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/cm^2 between a normalized minor radius of 0 to 0.2 where the central density and temperature are 4.5e19 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.

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

Motivation

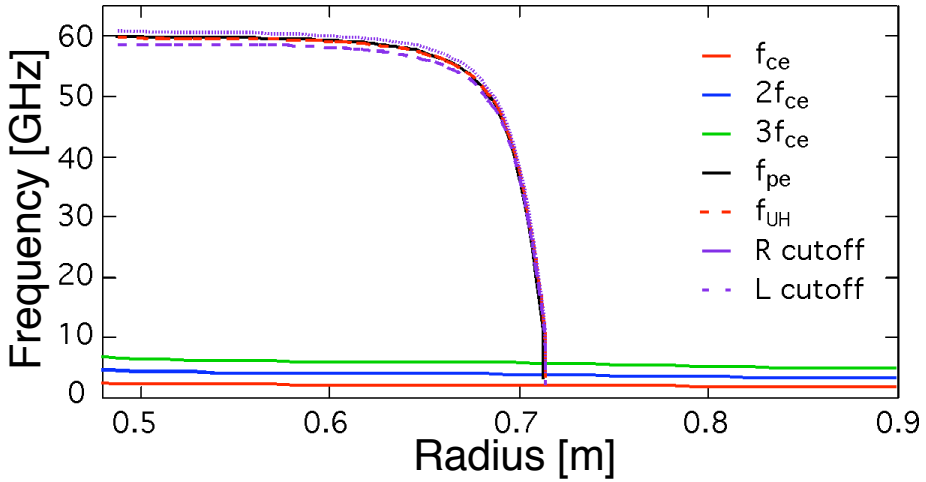
- Next generation ST experiments will require non-inductive heating and current drive (CD)
- ECRH and ECCD are standard but O- and X-modes will not propagate in overdense plasmas
  - STs, RFPs and spheromaks typically have low B-fields and high densities which cut off cold plasma waves
- PEGASUS provides 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

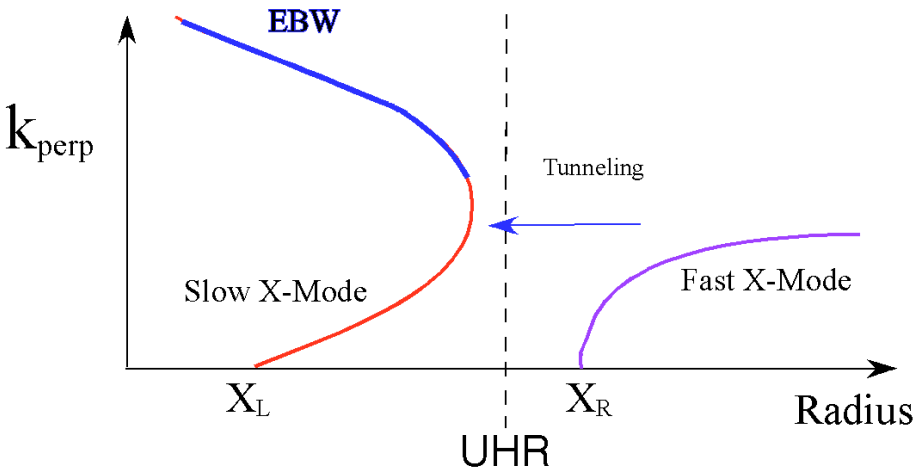
- EBWs are purely perpendicularly propagating, electrostatic, hot plasma waves that damp on electron cyclotron harmonics in an ST

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

where: $Q = \dfrac{\omega}{\Omega_e}$ and $\lambda = \dfrac{k_\perp^2 \kappa T_\perp}{m\Omega^2}$

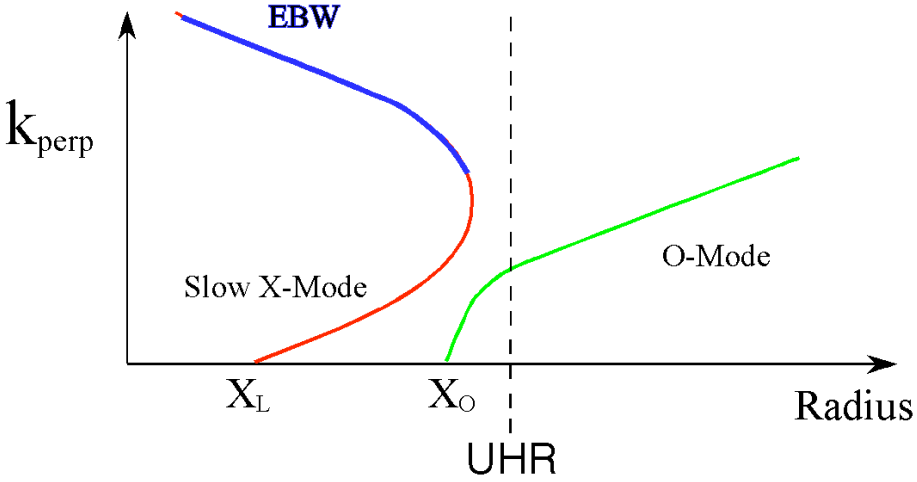
- Resonant when $\omega = n\Omega_e$
- EBWs do not experience a density cutoff in the plasma
- Cannot propagate in vacuum → must launch O- or X-modes to mode couple to EBW

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 ∇n_e)



O-X-B

- Tangential incidence of wave
- O converts to SX to EBW
- Requires shallow ∇n_e

EBWs provides heating and CD

- Heating
  - EBWs damp at the EC resonance
  - Absorption is preferentially on particles with large $v_{||}$ in the same direction as $n_{||}$
  - Electron heating is thus achieved by excitation of an electron tail
- Two methods of CD
  - Fisch-Boozer
    - An aysmmetric resistivity is developed by selective heating of electrons with one sign of $v_{||}$ 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

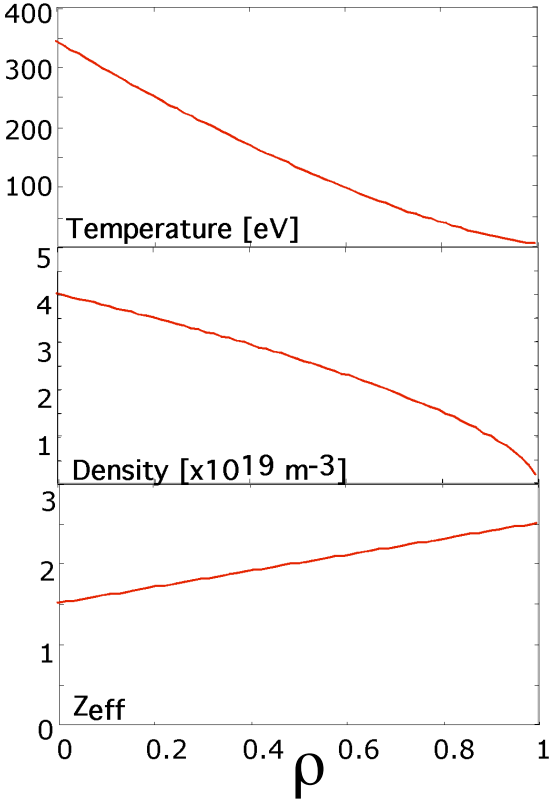
- General ray tracing code which calculates EM wave propagation
- Assumptions used:
  - antenna 10 cm high
  - $n_{||}$ is -0.45 to -0.55
  - 2.45 GHz with 200 kW of power distributed among 48 rays
  - Direct launch of EBW into plasma at ρ=0.95
- GENRAY just recently added the ability to model OXB coupling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

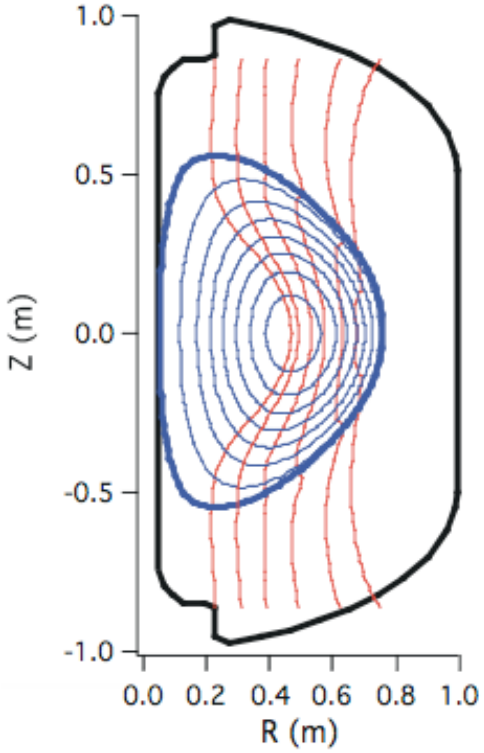
CQL3D

- Fokker-Planck code that calculates heating and CD profiles
- Uses ray tracing results from GENRAY

B_T scan performed to check robustness of EBW

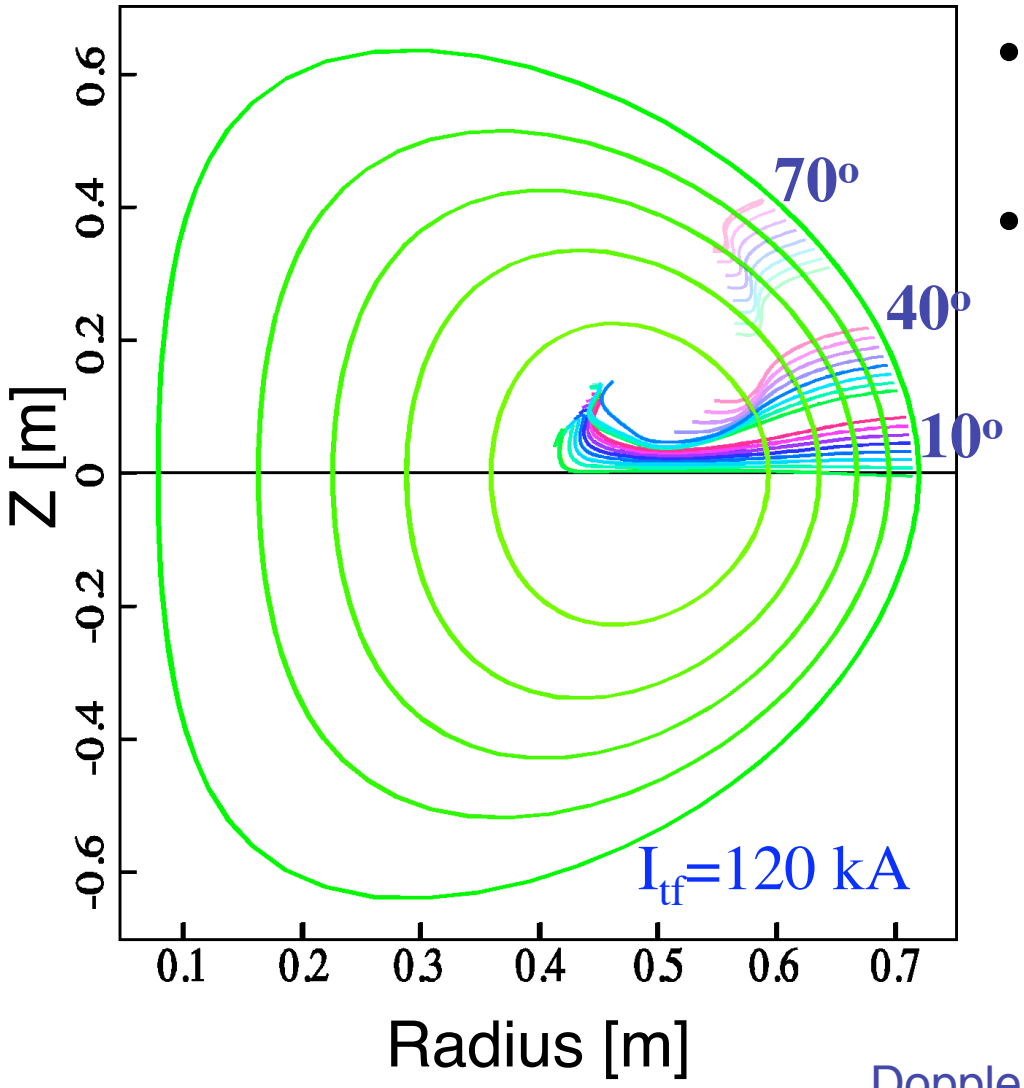
- Scan in toroidal field
  - Rod currents of 90, 120 and 150 kA studied
  - I_p=148 kA, κ~2, li-0.45, R_o=0.39 m, β~40%
  - Increasing B moves EC resonance location toward low-field-side of plasma edge





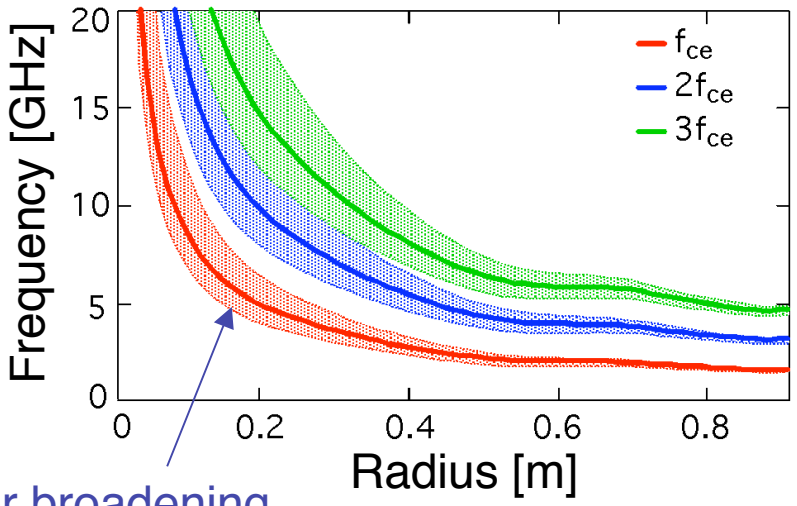
Red lines show the location of the fundamental 2.45 GHz resonance for I_{tf} = 90, 120, 150, 180, 210 and 240 kA.

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:
  - $n_{||}$ increases

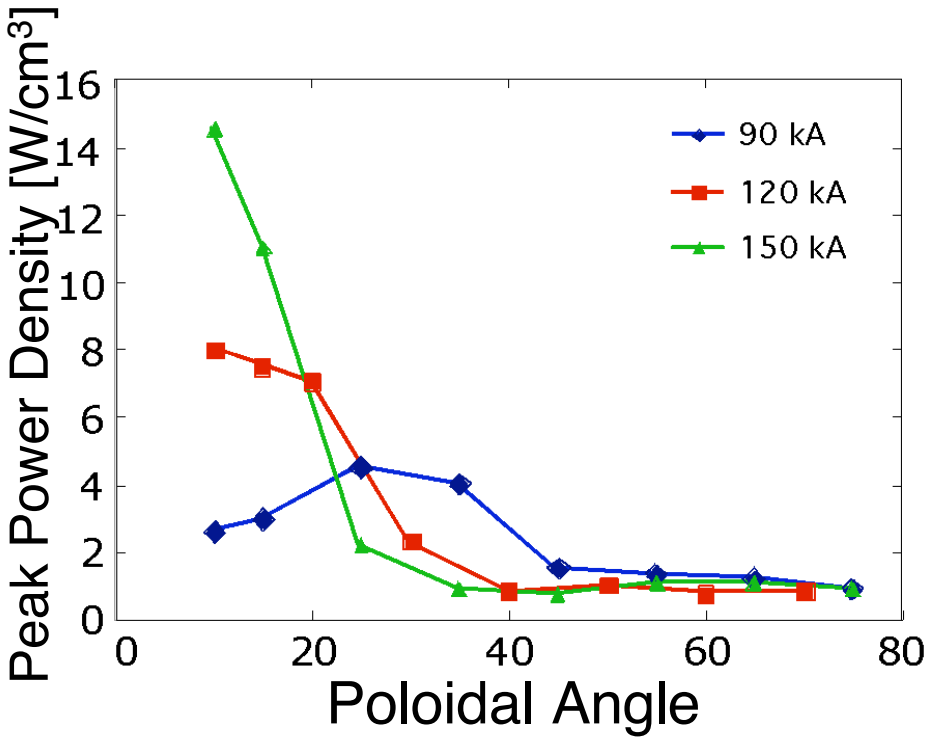
$$\omega - k_{||} v_{||} - n\Omega = 0$$

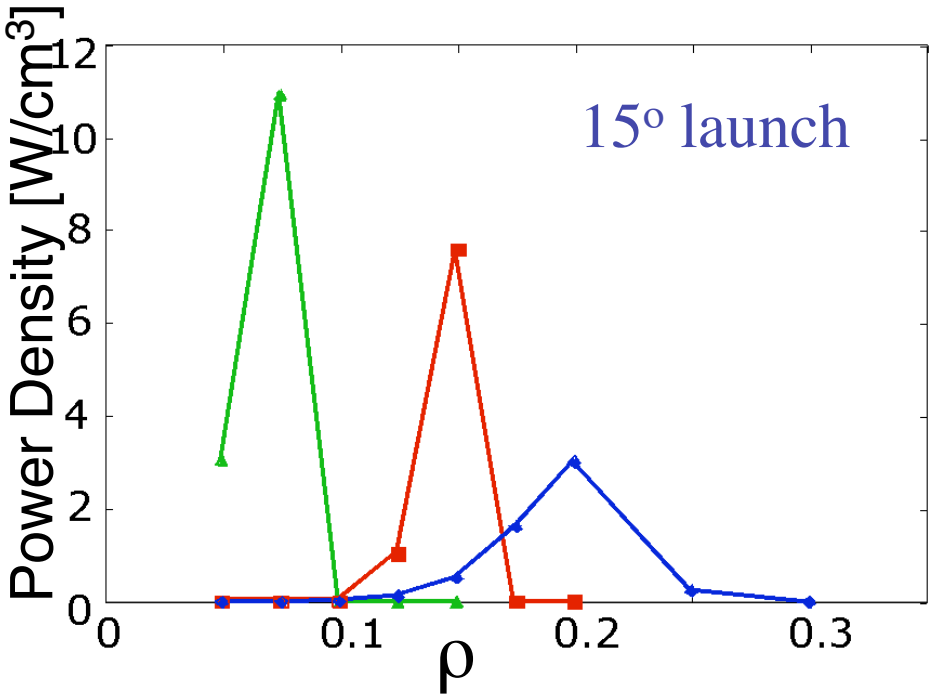


Doppler broadening due to $n_{||}$~4 near damping

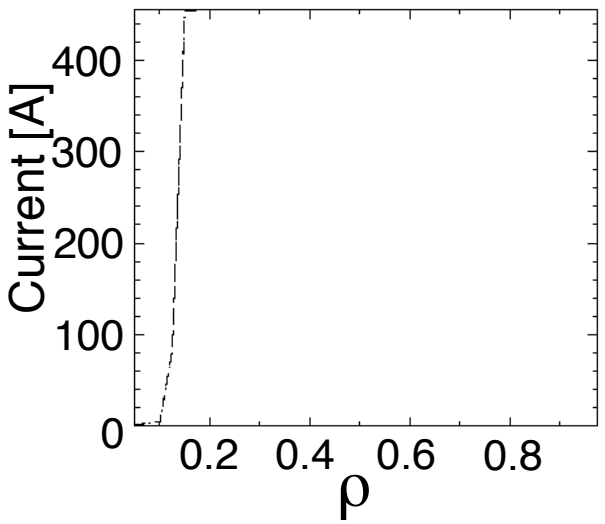
Near midplane launch gives optimal heating

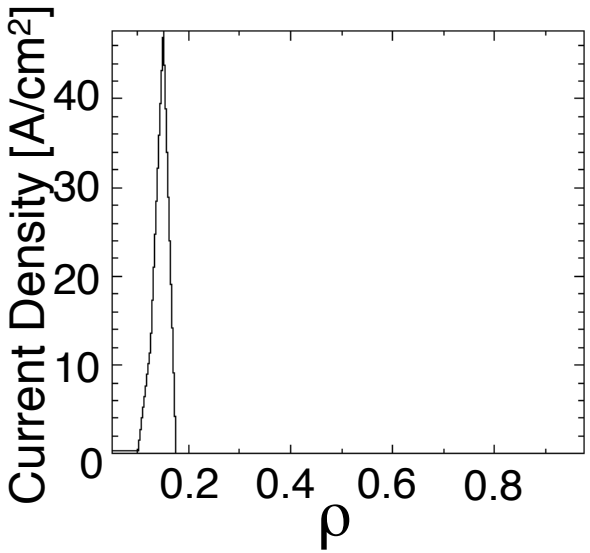
- EBWs damping near axis results in localized heating
  - Energy damped in smaller plasma volume leads to maximized heating



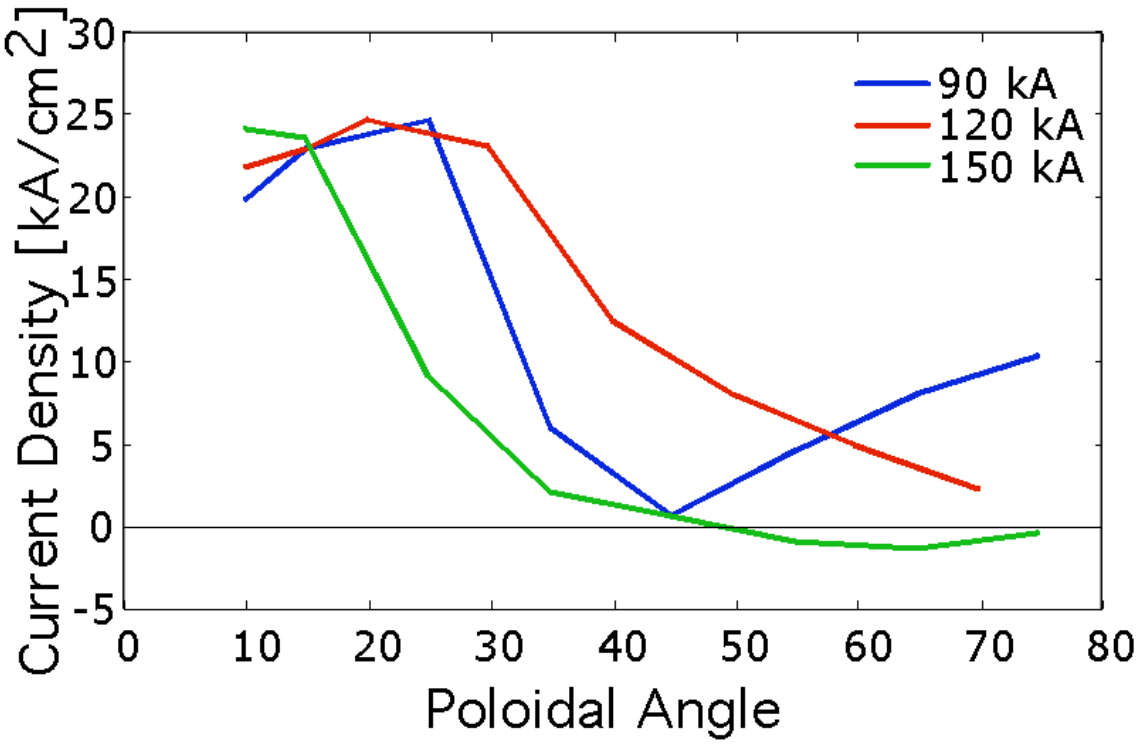


Near midplane launch maximizes current drive efficiency



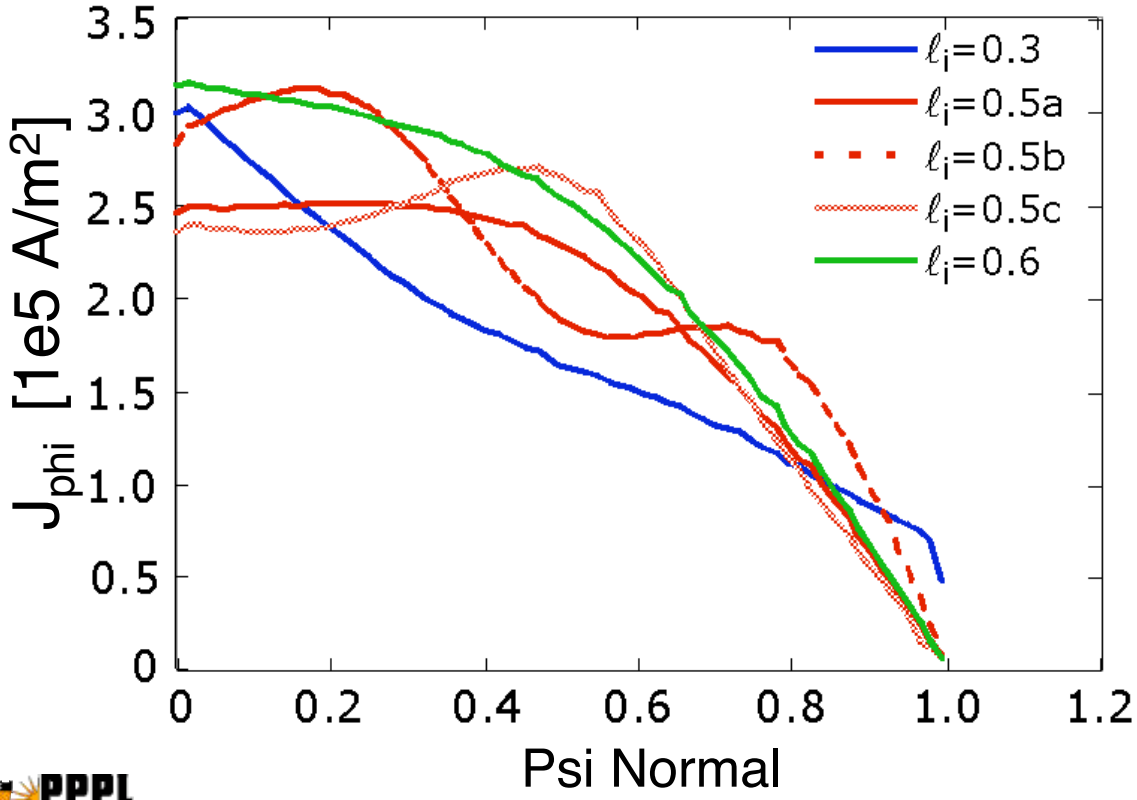


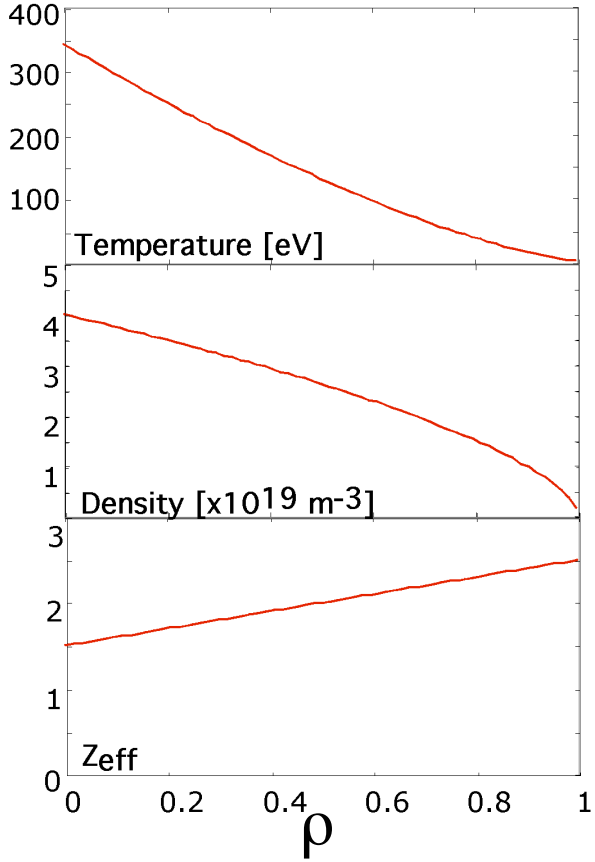
- EBWs can be used to tailor current profile
  - Can be used to affect tearing mode stability
  - Maximize pressure driven current (I_{BS})



ℓ_i scan performed to check effectiveness of EBWs for varying current profiles

- ℓ_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, κ~2, β~20%, and R_o=40 cm



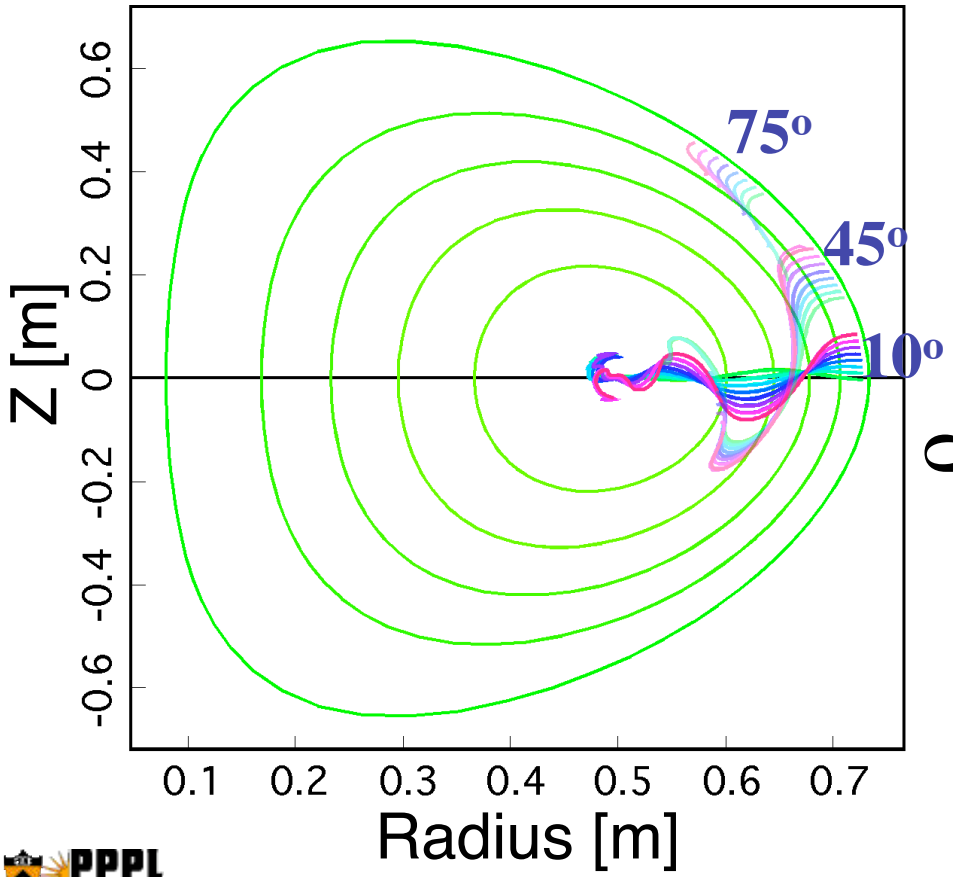


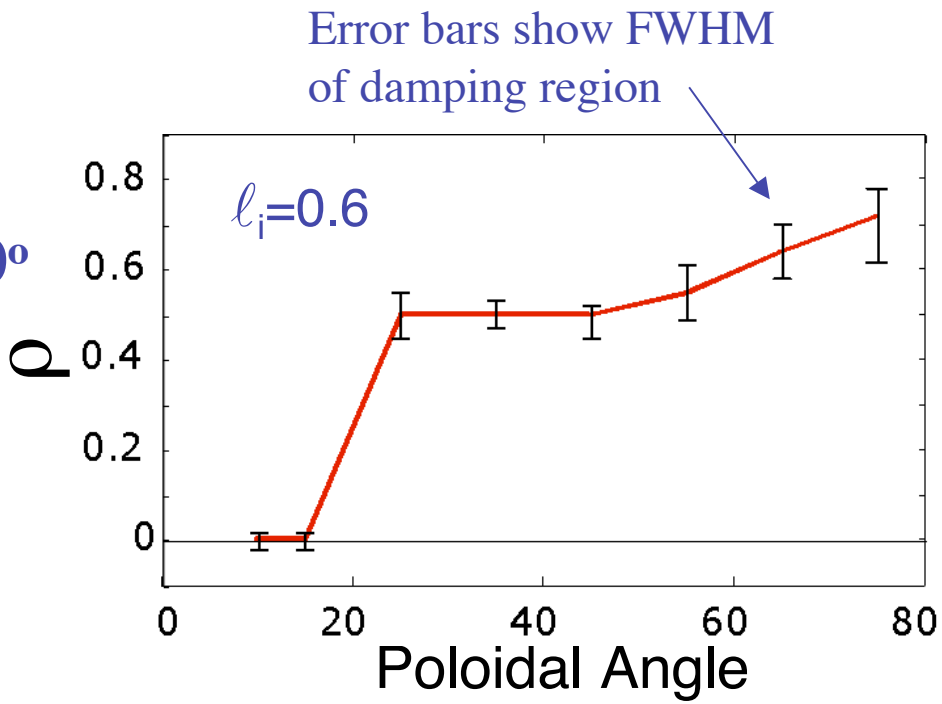
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Increase in poloidal launch angle increases Doppler shift & radius of damping location

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



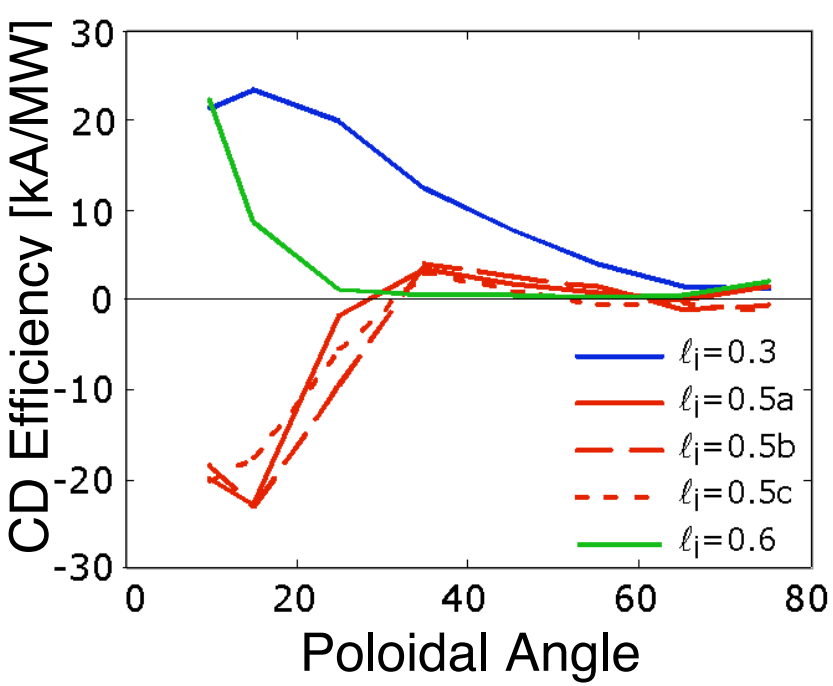


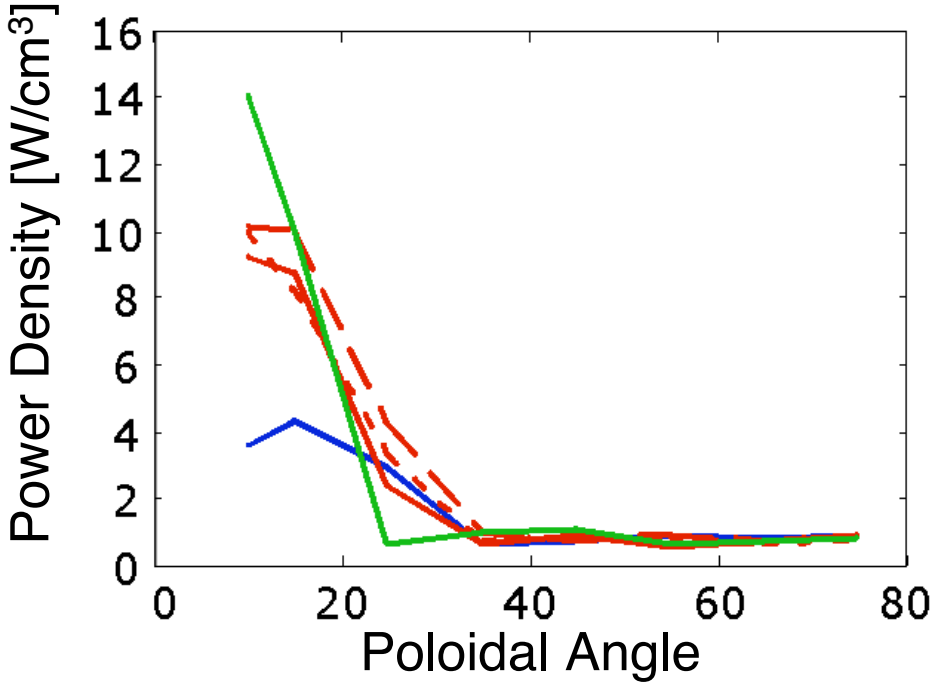
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Heating is peaked for near midplane launch at all ℓ_i values

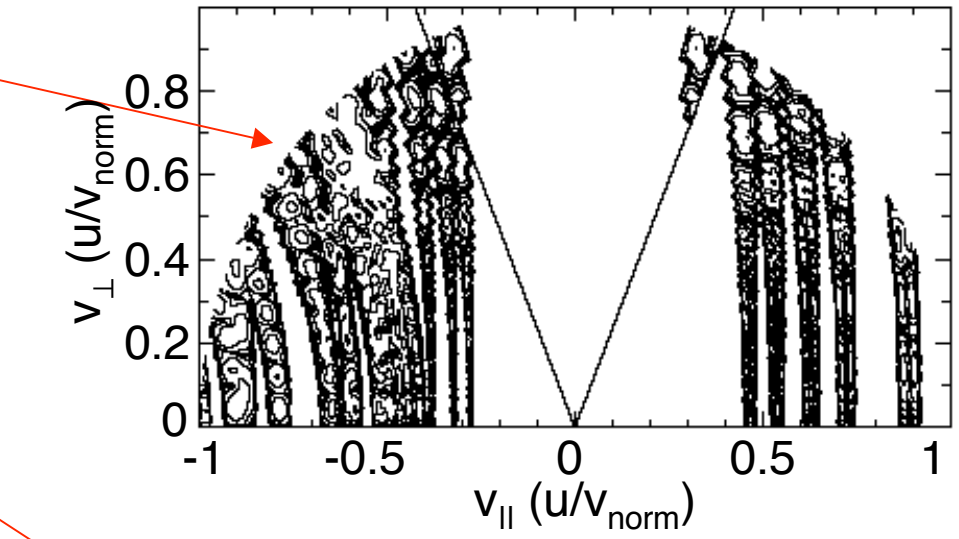
- At lowest possible ℓ_i, current still peaks near axis
- ℓ_i scan reveals sign of current is sensitive to profiles
  - A more extensive scan will be performed in the future to investigate this sensitivity

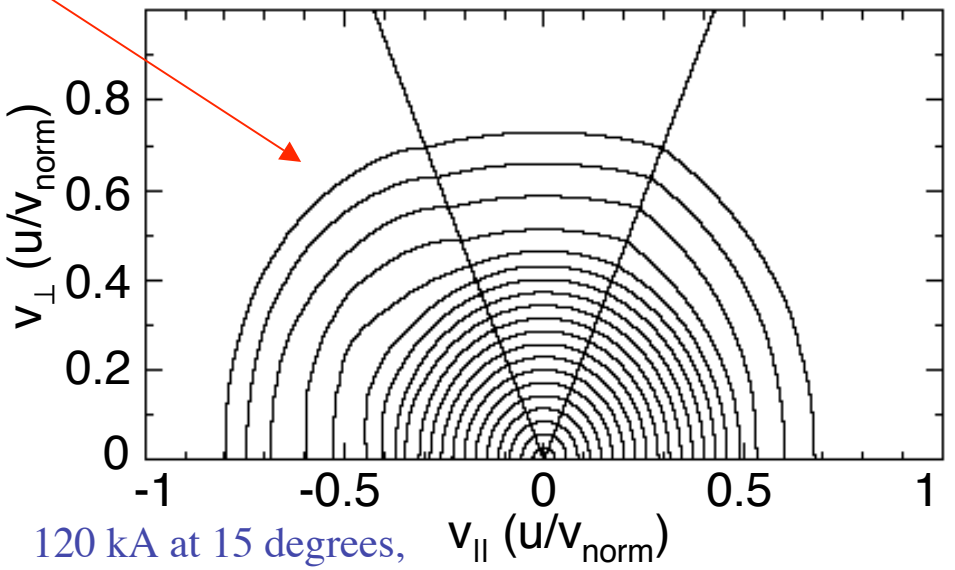




Fisch-Boozer CD is dominant CD mechanism for near-midplane launch

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



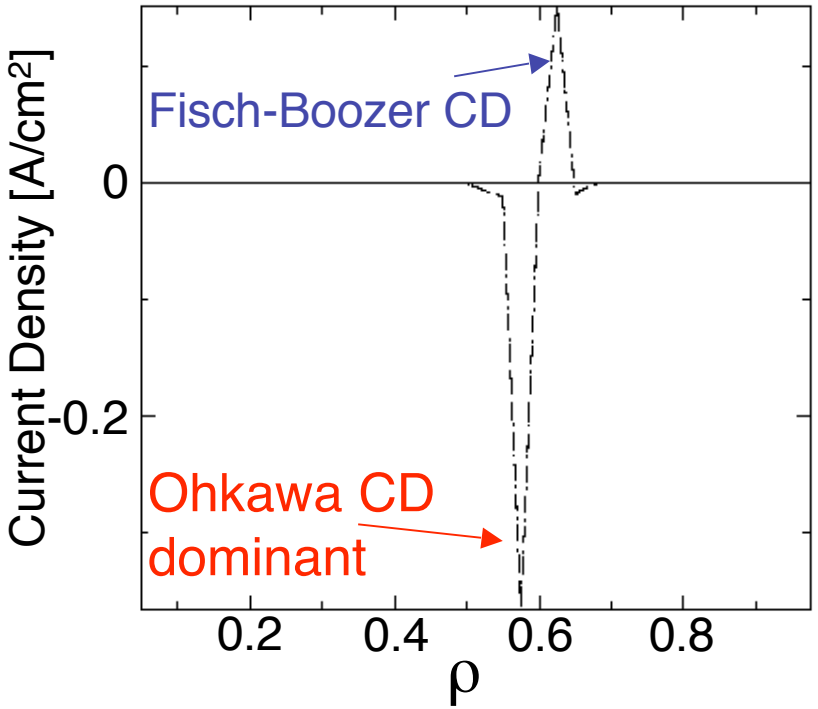


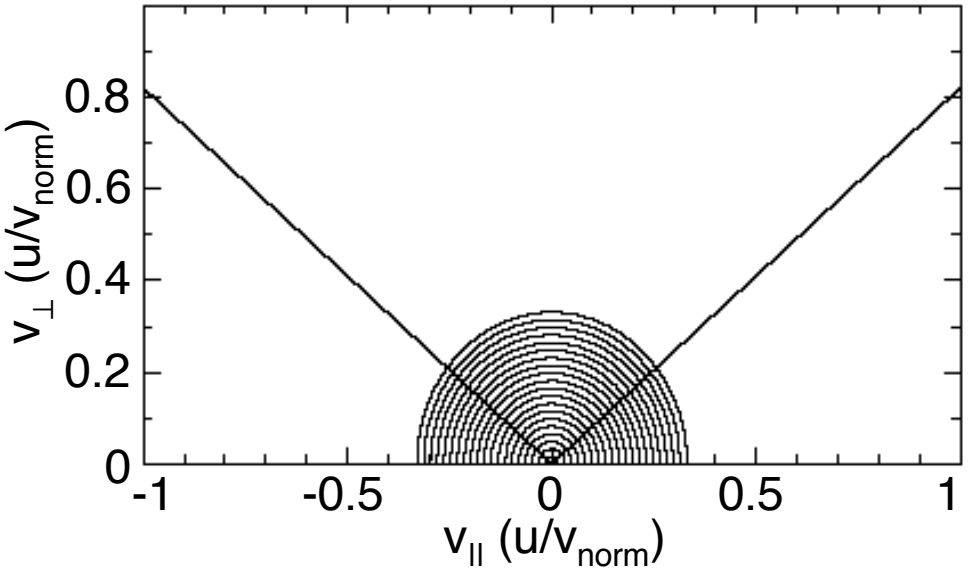
120 kA at 15 degrees,
ρ = 0.1 near the CD region

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

Ohkawa CD dominant at high I_{tf} and large poloidal launch angle

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

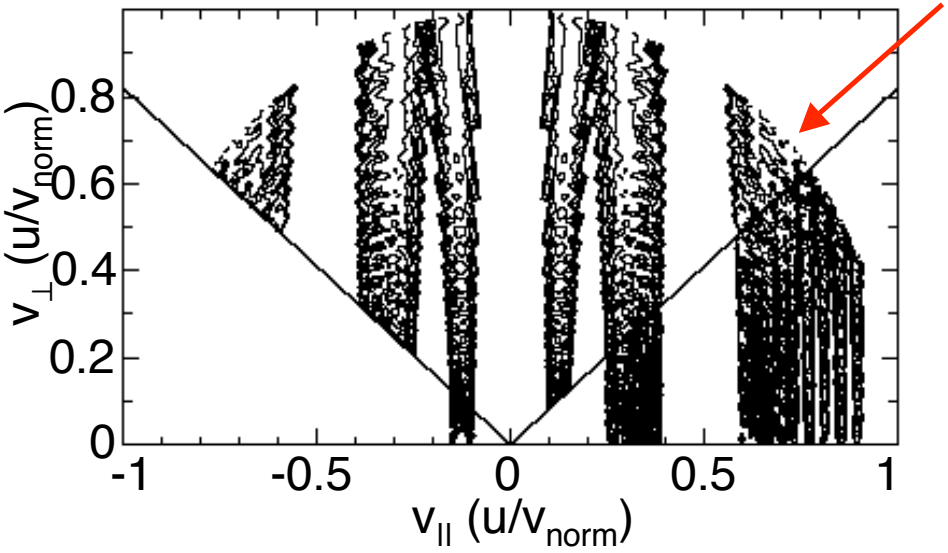




Distribution function shows no Fisch-Boozer characteristic shift at ρ=0.575.

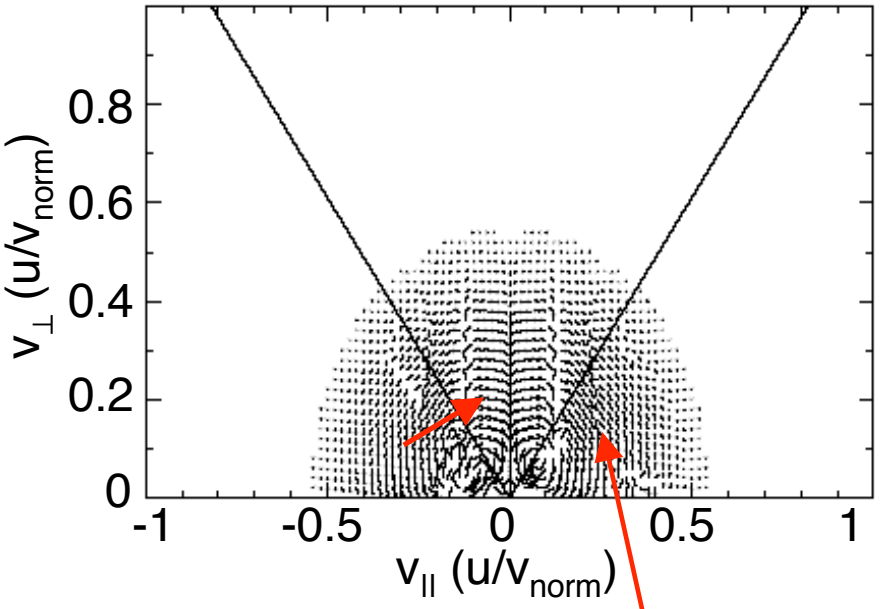
Ohkawa CD dominant at high I_{tf} and large poloidal launch angle

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



Quasilinear diffusion coefficient in velocity space at ρ=0.575

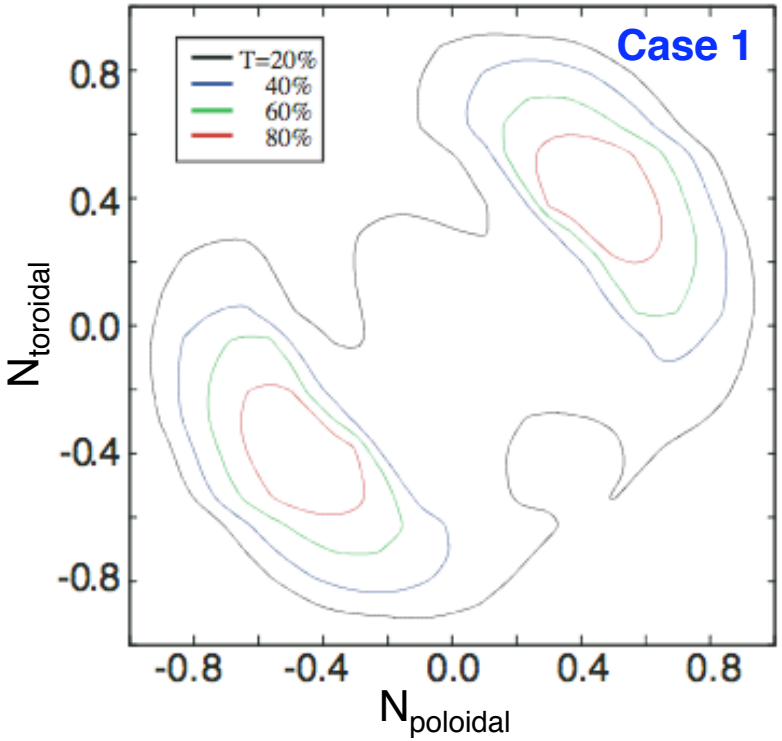
Electron flows in velocity space at ρ=0.575



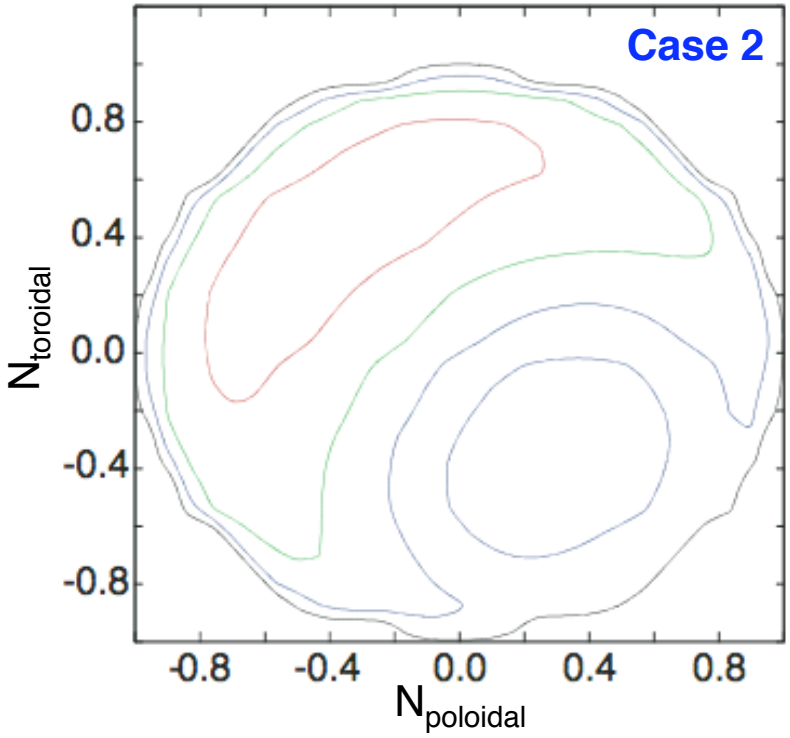
- Electron flows are into the trapped particle region

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

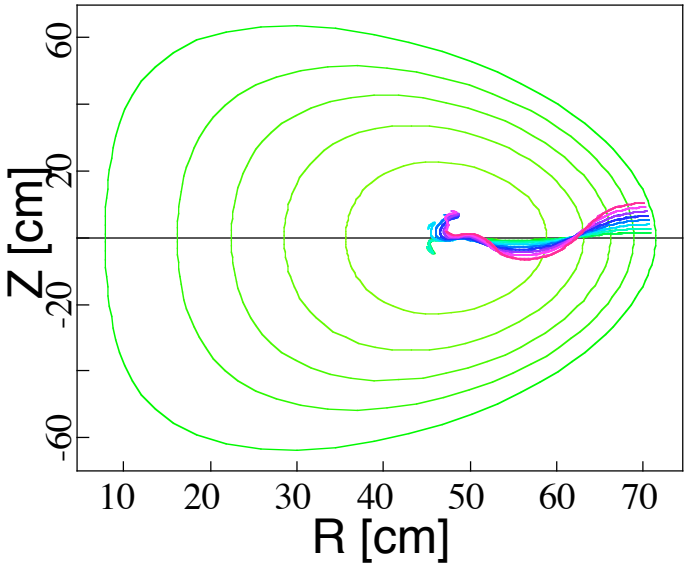


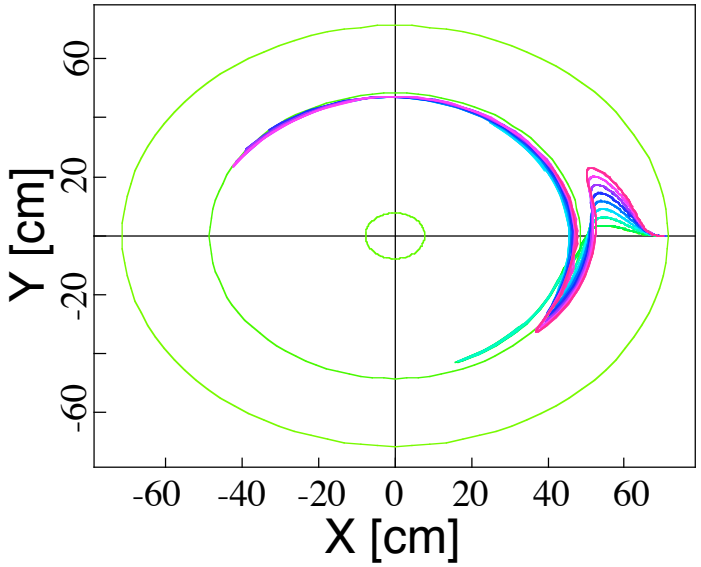
O-X-B dominant, L_n=2.9 cm



X-B dominant, L_n=0.4 cm

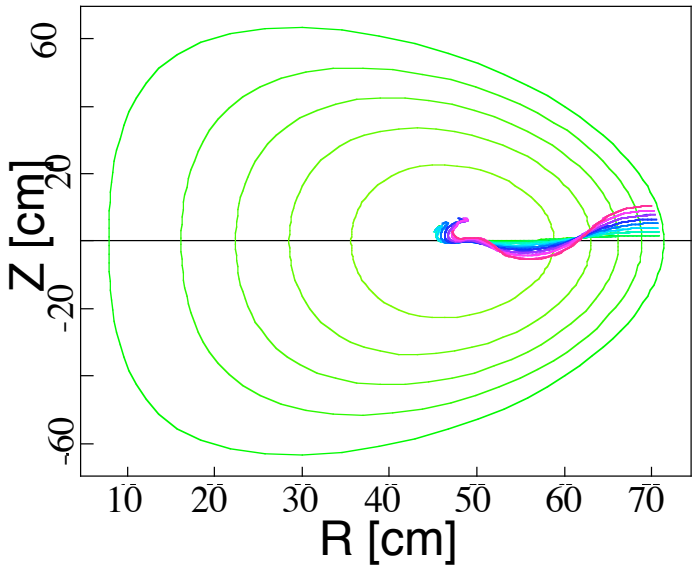
Near midplane X-mode launch experiments possible on PEGASUS

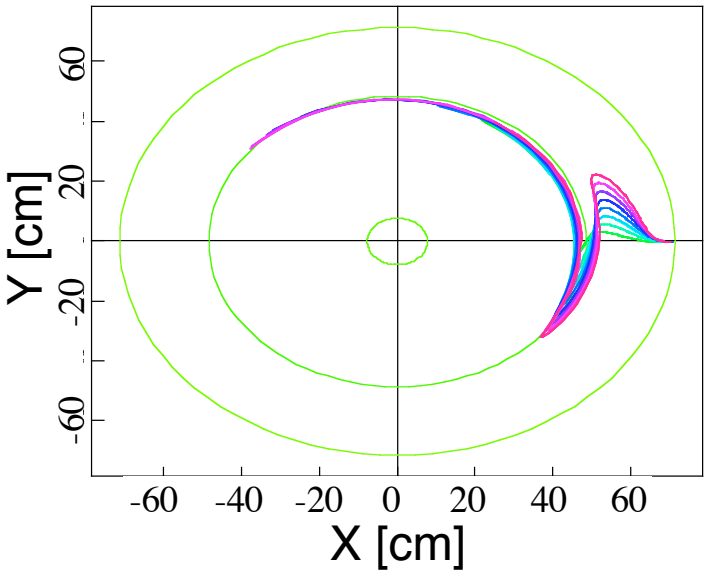




X-mode

- I_{tf}=150 kA
- 15° launch angle
- $n_{||}$=-0.05 to 0.05





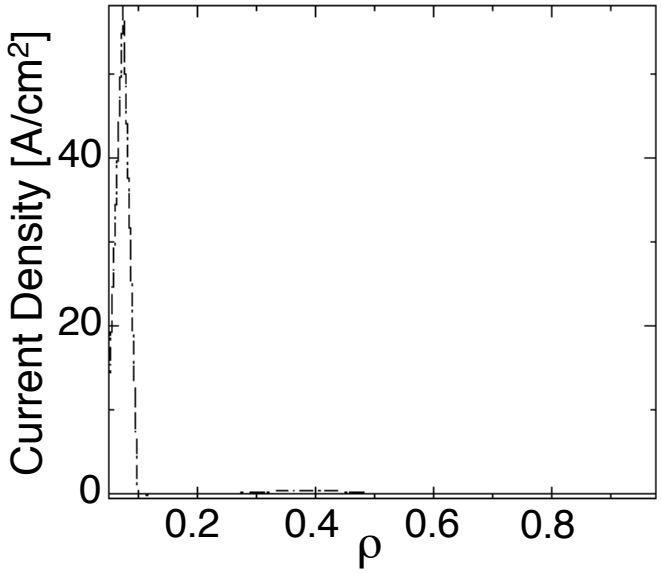
O-mode

- I_{tf}=150 kA
- 15° launch angle
- $n_{||}$=-0.55 to -0.45

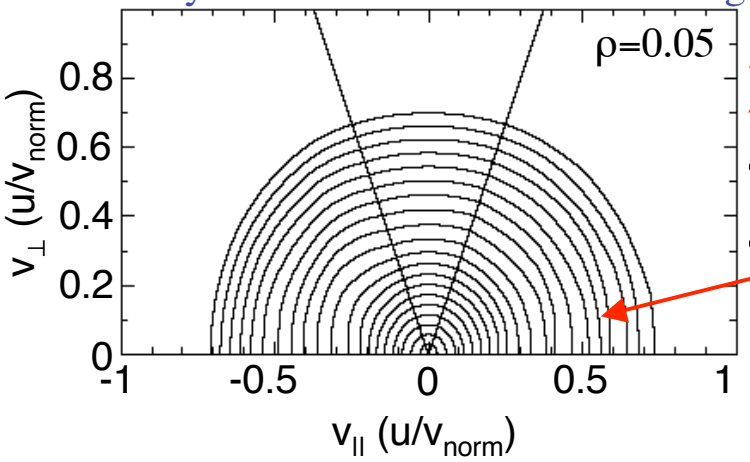
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Near midplane X-mode launch provides Fisch-Boozer current drive

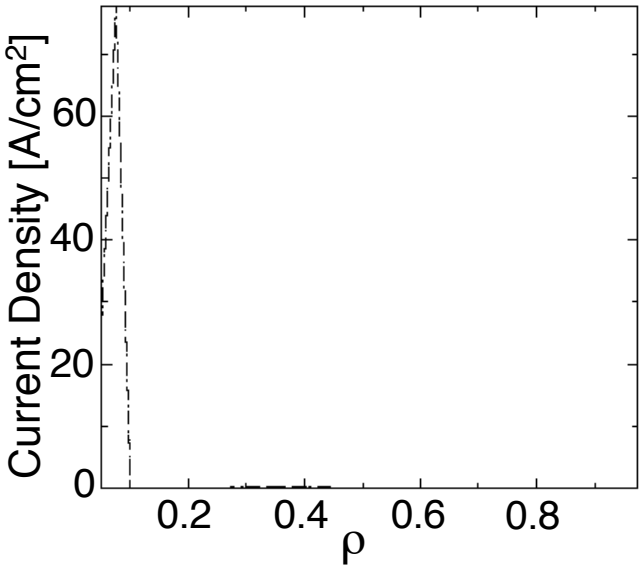


Velocity distribution function in CD region

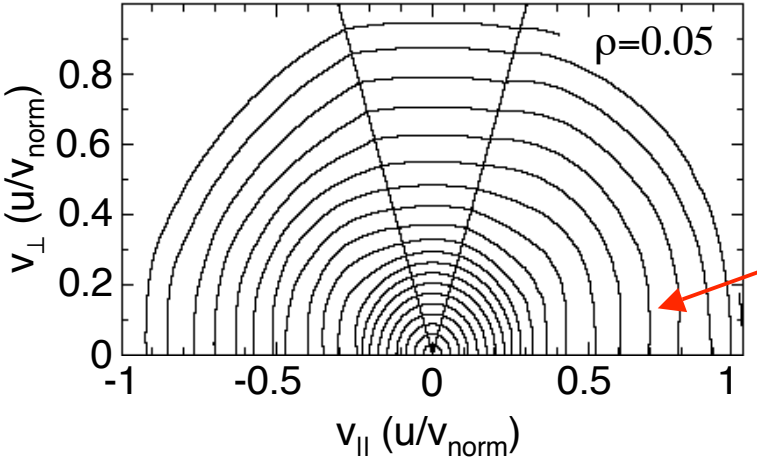


X-mode launch

- CD = 3.2 kA
- Fisch-Boozer CD



Velocity distribution function in CD region



O-mode launch

- CD = 4.7 kA
- Fisch-Boozer CD

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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_i on the sign of the driven current
  - Perform more modeling to optimize Ohkawa CD in support of NSTX



Reprints

PPPL PRINCETON PLASMA PHYSICS LABORATORY

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