Supported by Office of Fusion Energy Sciences
Excellent Science Attractive Energy
Office of Science

EBW Research on NSTX and Pegasus

S.J. Diem[1], G. Taylor[1], J.B. Caughman[2],
T. Bigelow[2], G.D. Garstka[3], R.W. Harvey[4],
B.P. LeBlanc[1], J. Preinhaelter[5],
S.A. Sabbagh[1], J. Urban[5], and J.B. Wilgen[2]

[1]PPPL, [2]ORNL [3]University of Wisconsin-Madison,
[4]CompX, [5]Czech Institute of Plasma Physics,
[6]Columbia University

Presented at the 17th Topical RF Conference
May 8th, 2007
Clearwater, FL

NSTX

PEGASUS

College W&M
Colorado Sch Mines
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAERI
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Outline

- Motivation
- EBW emission measurements on NSTX
- Numerical modeling of EBW heating and current drive (CD) for Pegasus
- Summary

Outline

- → Motivation
- EBW emission measurements in NSTX
- Numerical modeling of EBW heating and current drive (CD) for Pegasus
- Summary

EBW heating & CD may be critical to future non-inductive STs

- Next generation STs require non-inductive plasma startup and off-axis CD for sustained $\beta > 20\%$
- STs have low B-fields and high densities so electromagnetic waves at low EC harmonic frequencies cannot propagate
  - ECRH and ECCD not viable
- EBWs propagate in STs, strongly damp at EC resonances
  - Cannot propagate in vacuum, must couple to the O- or X-mode
  - Assess feasibility of O-X-B coupling by measuring B-X-O emission
  - Modeling EBW heating & CD guides system design

NSTX and Pegasus will investigate EBW heating & CD

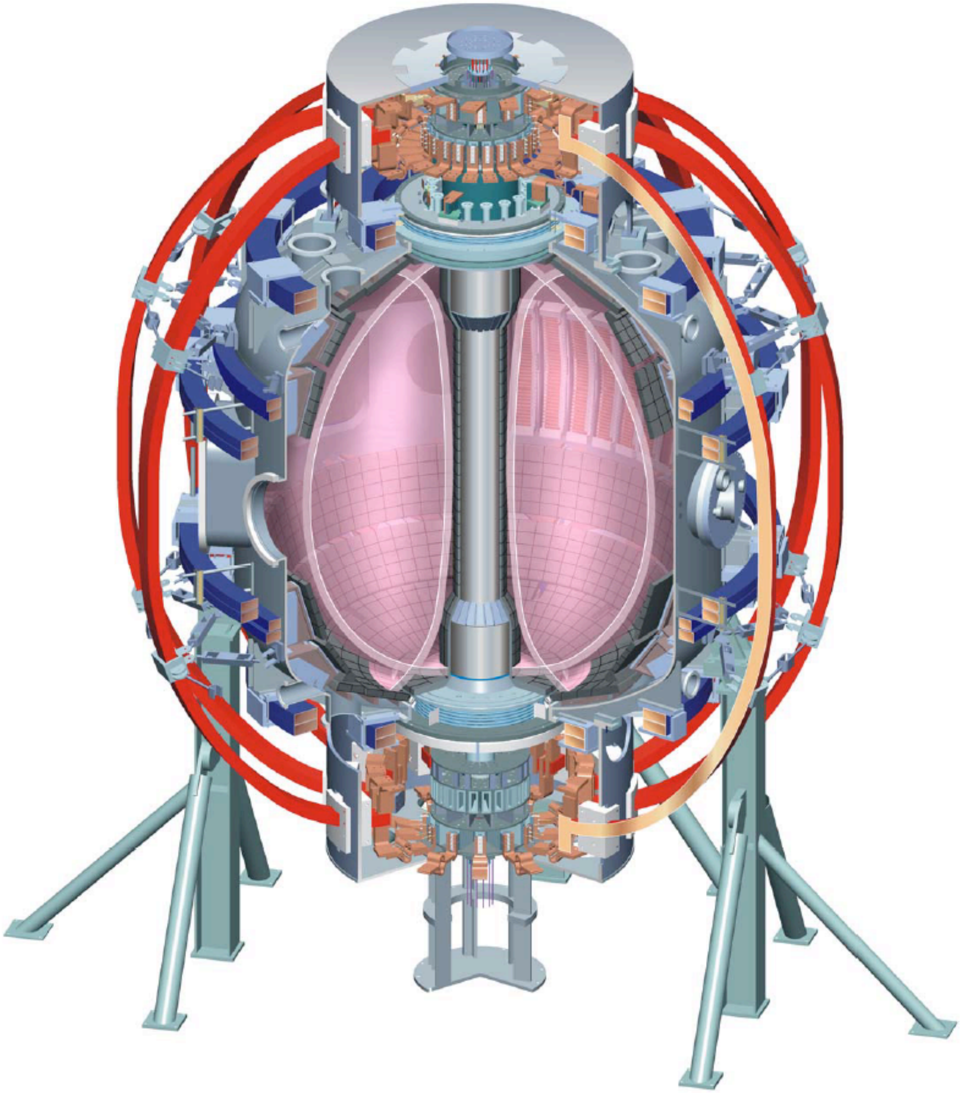
- Current NSTX EBW research focused on B-X-O emission studies
  - 30-point Thomson scattering and reflectometer support investigation of B-X-O coupling physics
  - 28 GHz heating system being installed for plasma startup & EBW experiments in 2009-10

- Pegasus provides economic test bed for assessing EBW heating and CD system in an ST
  - Modest scale university project; EBW research supports larger ST devices
  - Recently improved plasma control supports EBW research
  - Plan to install 2.45 GHz EBW heating & CD system

Outline

- Motivation
- → EBW emission measurements in NSTX
- Numerical modeling of EBW heating and current drive (CD) for Pegasus
- Summary

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
$n_e(0)$	$0.2\text{-}1\times10^{20}\ \mathrm{m}^{-3}$

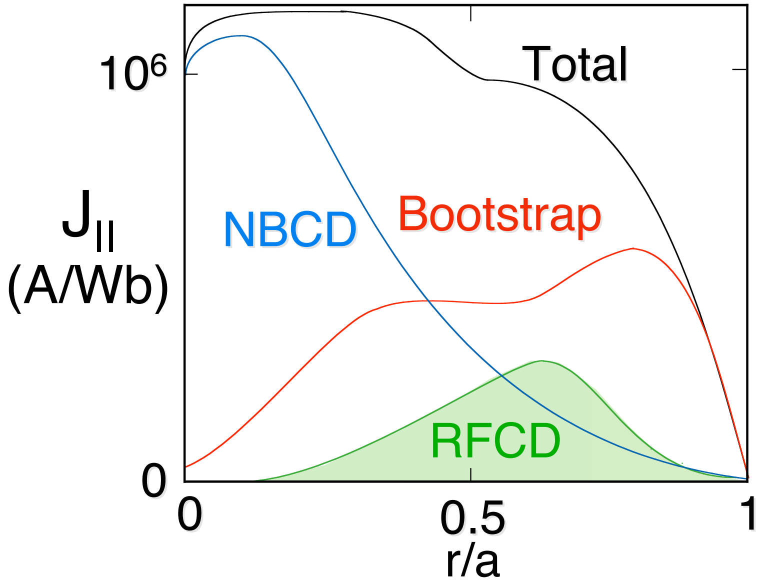
- *Maximum β ~ 40%*

Modeling predicts EBWs can provide needed current for non-inductive scenarios

- EBW must provide ~100 kA of off-axis current (Ohkawa CD)
- EBWCD possible across wide range of β at both f_{ce} & $2f_{ce}$

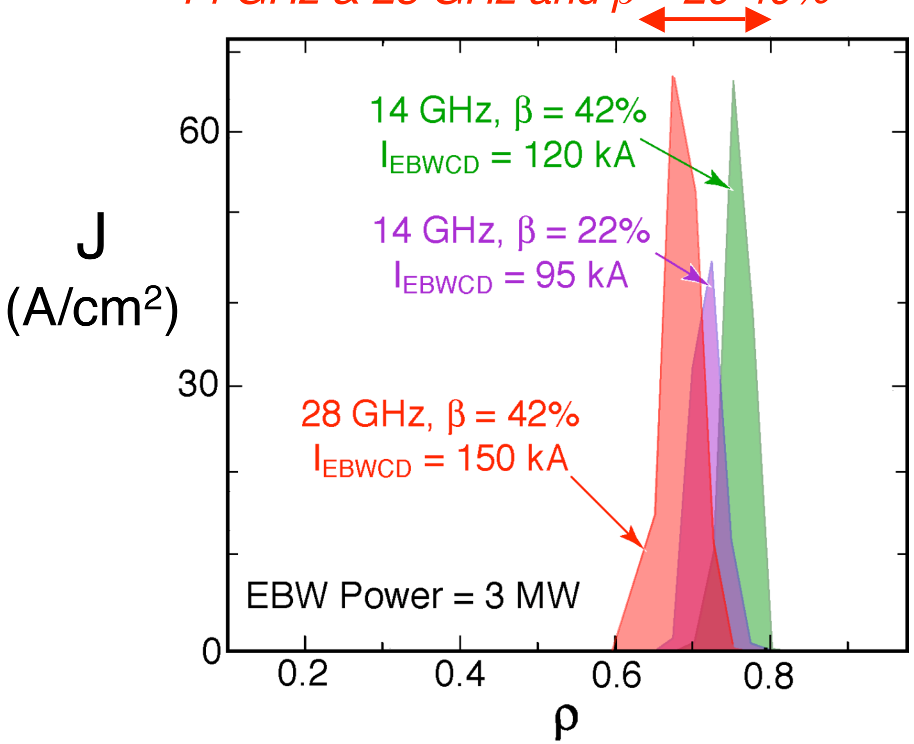
NSTX, $\beta_t = 42\%$, $\beta_{pol} = 1.6$
$B_t = 0.34$ T , $I_p = 1$ MA

TSC simulation



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

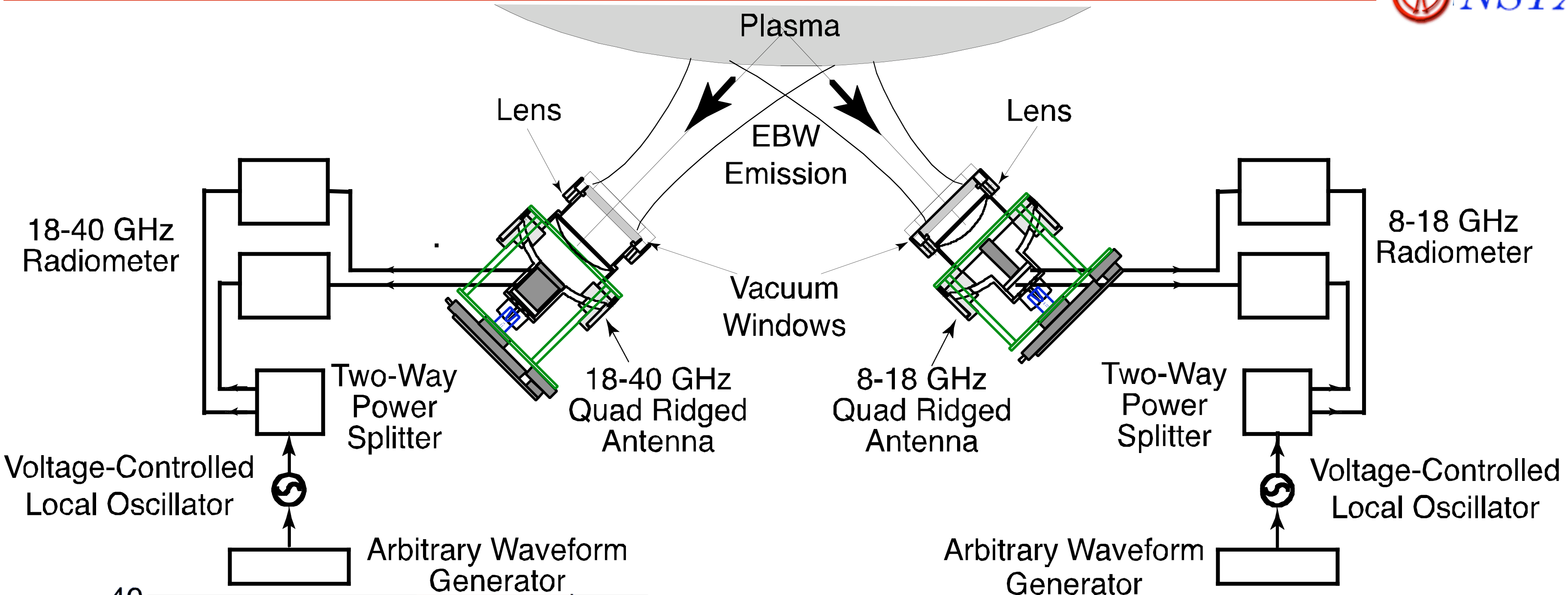
Deposition similar for
14 GHz & 28 GHz and β = 20-40%

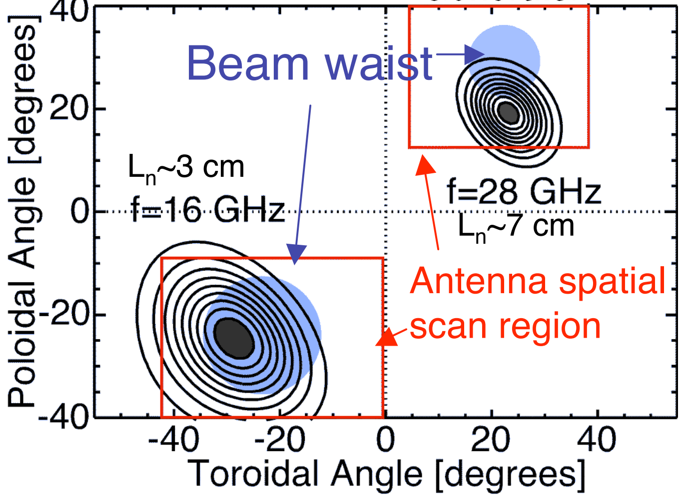


G. Taylor, et al ., Phys. Plasmas **11**, 4733 (2004)

Need efficient coupling of RF power to EBWs

Steered EBW antennas allow spatial mapping of B-X-O emission window



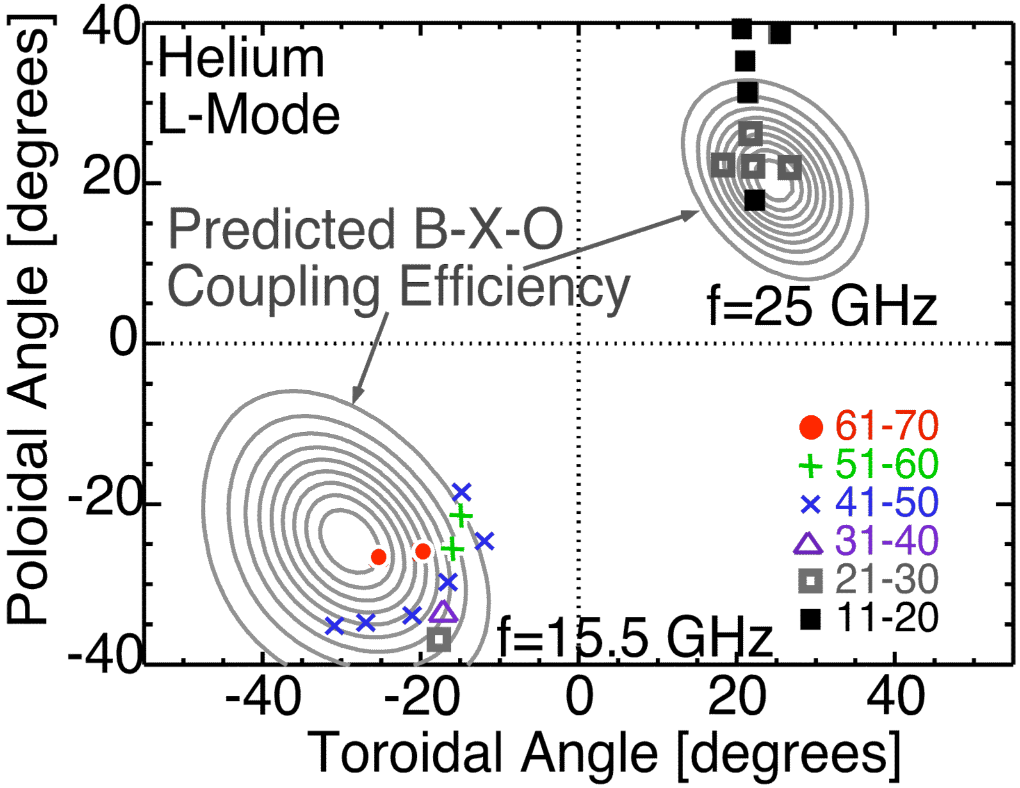


- ±10° scan in poloidal and toroidal directions during L-mode and H-mode EBE experiments
- Acceptance angle:
  8-18 GHz antenna ~ 22°
  18-40 GHz antenna ~ 14°

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

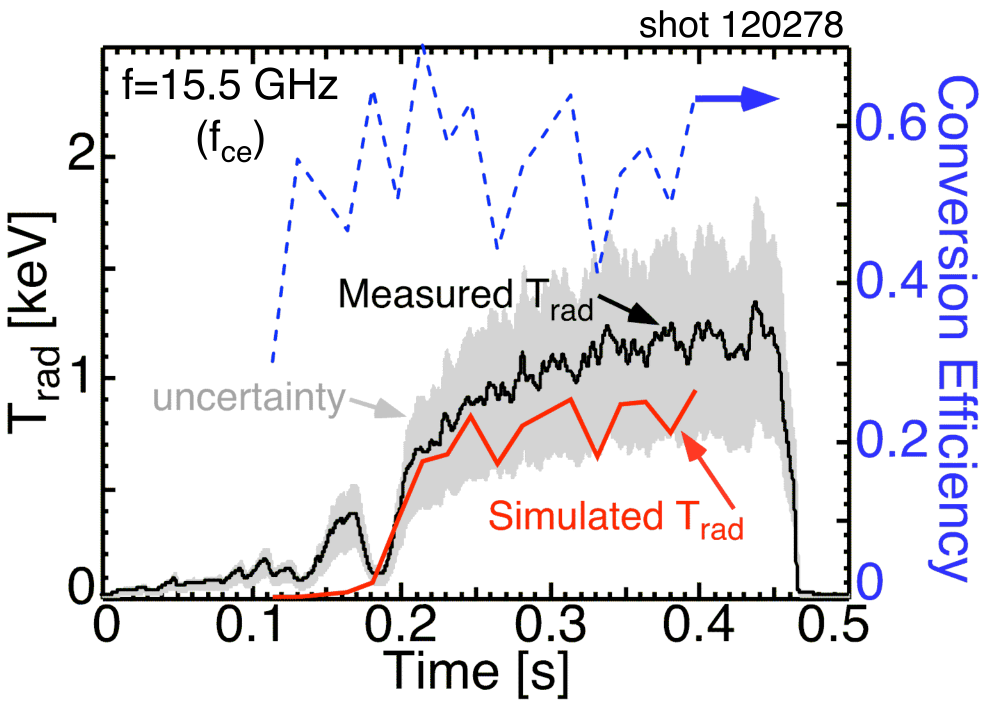
Antenna steering scan provides good coverage of L-mode B-X-O emission window

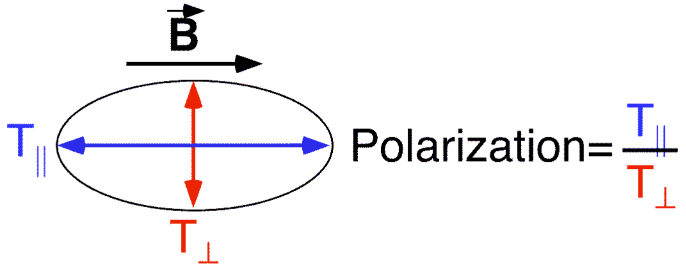
- To calculate B-X-O coupling efficiency:
  - Ray damping location obtained from GENRAY
  - Compare T_e from Thomson scattering at ray damping to T_{rad} from EBE diagnostic
- Magnetic field pitch (~40°) determines location of window
- Density scale length determines width of window

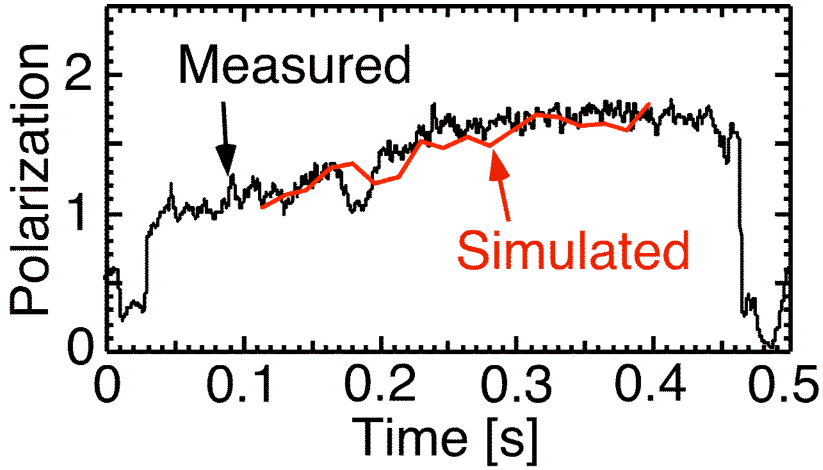


L-mode f_{ce}=15.5 GHz B-X-O coupling measurements agree with simulated results

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

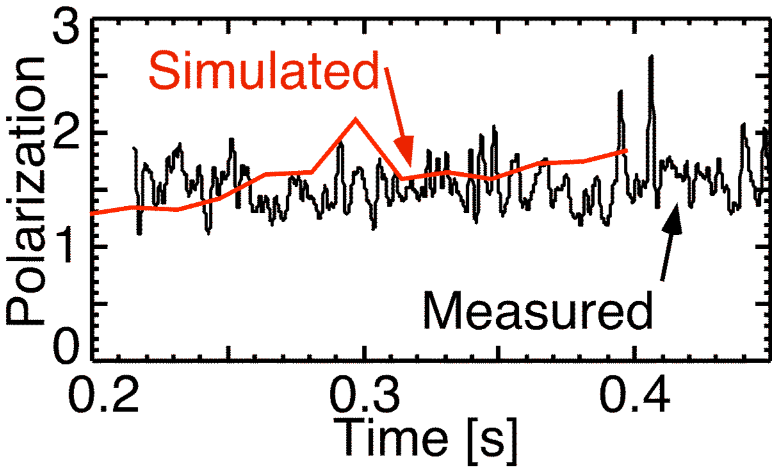


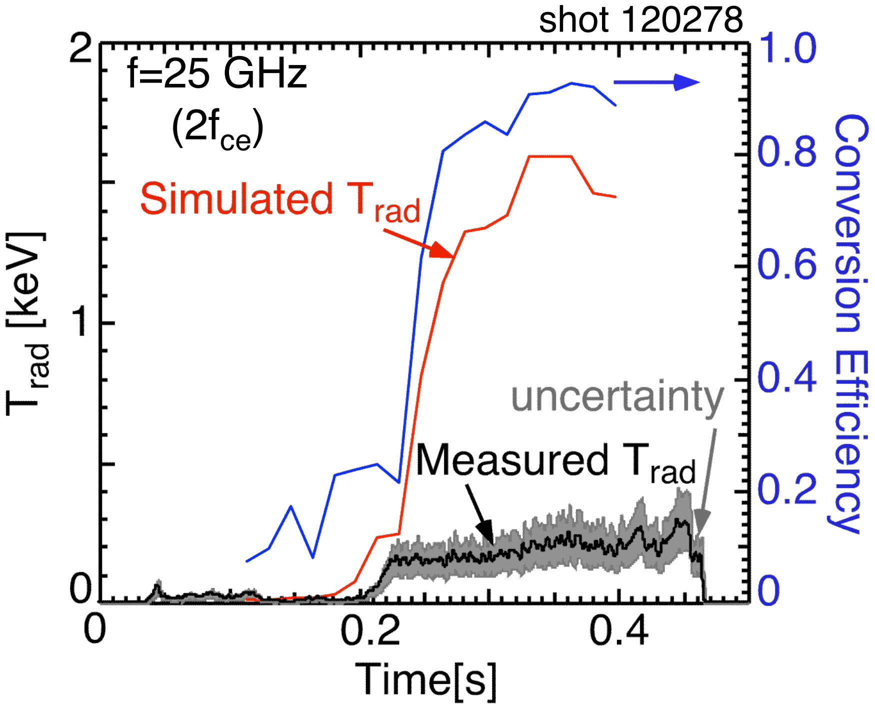




Large disagreement between measured & simulated T_{rad} at some f_{ce}, $2f_{ce}$ frequencies

- Experimental B-X-O coupling efficiency ~25±10%; simulated B-X-O coupling ~90%
- EBW $T_{para}/T_{perp}=1.6$ for both experimental measurements and simulated results





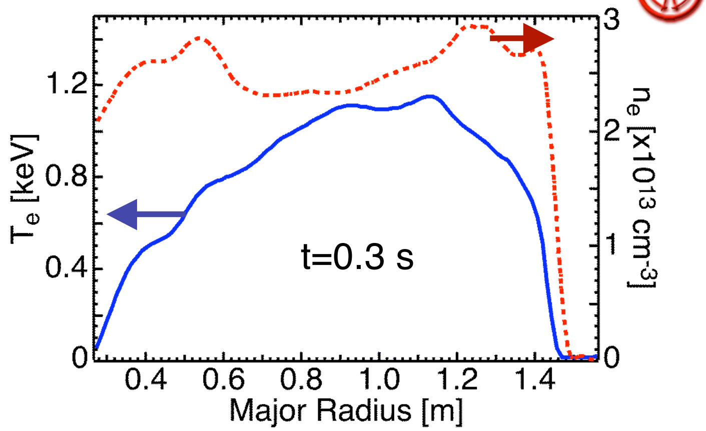
Disagreement may be due to inadequate EFIT reconstruction

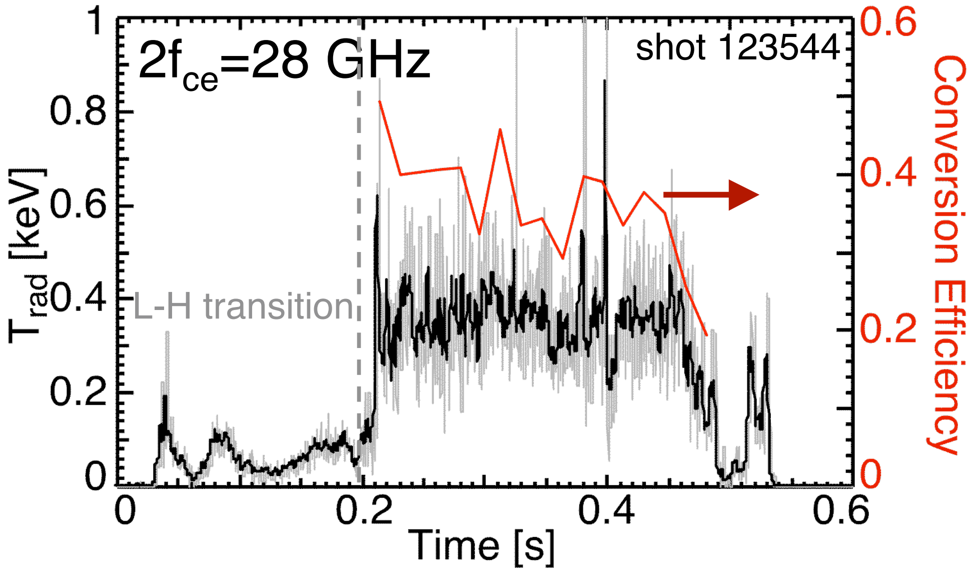
Preliminary H-mode results show good f_{ce} and $2f_{ce}$ B-X-O coupling in high κ, f_{BS} plasmas

- Target plasma: I_p=0.8 MA, κ~2.5, T_e~1 keV, and $n_e(0)$~2-4x10^{13} cm^{-3}

- Preliminary experimental B-X-O coupling efficiency:
  - 30-50% for f_{ce}=18 GHz, $2f_{ce}$=28 GHz

- EBE simulation work is ongoing

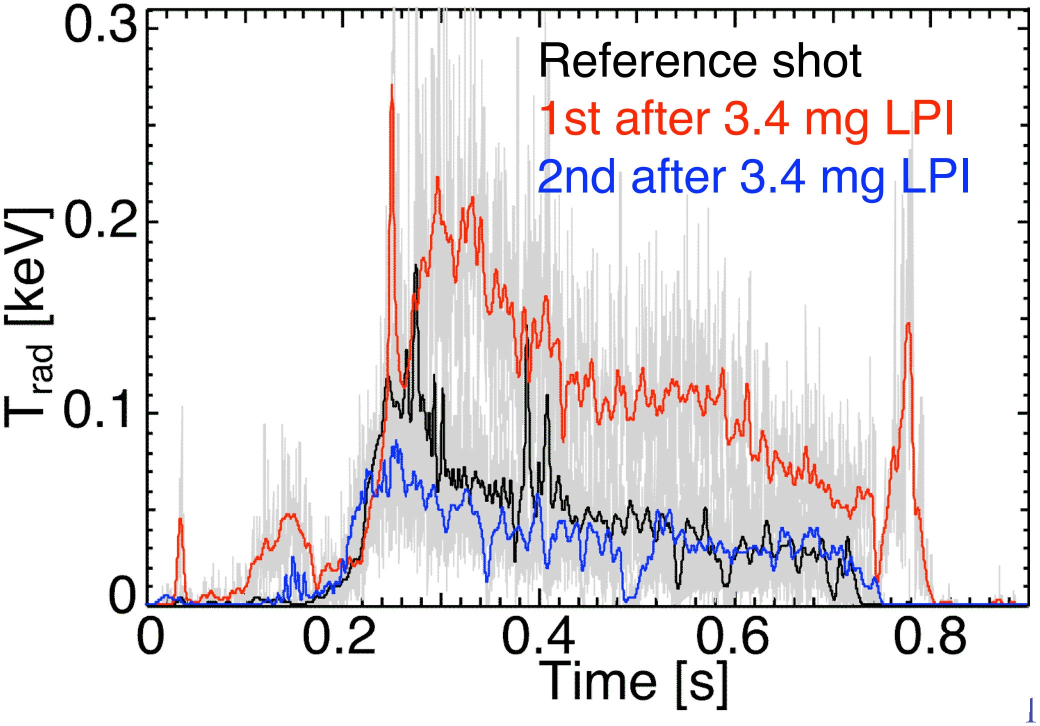




More near-term experiments to focus on studying this target plasma. Antenna location will be scanned to optimize emission.

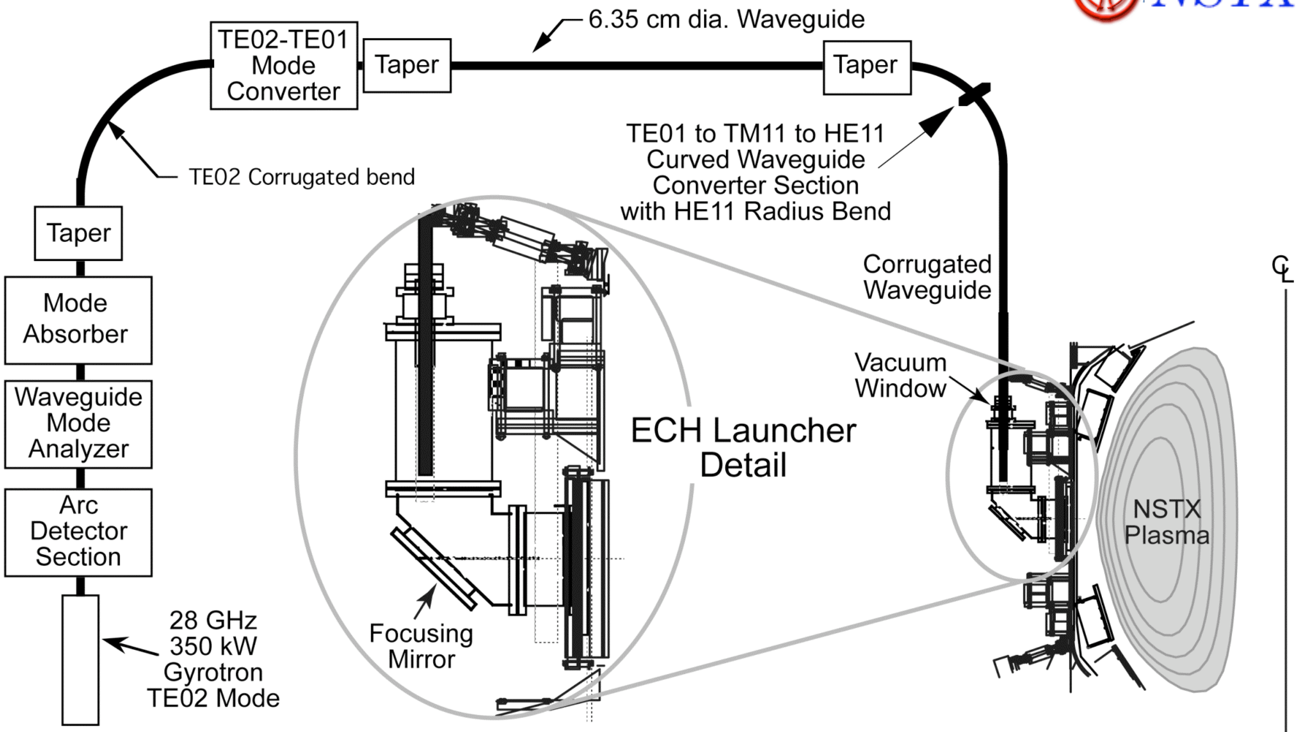
Preliminary H-mode results show increase in B-X-O coupling with Li conditioning

- Reference shot: $T_e(0)$=1 keV, $n_e(0)$~4-6x10^{13} cm^{-3}, I_p=1MA
- 3.4 mg Li pellet injection (LPI) into ohmic He L-mode plasma for conditioning
- 1st shot after LPI exhibited 2x increase in EBE
- 2nd shot after LPI, EBE reverted to pre-Li conditions



200 kW, 28 GHz ECH/EBWH for up to 500 ms to be installed on NSTX for 2009 run campaign

350 kW 28 GHz Gyrotron



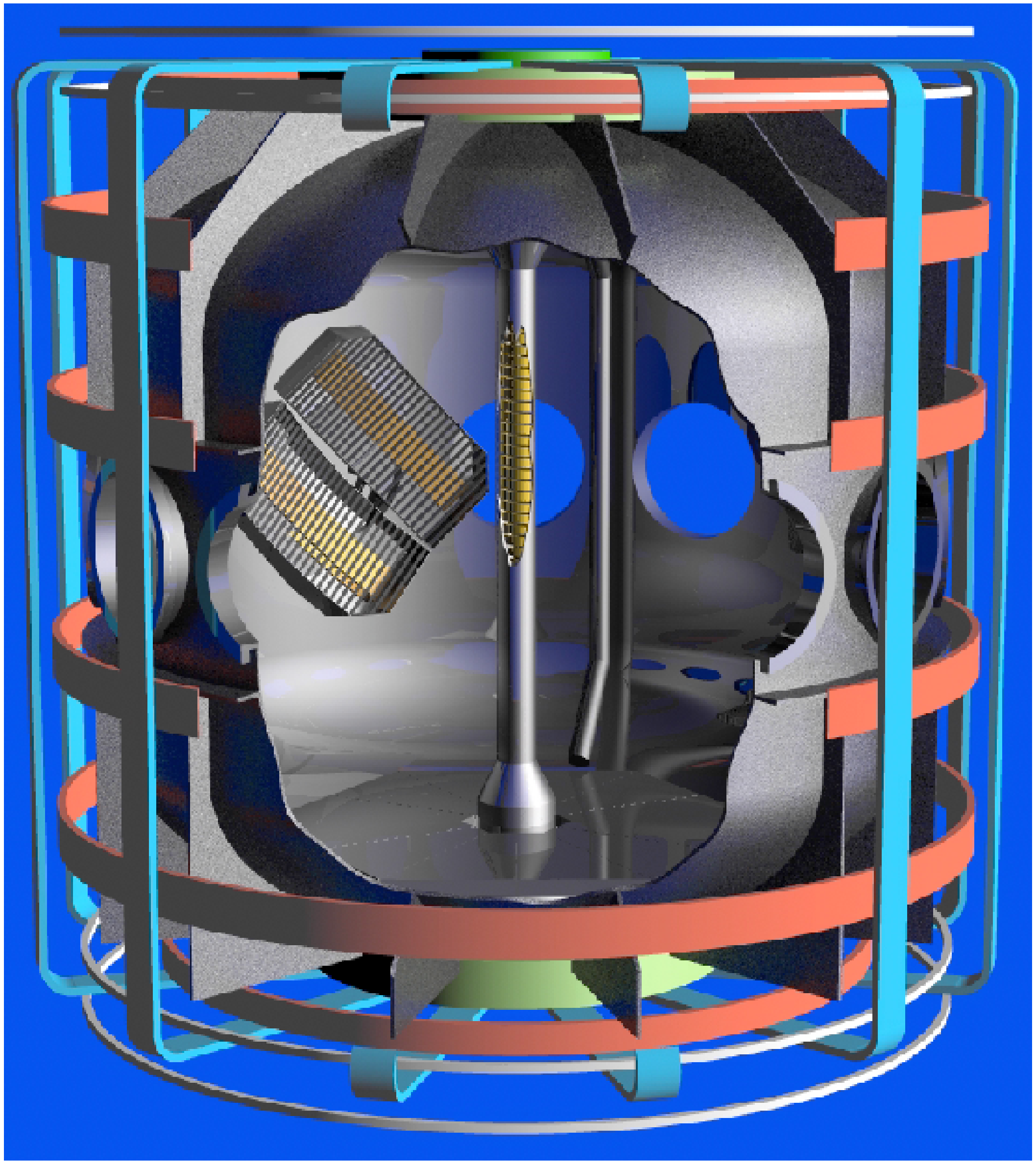
- 15.3 GHz operation being tested on low power gyrotron
- Installing power supply capability for up to 350 kW gyrotrons
- Heating for CHI & PF-only start-up plasmas
- Support ECH/EBWH/CHI transition to HHFW current ramp-up
- Conduct low power EBW coupling & heating during I_p flattop

G. Taylor et al., Poster Paper B30 this afternoon

Outline

- Motivation
- EBW emission measurements in NSTX
- → Numerical modeling of EBW heating and current drive (CD) for Pegasus
- Summary

Pegasus is a mid-sized, ultra-low A ST



Experimental Parameters

A	1.12-1.3
R	0.2-0.45 m
I_p	≤0.3 MA
κ	1.4-3.7
β_t	30 %
P_{HHFW}	2 MW

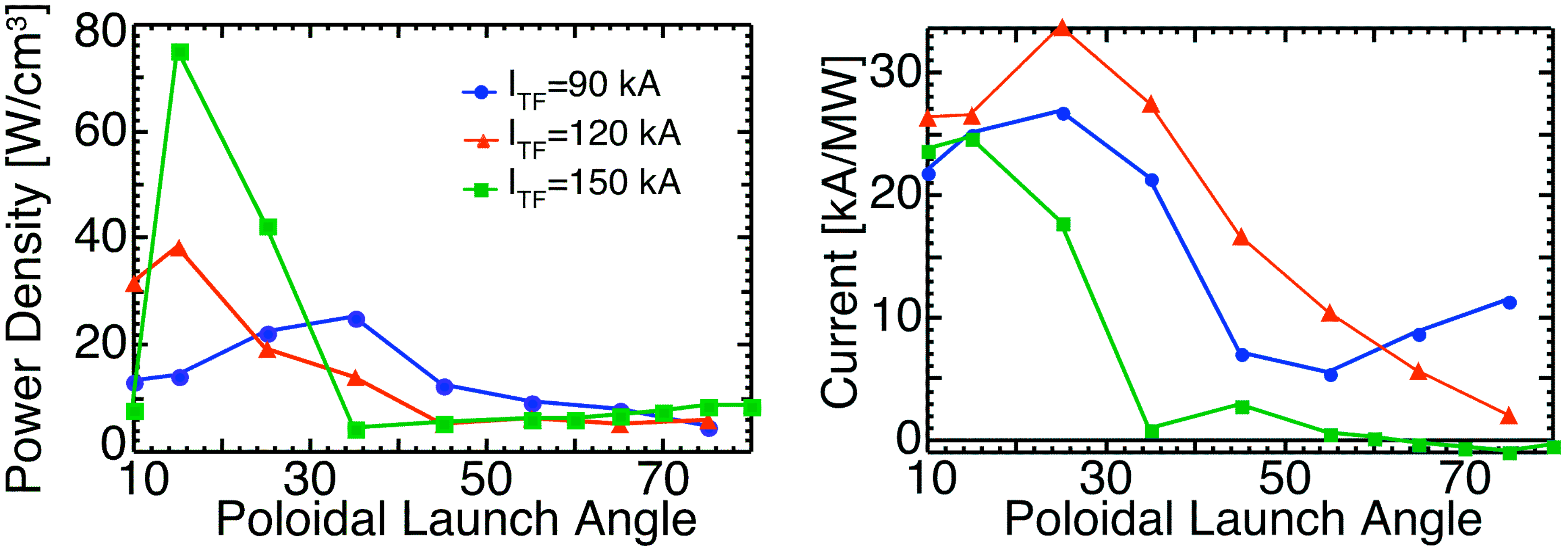
2.45 GHz system well suited for Pegasus

- Low toroidal field allows use of available low frequency klystrons
  - 2.45 GHz fundamental is resonant with 880 G on axis
  - Existing 2.45 GHz equipment will be used for the planned 0.9 MW system

Modeling Goal → find optimal antenna location to maximize EBW heating/CD for a variety of plasmas

Near mid-plane launch optimizes heating & CD

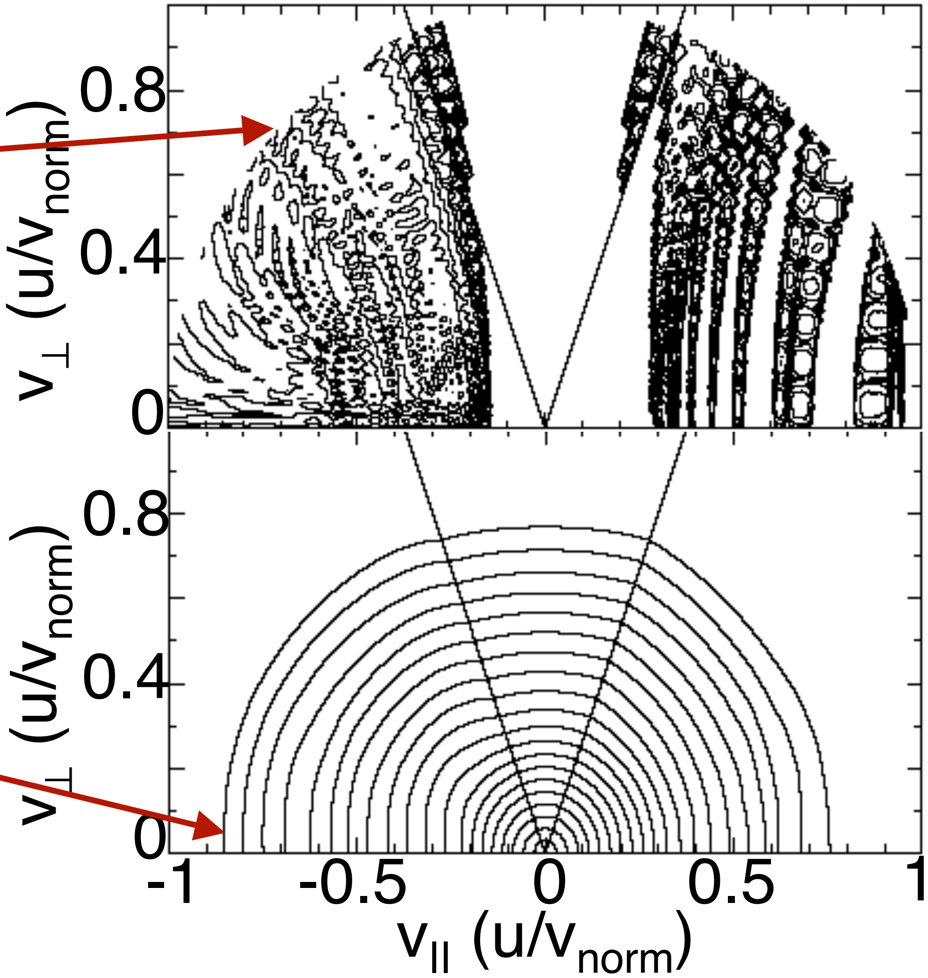
- Target plasma: $T_e(0)$=350 eV, $n_e(0)$=4.5x10^{19} cm^{-3}, I_p=150 kA
- Varied poloidal launch angle and I_{TF} from 90-150 kA
- GENRAY coupled to CQL3D used for modeling
  - max of 78 W/cm^3 heating and 33 kA per 1 MW of injected EBW power



Fisch-Boozer CD is dominant CD mechanism for near-midplane launch

- Quasilinear diffusion coefficient peaks in passing particle region

- Preferential heating of electrons with negative v_{II} is seen



These are characteristics of Fisch-Boozer CD and are observed for all cases with positive driven current.

Outline

- Motivation
- EBW emission measurements in NSTX
- Numerical modeling of EBW heating and current drive (CD) for Pegasus
- → Summary

EBWs can provide viable method of non-inductive heating/CD for STs

- EBE measurements on NSTX help guide the design of EBW antenna for NSTX EBW CD system
  - L-mode results show good coupling, 70±20%, for f_{ce}=15.5 GHz, agreeing with simulated results
  - Disagreement between experimental measurements and simulations for $2f_{ce}$ and f_{ce}=12-15 GHz
  - Preliminary H-mode coupling measurements of 30-50% coupling for $2f_{ce}$=28 GHz

- Pegasus numerical modeling supports near-midplane antenna placement for variety of B_{TF}
  - EBW heating of 10-80 W/cm^3
  - Provide 15-30 kA/MW of CD near ρ=0.1, 20% of I_p

Future work

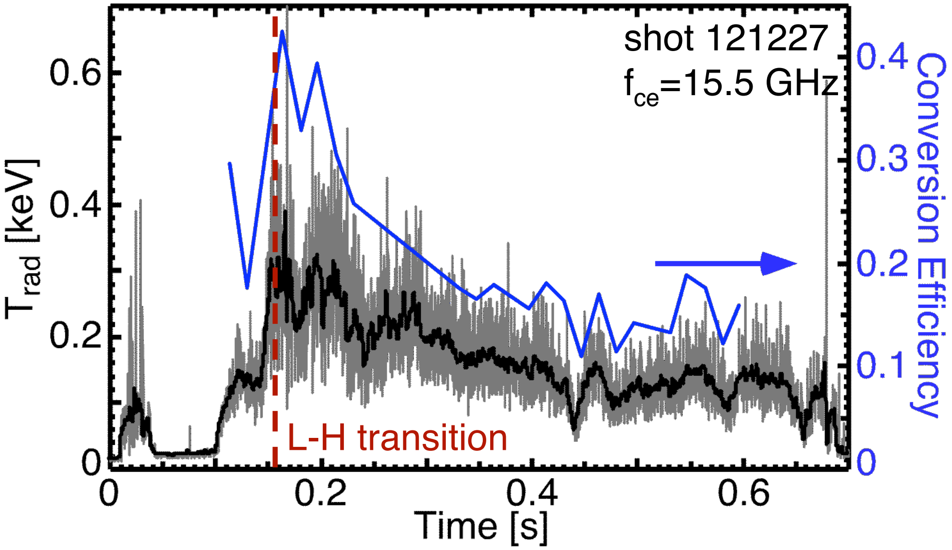
- NSTX will continue B-X-O coupling studies
  - Optimize emission in high κ, f_{BS} target plasma
  - Continue EBE simulations of H-mode plasmas
- NSTX to install 200 kW, 28 GHz gyrotron for 2009 run
  - Support ECH/EBWH/CHI transition to HHFW current ramp-up
  - Conduct low power EBW coupling & heating during I_p flattop
- Pegasus will develop tools to implement EBW heating/CD system
  - Plasma Control System being commissioned
  - Antenna and power supply designs have begun

Additional Slides

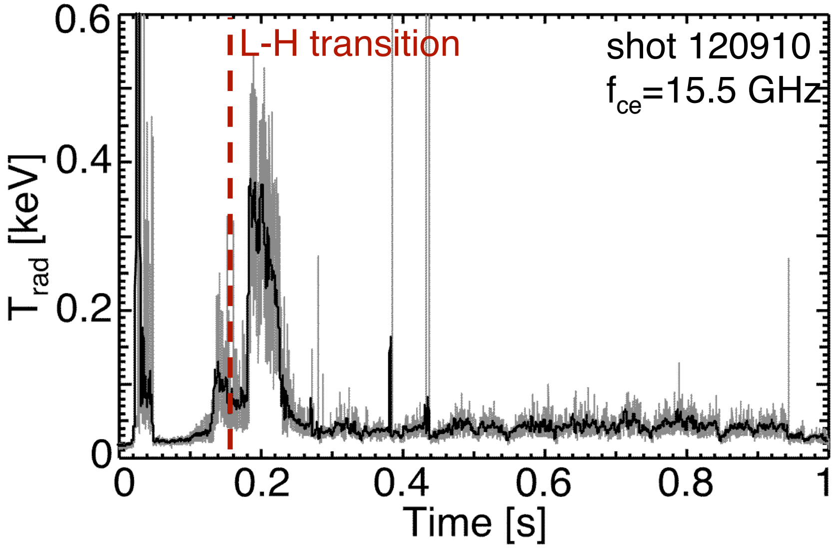
Previous measured H-mode B-X-O coupling very low

NSTX

- Emission slowly decays from 40% to 15% during discharge
- Possible causes:
  - Build up of edge I_{BS} changes B-field pitch at UHR layer
  - Collisional damping of EBW

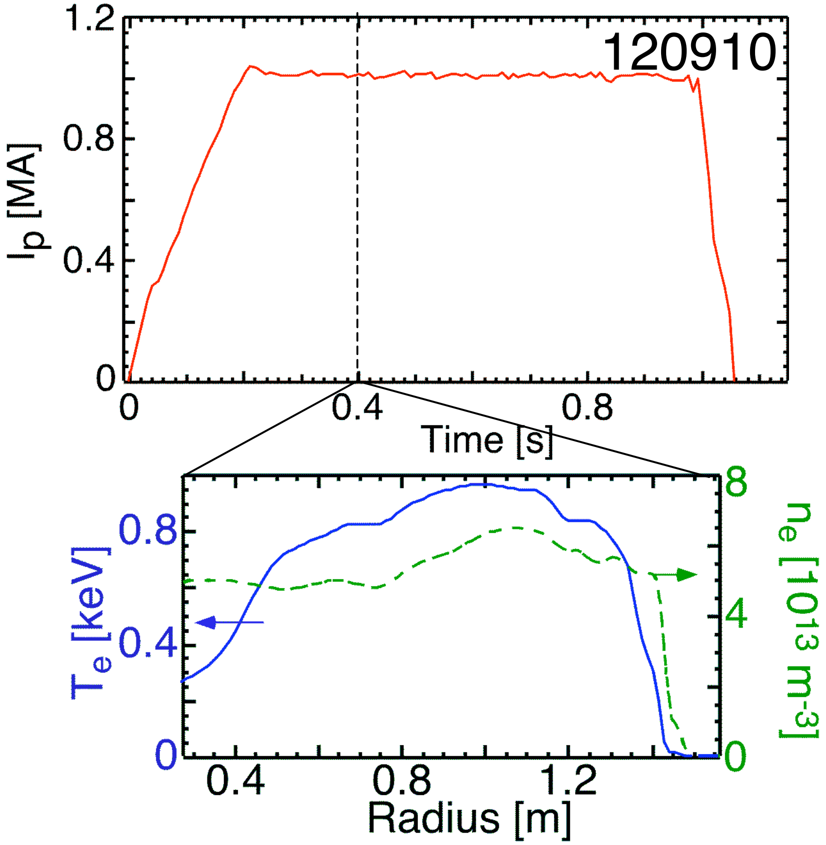


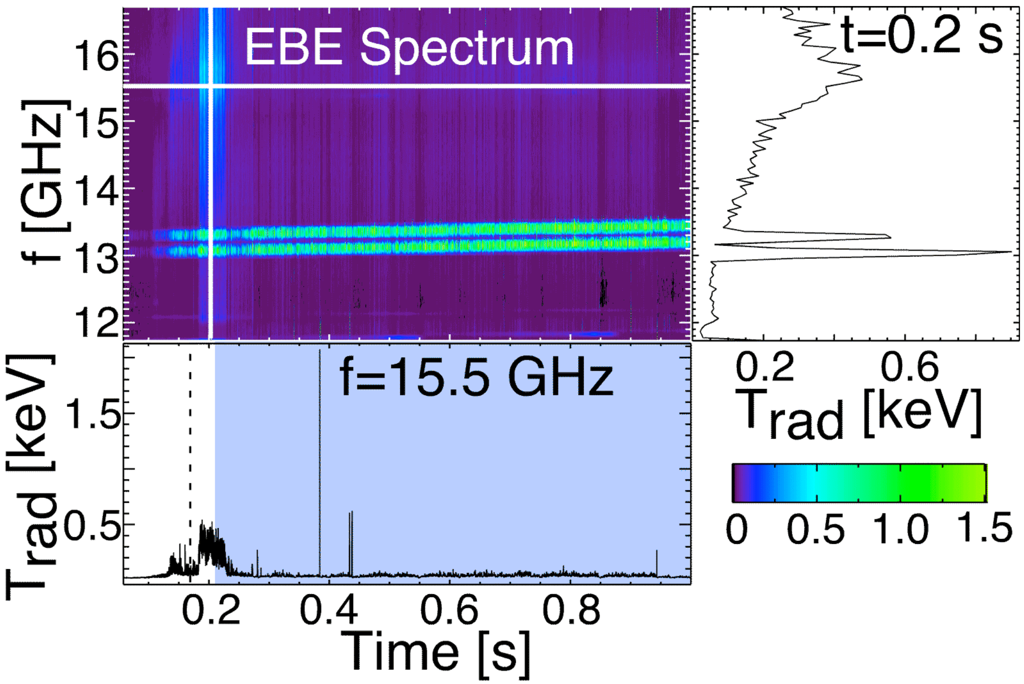
- Estimated 40% coupling shortly after L-H transition
- Emission unpolarized during I_p flattop
- Possible cause:
  - Downward motion of Z_{maxis} increases Doppler broadening



2006 Scan of H-Mode Window Indicates Very Low Emission

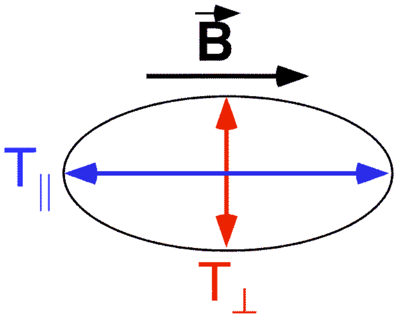
- Target discharge: I_p~1MA, $T_e(0)$~0.9 keV, $n_e(0)$~5e^{13} m^{-3}
- Burst of emission observed shortly after L-H transition



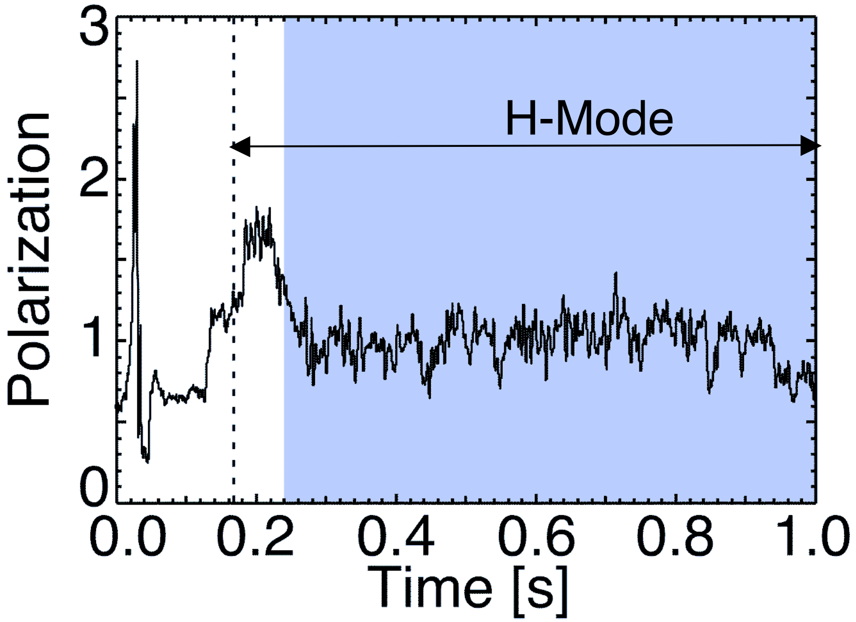


Very Low B-X-O Coupling Measured During H-mode Plasmas in 2006

- <10% coupling efficiency measured during I_p flattop (after emission burst)
- Emission unpolarized after t~0.25s, indicating diagnostic measuring scattered emission



$\text{Polarization}=\frac{T_\parallel}{T_\perp}$



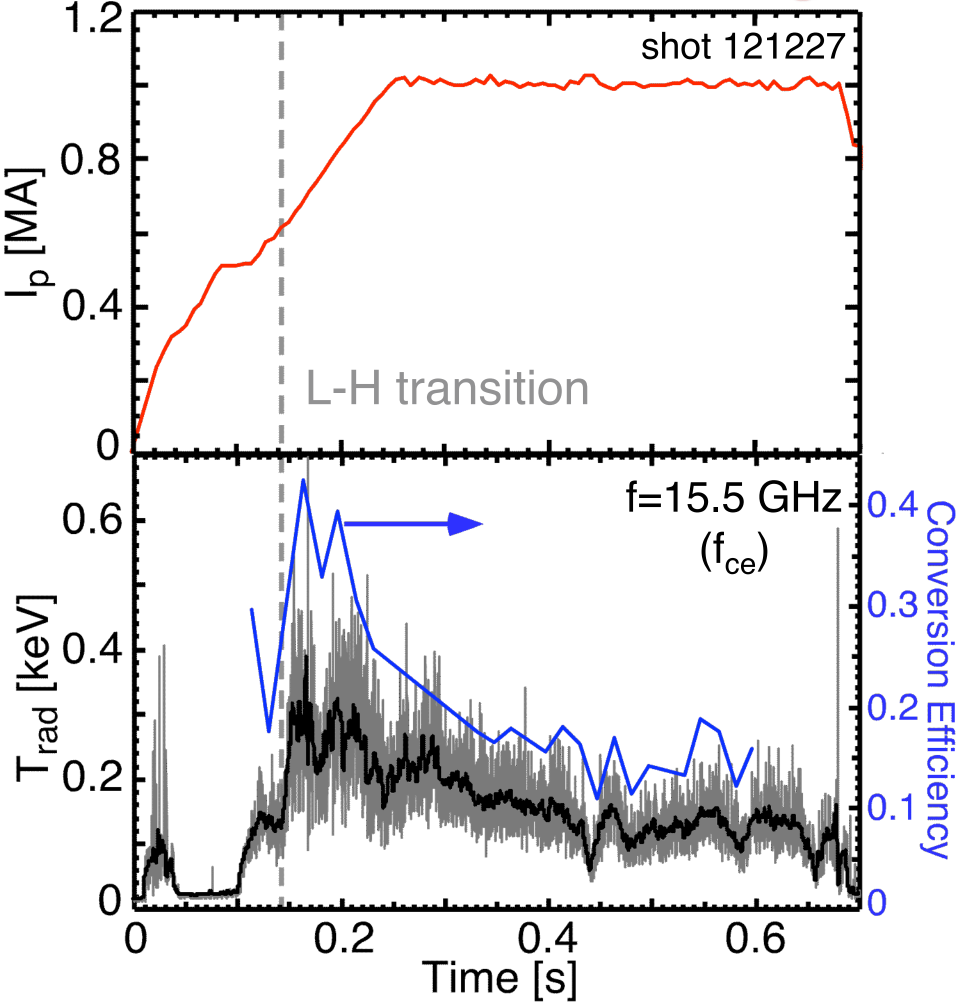
→ Possible causes: collisional damping, edge bootstrap current effects

Decay in EBE observed for some H-mode plasmas

- Emission slowly decays during discharge
- Build up of edge I_{BS} may be large enough to move EBE outside of antenna view
- Similar to MAST observations

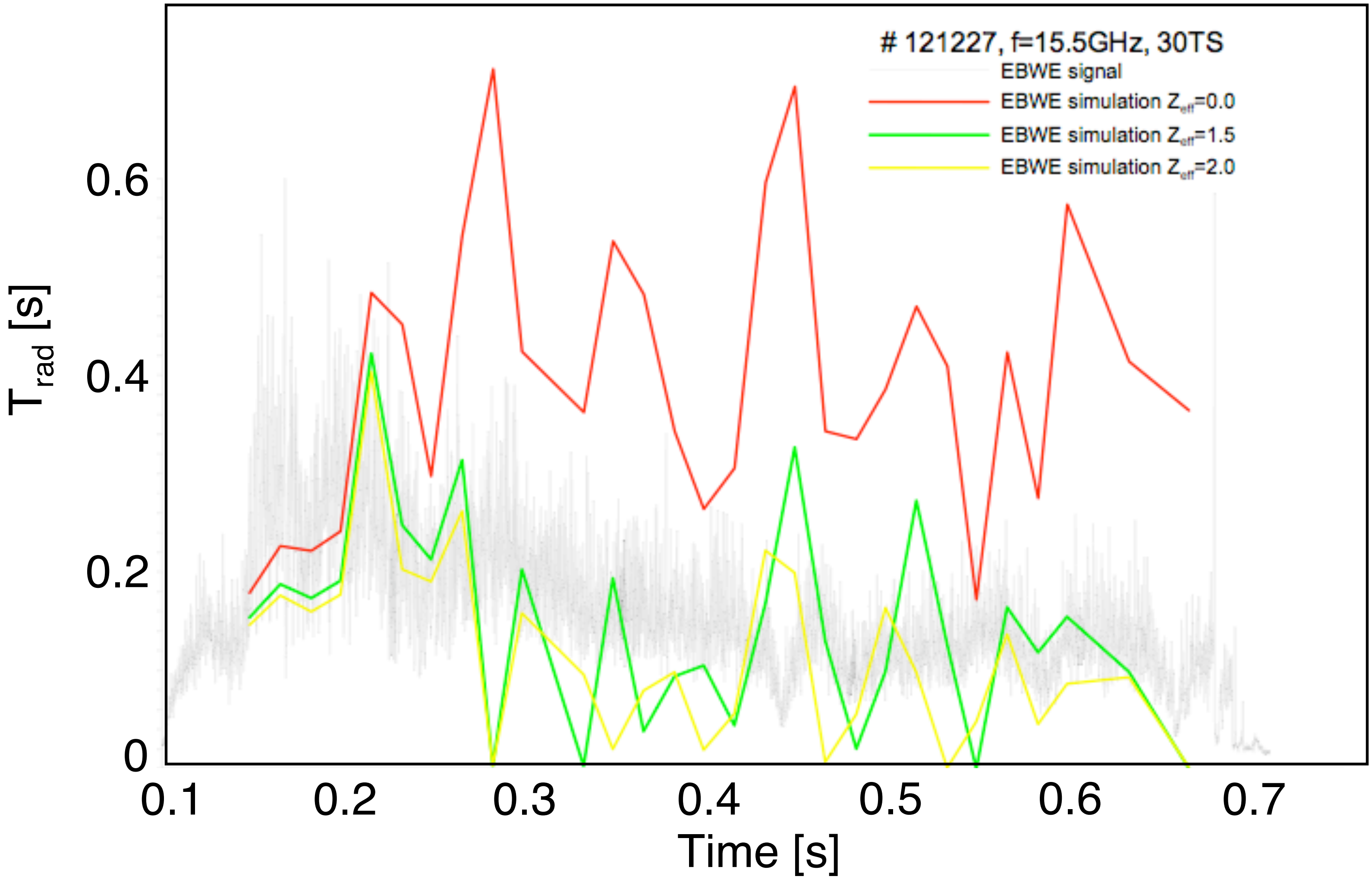
V. Shevchenko et al, Rev. EC-13

- EBE simulation suggests this emission decay due to collisional damping
- Rapid decay of emission also observed



A wide acceptance angle (80°) antenna has been installed to detect EBE outside steered antenna field of view

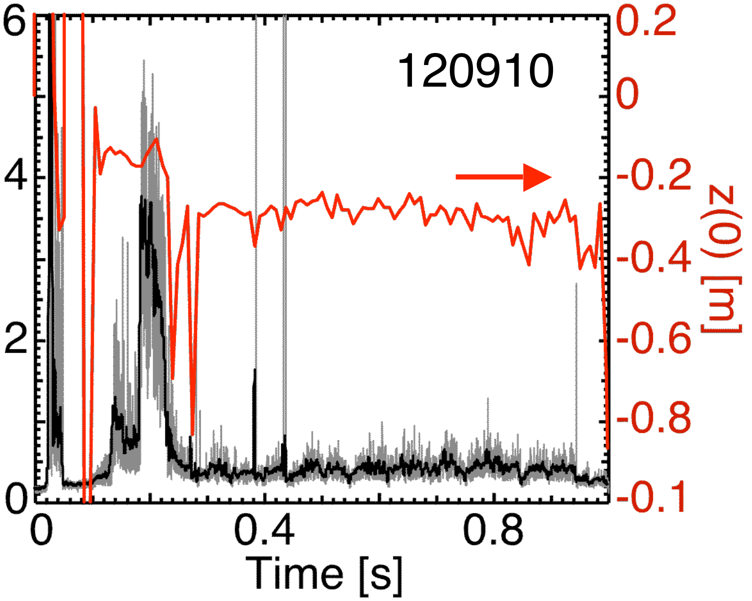
Preliminary EBE simulation suggests collsional damping causing EBE decay

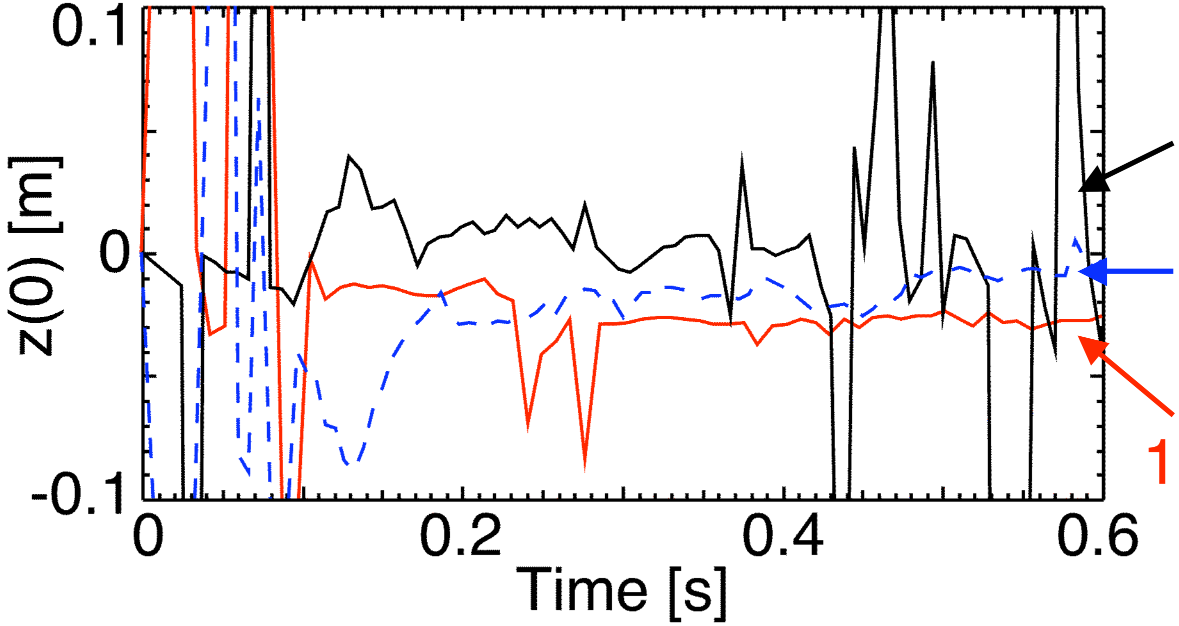


Data Mining Suggests Reduced Emission May be Coupled to Z-Position

- Emission burst occurs for z(0)>-2 cm and decays when z(0)<-2 cm

- Possibly similar to results observed during EBW heating experiments on TCV





121227 - decaying EBE

117970 - 30% [2005]

120910 - EBE rapid decay