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.

Work supported by U.S. D.O.E. Grant DE-FG02-96ER54375 and U.S. D.O.E. Contract DE-AC02-76CH03073.

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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

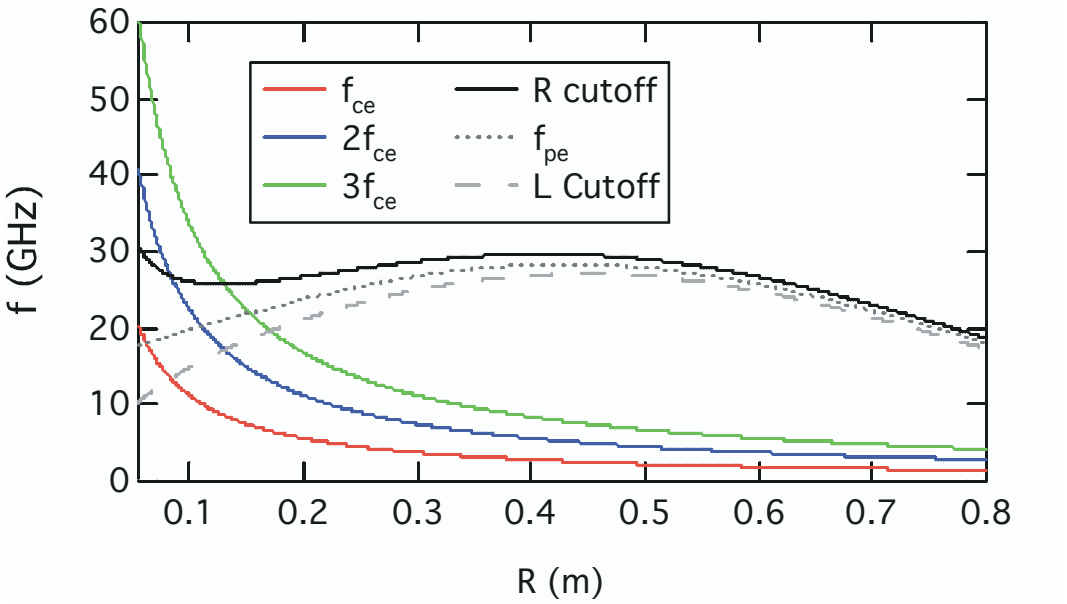
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Electron cyclotron waves cannot access "overdense" plasmas

- 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, spheromaks, etc.*
  - Only first 2-3 harmonics strongly emit/absorb

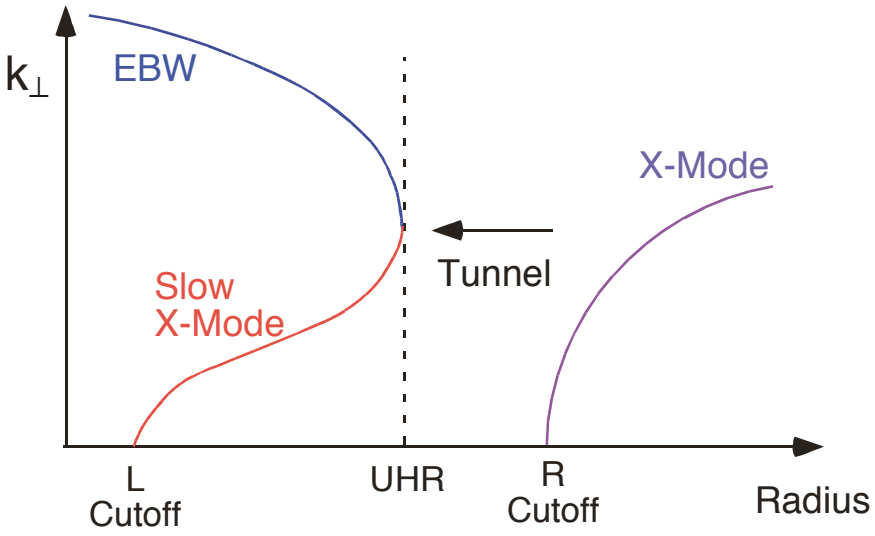
Model resonances & cutoffs for EC waves in PEGASUS

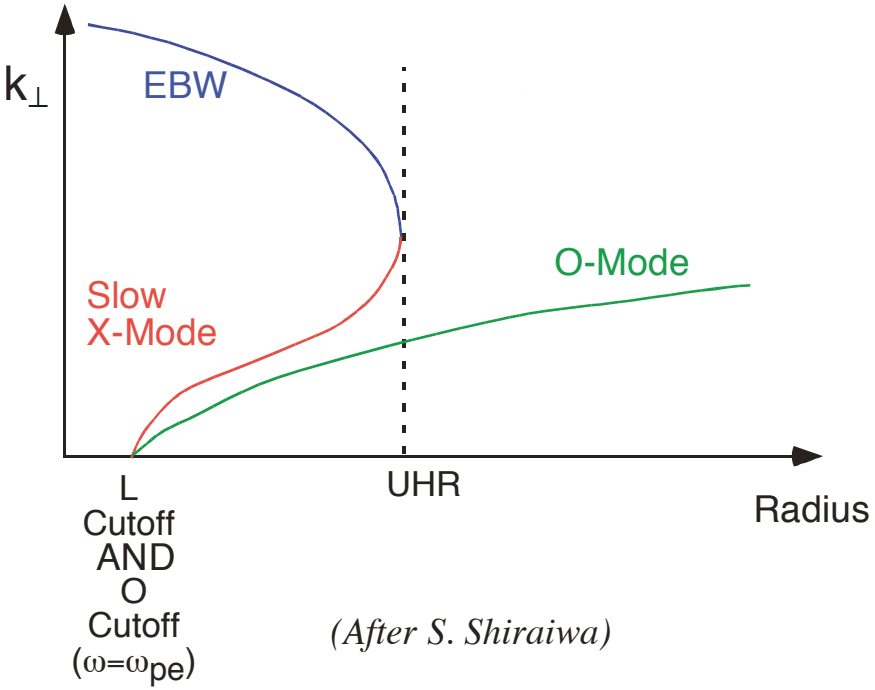


⇒ *First three EC harmonics are cut off over most of the plasma*

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EBW can propagate where EC waves are cutoff



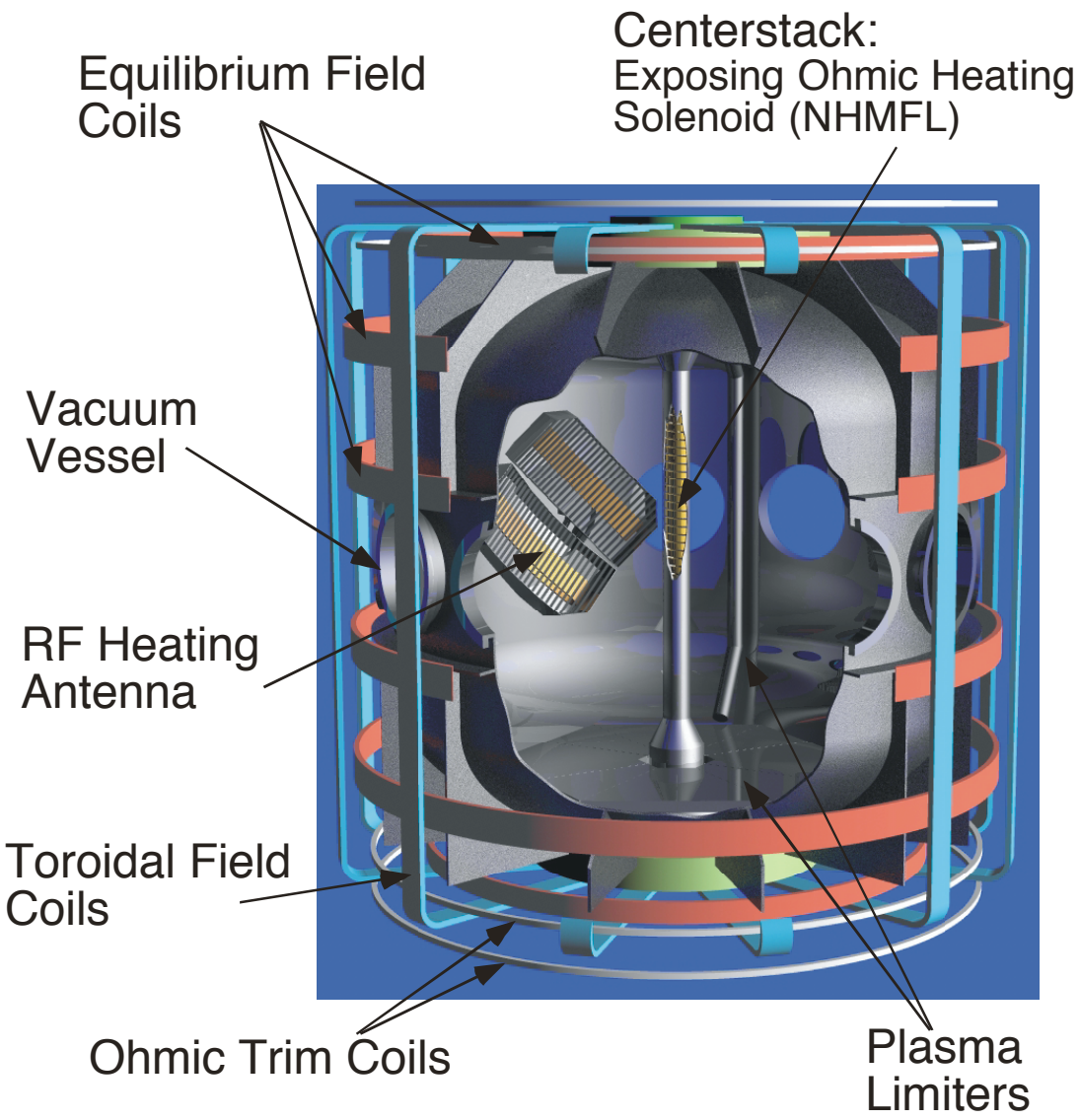


(After S. Shiraiwa)

- 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* ($n_{||}=0$)
    - = *cutoffs & UHR must be in close proximity (i.e. steep* ∇n_e*)*
    - = *tunnels from R cutoff to UHR*
  - O-mode
    - = *tangential incidence*
    - = *optimal* $n^2_{||}=\omega_{ce}/(\omega_{pe}+\omega_{ce})$
    - = *requires shallow* ∇n_e
    - = *O converts to SX to EBW*

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PEGASUS is a mid-sized, ultra-low A ST



Experimental Parameters

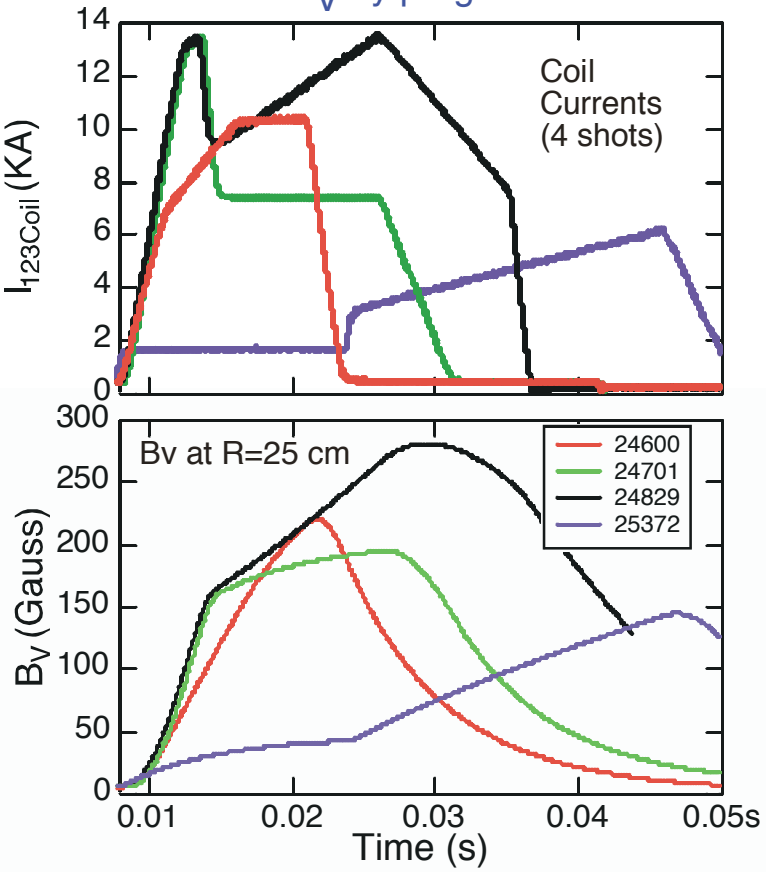
Parameter	Achieved	Phase II Goals
A	1.15-1.3	1.12-1.3
R (m)	0.2-0.38	0.2-0.45
I_p (MA)	≤ 0.16	≤ 0.30
I_N (MA/m-T)	6-8	15-20
RB_t (T-m)	≤ 0.03	≤ 0.1
κ	1.4–3.7	1.4–3.7
τ_{shot} (s)	≤ 0.02	≤ 0.05
n_e (10^{19} m^{-3})	1-5	≤ 10
β_t (%)	≤ 20	> 40
P_{HHFW} (MW)	0.2	1.0

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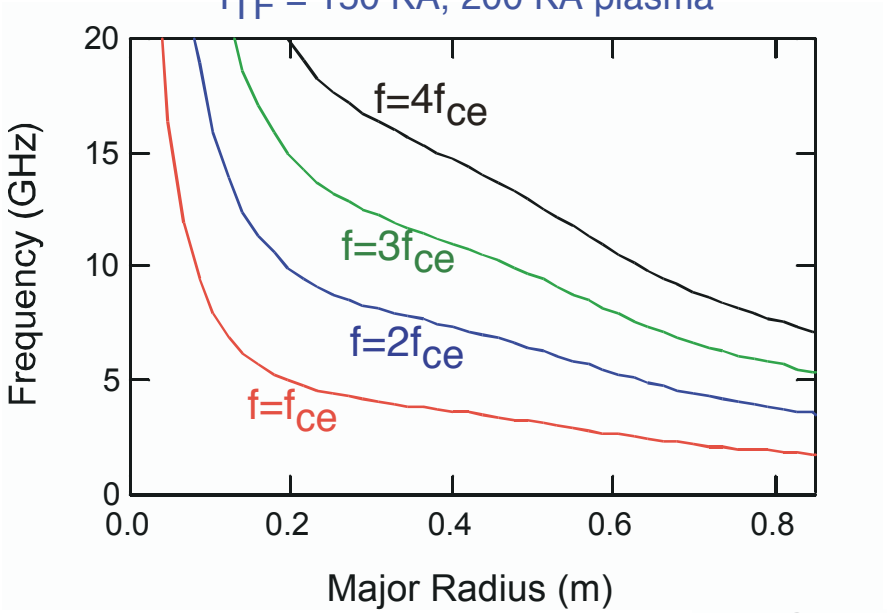
PEGASUS may offer a unique test bed for EBW experiments

- 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

Control of B_V by programmed coils



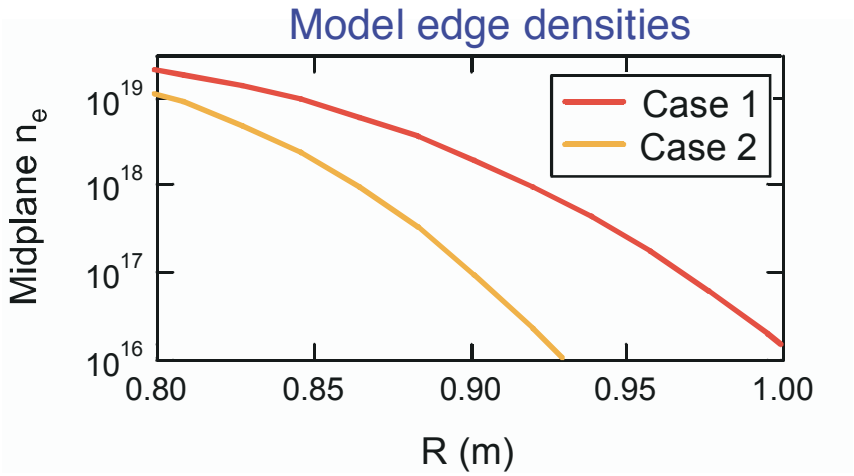
Example - First 4 Cyclotron Harmonics
I_{TF} = 150 KA, 200 KA plasma

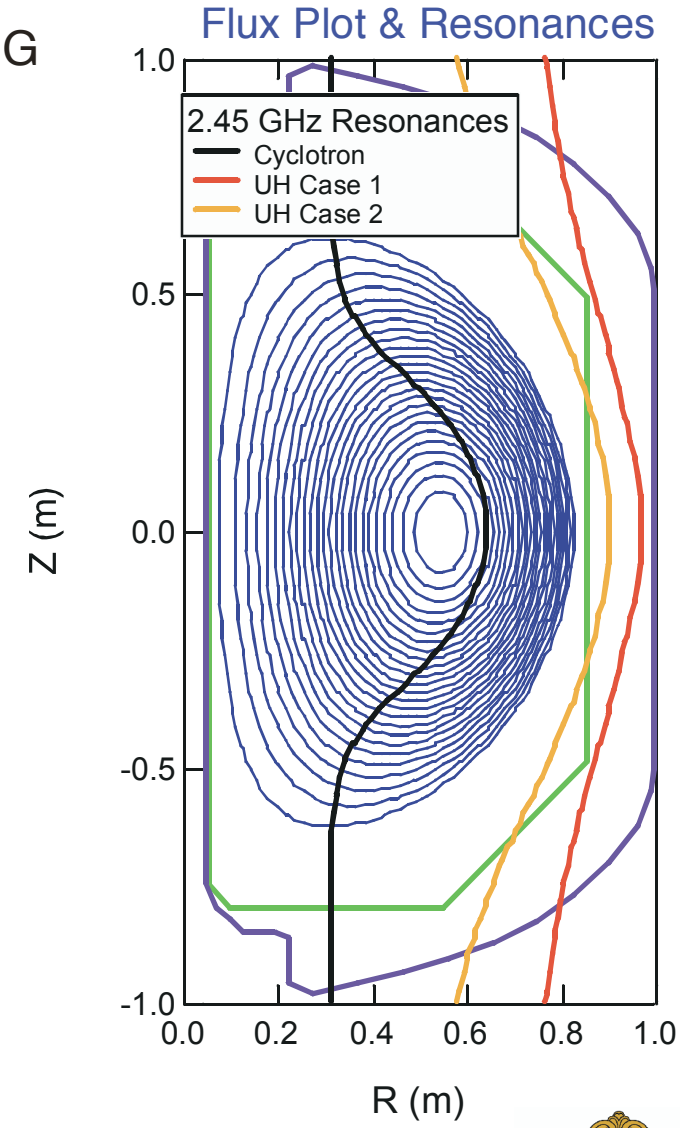


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2.45 GHz - good frequency match

- 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 7.5×10^{16} m^3
  - Local limiter likely needed
  - Need measurements of edge density
- Remainder of this poster assumes 2.45 GHz for PEGASUS

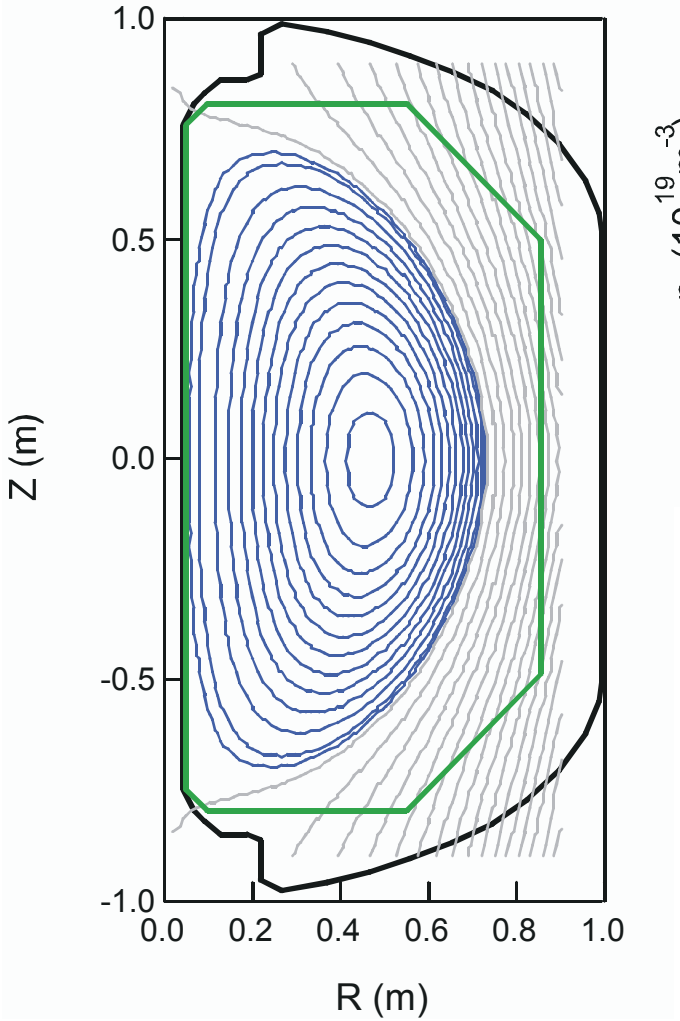


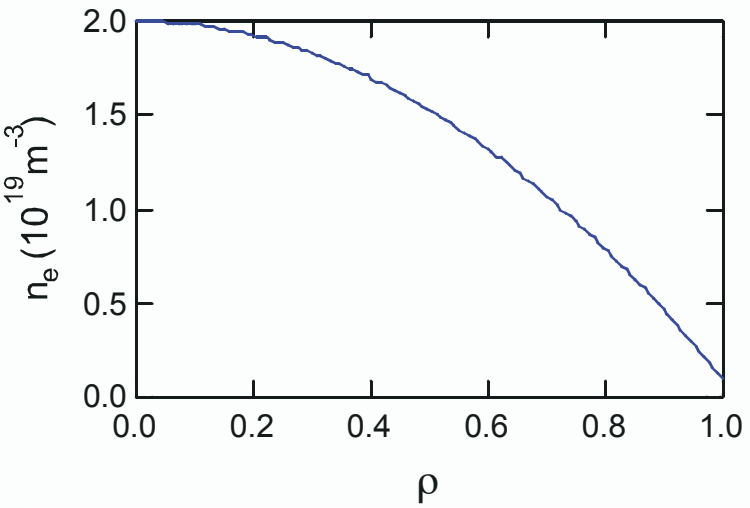


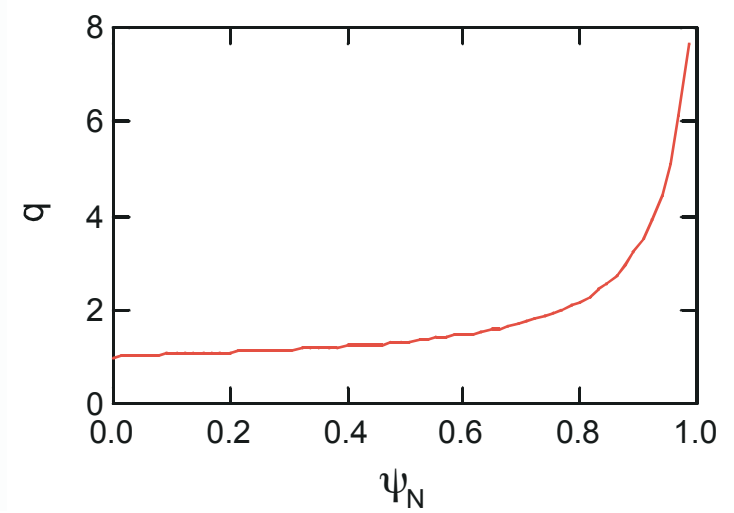
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Equilibrium used for preliminary raytracing calculations

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





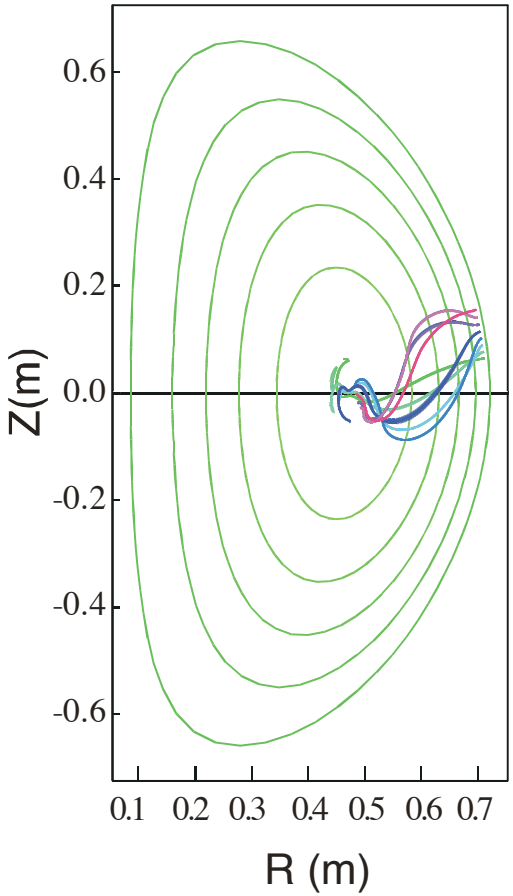


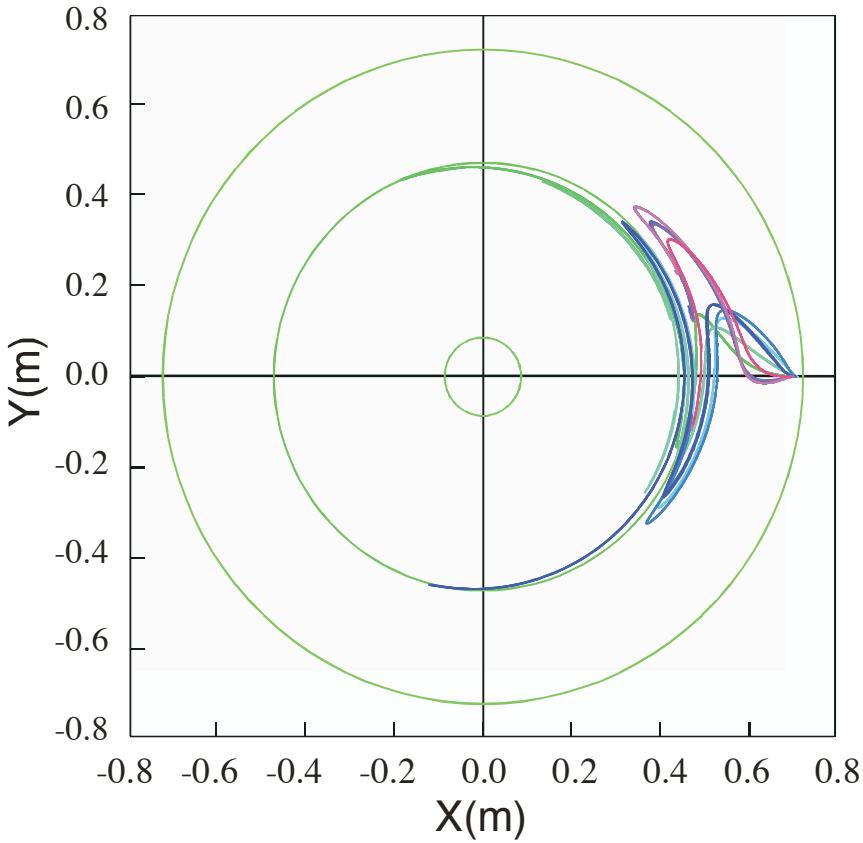
Equilibrium Parameters

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%

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Case I - Raytracing



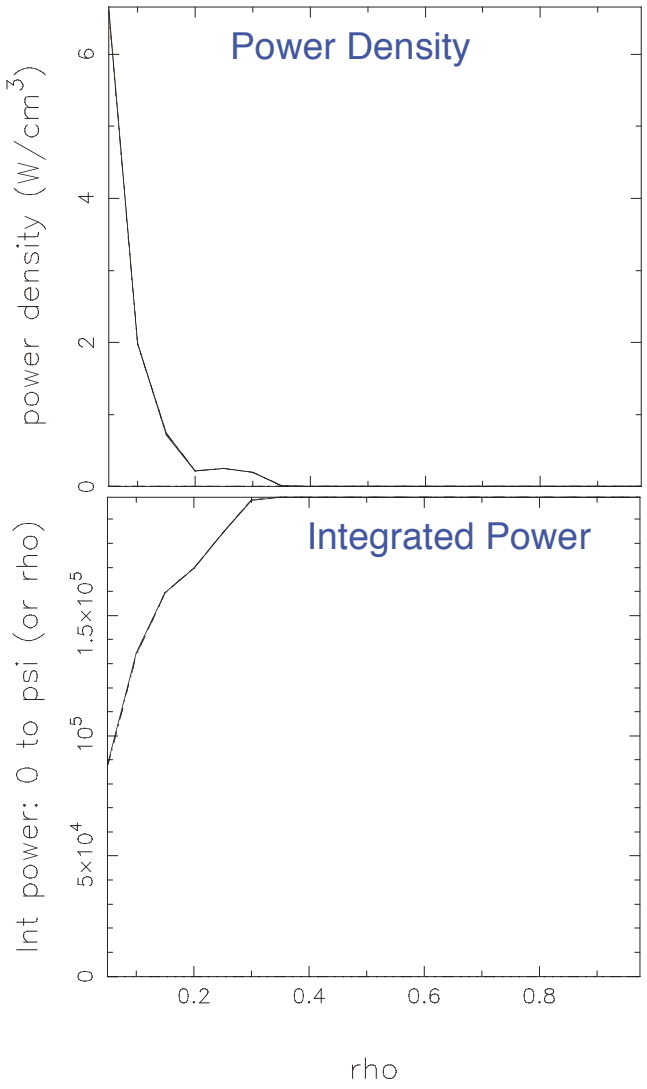


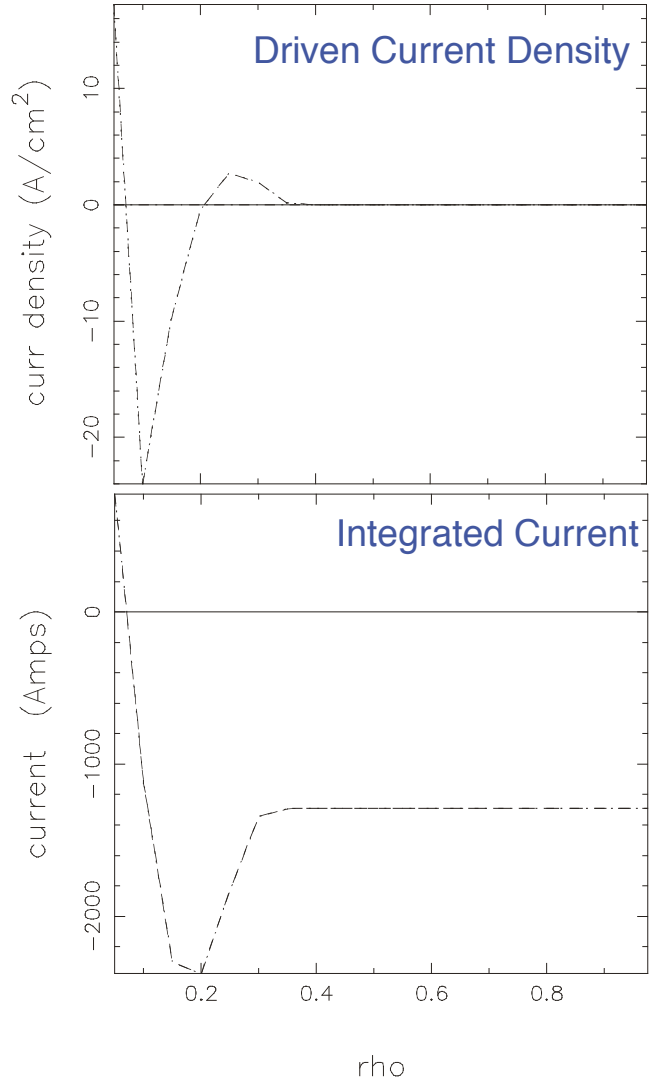
Oblique O-Mode Launch
200 kW
$n_{||} = 0.45 - 0.55$

48 Rays
Launch $\theta = 25°$
Antenna Length = 10 cm

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Case I - Heating and Current Drive

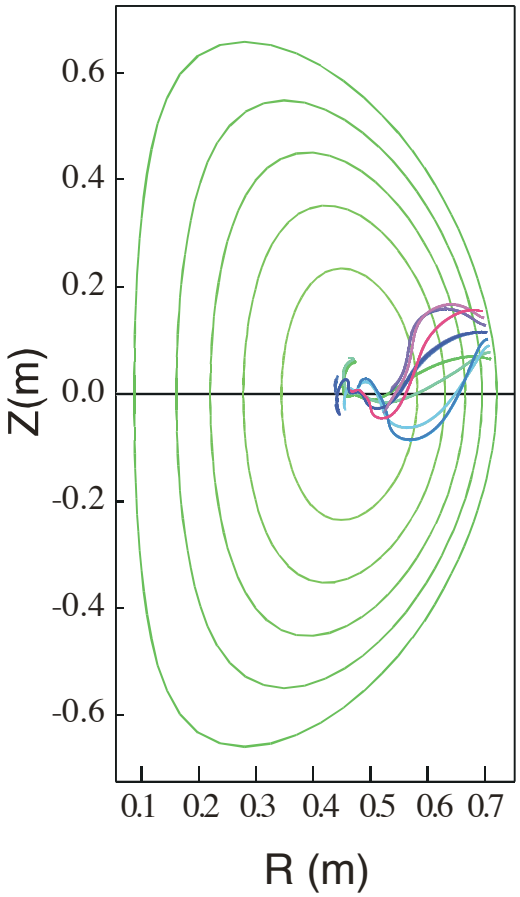


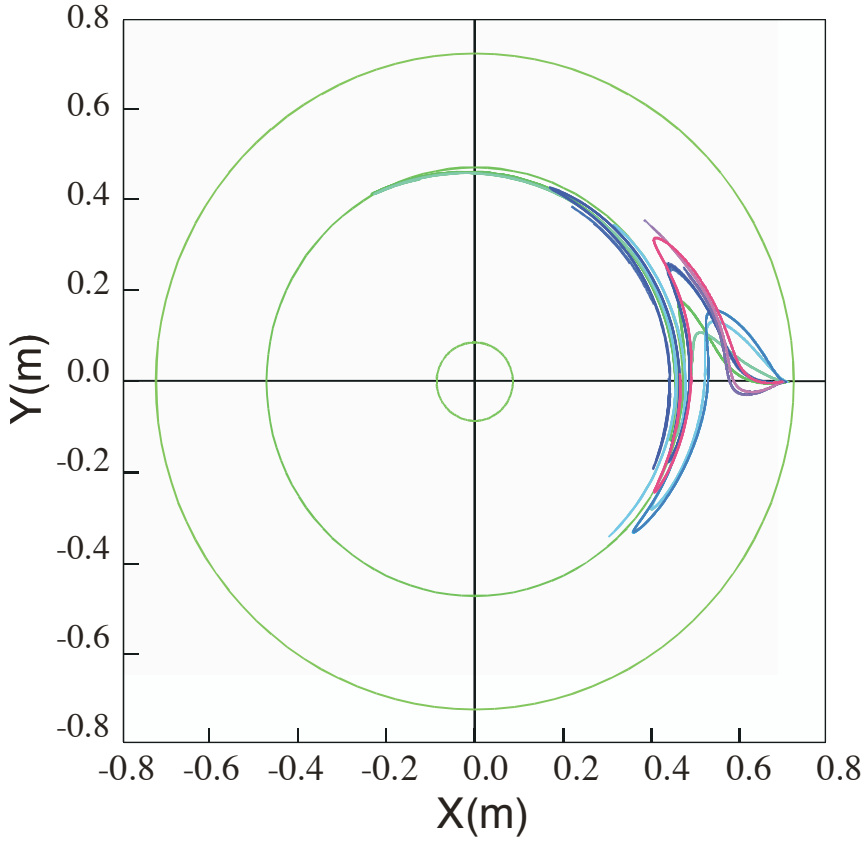


- Power deposited in inner 20% of plasma
- +1 KA, -2 KA driven near axis

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Case II - Raytracing



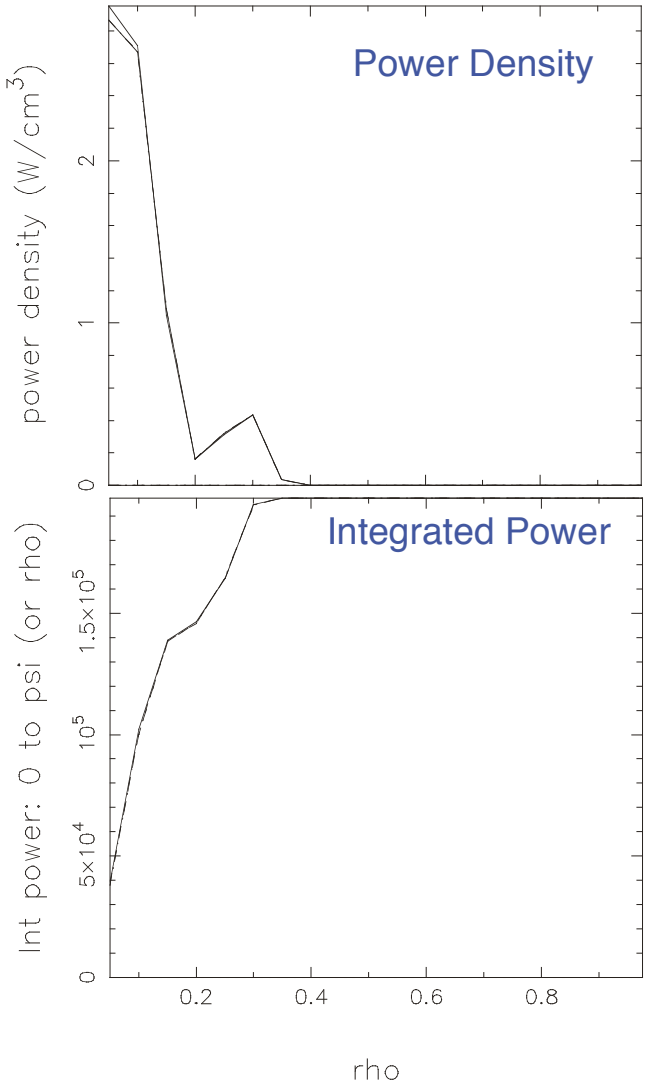


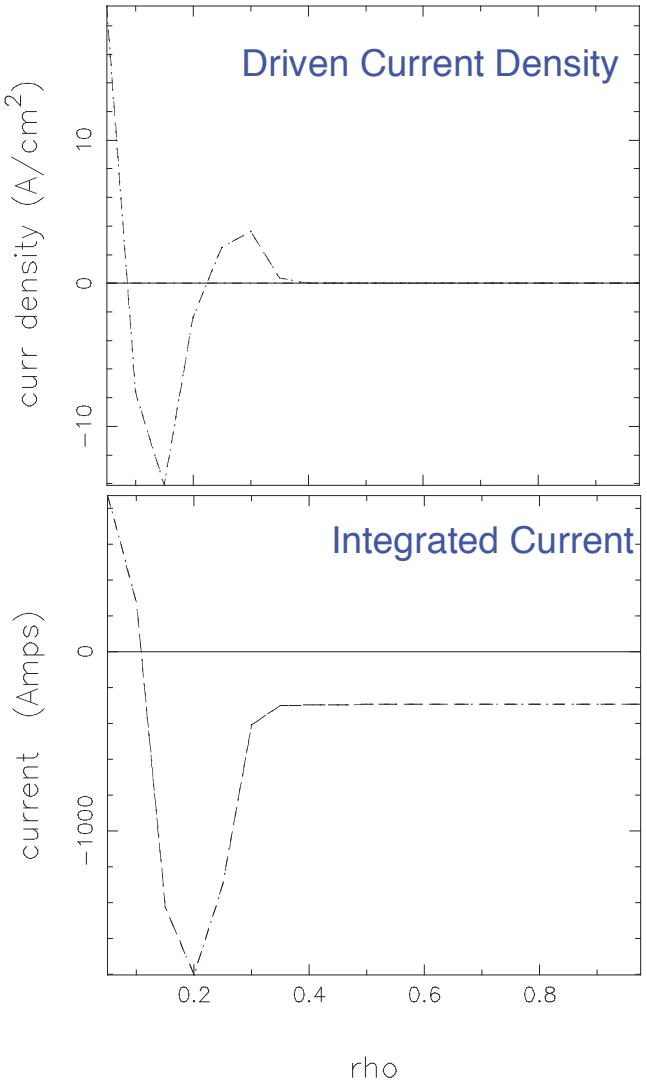
Oblique O-Mode Launch
200 kW
$n_{||}$ = -0.45 - -0.55

48 Rays
Launch θ = 25°
Antenna Length = 10 cm

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Case II - Heating and Current Drive

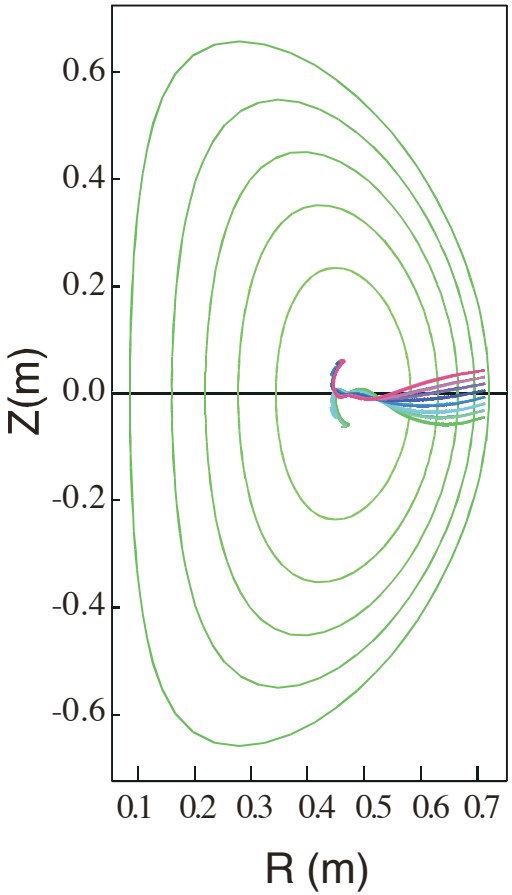


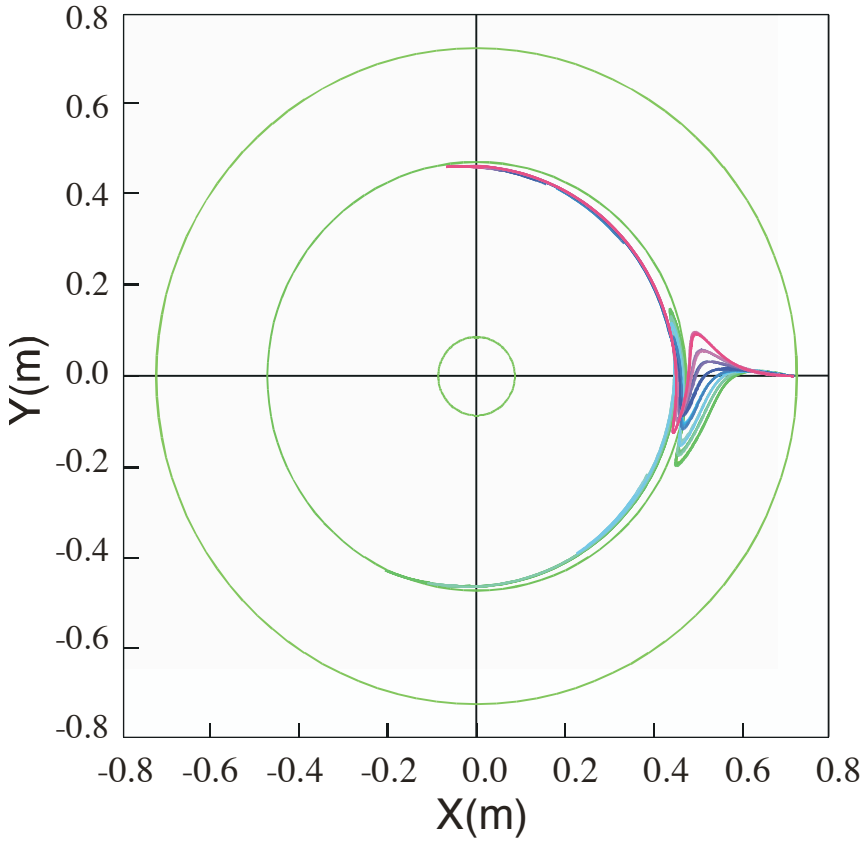


- Power deposited in inner third of plasma
- Drives +- 1 KA near axis

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Case III - Raytracing



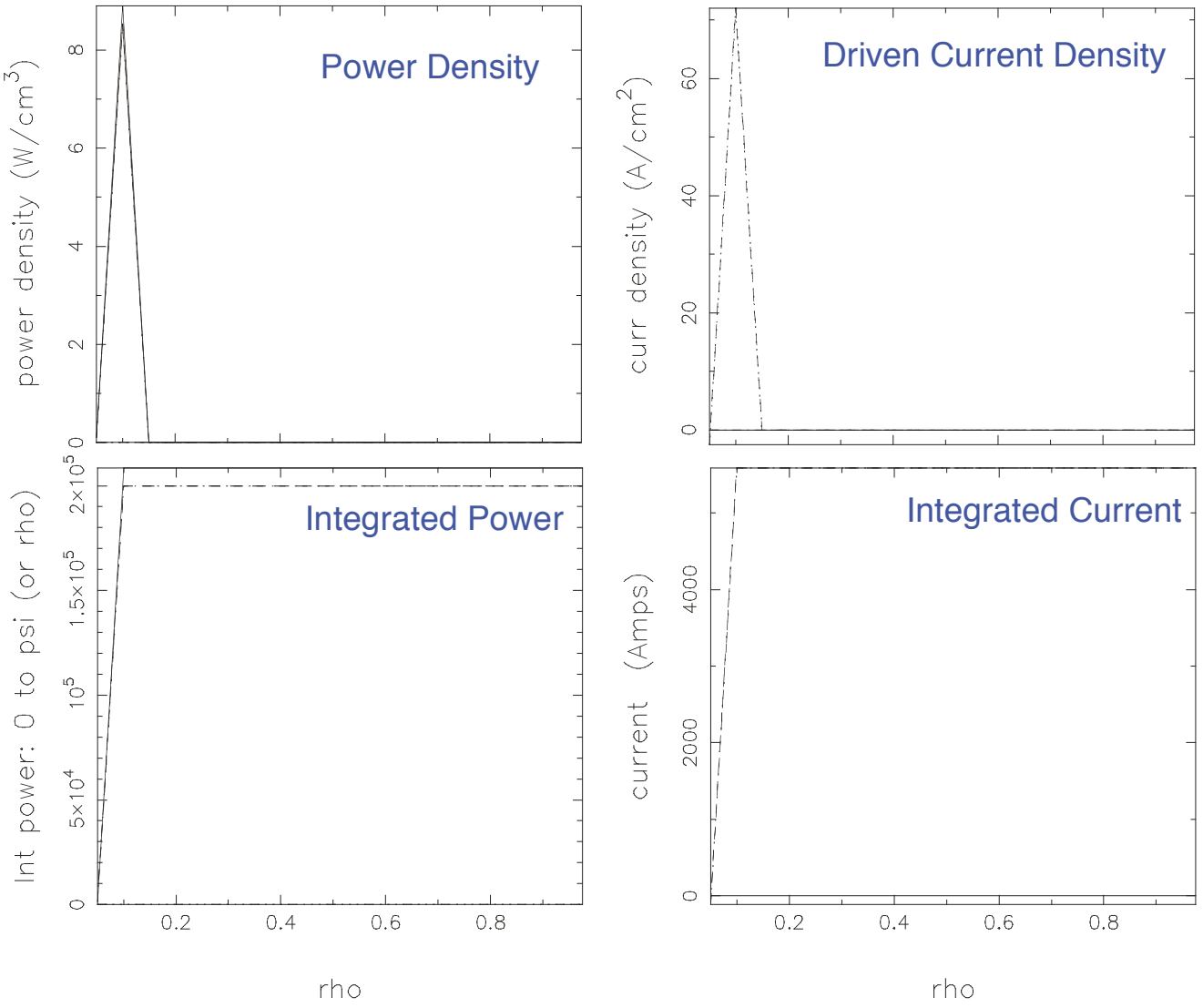


Oblique O-Mode Launch
200 kW
$n_{||} = 0.45 - 0.55$

48 Rays
Launch $\theta = 0°$
Antenna Length = 10 cm

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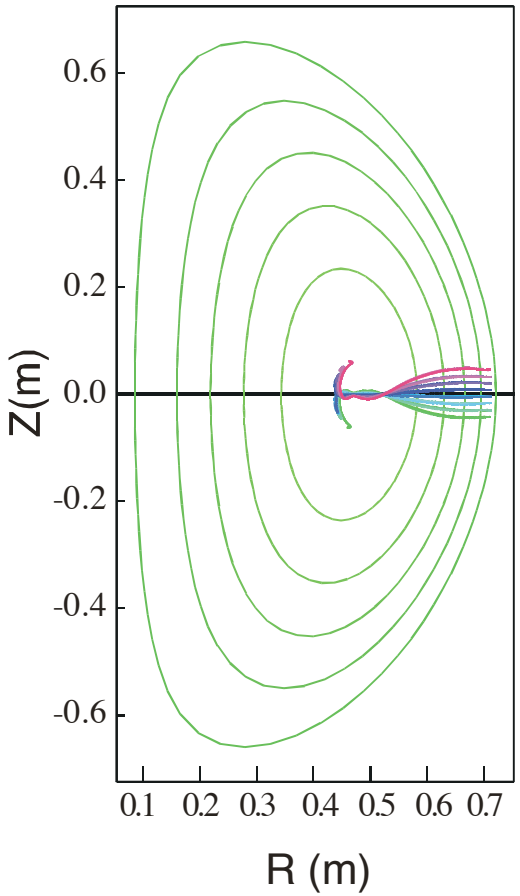
Case III - Heating and Current Drive

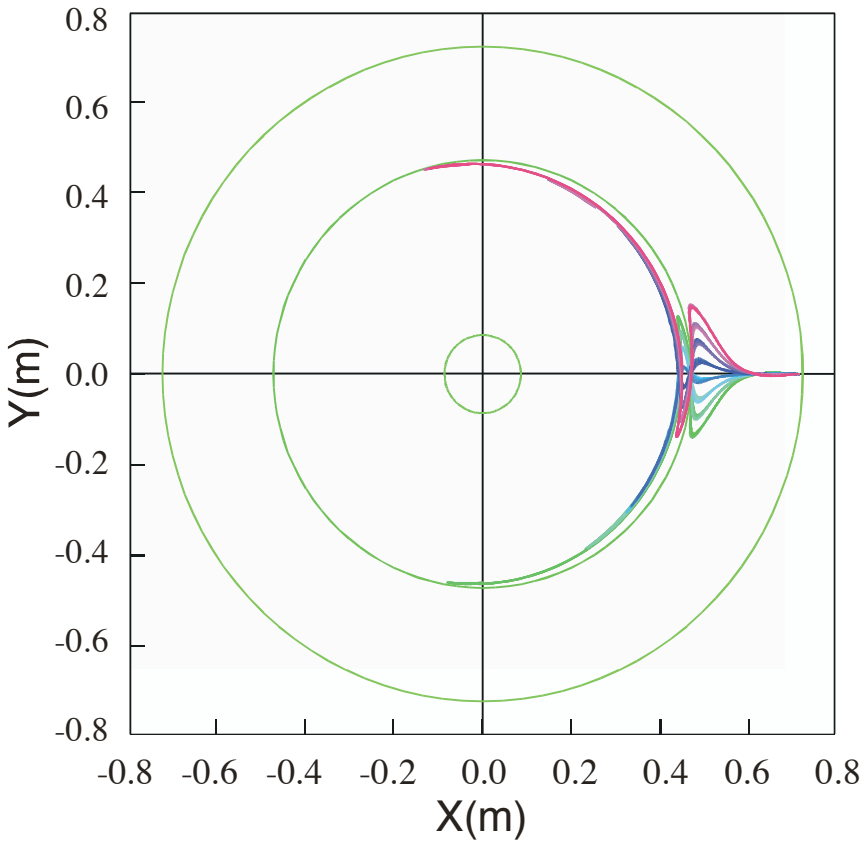


- Power deposited strongly at resonance
- 5 KA driven

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Case IV - Raytracing



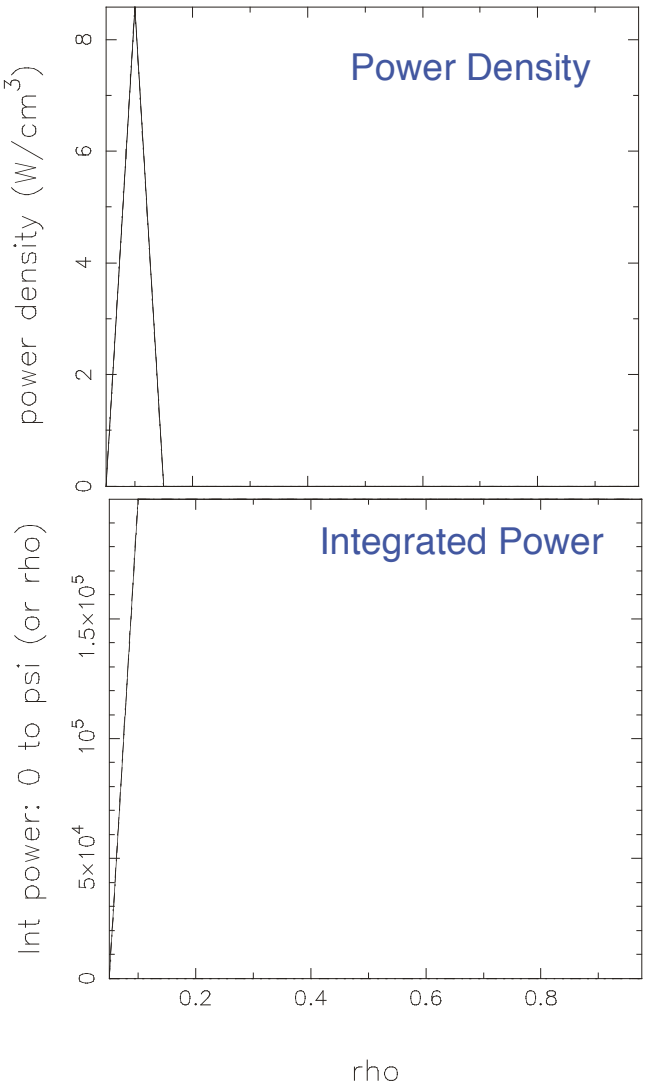


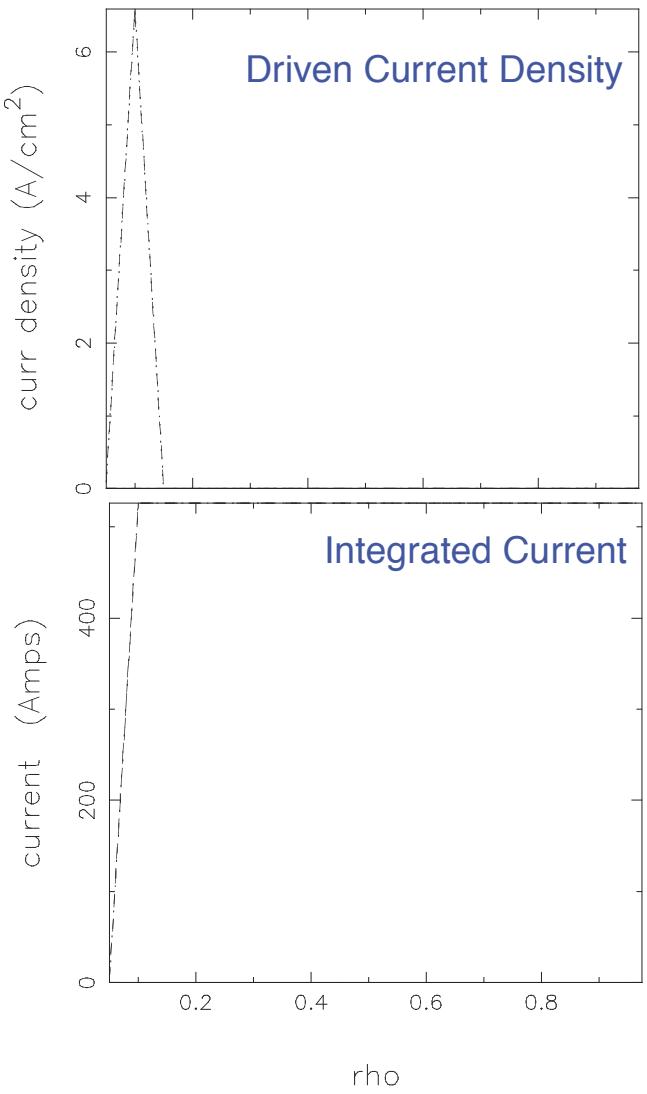
Normal X-Mode Launch
200 kW
$n_{||} = -0.05 - 0.05$

48 Rays
Launch $\theta = 0°$
Antenna Length = 10 cm

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Case IV - Heating and Current Drive





- Power deposited strongly at resonance
- 500 A driven

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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

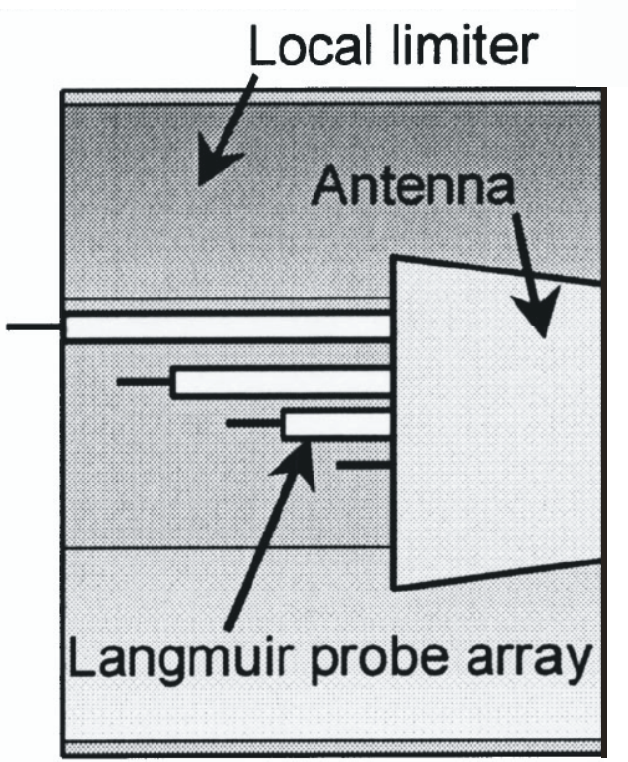
- Detailed plasma diagnosis beginning
  - Several diagnostics coming online (*=working):
    - = n_e: *1 mm IF*, VB*
    - = T_e: *Ross filters, PHA*
    - = *Impurities: bolometers*, SPRED**
  - Use CDX-U EBW diagnostic for edge characterization

- High-power heating components have been identified

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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.



CDX-U EBW Diagnostic

(B. Jones et al., *Phys. Plasmas* ***11****, 2004)*

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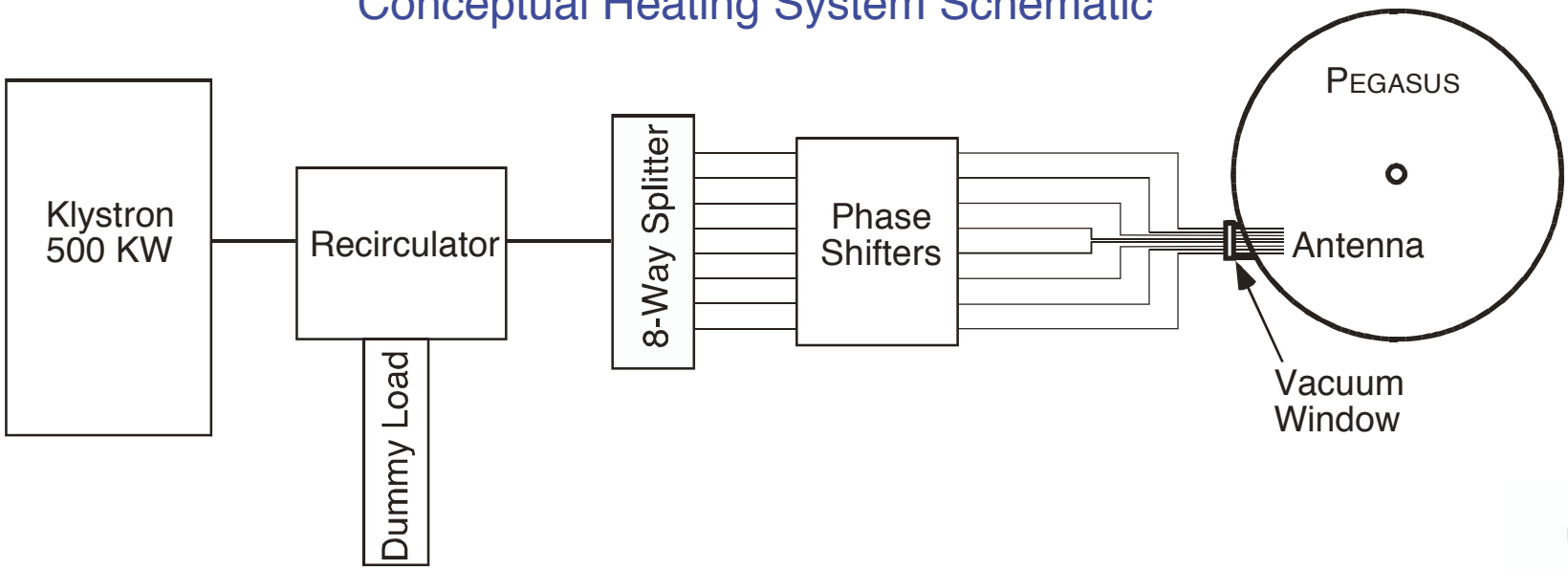
Stage 2 - Plasma heating system

- Significant advantage of EBW tests on PEGASUS ⟹
  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*

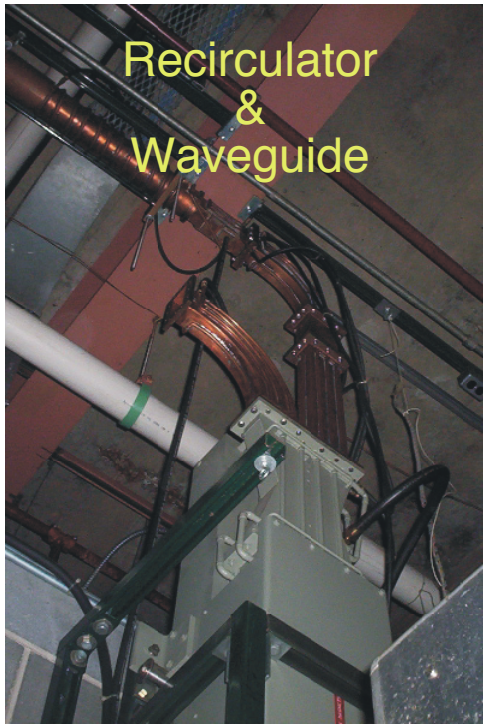
- Implementation of heating system depends on results of Stage 1

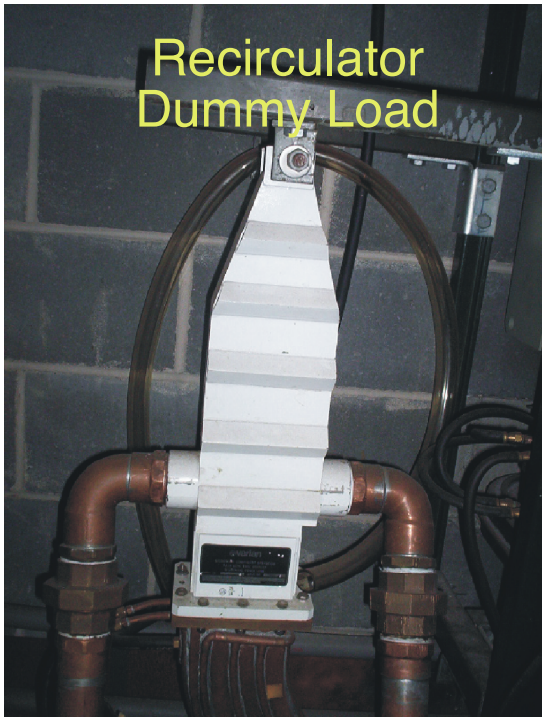
Conceptual Heating System Schematic

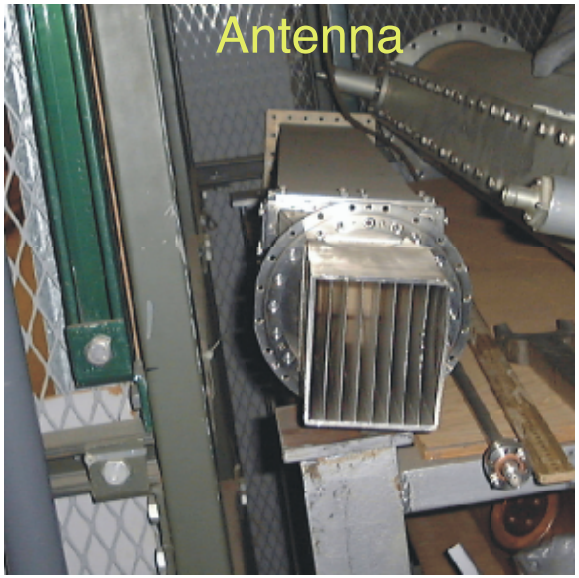


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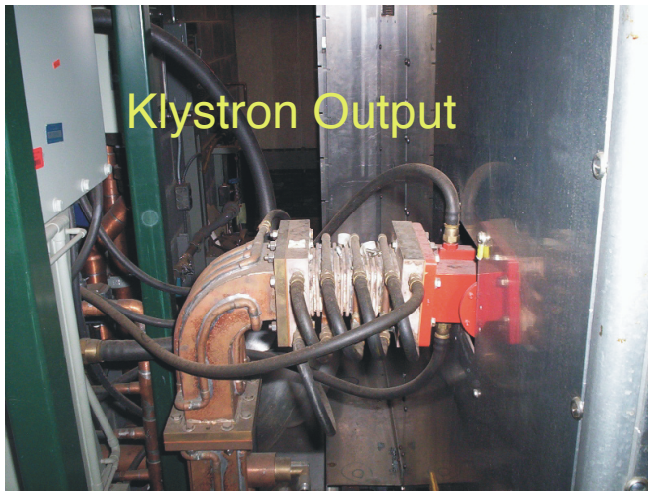
2.45 GHz hardware from PLT













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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

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