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Electron Bernstein Wave Emission and Mode Conversion Physics on NSTX

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EBW emission may be used for $T_e(R)$ profile measurements in the Spherical Torus (ST)

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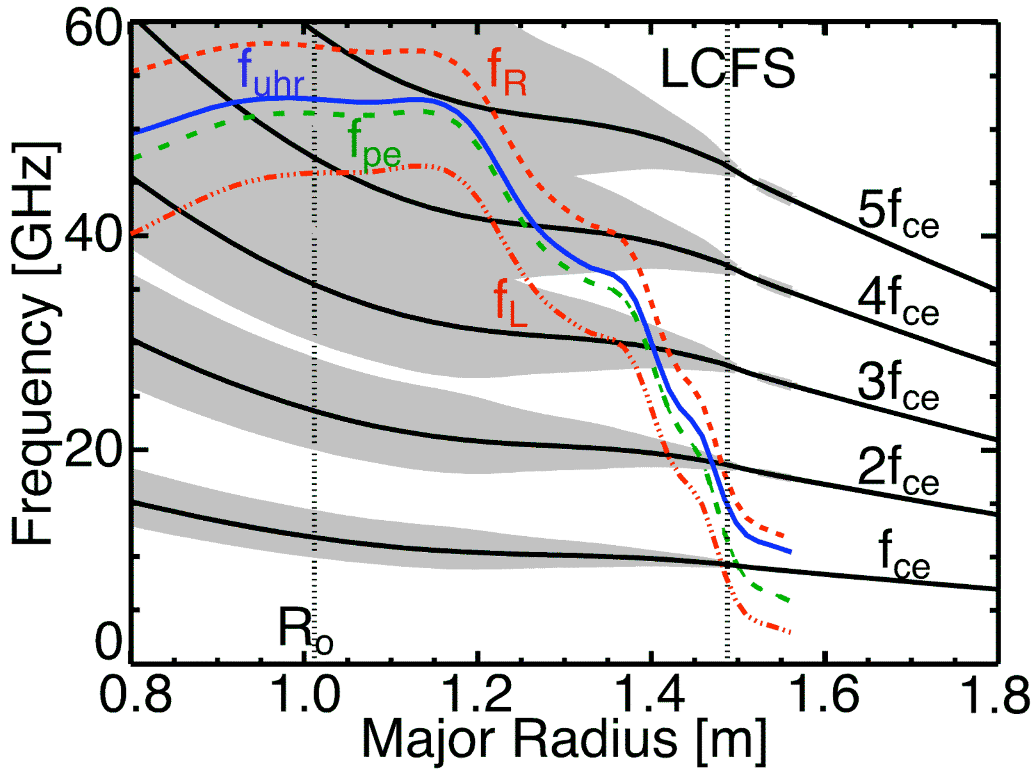
- NSTX assessing the feasibility of EBE based $T_e(R)$ measurements
  - Measure oblique B-X-O emission covering f_{ce}, $2f_{ce}$ & $3f_{ce}$
  - EBE diagnostic developed in collaboration with ORNL

- Need to optimize B-X-O transmission efficiency ($C_{B\text{-}X\text{-}O}$) for robust measurements
  - $C_{B\text{-}X\text{-}O}$ depends on L_n, T_e, Ω_{ce}/ω at mode conversion layer
  - Remotely steered antennas allow for investigating angular dependence on transmission level

- Modeling required to determine emission location and calculate $C_{B\text{-}X\text{-}O}$ for $T_e(R)$ reconstruction
  - EBE simulation code developed by Preinhaelter & Urban at Czech Institute of Plasma Physics

Low harmonic EC waves do not propagate in the ST

- ECE well established as a $T_e(R,t)$ diagnostic in conventional high aspect ratio tokamaks
  - EC waves cannot propagate in overdense plasmas: $\omega_{pe} >> \Omega_{ce}$



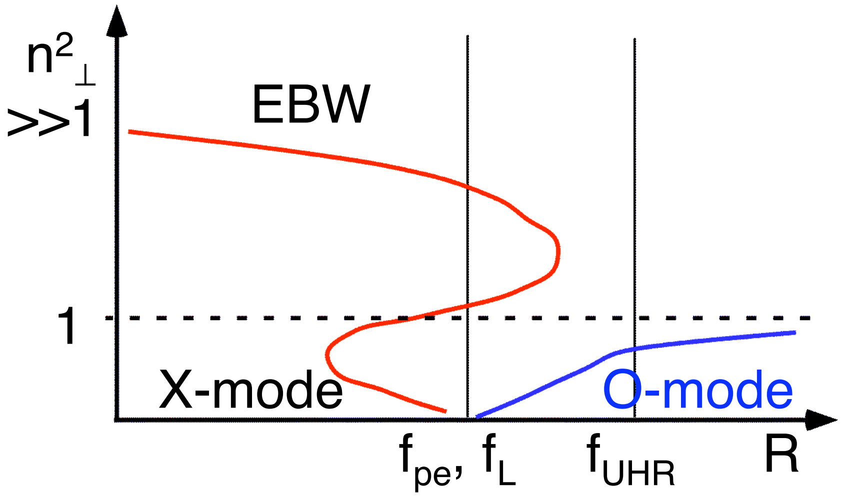
- NSTX has low B-fields and high n_e, cutting off up to first 6 EC harmonics

- EBWs are strongly emitted from EC harmonics

- EBWs cannot propagate in vacuum outside upper hybrid resonance (UHR) layer

Need efficient coupling from EBWs to EM waves for viable diagnostic measurements

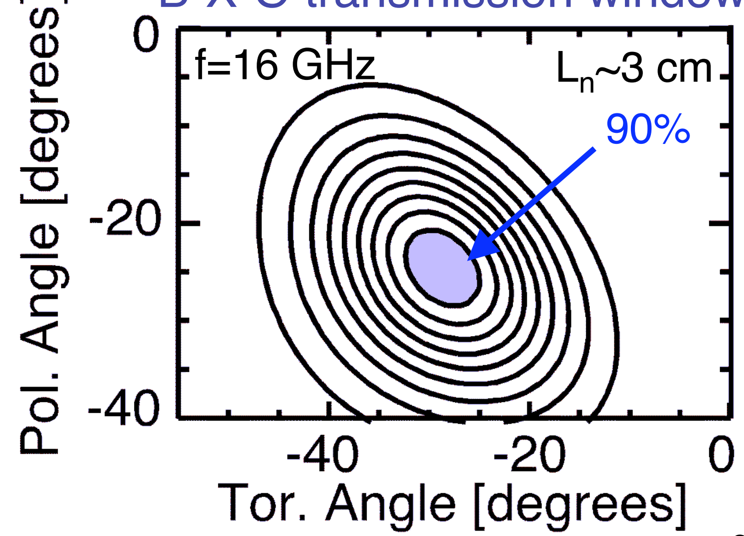
EBW coupling to electromagnetic waves



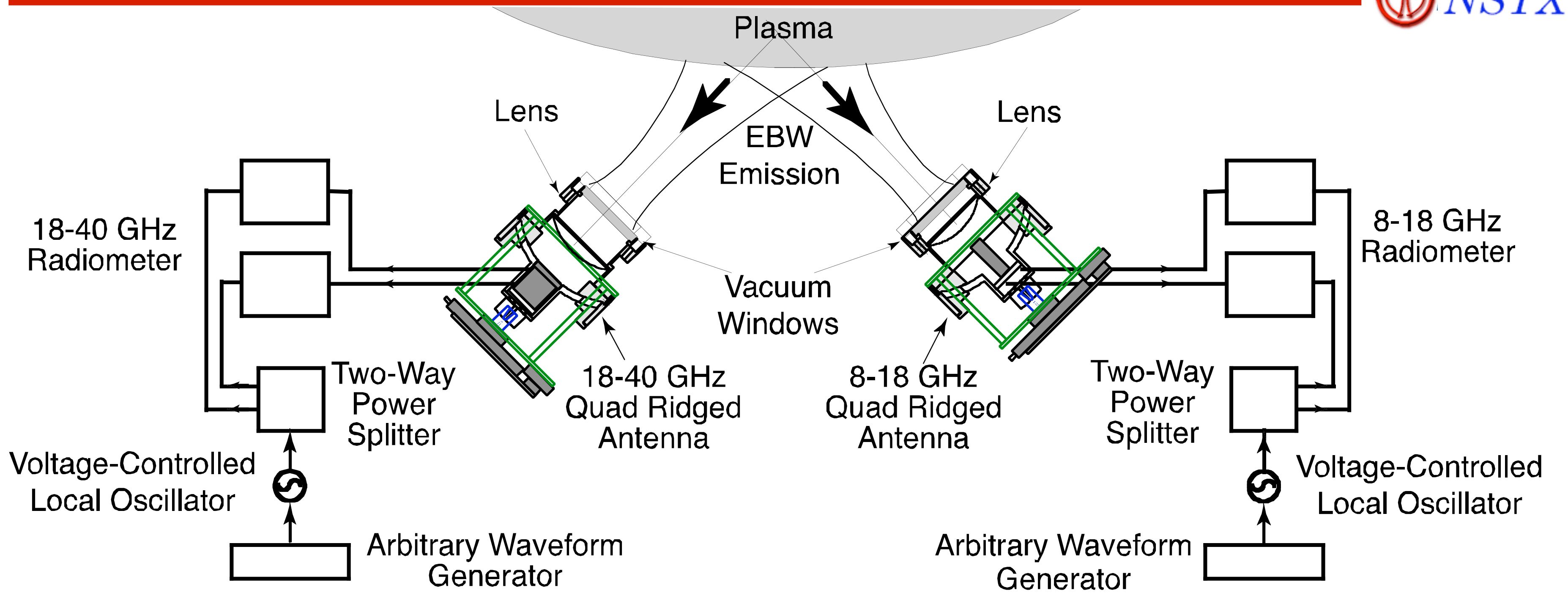
- EBW emitted at EC harmonic converts to X-mode at the UHR and then O-mode
- Emission elliptically polarized due to oblique view of plasma
- EBW coupling efficiency less sensitive to L_n than B-X conversion

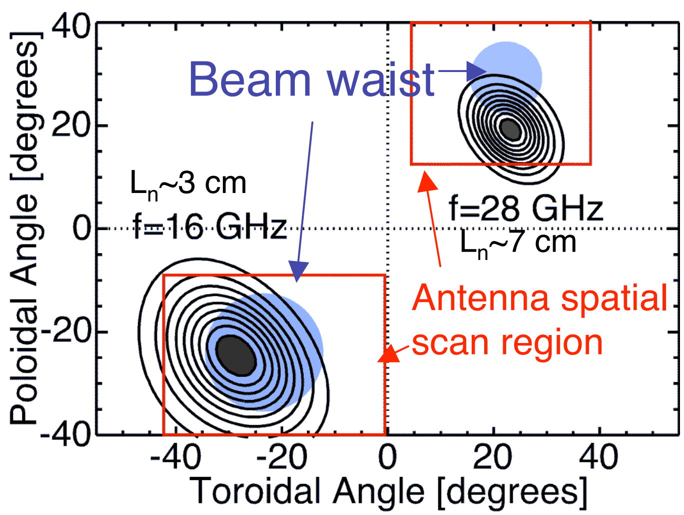
- B-X-O transmission angle depends on field pitch (~30-45°) at MC layer
- L_n at MC layer determines width of window
- Measured T_{rad} = local T_e provided $C_{B\text{-}X\text{-}O} \sim 100\%$

B-X-O transmission window



Remotely steered EBE diagnostic allows spatial mapping of emission window





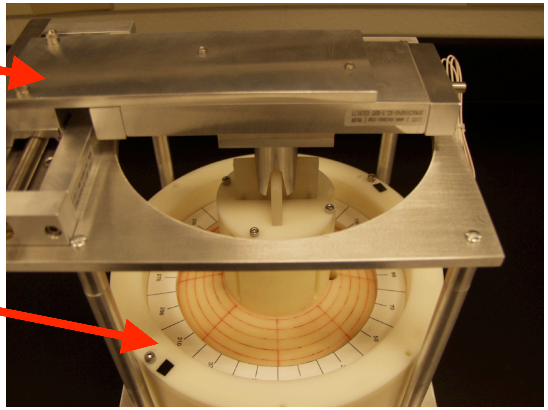
- ±10° scan in poloidal and toroidal directions between discharges
- Acceptance angle:
  - 8-18 GHz antenna ~22°
  - 18-40 GHz antenna ~14°

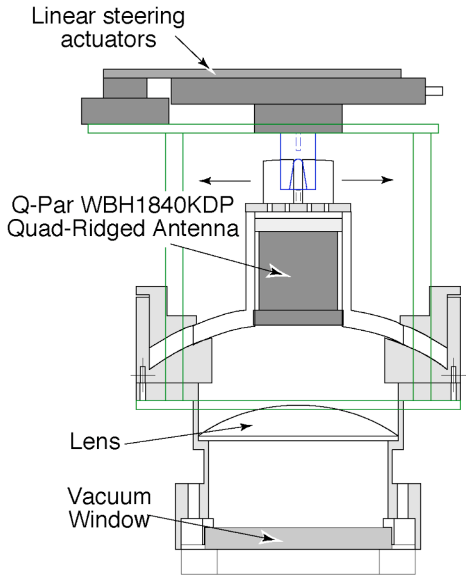
S.J. Diem, et al, Rev. Sci. Instrum. **77** (2006)

Linear actuators allow ± 10° poloidal and toroidal steering

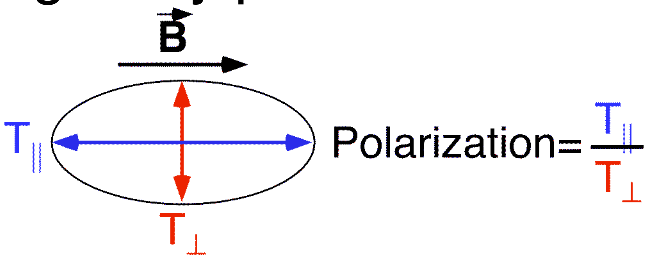
- Two drives provide motion in poloidal & toroidal direction
- Spherical housing provides steering
- Antennas located outside vacuum vessel

18-40 GHz EBW Antenna





- Quad-ridged antennas measure two orthogonally polarized radiation components
  - Dividing the components yields polarization
  - Adding components yields total power



- Remote steering allows for optimization of B-X-O transmission efficiency
  - Needed for robust $T_e(R,t)$ measurements

Emission location determined by EBE simulation code

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- Code inputs:
  - Magnetic equilibria (EFIT)
  - T_e & n_e profiles from Thomson scattering
  - Antenna pattern measurements

- $C_{B\text{-}X\text{-}O}$ is determined by the full wave solution for a cold plasma slab
  - Provides method to compute $C_{B\text{-}X\text{-}O}$ so that T_e profile can be reconstructed $\longrightarrow T_e(R) = T_{rad}(R) / C_{B\text{-}X\text{-}O}$

- 3D ray-tracing code describes EBW propagation after MC

- T_{rad} determined by simultaneously solving ray equations with the radiative transfer equation for each ray

J. Urban & J. Preinhaelter, Journal of Plasma Physics, 72 (2006)

Observed large T_{rad} fluctuations predominately due to changes in B-X-O transmission efficiency

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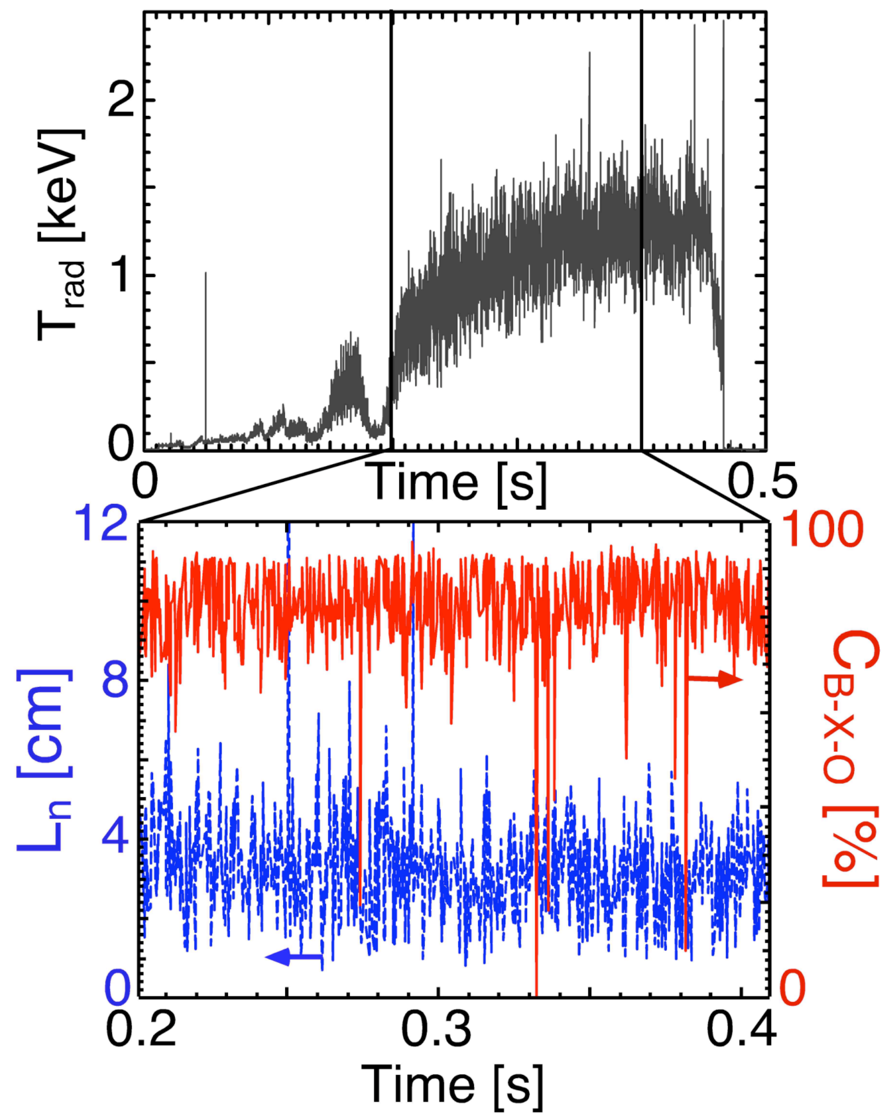
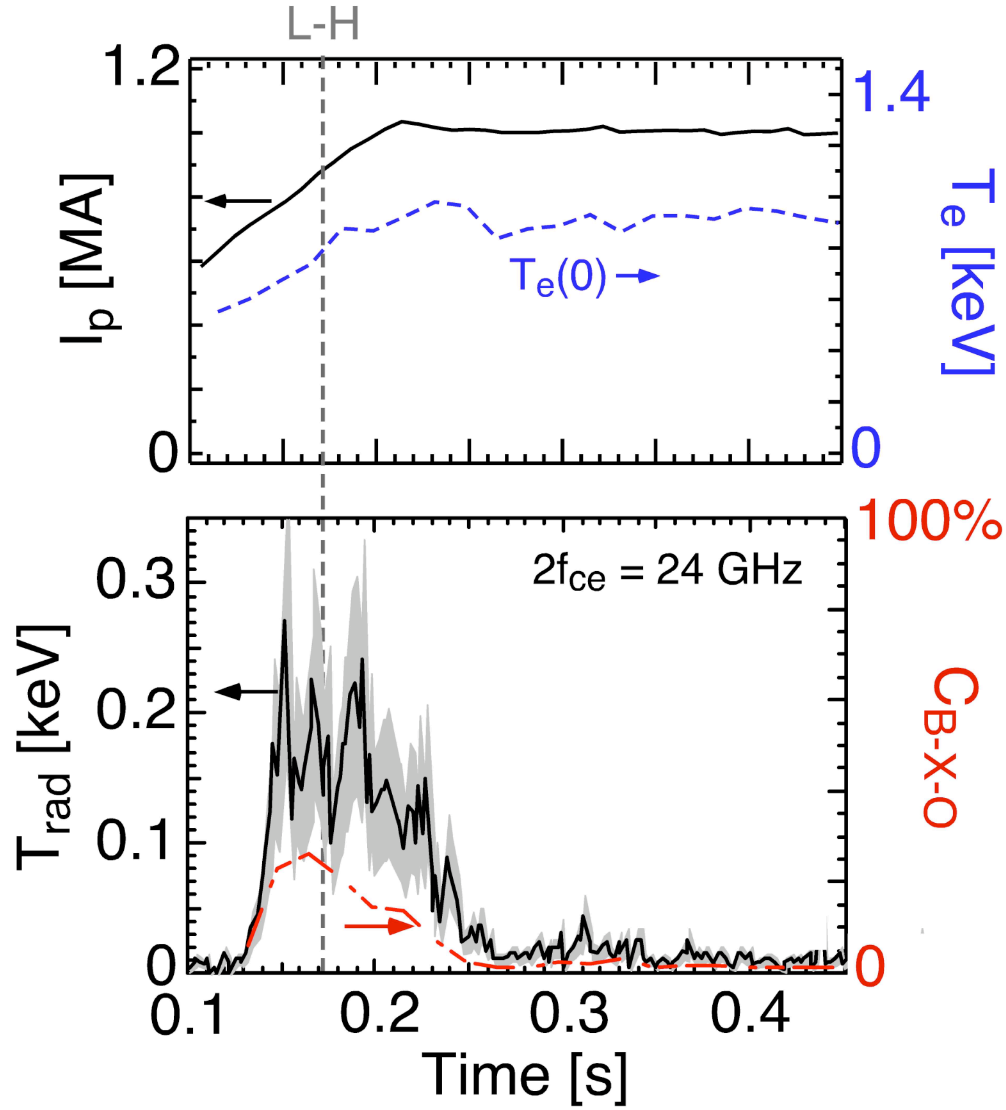
- T_{rad} fluctuates > 30% for all frequencies
- Microwave edge reflectometer used to measure n_e profile
  - Measured L_n fluctuates from 1 cm to 6 cm
- Theoretical $C_{B\text{-}X\text{-}O}$ computed using measured L_n values
  - Varies as ~ e^{L_n}
- Fluctuation levels of T_{rad} (30%) and $C_{B\text{-}X\text{-}O}$ (20%) comparable

Maximum T_{rad} used to calculate measured $C_{B\text{-}X\text{-}O}$



Initial H-mode EBE measurements exhibited decay in measured T_{rad} during H-mode phase

- Emission decays after L-H transition
  - Observed for f_{ce}, $2f_{ce}$ and $3f_{ce}$ emission
  - Emission location remains constant during discharge
- Leads to $C_{B\text{-}X\text{-}O} \sim 0\%$ during H-mode
  - Low emission levels prohibit $T_e(R,t)$ measurements
- EBW collisional damping suggested as explanation of measured T_{rad} evolution
  - Damping becomes significant for $T_e < 30$ eV at or inside the UHR layer



EBE simulations suggest low H-mode EBE due to EBW collisional damping

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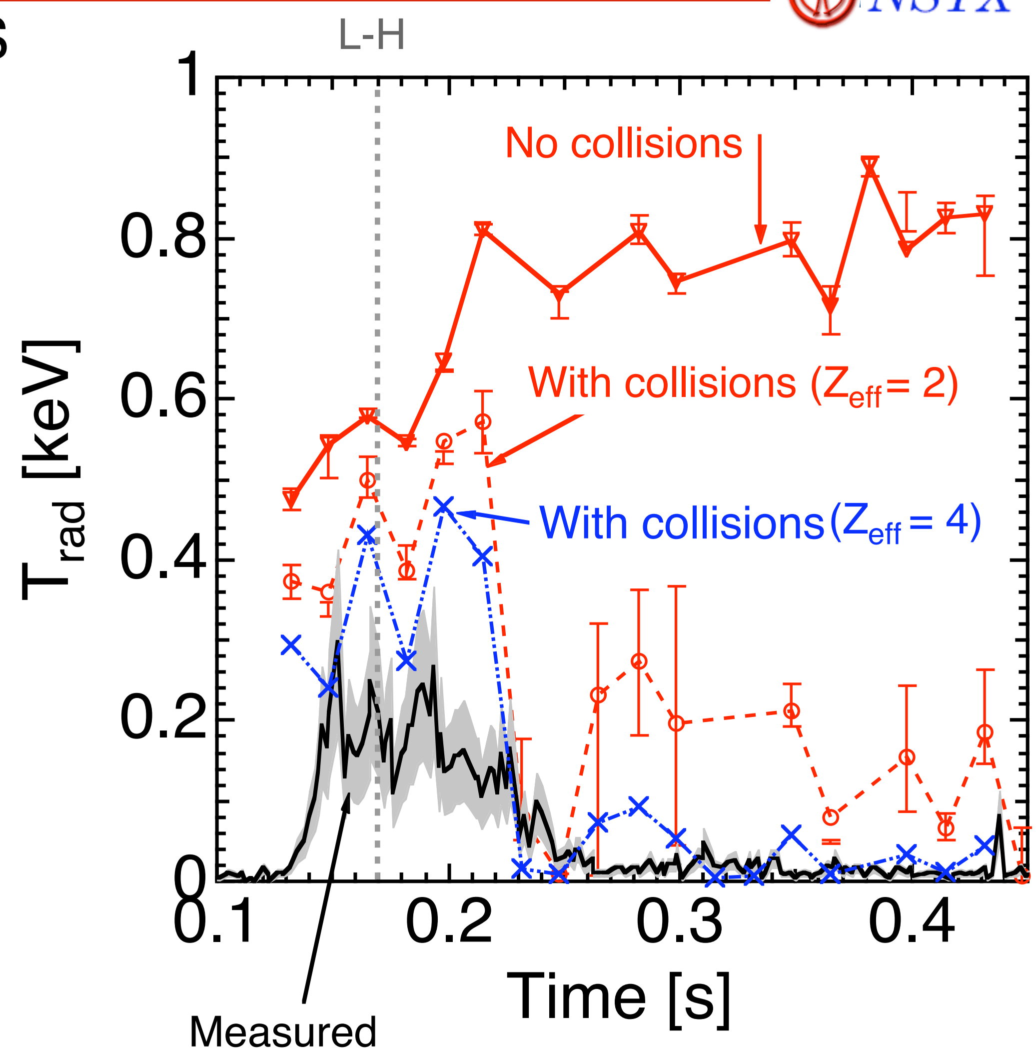
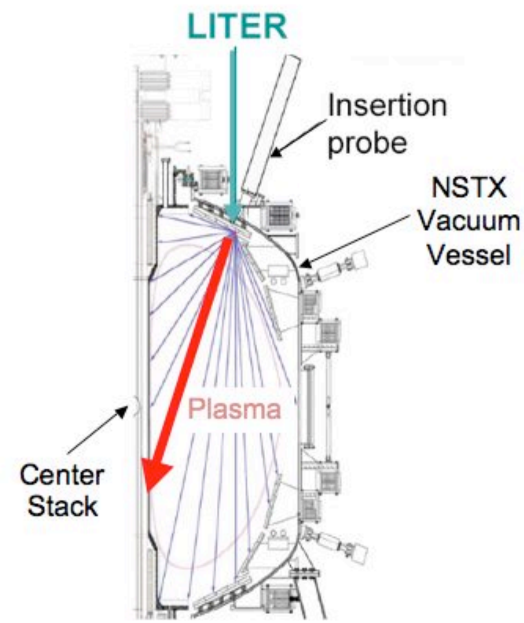
- MC layer moves outside LCFS after L-H transition
  - T_e < 20 eV outside LCFS
- EBE simulations with collisional damping predict T_{rad} decay during H-mode
- Relative collision frequency increases after L-H transition:
  - Peak υ_{ei}/ω increases from 5×10^{-5} to 1.2×10^{-4}
- Damped EBW power increases from 20-40% in the L-mode phase to 70-90% during H-mode

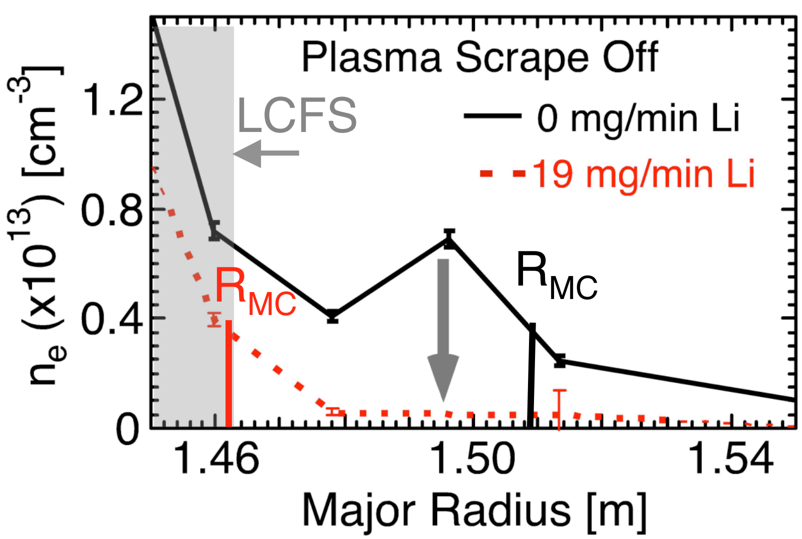


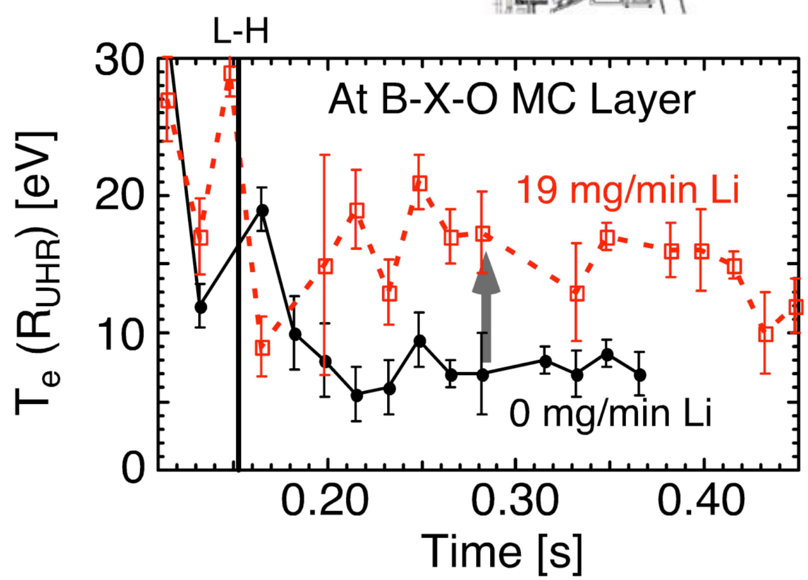
Need method to reduce edge collisionality ⟶ Li conditioning

LIThium EvaporatoR (LITER) provides edge conditioning tool for NSTX

- Improvement in edge n_e and T_e with LITER may be important for B-X-O coupling
  - Coupling depends on L_n and T_e
- Li conditioning:
  - Increases T_e at MC layer
  - Decreases n_e outside LCFS
- Reduction in edge n_e moves MC layer to LCFS where T_e ~ 20 eV

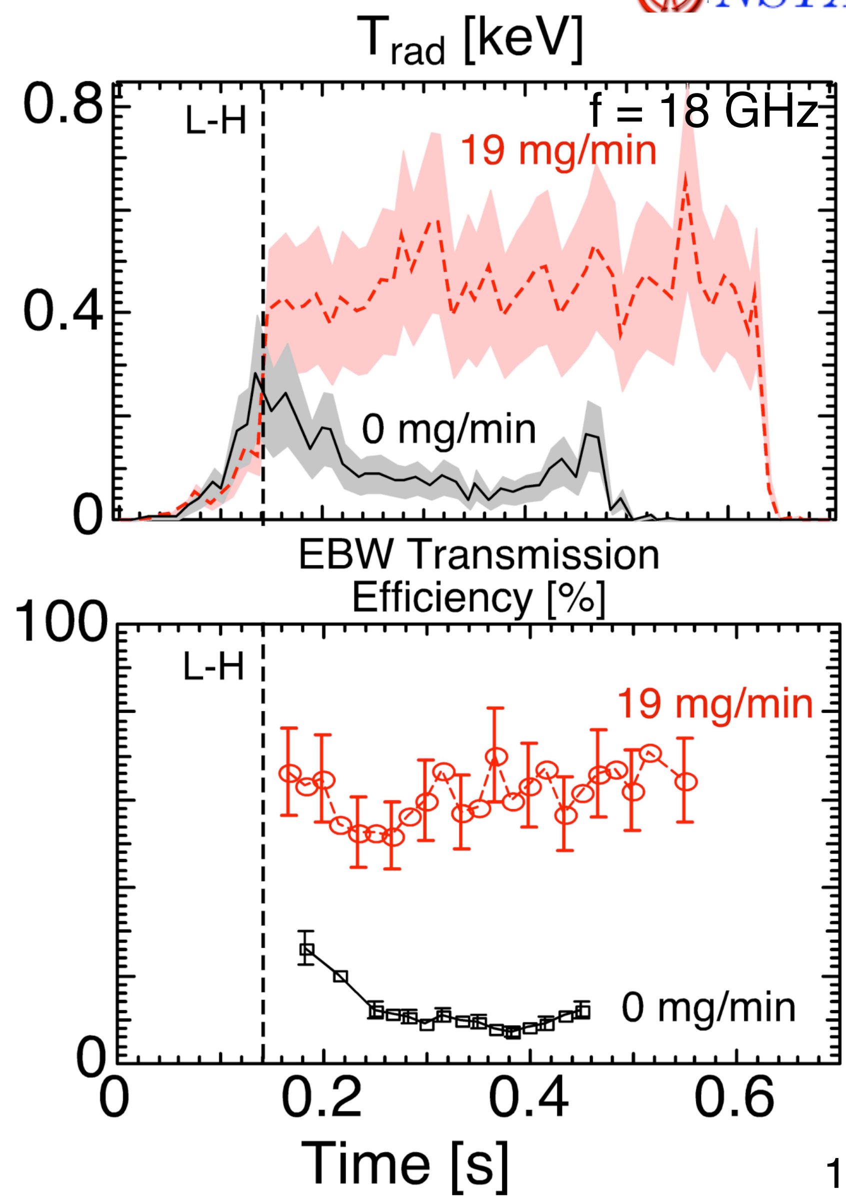






H-mode $C_{B\text{-}X\text{-}O}$ increased with Li edge conditioning

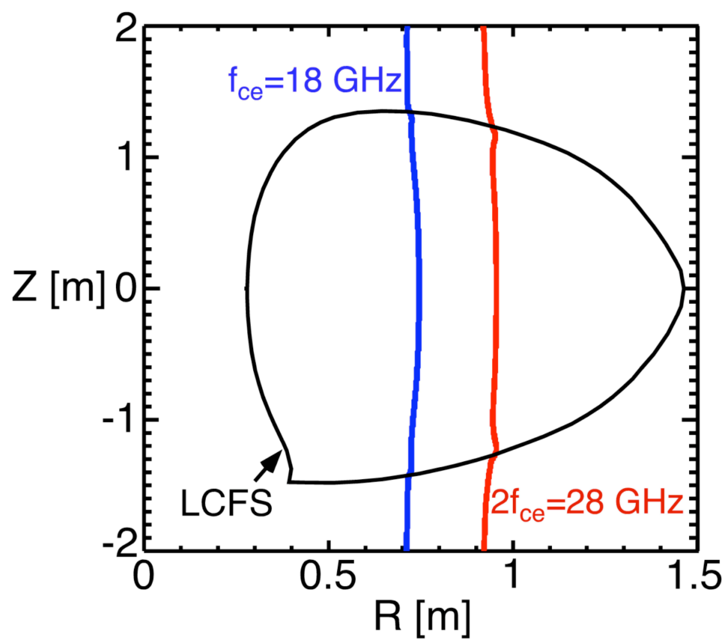
- Measured T_{rad} increased from ~ 50 eV to ~ 400 eV
  - 18 GHz emission from near plasma axis
- $C_{B\text{-}X\text{-}O}$ increased with Li conditioning:
  - From 10% → 60% for f_{ce}=18 GHz
  - From 20% → 50% for $2f_{ce}$=28 GHz
- Control of edge conditions provides good coupling to EBW

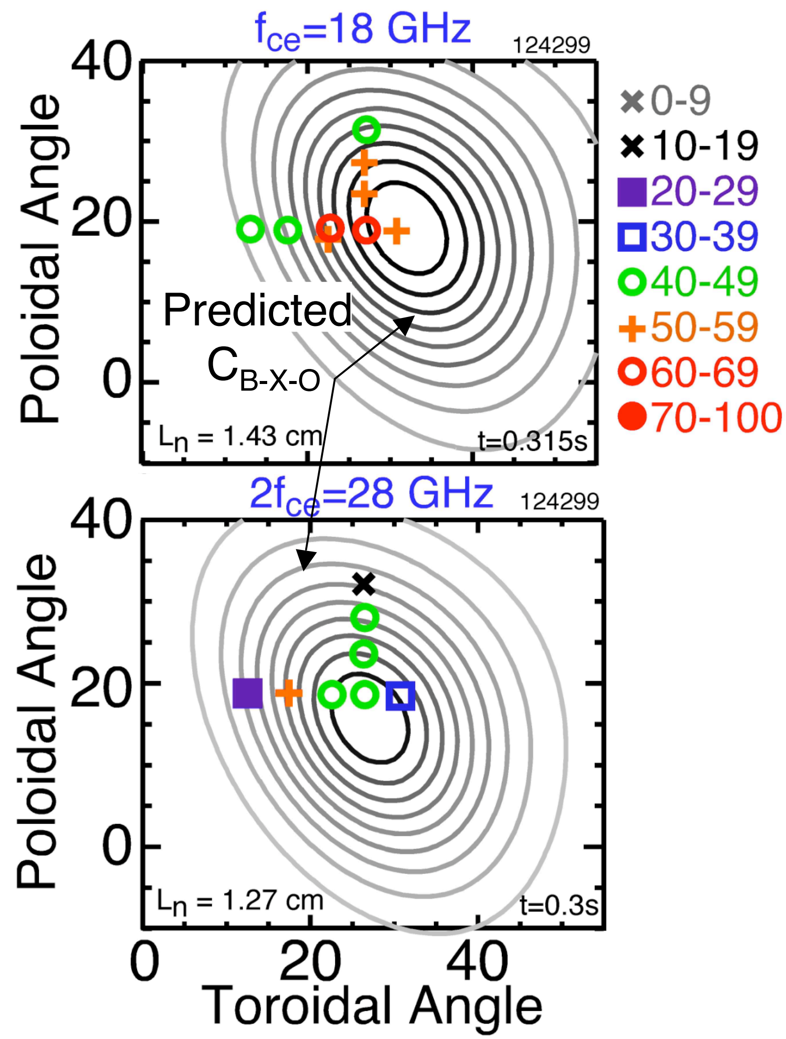


Increased B-X-O coupling allows for more robust conditions for $T_e(R,t)$ measurements

Angle of maximum B-X-O transmission consistent with theory in H-mode plasmas

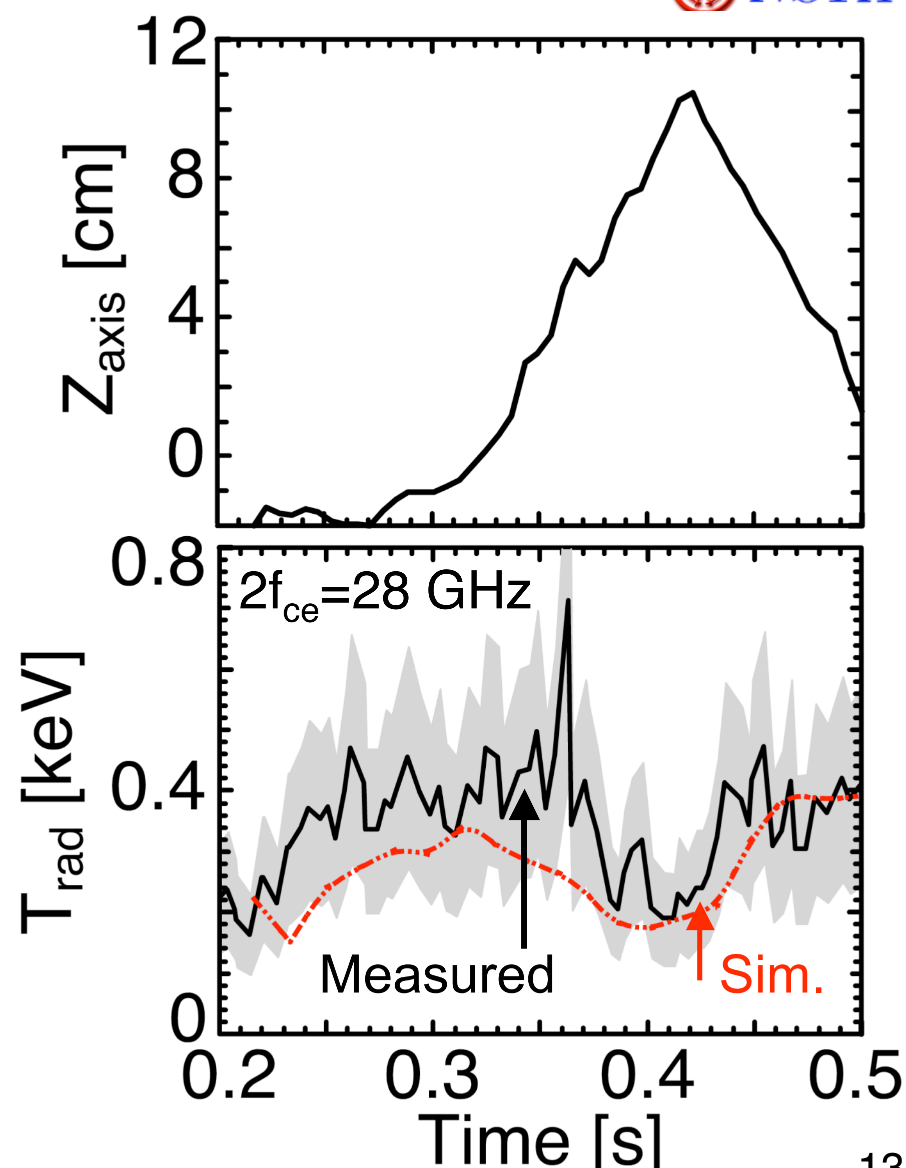
- Repeated target plasma, (I_p =0.9 MA, $T_e(0)$~1keV) with Li conditioning
- Maximum measured $C_{B\text{-}X\text{-}O}$:
  - 62±15% for f_{ce}=18 GHz near axis emission
  - 49±15% for $2f_{ce}$=28 GHz near axis emission
- Measured and predicted angle of peak emission consistent in L-mode as well





T_{rad} maximum at $Z_{axis} \sim 0$, in agreement with simulations

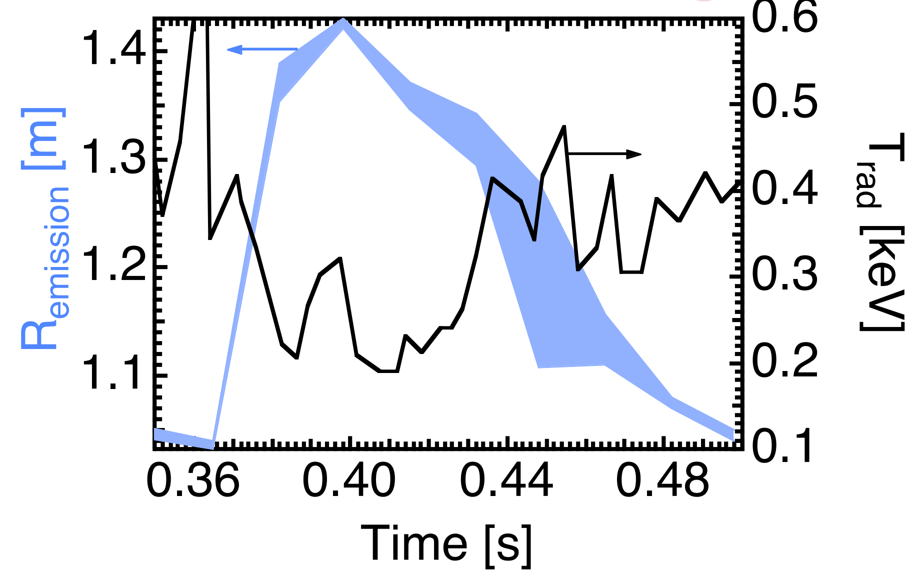
- Target H-mode plasma: I_p=0.8 MA, $T_e(0)$=0.8 keV, $n_e(0)=3\times10^{19}\,m^{-3}$
- Vertical position scanned from -2 to 11 cm
- Drop in measured T_{rad} coincides with increase in Z_{axis}
- Measured and simulated T_{rad} agree during Z_{axis} scan

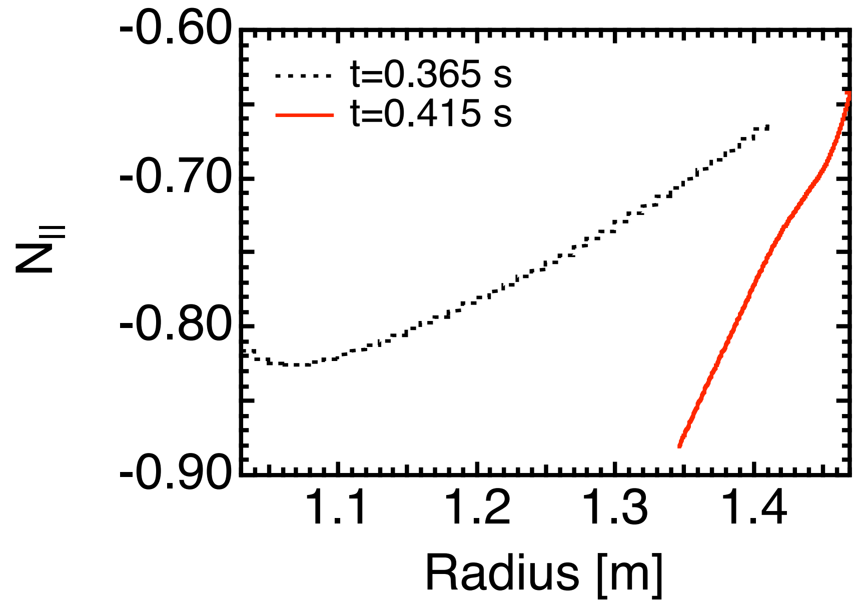


EBE simulation of Z_{axis} scan suggests increase in Doppler broadening

- Prior to Z_{axis} increase, emission originates near axis (R=1 m)
- At maximum Z_{axis}, $R_{emission}$ shifts out to R=1.4 m
- Simulations show increase $N_{||}$ with Z_{axis}
  - Leads to increase in Doppler broadening

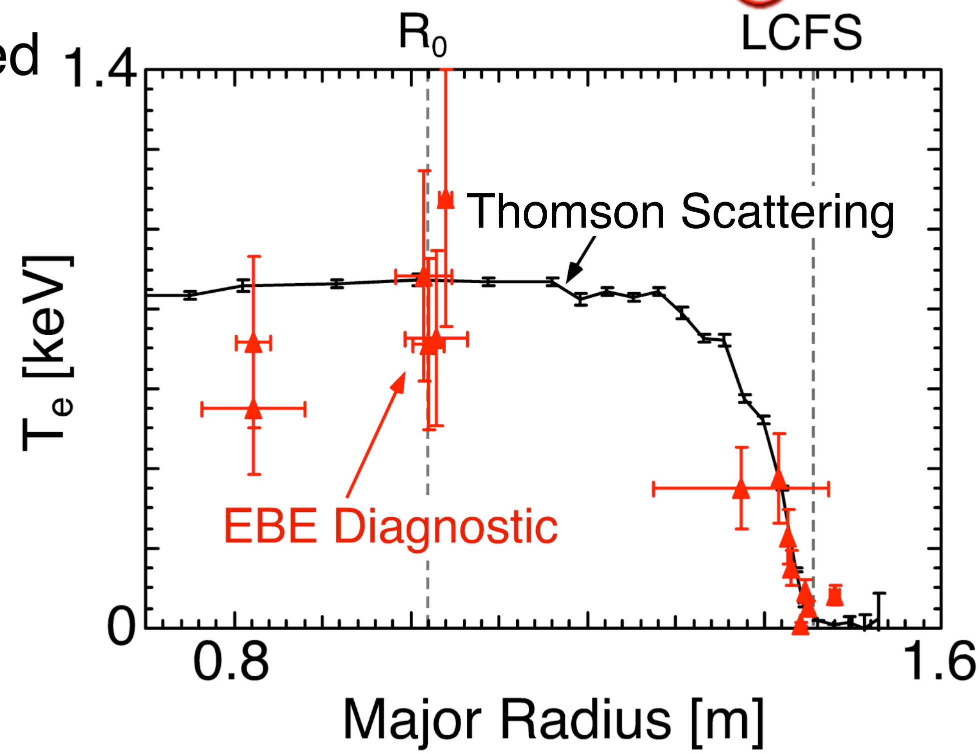
Doppler broadening restricts access to core T_e measurements





Lithium edge conditioning provides good target H-mode plasma for $T_e(R,t)$ measurements

- Lithium edge conditioning reduced collisional losses to < 20%
- EBE simulation calculates $C_{B\text{-}X\text{-}O}$ and ray emission location
  - Code accounts for losses due to re-absorption, re-emission & collisional damping
  - Emission location determined by weighted-average emission location of the simulated 41 rays



- T_e from EBE diagnostic computed by: $T_e = T_{rad} / C_{B-X-O}$
- Edge EBE simulations more accurate because rays travel through less plasmas

Non-localization of $T_e(R)$ measurements from EBE diagnostic due to multi-harmonic emission

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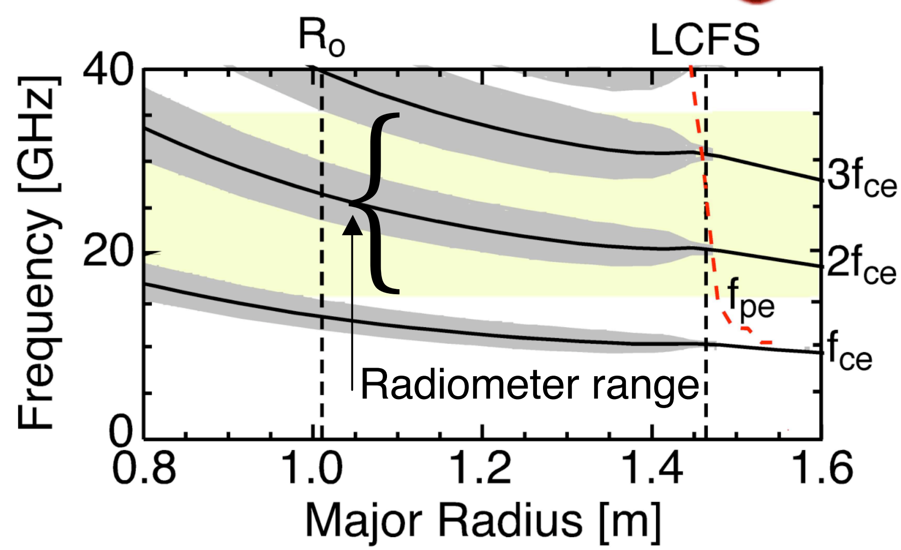
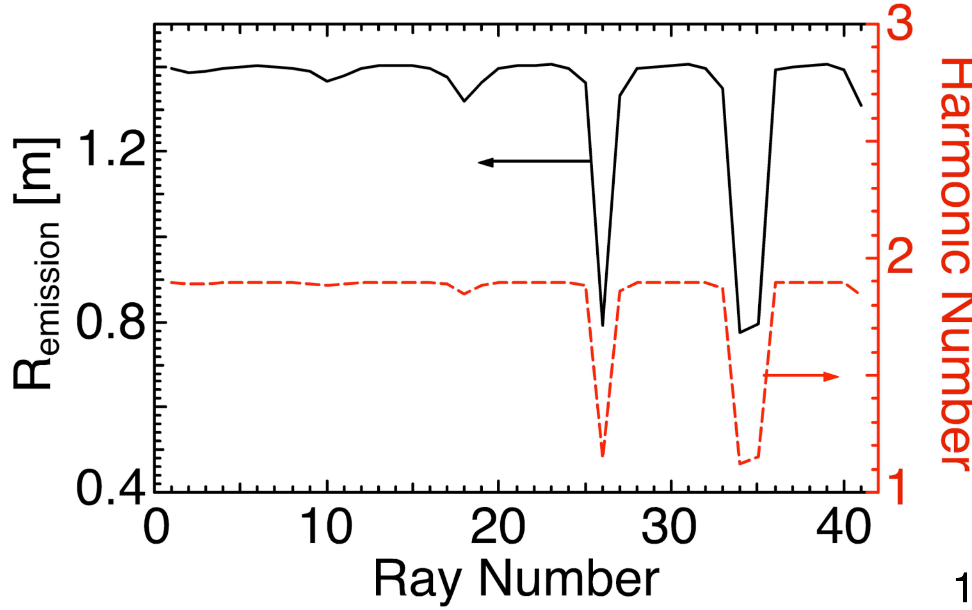
- Harmonic overlap in ST occurs from high toroidicity
  - Accurate simulations very important
- Finite size of beam can lead to non-localized measurements
  - Spread in emission location due to Doppler broadening
  - Diagnostic sensitive to emission from multiple harmonics
- Need detailed edge measurements to accurately model EBE process





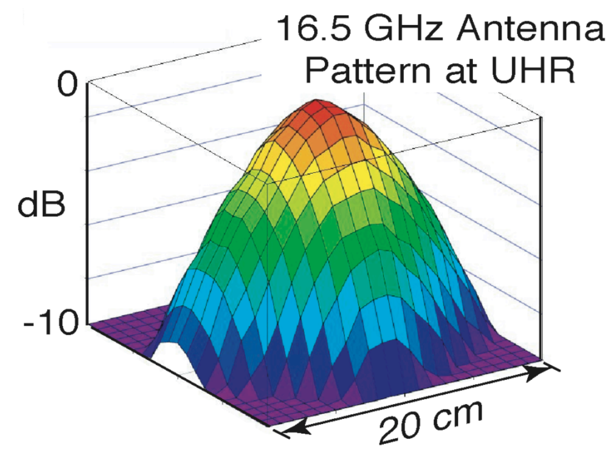
EBE based $T_e(R,t)$ measurements in the ST are challenging

- Local T_e equal to T_{rad} from EBE measurements provided $C_{B\text{-}X\text{-}O} \sim 100\%$
  - Coincidence of X- and O-mode cutoffs required for $C_{B\text{-}X\text{-}O} = 100\%$
- Reconstruction of $T_e(R)$ profile is difficult in the ST
  - Rapid fluctuations in edge L_n lead to > 20% fluctuations in $C_{B\text{-}X\text{-}O}$
  - EBW collisional damping in H-mode can quench low harmonic EBE
  - Non-optimal plasma vertical position restricts core $T_e(R)$ measurements
  - Requires knowledge of actual magnetic configuration which is strongly varied by large internal currents
- $T_e(R)$ reconstruction of NSTX H-mode plasma shows agreement with edge T_e from Thomson
  - Larger disagreement with central T_e occurs where Doppler broadening and harmonic overlap effects are increased

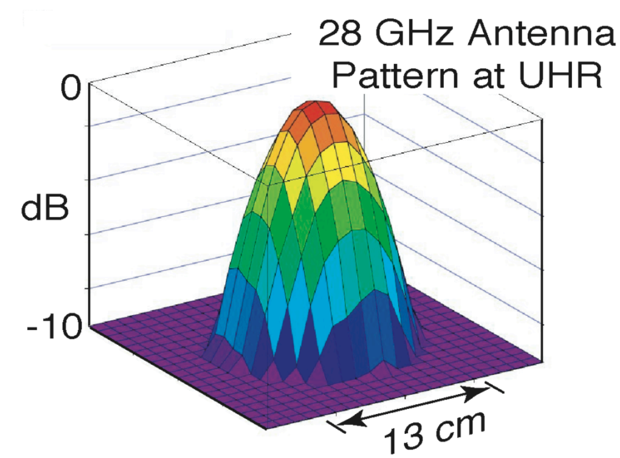
Supporting Slide

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



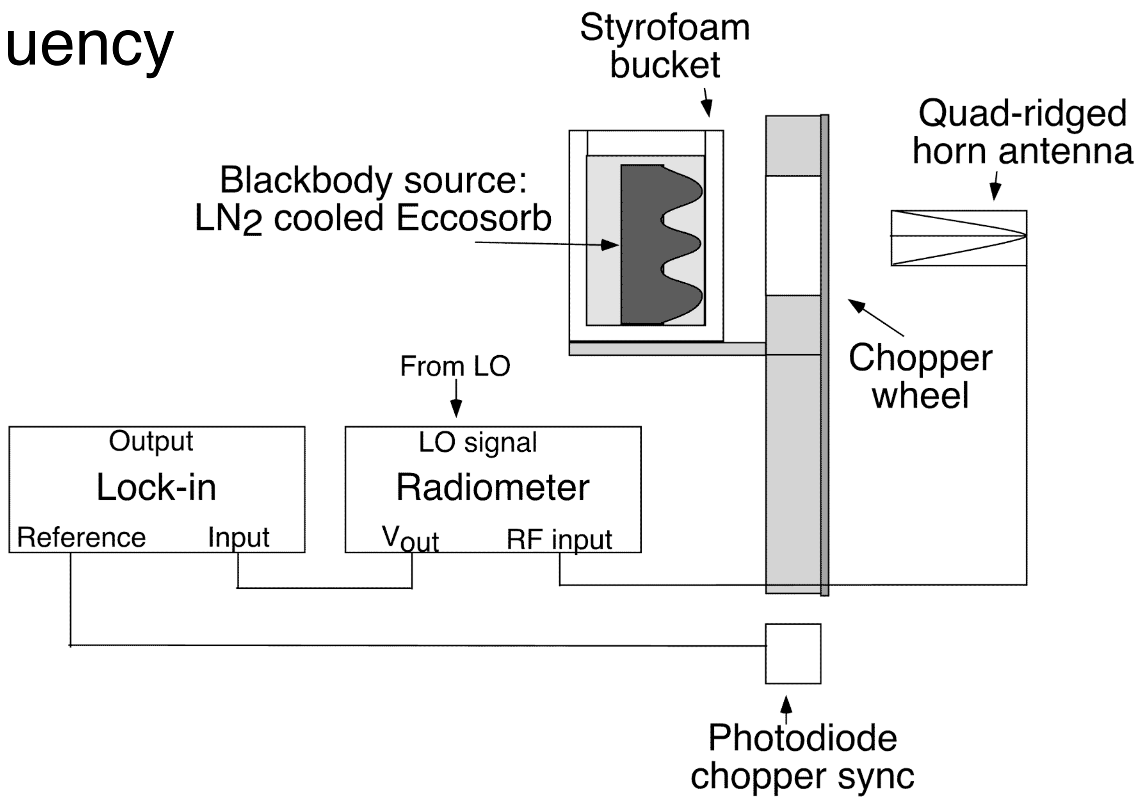
- 18-40 GHz antenna
  - 25 cm focal length lens provides beam waist of 6.5 cm at plasma edge for 28 GHz
  - Focal length ~12.5 cm for microwaves



Allows for localized measurements

Dicke switching method provides absolute calibration

- 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)



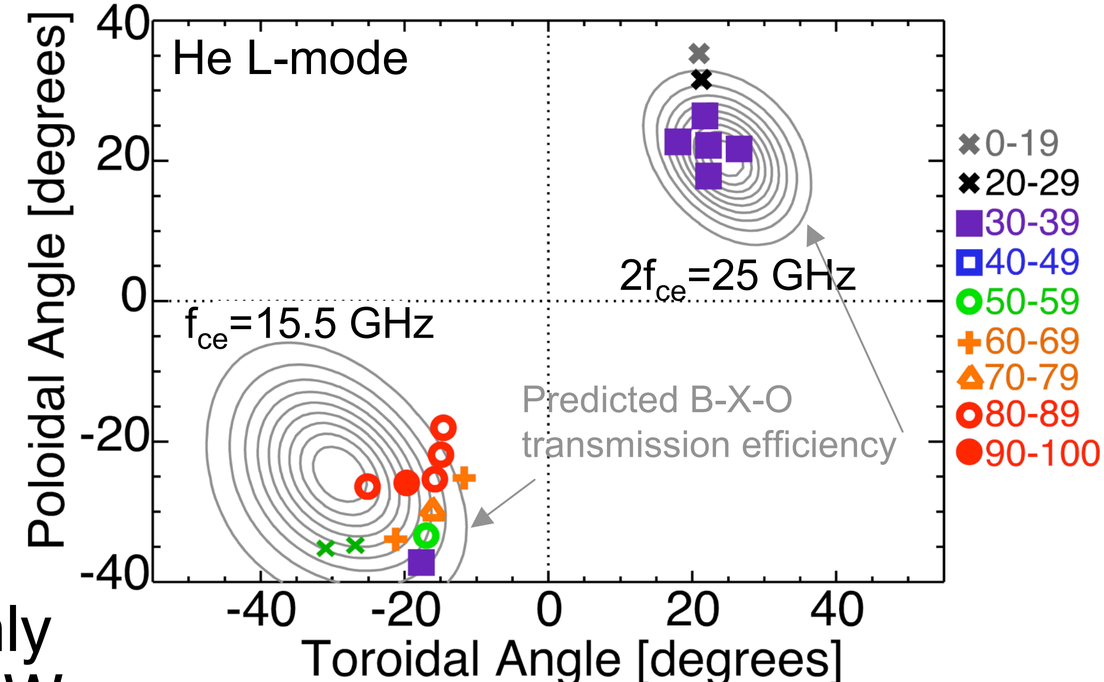
- All vacuum windows, lenses, antennas, and cables used in the experiment included in calibrations

Antenna steering scan provides good coverage of B-X-O window

- Repeated target helium L-mode plasma (I_p=0.8 MA, $T_e(0)$=1.5 keV, $n_e(0)=3x10^{19}$ m^{-3})
  – Moved EBE antennas to new position between shots

- Experimental B-X-O transmission efficiency:

$$\text{Transmission}_{EBW} = \frac{T_{rad}(\text{measured})}{T_{e,\text{Thomson}}(R_{\text{emission}})}$$



- Maximum measured transmission efficiencies:
  – 90% for f_{ce}=15.5 GHz
  – 40% for $2f_{ce}$=25 GHz

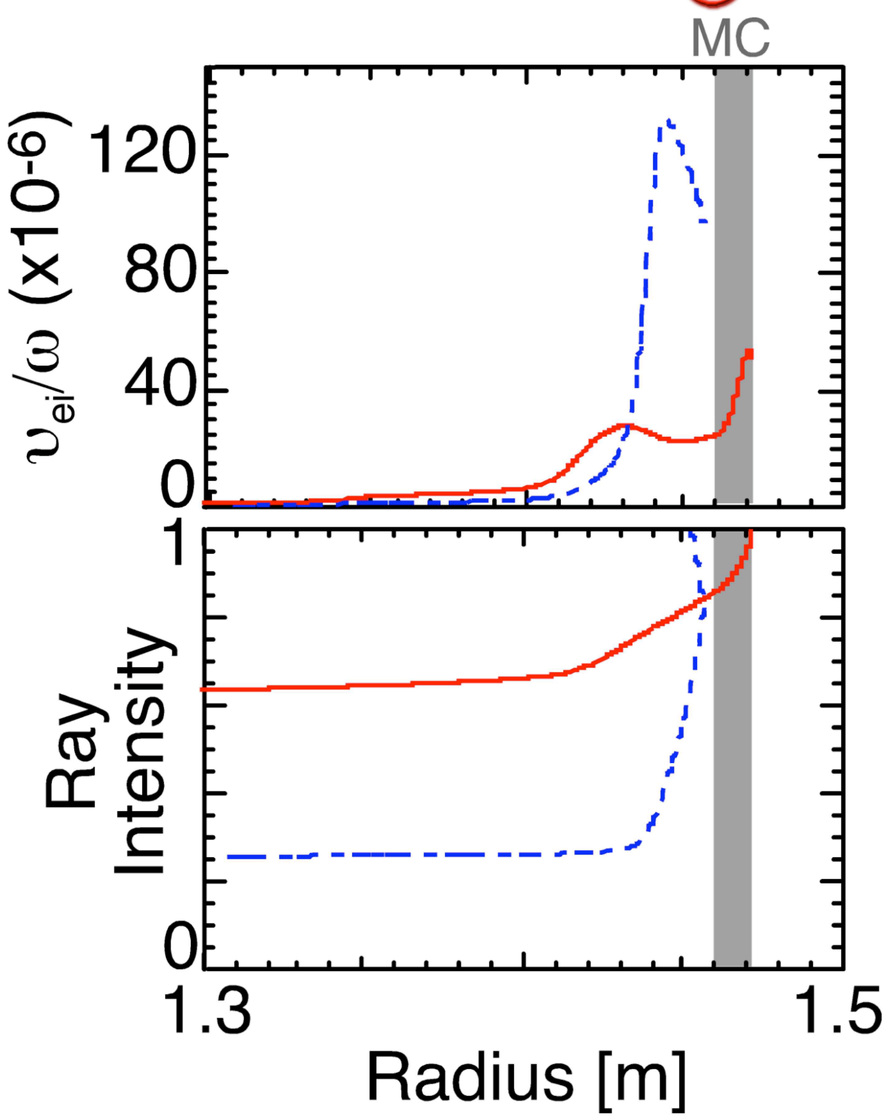
- Predicted transmission only accurate for MC layer; EBWs may be re-absorbed and re-emitted before MC

EBE simulations indicate increase in υ_{ei} near MC results in significant loss in ray intensity

- High emission (t <0.2 s):
  - $\upsilon_{ei}/\omega \sim 3x10^{-5}$
  - Ray intensity decreased by 40% in edge

- Low emission (t >0.2 s):
  - $\upsilon_{ei}/\omega \sim 1.2x10^{-4}$
  - Ray intensity decreased by 80% in edge

Edge Li conditioning may reduce edge collisionality

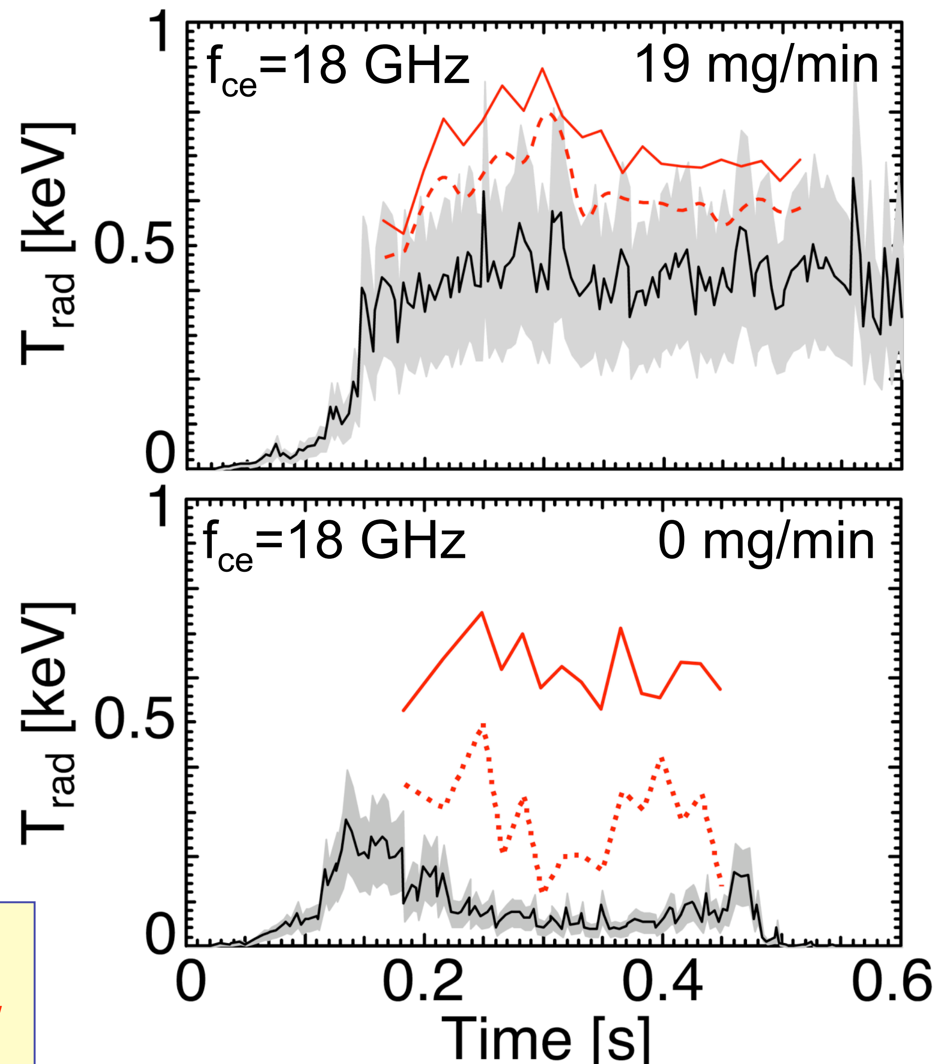


Better T_{rad} agreement with EBE simulation in 19 mg/min Li conditioned plasma

- For highest Li evaporation rate, 19 mg/min:
  - Measured T_{rad}~0.4 keV
  - Simulated T_{rad}~0.6 keV

- For 0 mg/min:
  - Measured T_{rad}~0.1 keV
  - Simulated T_{rad} ~0.4 keV

Control of edge conditions allows for good coupling to EBW



Good agreement between measured and simulated T_{rad} in H-mode

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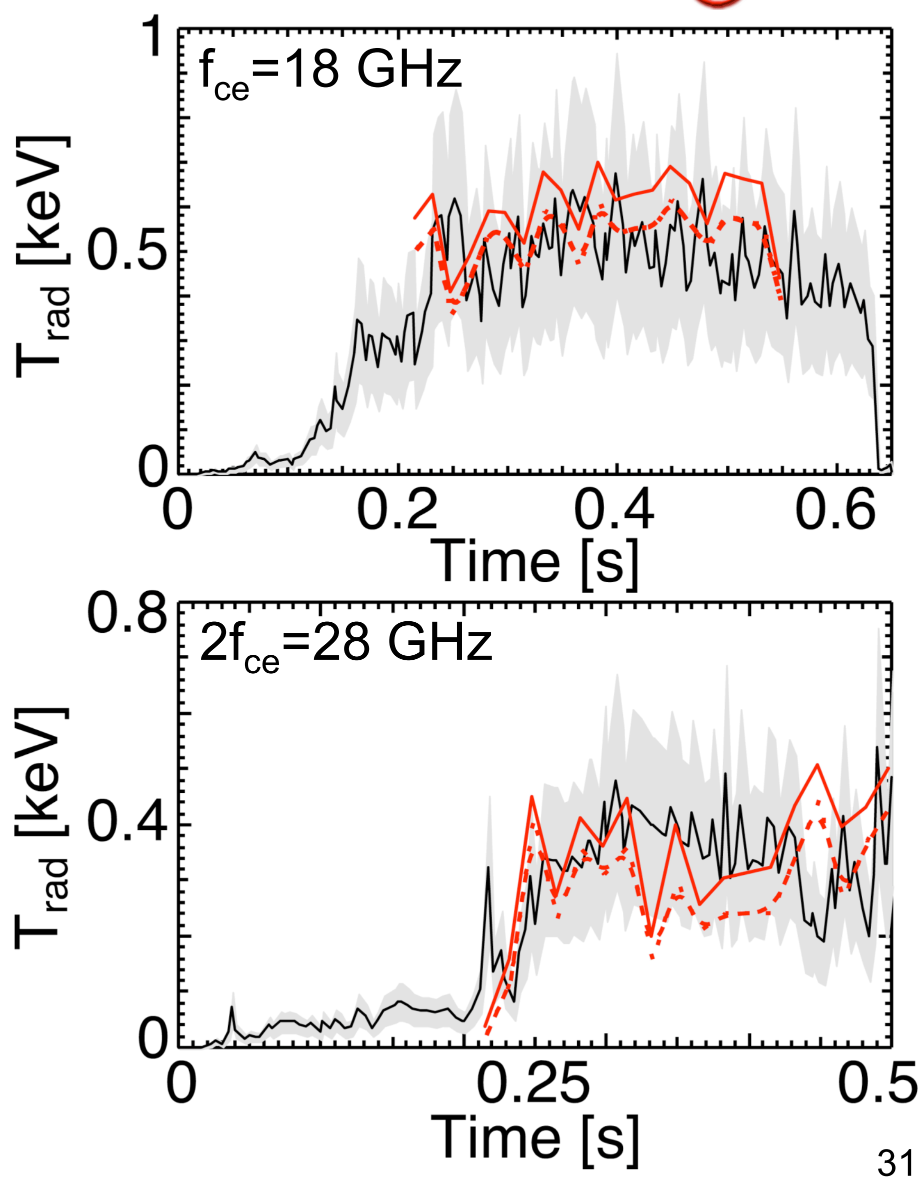
- T_{rad} (measured)
- T_{rad} (sim., no collisions)
- T_{rad} (sim., with collisions)



- Simulated & measured T_{rad}
  - 0.6 keV for f_{ce}=18 GHz
  - 0.4 keV for $2f_{ce}$=28 GHz

- Low EBW collisional damping observed during H-mode scan