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NSTX

Electron Bernstein Wave Coupling and Emission Measurements on NSTX

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Abstract

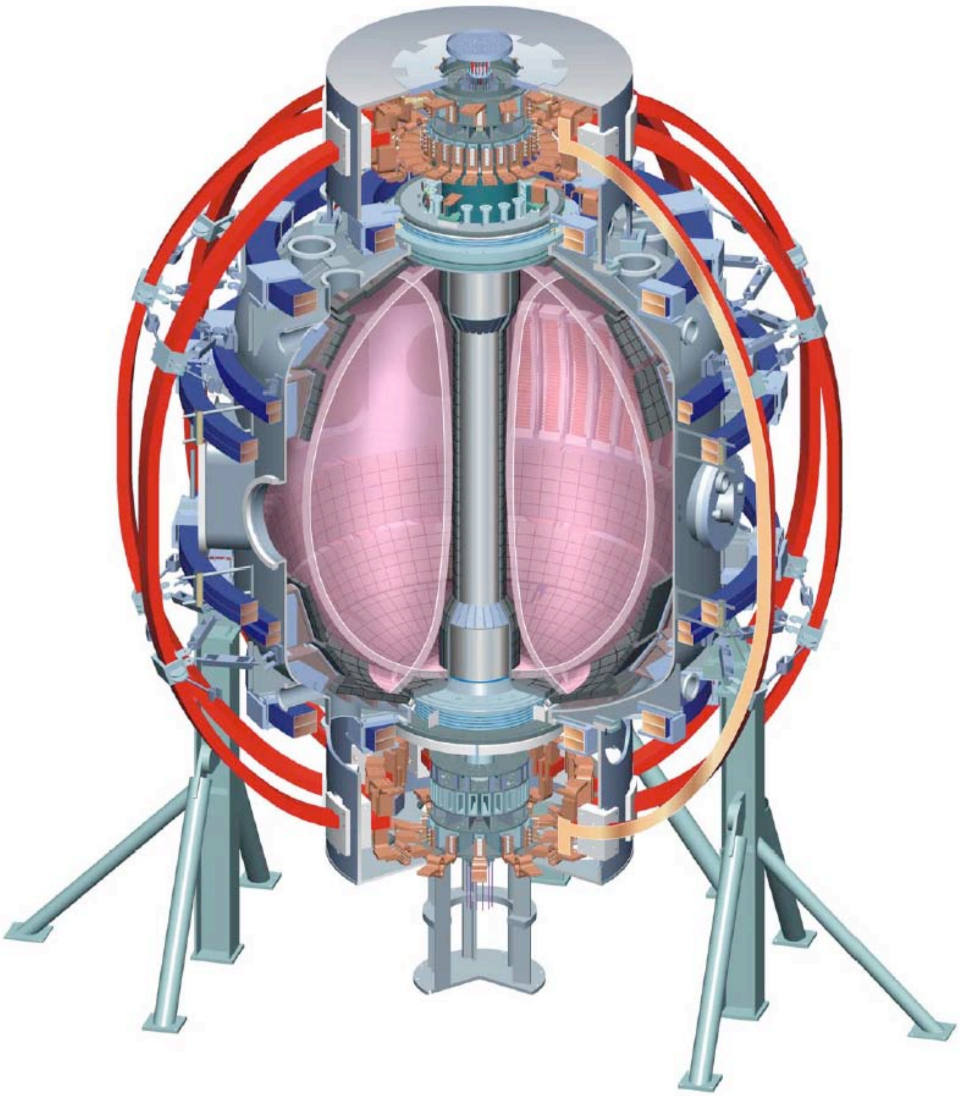
Electron Bernstein waves (EBWs) offer the potential for $T_e(R,t)$ measurements and local current drive in overdense NSTX plasmas. However, these applications require resilient and efficient coupling between EBWs and electromagnetic waves outside the plasma. Two new remotely steered, obliquely viewing, quad-ridged horn antennas connected to absolutely calibrated dual-channel radiometers have simultaneously measured 8-18 GHz (fundamental) and 18-40 GHz (second and third harmonic) B-X-O emission. Emission data combined with EBW ray-tracing and Thomson scattering $T_e(R,t)$ data allow the EBW coupling efficiency to be calculated. The EBW coupling efficiency and emission polarization have been mapped as a function of poloidal and toroidal angles for L- and H-mode plasmas and the results are compared to theoretical predictions. Coupling efficiencies of 50-100% have been measured in L-mode discharges while much lower values have been measured in H-mode discharges.

* *This work is supported by USDOE contract DE-AC02-76CH03073 and a grant to encourage innovations in fusion diagnostic systems.*

Outline

- Motivation for electron Bernstein wave (EBW) emission measurements on NSTX
- EBW-Extraordinary-Ordinary (B-X-O) mode conversion description
- EBW emission diagnostic overview
- EBW emission measurements
- Future work

Major NSTX Research Goal to Sustain β>20% Without Using Central Solenoid



R	0.85 m
a	0.68 m
I_p	~ 1 MA
B_t	0.3 - 0.6 T
$T_e(0)$	~ 1 keV
$n_e(0)$	0.2-1x10^{20} m^{-3}

- *Maximum β ~ 40%*

Modeling Predicts EBW Can Provide Needed Current for Non-Inductive Scenarios

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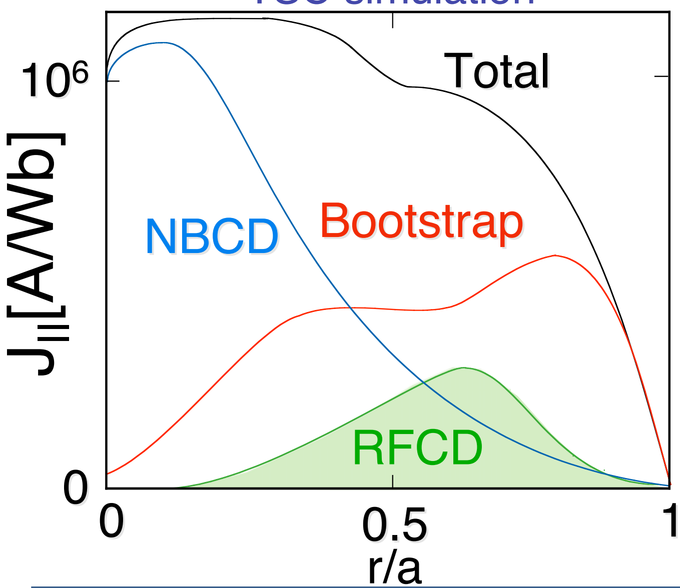
- EBW must provide ~100 kA of off-axis current
- Possible across wide range of β at both f_{ce} & $2f_{ce}$

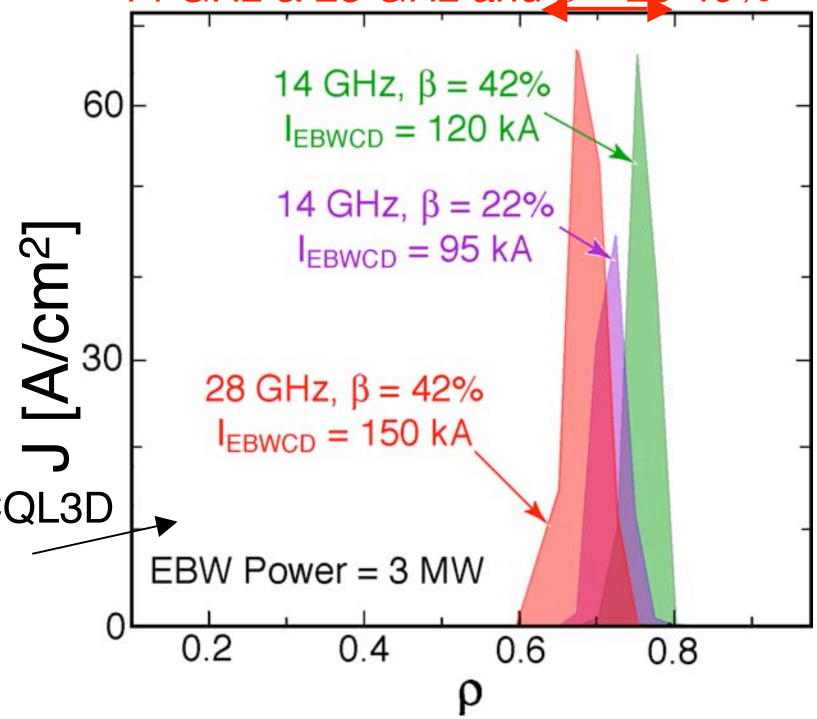
NSTX, β_t = 42%, β_{pol} = 1.6
B_t = 0.34 T , I_p = 1 MA

TSC simulation



GENRAY/CQL3D Modeling

Deposition similar for 14 GHz & 28 GHz and β = 20-40%



C. Kessel, et al ., Nucl. Fusion ***45****, 814 (2005)*

G. Taylor, et al ., Phys. Plasmas ***11****, 4733 (2004)*

Need efficient coupling of RF power to EBWs; assess oblique O-X-B coupling by measuring B-X-O emission (EBE)

EBW Background

EBWs Can Propagate in Overdense Plasmas

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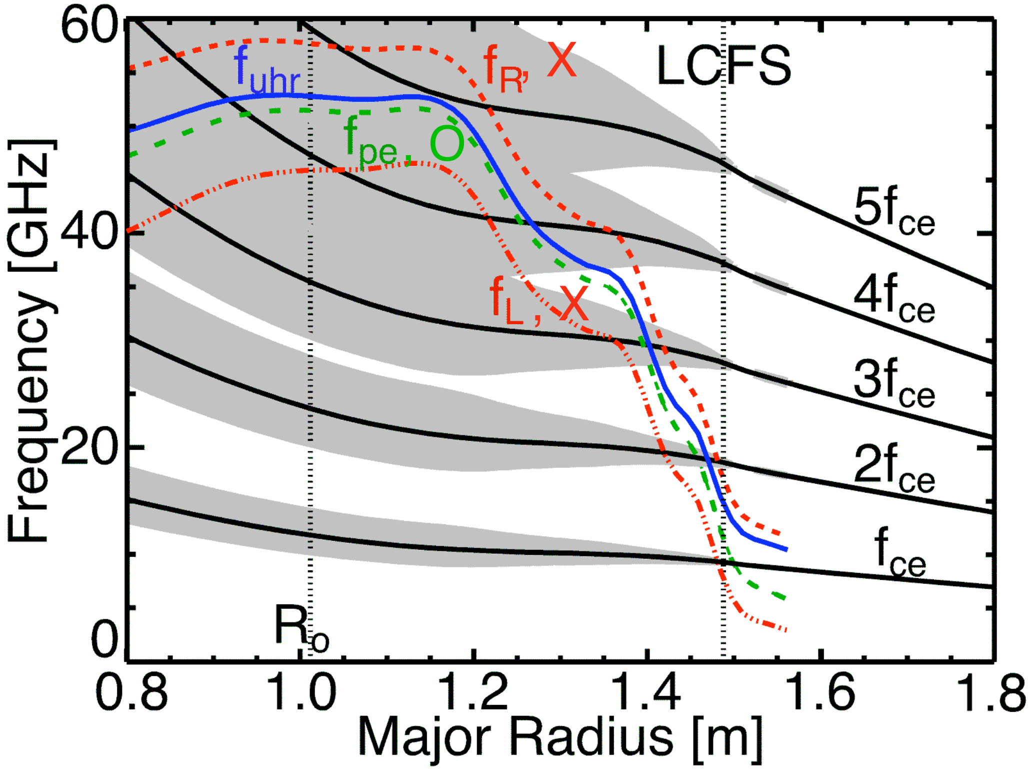
- Electromagnetic waves cutoff in overdense plasmas
- NSTX has low magnetic fields (< 0.6 T) and high n_e (1-5x19 m^{-3}), cutting off up to first 6 EC harmonics
  - EBWs are strongly absorbed/emitted from EC harmonics
- Coupling to EBW is a challenge because wave cannot propagate in vacuum



EBW emission data can be used to provide coupling efficiency and polarization information for heating and current drive system

EBW Coupling to Electromagnetic Waves

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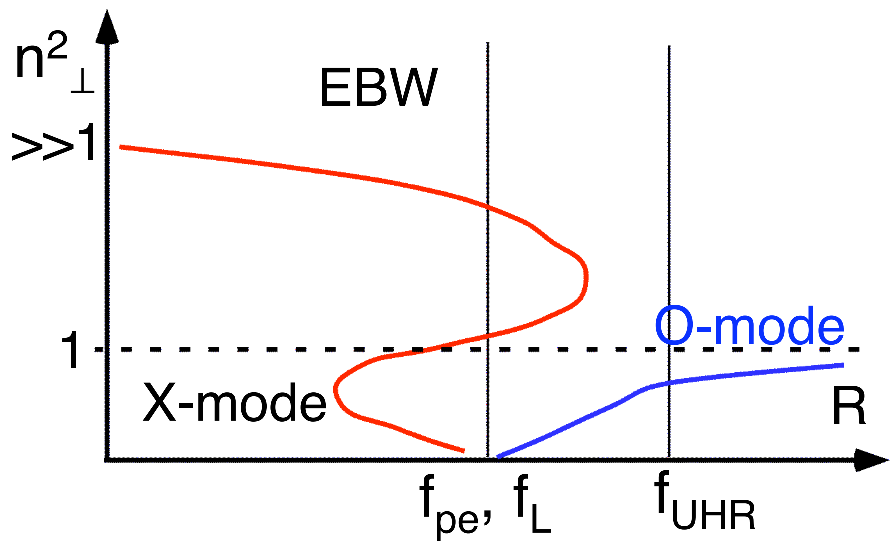
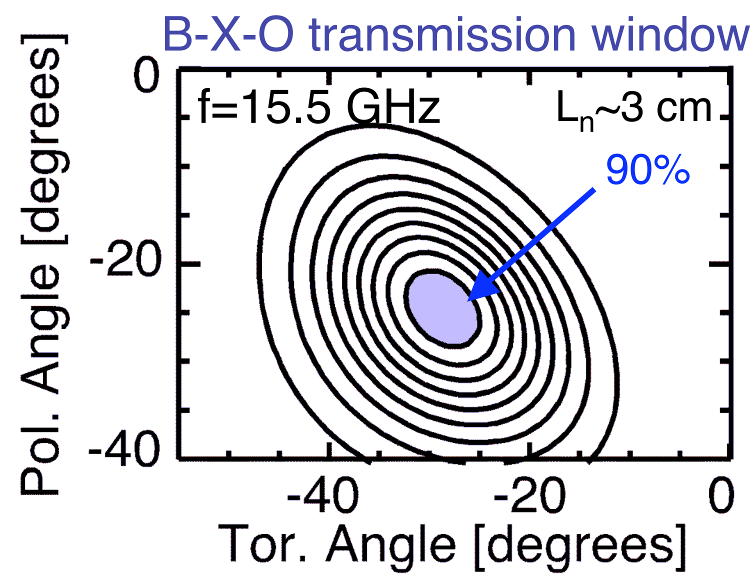


- EBW emitted at EC harmonic converts to the X-mode at the UHR and then O-mode
- Emission will be elliptically polarized (~1.6) due to oblique view of plasma



- B-X-O transmission window depends on:
  - Magnetic field pitch (~30-45% in NSTX)
    - determines location of window
  - Density scale length
    - determines width of window

~ 80% B-X-O Coupling in L-Mode Edge Plasmas, Consistent with EBE Simulation

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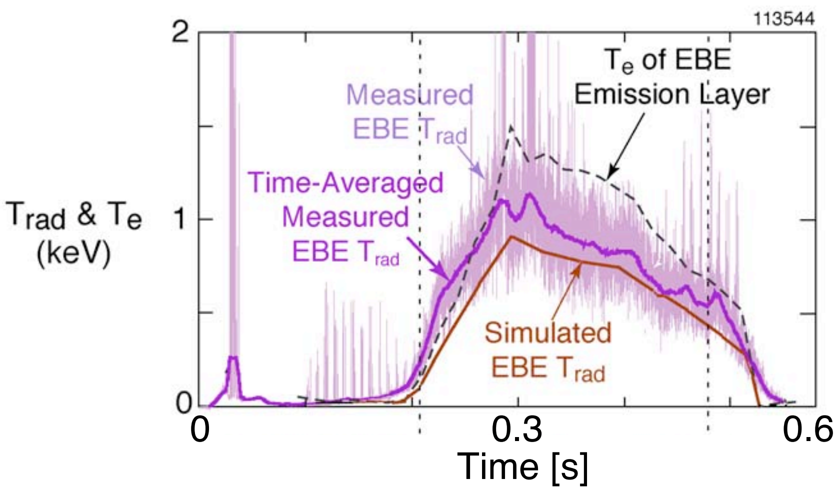
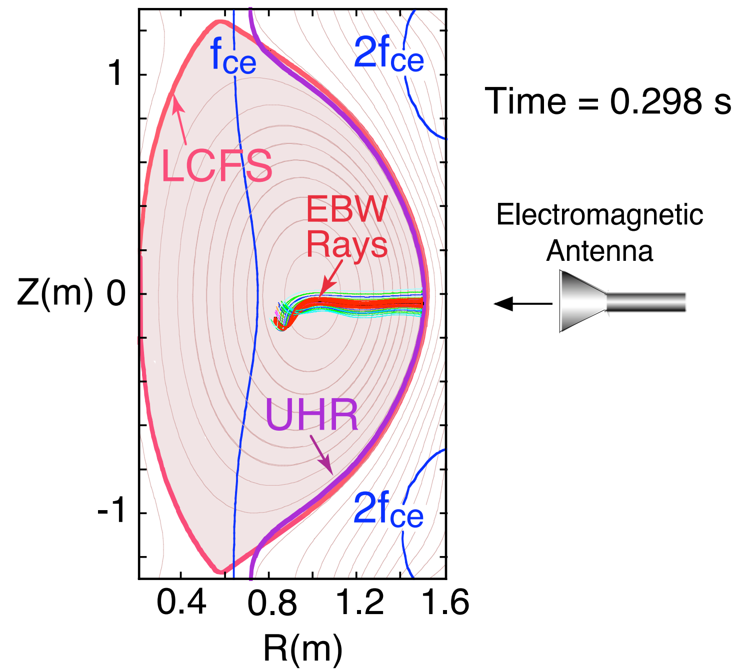
- 2004 L-mode data used fixed 8-18 GHz quad-ridged antenna to study B-X-O emission
  - Quad-ridged antenna measures orthogonally polarized emission

Frequency = 16.5 GHz, $B_t(0)$ = 4 kG





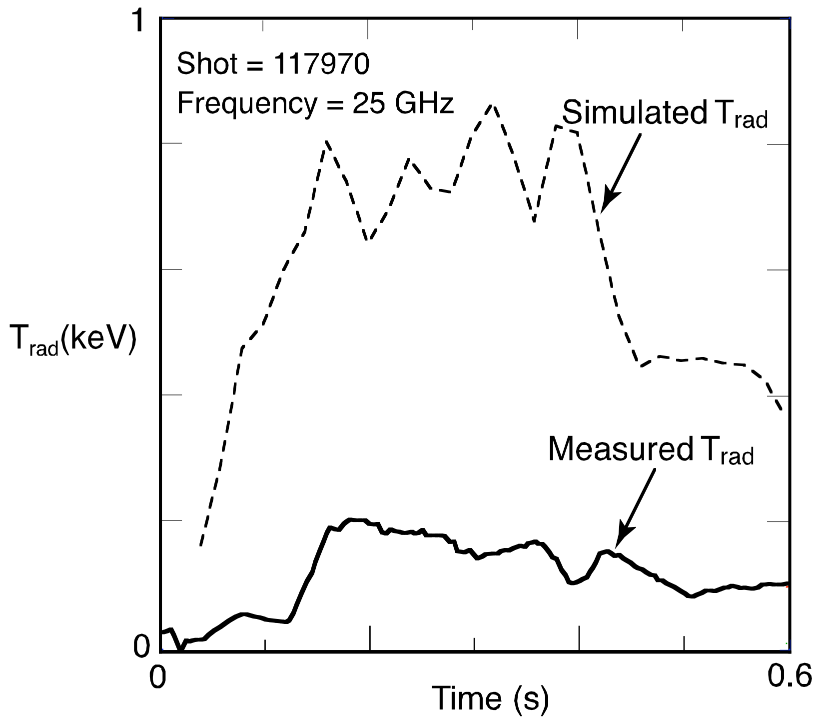
G. Taylor et al., Phys. Plasmas ***12****, 052511 (2005)*
J. Preinhaelter et al., AIP Proc. ***787****, 349 (2005)*

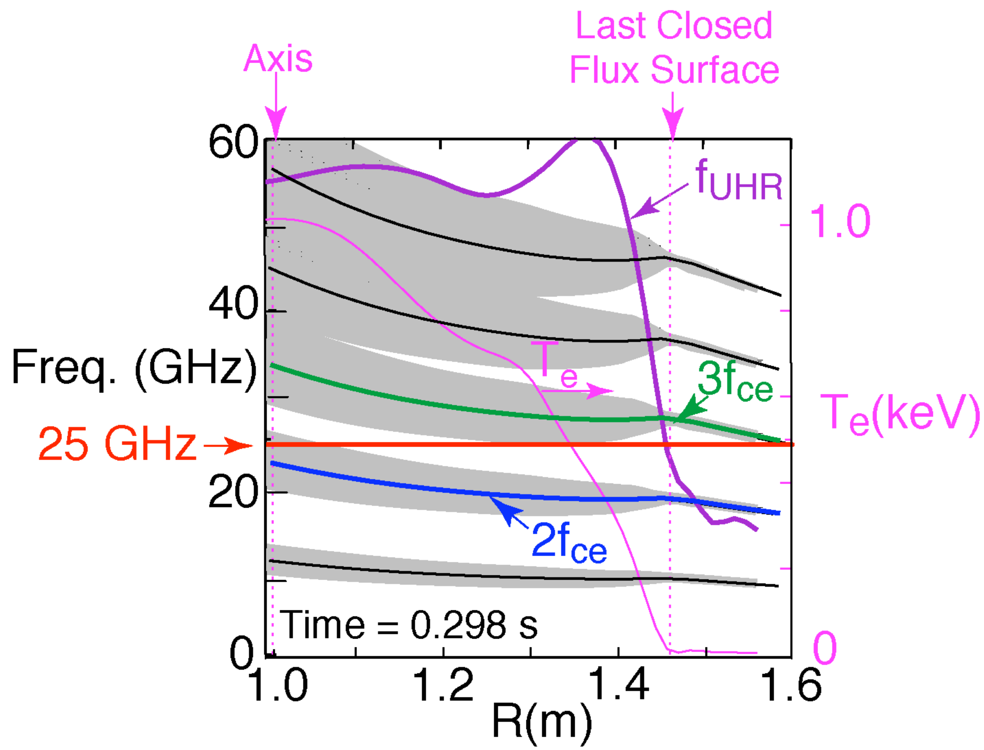
- EBW ray tracing & mode conversion model uses EFIT magnetic equilibrium & measured T_e & n_e

Large Disagreement Between Measured $2f_{ce}$ B-X-O T_{rad} & Simulated T_{rad} in H-Mode

NSTX

- 2005 H-mode data used fixed 18-40 GHz quad-ridged antenna to study B-X-O emission



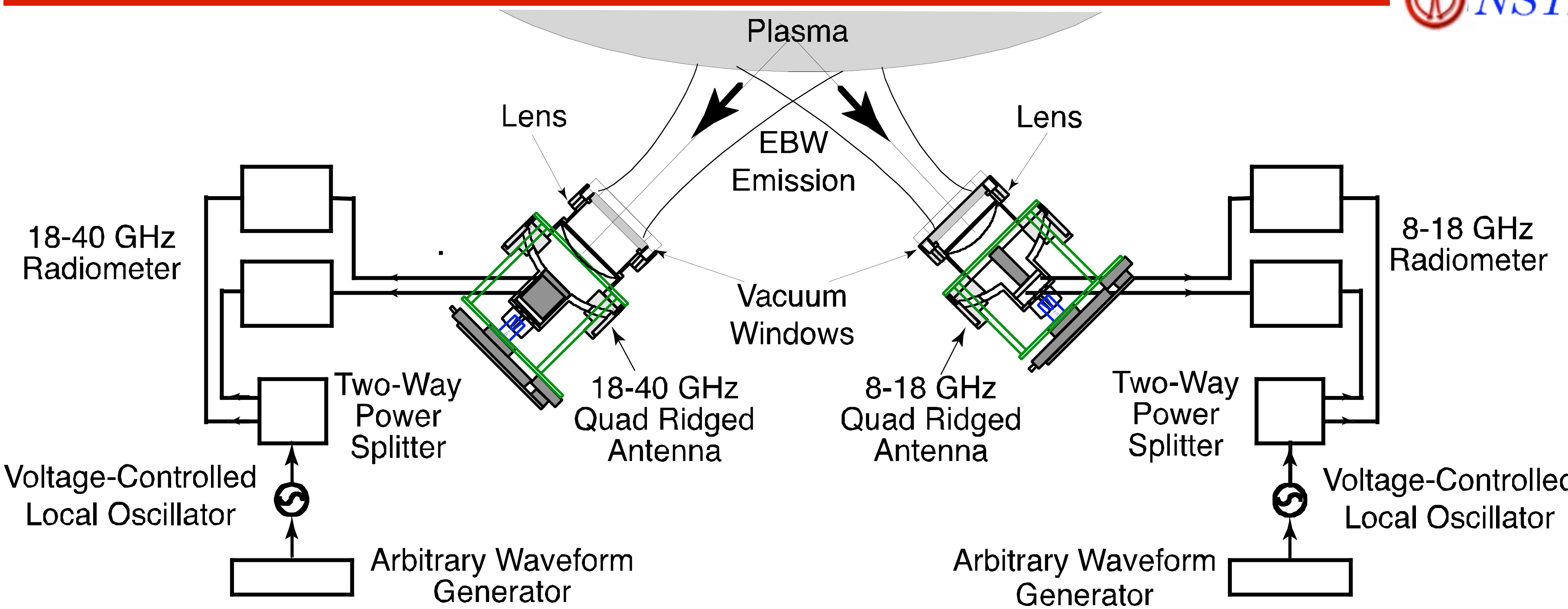


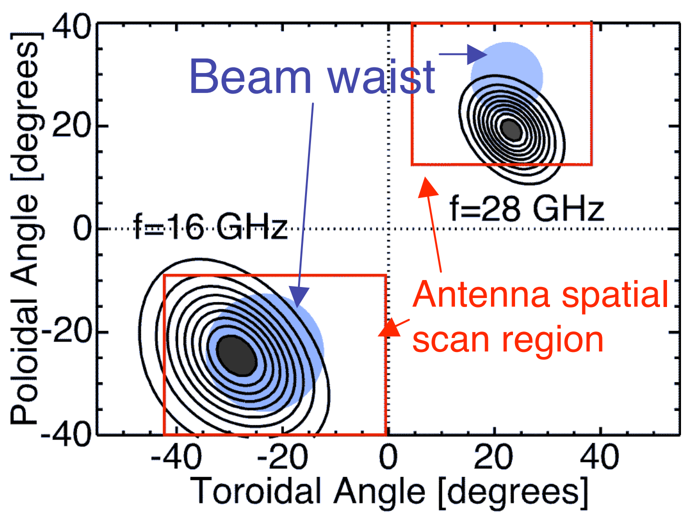
- Discrepancy between simulated and measured T_{rad} requires thorough investigation of B-X-O coupling window

Upgraded diagnostic allows investigation of wide range of frequencies and mapping of B-X-O coupling window to support EBWCD system

Diagnostic Description

Remotely Steered EBE Diagnostic Allows Spatial Mapping of Emission Window



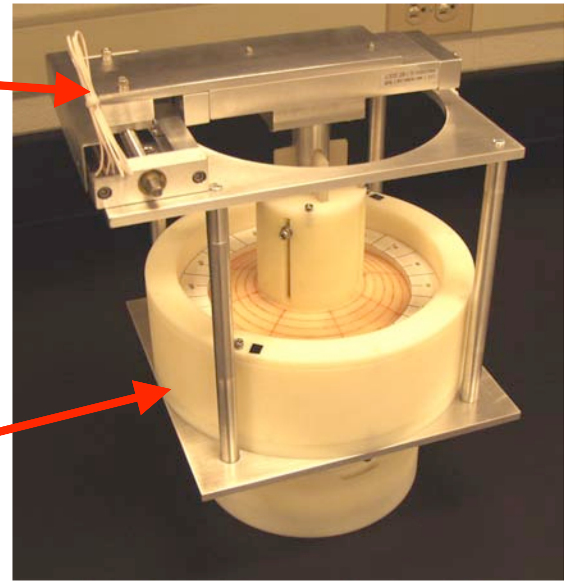


- ±10° scan in poloidal and toroidal directions during L-mode and H-mode EBE experiments
- Acceptance angle:
  - 8-18 GHz antenna ~ 22°
  - 18-40 GHz antenna ~ 14°

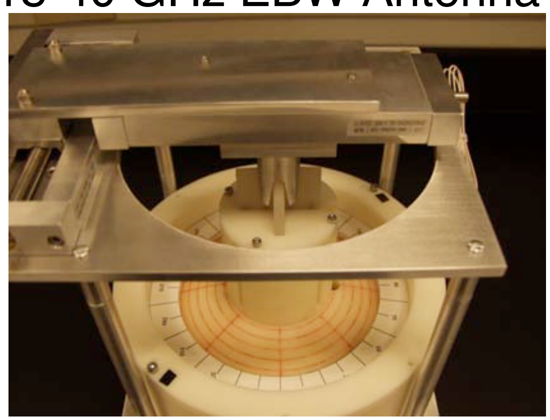
Linear Actuators Allow ± 10° Poloidal & Toroidal Steering

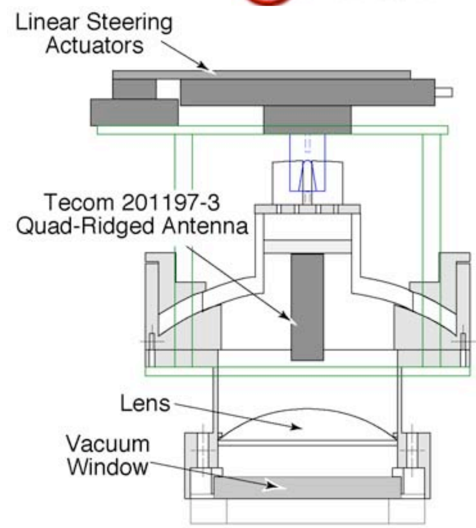
- Two drives provide motion in poloidal and toroidal direction
- Nylon housing allows for steering
- Antennas located outside vacuum vessel ~ 50 cm from plasma edge

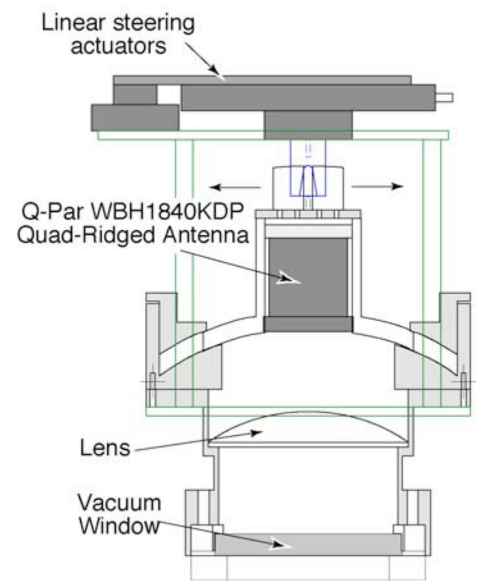
8-18 GHz EBW Antenna



18-40 GHz EBW Antenna

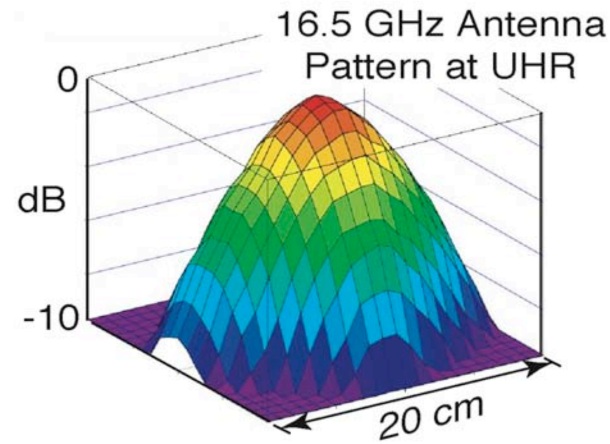




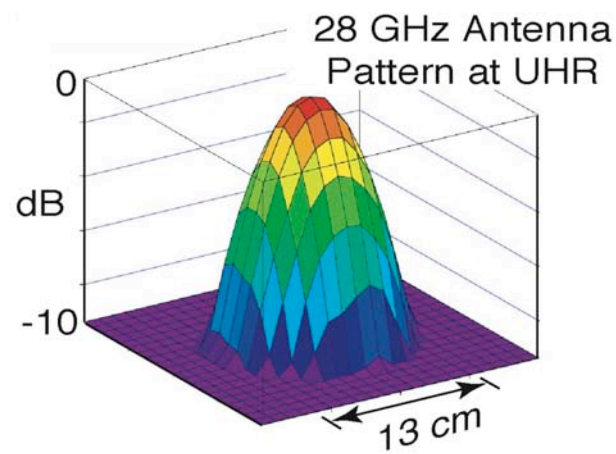


Lens Optimization Provides Minimal Beam Waist

- 8-18 GHz antenna
  - 20 cm focal length lens provides beam waist of 10 cm at plasma edge (50 cm in front of the antenna) for 16.5 GHz
  - Focal length ~10 cm for microwaves



- 18-40 GHz antenna
  - 25 cm focal length lens provides beam waist of 6.5 cm at plasma edge for 28 GHz
  - Focal length ~12.5 cm for microwaves



Allows for localized measurements

Dicke Switching Method Provides Absolute Calibration

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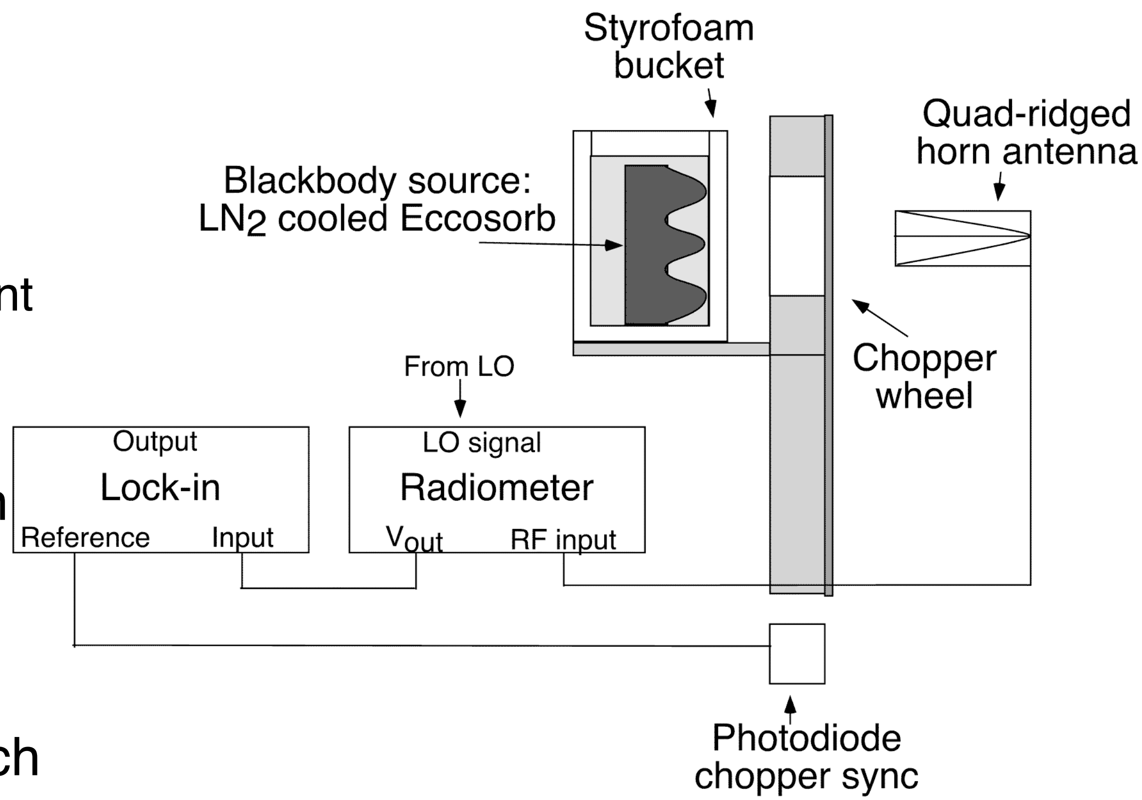
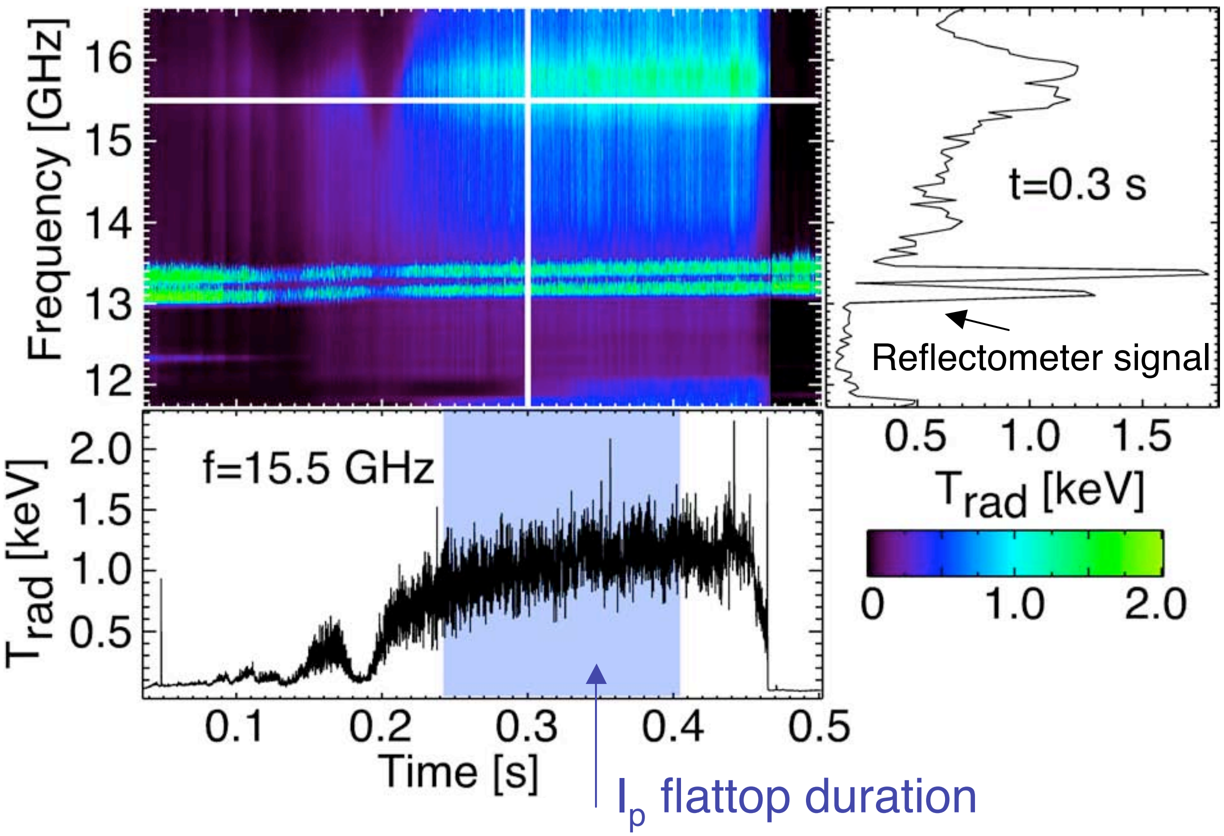
- Antenna assembly viewed blackbody source (LN_2 cooled Eccosorb) through chopper wheel
- Blackbody emission signal from antenna fed into radiometer tuned to a particular frequency
- Radiometer yields an output voltage proportional to input intensity
  - $V_{out}=G(f)T_{rad}$
  - G(f) is a frequency dependent gain factor (V/eV)
- All vacuum windows, lenses, antennas, and cables used in the experiment included in calibrations
- Statistical error 10-20%; systematic errors can be much larger

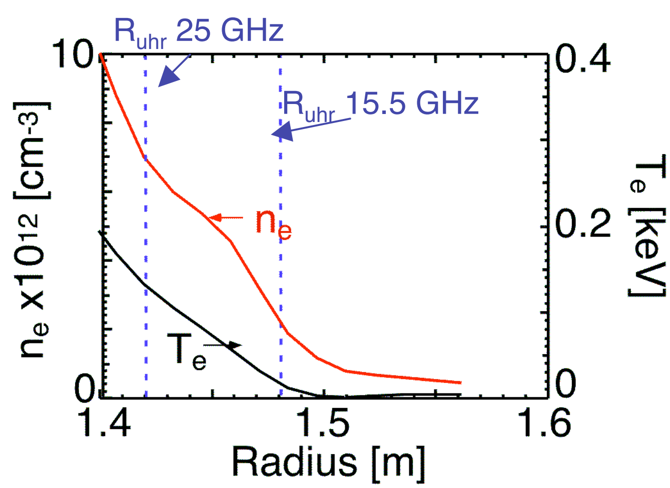


Experimental Measurements

Strong f_{ce} Emission Observed During L-Mode Scan

- L-mode helium discharge with I_p=800 kA and $T_e(0)$=1.6 keV
- L_n~3.5 cm for 15.5 GHz and L_n~ 5.5 cm for 25 GHz (from reflectometer)





Antenna Steering Scan Provides Good Coverage of L-Mode B-X-O Emission Window

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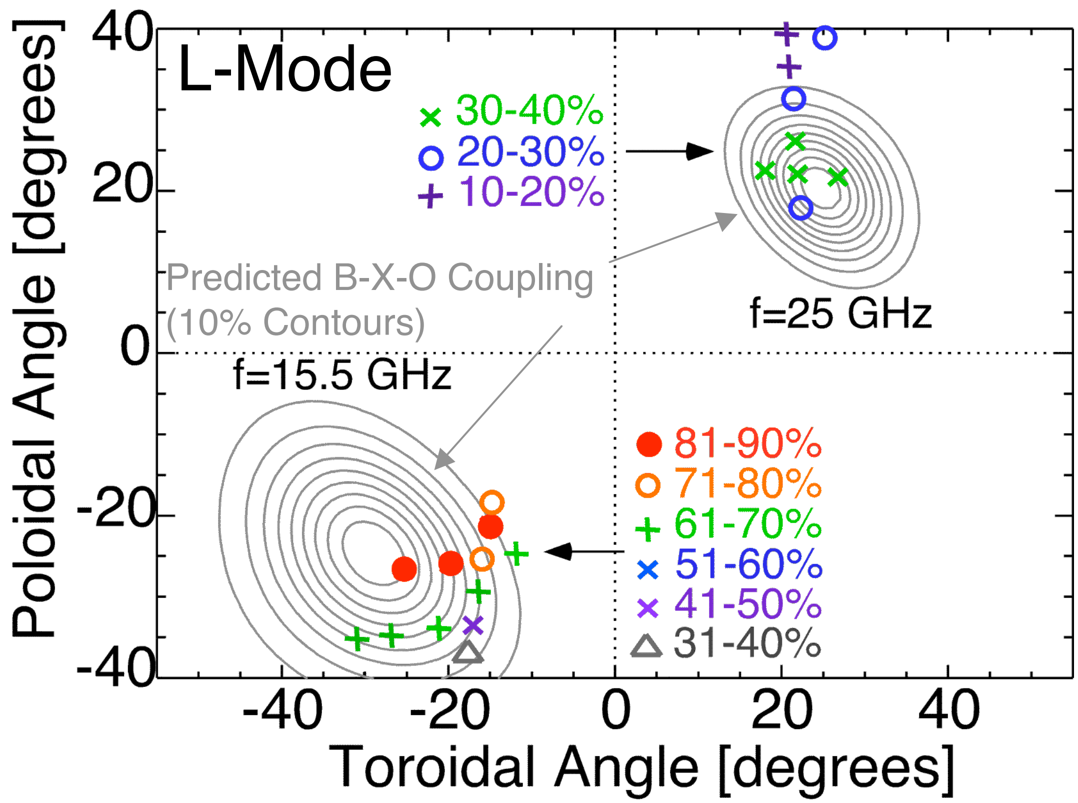
- To calculate B-X-O coupling efficiency:
  - Ray damping location obtained from GENRAY
  - Compare T_e from Thomson at ray damping to T_{rad} from EBE diagnostic
- L_n (edge density gradient) determined from reflectometer
- Magnetic field pitch ~ 40% ; determined from EFIT



Edge information scarce; may account for discrepancy between experimental and calculated B-X-O coupling map

L-Mode f_{ce} B-X-O Coupling Measurements Agree with to Simulated Results

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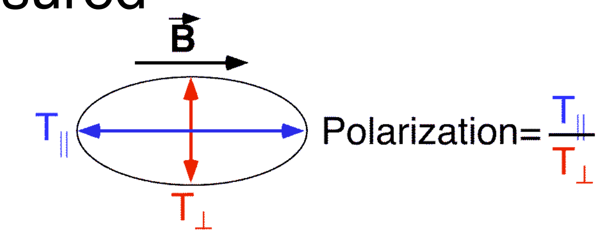
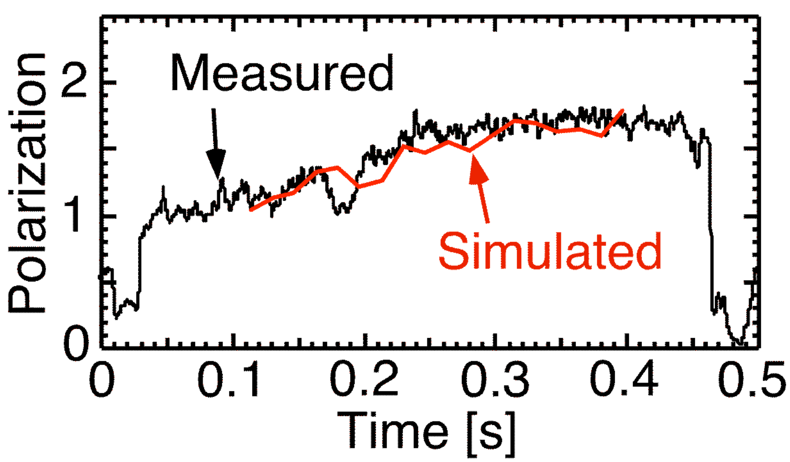
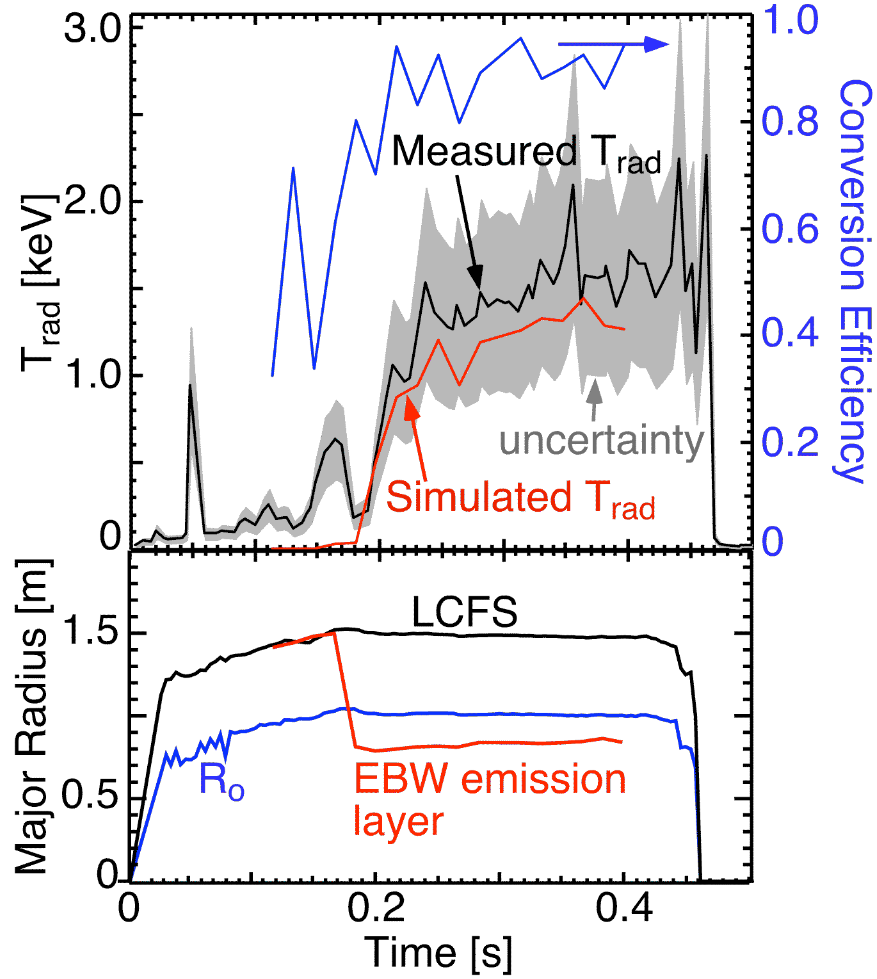
- Simulated results from EBW ray tracing & mode conversion model
  - Inputs are EFIT magnetic equilibrium, measured T_e & n_e
- EBW $T_{||}/T_{\perp}$=1.6-1.7 for peak emission angle for simulated and measured







L-Mode $2f_{ce}$ Measured T_{rad} Significantly Lower Than Simulated T_{rad}

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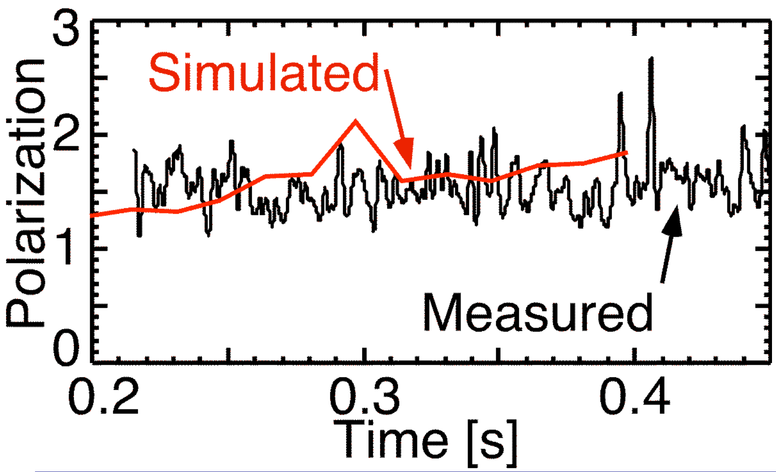
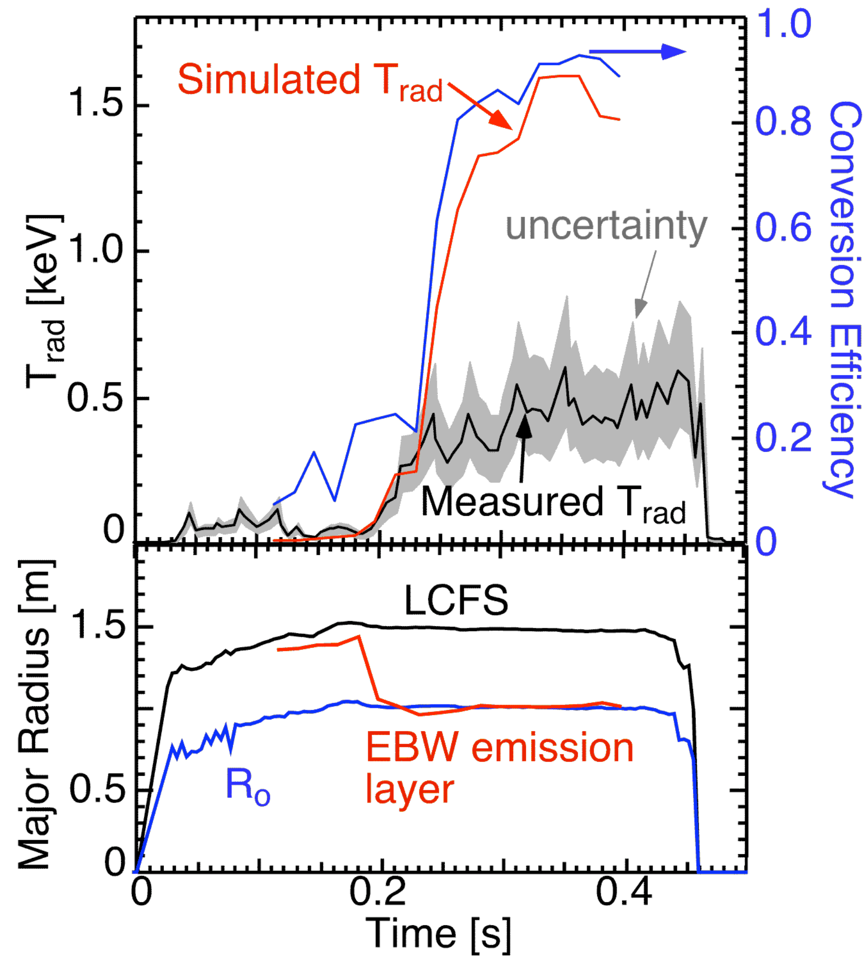
- Experimental B-X-O coupling efficiency ~30-40%; simulated B-X-O coupling ~90%

- EBW $T_{||}/T_{\perp}$=1.6 for both experimental measurements and simulated results

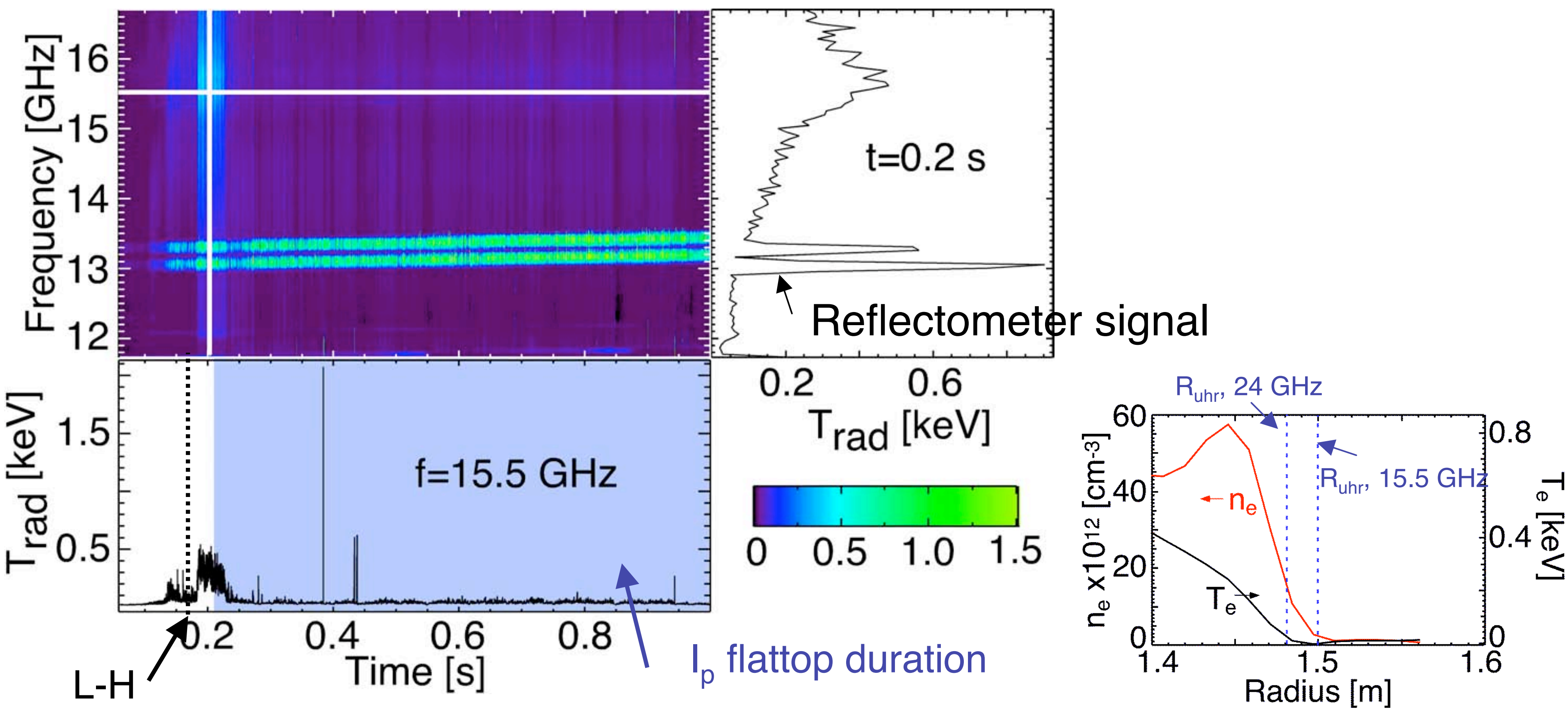




Edge information scarce; may account for discrepancy between experimental and calculated B-X-O coupling map

Scan of H-Mode B-X-O Window Indicates Very Low Emission Levels

- H-mode discharge with I_p=1 MA and $T_e(0)$=1 keV
- L_n~4 cm for 15.5 GHz and L_n~ 4.5 cm for 24 GHz



Angular Scan of H-Mode B-X-O Window Indicates Very Low Emission Levels

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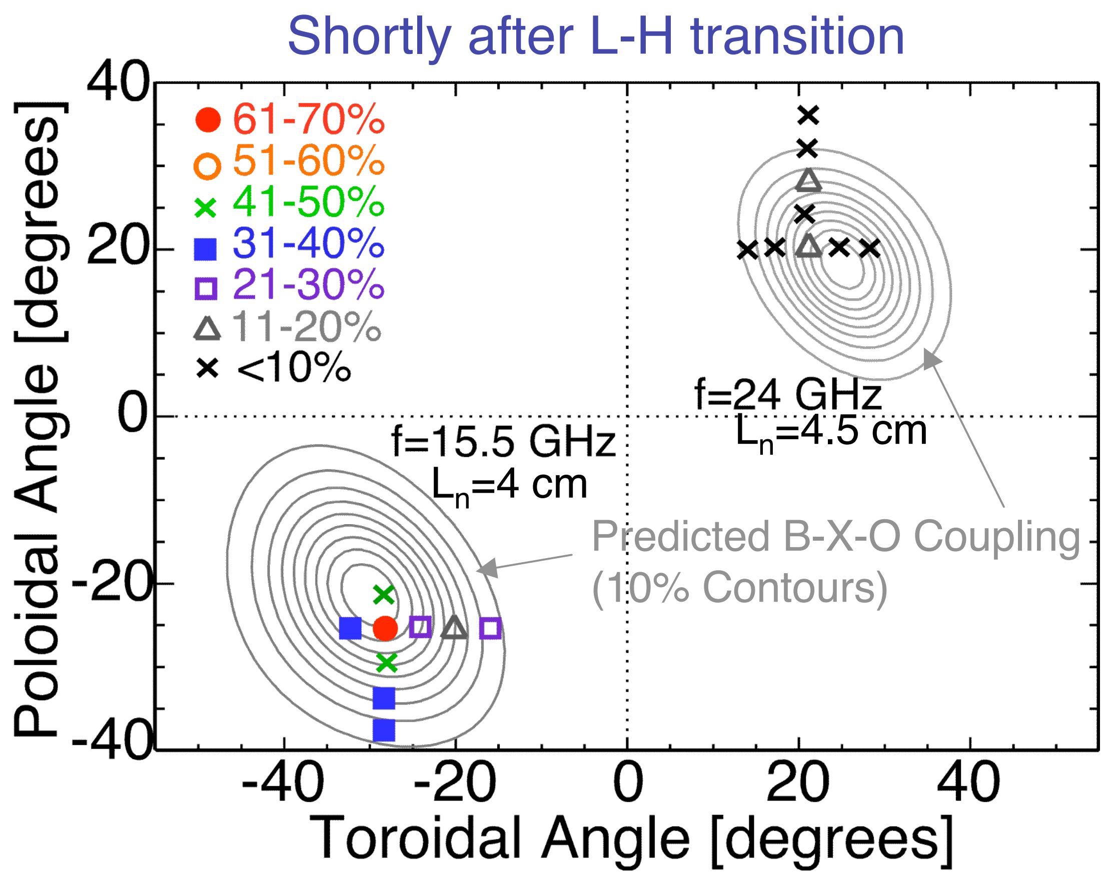
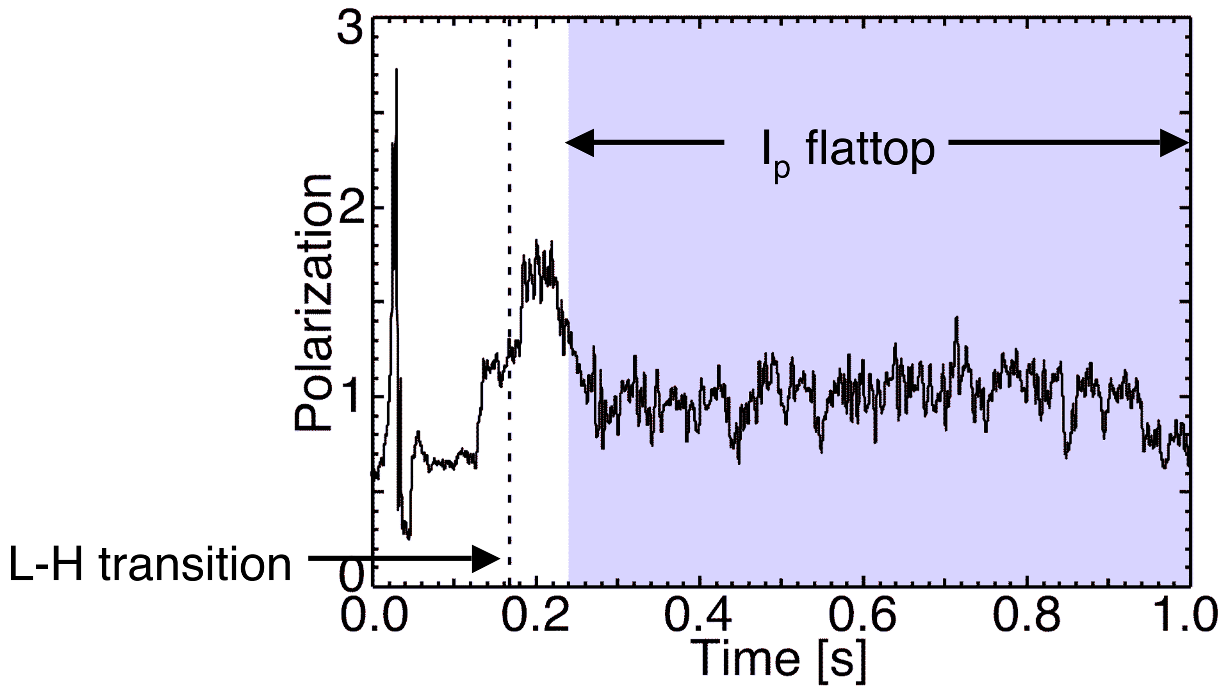
- Fundamental B-X-O converison efficiency reaches ~60-70% during burst of emission before I_p flattop
- Harmonic B-X-O conversion efficency <20% during burst of emission
- During I_p flattop, B-X-O mode conversion efficiency for all frequencies <10%



Emission Unpolarized During I_p Flattop

- $T_{||}/T_{\perp}$~1.7 at t~0.2 s, agrees with simulations
- $T_{||}/T_{\perp}$ falls to <1, indicating diagnostic measuring scattered emission



Good EBW Coupling Only from L-Modes at f_{ce}; Poor Coupling from H-Modes

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- ~90% f_{ce} EBW coupling from L-modes; agreeing with simulation
- ~40% $2f_{ce}$ EBW coupling from L-modes; EBW simulation predicts ~90%
- Low H-mode emission could be due to EBW damping at MC layer and/or edge pedestal-driven current not included in EBE simulation
- More extensive, dedicated H-mode EBE experiments next year, with improved antenna steering, wide-angle survey antenna & local gas puffs

Low EBE During H-Mode Will Be Investigated During 2007 NSTX Campaign

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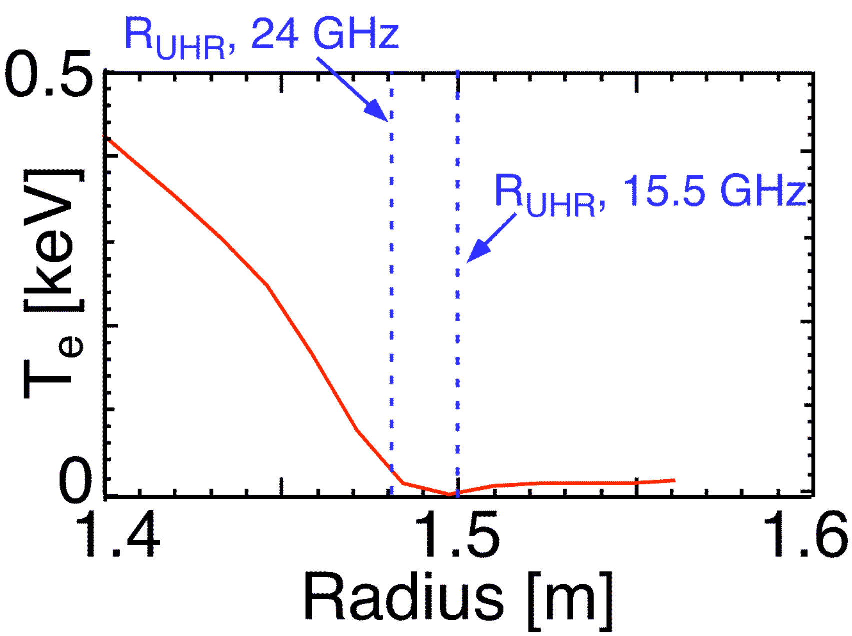
- Low measured T_e at EBW mode conversion (MC) layer during H-mode may result in EBW collisional losses at UHR:
  - Local gas injector to be installed at EBW antennas to change collisionality at UHR
  - Kinetic model for MC being added to EBE simulation code, current treatment uses electrostatic WKB approximation



Low EBE During H-Mode Will Be Investigated During 2007 NSTX Campaign

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- Bootstrap current associated with pressure gradient at H-mode pedestal can change field pitch at UHR:
  - Pitch may be large enough to move B-X-O emission window outside antenna acceptance angle
  - Edge field can block EBW access to plasma core, especially at > f_{ce}
  - Include H-mode edge current in equilibrium used by EBE simulation
  - Install wide acceptance angle, cavity-backed spiral antenna to detect any EBE outside acceptance angle of steered B-X-O antenna

Summary

- New EBW diagnostic operational on NSTX
  - Provides emission measurements of 8-40 GHz - up to 3rd EC harmonic
  - Remotely steerable quad-ridged horn antennas provide detailed information on B-X-O coupling physics

- EBW emission data will provide coupling efficiency and polarization information for a heating and current drive system

- L-mode f_{ce} B-X-O conversion efficiencies of ~90% observed; ~40% EBW coupling for $2f_{ce}$

- <10% EBW coupling observed during I_p flattop in H-mode plasmas

Reprints