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NSTX

Investigation of Electron Bernstein Wave Coupling and its Critical Dependence on EBW Collisional Loss in High-β, H-Mode ST Plasmas

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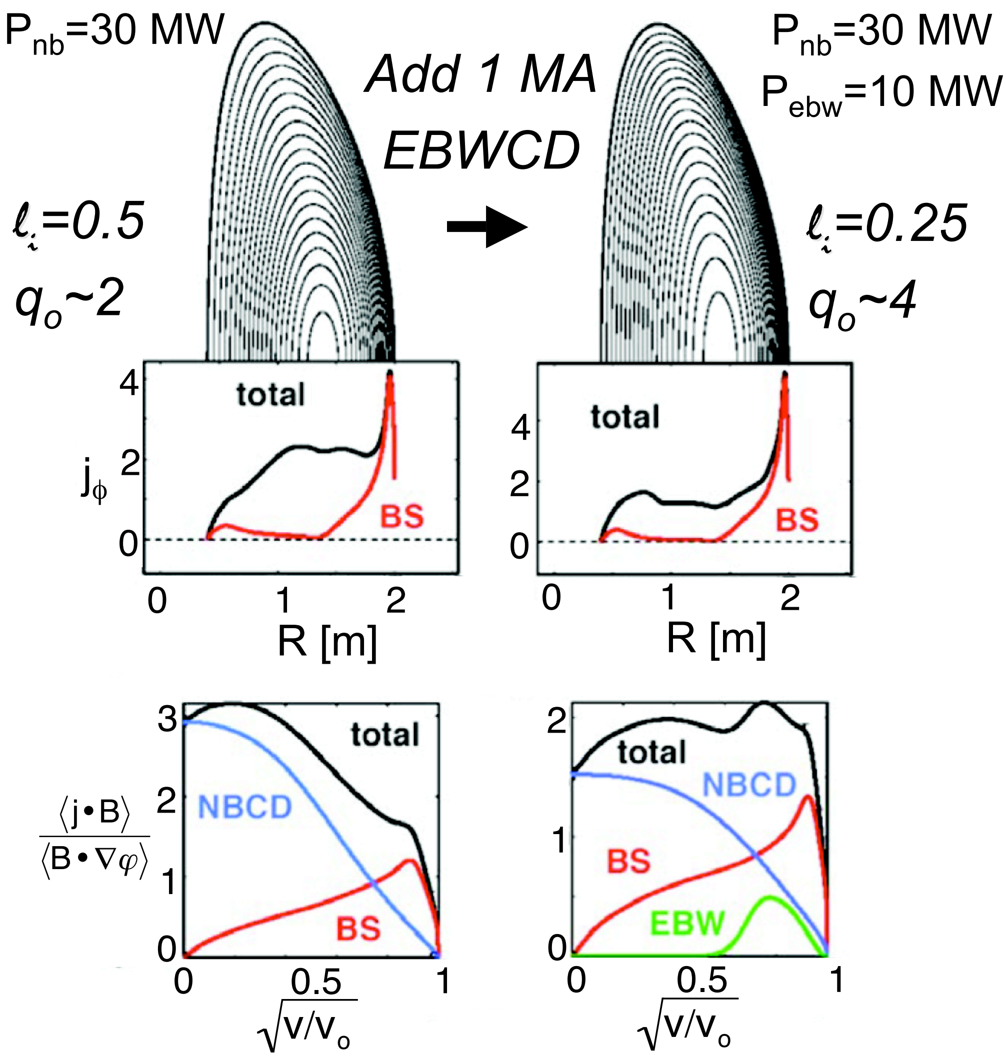
EBW emission measurements provide guidance for future ST heating & current drive systems

- Next generation STs require non-inductive plasma startup and off-axis current drive (CD) to sustain $\beta > 20\%$ plasmas
  - Low magnetic field and high n_e prevent propagation of low EC harmonics used in traditional tokamaks
- Feasibility of EBW heating & CD in the ST critically dependent on coupling to EBWs in H-mode
  - EBW coupling studied by measuring thermal EBW emission (EBE)
- Studied efficiency of B-X-O mode conversion in H-mode & compared to theoretical predictions
  - Investigate effects of edge conditioning on EBW coupling
  - Experimentally map B-X-O transmission efficiency, $\eta_{B\text{-}X\text{-}O}$

EBW research objective to assess ability of EBWCD to generate off-axis stabilizing current in ST-CTF



Y-K. M. Peng, et al., PPCF, **47** B263 (2005)

- Modeling shows adding 1 MA of off-axis EBWCD to ST-CTF plasma significantly increases stability:
  - β_n increases from 4.1 to 6.1
  - β_t increases from 19% to 45%
- EBW also candidate for NTM suppression via j(R) control
- Need efficient coupling of RF power to EBWs

→ Assess oblique O-X-B coupling by measuring B-X-O emission

Propagation of EC waves prohibited in the ST

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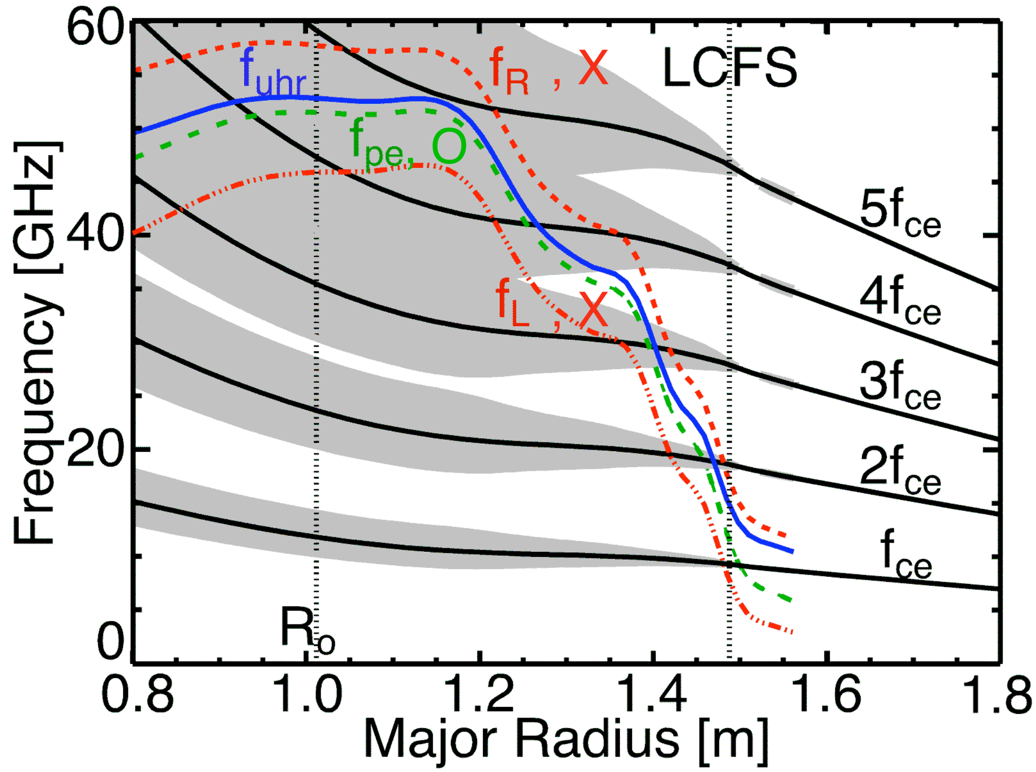
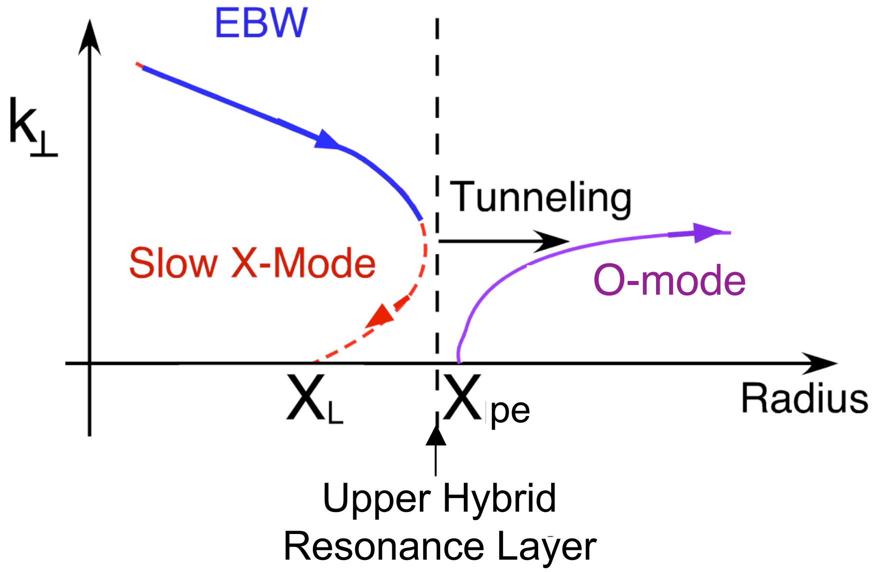
- EC waves used in tokamaks for current drive (CD), heating and $T_e(R)$ measurements
- NSTX has low magnetic fields and high n_e, cutting off up to first 6 EC harmonics
  - EBWs are strongly absorbed/emitted from EC harmonics
- EBWs cannot propagate in vacuum outside upper hybrid resonance (UHR) layer



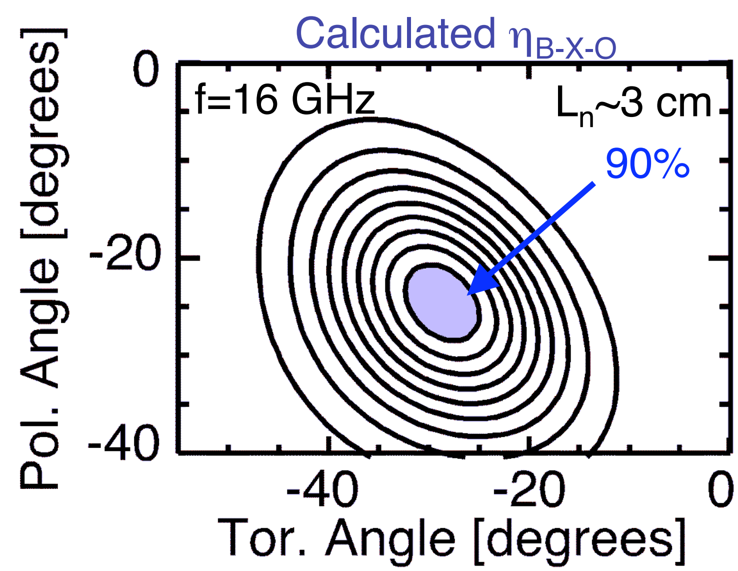
EBW emission data can be used to provide coupling efficiency and polarization information for heating and current drive system

EBW coupling to electromagnetic waves



- EBW emitted at EC harmonic converts to X-mode at UHR and then O-mode
- Emission elliptically polarized due to oblique view of plasma
- $\eta_{B\text{-}X\text{-}O}$ less sensitive to L_n than $\eta_{B\text{-}X}$

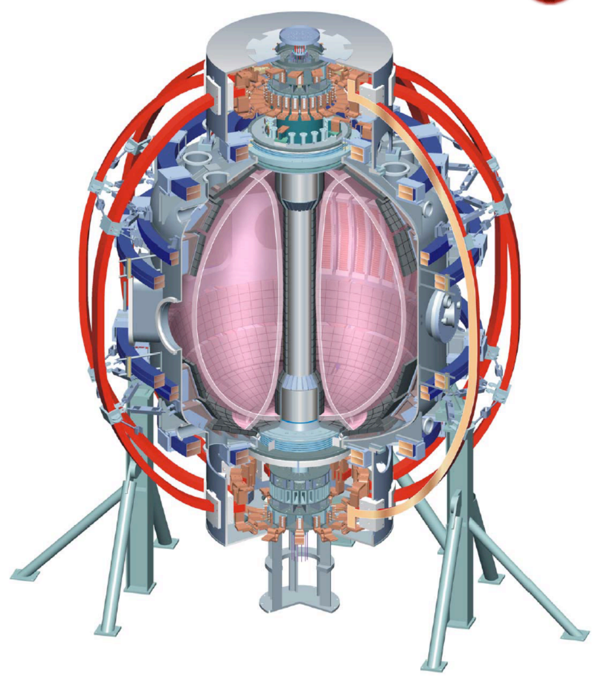
- B-X-O transmission angle depends on field and pitch (~30-45°) at MC layer
- L_n at MC layer determines width of window
- Measured T_{rad} = local T_e provided $\eta_{B\text{-}X\text{-}O}$ ~ 100%



B-X-O emission provides method to investigate feasibility of O-X-B injection

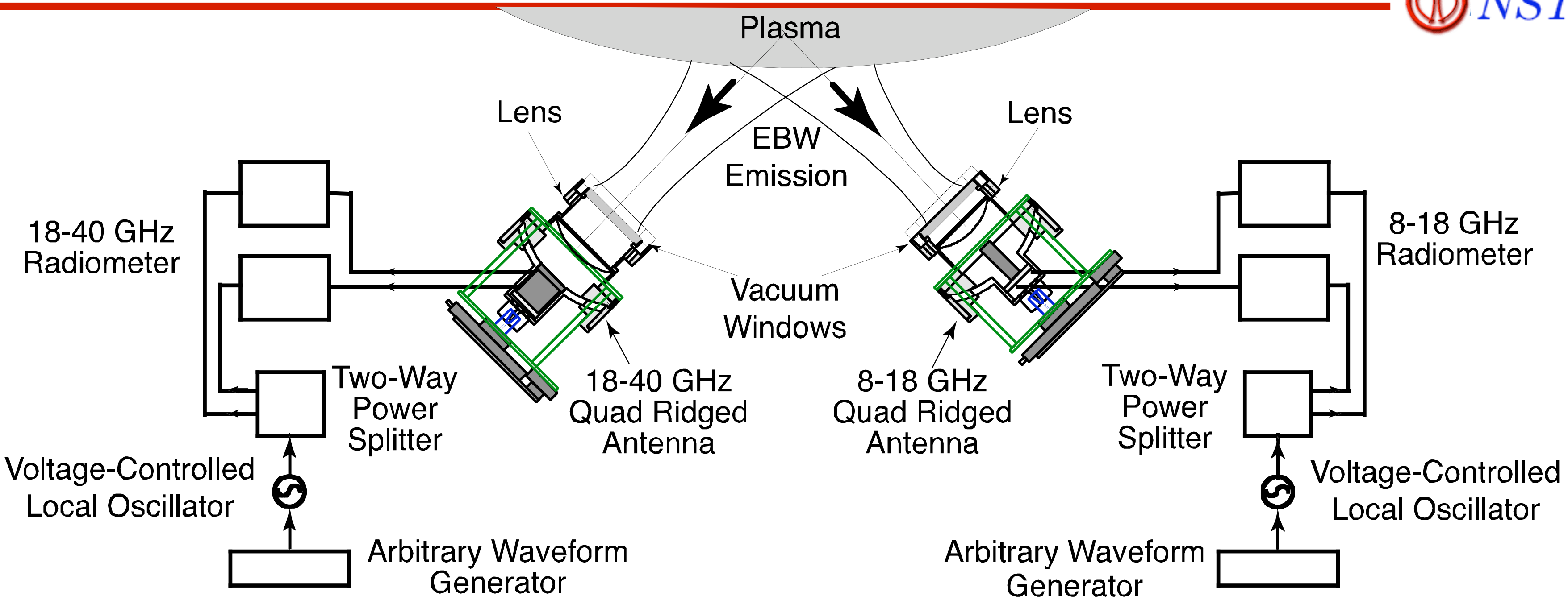
NSTX

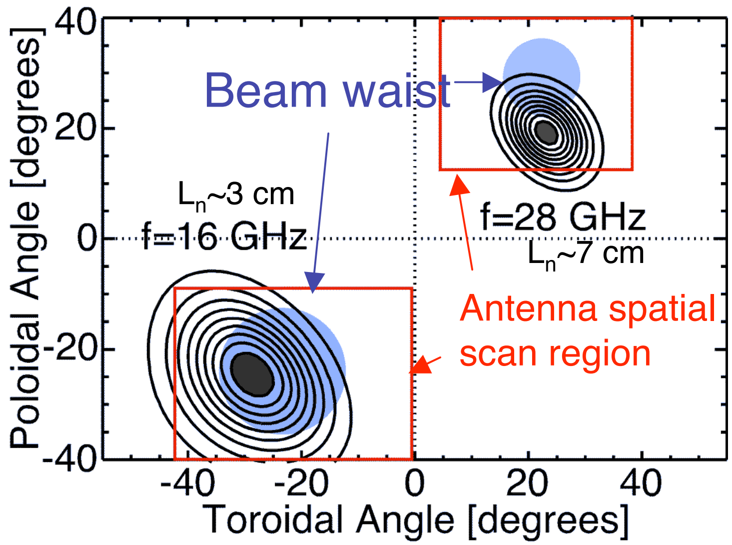
- For NSTX plasmas, τ~3000 near EC harmonics
  - EBW emission is at blackbody levels
  - Radiometer can be absolutely calibrated to provide $T_e(R,t)$
- Experiments focused on optimizing $\eta_{B\text{-}X\text{-}O}$ and comparing to theoretical predictions
  - Physics of B-X-O emission and O-X-B injection are symmetric
  - Finding optimal conditions of B-X-O emission economically provides information on optimizing O-X-B injection



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}

Remotely steered EBE diagnostic allows spatial mapping of emission window





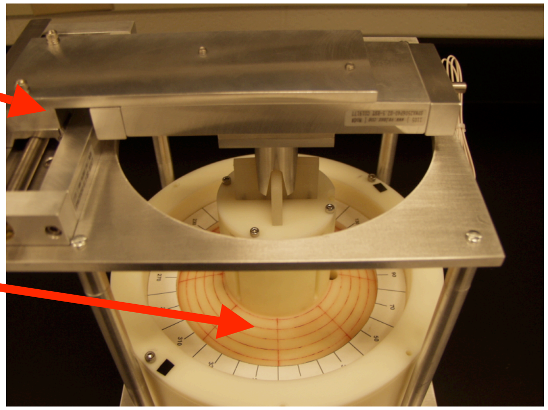
- ±10° scan in poloidal and toroidal directions between discharges
- Acceptance angle:
  - 8-18 GHz antenna ~ 22°
  - 18-40 GHz antenna ~14°

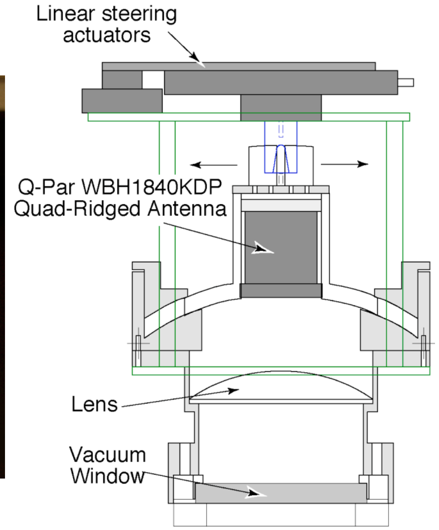
S.J. Diem, et al, Rev. Sci. Instrum. **77** (2006)

Linear actuators allow ± 10° poloidal and toroidal steering

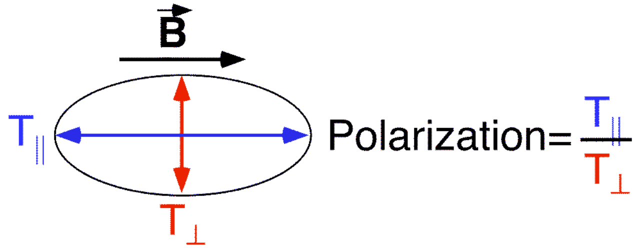
- Two drives provide motion in poloidal & toroidal direction
- Spherical housing provides steering
- Antennas located outside vacuum vessel

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 optimization of B-X-O transmission efficiency
  - Needed to explore the feasibility for EBW based heating & CD

Mounting system designed by J. Caughman (ORNL)

EBE simulation code includes EBE antenna pattern and 3-D plasma equilibrium

NSTX

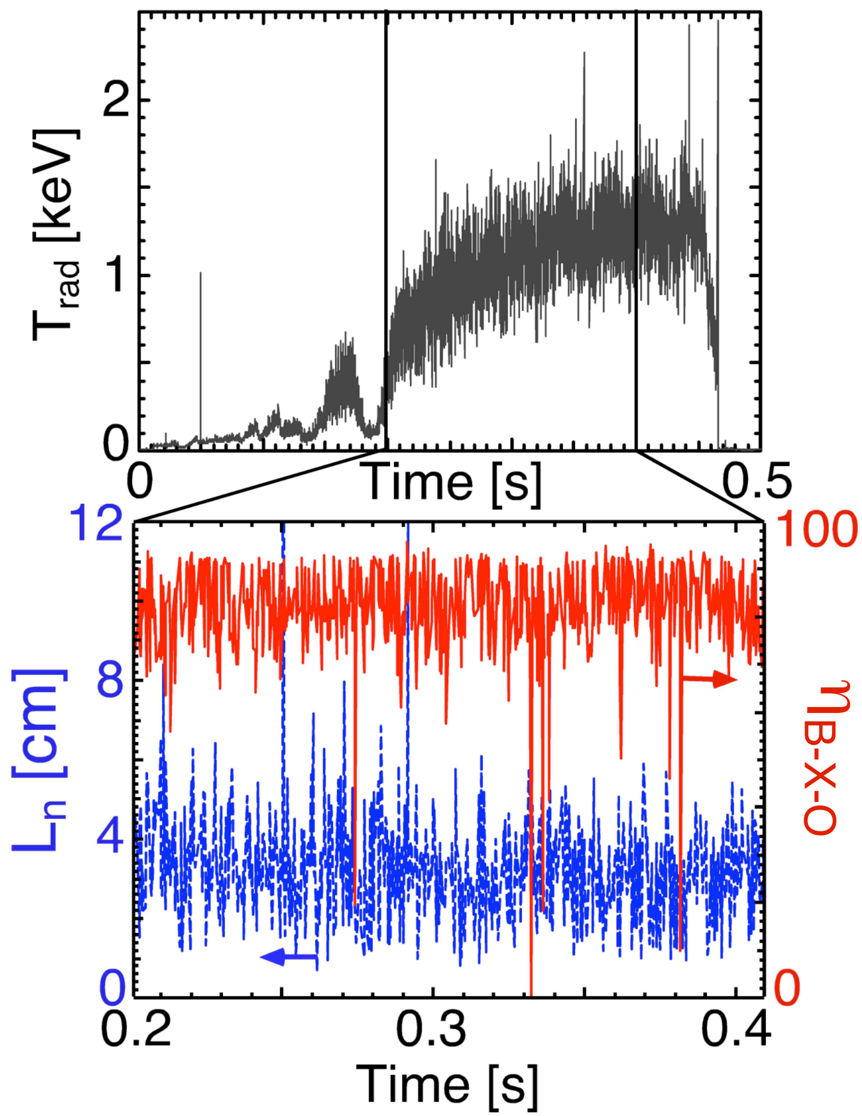
- Code inputs:
  - Magnetic equilibria (EFIT)
  - T_e & n_e profiles from Thomson scattering
  - Antenna pattern measurements
- Beam is modeled by a symmetric distribution of 41 rays
- Mode conversion (MC) efficiency is determined by the full wave solution for a cold plasma slab
- 3D ray-tracing code 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)

Large T_{rad} fluctuation are predominately due to changes in B-X-O transmission efficiency

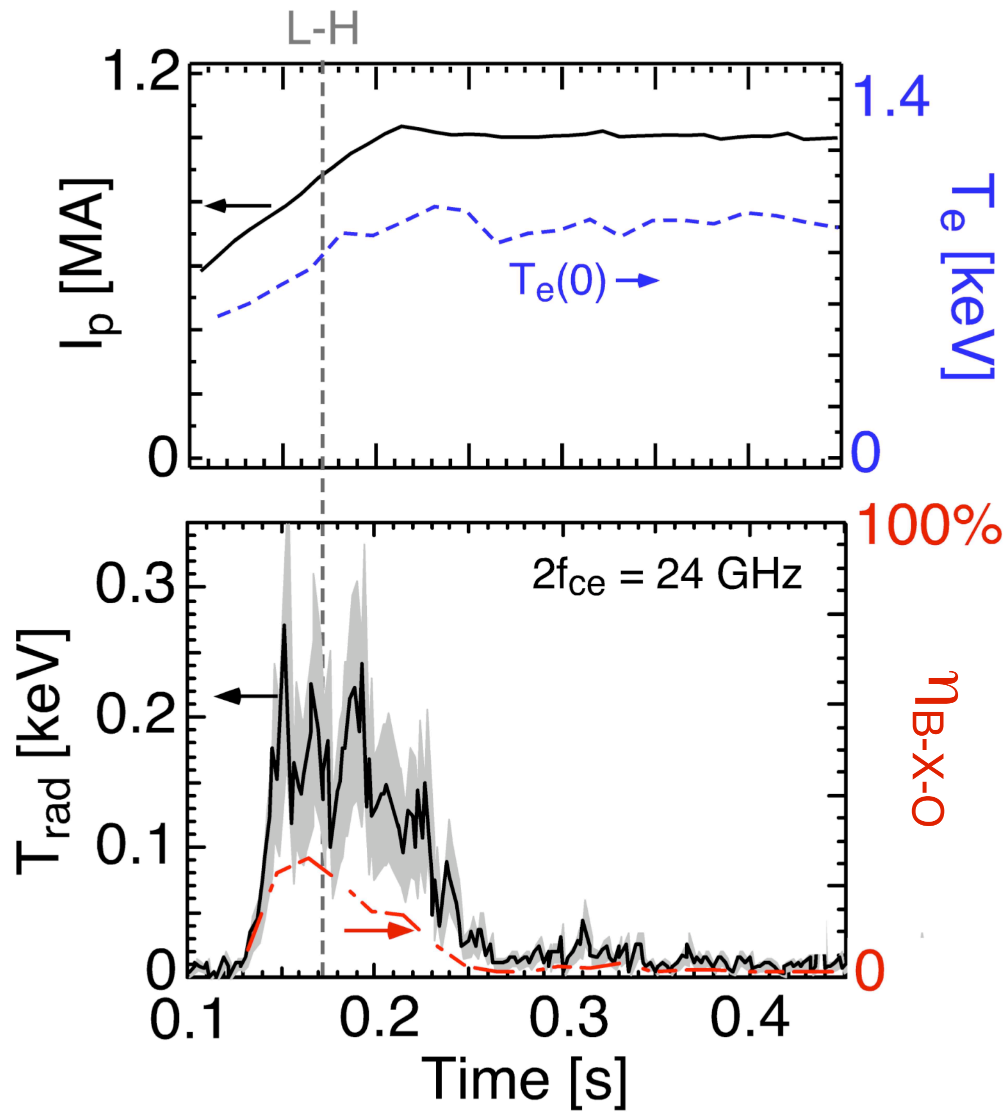
- T_{rad} fluctuates > 30% for all frequencies
- Edge reflectometer used to measure n_e profile
  - Measured L_n fluctuates from 1 cm to 6 cm
- Theoretical $\eta_{B\text{-}X\text{-}O}$ computed using measured L_n values
  - Varies as ~ e^{L_n}
- Fluctuation levels of T_{rad} (30%) and $\eta_{B\text{-}X\text{-}O}$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

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



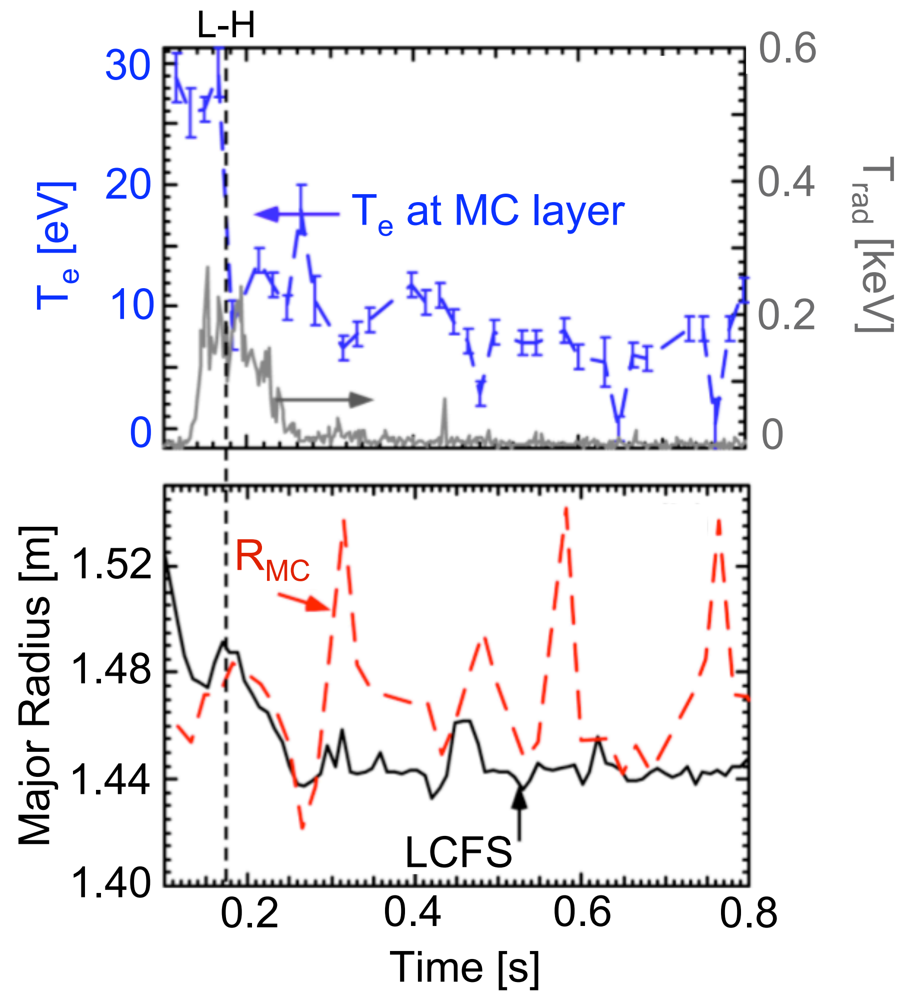
Initial H-mode EBE measurements exhibited decay in measured T_{rad} during H-mode phase

- H-mode regime focus of ST research
  - Need efficiency EBW coupling in H-mode
- Emission decays after L-H transition
  - Observed for f_{ce}, $2f_{ce}$ and $3f_{ce}$ emission
  - Emission location remains constant during discharge
- Leads to $\eta_{B\text{-}X\text{-}O} \sim 0\%$ during H-mode
  - Low EBE levels do not support EBW heating & CD



Explanation for reduced EBE: Collisional damping

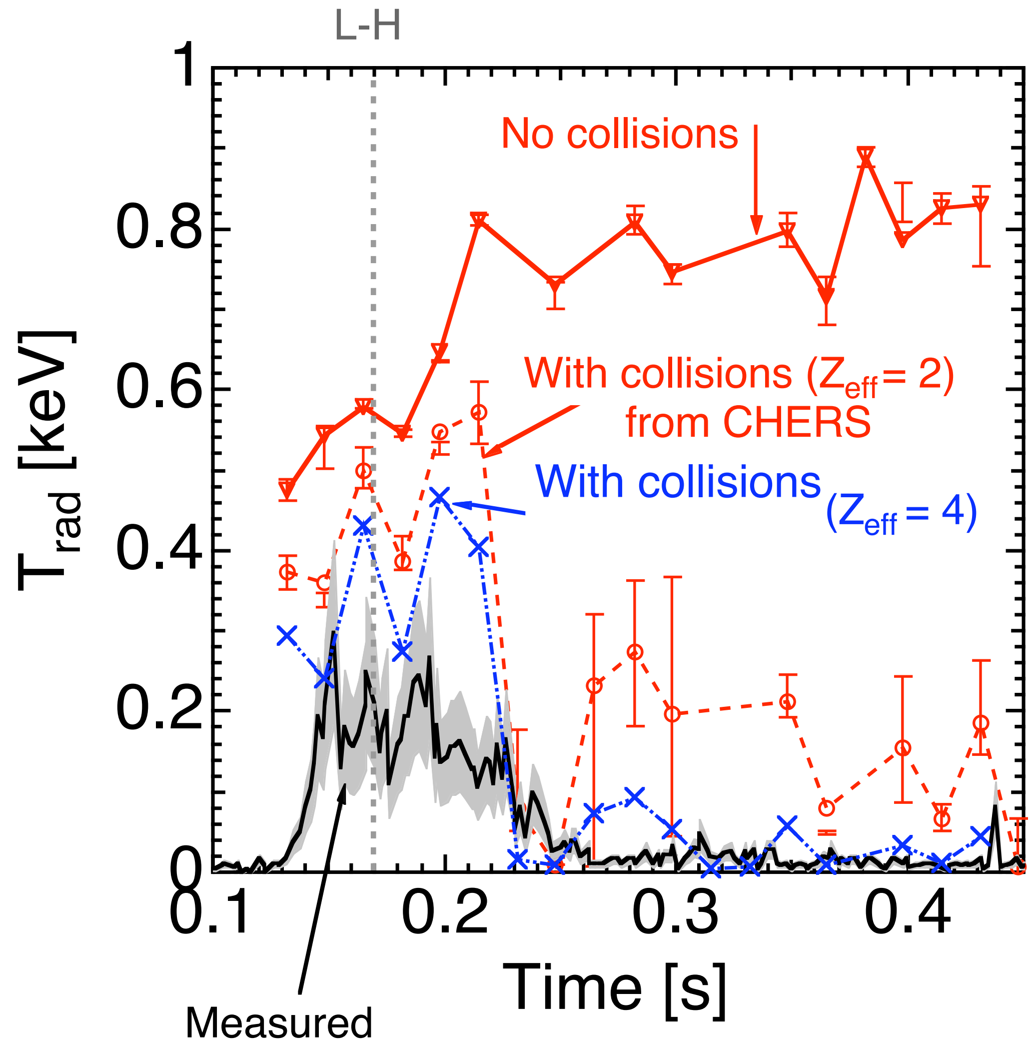
- After L-H transition, the MC layer moved outside last closed flux surface (LCFS)
  - T_e at MC layer reduced from 25 eV to 10 eV, increasing collisionality
- Simulations show collisional damping becomes significant for $\upsilon_{ei}/\omega > 10^{-4}$
  - Typically occurs for T_e < 20 eV near MC layer in NSTX
- Only the e-i collisions contribute to EBW collisional damping
  - e-e collisional effects neglected due to momentum conversion
  - e-neutral effects neglected because neutral density is less than $0.05n_e$



Introducing EBW collisional damping to simulations reproduces observed EBE collapse at L-H transition

- MC layer moves outside LCFS after L-H transition
  - T_e < 20 eV outside LCFS

- Simulations with collisional damping predict T_{rad} decay during H-mode
  - CHERS measurement 5 cm inboard from UHR yields Z_{eff} = 2
  - Simulations with Z_{eff} = 3,4 have closer agreement with measured T_{rad}

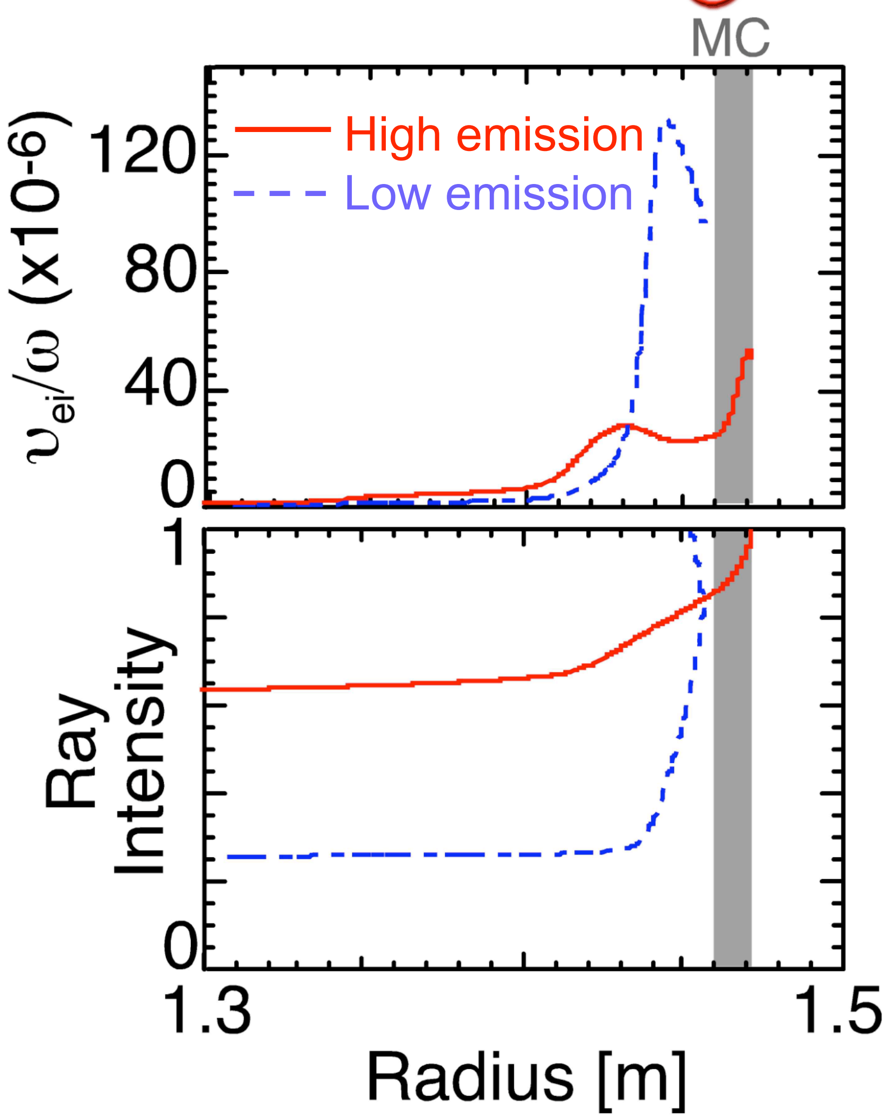


EBE simulations indicate increase in edge υ_{ei} results in significant loss in ray intensity

- Relative collision frequency increases after L-H transition:
  - Peak υ_{ei}/ω increases from $5x10^{-5}$ to $1.2x10^{-4}$

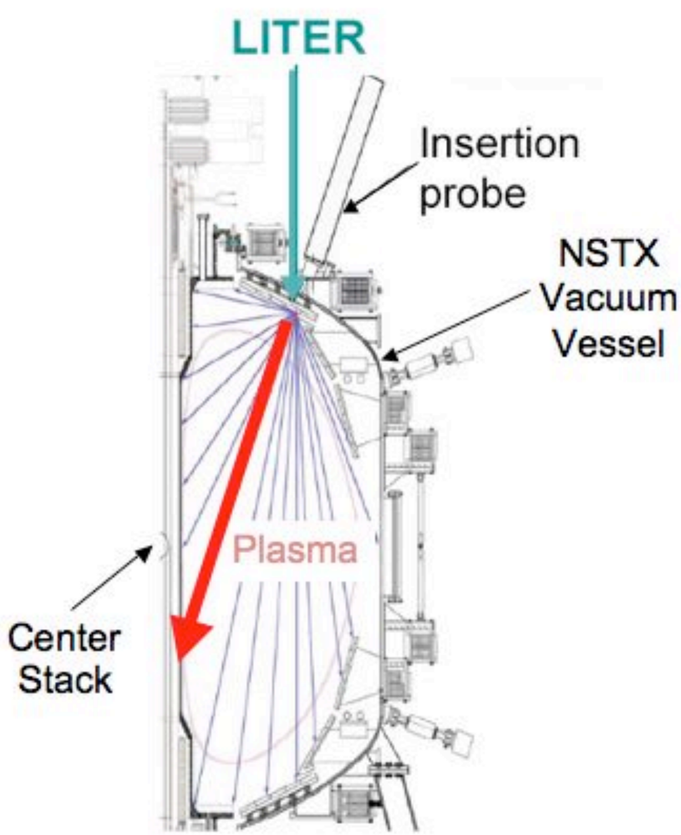
- Damped EBW power increases from 20-40% in the L-mode phase to 70-90% during H-mode

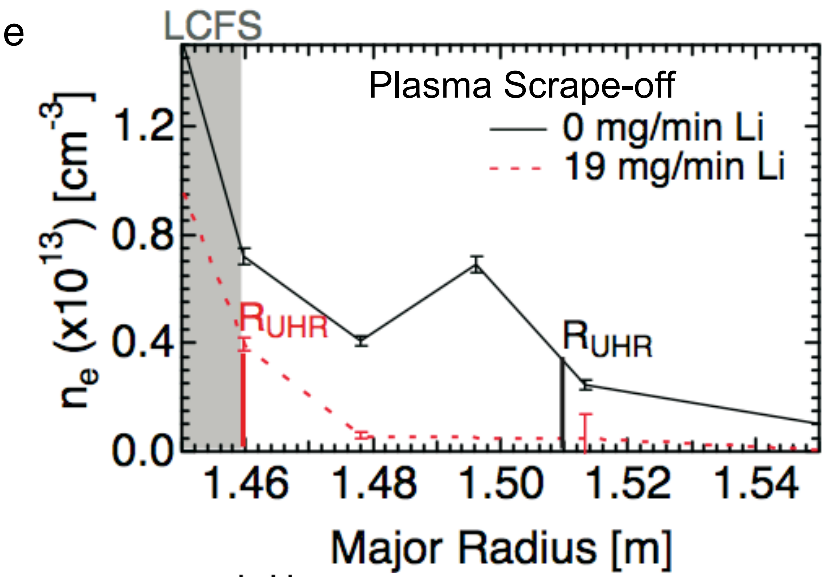
Need method to reduce collisionality near UHR layer → Li conditioning

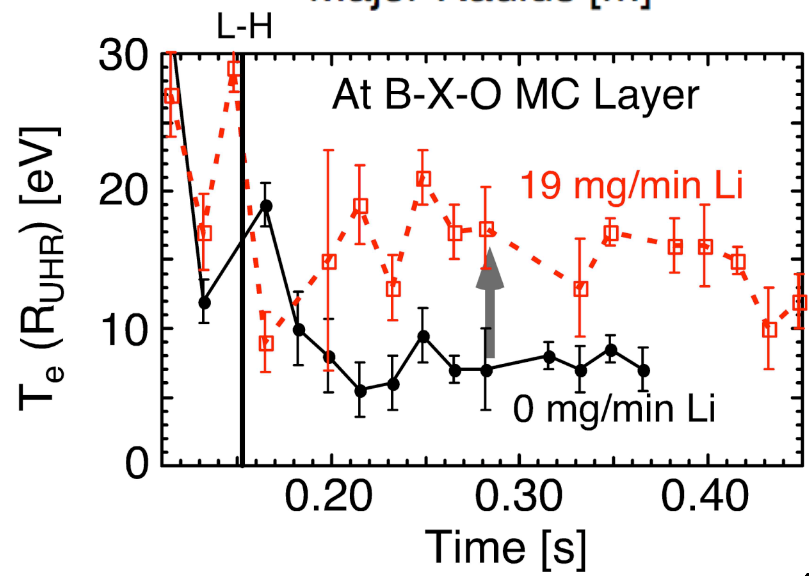


LIThium EvaporatoR (LITER) provides edge conditioning tool for NSTX

- B-X-O coupling depends on L_n and T_e
  - Li conditioning ↑T_e & ↓n_e near MC
- Reduction in edge n_e moves MC layer to LCFS where T_e ~ 20 eV



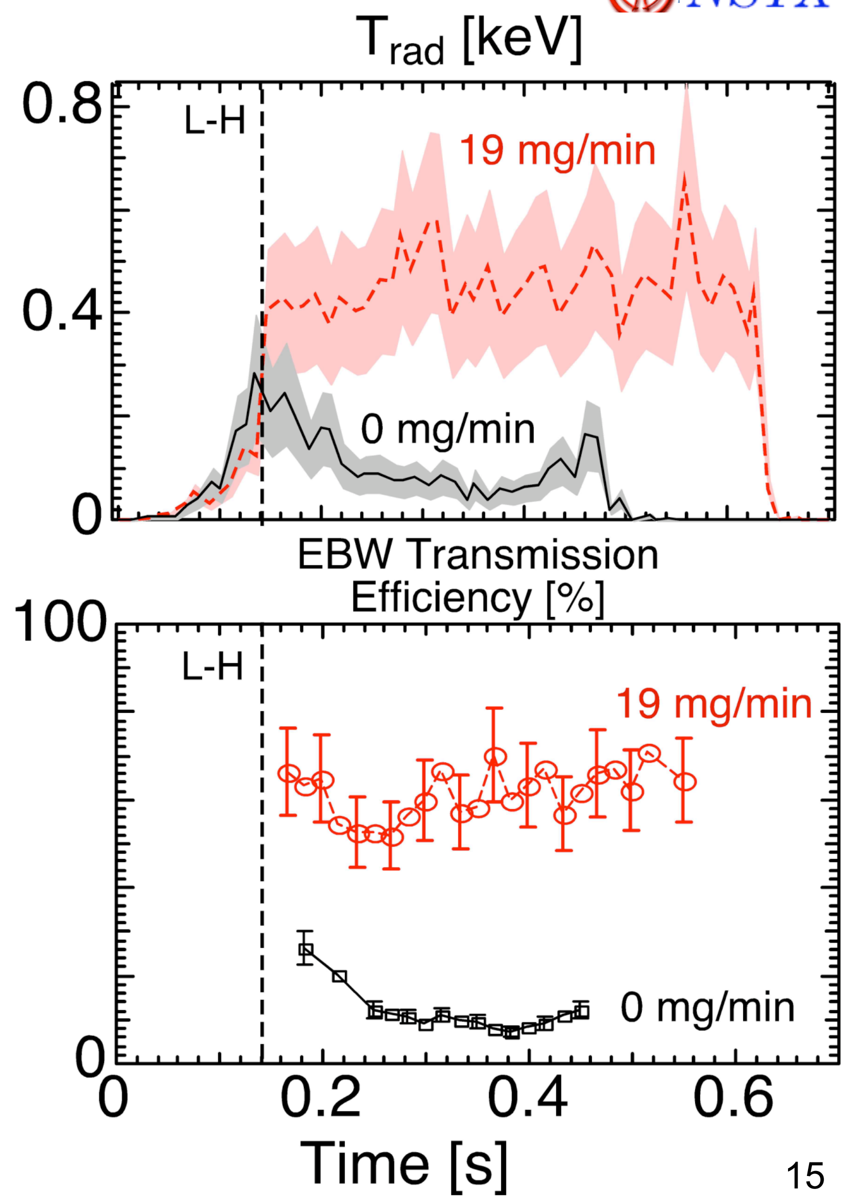




H-mode $\eta_{B\text{-}X\text{-}O}$ increased with Li edge conditioning

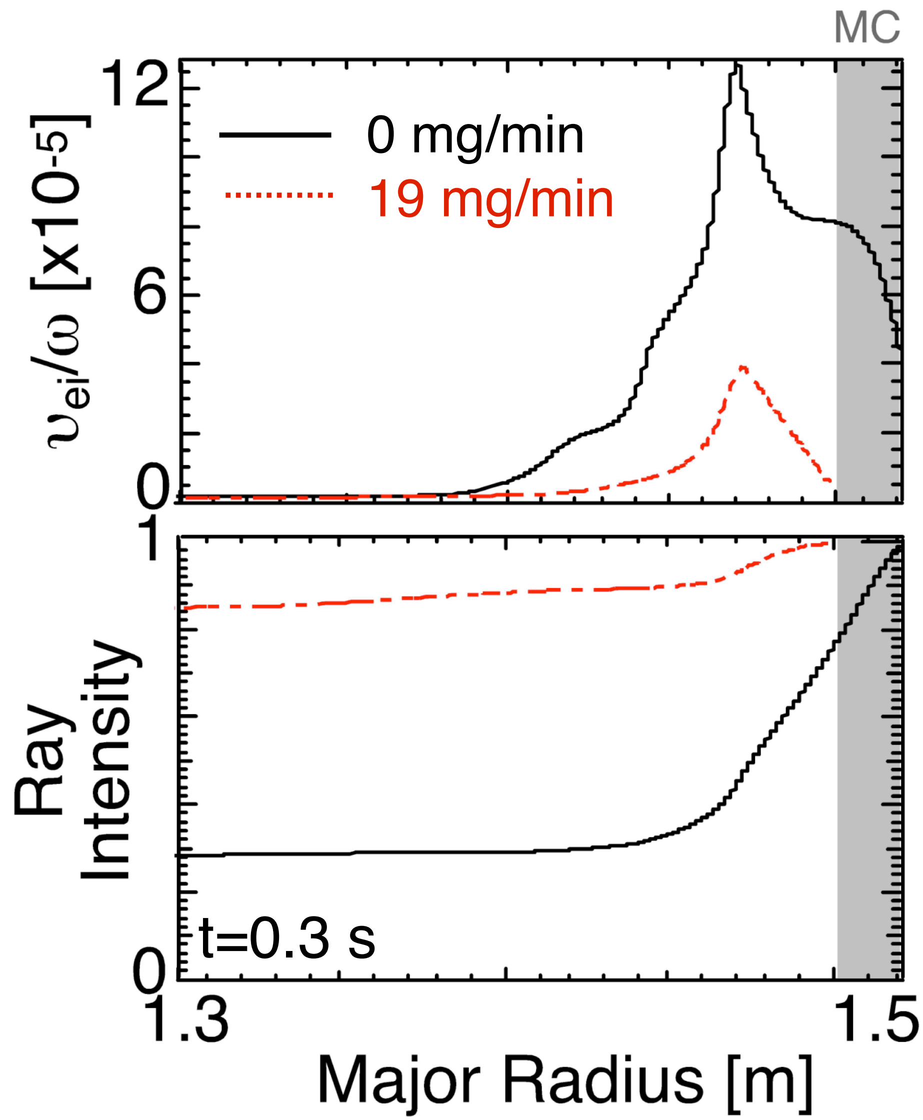
- Measured T_{rad} increased from ~ 50 eV to ~ 400 eV
  - 18 GHz emission from near plasma axis
- $\eta_{B\text{-}X\text{-}O}$ increased with Li conditioning:
  - From 10% ⟶ 60% for f_{ce}=18 GHz
  - From 20% ⟶ 50% for $2f_{ce}$=28 GHz
- Control of edge conditions provides good coupling to EBW

Increased B-X-O coupling supports EBW heating & CD possible in future ST devices



EBE simulations show reduction in edge collisionality with increased Li evaporation

- Collisional effects dominate without edge conditioning and reduce emission
  - υ_{ei} decreased by factor of 4
- Without edge conditioning, 70% of EBW power lost through collisional damping
- Simulations suggest ray intensity increases from 30% to > 80% near MC with Li

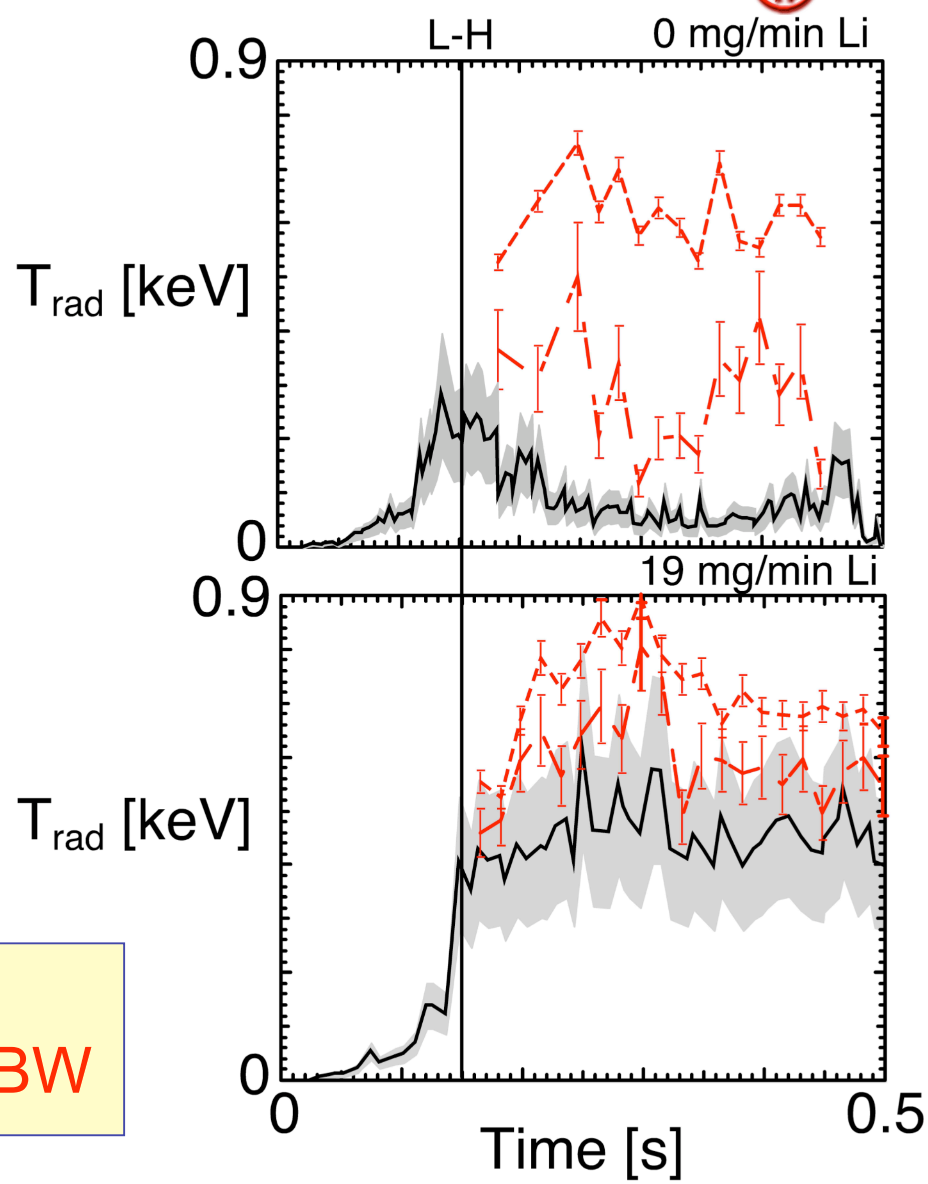


Better T_{rad} agreement with EBE simulation in Li conditioned plasma

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

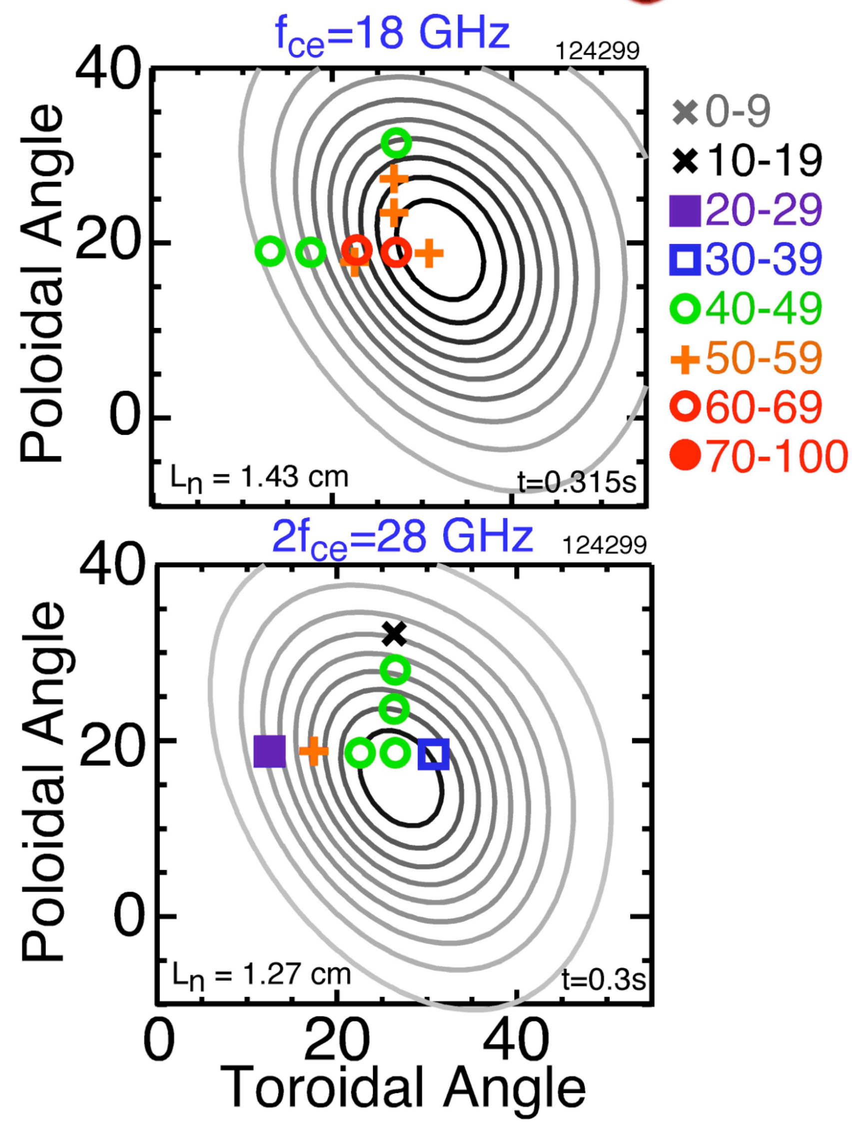
- For highest Li evaporation rate, 19 mg/min:
  - Measured T_{rad}~0.4 keV
  - Simulated T_{rad}~0.6 keV
- For 0 mg/min:
  - Measured T_{rad}~0.1 keV
  - Simulated T_{rad} ~0.4 keV

Control of edge conditions allows for good coupling to EBW



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

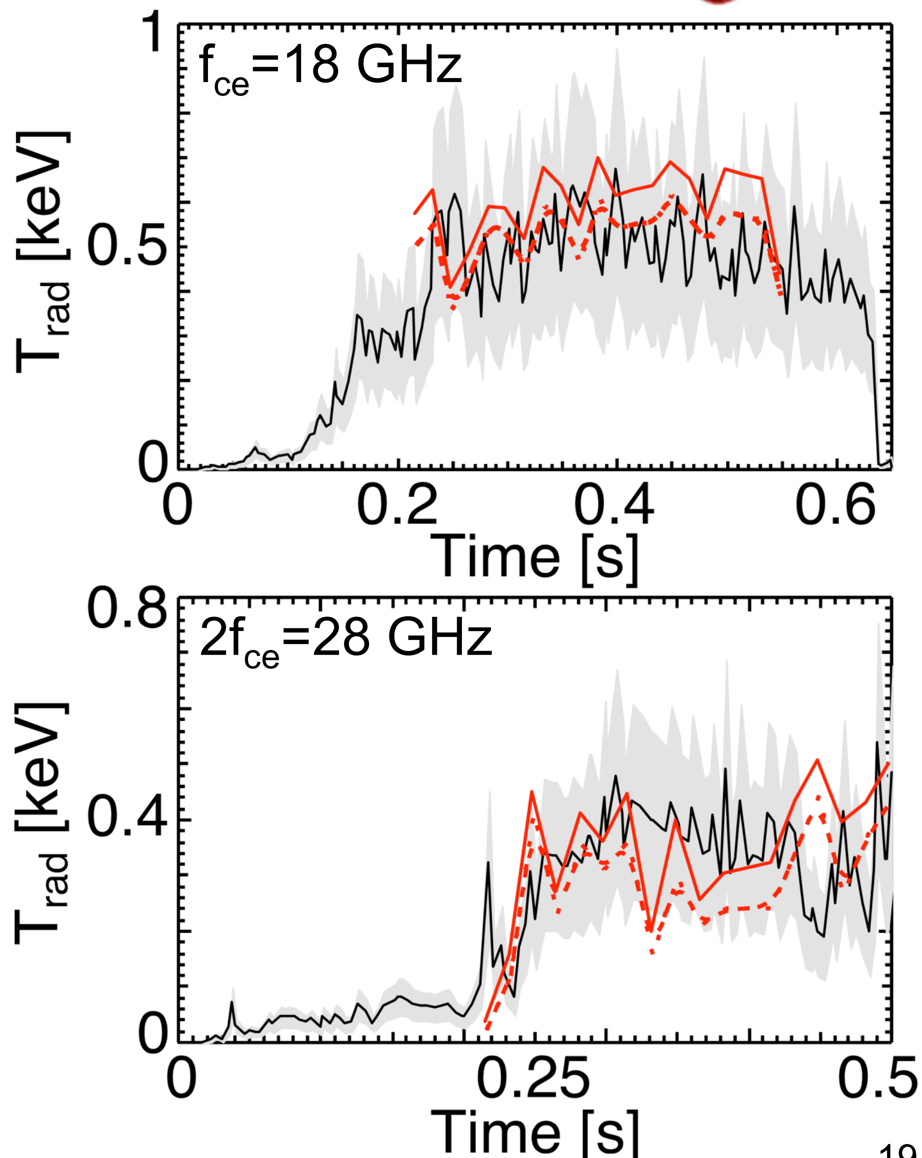
- Repeated target plasma, (I_p =0.9 MA, $T_e(0)$~1keV) with Li conditioning
- Maximum measured transmission efficiencies:
  - 62±15% for f_{ce}=18 GHz near axis emission
  - 49±15% for $2f_{ce}$=28 GHz near axis emission
- Comparable to the simulated $\eta_{B\text{-}X\text{-}O}$ values
  - 90±10% for f_{ce} = 18 GHz
  - 70±10% for $2f_{ce}$ = 28 GHz



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

NSTX

- 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
- Simulated and measured optimal pointing angle agree within 3°

Efficient EBW coupling demonstrated in NSTX H-mode - essential prerequisite for EBWCD in ST-CTF

- Early H-mode EBE measurements exhibited rapid decay in emission level after L-H transition
  - Modeling revealed very low EBE explained by collisional damping of the EBW prior to mode conversion
- First experimental observation of EBW collisional damping
  - Lithium edge conditioning used to reduce edge collisionality
  - $\eta_{B\text{-}X\text{-}O}$ increased from 10% to 60% for fundamental emission at 18 GHz; 20% to 50% for second harmonic emission at 28GHz
- B-X-O transmission efficiency mapped in H-mode
  - 50-60% maximum transmission for f_{ce}=18 GHz & $2f_{ce}$=28 GHz in H-mode
  - Measured, simulated and theoretical optimum angles agree within 5°