High Harmonic Electron-Bernstein Wave Mode Conversion Calculations for NSTX

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Outline

- Goals and status
- Procedure for emission analysis
- EBW coupling calculations for shot 113544
- Conclusions

Goal: To calculate EBW launch using realistic antenna and plasma conditions

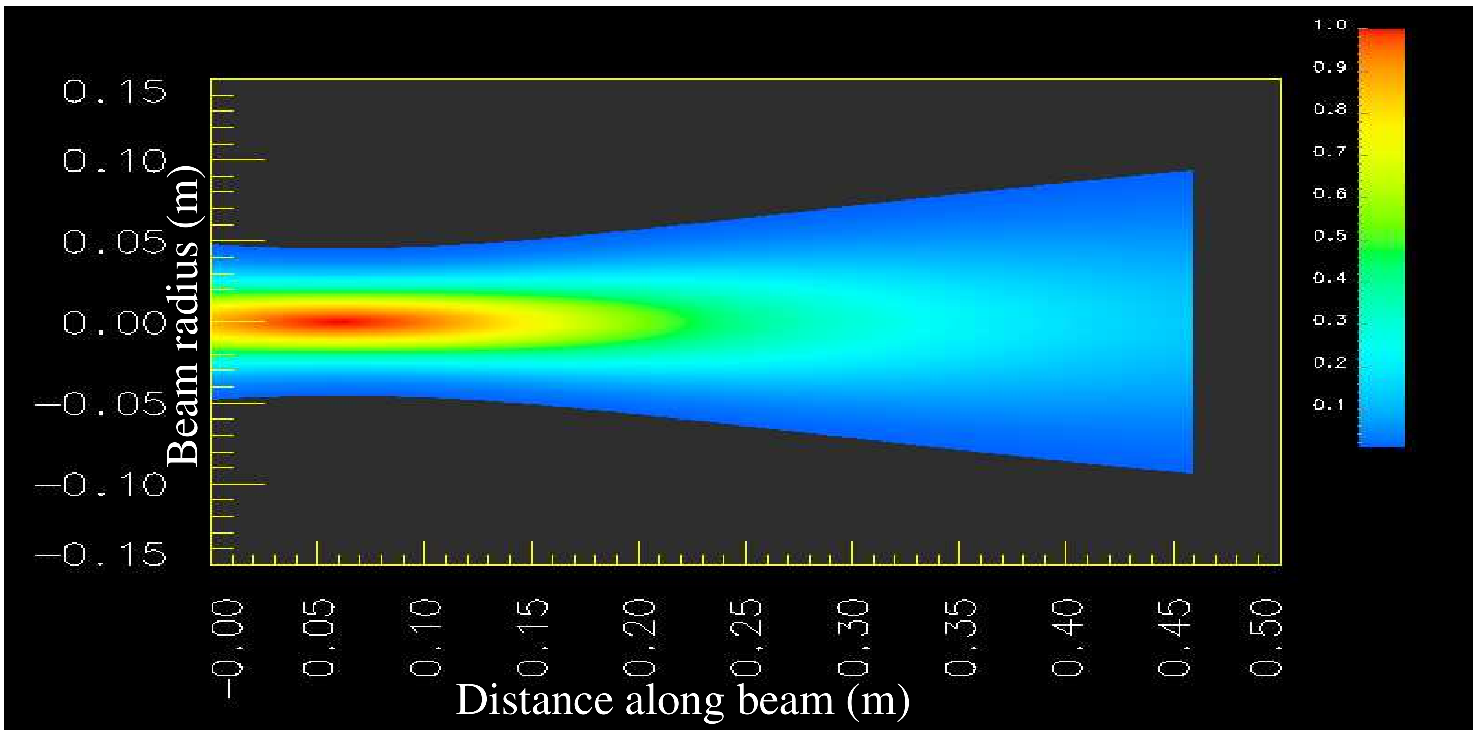
- Realistic launch geometries: REALIPOL code
  - Gaussian beam optics in machine coordinate frame
  - EQDSK equilibrium geometries from NSTX data base
  - Polarization tracking between launcher and plasma
- Transmission and emission calculations
  - Benchmark with emission experiments by combining OPTIPOL (using GLOSI) and REALIPOL codes
  - Analyze high-power EBW launcher designs
- Study high harmonic EBW launch by combining RELIPOL and OPTIPOL with AORSA1D

Status

- REALIPOL
  - Accepts EQDSK files from NSTX data base
  - Accepts Gaussian beam parameters in cylindrical machine coordinates based on port location
  - Uses OPTIPOL results to estimate polarization and transmission for emission studies
  - Interfaced with GLOSI (less than 2^{nd} harmonic)
  - Ready for comparison with emission experiments
- AORSA1D
  - Accepts experimentally supplied density profiles
  - Solves for EBW mode conversion at arbitrary frequency using periodic Fourier basis sets

Gaussian Beam Optics in REALIPOL

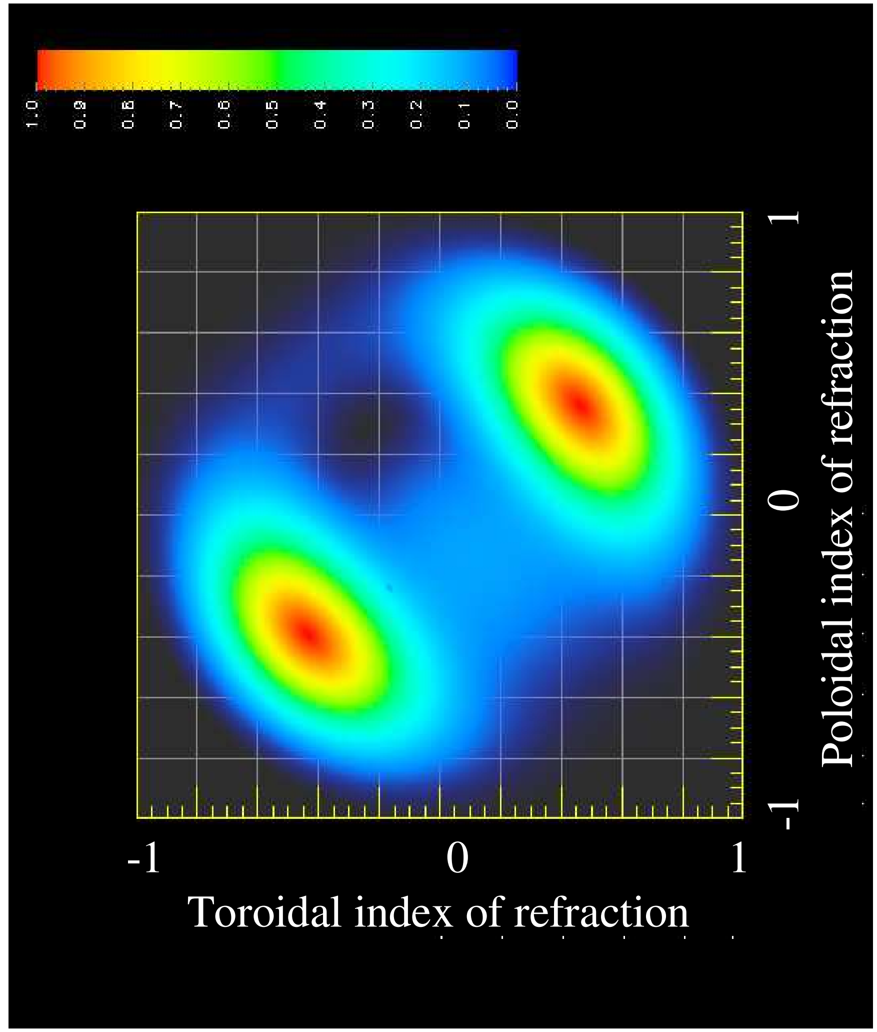
- Field components: $\psi = \frac{w_0}{w(z)} \exp(\frac{-r^2}{w^2(z)}) \exp(-ikz) \exp(\frac{-i\pi r^2}{\lambda R(z)}) \exp[i\, Atan(\frac{\lambda z}{\pi w_0^2})]$
  - Beam waist is $w(z) = w_0[1+(\lambda z/\pi w_0^2)^2]^{1/2}$
  - w_0 is the minimum waist radius (z=0)
  - Wavefront radius of curvature is $R(z) = z[1+(\pi w_0^2/\lambda z)^2]$



OPTIPOL Overview

- Uses plasma surface impedance from GLOSI to scan EBW transmission over all polarization possibilities at all launch angles in Fourier space
- Saves maximum transmission and associated polarization information at each launch angle
- Formats information for use by REALIPOL

Maximum achievable transmission



Transmission/Reflection of incoming plane waves from surface impedance

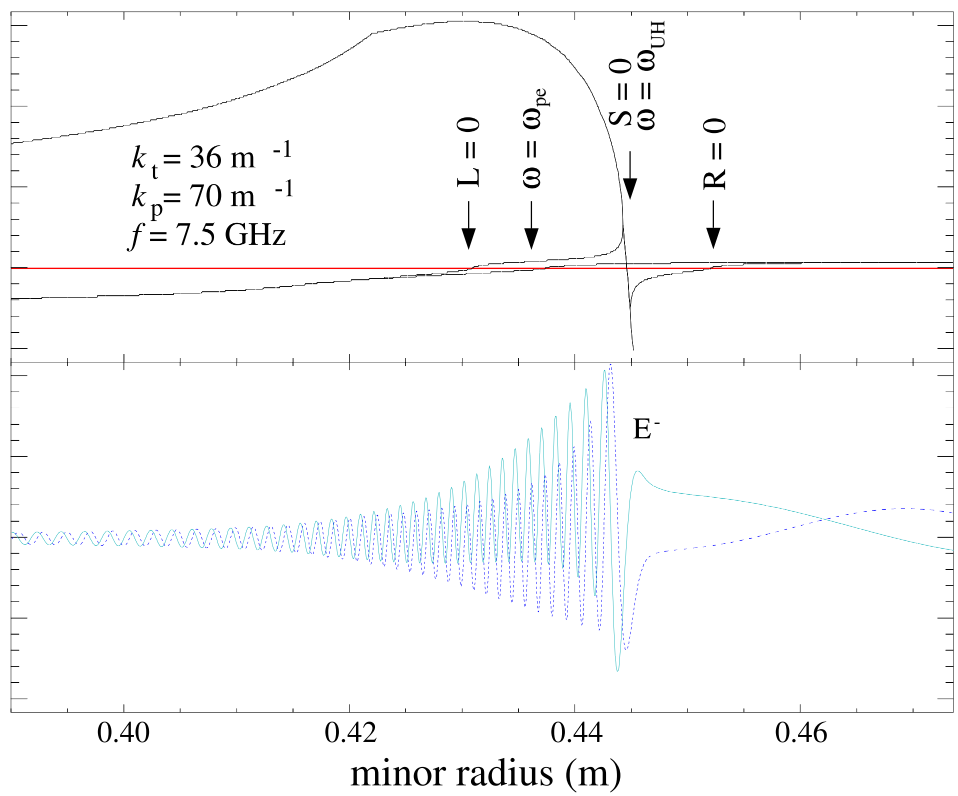
- Assume incoming and reflected plane waves from infinity in vacuum: $\underline{E}^{mn}(x) = \underline{E}_l^{mn} e^{-ikx} + \underline{E}_r^{mn} e^{+ikx}$
- Fourier analyze Maxwell's equations in slab, isolate tangential components: $\underline{E}_T$ and $\underline{B}_T$
- GLOSI calculates plasma surface impedance for range of Fourier modes: $\underline{E}_T^{mn}(x=0) = \underline{\underline{Z}}_s^{mn} \cdot \underline{B}_T^{mn}(x=0)$
- From $\underline{\underline{Z}}_s^{mn}$, generate directional impedances:

$$\underline{E}_{Tl}^{mn} = \underline{\underline{Z}}_{El}^{mn} \cdot \underline{B}_{Tl}^{mn} \,;\, \underline{E}_{Tr}^{mn} = \underline{\underline{Z}}_{Er}^{mn} \cdot \underline{B}_{Tr}^{mn} \,;\, \underline{B}_{Tr}^{mn} = \underline{\underline{Z}}_{Br}^{mn} \cdot \underline{B}_{Tl}^{mn}$$

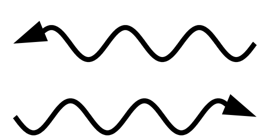
- Transmission is: $$T = 1 - \frac{\mathrm{Re}\left(\underline{E}_{Tr}^{mn} \times \underline{B}_{Tr}^{mn\,*}\right)}{\mathrm{Re}\left(\underline{E}_{Tl}^{mn} \times \underline{B}_{Tl}^{mn\,*}\right)}$$

GLOSI solves for mode converted wave fields in the plasma edge

- Assumes warm plasma, so restricted to frequencies below twice the electron cyclotron frequency

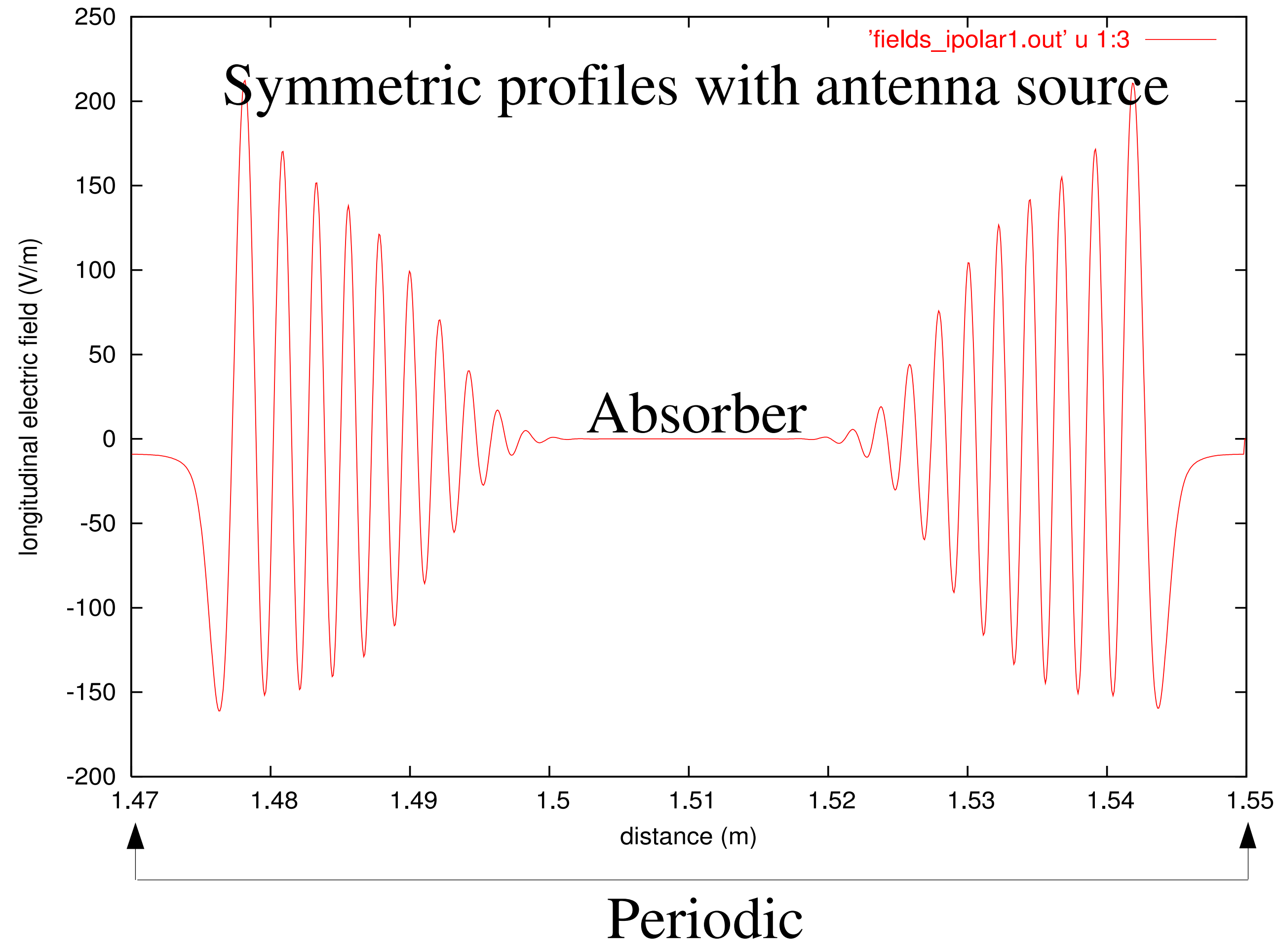


Surface Impedance from GLOSI (each *m*,*n*)



AORSA1D calculations at 28 GHz

- All orders code required for frequencies above 2nd harmonic at mode conversion layer



Boundary condition issues in AORSA1D

- Derivative boundary conditions are needed to calculate impedance match with beam in vacuum
- Original spectral algorithm solves for Fourier coefficients of electric fields in periodic basis set
  - Effectively specifies a periodic boundary condition
- Attempts to "trick" the boundary conditions have all failed so far… any suggestions?
- Obvious modification is to use convolution with finite differences for the curl curl operator
  - Tedious to implement and requires care with approximations

Work remaining

- REALIPOL
  - Add single polarization analysis to optimum polarization analysis that is now done with OPTIPOL
  - Calculate the reflection pattern for a realistic, high power launcher and compare with possible experiment?
  - Add AORSA1D interface once AORSA1D is ready
  - Make code available to NSTX researchers
- AORSA1D
  - Modify solution method to allow Neumann boundary conditions (required for OPTIPOL and REALIPOL)
  - Parallel coding in linux cluster environment

General Emission Analysis

(1) Input Gaussian beam parameters, location, and aiming angles, and read equilibrium from EQDSK (REALIPOL)

(2) Perform geometry analysis (REALIPOL)

  a) Track Gaussian beam axis to last closed flux surface and project Gaussian beam onto plasma

  b) Analyze equilibrium at beam intercept location to generate a slab model tangential to the location where beam strikes the plasma

(3) Mode conversion analysis (GLOSI, eventually AORSA1D)

  a) Combine density profile information with magnetic field results from geometry analysis to generate the plasma impedance matrix in a slab tangential to plasma at the beam strike point

(4) Find polarization giving maximum transmission in Fourier space (OPTIPOL)

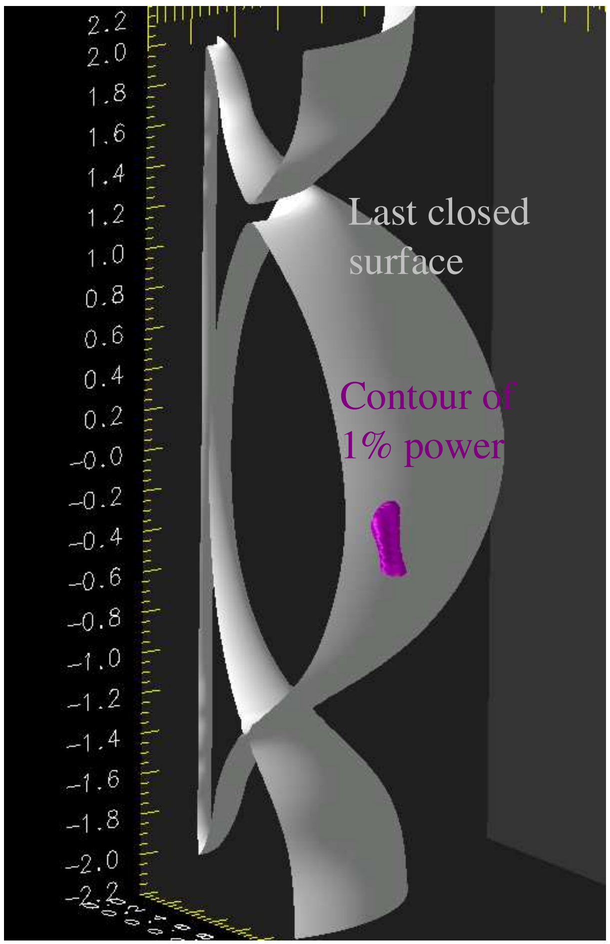
(5) Weight polarization by Fourier spectrum of beam projection on plasma surface to estimate average polarization at peak of emission (REALIPOL using OPTIPOL results)

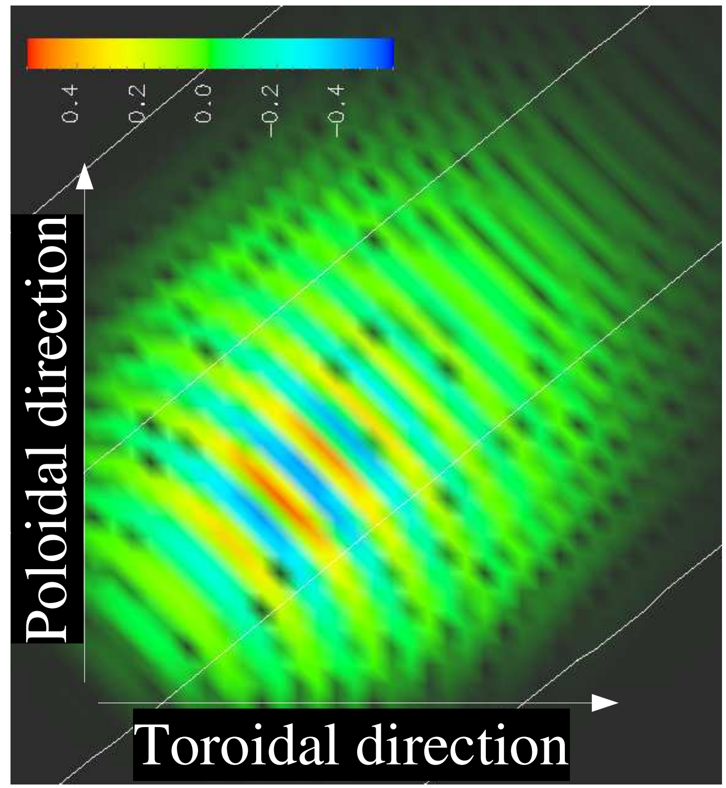
(6) Transform emission polarization from slab back to launcher (REALIPOL)

REALIPOL results at 16.5 GHz for NSTX shot 113544

- REALIPOL allows automated quantitative, analysis of antenna and plasma geometry
  - Launcher coordinates based on port and minimum beam waist coordinates, EQDSK g113544.00325
- Frequency below 2nd harmonic at mode conversion layer so GLOSI is valid
- Existing horn launch is oriented to be very close to the peak of transmission
  - Emission received should be mostly elliptically polarized, and nearly circular
  - Density profile variations cause a change in polarization of about 30 degrees

Experimental conditions project the beam nearly along field lines at the plasma surface for shot 113544

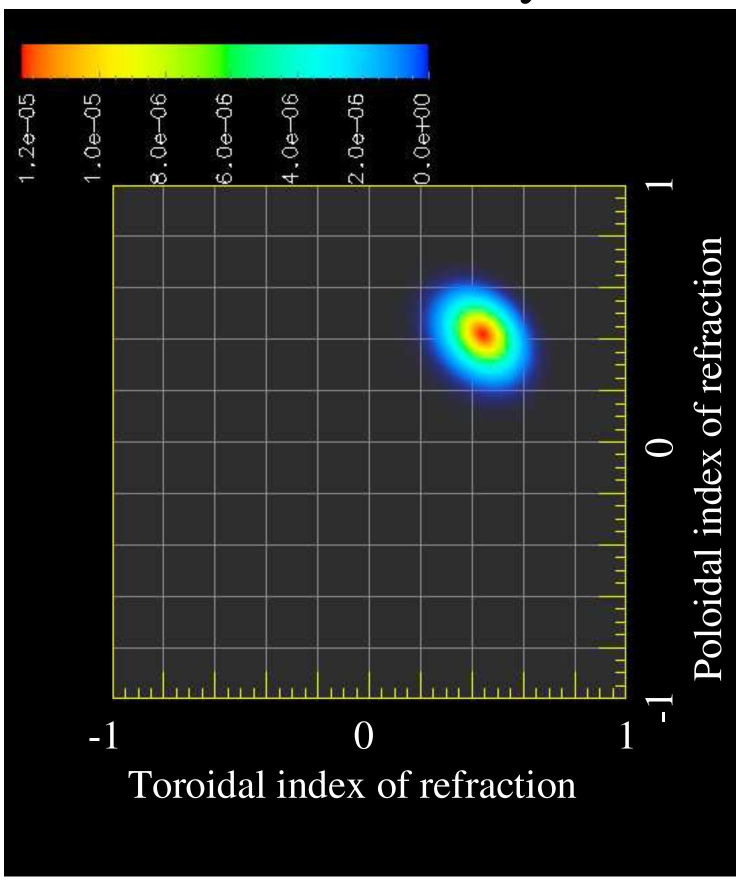




Beam projection on plasma surface
(real space, normal out of paper)

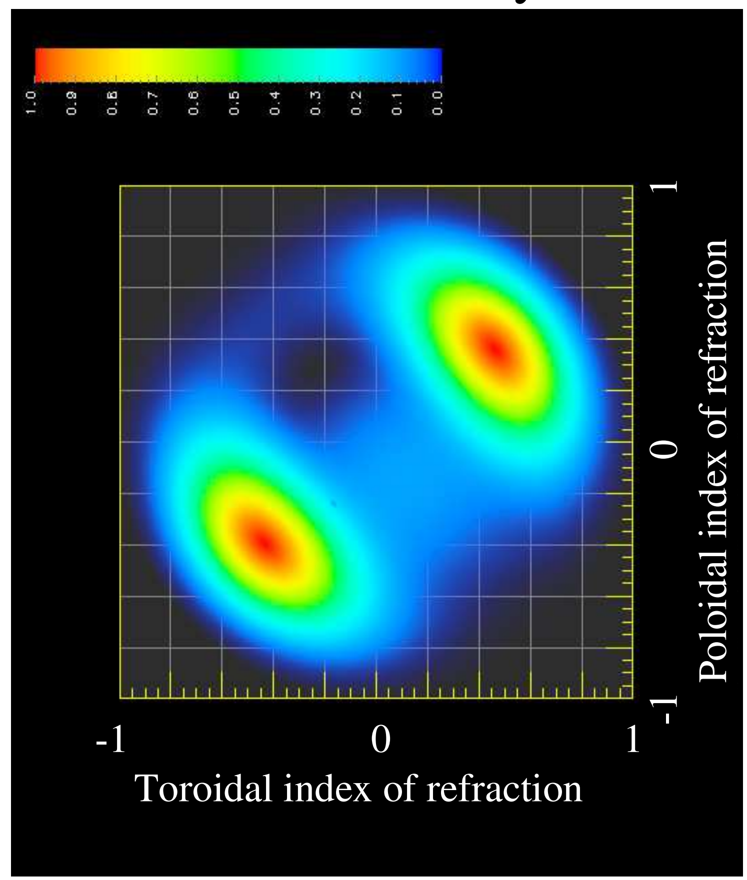
Fourier space for beam projection and maximum possible transmission

REALIPOL analysis



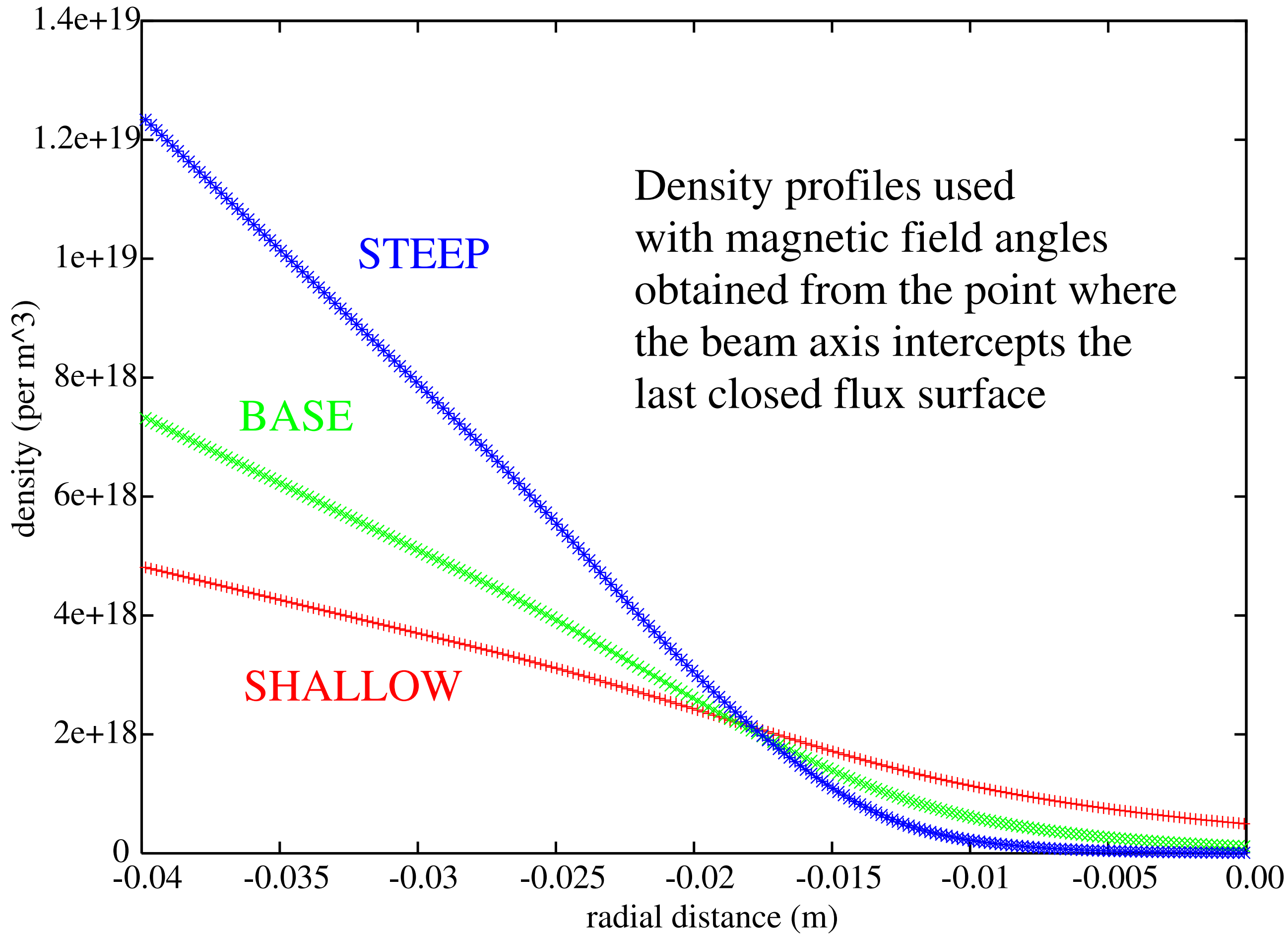
Beam projection in refractive index space

OPTIPOL analysis



Maximum obtainable transmission in refractive index space

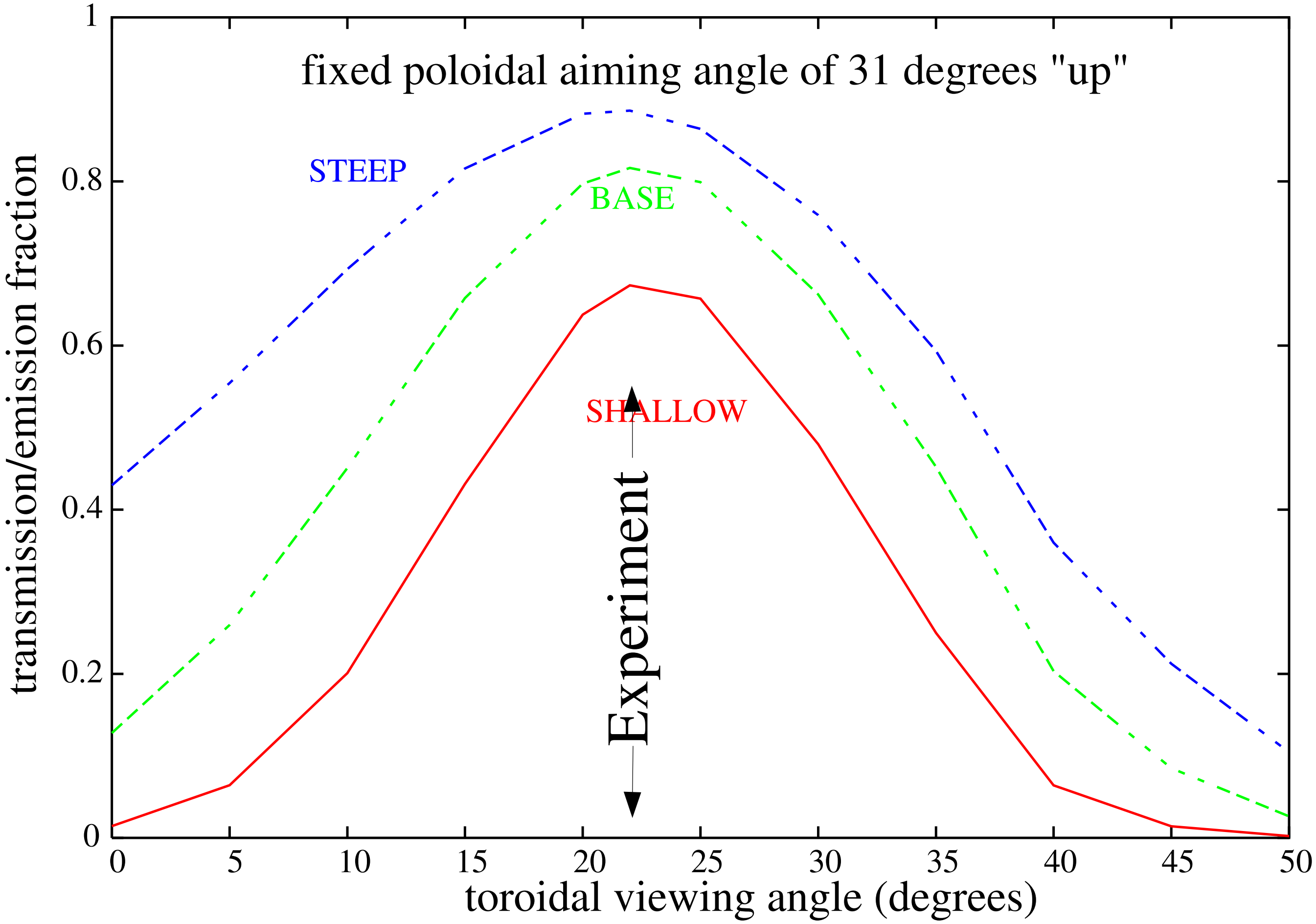
Density profiles significantly influence mode conversion, so a reasonable range was chosen for a sensitivity study



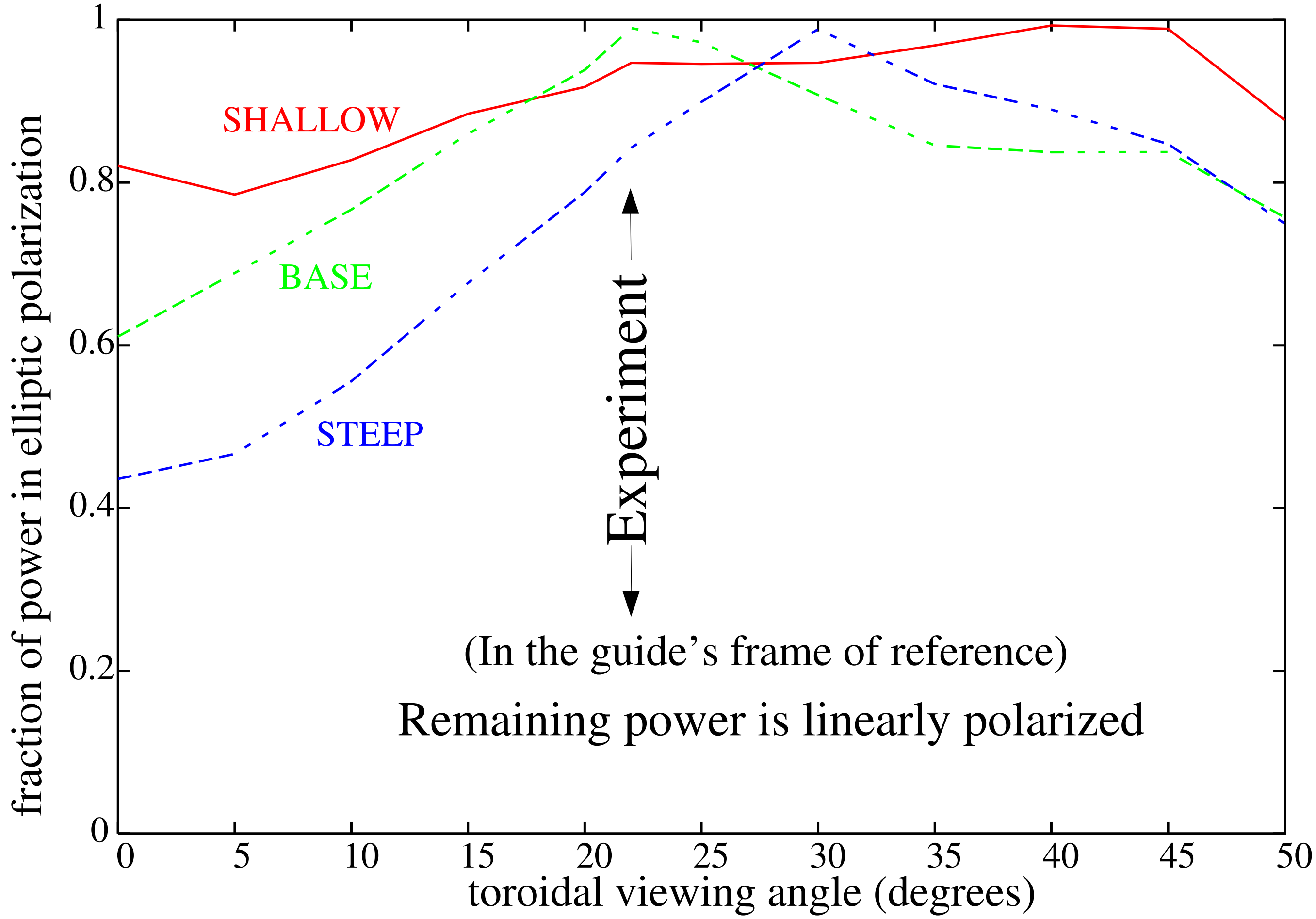
Toroidal aiming sensitivity

- To test REALIPOL, the beam aiming angle was swept toroidally from 0 to 50 degrees for a fixed poloidal angle of 31 degrees “up”
  - Actual experiments performed at 22 degrees
- Static magnetic field line angles at the point where the beam strikes the plasma are insensitive to aiming angle over the range studied (~1%)
  - Same 3 GLOSI impedance values, with field angles chosen from the experimental case were used for all aiming angles

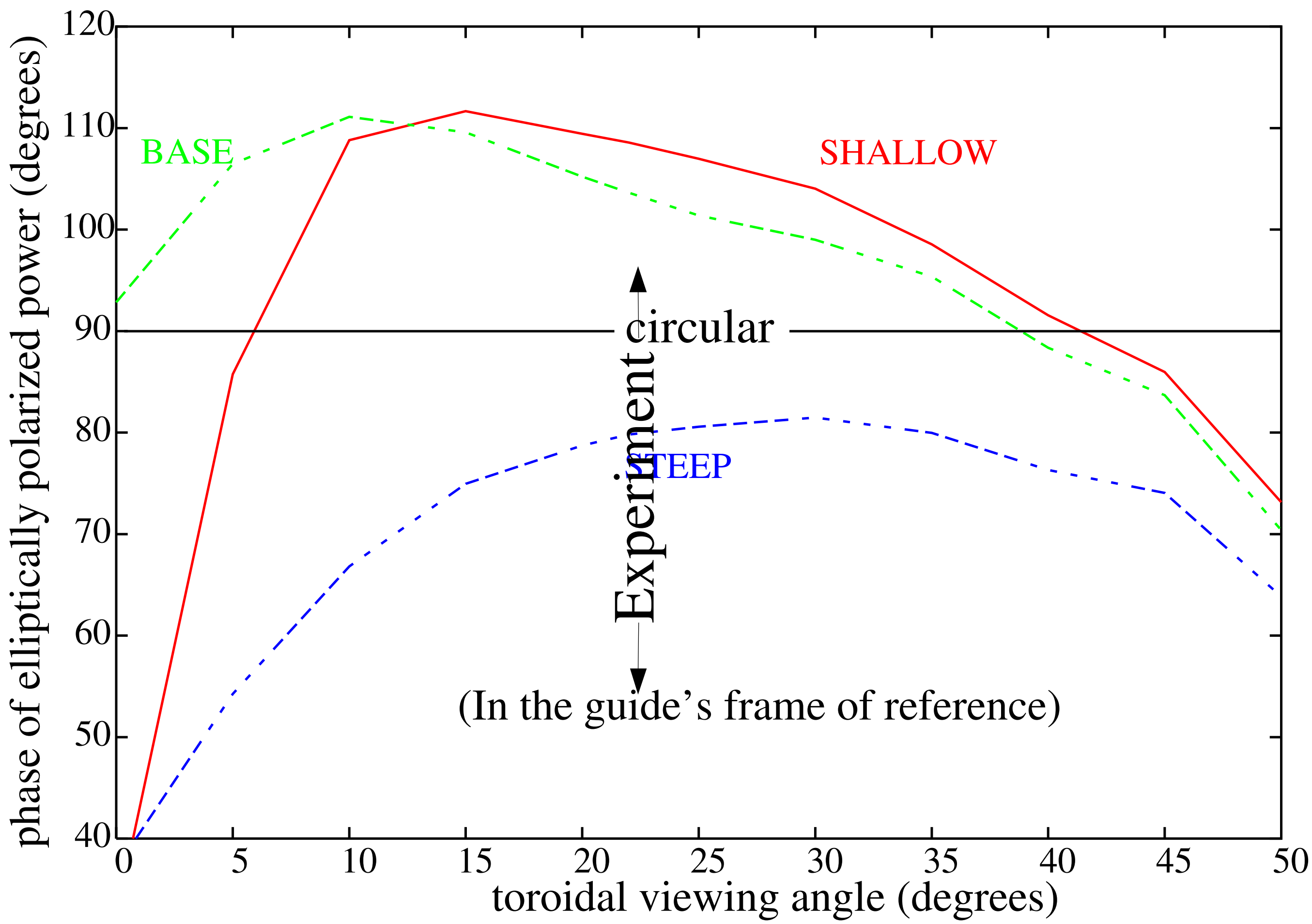
Experiment, at 22 degrees, is close to maximum transmission



At 22 degrees, polarization is mostly elliptical rather than linear



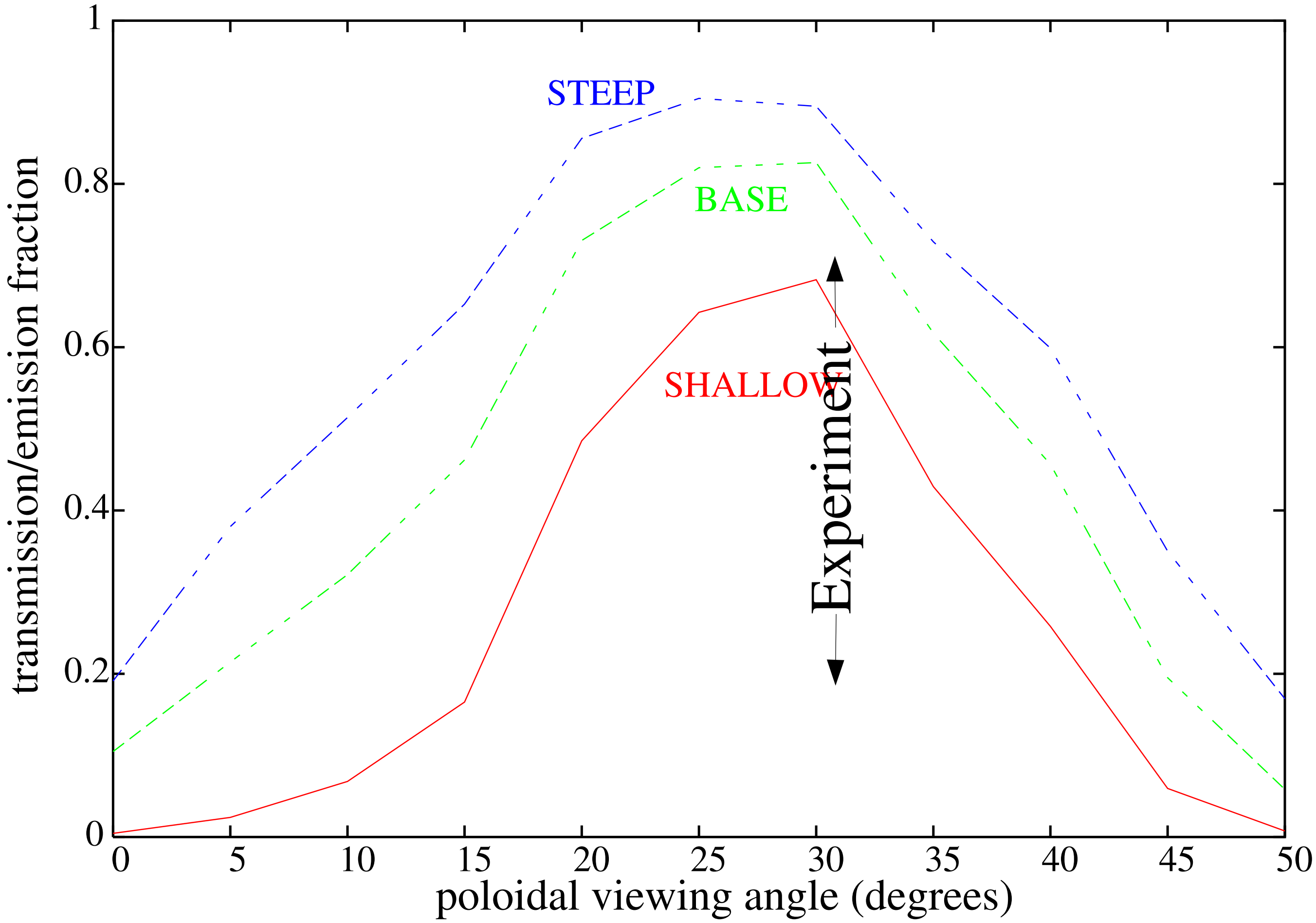
Polarization at launcher is nearly circular for experiment, but varies with density profile



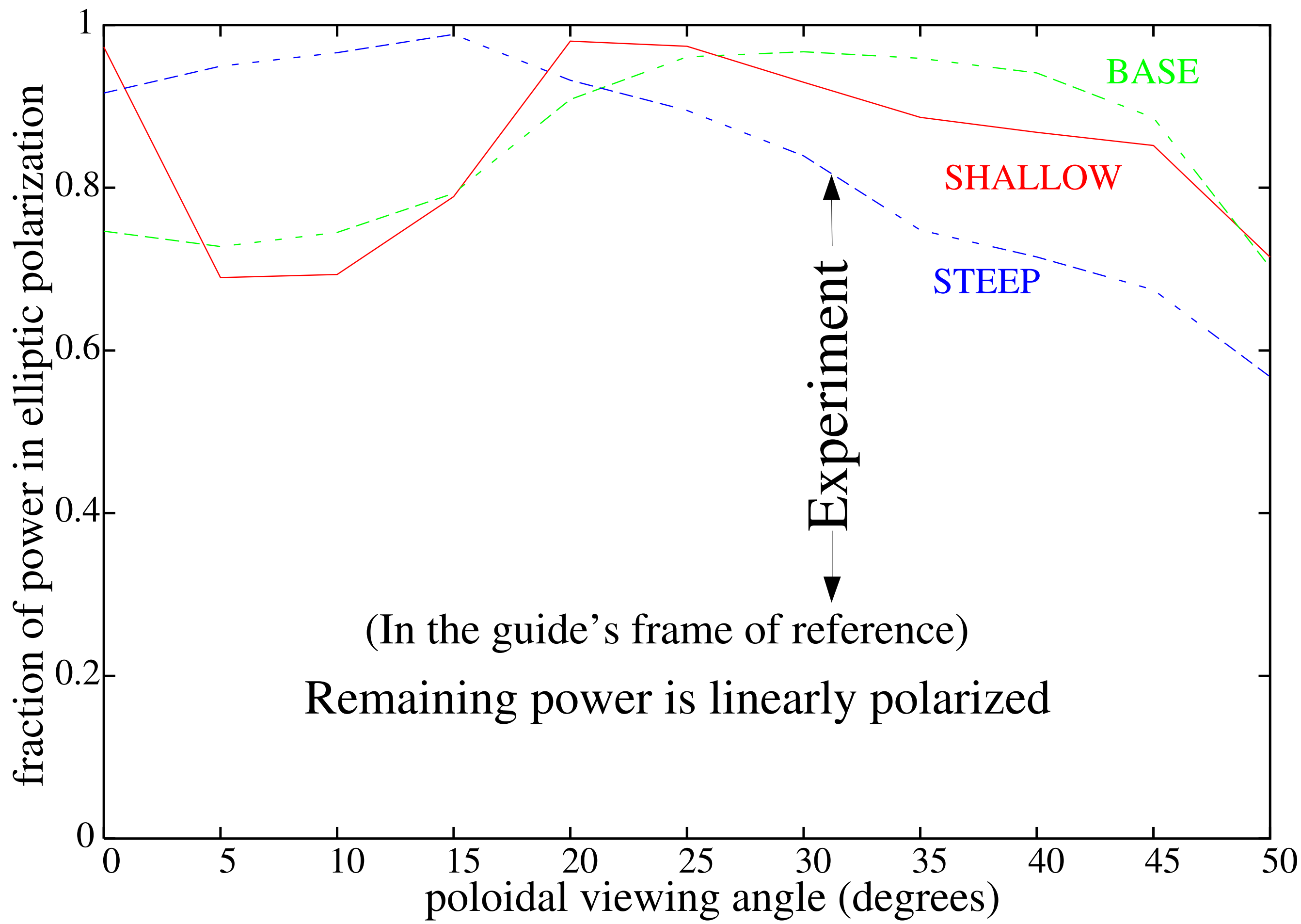
Poloidal aiming study

- For further testing, the beam aiming angle was swept poloidally from 0 to 50 degrees for a fixed toroidal aiming angle of 22 degrees
- Static magnetic field angle changes at the strike point are larger than for the toroidal sweep, but still not more than 5%.
  - For simplification, use the same 3 GLOSI impedance cases as used for toroidal scan

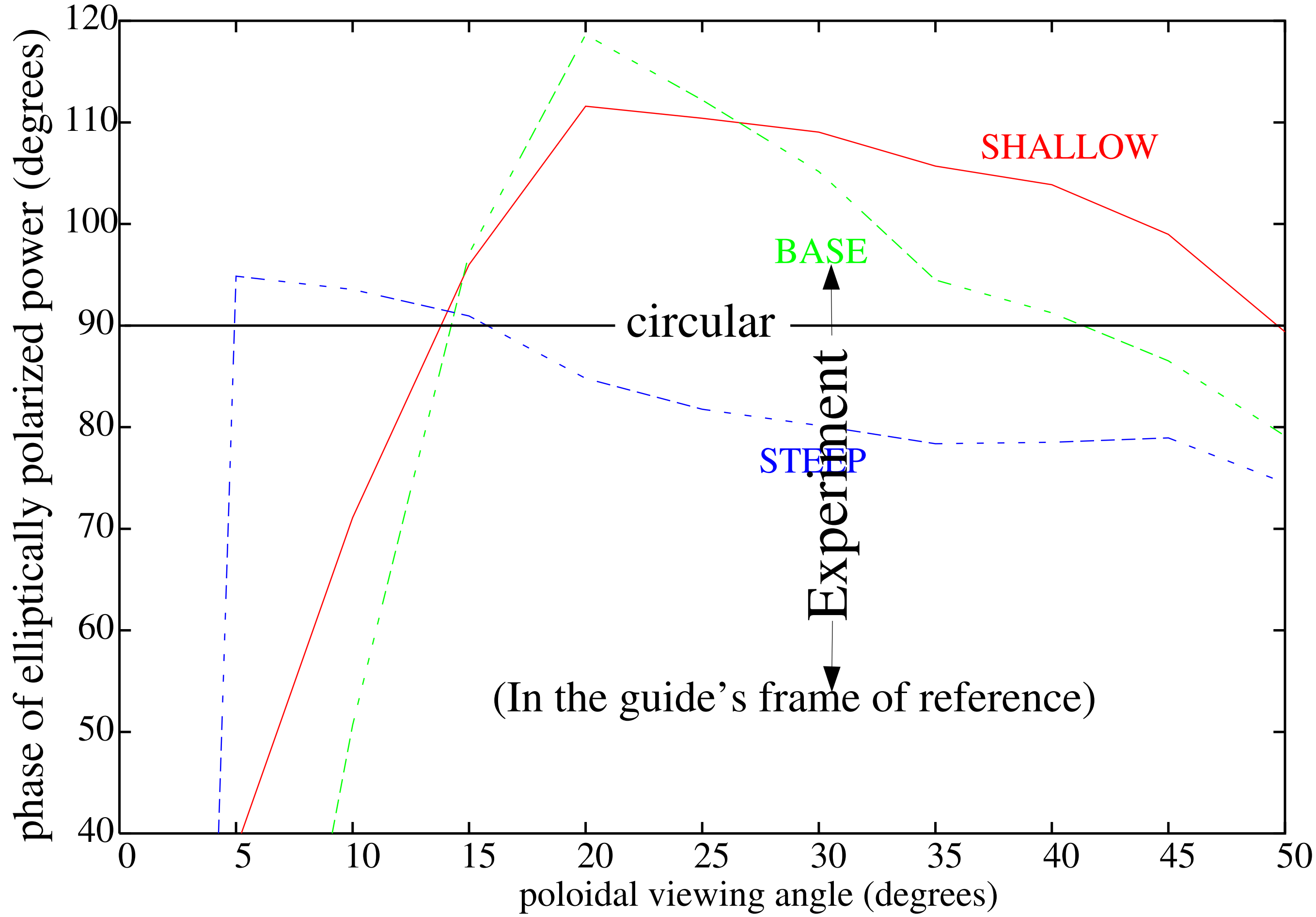
Poloidal aiming at 31 degrees "up" in experiment is near maximum



Fraction of power identifed with elliptic polarization depends on profile



Elliptic angle is nearly circular



Physics Conclusions

- Polarization is nearly circular for the experimental case, but phase depends weakly on density profile
- In scans, O-X-B looks best for NSTX, especially if the density gradient is “shallow”
- Aiming and polarization angles are very important for interpreting transmission
- Poloidal aiming seems more sensitive than toroidal because of rapid mis-alignment of the beam with emission along field lines

Numerical Conclusions

- REALIPOL/OPTIPOL/GLOSI analysis tools are ready for transmission and emission analysis when the frequency at the mode conversion layer is below twice the electron cyclotron frequency
- It would be straightforward to extend REALIPOL to calculate the reflection of a launched microwave beam from the plasma
  - Suggests an alternative experiment for low-power launch
- AORSA1D can solve for high-harmonic EBWs but a different solution algorithm must be implemented to satisfy the required boundary conditions
  - The modular nature of the code should allow AORSA1D results to be integrated easily into REALIPOL/OPTIPOL when available