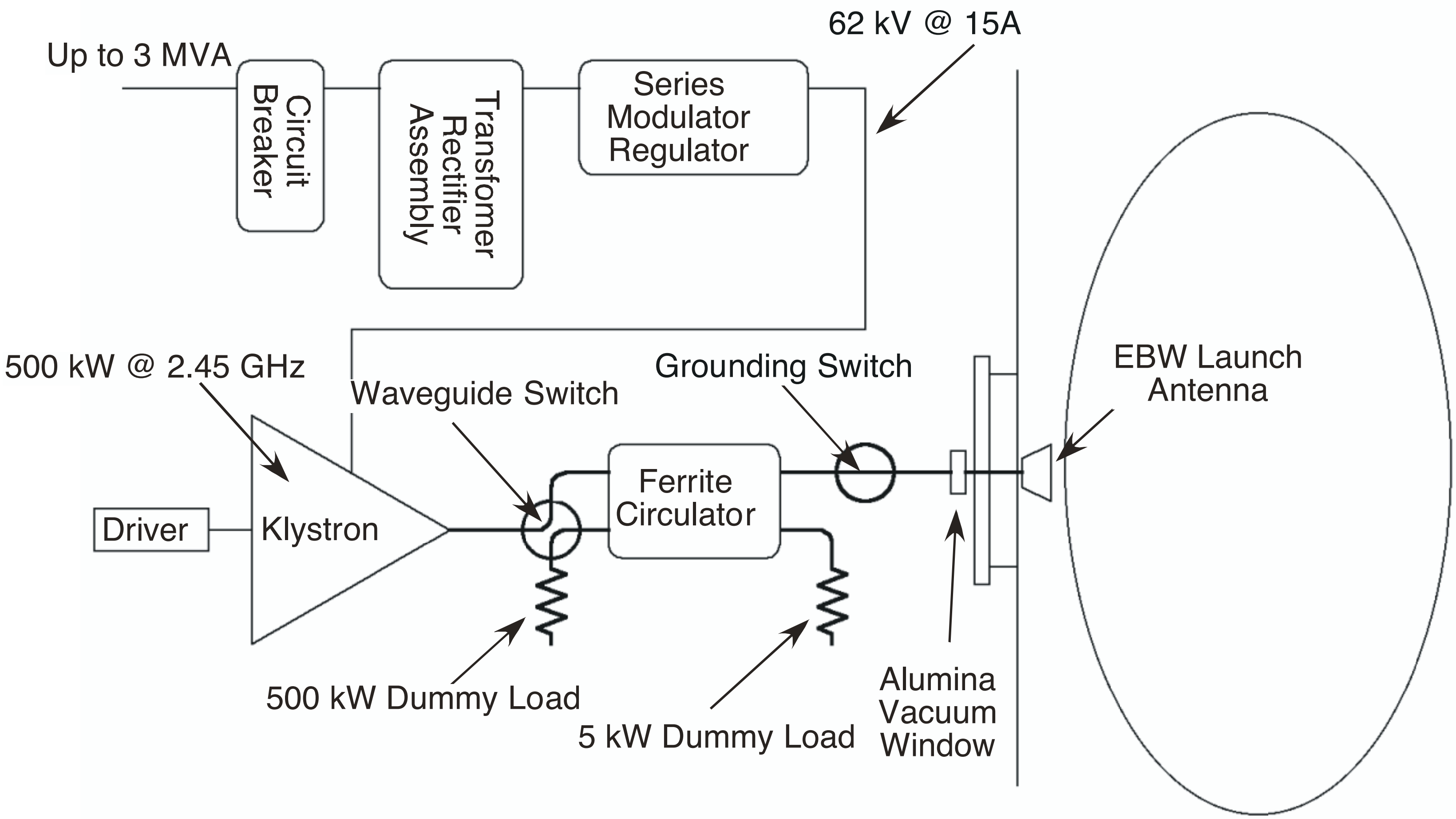


Experimental evidence for HHFW heating



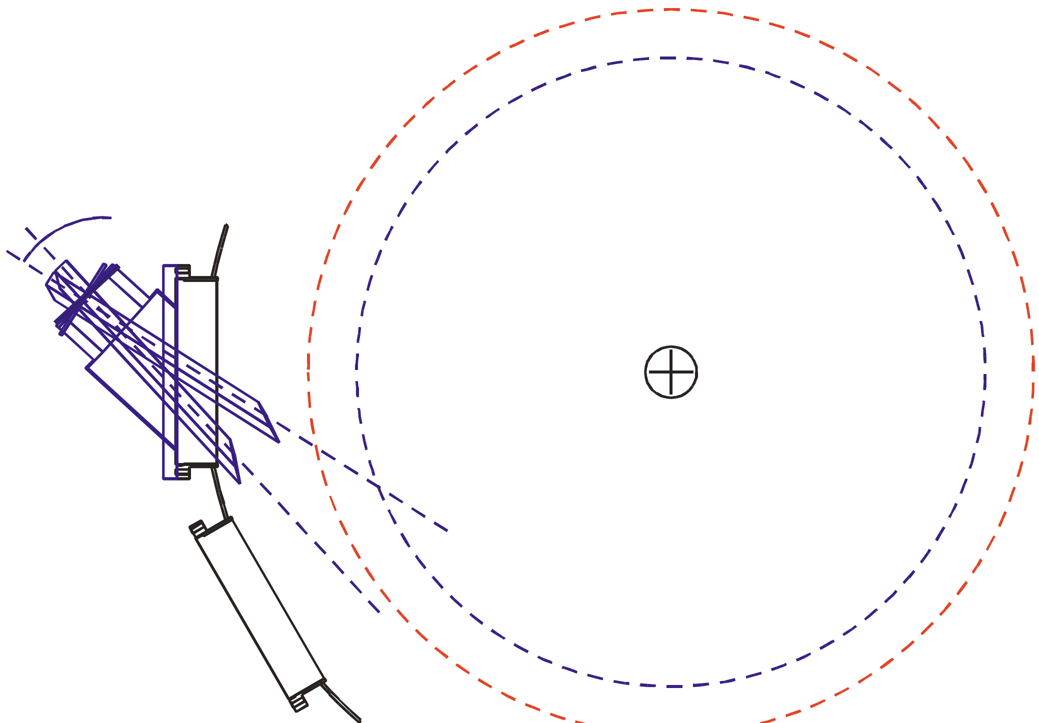
Conceptual heating system design

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

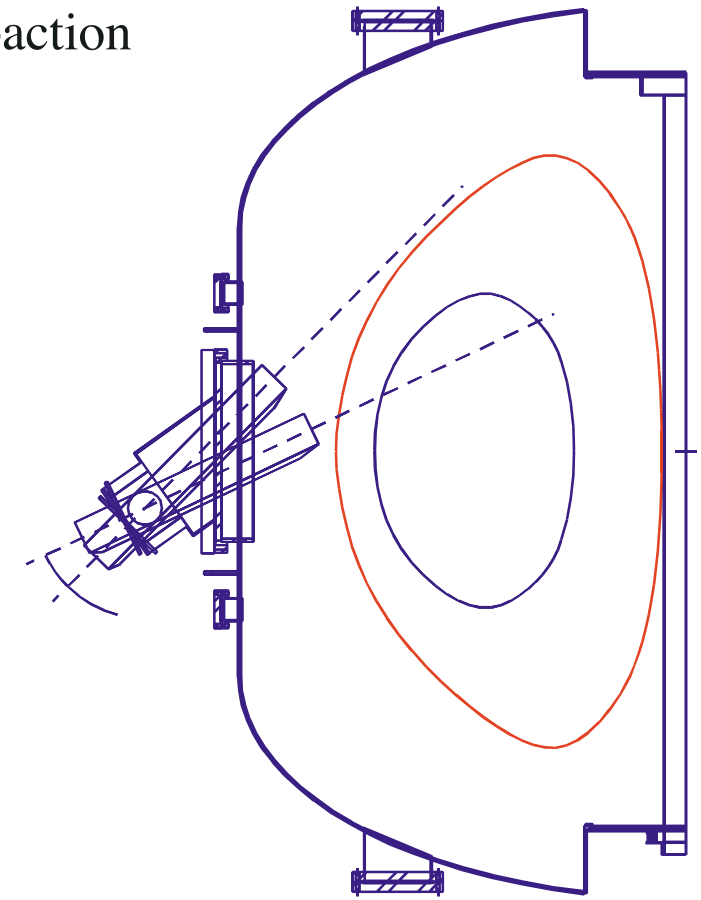


Conceptual antenna design requires single waveguide

- 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



Top View



Side View

G.D. Garstka
47th APS-DPP Denver
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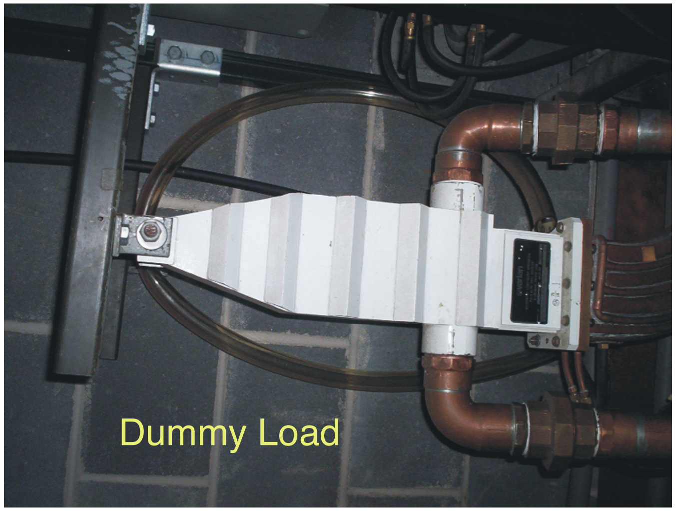
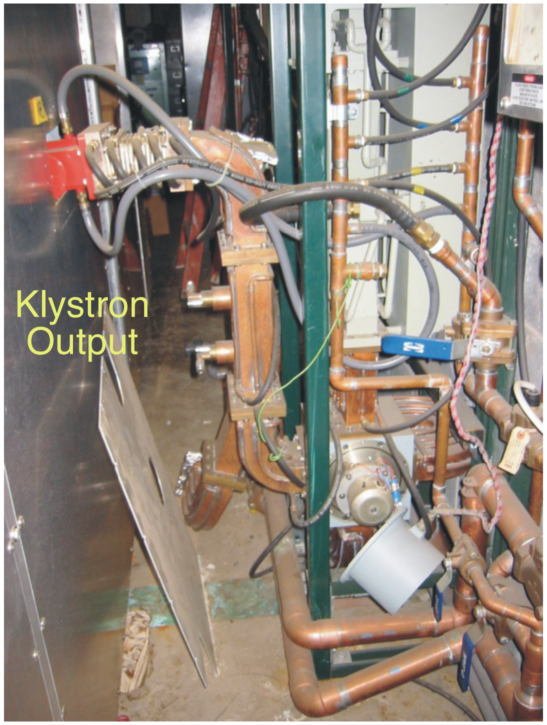
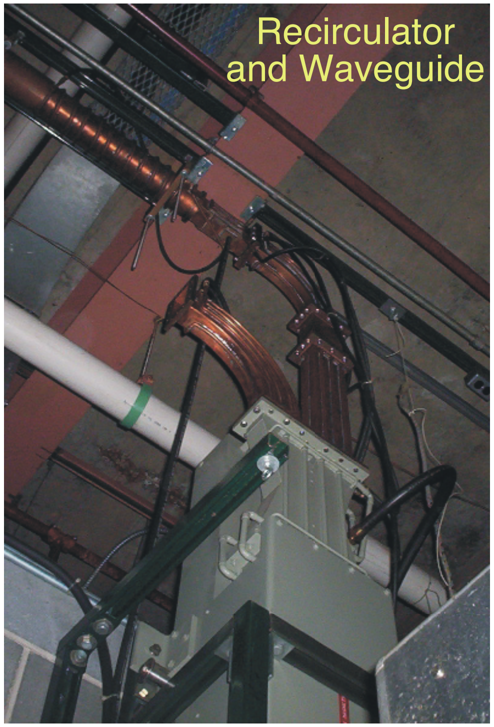
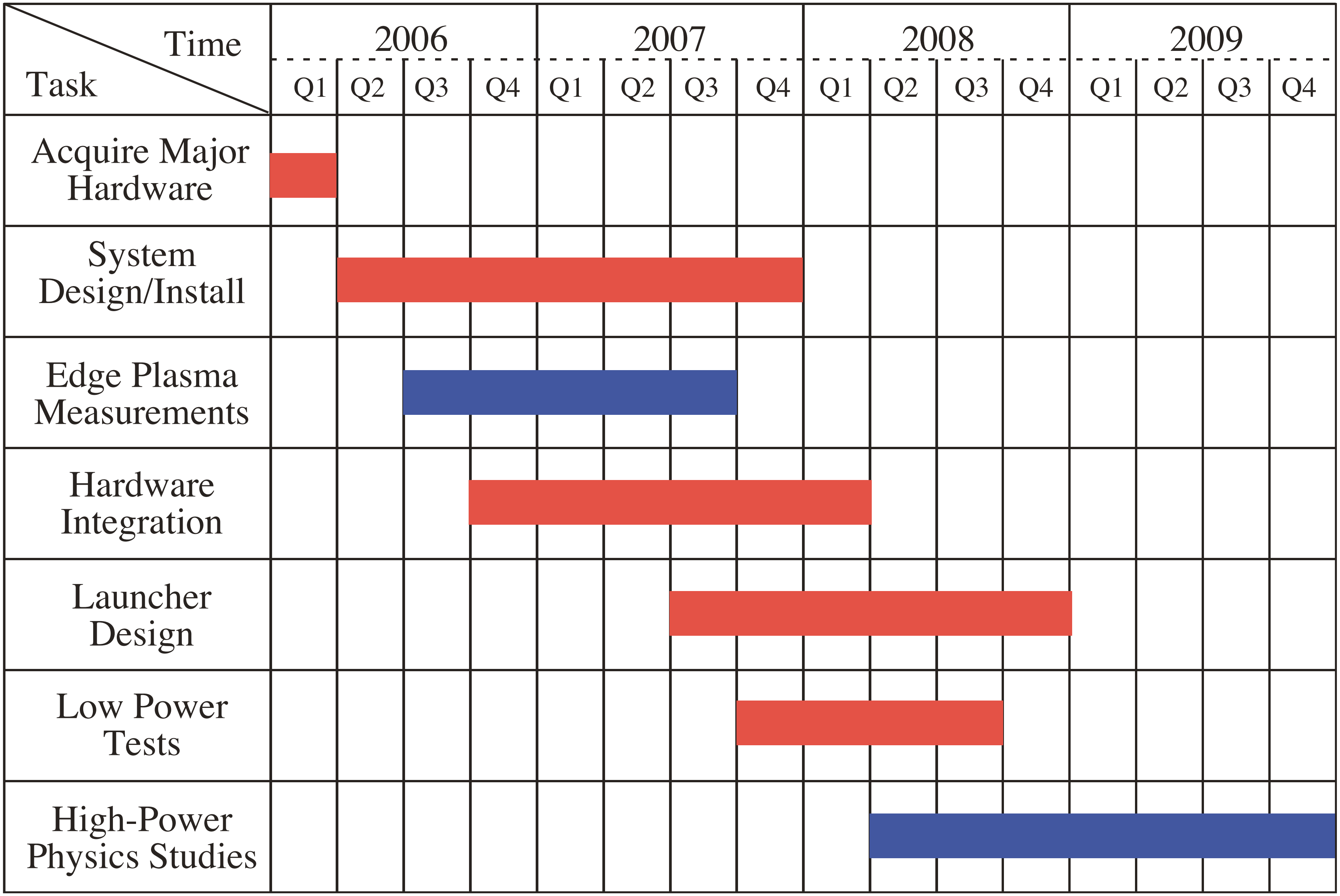
Hardware to be shipped from PPPL to UW







Proposed implementation schedule



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

GDG Titlestrip

Abstract	MC Layer	TF Match	Angle Scan Raytracing	System Schematic	Photos
Why EBW on Peg?	MC Setup	TF Scan	Angle Scan Results	Antenna Concept	Schedule
Issues to address	Optipol	Nonlinear Effects	CD Fisch-Boozer	Heating increases CD	Summary