Supported by Office of Science

NSTX

Recent EBW Emission Results and Plans for a 350 kW, 28 GHz EC/EBW Heating System on NSTX

G.Taylor[1], S.J. Diem[1], T.S. Bigelow[2], J.B. Caughman[2], R.A. Ellis[1], N.M. Ershov[3], E. Fredd[1], N. Greenough[1], R.W. Harvey[3], J.C. Hosea[1], J.Preinhaelter[4], A.K. Ram[5], D.A. Rasmussen[2], P.M. Ryan[2], A.P. Smirnov[3], J. Urban[4], J.B. Wilgen[2]

(1) PPPL, (2) ORNL, (3) Comp-X, (4) Czech Inst. Plasma Physics, (5) MIT

49th APS-DPP Meeting
Nov. 12-16, 2007
Orlando, Florida

Abstract

Electron cyclotron heating (ECH) and electron Bernstein wave EBW heating (EBWH) can assist plasma startup on the low aspect ratio NSTX device and provide sufficient electron heating to allow effective high harmonic fast wave (HHFW) coupling during current ramp up. EBW current drive (EBWCD) can also provide off-axis current to stabilize solenoid-free NSTX plasmas at β >20%. Efficient coupling of externally launched electromagnetic waves to EBWs is required for EBWH and EBWCD. The prospect for EBWH and EBWCD is supported by EBW emission studies on NSTX that show efficient EBW coupling for some edge conditions. A 350 kW 28 GHz ECH/EBWH system is being installed on NSTX to support solenoid-free startup, HHFW current ramp up and initial EBW coupling and heating studies. This system will provide on-axis second harmonic ECH/EBWH in NSTX. Fundamental on-axis heating may also be possible by operating the gyrotron at 15.3 GHz.

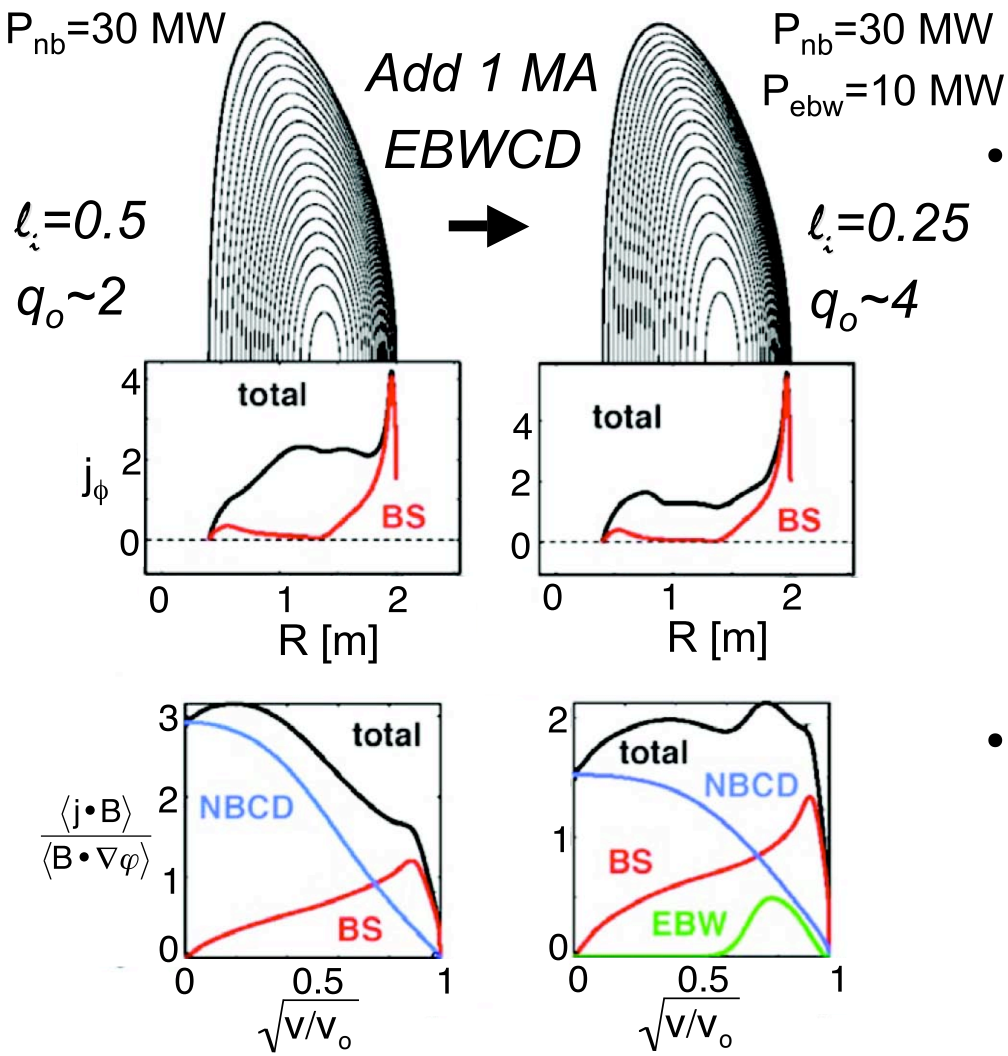
This work is supported by USDOE contract DE-AC02-76CH03073 and a grant to encourage innovations in fusion diagnostic systems.

Outline

NSTX

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

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%

- Need efficient coupling of RF power to EBWs

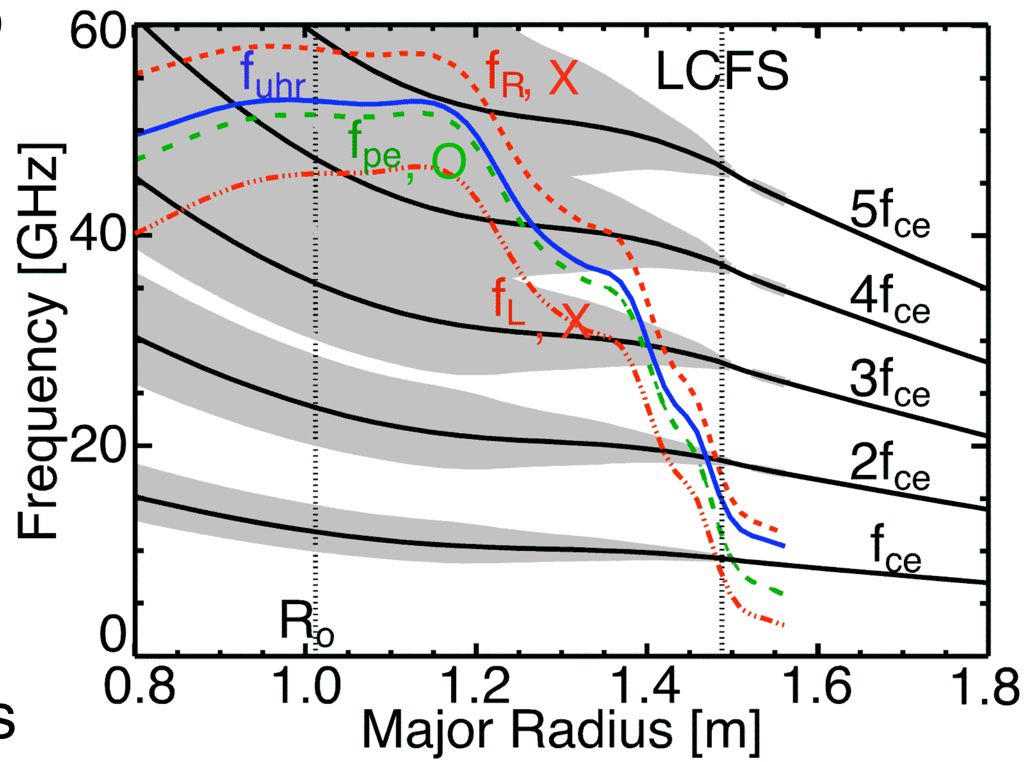
→ Assess oblique O-X-B coupling by measuring B-X-O emission (EBE)

EBW Background

EBWs can propagate in overdense plasmas

NSTX

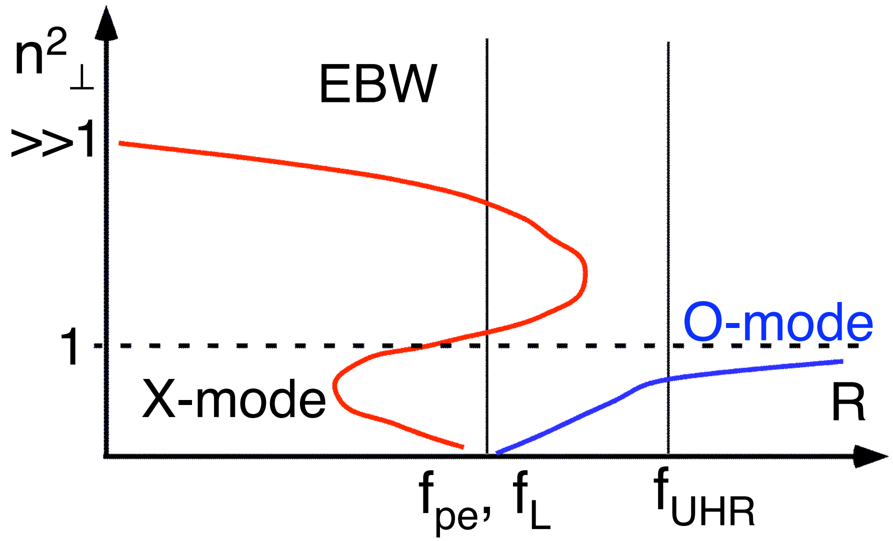
- Electromagnetic waves cutoff in overdense plasmas
- NSTX has low magnetic fields (< 0.6 T) and high n_e ($1\text{-}5 \times 10^{19}$ m^{-3}), cutting off up to first 6 EC harmonics
  - EBWs are strongly absorbed/emitted from EC harmonics



- EBWs cannot propagate in vacuum
- Couple to EBWs via mode conversion from microwaves

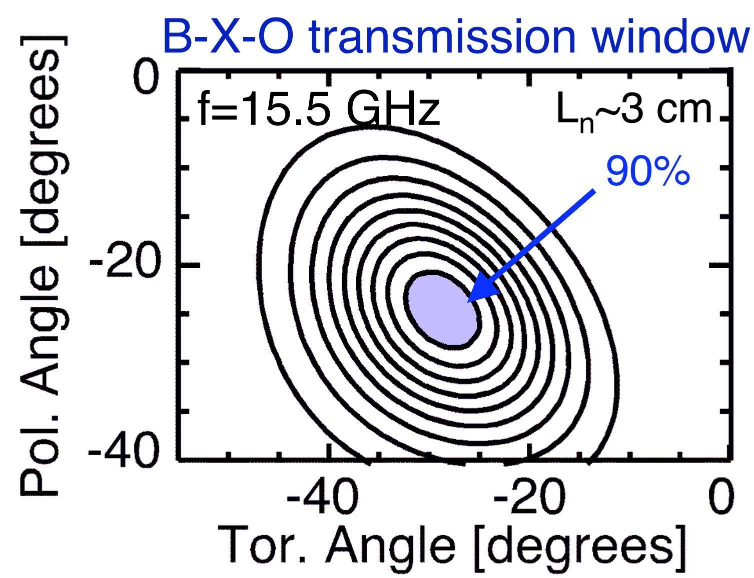
EBW emission data can be used to provide coupling efficiency and polarization information for heating and current drive system

EBW coupling via double (B-X-O) mode conversion (MC) to electromagnetic waves

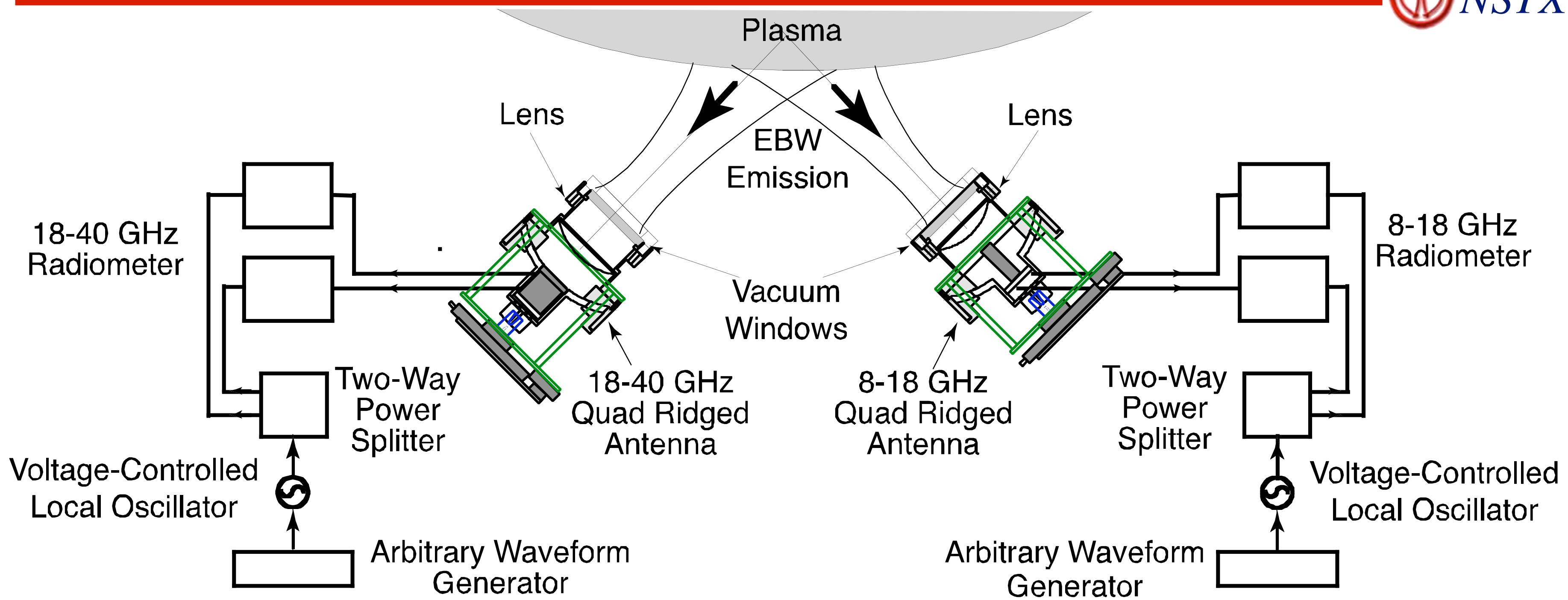


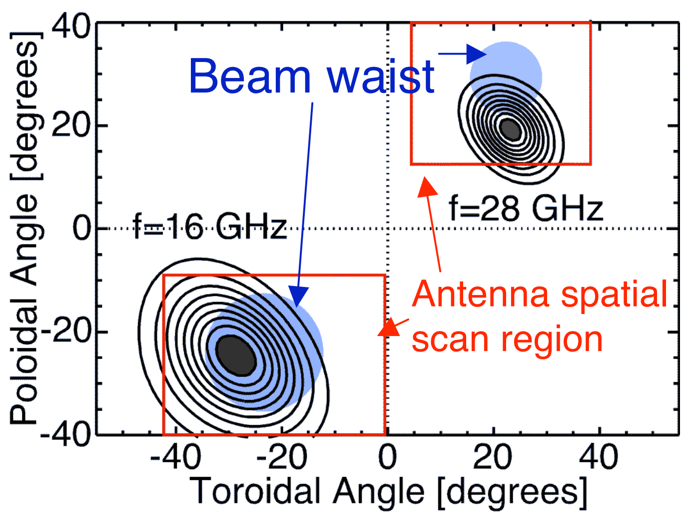
- EBW emitted near EC harmonic converts to X-mode at upper hybrid resonance and then to O-mode
- Emission elliptically polarized ($E_{para}/E_{perp} \sim 1.6$) due to oblique view of plasma

- B-X-O emission leaves plasmas via angular transmission window:
  - 30º-40º magnetic field pitch at edge determines window location
  - Lower density scale length, L_n, at MC layer enlarges B-X-O coupling window



Remotely steered EBE diagnostic allows spatial mapping of emission window



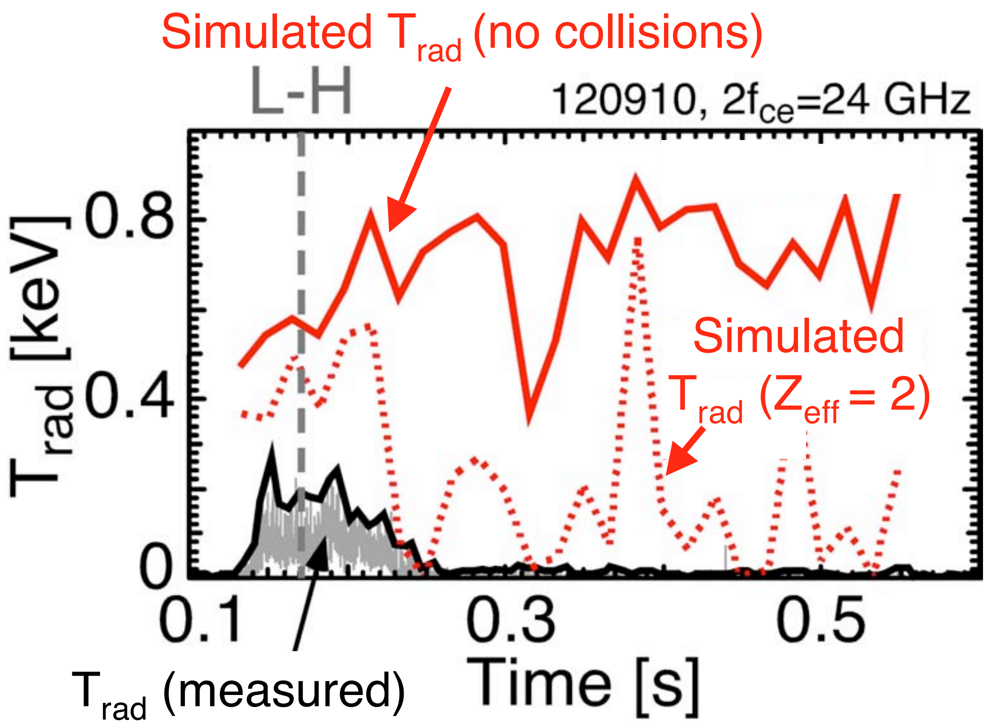


- ±10° scan in poloidal and toroidal directions during L-mode and H-mode EBE experiments
- Acceptance angle:
  8-18 GHz antenna ~ 22°
  18-40 GHz antenna ~ 14°

EBE simulations suggest low B-X-O emission from H-mode in 2006 was due to EBW collisional damping

NSTX

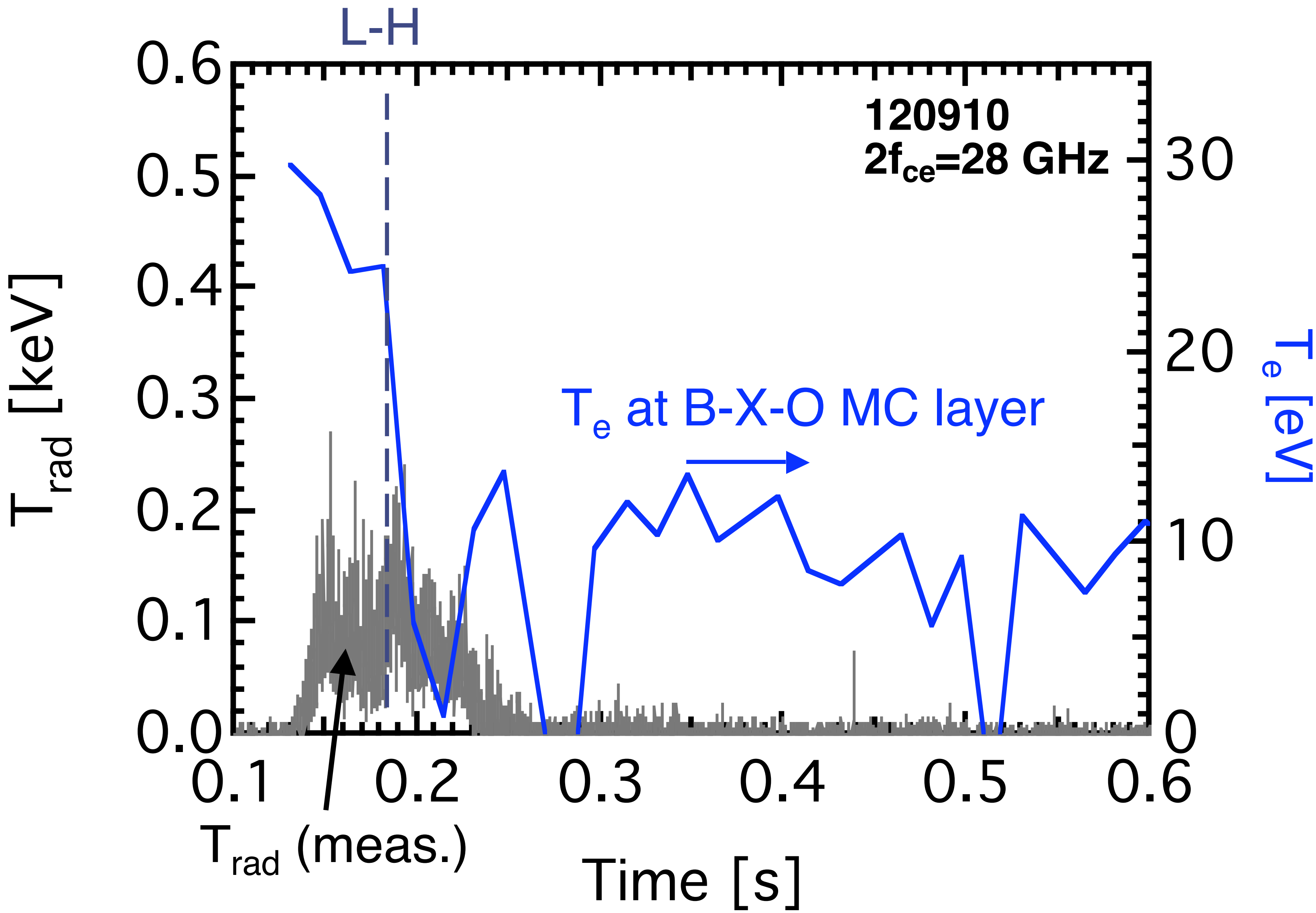
- Emission from f_{ce}, $2f_{ce}$ exhibited rapid decay after L-H transition
- Simulated B-X-O EBE $T_{rad} \sim 0.8$ keV for 24 GHz, measured $T_{rad} < 0.2$ keV:
  - EBE simulation uses EFIT magnetic equilibrium and measured T_e, n_e



- Including collisional model (with Z_{eff}=2) results in closer agreement to measured T_{rad}

Edge lithium conditioning may reducing edge collisionality

2006 H-mode plasmas showed T_e decrease at B-X-O MC layer being coincident with EBW T_{rad} decrease

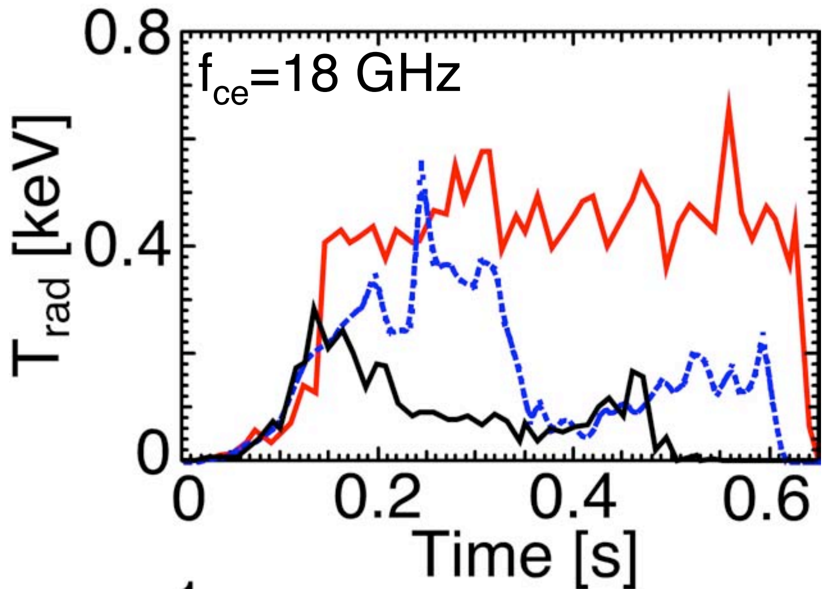


Measurements & Simulation

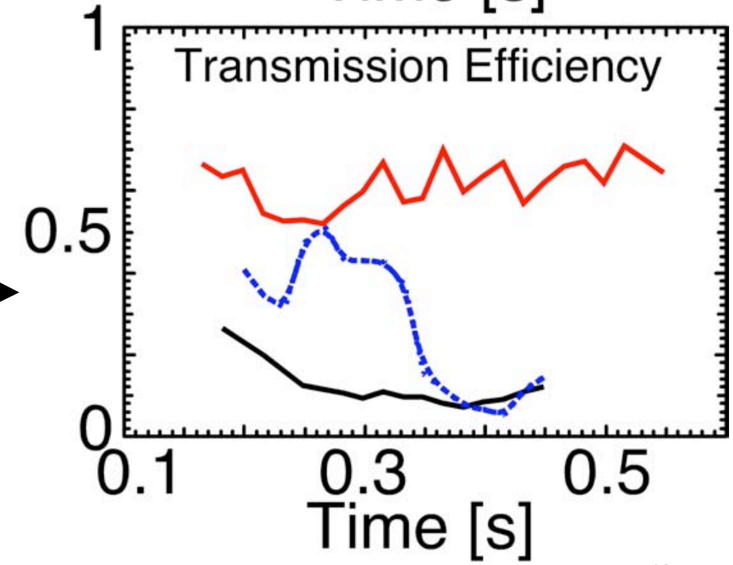
EBE transmission efficiency increased with lithium evaporation rate for f_{ce}=18 GHz

— 0 mg/min (124284)
···· 11 mg/min, total = 171 mg (124290)
— 19 mg/min, total = 286 mg (124309)

- Measured T_{rad} increased from 200 eV to ~ 450 eV



- Transmission efficiency at 18 GHz increased with Li deposition from 20% to 60%



Better T_{rad} agreement with EBE simulation in highest Li evaporation rate case for f_{ce}=18 GHz

NSTX

- For highest Li evaporation rate, 19 mg/min:

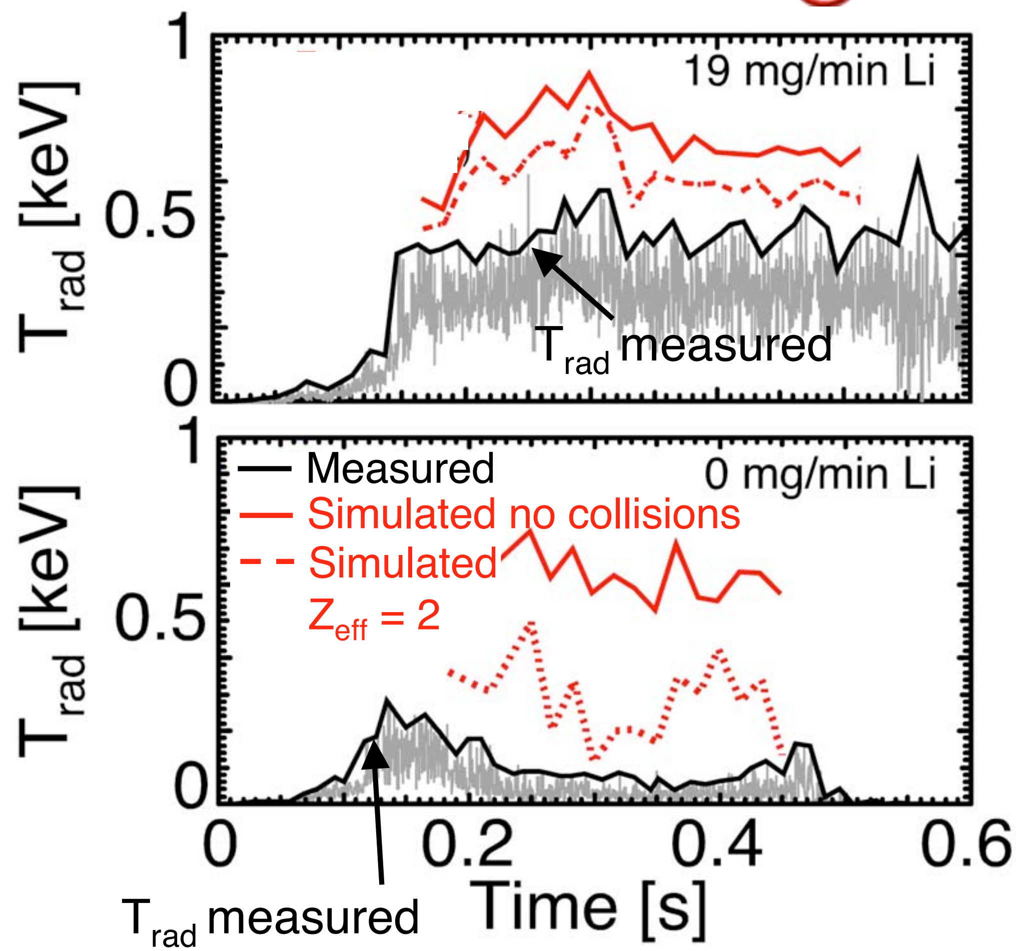
  Measured $T_{rad} \sim 0.4$ keV

  Simulated $T_{rad} \sim 0.6$ keV

- For 0 mg/min:

  Measured $T_{rad} \sim 0.1$ keV

  Simulated $T_{rad} \sim 0.4$ kev



For 19 mg/min of Li conditioning, T_e near MC may be high enough to significantly reduce EBW collisional damping before B-X-O conversion

EBE transmission efficiency increased with lithium evaporation for $2f_{ce}$=28 GHz

NSTX

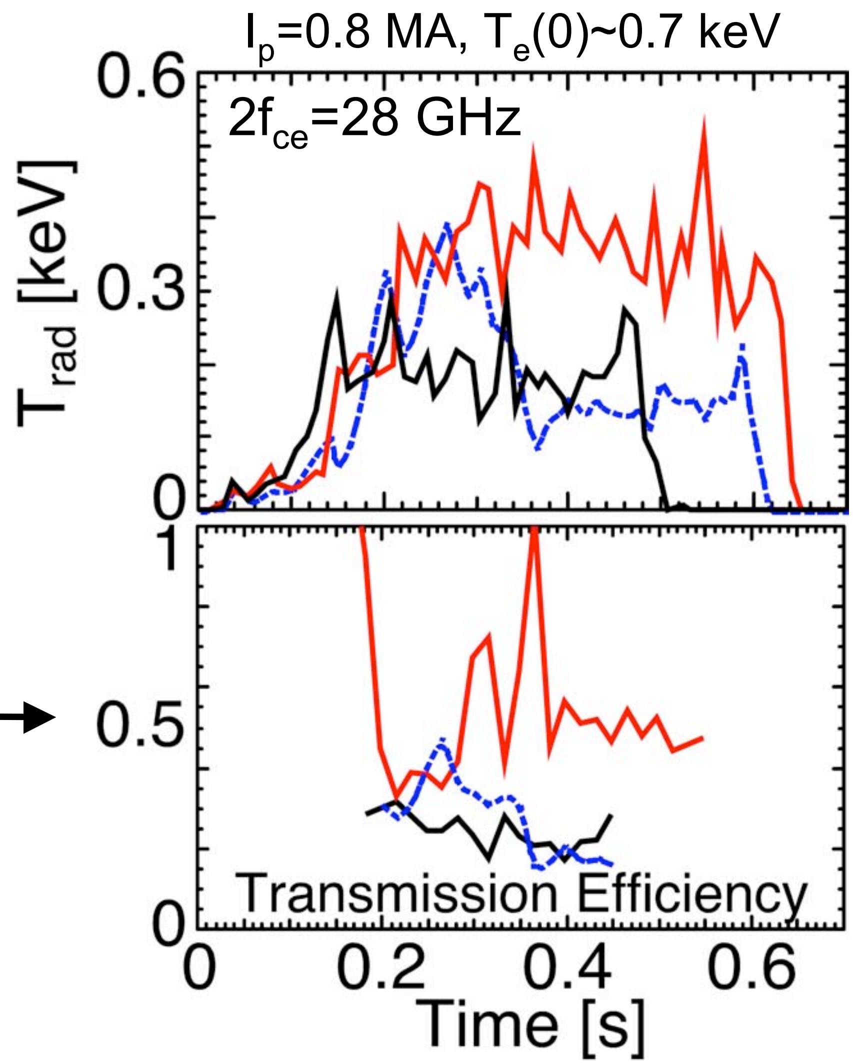
0 mg/min (124284)

11 mg/min, total = 171 mg (124290)

19 mg/min, total = 286 mg (124309)

- Measured T_{rad} increased from 0.2 keV to ~ 0.4 keV

- Transmission efficiency at 28 GHz increased with Li deposition from 20% to 50%



Good T_{rad} agreement with EBE simulation in highest Li evaporation case for $2f_{ce}$=28 GHz

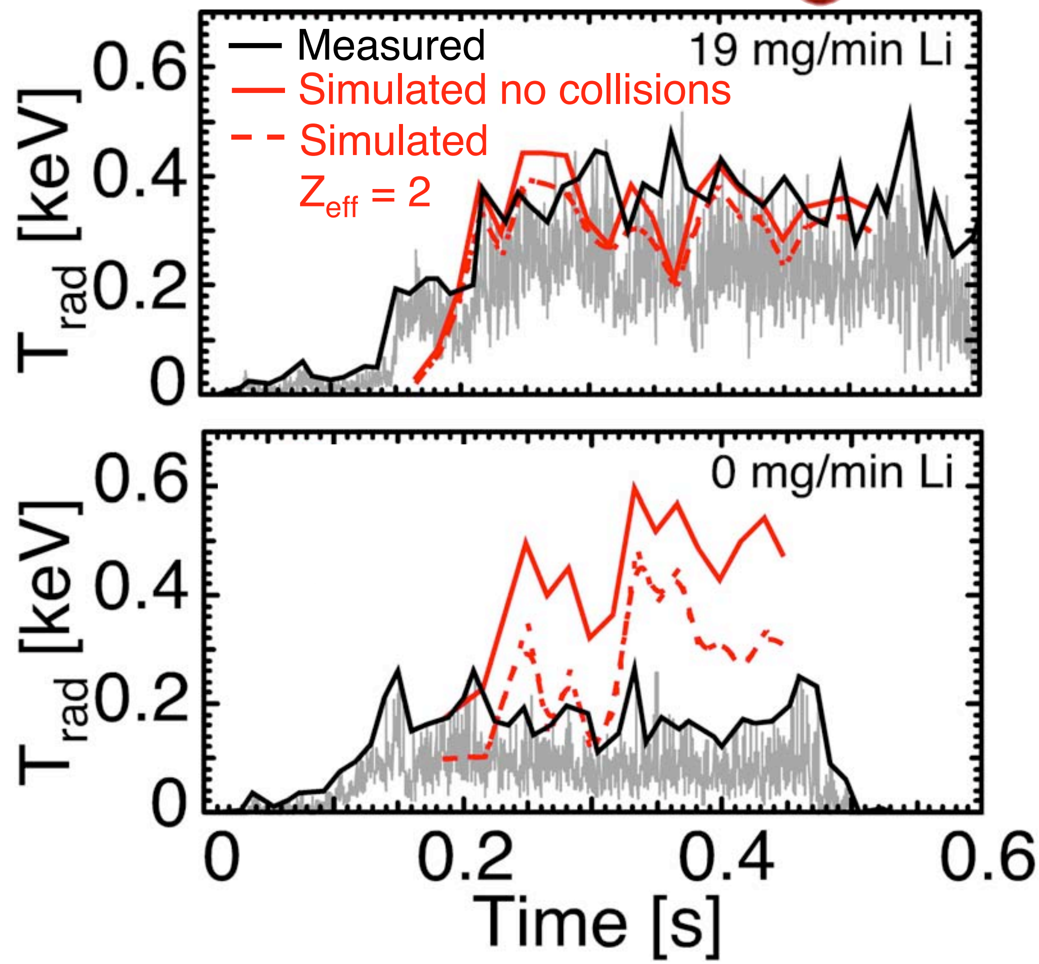
NSTX

- For highest Li evaporation rate, 19 mg/min:
  - Measured and simulated T_{rad} agree

- For no Li:

  measured $T_{rad} \sim 0.2$ keV

  simulated $T_{rad} \sim 0.4$ - 0.6 keV

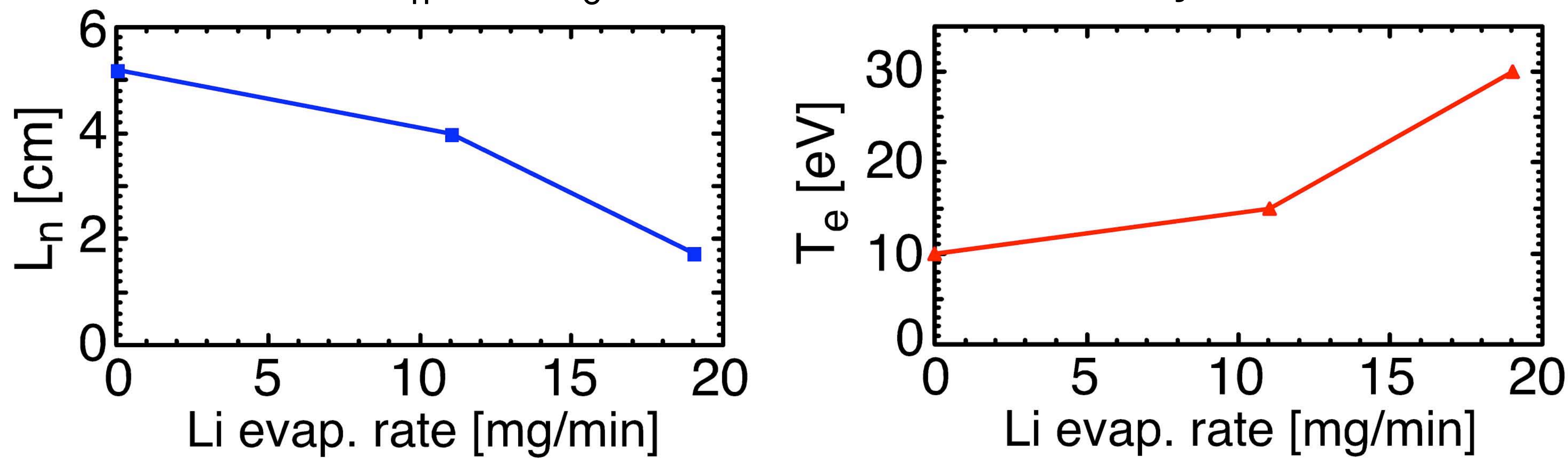


For 19 mg/min of Li conditioning, T_e near MC may be high enough to avoid EBW collisional damping before B-X-O conversion

Lithium conditioning increases edge T_e and reduces L_n in plasma edge

NSTX

L_n and T_e at 28 GHz B-X-O MC layer



- 28 GHz Mode conversion (MC) layer typically between R = 145 and R = 151 cm
- At t = 0.3 s, T_e at B-X-O MC layer increased from 10 eV to 30 eV when Li evaporation rate increased from 0 to 19 mg/min
  - For $T_e < 20$ eV, EBW collisional damping becomes significant

Angle of maximum B-X-O transmission consistent with theory

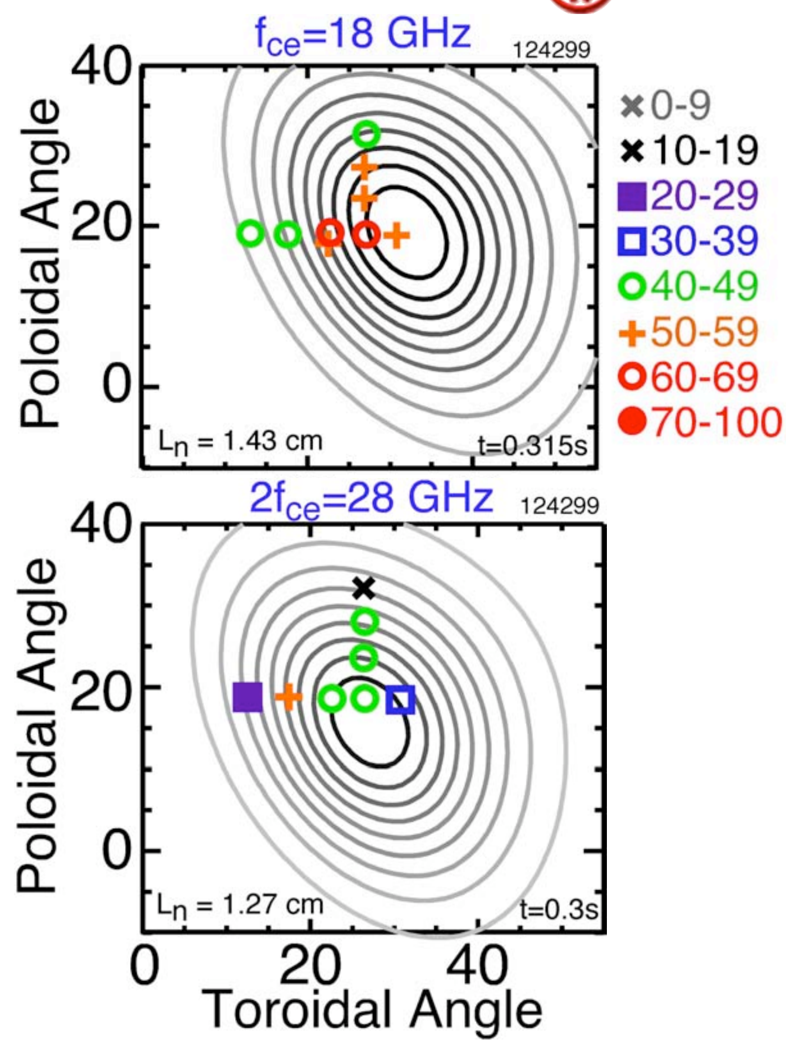
NSTX

- Repeated target plasma, (I_p =0.9 MA, $T_e(0)$~1keV) with Li conditioning

- Experimental B-X-O transmission efficiency:

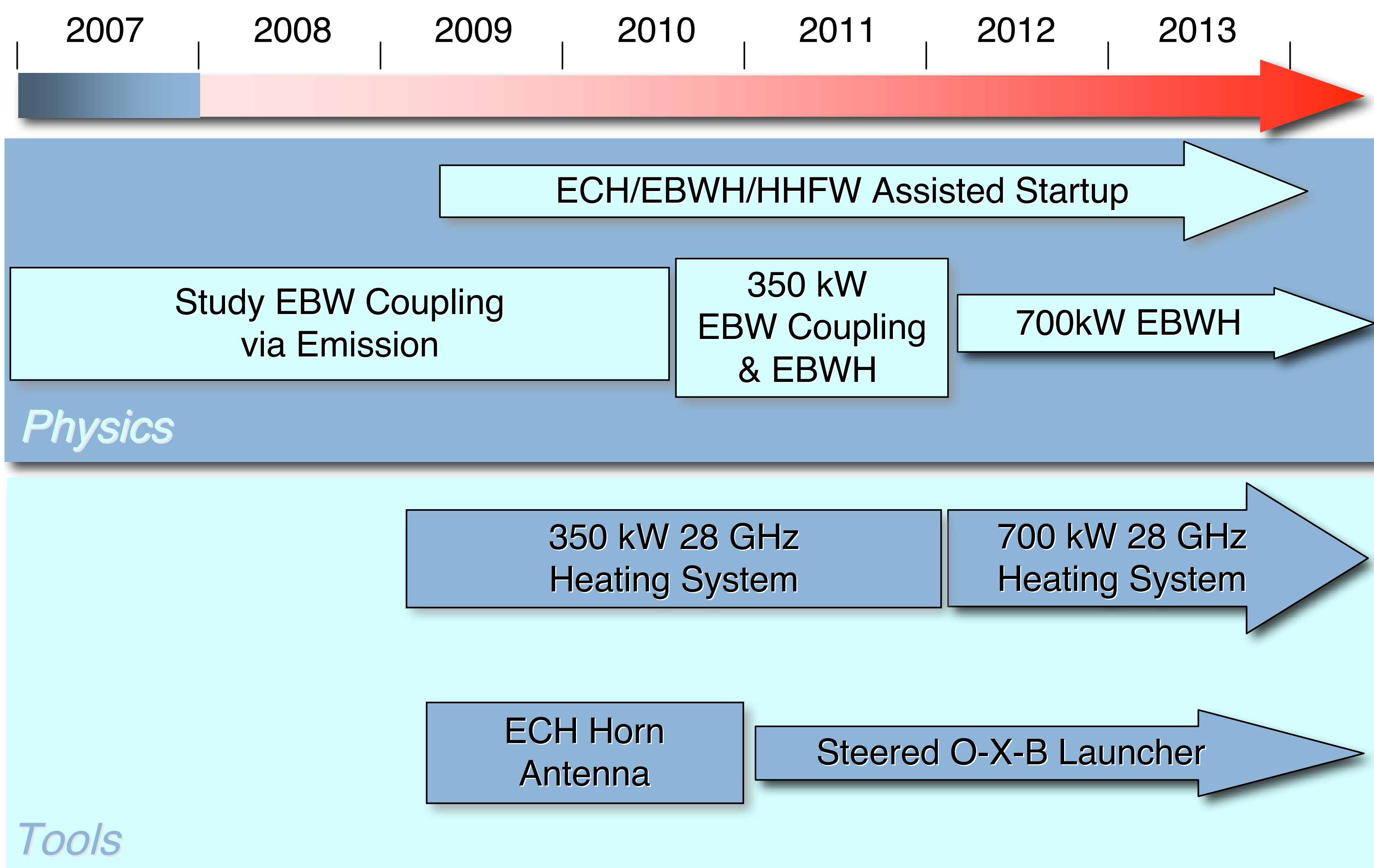
$$\text{Transmission}_{EBW} = \frac{T_{rad}(\text{measured})}{T_{e,\text{Thomson}}(R_{\text{emission}})}$$

- Maximum measured transmission efficiencies:
  - 62% for f_{ce}=18 GHz near axis emission
  - 49% for $2f_{ce}$=28 GHz near axis emission

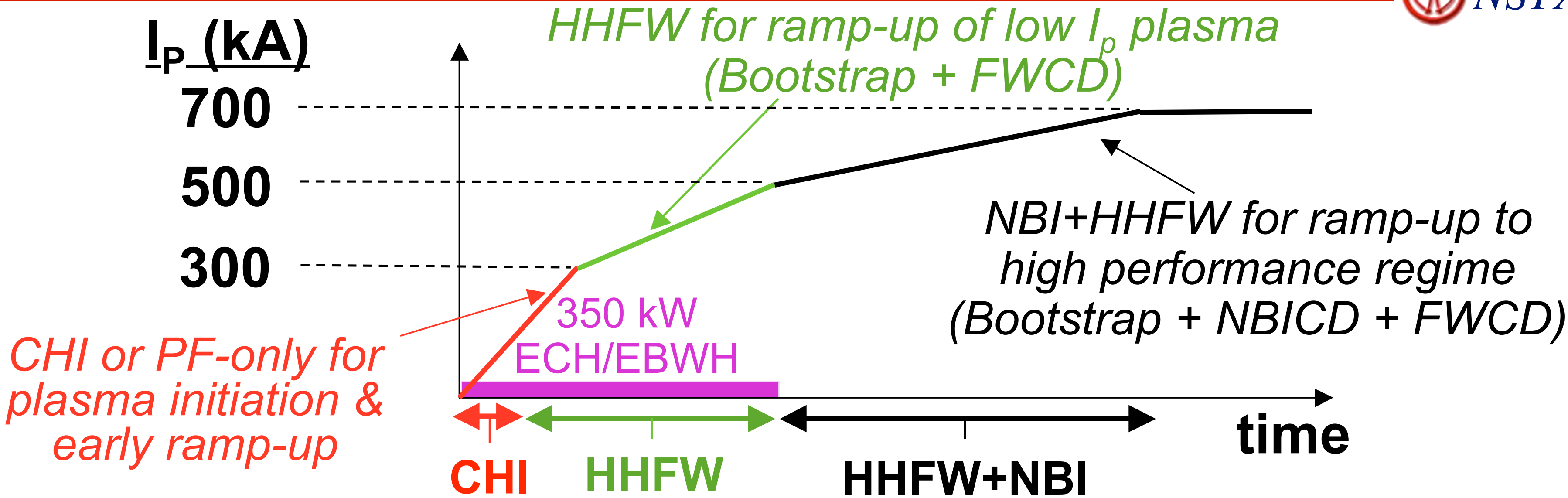


28 GHz NSTX Heating System

Timeline for 2008-13 NSTX Plan for 28 GHz ECH/EBWH Research



28 GHz ECH/EBWH System Provides Transition from Non-Solenoid Startup to HHFW I_p Ramp-up



28 GHz ECH/EBWH needed for preionization and early heating

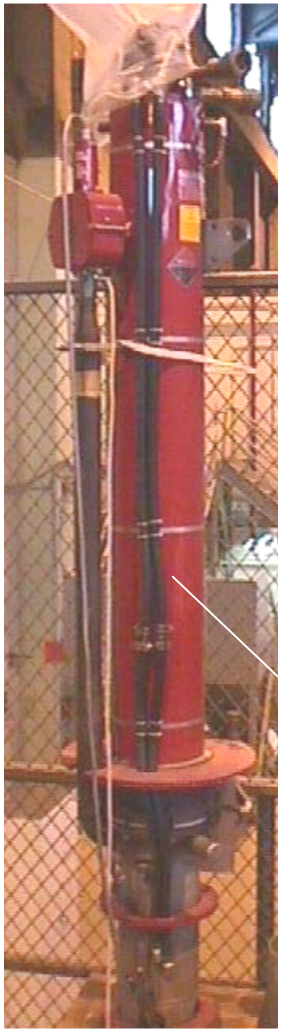
- Single pass HHFW absorption on a CHI-only target is 0%

METS Single-Pass Modeling Estimates

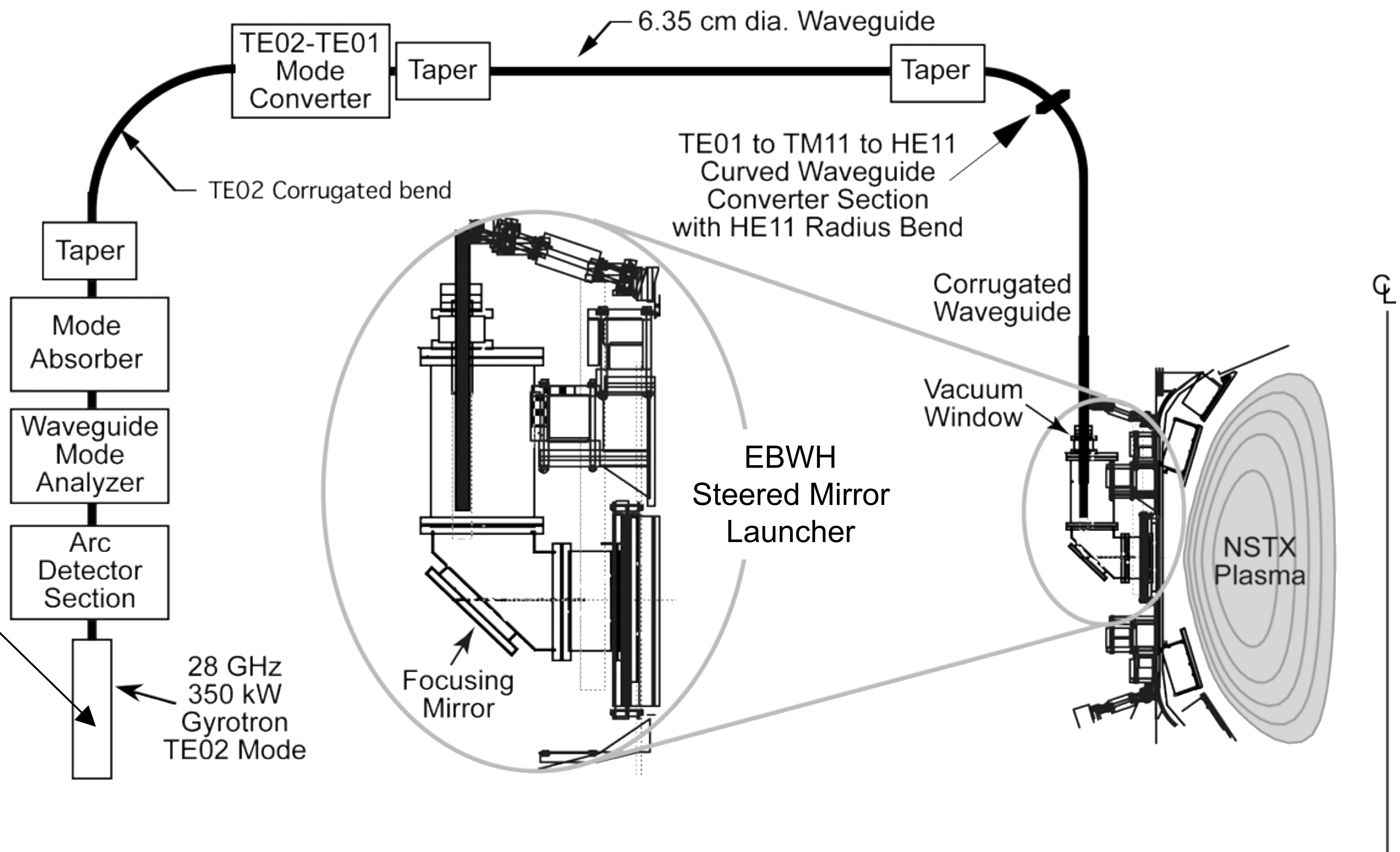
ECRH can create n_e, T_e for adequate HHFW absorption →

$T_e(0)$	$n_e(0)$	% HHFW absorbed
100 eV	$5x10^{18}m^{-3}$	2%
100 eV	**$9x10^{18}m^{-3}$**	**~10%**
300 eV	$9x10^{18}m^{-3}$	~30%

Two 28 GHz, 350 kW, 500 ms Pulsed Gyrotrons Installed by 2012, Providing ~ 750 kW EBWH



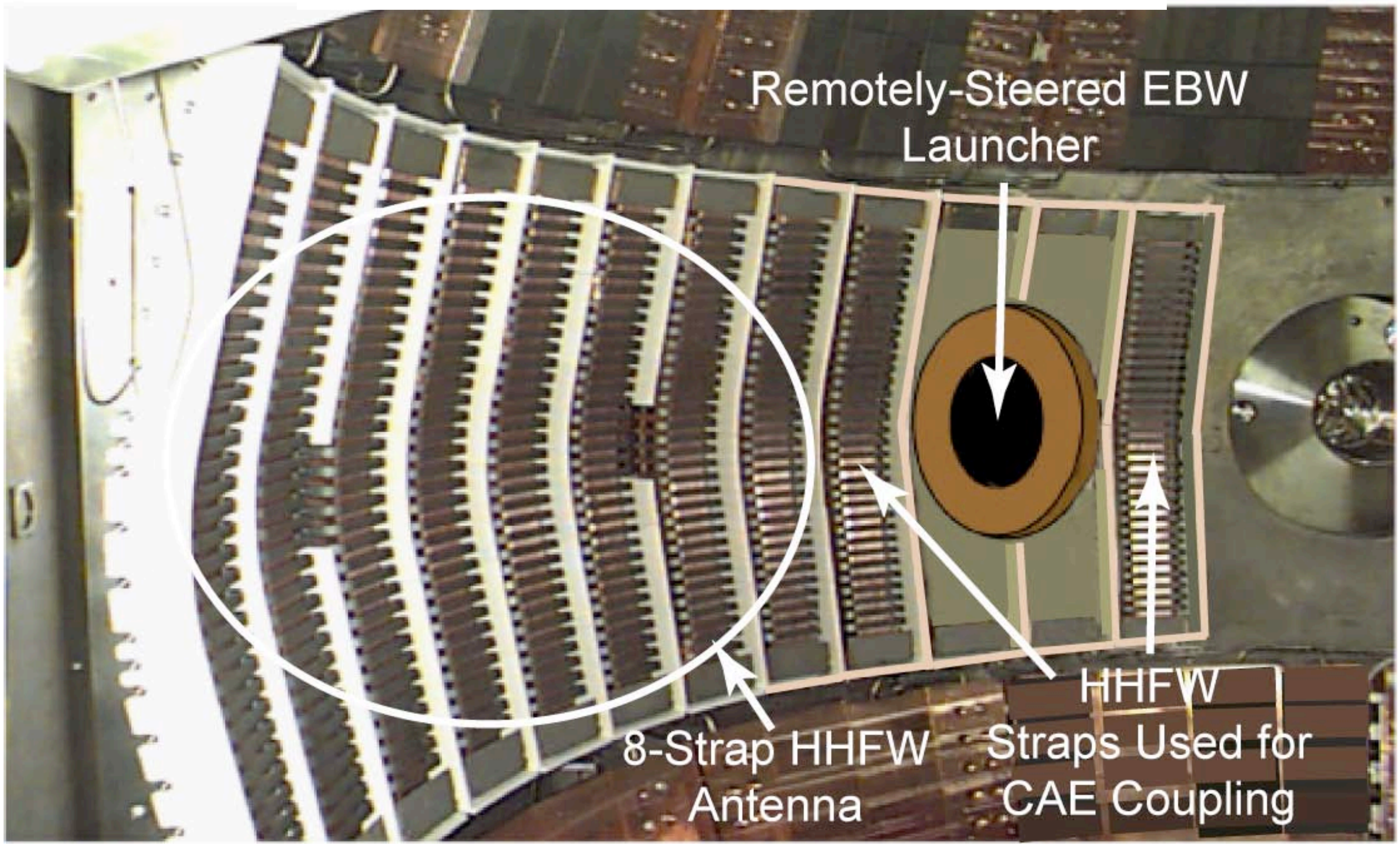
28 GHz Gyrotron



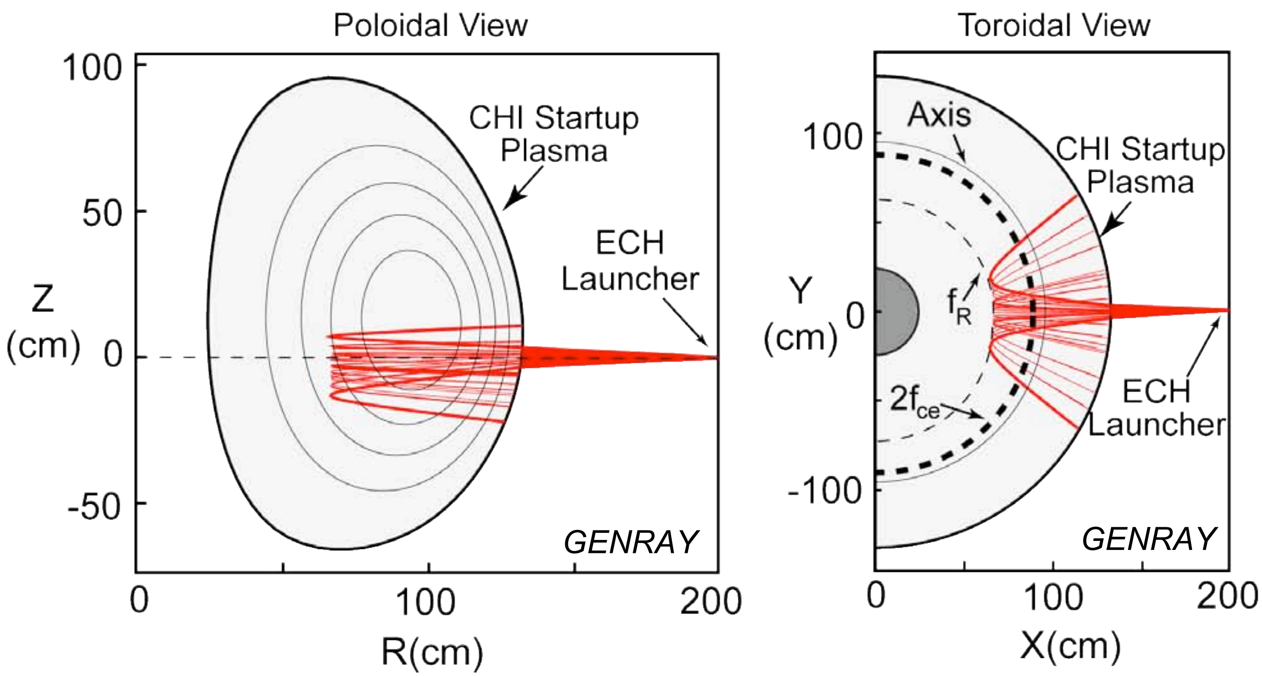
- First gyrotron operational, with ECRH horn antenna, for 2009 run campaign:
  - Gyrotron may also operate in TE01 at 15.3 GHz

Steered EBW Mirror Launcher Operational by 2011

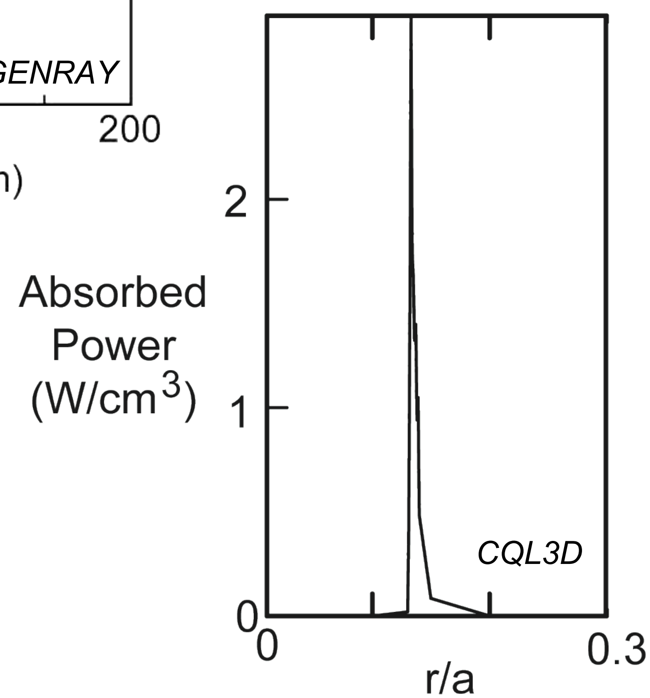
HHFW Antenna (Circa 2011)



Modeling of 28 GHz ECH in CHI Plasma Predicts 15% $2f_{ce}$ Absorption, Excluding Wall Reflection

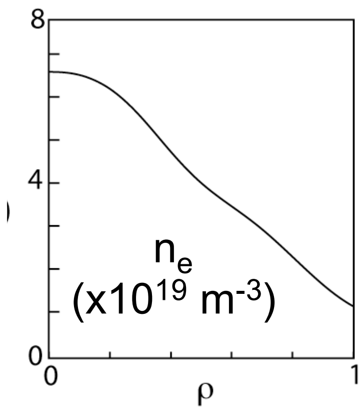


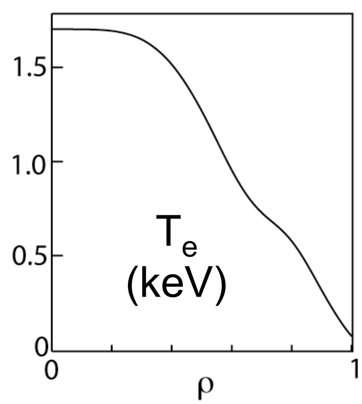
- RF power reflects off right hand cutoff



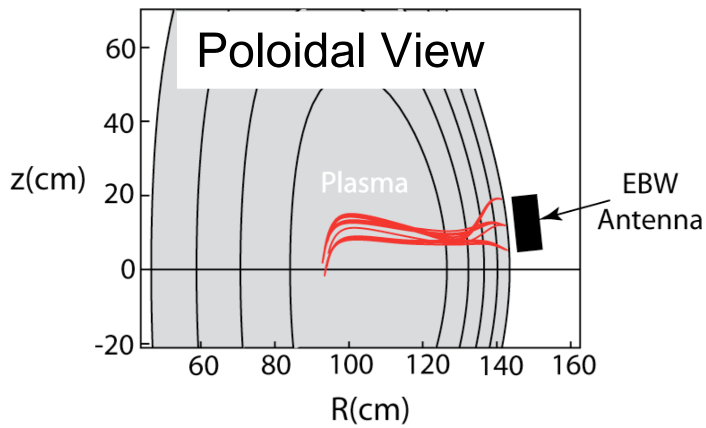
- ECH absorption rises to 75% as T_e increases to ~ 200 eV
- RF power is absorbed in narrow radial region around r/a = 0.15

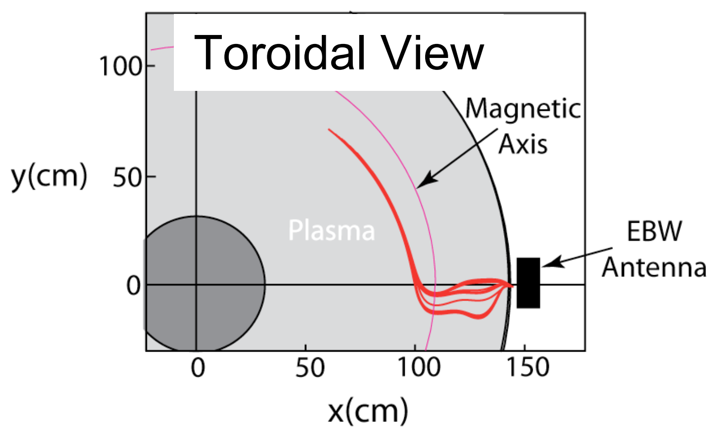
Modeling Predicts Local Core Heating & 40 kA/MW for On-Axis 28 GHz EBWCD in β = 20% NSTX Plasma





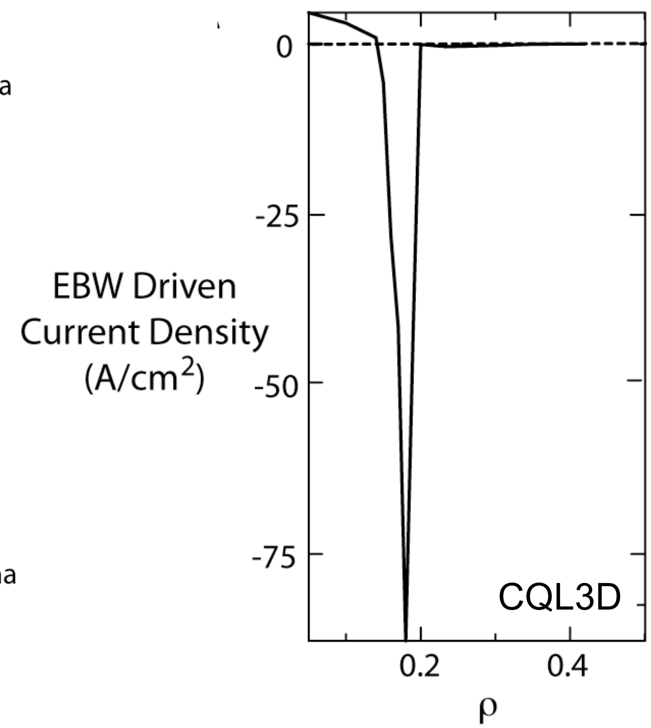
GENRAY





P_{ebw} = 750 kW

I_{EBWCD} = 29 kA



- Off-axis (r ~ 0.6) Ohkawa CD possible with similar CD efficiencies at higher T_e and lower n_e
- MSE can measure this level of CD, especially by using RF modulation

Summary and future work

- EBE simulations suggest that previously measured low emission due to EBW collisional damping in plasma edge
- Lithium conditioning scan increased measured EBE transmission efficiency
- Highest measured EBW transmission efficiency for H-mode plasmas of 50-60% observed with edge conditioning
- ECH/EBWH assisted startup system planned for 2010 experiments

Reprints