Electron Bernstein Wave Research on NSTX & CDX-U

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Electron Bernstein Waves (EBWs) May Provide Local Heating, Current and $T_e(R,t)$ for High β Plasmas

- In high β plasmas, such as the spherical torus (ST), $\omega_{pe} >> \omega_{ce}$
- ECH, ECCD and ECE cannot be used on these high β plasmas
- Electron Bernstein waves (EBWs) propagate when $\omega_{pe} >> \omega_{ce}$
- EBWs have high optical thickness (τ) at ECE resonances; $\tau \sim 300$ for CDX-U, $\tau \sim 3000$ for NSTX
- EBWs do not propagate outside the upper hybrid resonance but can convert to electromagnetic modes

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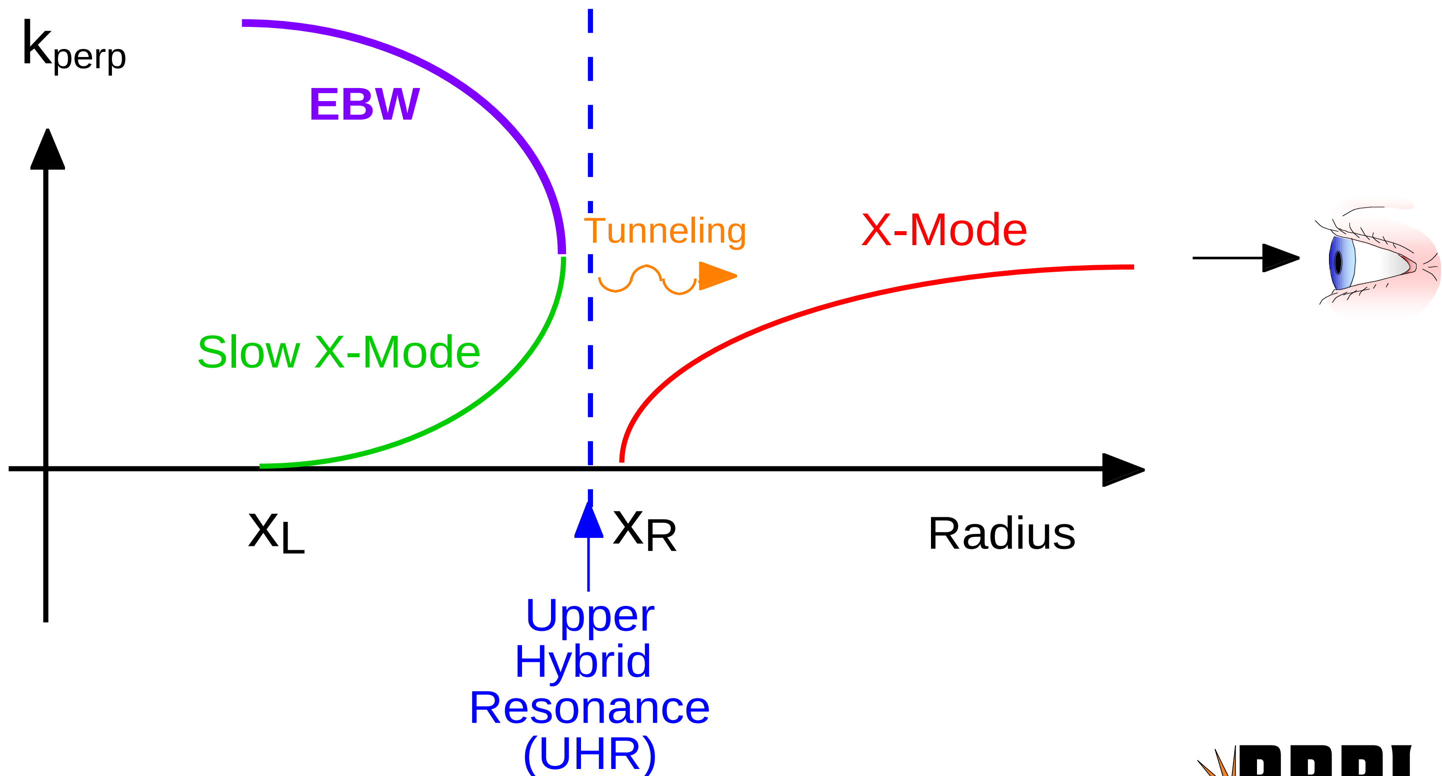
EBW Emission on NSTX and CDX-U Measured via Mode Conversion to Fast X-Mode

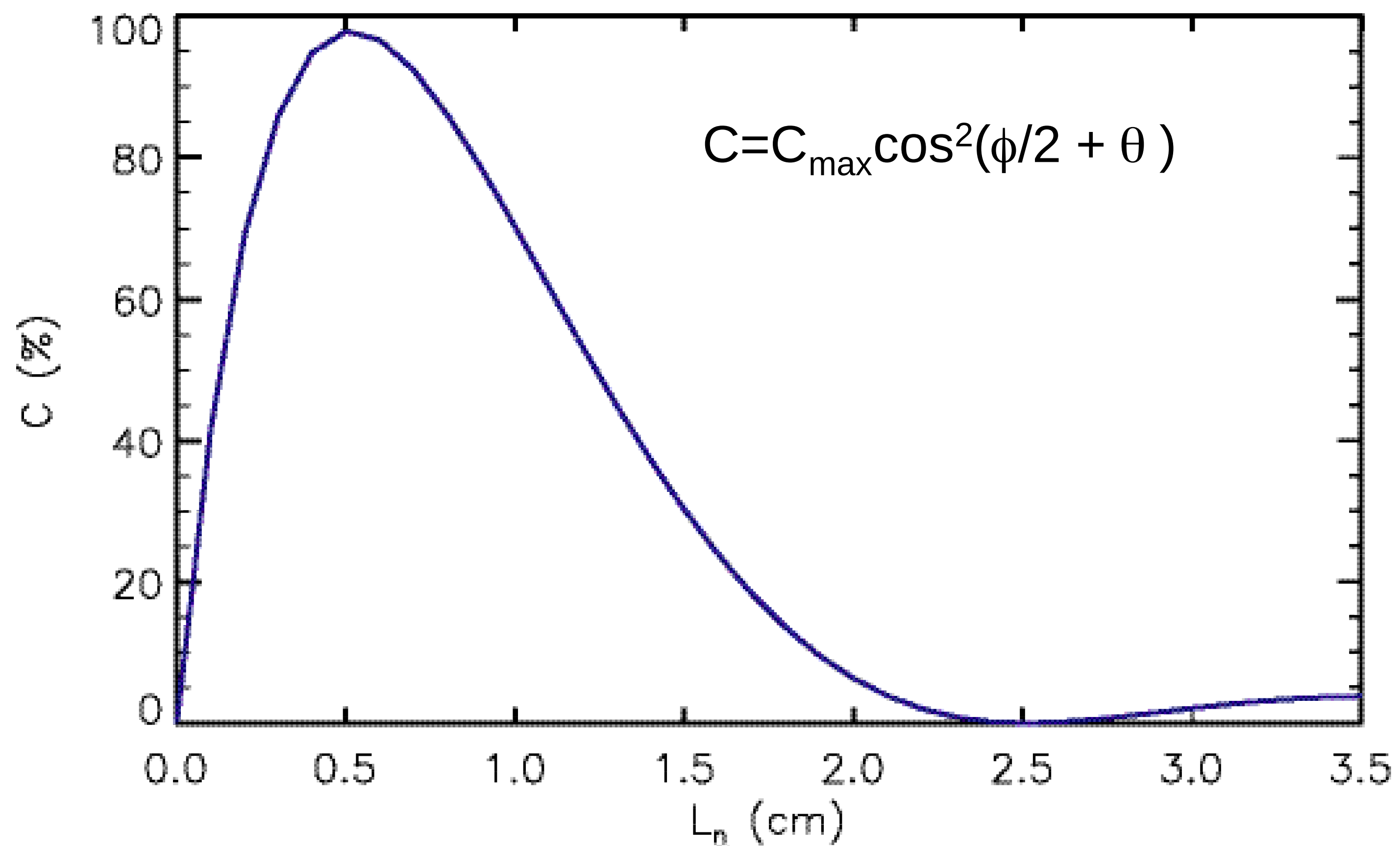
- If L_n is short at UHR, EBW tunnels to fast X-mode:

$$C_{max} = 4e^{-\pi\eta}(1-e^{-\pi\eta}), \qquad \eta \propto L_n$$



For Fundamental EBW Emission on CDX-U, Conversion Efficiency, C ~ 95% for L_n ~ 0.5 cm

CDX-U



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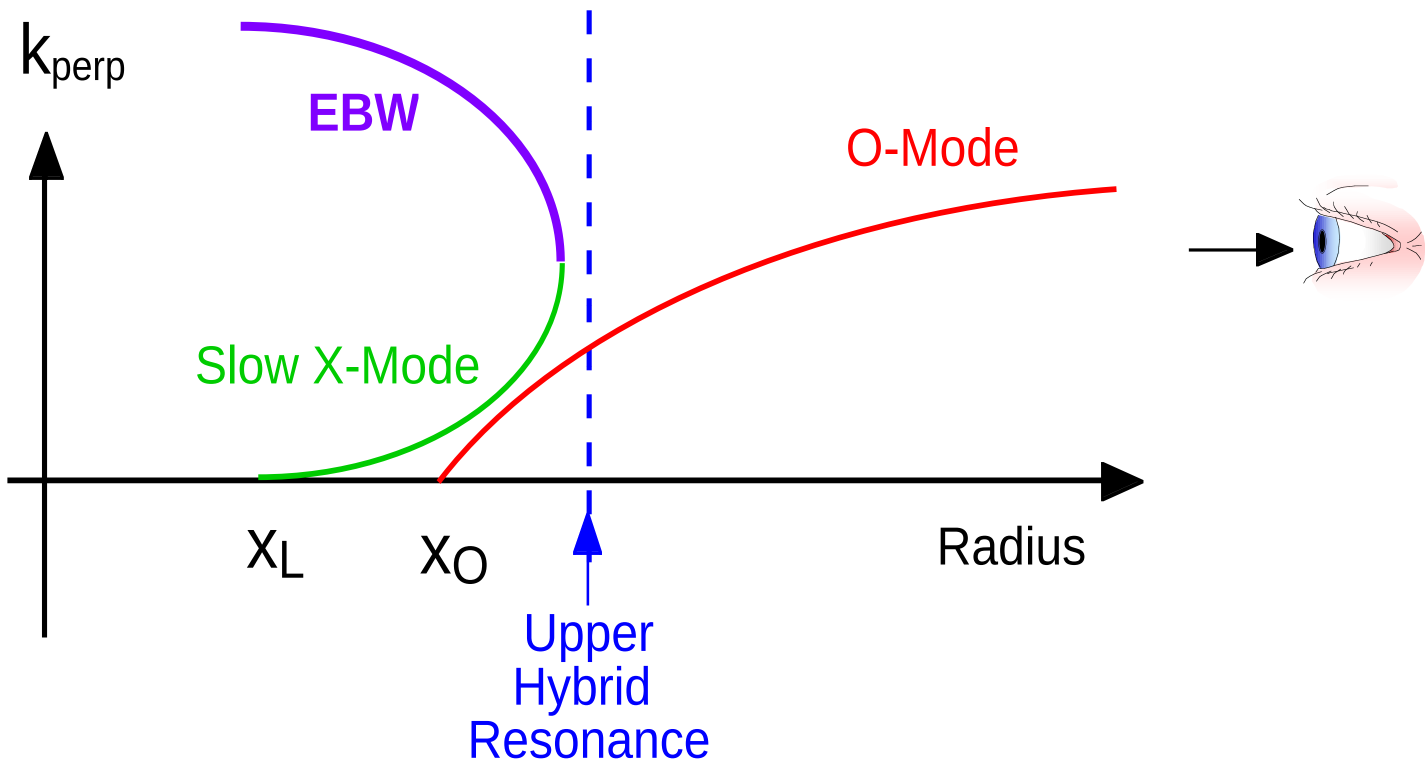
EBW Mode Conversion to O-Mode Possible with Oblique View

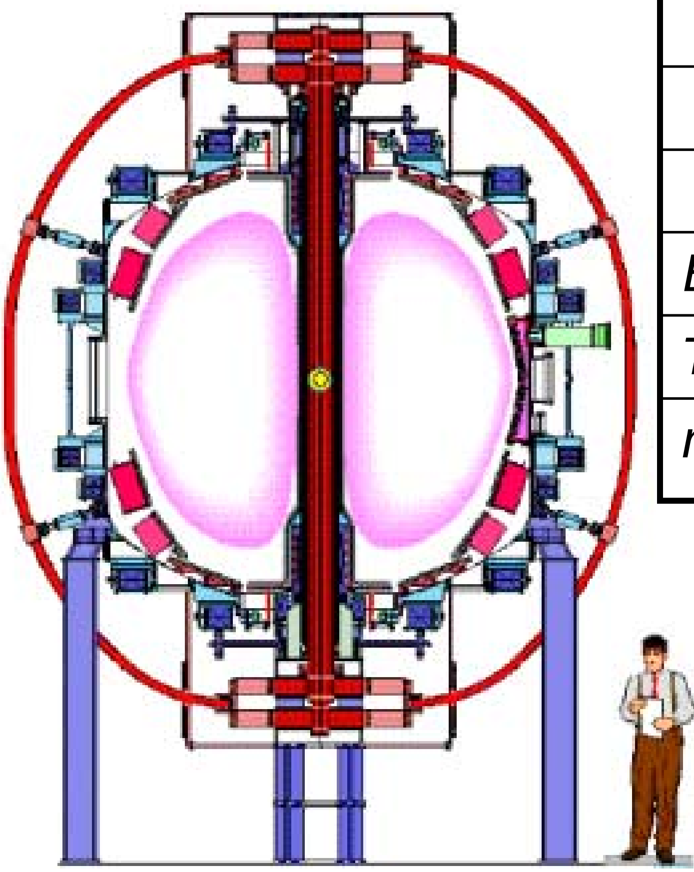
- Extensively studied on W7-AS stellarator



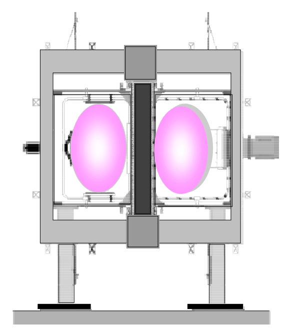
$$T(N_\perp, N_{//}) = \exp\left\{-\pi k_o L_n \sqrt{(Y/2)}\left[2(1+Y)(N_{//,opt} - N_{//})^2 + N_\perp{}^2\right]\right\}$$

On NSTX & CDX-U ω_{pe}/ω_{ce} ~ 3-10 on Axis and ω_{pe}/ω_{ce} >1 Beyond LCFS

NSTX



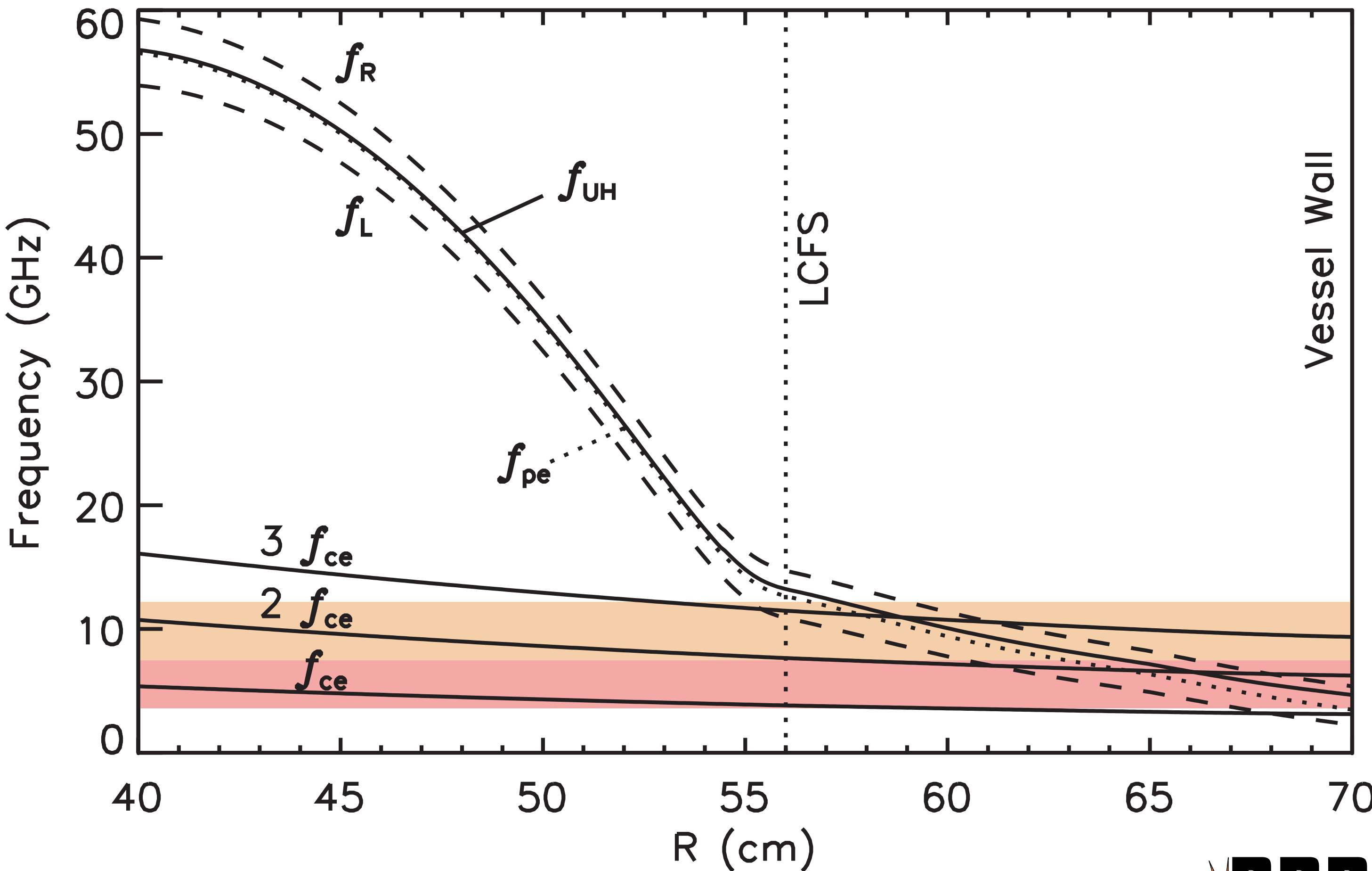
	NSTX	CDX-U
R	85 cm	34 cm
a	68 cm	22 cm
I_p	~ 1 MA	~ 70 kA
$B_t(T)$	0.3 - 0.6	~ 0.2
$T_e(0)$	~ 1 keV	~ 100 eV
$n_e(0)$	0.2-1x10^{14}cm^{-3}	~4x10^{13}cm^{-3}



CDX-U

On CDX-U, f_{ce} & $2f_{ce}$ EBWs Convert to X-Mode Outside Last Closed Flux Surface

CDX-U



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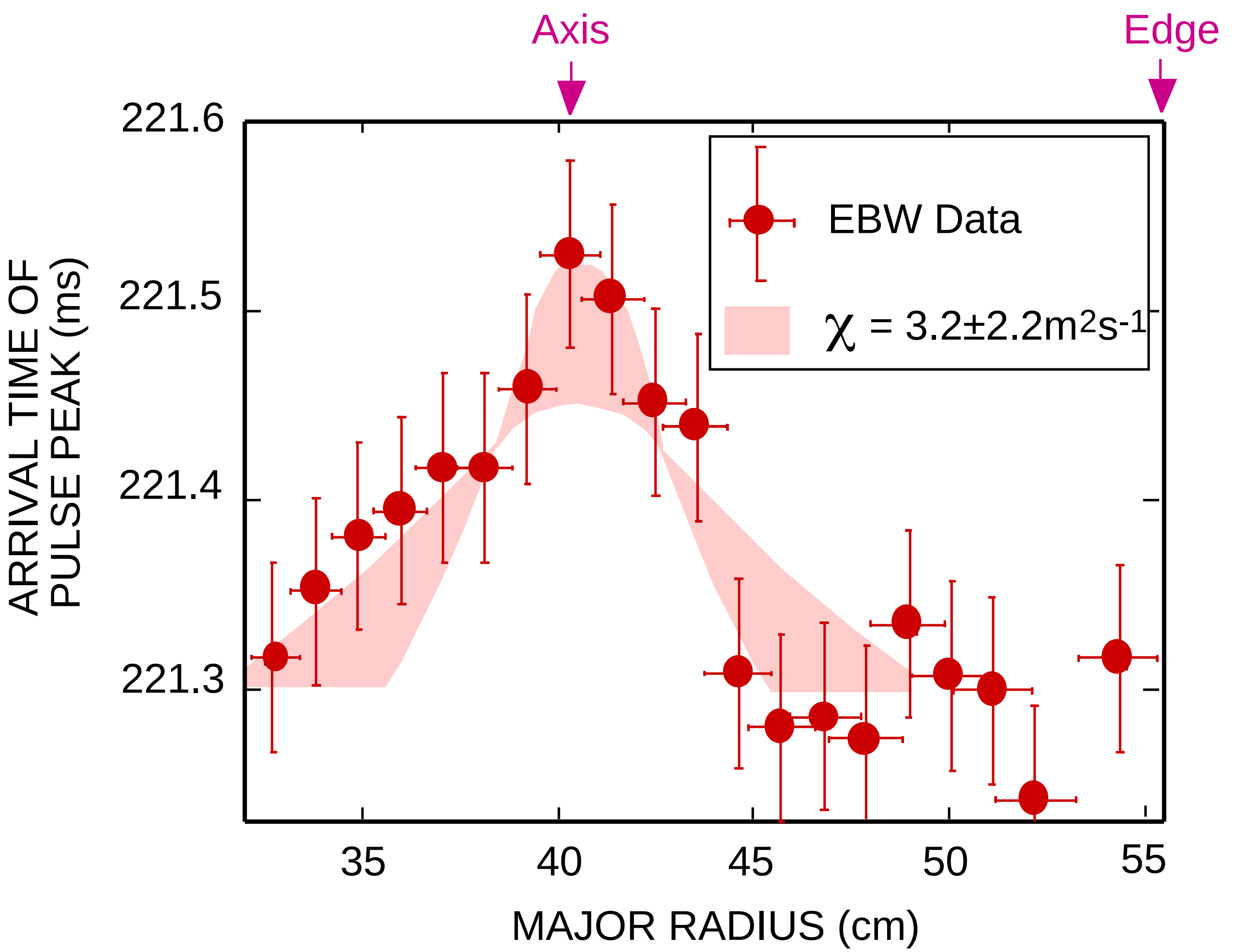
Transport of Cold Gas Puff Measured by EBW Emission; Source Localized at ECE Resonance



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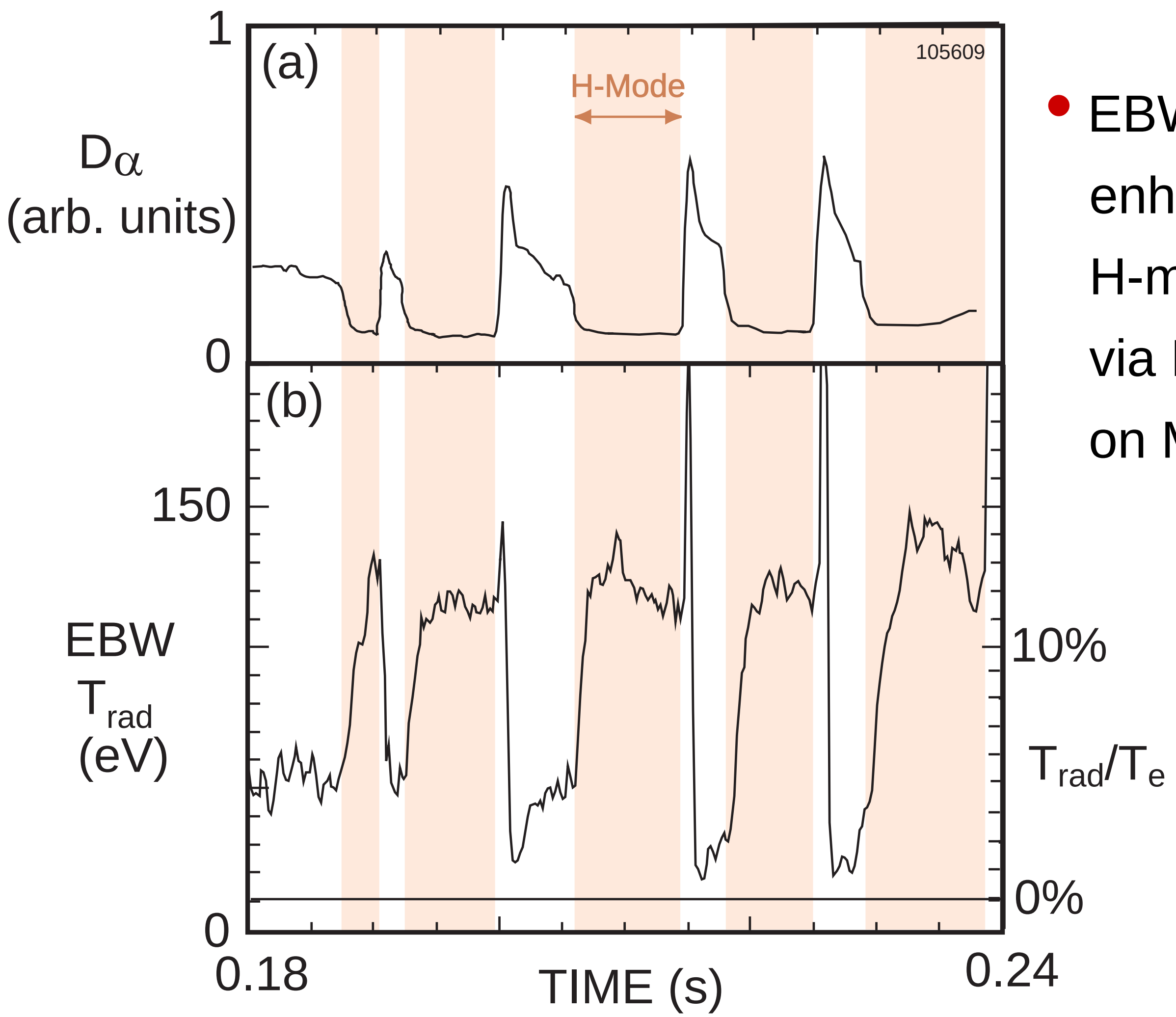
EBW Conversion Efficiency Increases During H-Mode Phase when Edge Density Profile Steepens

NSTX



- EBW conversion enhancement during H-mode also seen via B-X-O conversion on MAST

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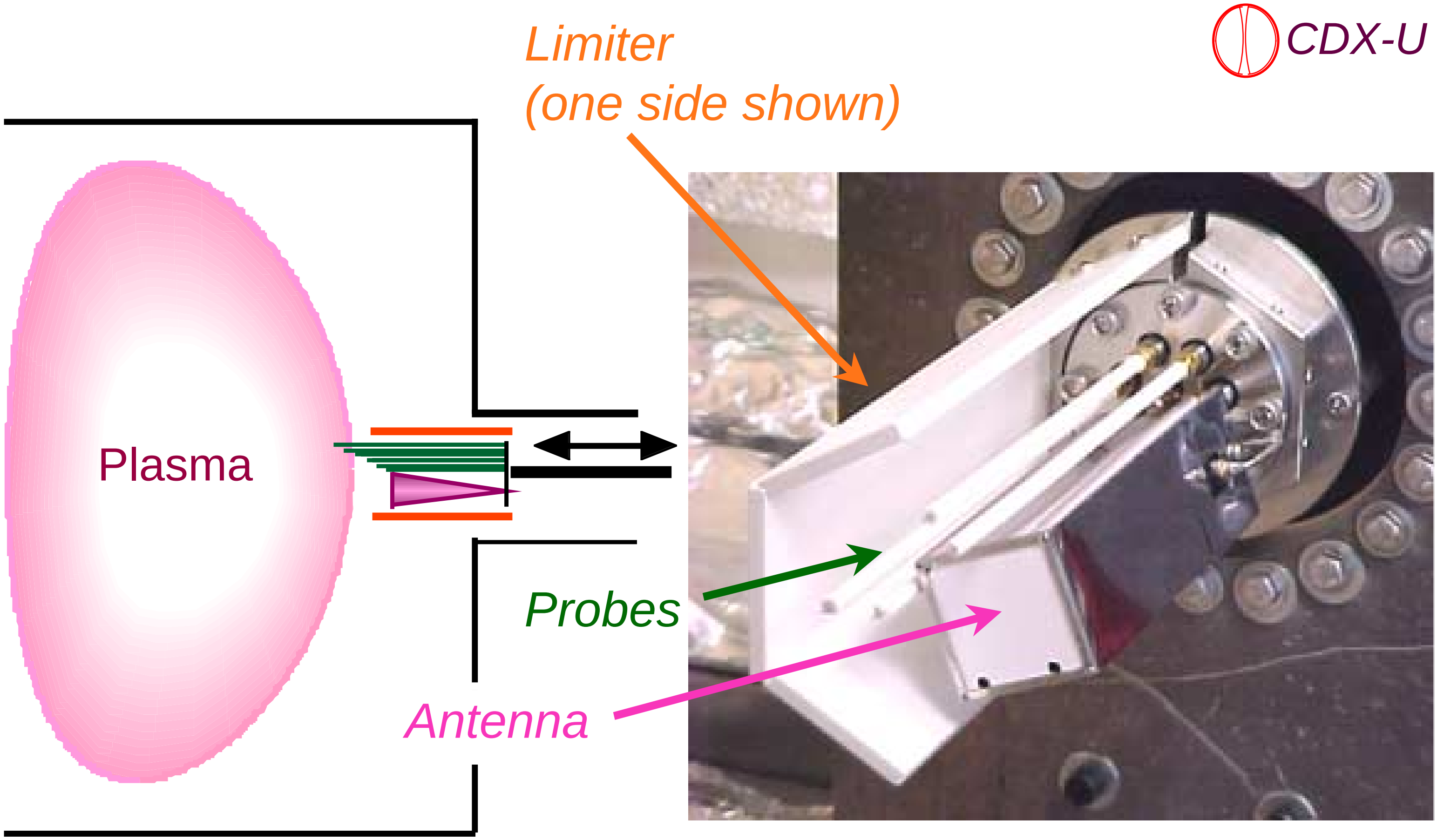
In-Vacuum EBW Antenna with Limiter to Optimize L_n for High Mode Conversion Installed on CDX-U

CDX-U



- Local limiters define L_n in front of antenna
- Probes measure L_n and EBWs directly

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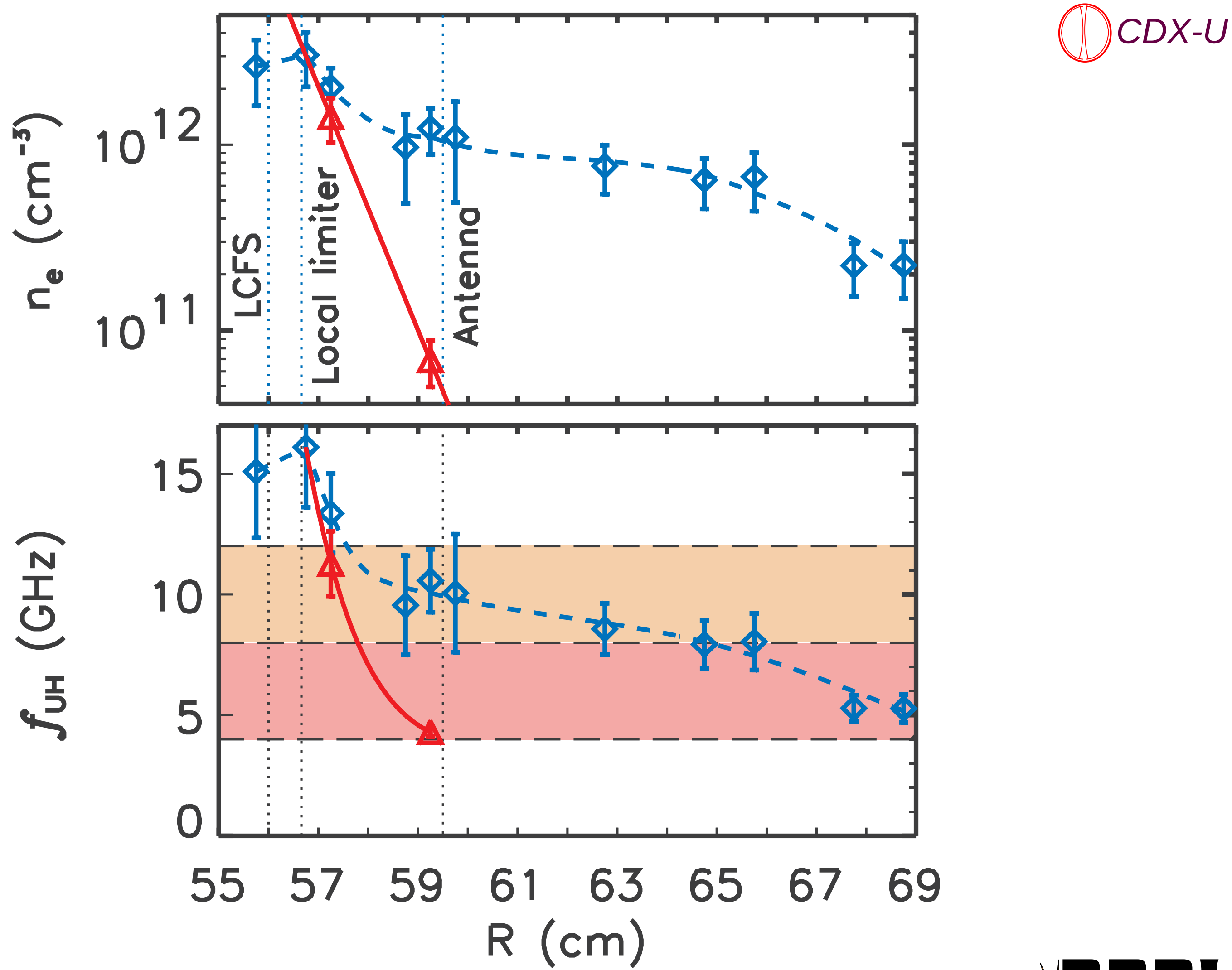
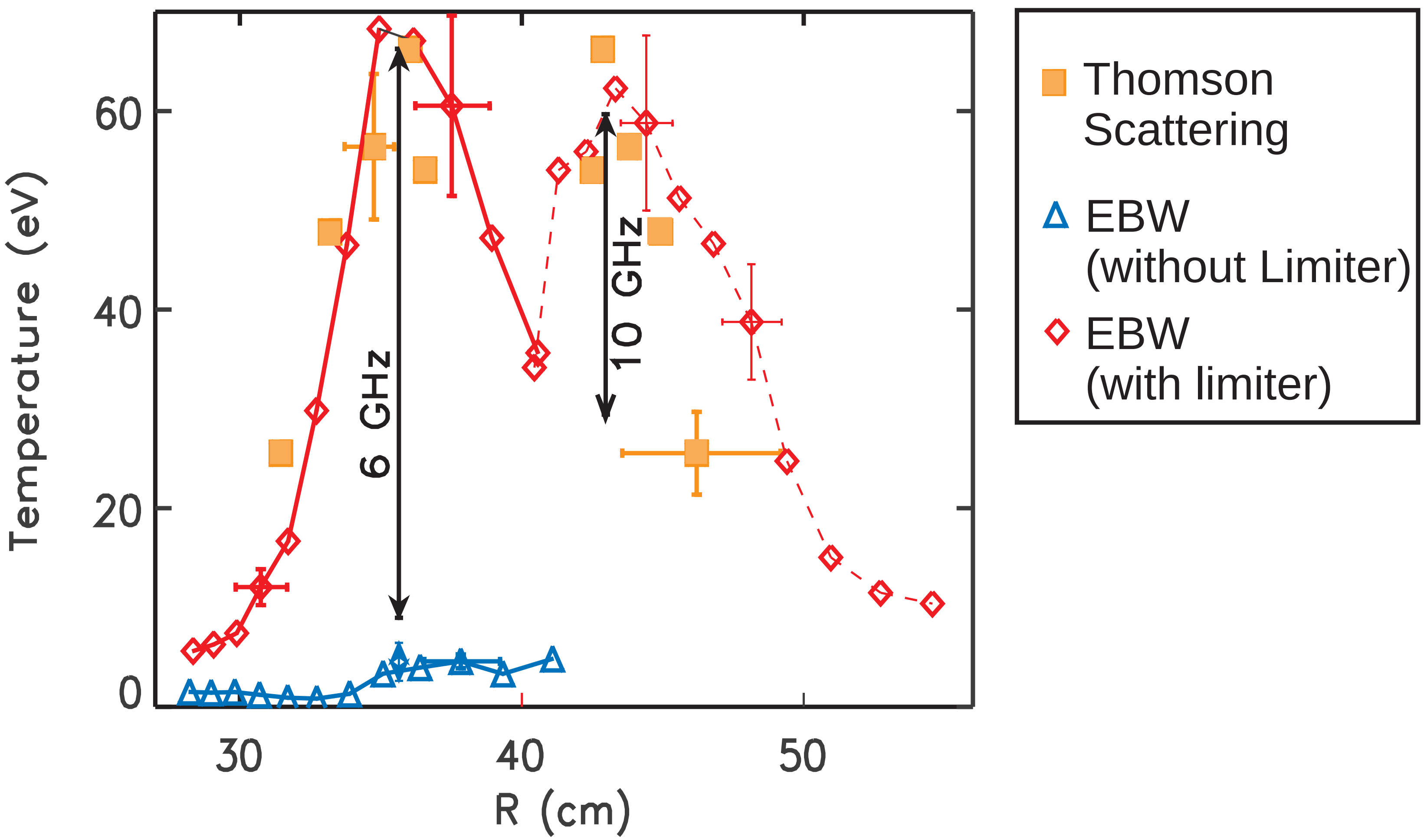
Local Limiter Steepens L_n from 3-6 cm to ~ 0.7 cm in B-X Conversion region for ω_{ce} and $2\omega_{ce}$ EBW



Order of Magnitude Increase in B-X Conversion to T_{rad}/T_e ~ 100% with Local Limiter

CDX-U



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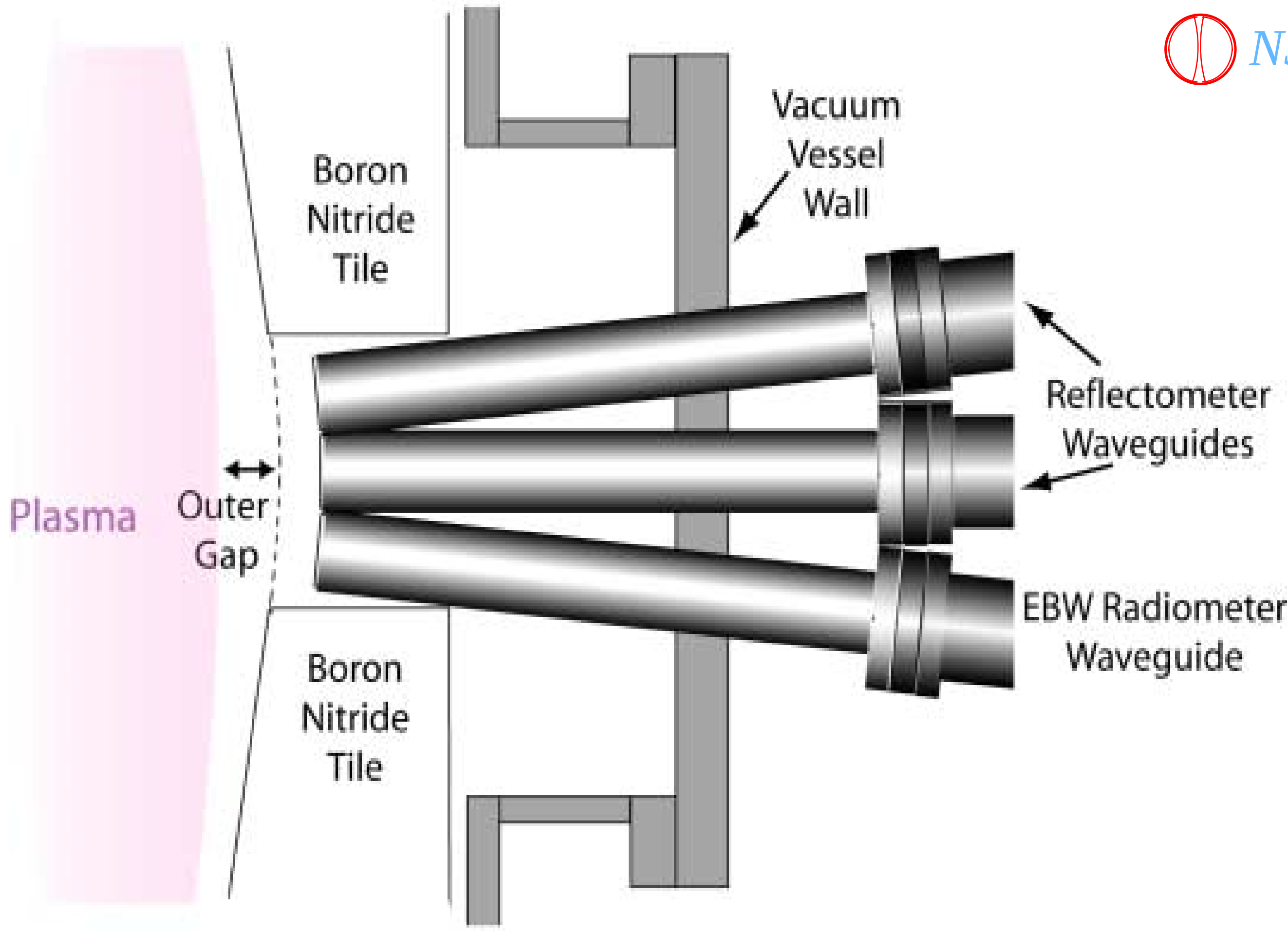
Increased C_{BX} by Using Tiles in HHFW Antenna as Local Limiter to Shorten L_n at UHR and Increase C_{BX}

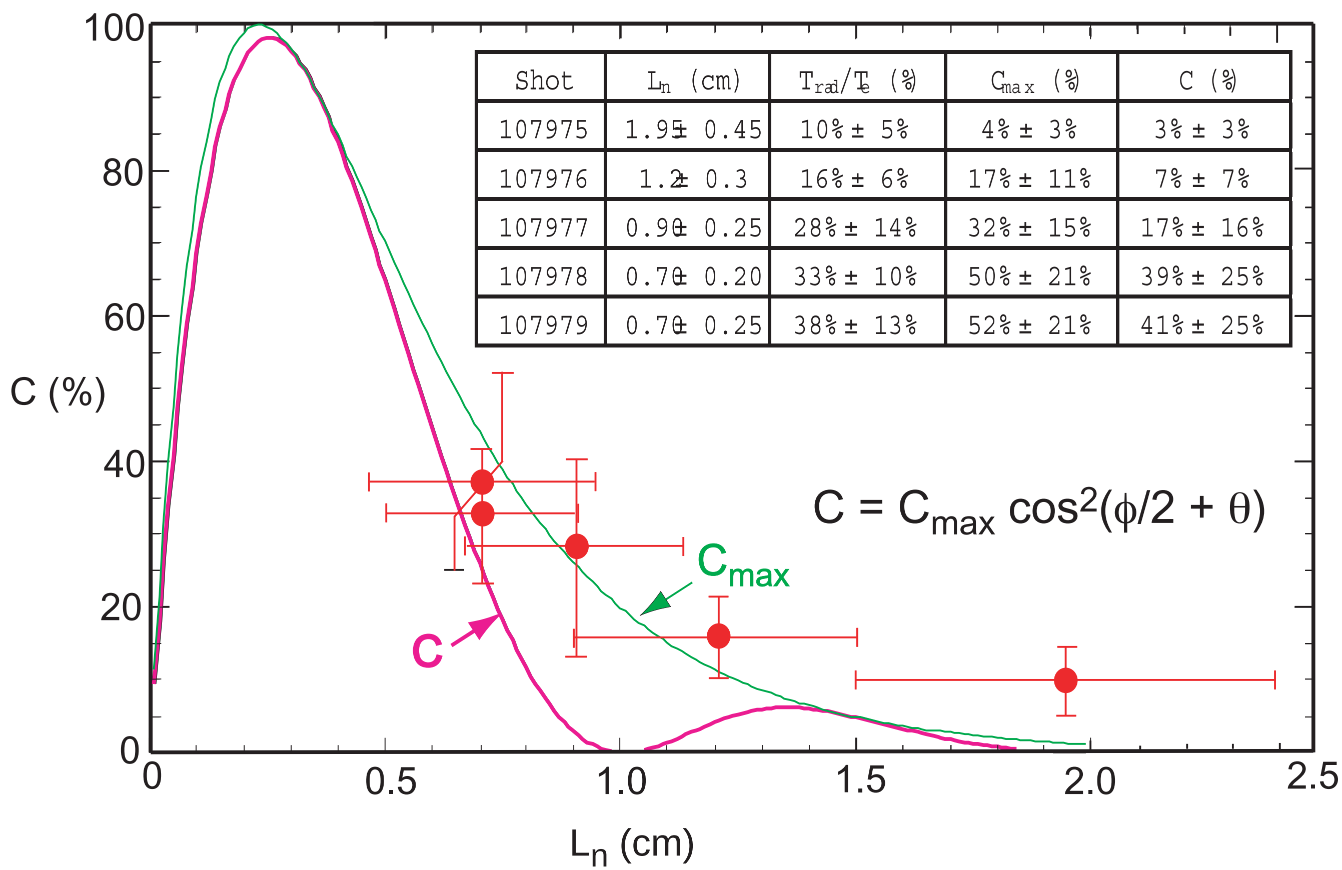
NSTX



- Measure L_n with X-Mode Reflectometer

On NSTX, B-X Conversion Increased from 10% to 50% as L_n Shortened from 2 to 0.5 cm, Agreeing with Theory

CDX-U



Shot	L_n (cm)	T_{rad}/T_e (%)	C_{max} (%)	C (%)
107975	1.95 ± 0.45	10% ± 5%	4% ± 3%	3% ± 3%
107976	1.2 ± 0.3	16% ± 6%	17% ± 11%	7% ± 7%
107977	0.90 ± 0.25	28% ± 14%	32% ± 15%	17% ± 16%
107978	0.70 ± 0.20	33% ± 10%	50% ± 21%	39% ± 25%
107979	0.70 ± 0.25	38% ± 13%	52% ± 21%	41% ± 25%

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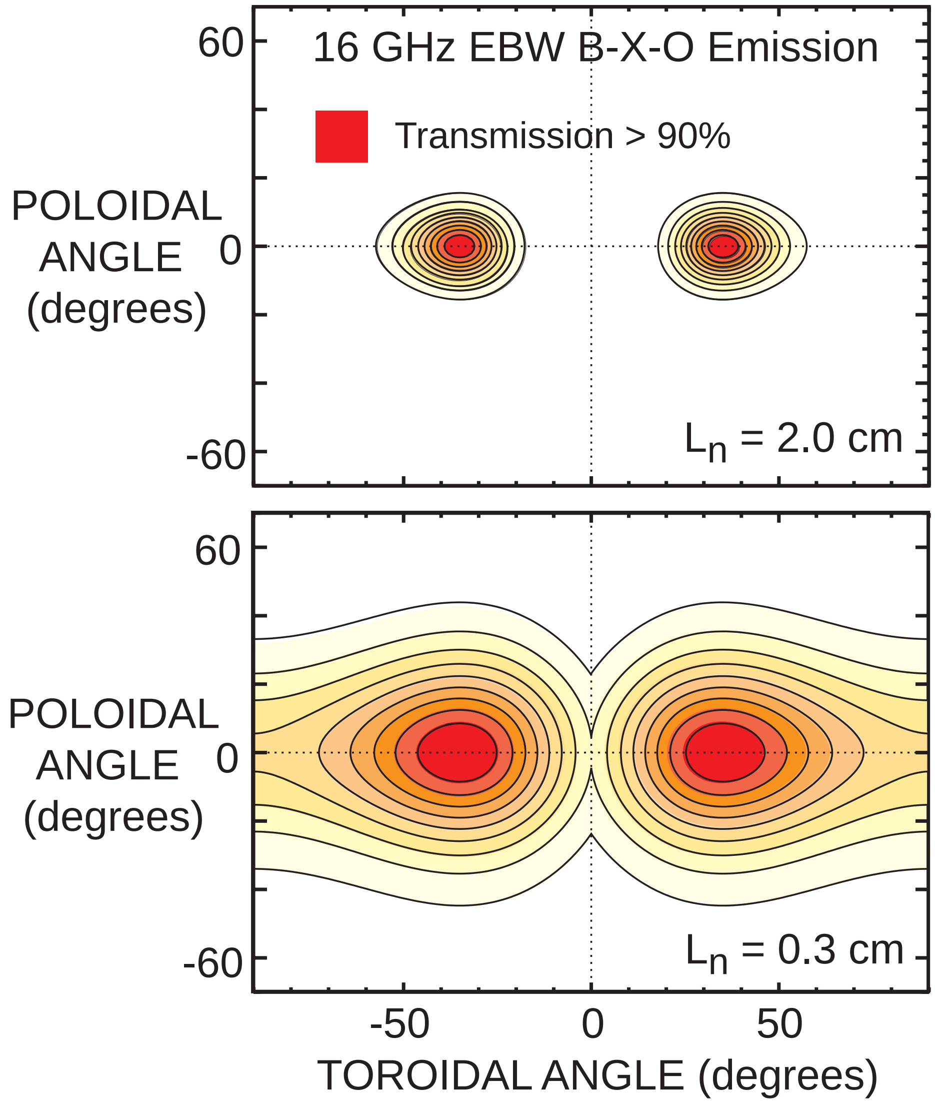
Local Limiter May Also Widen B-X-O Transmission Window By Shortening L_n at the O-Mode Cut-off



NSTX

- Plan to install B-X and B-X-O in-Vessel antennas, with local limiters on NSTX later this year

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EBW Heating and Current Drive May Optimize Equilibrium for High β Plasmas by Suppressing MHD

NSTX

- Trapped particle effects make high field side (HFS) EBW power deposition more attractive.

- Three β regimes in STs, each present a different challenge for HFS power deposition:
  - β ~ 10% harmonic overlap limits HFS access.
  - β ~ 20% mod B flattening on LFS helps HFS access.
  - β ~ 40% mod B well at axis complicates access to HFS.

- EBW heating and current drive scenarios modeled for NSTX with GENRAY ray tracing code and CQL3D bounce-averaged Fokker-Planck code

EBW Heating and Current Drive Is An Integral Part of the NSTX Non-inductive Steady State Program

NSTX

- ECCD & ECH will be used for plasma startup.

- EBW has a critical role in providing current during the current ramp up. The current needs to be ramped from ~ 50 kA level until the temperature is sufficient for HHFW to provide current up to 500 kA, where neutral beams particles are confined and can provide the majority of the current through bootstrap current.

- During steady state high current, EBW will provided the local current for plasma stability and suppression of NTMs.

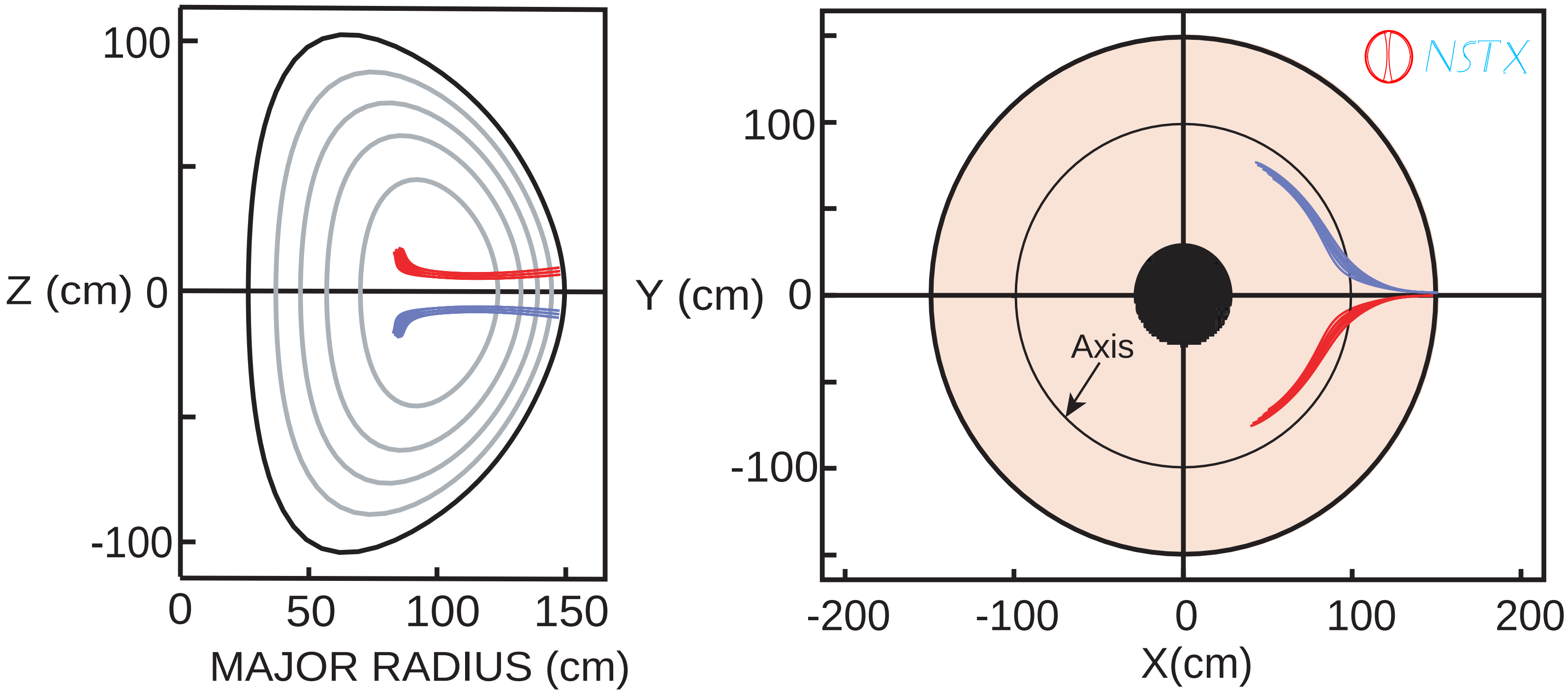
EBW Current Drive Direction Changed via Poloidal Launch Angle

EBW Frequency = 12 GHz, $-0.25 < n_{//} < 0.25$, 10 cm pol. length

Launched 10 deg. above mid-plane

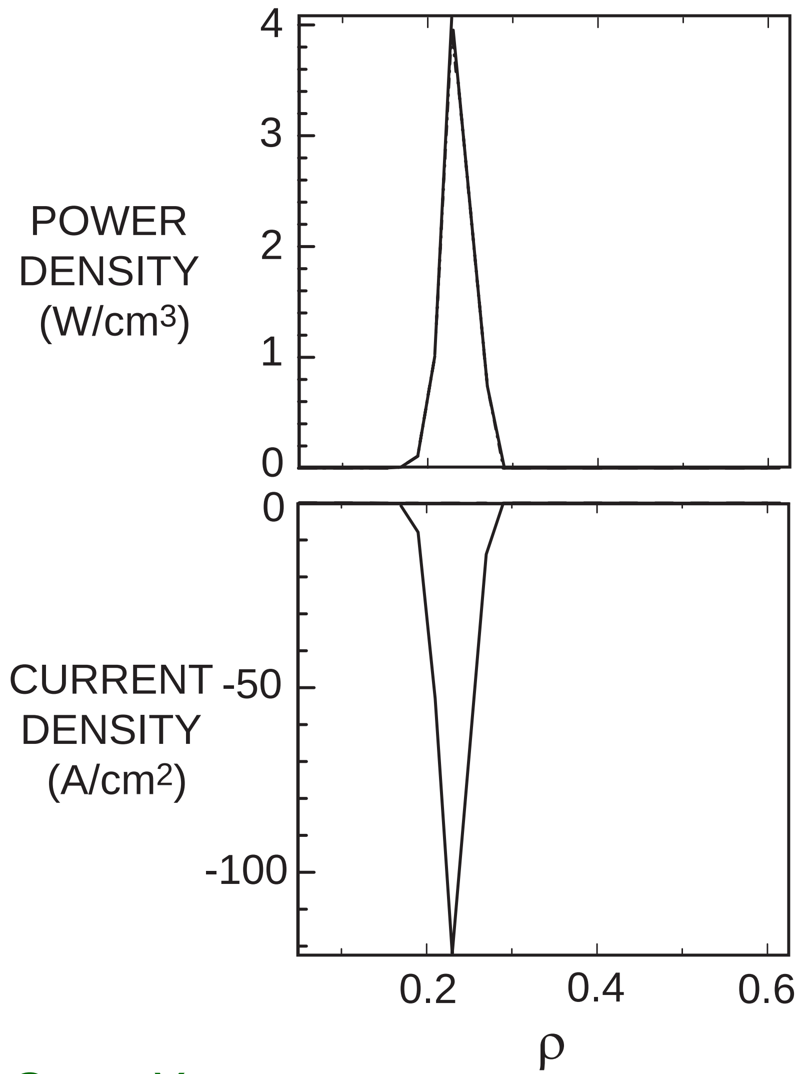
Launched 10 deg. below mid-plane

NSTX $\beta = 12\%$, $n_{eo} = 2\times10^{19} m^{-2}$, $T_{eo} = 1$ keV



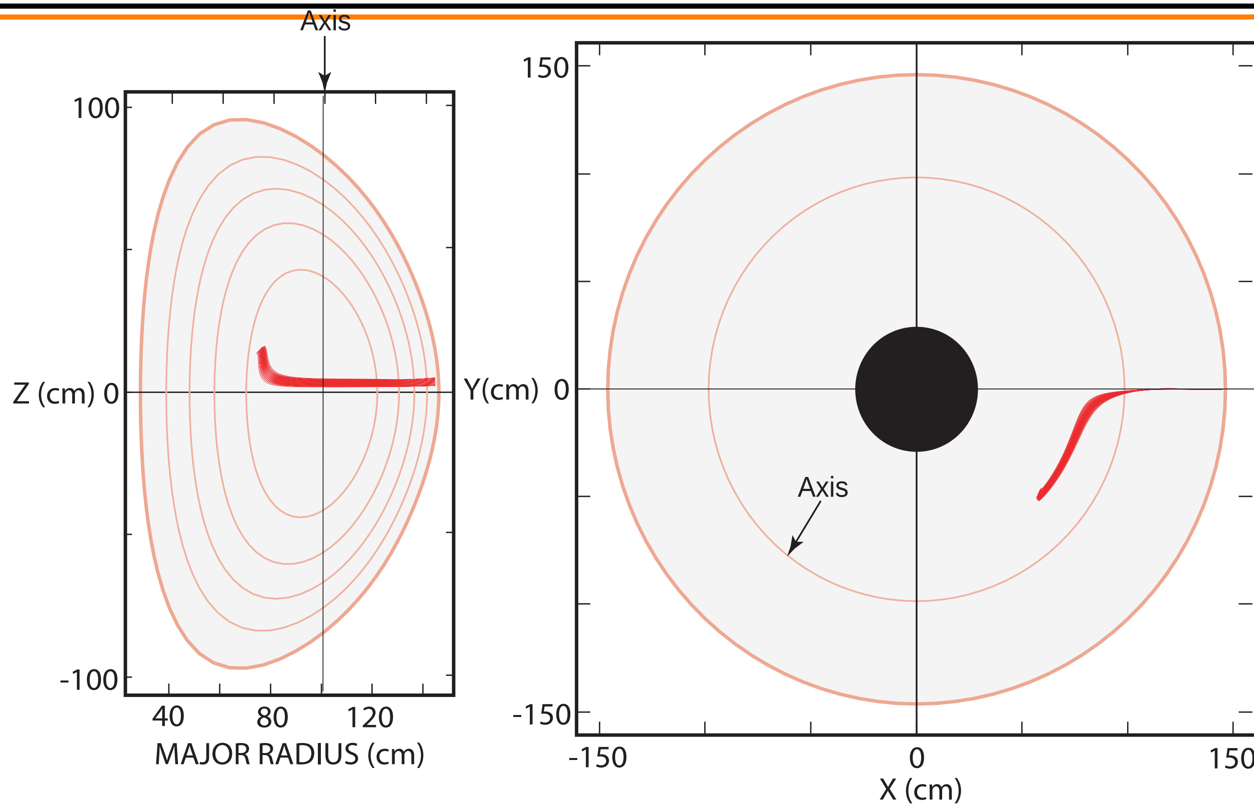
C. Forest *et al* , Phys. Plasmas **7**, 1352 (2000)

At β = 12% NSTX Plasmas with n_{eo}=2x10^{19}m^{-3},T_{eo}=1 keV EBW Current Drive Efficiency with 1 MW is ~ 0.1 AW^{-1}



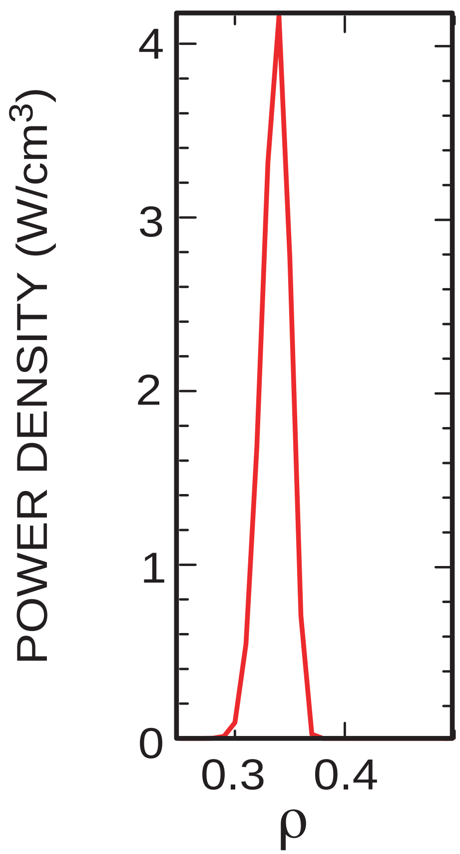
- At β ~ 10% it is hard to access HFS beyond ρ = 0.2-0.3.
- Stabilization of NTMs requires ρ = 0.6 on LFS with reduced CD efficiency.
- Further optimization of $n_{//}$ at the EBW power deposition region.

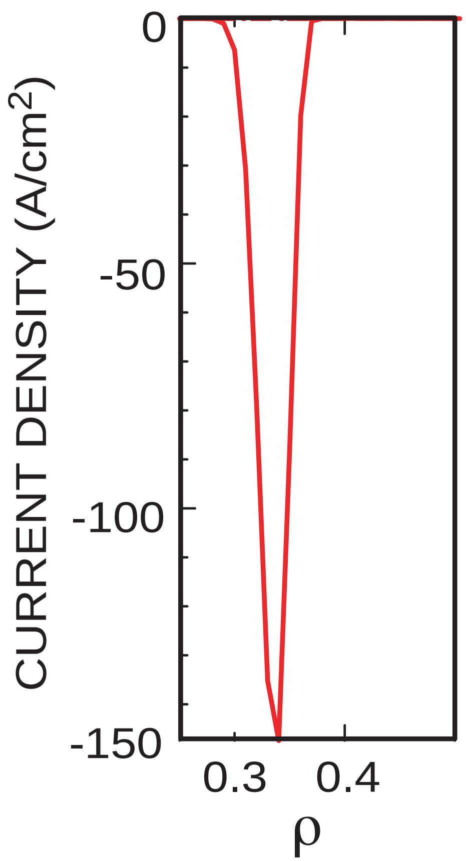
EBW Current Drive For β = 20%



EBW Frequency = 14.5 GHz, -0.1 < $n_{//}$ < 0.1, 10 cm pol. length
Launched 5 deg. above midplane.
NSTX β= 20%, n_{eo} = 3×10^{19} m^{-3}, T_{eo} = 1 keV

At β = 20%,a Tight $n_{//}$ Launch Spectrum Avoids $2\Omega_{ce}$ Absorption & Achieves Localized Damping

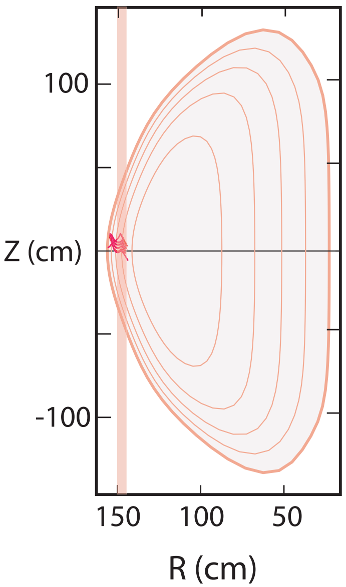


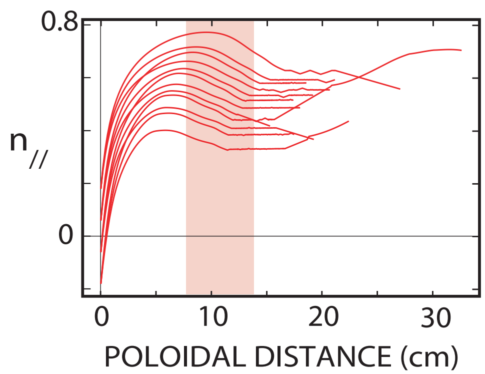


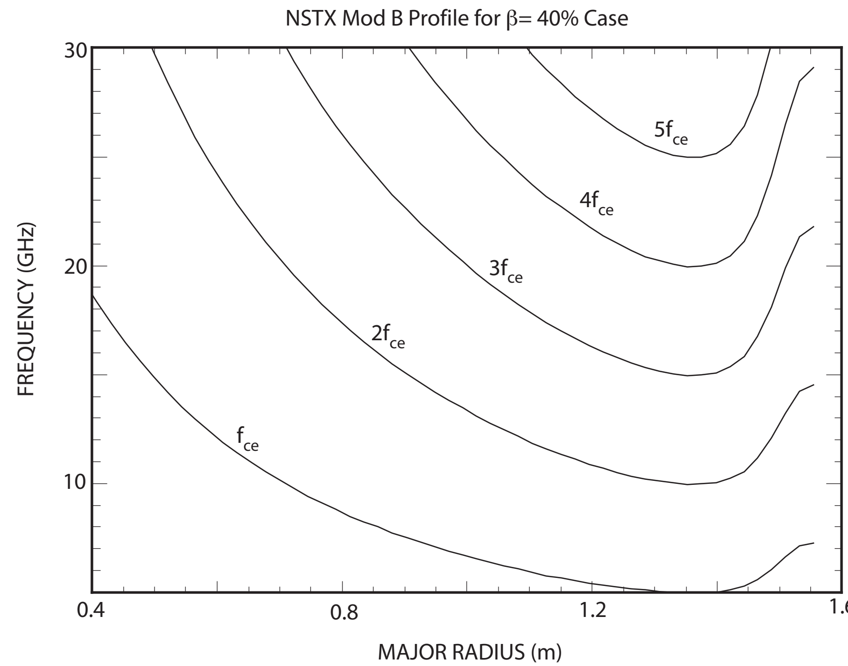
Current drive is on HFS, improving efficiency (0.065 A/W).
This is comparable to ECCD. Current density is for 1 MW.

EBW Current Drive For β = 40% Can Provide Stability with Current Near the Edge

NSTX







EBW Frequency = 14.5 GHz, $-0.1 < n_{//} < 0.1$, 10 cm pol. length
Launched 5 deg. above midplane.
NSTX β= 40%, $n_{eo} = 2.7 \times 10^{19}$ m^{-3}, T_{eo} = 3 keV

Summary

- Limiter in CDX-U scrape-off shortened L_n to increase C_{BX} from ~10% to > 95%
- Similar technique on NSTX shows a five-fold increase in C_{BX} to ~ 50% ; Limiter can also widen B-X-O transmission window
- Measured C_{BX} are in good agreement with theoretical predictions that use measured L_n on both CDX-U and NSTX
- EBWCD modeling of NSTX β ~ 20% plasma, shows good localization, suitable for NTM suppression, and CD efficiencies at least as good as ECCD
- Next year will attempt to achieve C_{BX} and C_{BXO} > 80% as a prerequisite to installing ~ 1 MW EBW heating system