HHFW and ECW/EBW Progress and Plans for 2009-13

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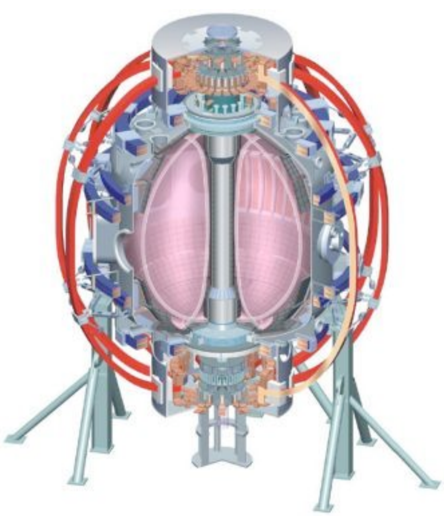
G. Taylor, PPPL

For the NSTX Research Team

NSTX 5 Year Plan Review for 2009-13
Conference Room LSB-318, PPPL
July 28-30, 2008



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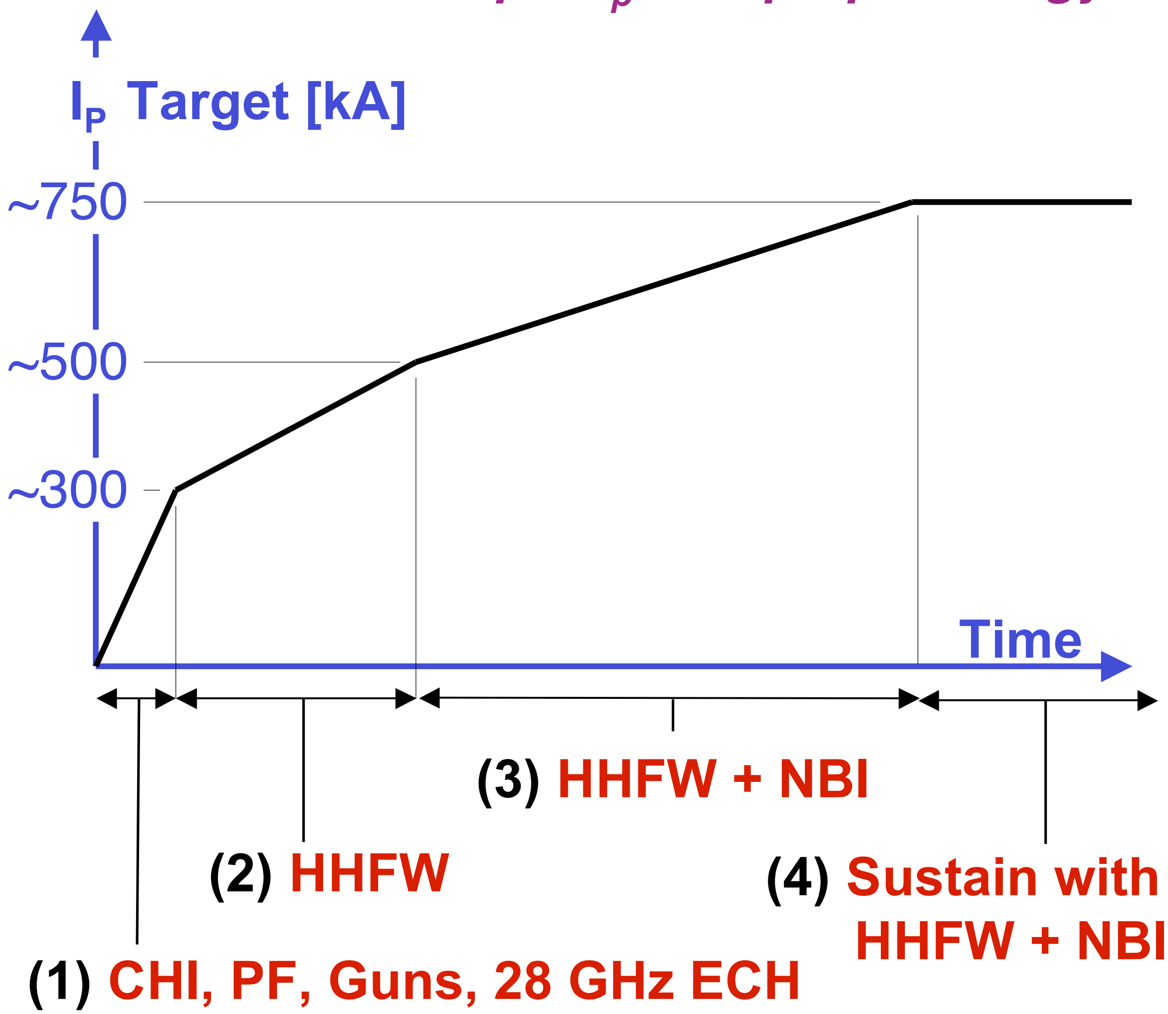
30 MHz HHFW & 28 GHz ECW/EBW Enable Non-Inductive Ramp-up, q(0) Control & Bulk Heating

NSTX Start-up & I_p Ramp-up Strategy



Start-up/Ramp-up Requirements

(1→2) 28 GHz ECH generates plasma for HHFW heating & CD

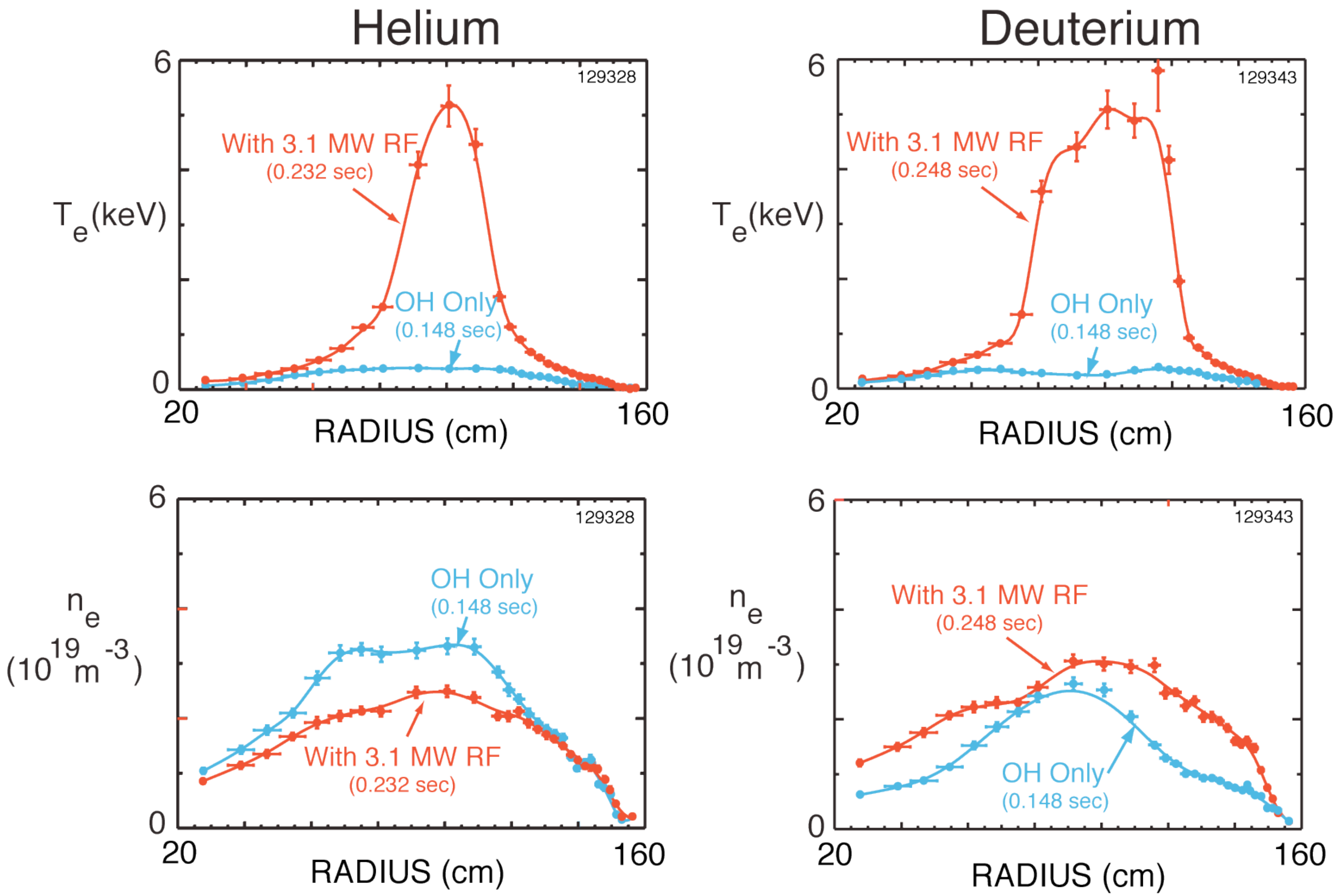
(2) I_P overdrive using bootstrap & HHFW CD

(2→3) HHFW generates sufficiently high I_P to absorb NBI

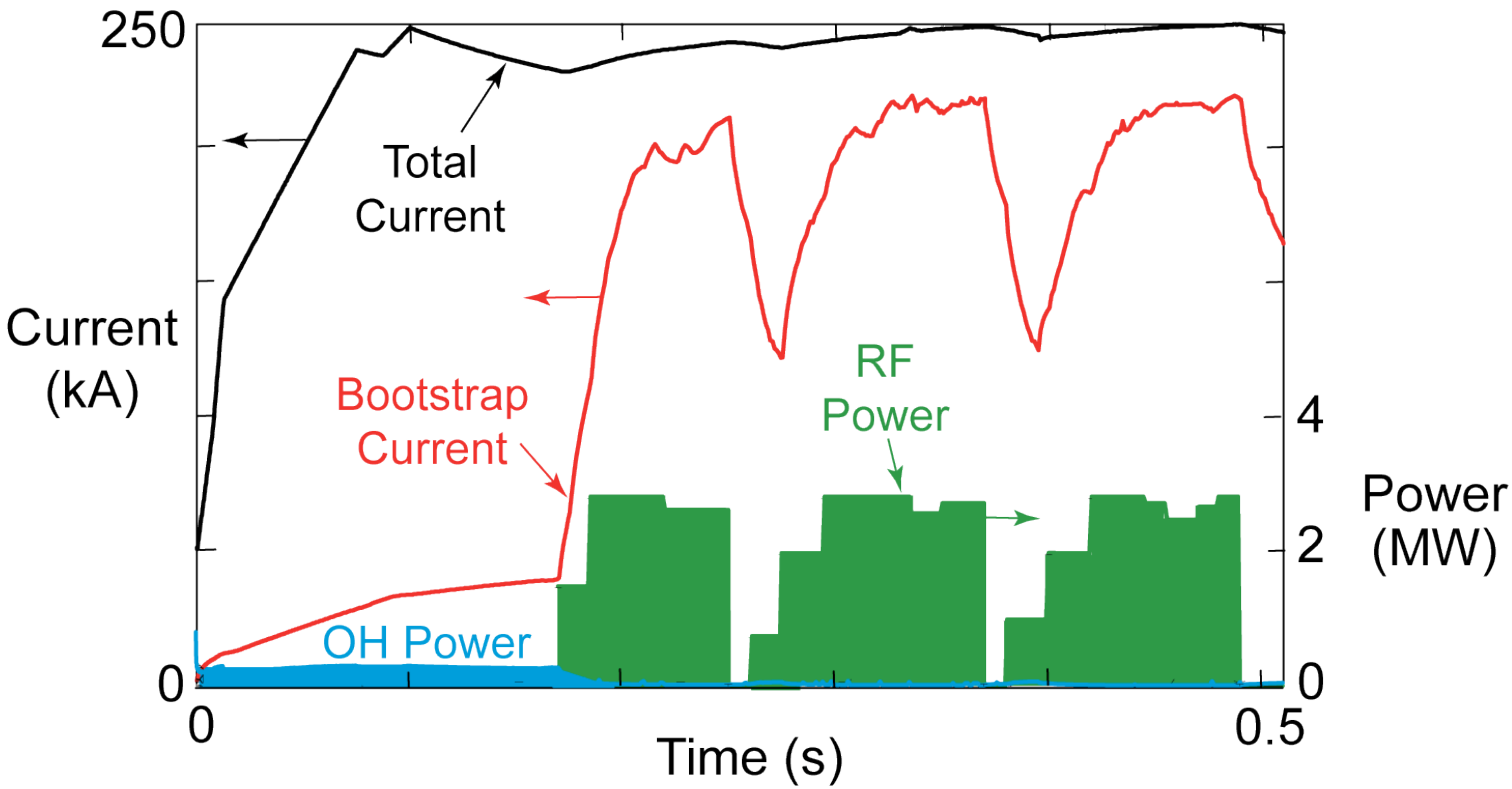
(4) HHFW provides q(0) control & bulk heating

HHFW Progress & Plans

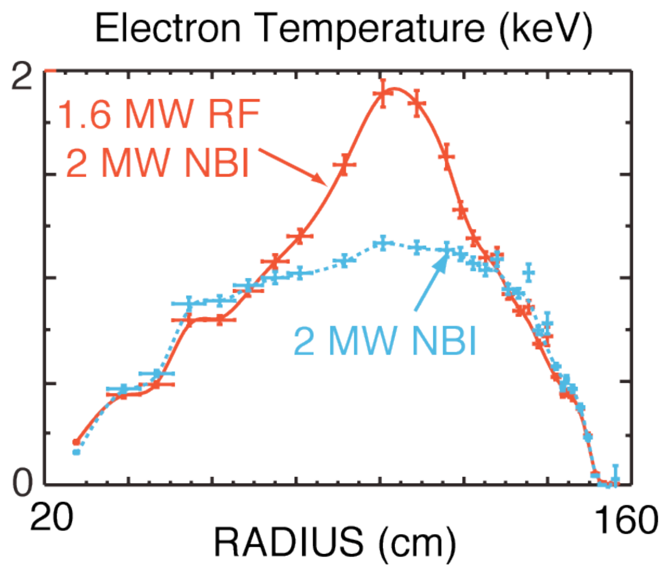
Recently Heated D, He Plasmas to 5 keV with 3.1 MW of $k_{||}$ = 14 m^{-1} HHFW

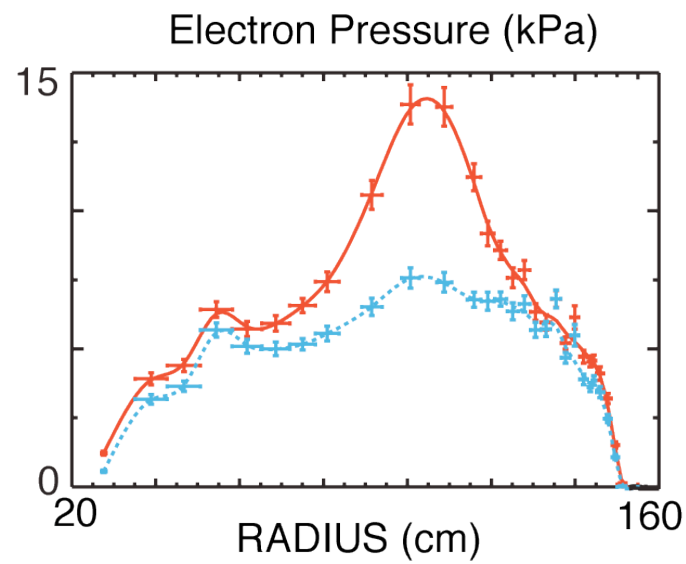


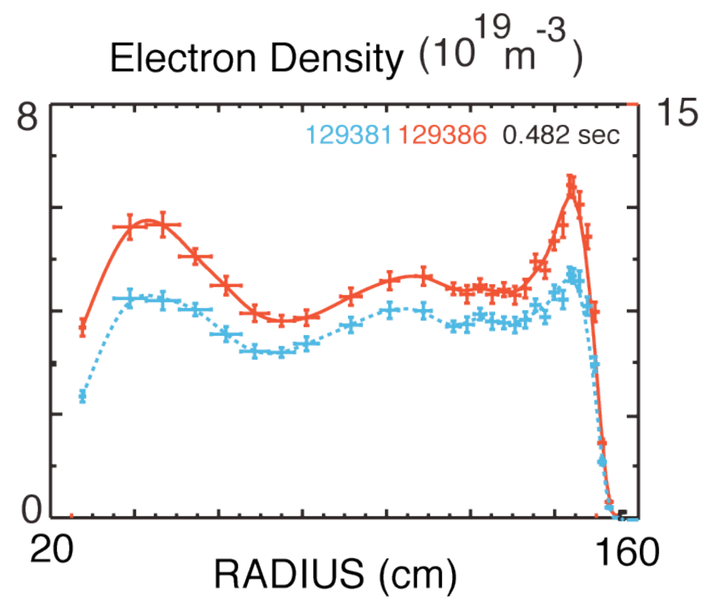
HHFW Heated I_p = 250 kA H-Mode Plasma to $T_e(0)$ > 1 keV & Generated 85% Bootstrap Fraction



Recently Measured Core HHFW Electron Heating in Deuterium NBI H-Mode Plasma







- Experiments starting to study HHFW coupling into deuterium H-modes

HHFW Provides Efficient & Controllable Heating & Core CD in H-Mode for Next-Step ST's & ITER

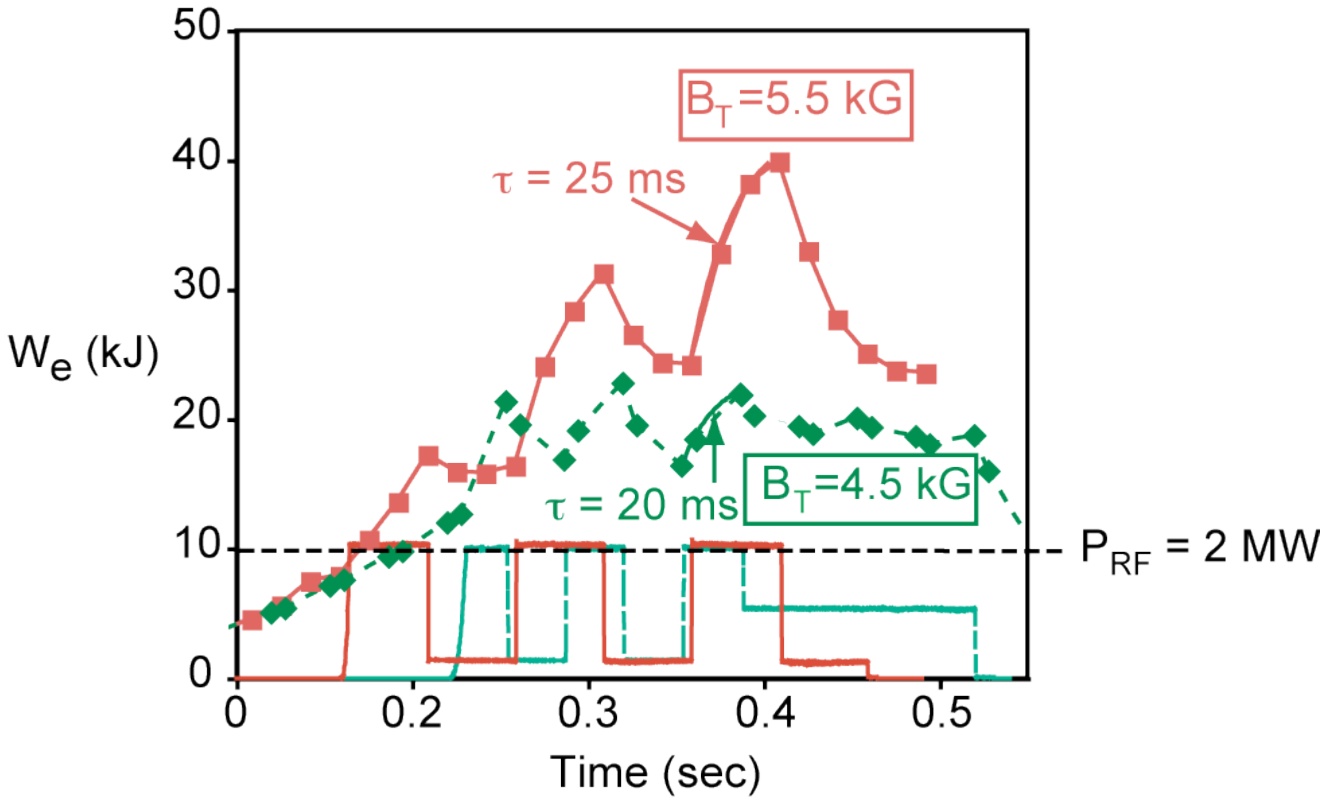
- Recent improved HHFW heating results from discovery of important role of surface waves in limiting coupling

- Significantly advanced HHFW heating & CD performance by increasing $B_t(0)$ & using edge density control

- HHFW to provide 4 MW of auxiliary heating & q(0) control needed for fully non-inductive NSTX H-mode scenarios

- HHFW bootstrap current drive will also be important tool for non-inductive current overdrive during ramp-up

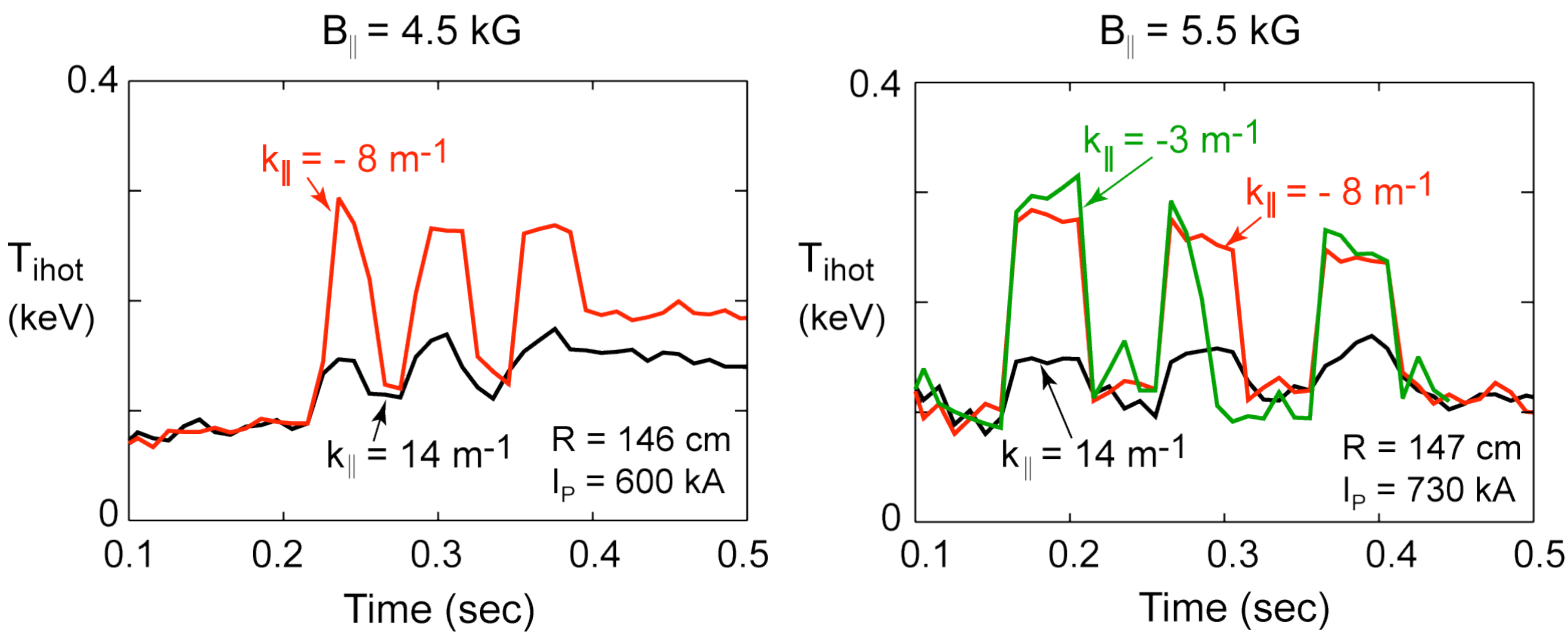
Heating Efficiency for $k_{||}$ = - 8 m^{-1} Increased Substantially as B_T Increased from 0.45 T to 0.55 T



- ΔW_e for B_T = 0.55 T is ~ twice value for 0.45 T over same time interval
- RF power deposition to electrons increases from ~ 22% to ~ 40% at higher B_T, total efficiency increases from ~ 44% to ~ 65%

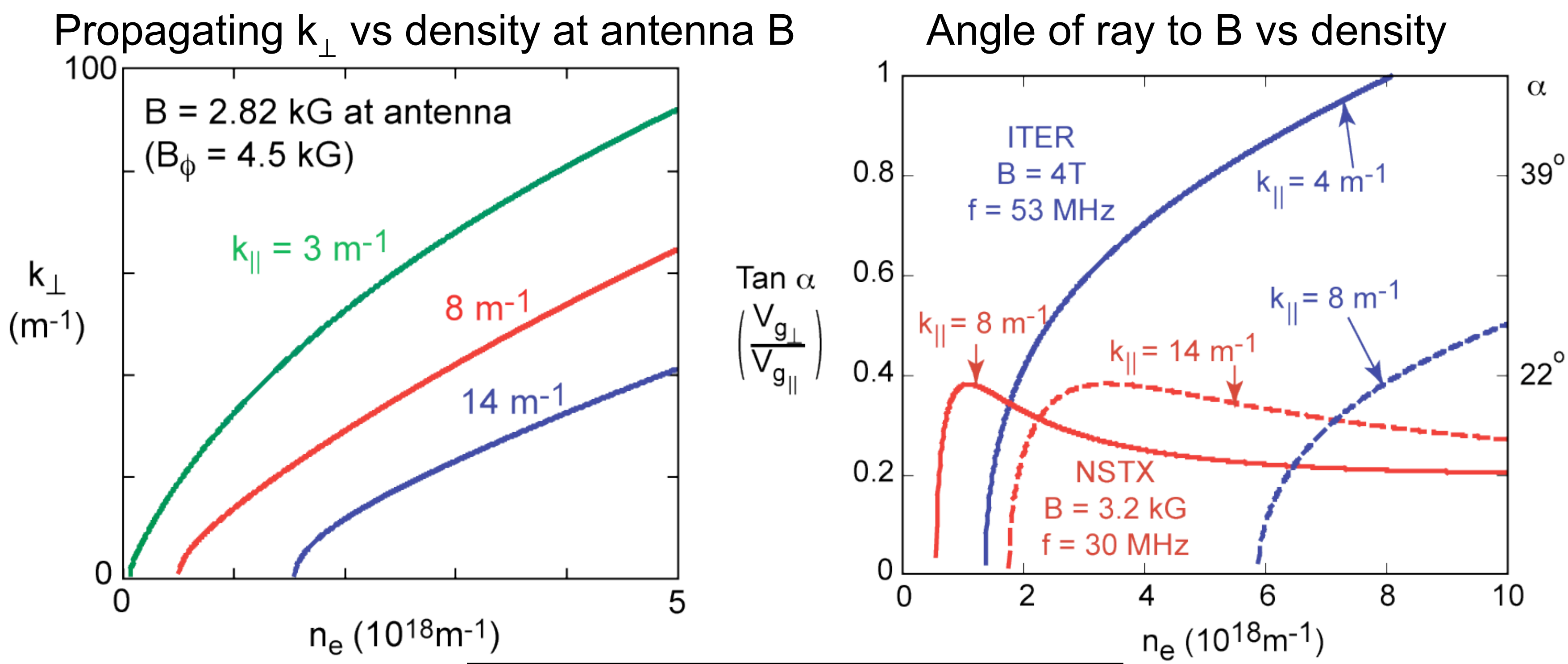
Improved Heating at $k_{||}$ = - 8 m^{-1} Not Due to Reduced Parametric Decay Instability (PDI) Edge Heating

Edge ion heating as a measure of PDI losses



- Edge ion heating not increased significantly at higher B_T at $k_{||}$ = - 8 m^{-1}
- PDI edge heating similar at $k_{||}$ = - 3 m^{-1} and - 8 m^{-1}, suggests surface wave losses and reduced core damping account for decrease in heating efficiency

Surface Fast Wave Propagation Explains Reduced HHFW Heating Efficiency at Lower $k_{||}$

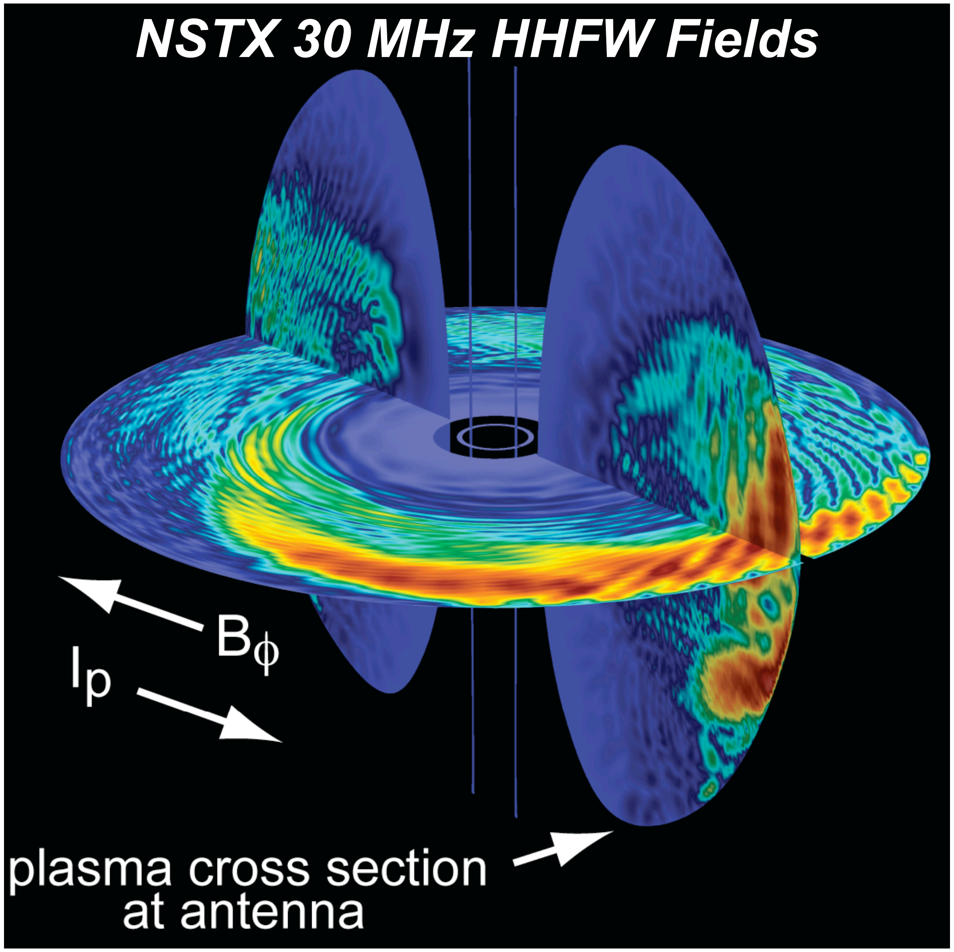


Onset density is $\propto B^* k_{||}^2/\omega$

- Propagation in NSTX close to wall at $k_{||}$ = 8 m^{-1}, on wall at $k_{||}$ = 3 m^{-1}
- Losses in surface higher for lower $k_{||}$
- Propagation angle relative to B much less than for low harmonic ICRF
- Higher B moves propagation onset away from antenna, improving heating

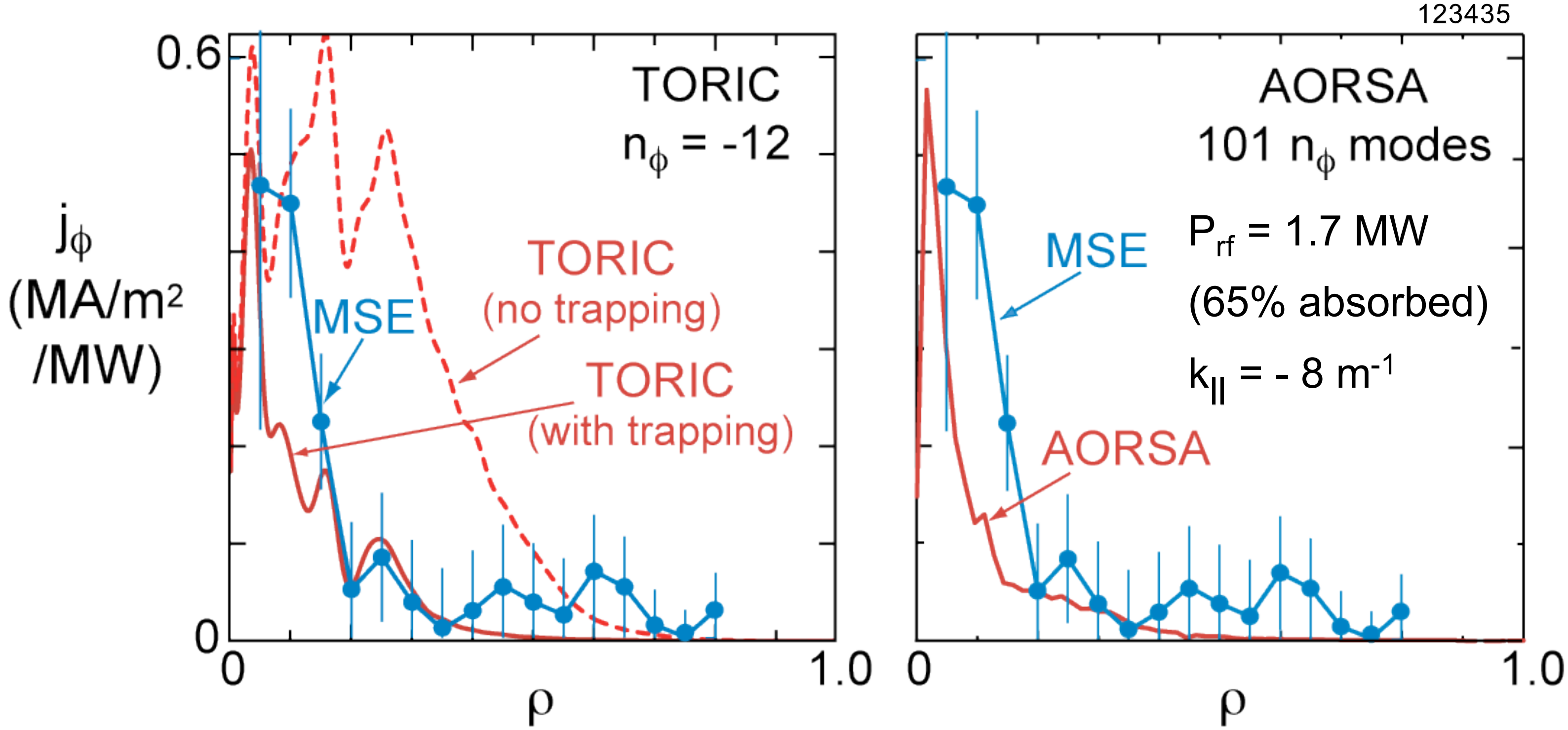
3D Codes Using Full Toroidal Spectrum to Include Surface Damping, Core Damping and CD Effects

AORSA $|E_{RF}|$ field amplitude for -90° antenna phase case with 101 n_ϕ



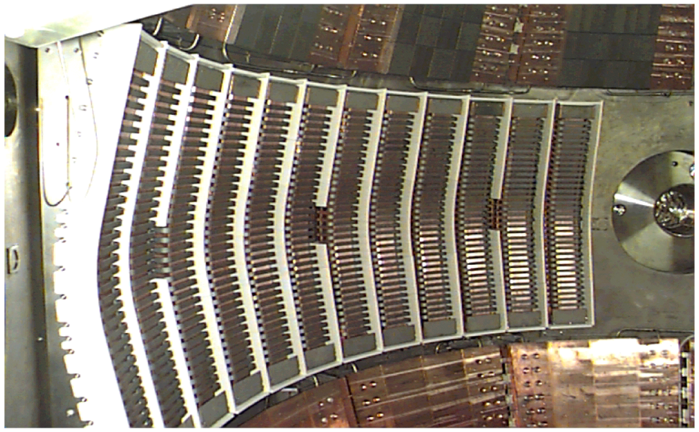
- Waves propagate around plasma axis in + B_ϕ direction
- Wave fields very low near inner wall, strong first pass damping
- This case has only 60% coupling efficiency making it a good test case for theory
- SciDAC project extending codes to include edge loss mechanisms

First Motional Stark Effect (MSE) Measurement of Core HHFW CD in NSTX Plasma



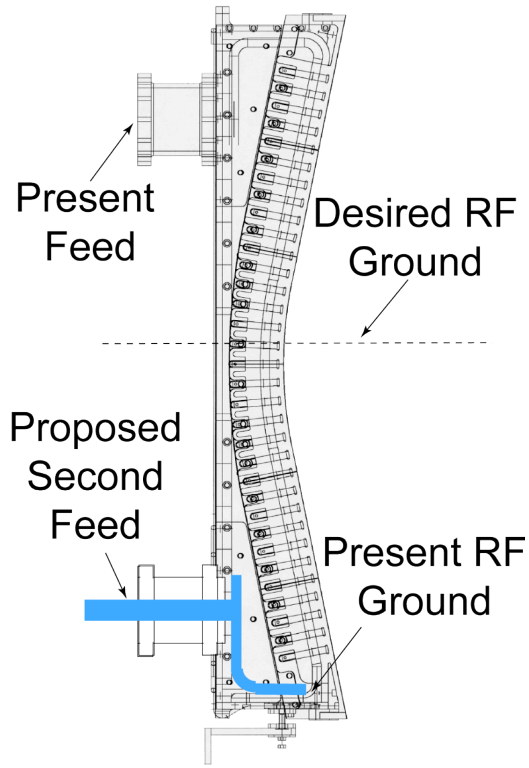
- Measured q(0) decreases from 1.1 to 0.4 with HHFW CD
  - Offers prospect of controlling q(0) in integrated scenarios
- Measured j_ϕ profile consistent with predictions from TORIC & AORSA full-wave codes
  - TORIC predicts electron trapping significantly reduces CD efficiency

Antenna Upgrades Double Coupled Power for Same Voltage/Strap & Increase ELM Resilience in H-mode



NSTX 12-Strap HHFW Antenna

- Double feed upgrade will permit larger plasma-antenna gap, with more stability and power per strap in 2009
- ELM dump will be added in 2010
- Increased antenna capability will provide bulk heating for advanced scenarios, q(0) control & I_p ramp-up with bootstrap overdrive, with HHFW CD if possible



Double Feed Upgrade Implemented for 2009 Run Campaign

HHFW Research Plan for 2009-10

2009:

- Assess heating & CD operation with NBI using upgraded double fed antenna and using guidance of modeling
- Heating & CD studies in D_2 H-mode with Li injection & LLD
- Coupling/heating into low I_p,T_e OH plasma
- Optimize HHFW coupling into I_p ramp-up

2010:

- Heating & CD operation with NBI H-mode using ELM resilience system:
  - Larger plasma-antenna gap for greater stability & higher power coupling
  - Fast feedback control to reduce neutral beam ion interaction with antenna
  - Use LLD to control antenna neutral pressure

HHFW Research Plan for 2011-13

2011:

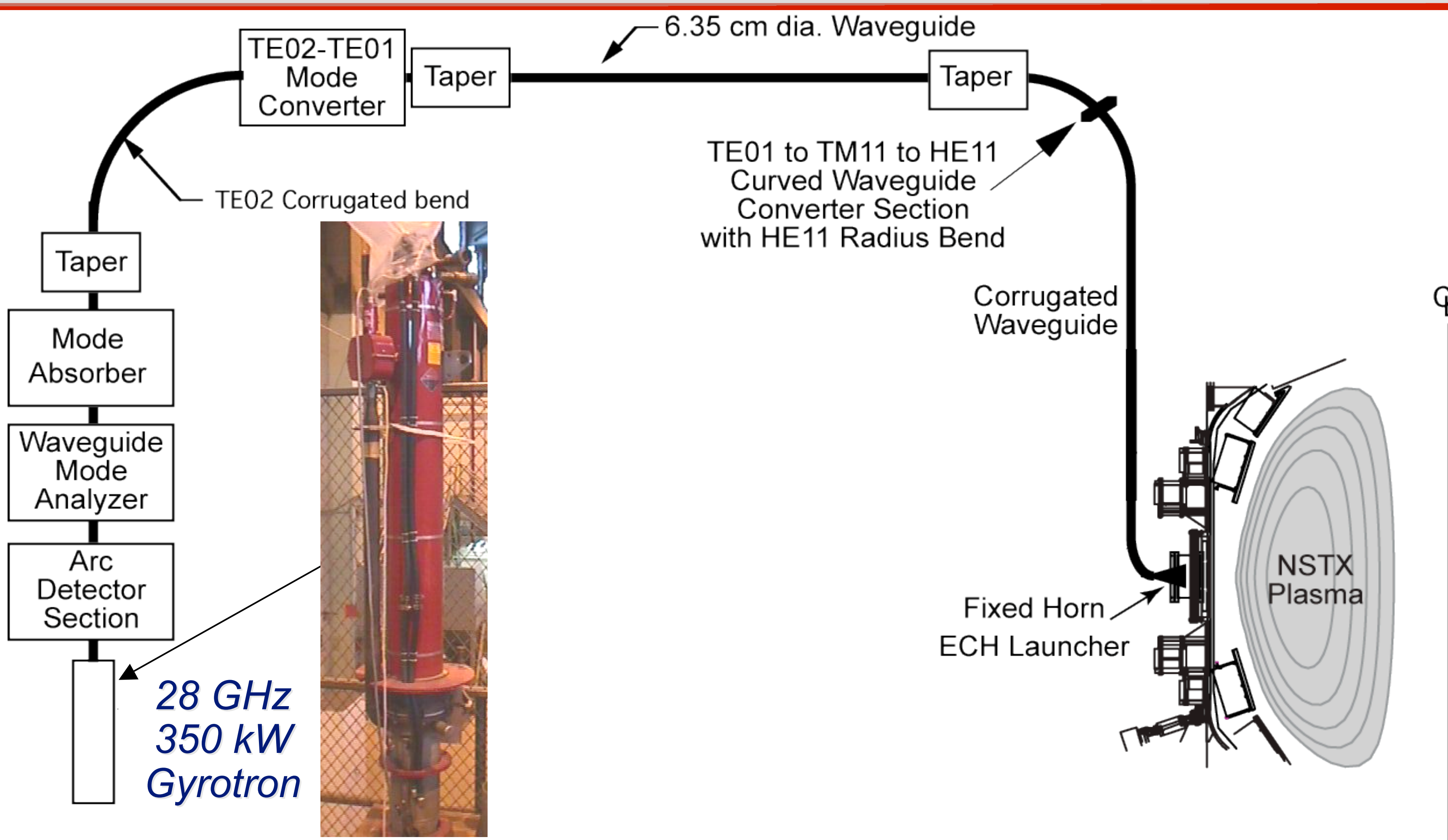
- Heating & CD operation with NBI H-mode with fully upgraded HHFW antenna, Li injection & LLD:
  - Benchmark core CD against advanced RF codes upgraded to include interaction with fast ions & use FIDA to diagnose interaction
- HHFW coupling into ramp-up with 28 GHz ECH-assisted start-up

2012-13:

- Explore high power long pulse HHFW heating & CD at $B_t(0) \sim 1$ T
  - Study electron transport at higher TF with HHFW
  - Extend investigation of surface wave physics to higher TF
  - Study fast-ion interaction versus harmonic
- Support very long pulse scenario:
  - Integrate into Plasma Control System
  - Control q(0)
  - Provide 4 MW bulk heating
- Optimize HHFW with 28 GHz ECH-assisted CHI or PF-only startup to support fully non-inductive plasma startup & ramp-up

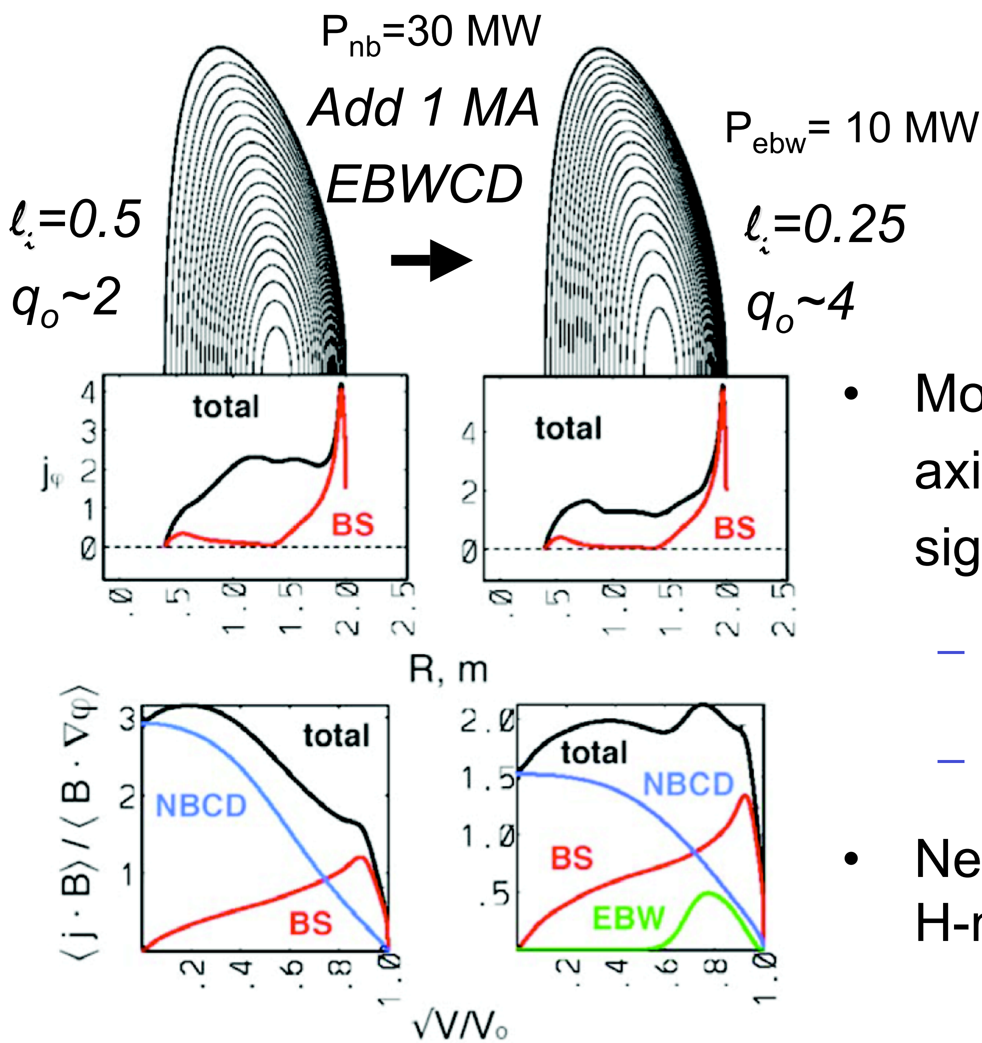
ECW/EBW Progress & Plans

28 GHz, 350 kW Gyrotron to Provide Pre-Ionization & ECH-Assisted Non-Inductive Startup in 2011



- Additional 350 kW gyrotron proposed in 2012 [Incremental]
- Collaborate with MAST on 28 GHz ECH/EBWH

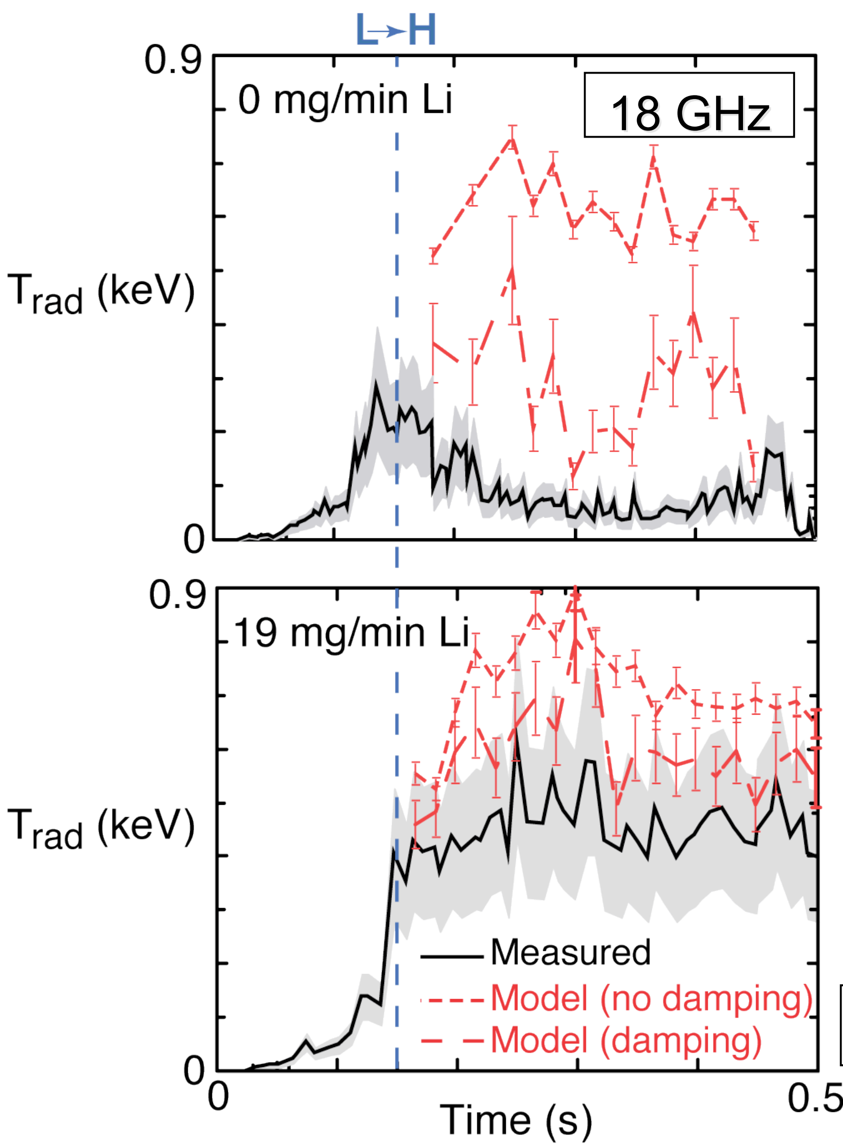
EBW Research Objective to Generate Off-axis EBWCD to Stabilize ST-CTF



- Modeling predicts adding 1 MA of off-axis EBWCD to ST-CTF plasma significantly increases stability:
  - β_n limit increases from 4.1 to 6.1
  - β_t limit increases from 19% to 45%
- Need efficient EBW coupling in H-mode

Y-K. M. Peng, et al., Plasma Phys. Control. Fusion, **47** B263 (2005)

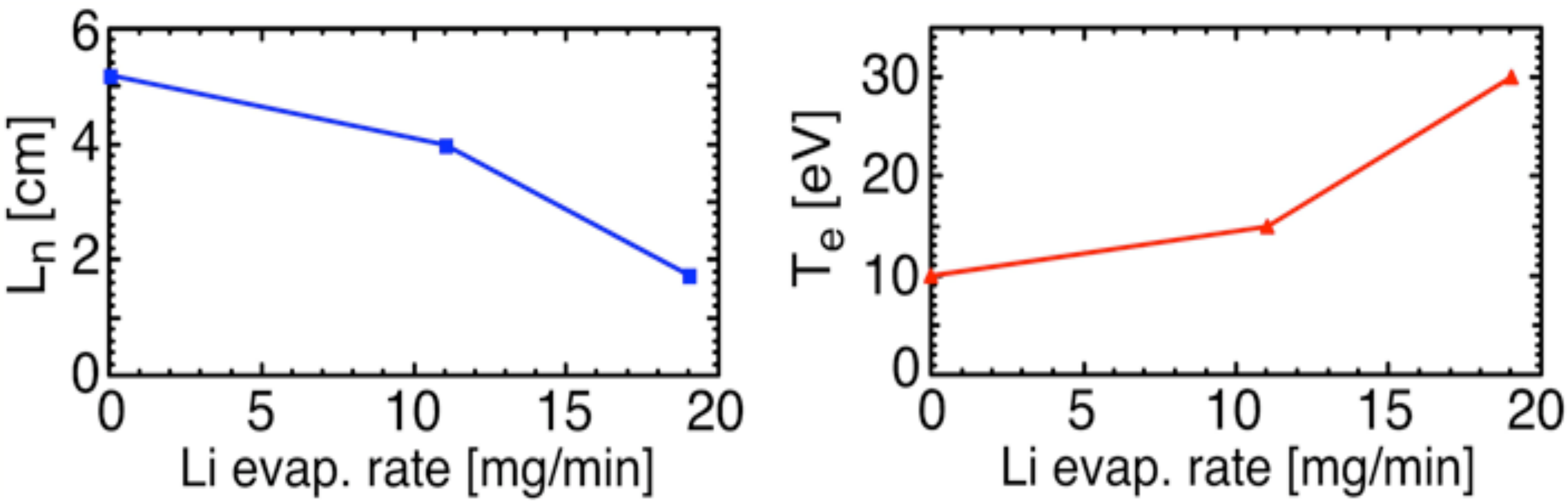
EBW Emission from Core of H-Mode Increased Significantly with Increased Li Evaporation



PhD Thesis

- Fundamental EBW coupling efficiency increased from < 10% to 65% with Li
- Simulation predicts much less EBW collisional damping for shot with Li
- Expect LLD & higher B_T could decrease damping
- Fluctuations in EBW emission due to changes in coupling caused by n_e fluctuations at EBW MC layer, located in scrape-off

Lithium Evaporation Increases T_e & Reduces L_n Near f_{ce} & 2 f_{ce} B-X-O Mode Conversion (MC) Layer



- f_{ce} & $2f_{ce}$ B-X-O MC layers typically in plasma scrape off
- T_e increased from 10-30 eV with addition of Li
  - Theoretically B-X-O MC more sensitive to T_e than L_n
  - Significant EBW collisional damping for $T_e < 20$ eV
  - Ongoing theory/modeling collaborations with Josef Preinhaelter (Prague), Bob Harvey (CompX) & Abhay Ram (MIT)

J. Preinhaelter, Rev. Sci. Instrum. **77**, 10F524 (2006)

ECW/EBW Research Plan for 2009-11

2009-10:

- Optimize EBW emission coupling in H-mode with Li evaporation & LLD
  - Assess effect of integrated Li
  - Explore low density plasmas on NSTX with EBW MC inside LCFS
- Collaborate with MAST 28 GHz ECH/EBWH startup experiments
  - ORNL providing 350 kW gyrotron this year
  - MAST 28 GHz system uses grooved center stack tile to change polarization from O- to X-mode which then 100% coverts EBW near axis

2011:

- 350 kW 28 GHz ECH-assisted CHI, PF ramp and plasma gun start-up with fixed horn antenna
  - Explore transition from ECH-assisted startup to HHFW current ramp-up
  - Study whether Li evaporation & LLD can improve EBW coupling with fixed horn antenna during current ramp-up

ECW/EBW Research Plan for 2012-13

2012:

- Install second 350 kW 28 GHz gyrotron [Incremental]
- 700 kW ECH-assisted startup and plasma current ramp-up [Incremental]
- Install 28 GHz O-X-B oblique EBW launcher (or possibly expand MAST EBW collaboration) [Incremental]
- EBW emission/transmission studies at higher TF
- Fundamental 28 GHz on-axis EBWH experiments at 1 T [Incremental]

2013:

- 700 kW core & off-axis EBW heating studies (benchmark deposition codes) [Incremental]

Summary

- Discovered surface waves can significantly limit HHFW coupling
  - Major increase in HHFW heating & CD performance by increasing $B_t(0)$ & edge density control
- HHFW antenna upgrade in 2009-10 provides higher power, reduced fast ion-antenna interaction & better resilience to ELMs
- HHFW H-mode & ramp-up experiments in 2009-11 will benefit from combination of LLD & Li injection
- Better HHFW coupling at $B_t(0)$ = 1 T in 2012-13 will enable q(0) control & bulk heating for long pulse non-inductive H-mode
- Order of magnitude improvement in EBW coupling in H-mode through Li edge conditioning
  - Improve H-mode EBW coupling with LLD & Li injection in 2009-10
- 350 kW 28 GHz ECH system will support CHI and outer PF non-inductive start-up in 2011-13
  - Incremental funding needed for 700 kW 28 GHz ECH/EBWH

2009-13 HHFW/ECW/EBW Research Timeline