Supported by

Office of Fusion Energy Sciences

Office of Science

EBW & HHFW Research

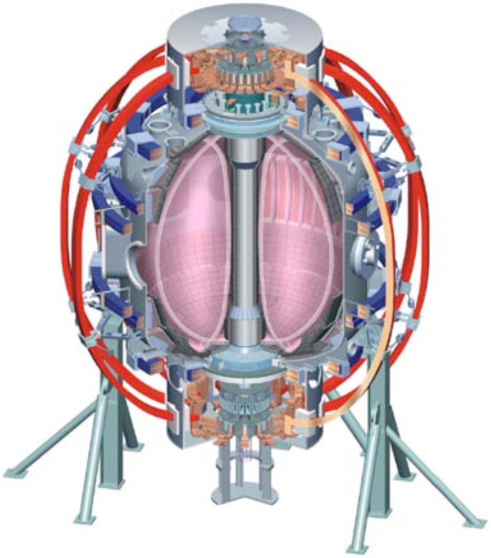
(Including EBW Collaborations with MAST & PEGASUS)

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

Gary Taylor
For the NSTX Team

19th NSTX Program Advisory Committee Meeting
(PAC-19)
February 22-24, 2006

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



NSTX EBW Research

(including MAST & PEGASUS)

- EBWCD for $\beta > 20\%$ non-inductive operation in NSTX & CTF
- Test coupling & current drive physics
- Develop time-continuous T_e profile evolution diagnostic

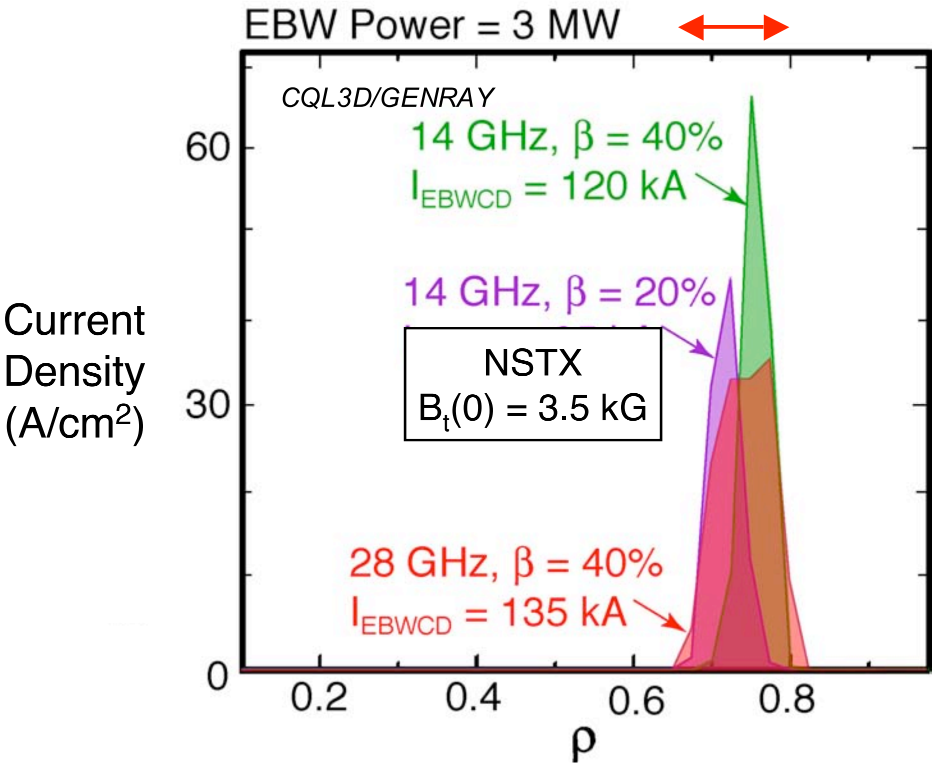
EBWCD Needed to Sustain β > 20 % Non-Inductive NSTX Plasmas

- *Need ~100 kA RFCD between ρ = 0.4 & ρ = 0.8; CD localization is not critical*

- *Large trapped particle fraction on low field side enables off-axis Ohkawa EBWCD*

- *Need resilient coupling to EBWs for viable EBWCD scheme*

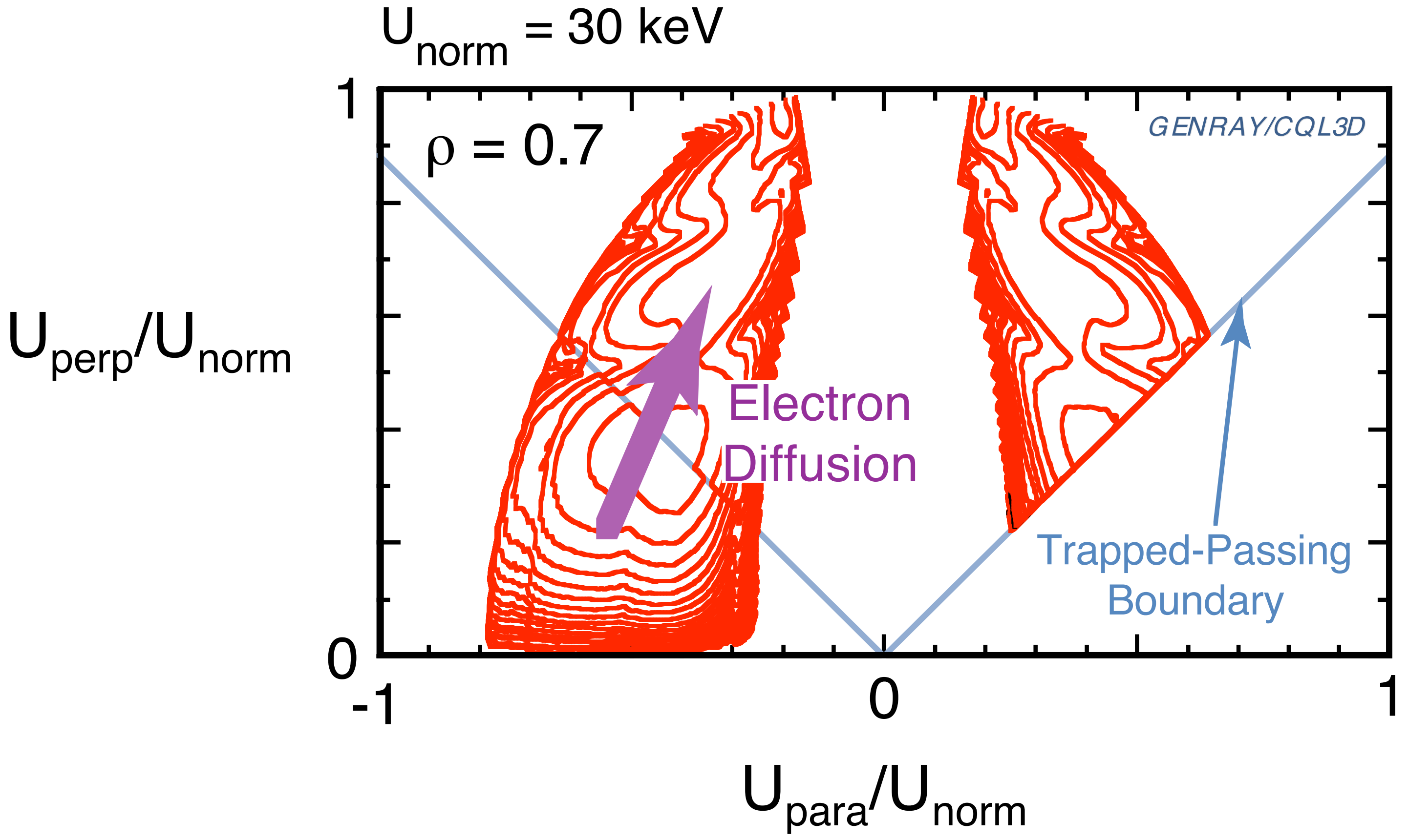
Deposition similar for 14 GHz & 28 GHz and β ~ 20-40%



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

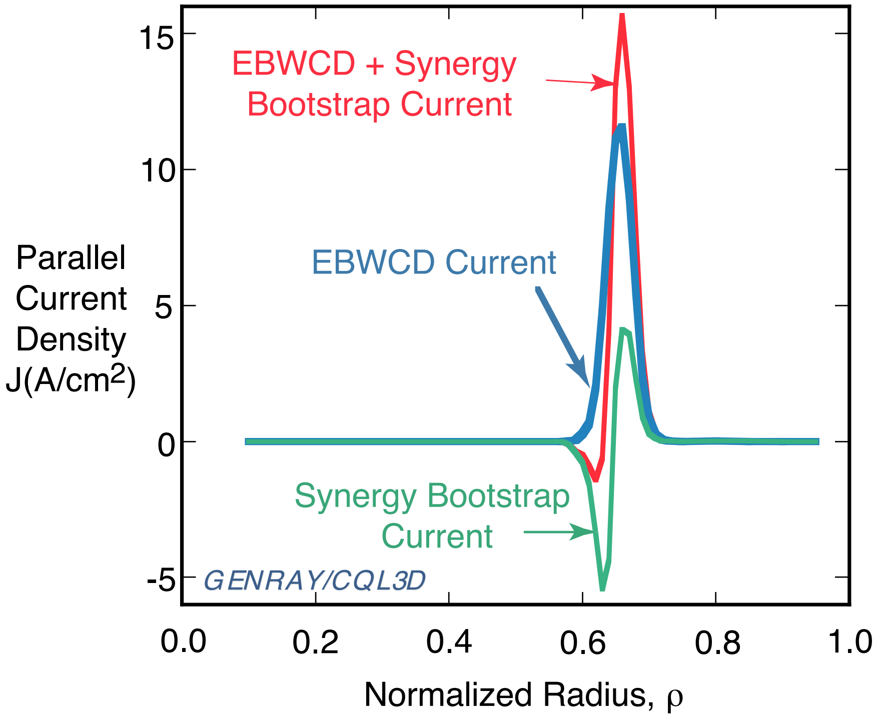
Strong Diffusion Near Trapped-Passing Boundary Enables Efficient Ohkawa EBWCD

Contours of Quasilinear RF Velocity Space Diffusion Operator



Synergistic Bootstrap Current Results from EBW-Induced Pitch Angle Scattering Into Trapped Electron Population

NSTX β = 40%, P_{EBW} = 1 MW, Co-EBWCD

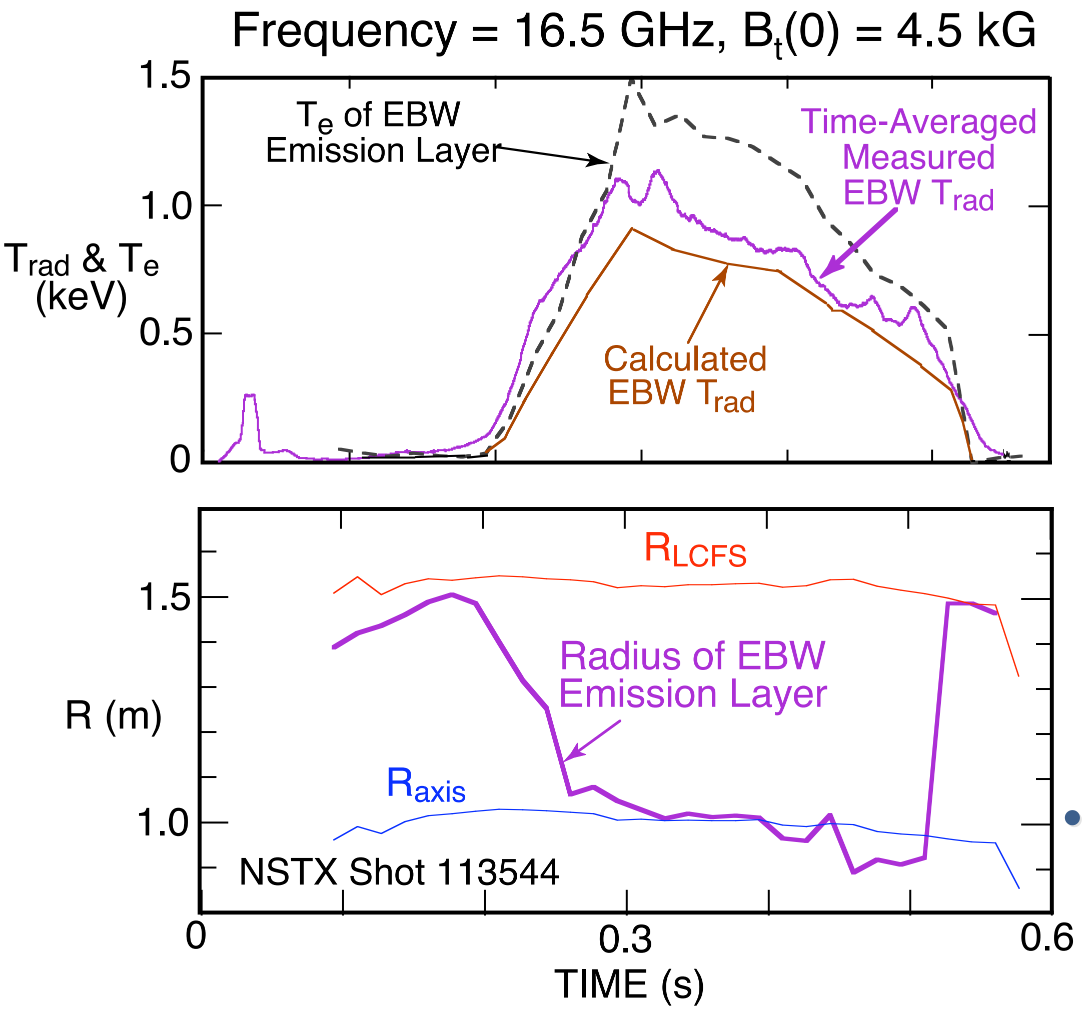


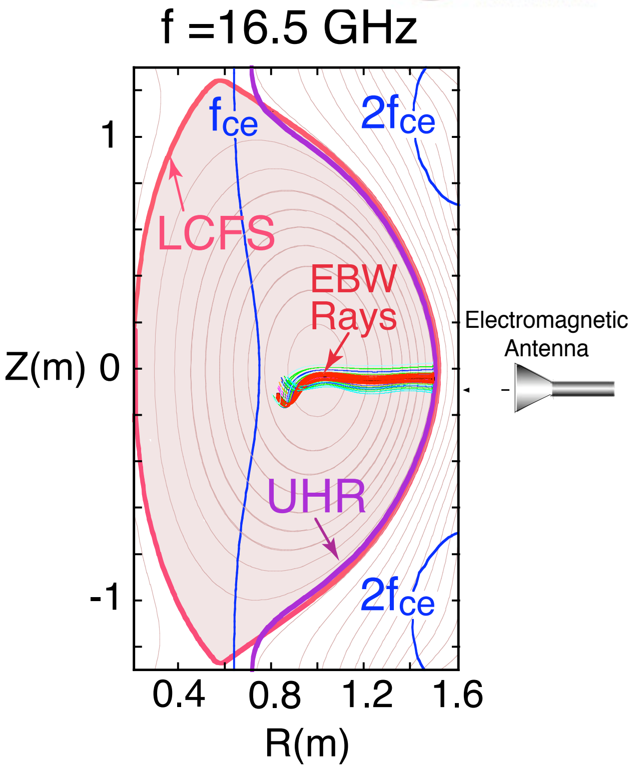
- *Synergy bootstrap current modifies CD by < 10%*
- *Radial diffusion broadening is marginally important for β = 40% case: $\Delta\rho \sim 0.05$ @ $\rho \sim 0.7$*
- *CD modeling assuming diffusion constant in velocity space, being performed for range of NSTX conditions*

*R.W. Harvey & G. Taylor, Phys. Plasmas **12**, 051509 (2005)*

- *CQL3D being upgraded to improve radial transport calculation, including possible self-consistent anti-pinch effect of Ohkawa EBWCD & its effect on bootstrap current*

Measured 80% B-X-O Coupling in L-Mode Edge Plasmas, Consistent with Modeling

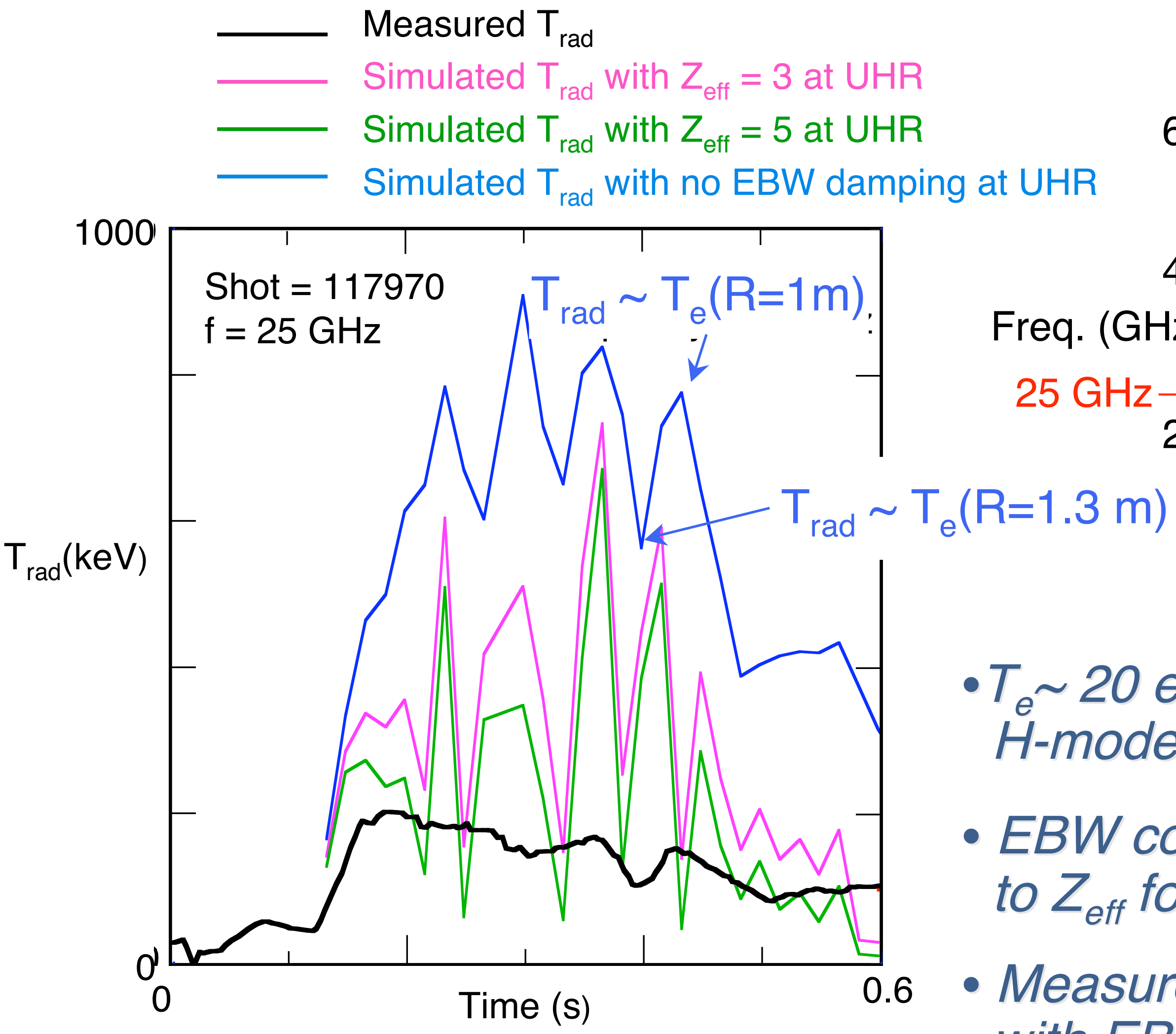


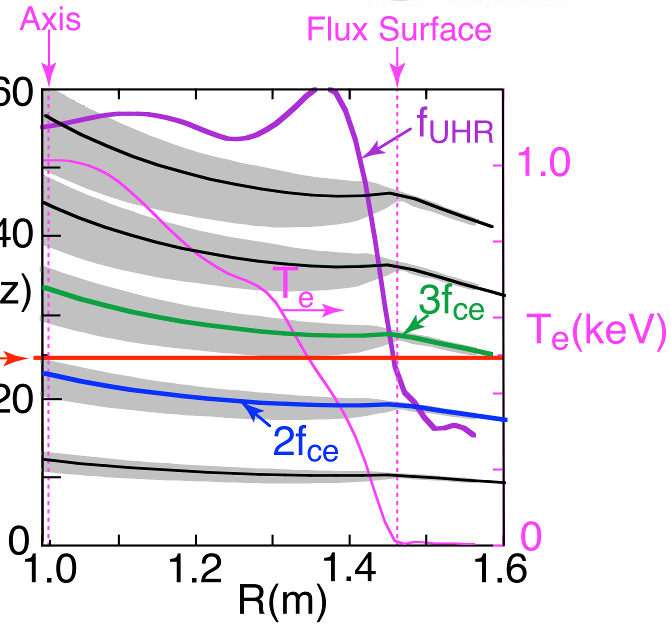


- *3-D ray tracing & full wave EBW mode conversion model using EFIT magnetic equilibrium & Thomson scattering T_e & n_e*

*G. Taylor et al., Phys. Plasmas **12**, 052511 (2005)*
*J. Preinhaelter et al., AIP Proc. **787**, 349 (2005)*

~ 30% B-X-O Coupling in H-Modes Consistent with Collisional 3f_{ce} EBE Damping at Upper Hybrid Layer

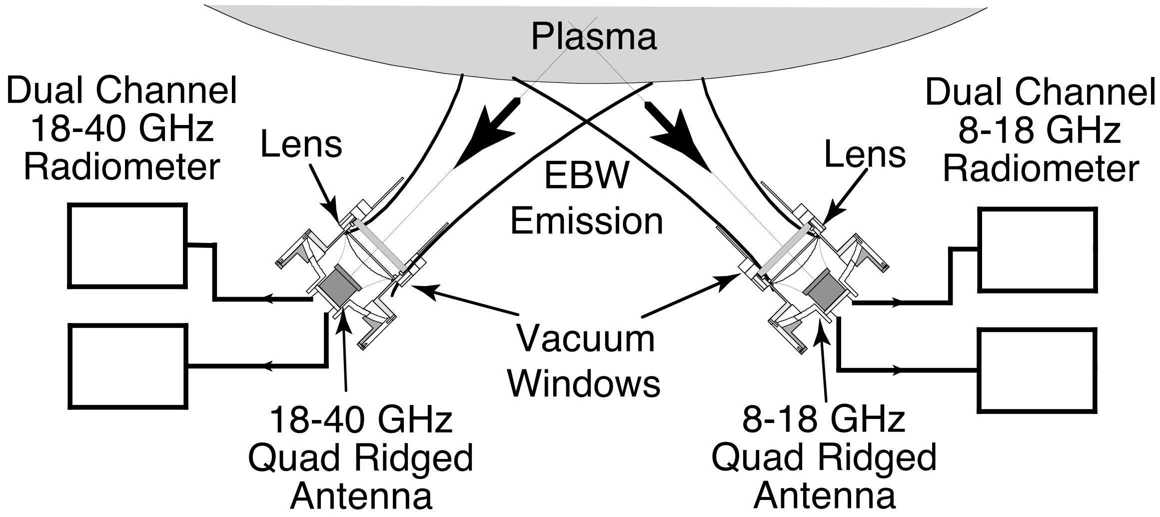




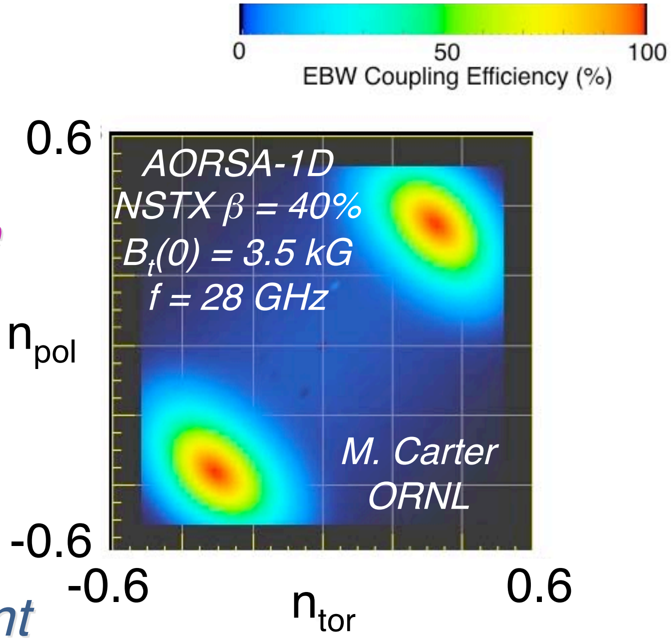
- *T_e~ 20 eV at UHR, near foot of H-mode pedestal*
- *EBW collisional damping sensitive to Z_{eff} for $T_e < 30$ eV*
- *Measured T_{rad} behavior consistent with EBE only from 3f_{ce} off-axis*

- *Li conditioning may significantly improve B-X-O coupling from H-modes by increasing T_e at UHR*

Remotely-steered B-X-O Antennas, Covering 8-40 GHz, will Test EBW Coupling Efficiency Predictions from Models



- *Experiments will study L- & H-mode plasmas and effect of Li pumping on EBW edge coupling*



- *Scanning frequency & antenna viewing angle provides key information on angle of peak EBW coupling & emission polarization*
- *EBW coupling study critical for assessing technical feasibility of EBWCD in FY06*
- *Supports EBW $T_e(R,t)$ diagnostic development*

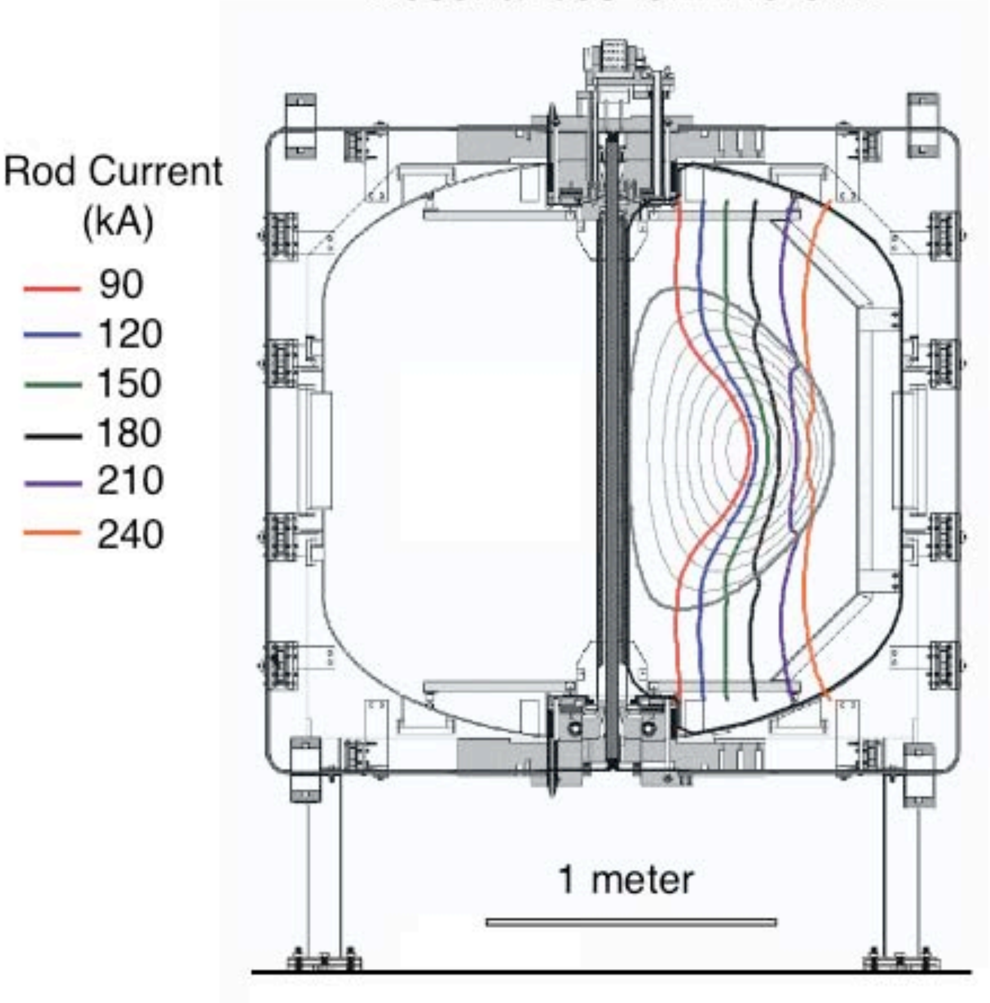
MAST EBW Collaboration

- EBWCD benchmarking between GENRAY/CQL3D & BANDIT shows reasonably good agreement for β = 40% NSTX case:
  - Both codes predict Ohkawa EBWCD, peaked at r/a ~ 0.7
  - BANDIT: 26 kA/MW, GENRAY/CQL3D: 37 kA/MW
  - BANDIT includes EBW coupling at UHR, GENRAY did not
  - In 2006, will include EBW coupling in GENRAY
- 28 GHz EBW I_p initiation/ramp-up system will be tested on MAST in late 2006 (installation in summer 2006):
  - collaborate with 28 GHz startup/ramp-up experiments in 2006-7
  - possible 28 GHz B-X-O experiments in 2007-8
- B-X-O coupling measurements from spinning mirror EBE diagnostic (March 2006) will contribute to FY06 decision on technical feasibility of EBWCD on NSTX

2.45 GHz EBW Experiments on PEGASUS will Study Coupling, Propagation, Heating & CD

- *Existing 2.45 GHz PLT equipment to be used for 0.9 MW EBW system*
- *Demonstrate EBW coupling at significant power via O-X-B & X-B*
- *Study nonlinear EBW coupling effects*
- *Validate ray tracing, demonstrate electron heating*
- *Measure EBWCD*

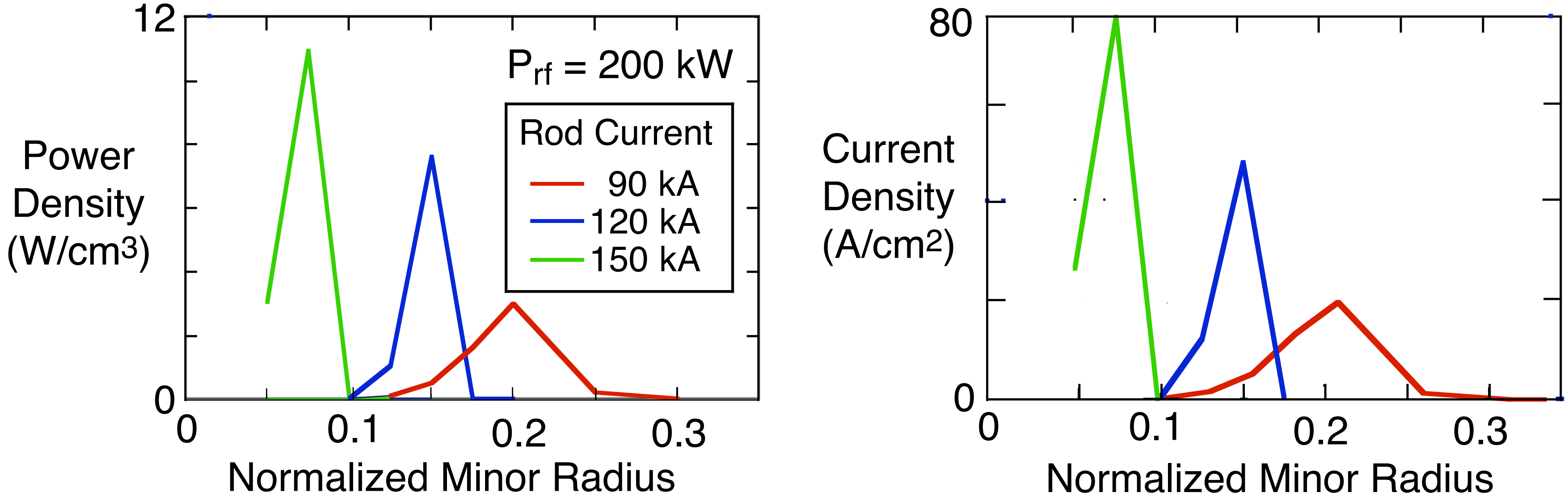
PEGASUS Fundamental Cyclotron Resonances for 2.45 GHz



Near Midplane EBW Launch Provides Significant EBW Electron Heating & Current Drive Near Axis

- *Initial modeling completed for PEGASUS 2.45 GHz EBW heating & CD system for I_{rod} = 90-150 kA*
  - *CD efficiency ~ 20-25 kA/MW ;*
  - *Fisch-Boozer CD dominates on axis for I_{rod} = 90-150 kA*
  - *I_{rod} ~ 210-240 kA may allow dominant off-axis Ohkawa CD*
- *200-400 kW EBW experiments could begin on PEGASUS in 2008-9*

Frequency = 2.45 GHz, Poloidal Angle of Antenna Location = 15 deg.



EBW Models & Emission Coupling Studies on NSTX Being Significantly Improved in FY06

- *NSTX & MAST EBW emission studies will contribute to FY06 technical assessment of EBWCD:*
    - *NSTX remotely steered antennas will study B-X-O coupling from L- & H-mode & effect of Li conditioning (PhD Thesis)*
    - *MAST spinning mirror diagnostic will study B-X-O coupling*
- *2.45 GHz EBWCD modeling of PEGASUS* plasmas *at $I_{rod} > 200$ kA to identify scenarios with dominant Ohkawa CD*
- *CQL3D/GENRAY modeling of EBE from non-thermal electron distributions (model used for ITER ECE) [Harvey, CompX]*
- *Include EBW mode conversion model in GENRAY [Ram, MIT]*
- *Benchmark CQL3D/GENRAY(with EBW MC) & BANDIT for NSTX cases*
- *Improve interface to EBW emission modeling code [Preinhaelter]*
- *CQL3D/GENRAY EBWCD calculations assuming constant diffusion in velocity space for a range NSTX conditions [Harvey, CompX]*

EBW Priorities for FY 2007-2008

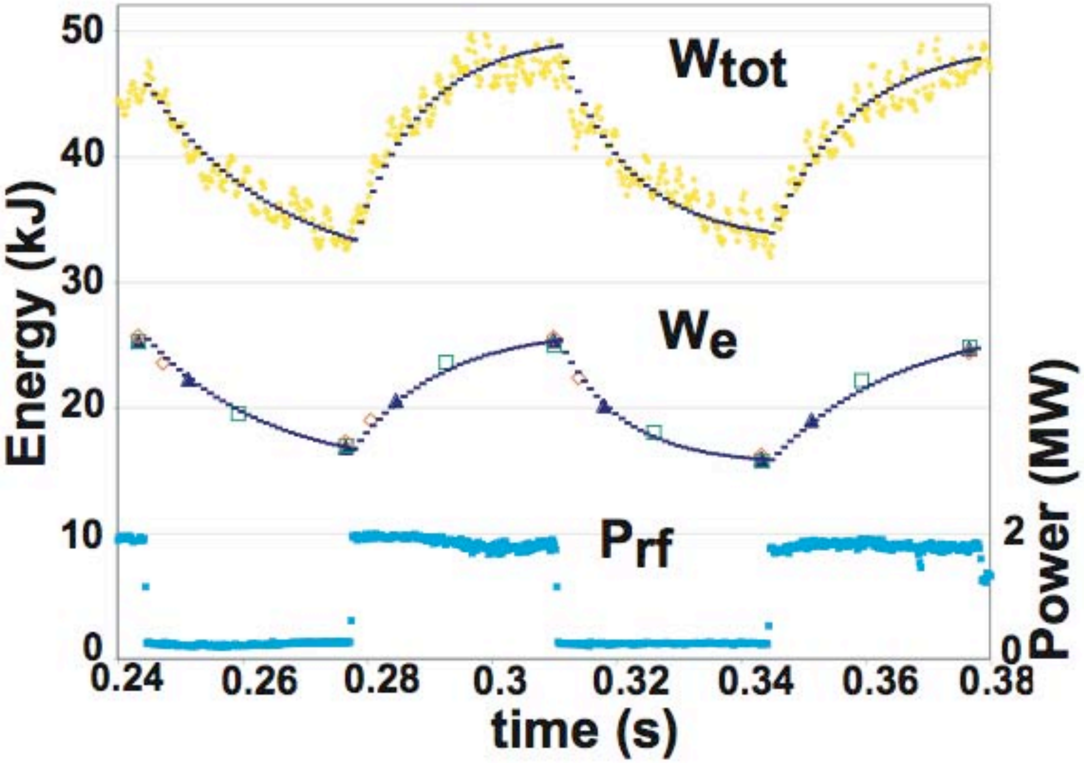
- *Complete detailed study of EBE coupling with NSTX remotely steered antennas*
- *Collaborate with 28 GHz startup/ramp-up MAST experiments in 2006-7 & possibly 28 GHz B-X-O experiments in 2007-8*
- *Upgrade radial transport calculation in the CQL3D (Model used for ITER) [Harvey, CompX]*
- *Examine possible role of self-consistent anti-pinch effect in Ohkawa EBWCD and its effect on bootstrap current [Harvey, CompX]*
- *Analytical study of EBWCD and scenarios for optimizing the current drive efficiency [Ram, MIT]*
- *Possible collaboration on NSTX ~1 MW, 28 GHz EBW experiments*
- *Implement ~ 400 kW, 2.45 GHz EBW heating & CD capability on PEGASUS*

NSTX HHFW Research

- *Identify & mitigate mechanisms for RF power loss in edge [ITER relevant]*
- *HHFW heating/CD to bridge gap between CHI plasma initiation & NBI [CTF relevant]*

HHFW Power Modulation Experiments Show Decreasing RF Absorption with Decreasing $k_{//}$

$k_{//}(m^{-1})$	% Power absorbed
14	80
+7	70
-7	55
+3	< 20



- *Parametric decay into surface waves may explain some of the power absorption dependence on $k_{//}$*
- *Field pitch angle may explain differences between co & counter*

Possible HHFW Power Loss in Plasma Edge via Parametric Decay & Waves in the Periphery

- *Ion heating through parametric decay was observed in 2004 & confirmed with improved time resolution in 2005*

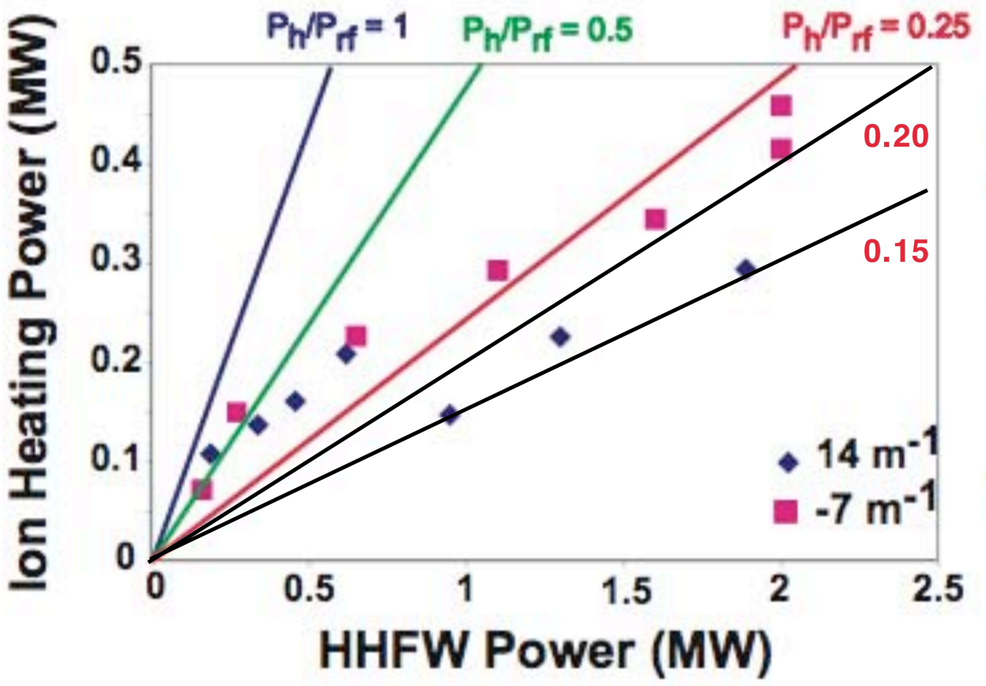
- *Waves in the surface can cause power deposition in sheaths and in the plasma periphery through collisions*

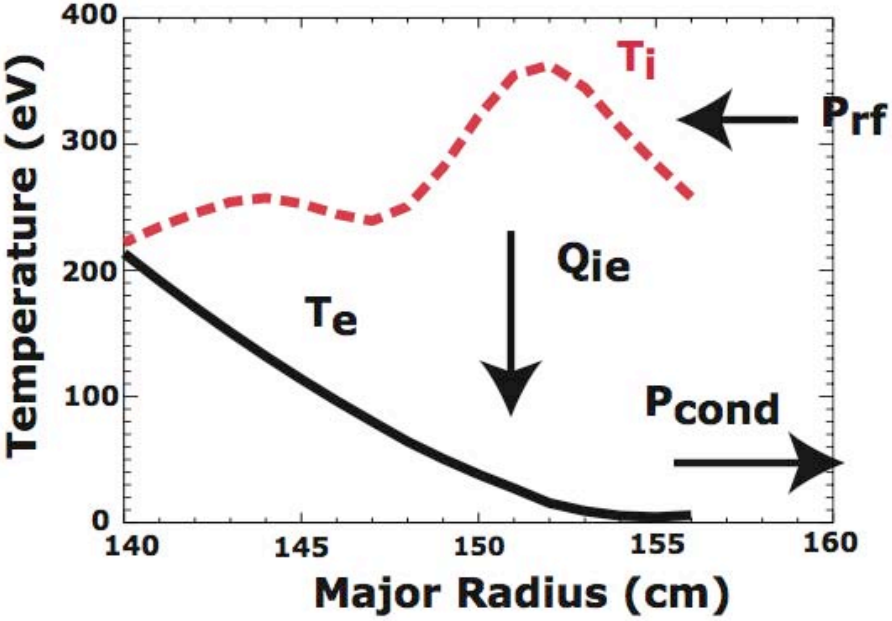
- *For lower $k_{//}$, fast waves propagate at lower density and reach much higher $k_{\perp}$ at a given density*

- *Wave fields in the edge are enhanced at lower $k_{//}$ and should contribute to greater power loss via parametric decay, sheath damping & collisions*

Parametric Decay Accounts for Significant Fraction of RF Power Losses at $k_{||} = 14\ m^{-1}$ & $-7\ m^{-1}$

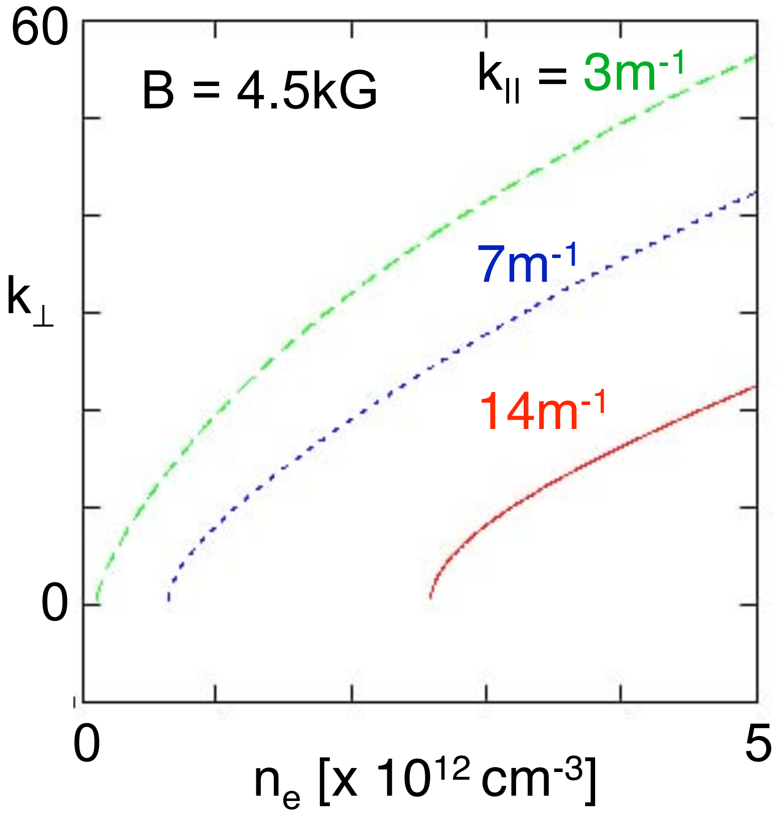
- *Significant RF power required to sustain large temperature difference between edge ions and electrons*





- *Edge ion heating via parametric decay increases with wavelength:*
  16% @ $k_{||} = 14\ m^{-1}$, 23% @ $k_{||} = -7\ m^{-1}$
- *Represents lower limit estimate of power loss by this process*

Fast Wave Propagation Begins at Lower Density at Lower $k_{//}$



- *Density onset is function of ~ $B^*k_{//}^2$*
- *Propagation is very close to wall at 7 m^{-1} and on the wall at 3 m^{-1}*

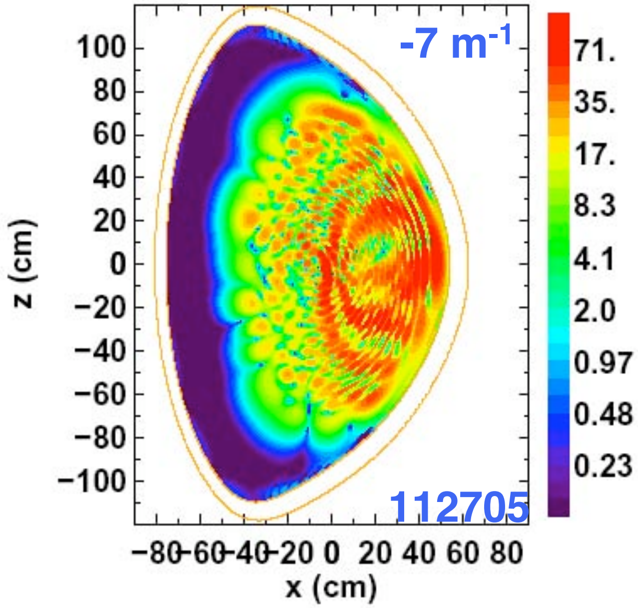
- *Losses in surface should be higher for lower $k_{//}$*
- *Motivation for antenna modification to provide 14 m^{-1} directed launch*

Higher Magnetic Field Should Yield Higher HHFW Heating Efficiency

- *PDI instability observed at 4.5 kG, PDI should be weaker at higher magnetic field*
- *Onset density for propagation of HHFW is approximately proportional to magnetic field at a given $k_{||}$:*
  - *- waves propagate further from plasma edge at higher field*
- *Wave propagation into core faster with increased magnetic field:*
  - *- surface fields decrease with increasing magnetic field*
- *In 2006 will measure HHFW power loss properties as function of magnetic field at constant q*

Understand Edge RF Power Loss by Extending Measurements and Models

No integrated model for antenna-edge-core fields exists



Modeling Collaborations:

- *Predict wave-driven density perturbations for probes/reflectometer [Bonoli et al, PSFC-MIT]*
- *Develop nonlinear sheath boundary conditions for wave codes*

  [Myra et al, RF SciDAC]
- *PIC simulations of rf-edge interactions [Smithe et al, RF SciDAC]*

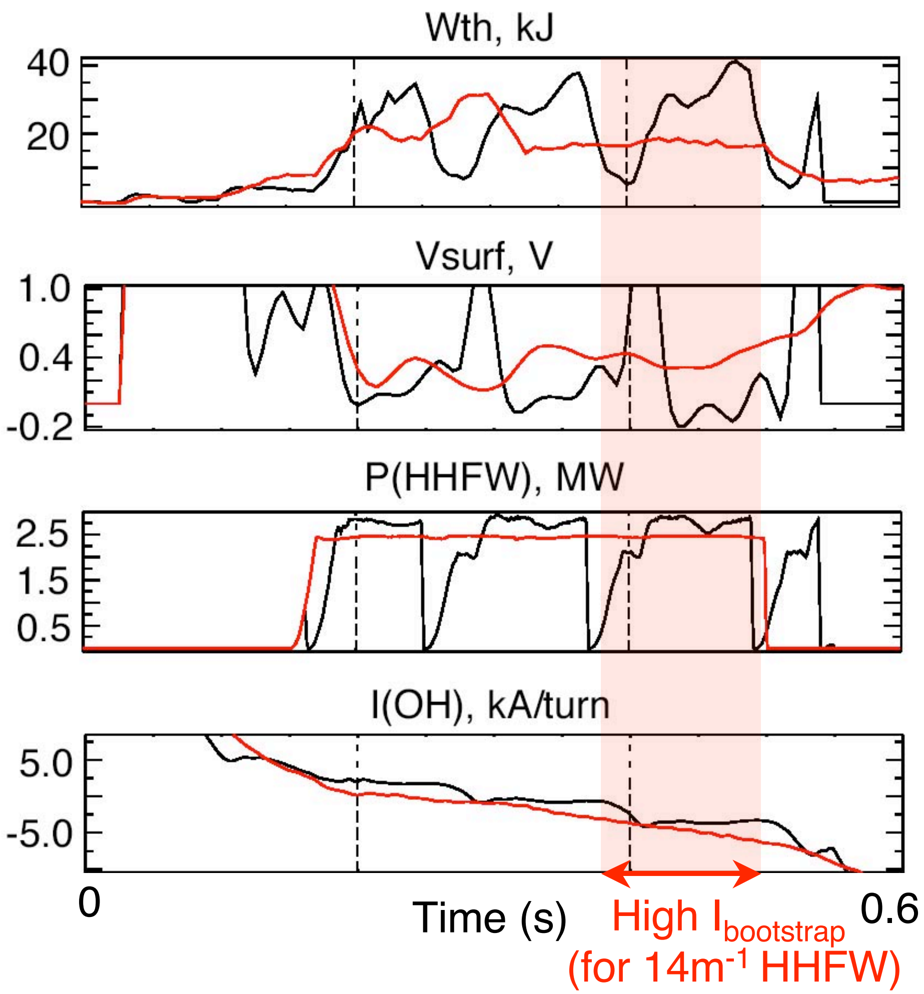
NSTX Experimental Studies:

- *New RF probes and modified UCLA reflectometer (allowing measurement to $n_e = 2.5 \times 10^{19} m^{-3}$) will detect waves propagating in periphery*
- *Possible sheath diagnostics, depending on modeling results*
- *Continue using Edge Rotation Diagnostic to measure edge ion heating*

➢ *Important for projections to the higher field regime of ITER & ST CTF; even 5-10% loss significant with ~ 20 MW RF power*

This Year Early Solenoid-Free I_P Ramp-up Experiments using HHFW Heating will Benefit from Antenna Voltage Feedback

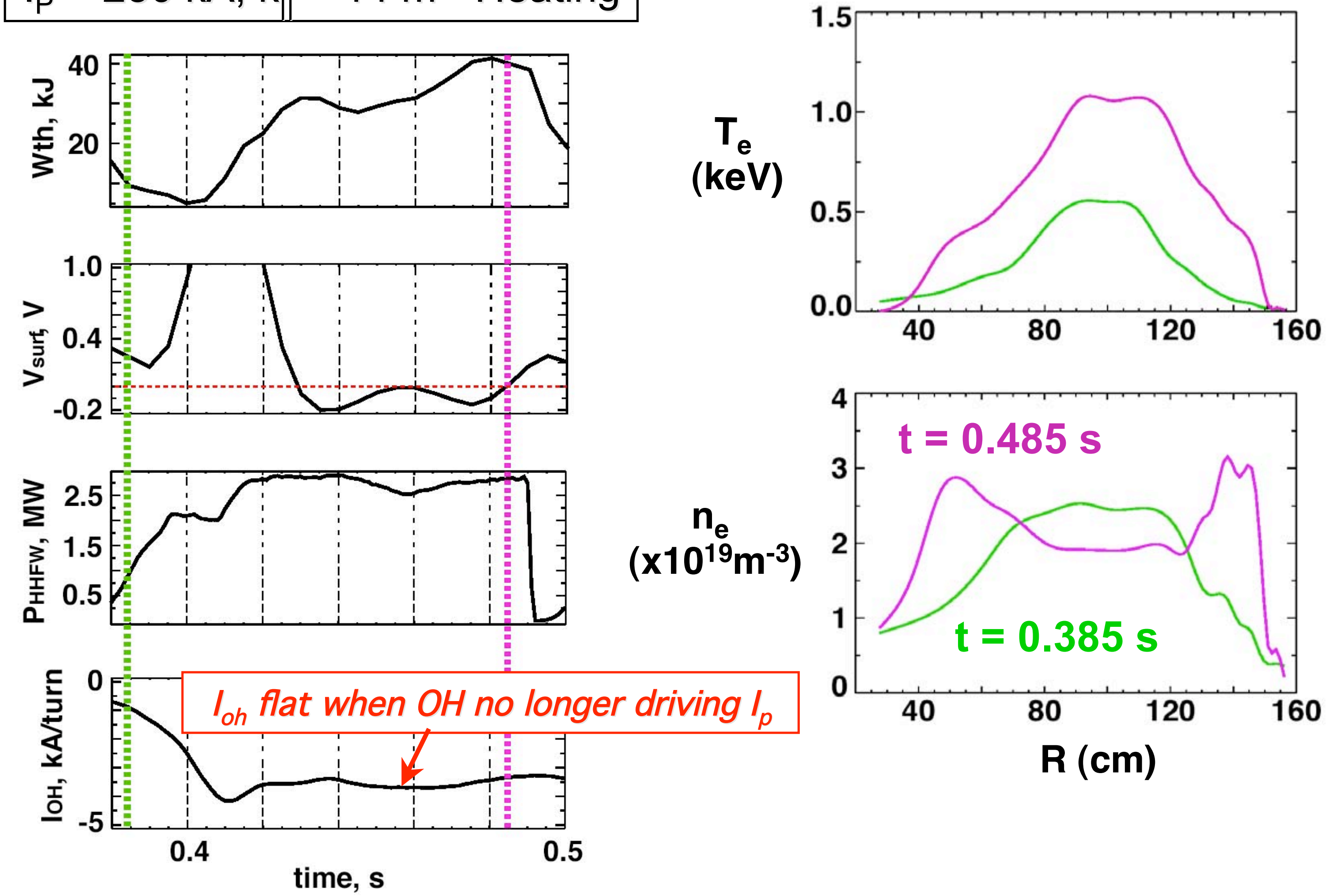
I_P = 300 kA, $k_{||}$ = 7 m^{-1} co-CD
I_P = 250 kA, $k_{||}$ = 14 m^{-1} heating



- *Need to avoid RF tripping for 14 m^{-1} to get relaxation*
- *New antenna voltage feedback algorithm to reduce RF power as voltage on antenna increases*
- *14 m^{-1} shows robust H-mode 7 m^{-1} does not*

HHFW Heating Has Generated 65-80% Bootstrap Current Fraction at I_p =250 kA

I_P = 250 kA, $k_{||}$ = 14 m^{-1} Heating



I_{oh} flat when OH no longer driving I_p

- *Possibility of >100% bootstrap CD to get ramp-up at lower I_p*

HHFW Experiments in 2006 Continue Exploring Coupling Physics & Application of HHFW to ST's

- ***RF Edge Field Study:***
  - *Investigate magnetic field dependence of RF power loss, PDI ion heating and surface wave propagation & damping*
  - *physics basis for possible 14m^{-1} directed launch antenna modification*
  - *new RF probes to measure waves in plasma periphery*
  - *UCLA reflectometer upgrade for measuring up to 2.5 X 10^{13} cm^{-3}*
  - *Effect of Li conditioning on HHFW antenna coupling*
  - *B_t & I_p campaign would allow HHFW experiments to elucidate coupling physics using reversed fields*
- ***Applications of HHFW:***
  - *Non-inductive current ramp up using HHFW*
  - *Heat CHI discharges with HHFW*
  - *Early HHFW heating to reduce volt-sec consumption in long pulse*
- *GENRAY/CQL3D calculations of HHFW interaction with non-thermal ion distribution to synthesize NPA diagnostic [Harvey, CompX]*

HHFW Priorities for FY 2007-2008

- HHFW applications during current ramp-up phase of discharge:
  - bridge gap between CHI initiation and NBI heating
- Decision on HHFW antenna upgrade design (depending on results from FY2006 studies):
  - provide directed spectra at 14 m^{-1} for better CD efficiency
  - also allow higher power operation
  - provide early start up coupling when $T_e \sim 50$ eV with 28 m^{-1}
- HHFW system will support driven CAE mode studies [see Fredrickson's previous talk]