Supported by Office of Science

NSTX

HHFW and EBW Progress and Plans

Gary Taylor
for the NSTX Team

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
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

23rd NSTX Program Advisory Committee Meeting
(PAC-23)
January 22-24, 2008

Action Items from PAC-21 in HHFW & EBW Research Area Addressed in this Presentation

NSTX

HHFW:

- ✓ PAC21-12: HHFW CD MSE measurement & coupling dependence on B_t
- ✓ PAC21-13: Investigate alternate HHFW CD phasings
- ✓ PAC21-14: Allocate runtime for HHFW + NBI

EBW:

- ✓ PAC21-11: Encourage MAST EBW collaboration & strong theory support
- ✓ PAC21-37: Advance plan to implement 28 GHz EBW heating
- ✓ PAC21-38: Control EBW coupling mechanism

HHFW Progress & Plans

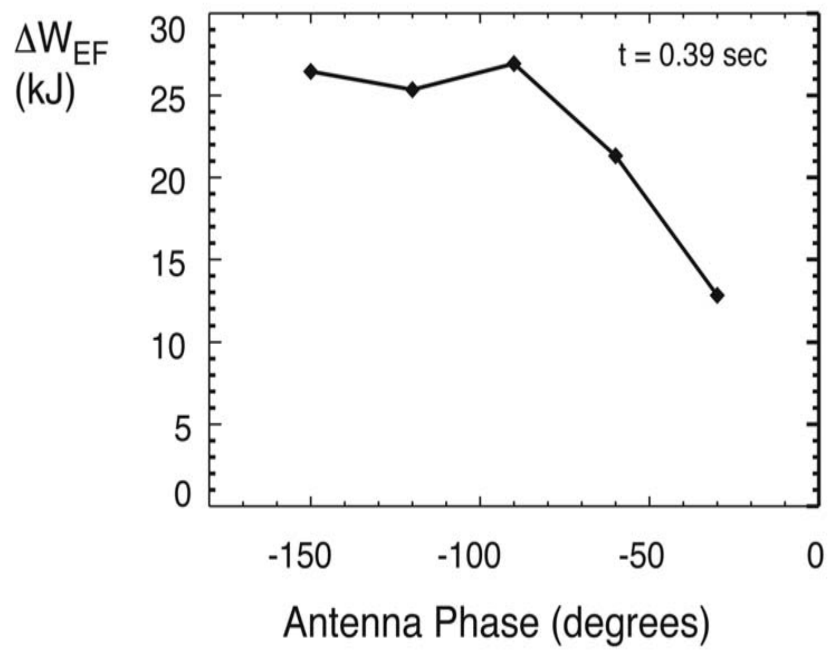
Long-Term HHFW Research Objective: Sustain Reactor-Grade H-Mode & Assist Non-Inductive ST-CTF Startup

NSTX

- ITER ICRF will operate at high RF power with large antenna-plasma gap:
  - even low RF edge loss fraction during long pulses could damage in-vessel components
- NSTX HHFW parameters provide test bed to quantify RF edge power loss mechanisms:

→ Core heating efficiency shows strong dependence on launched wavelength:

- consistent with enhanced surface loss when edge densities exceed density for onset of perpendicular wave propagation
- understanding this phenomenon important for ITER ICRF antenna design and for NHTX/ST-CTF



PAC21-12

Considerable Progress on HHFW Heating & CD in FY07 by Increasing $B_t(0)$ from 4.5 to 5.5 kG & Lowering Edge n_e

NSTX

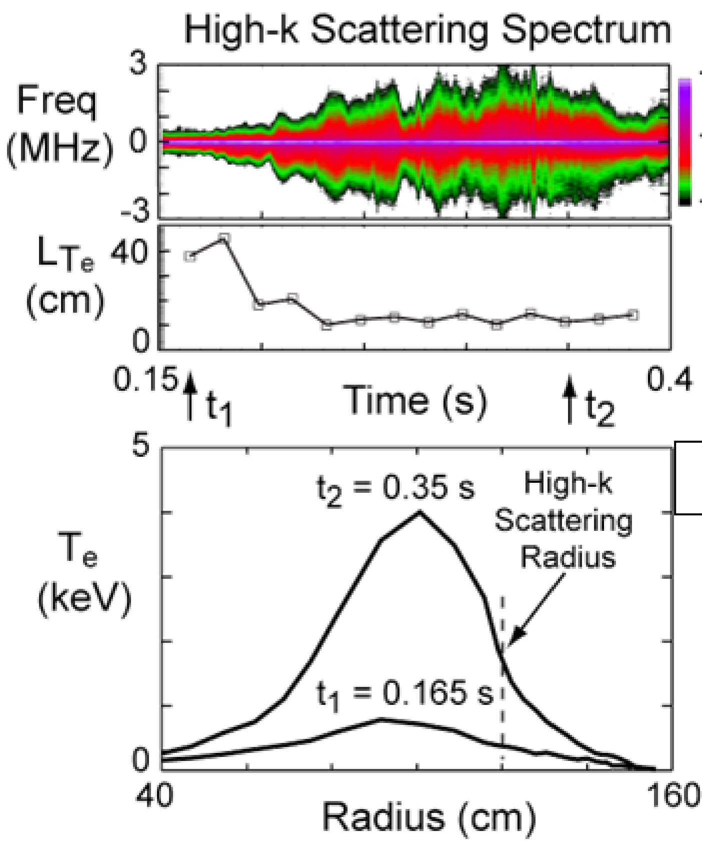
- Earlier HHFW CD experiments using He L-mode plasmas at $B_t(0)$ = 4.5 kG had poor heating efficiency
- Previous attempts to heat deuterium H-modes at $B_t(0)$ = 4.5 kG also showed little heating
- HHFW heating of deuterium NBI L-mode plasmas early in the discharge was successfully demonstrated in FY06
- Operation with NBI at $B_t(0)$ = 4.5 kG required a small plasma-antenna gap for good coupling, causing increased impurity influx
- He L-mode experiments at B_t = 5.5 kG in FY07 exhibited improved HHFW heating with CD phasing, with and without NBI
- MSE measurements showed clear evidence of on-axis CD with efficient $k_\phi = -8\ m^{-1}$ heating at $P_{rf} \sim 1.8$ MW in He L-mode:
  - TORIC & AORSA full wave codes also predict on-axis CD

Coupling Improved Substantially by Keeping Density Near Antenna Below Level Needed to Generate Surface Waves

NSTX

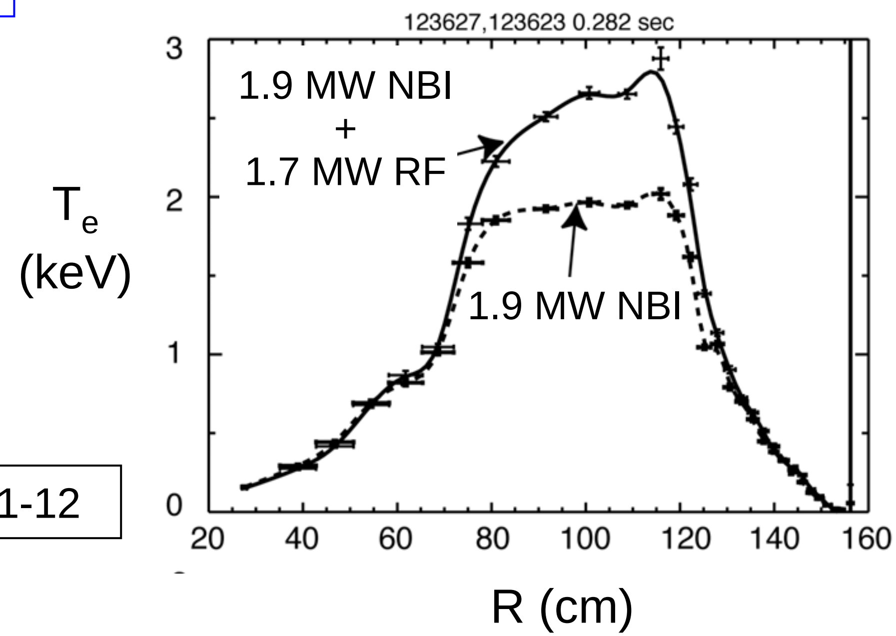
- At $B_t(0)$ = 5.5 kG, significant core electron heating now obtained in L-mode He plasmas for CD antenna phasing with RF only and during RF+NBI

HHFW provides tool to create steep T_e gradient where enhanced High-k scattering is observed



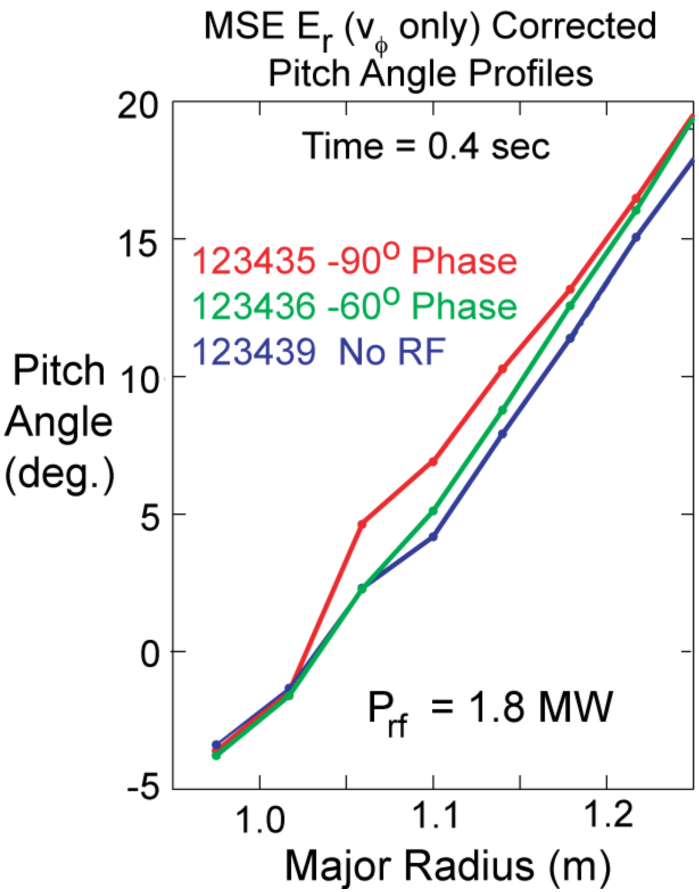
PAC21-12

HHFW heating with CD phasing observed in NBI-heated He L-mode

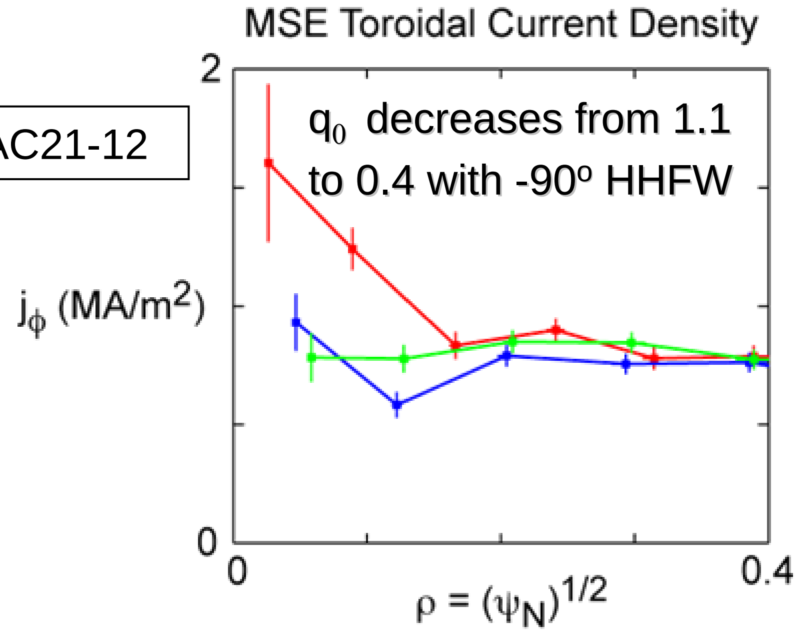


- FY08 experiments to focus on heating & CD in deuterium H-mode at $B_t(0)$ = 5.5 kG & assess effect of Li on HHFW coupling

FY07 MSE Results Show Clear Change in Core Field Pitch Angle for -90º Antenna Phase (k_ϕ = - 8 m^{-1})



PAC21-12



- j_ϕ from MSE using LRDFIT B field surfaces
- j_ϕ integral for -90º phase, gives ~ 15 kA inside R = 1.2 m
- Only 80 ms RF pulse, need longer duration

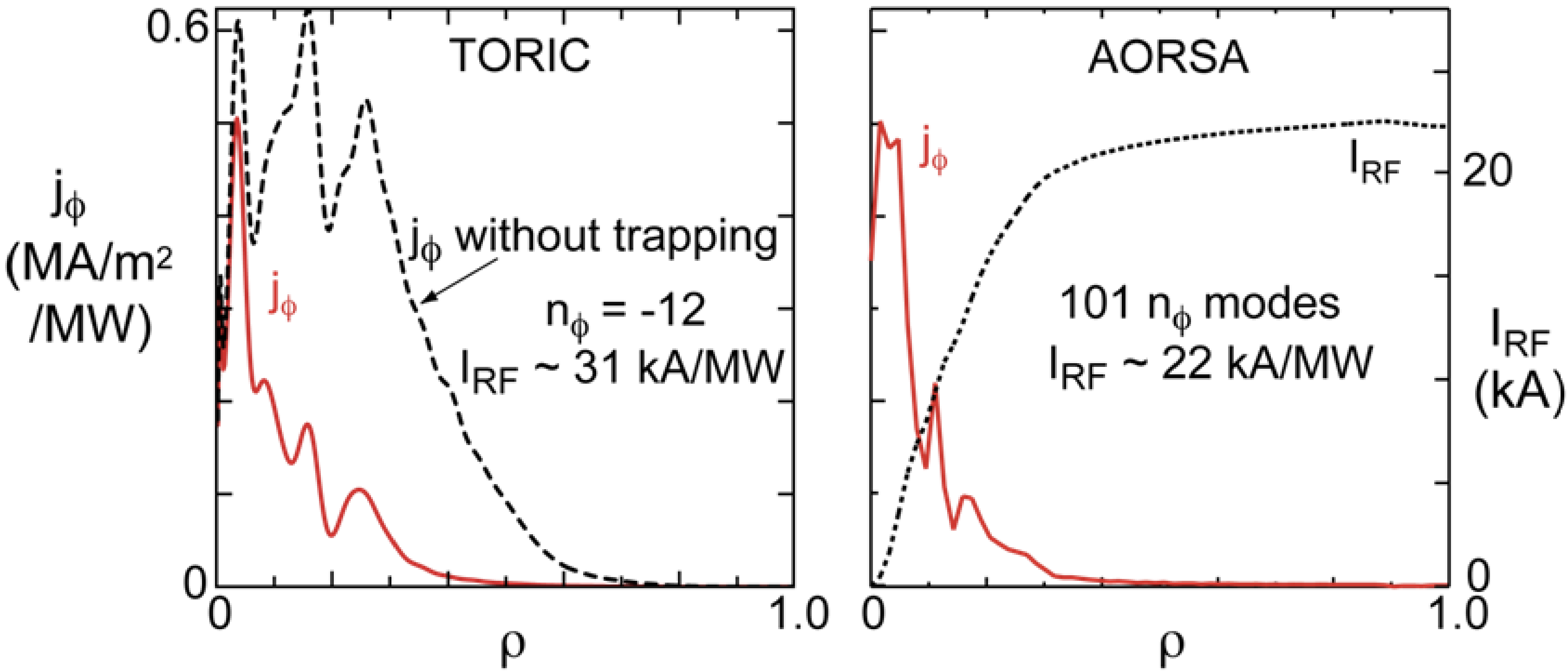
- Sawteeth seen sometimes with co CD, not with counter CD

- FY08 HHFW CD experiments will use longer HHFW heating pulse at higher power, and deuterium plasmas at $B_t(0)$ = 5.5 kG in L- & H-mode

Current Drive at - 90° Antenna Phase (k_ϕ = - 8 m^{-1}) Predicted to Peak in Core

NSTX

Steady state full wave code predictions for j_ϕ

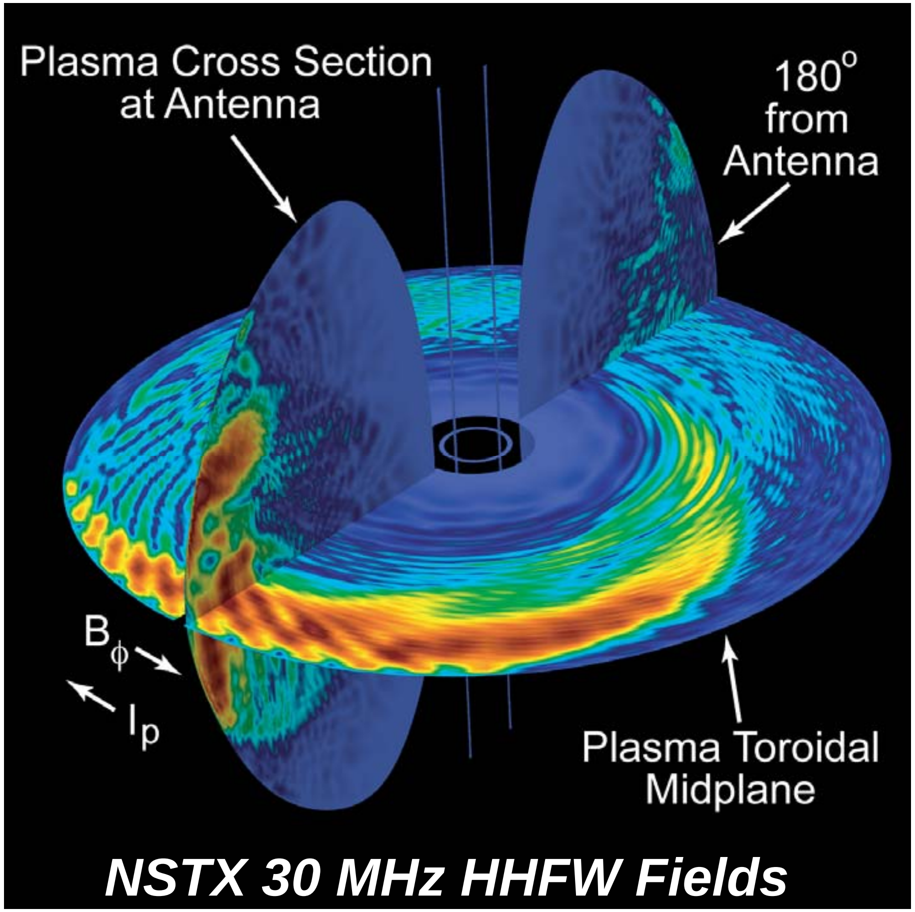


- j_ϕ peaks up for $\rho = (\psi_N)^{1/2} < 0.2$, AORSA peaks more
- TORIC code predicts ~ 37 kA at 1.2 MW (65% heating efficiency)
- AORSA 2D code predicts ~ 26 kA, includes counter CD spectrum
- Back EMF effect not included in prediction

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

NSTX

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

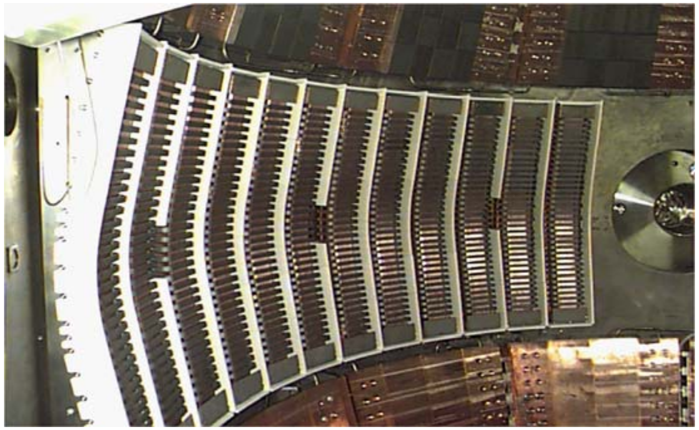


- Waves propagate around plasma axis in + B_ϕ direction
- Wave fields very low near inner wall, strong first pass damping
- NSTX is good platform for benchmarking surface damping with advanced RF codes

SciDAC project extending codes in FY08 to include edge loss mechanisms

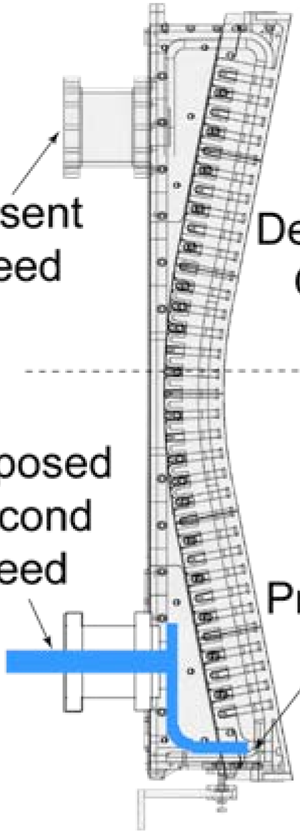
Antenna Upgrades Double the Coupled Power for Same Voltage Per Strap & Increase ELM Resilience in H-mode

NSTX



NSTX 12-Strap HHFW Antenna

Antenna double feed upgrade planned for FY09



- Double feed upgrade permits larger plasma-antenna gap, with more stability and power per antenna strap for FY09 run
- Add system for increased resilience to ELMs during H-mode for FY10 run
- Improved diagnostics to monitor arcing, surface waves, plasma-antenna interaction and parametric decay instability for FY09-10 run
- Direct observation of 30 MHz RF wave in the core with UCLA reflectometer (FY08) and high-k scattering (FY09)

HHFW Research Plan for FY08-10

PAC21-13 & 14

FY08:

- Extend L-mode coupling physics studies to D plasma; improve operation with NBI, assess effect of Li, and optimize heating efficiency:
  - Test $\phi = -150^o$ CD phasing (pure spectrum)
- Begin heating & CD studies in D H-mode plasmas & assess effect of Li
- Explore coupling/heating of CHI/ECH plasma using low I_p,T_e OH plasma

FY09:

- Assess heating & CD operation with NBI with double fed antenna
- Optimize HHFW coupling into I_p ramp-up

FY10:

- Heating & CD operation with NBI H-mode using ELM resilience system
- HHFW coupling into ramp-up combined with 28 GHz ECH-assisted non-inductive startup
- If no NSTX run in FY10 no test of fully upgraded HHFW antenna

* Note: Plan element assuming 10% increment over the base funding

HHFW Research Plan for FY11-13

FY11:

- Optimize heating and CD operation with NBI H-mode with fully upgraded HHFW antenna & Li conditioning:
  - Benchmark core CD against advanced RF codes
- Optimize HHFW coupling into plasma startup/ramp-up and combine with 28 GHz ECH-assisted non-inductive startup

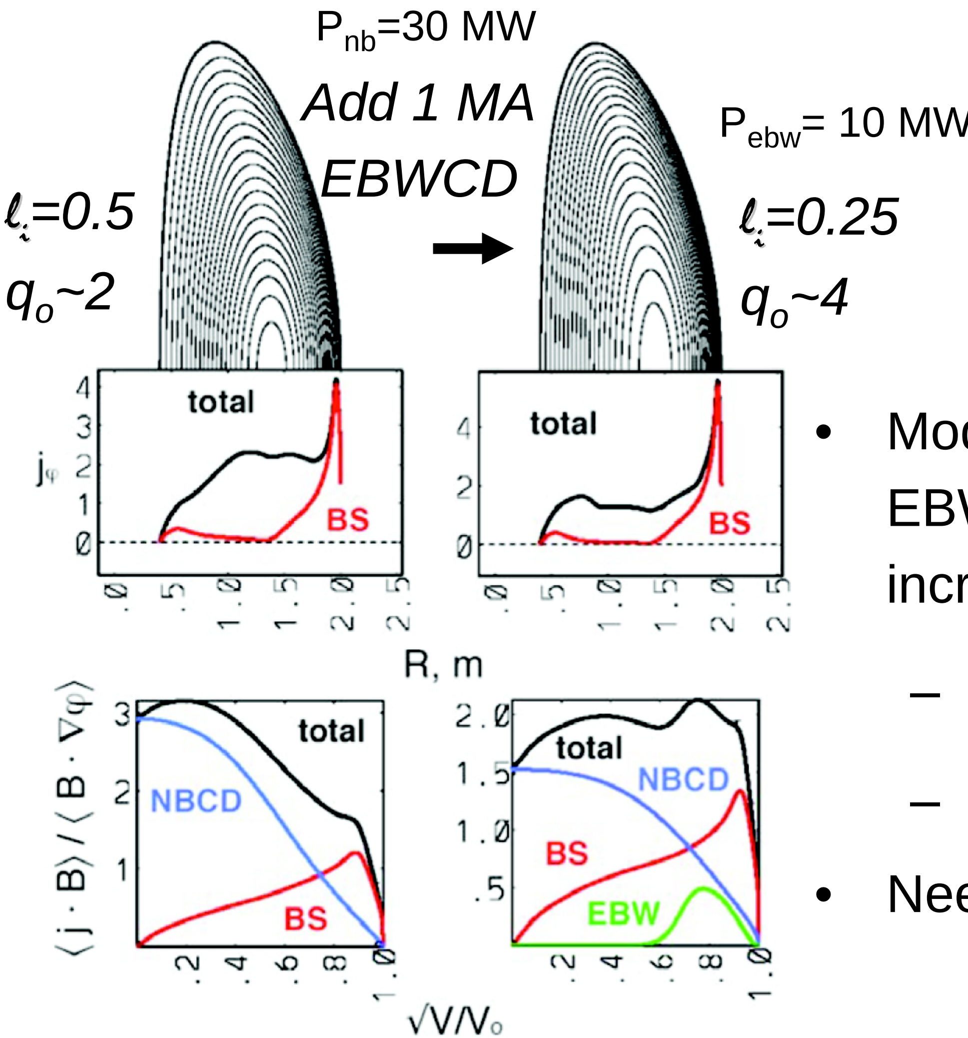
FY12-13:

- Support very long pulse scenario:
  - Integrate into Plasma Control System
  - Control q on axis
  - Very long pulse, high power operation
- Optimize HHFW with ECH-assisted CHI or PF-only startup to support fully non-inductive plasma startup & ramp-up
- Study synergy between HHFW & EBW heating, with & without NBI

* Note: Plan element assuming 10% increment over the base funding

EBW Progress & Plans

Long Term EBW Research Objective: Assess Ability of EBWCD to Generate Off-axis Stabilizing Current in 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)

H-mode EBW Coupling Significantly Improved in FY07 by Adding Li Conditioning

NSTX

- Significantly improved EBW coupling during H-mode by adding Li evaporation to reduce EBW collisional damping in scrape off
- Transmission efficiency increased from 10% to 65% at 18 GHz (f_{ce}) & from 10% to 50% at 28 GHz ($2f_{ce}$)
- FY08 EBW emission experiments to focus on further increasing EBW coupling during H-mode by adding more Li evaporation

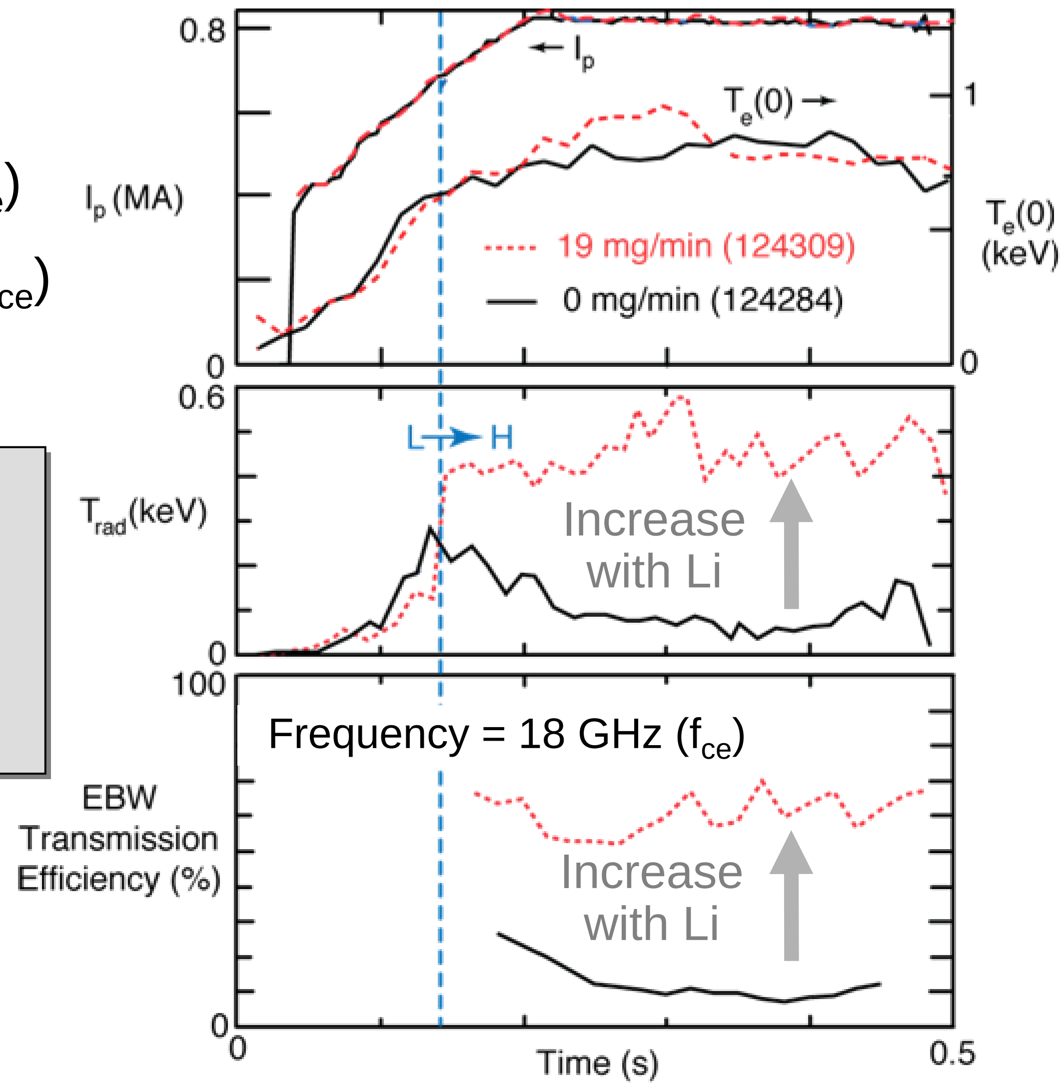
Transmission of Thermal EBW Emission from Core Increased Significantly with Increased Fresh Li Evaporation

NSTX

- Transmission efficiency increased with Li:
  - 10% ⟶ 65% at 18 GHz (f_{ce})
  - 10% ⟶ 50% at 28 GHz ($2f_{ce}$)

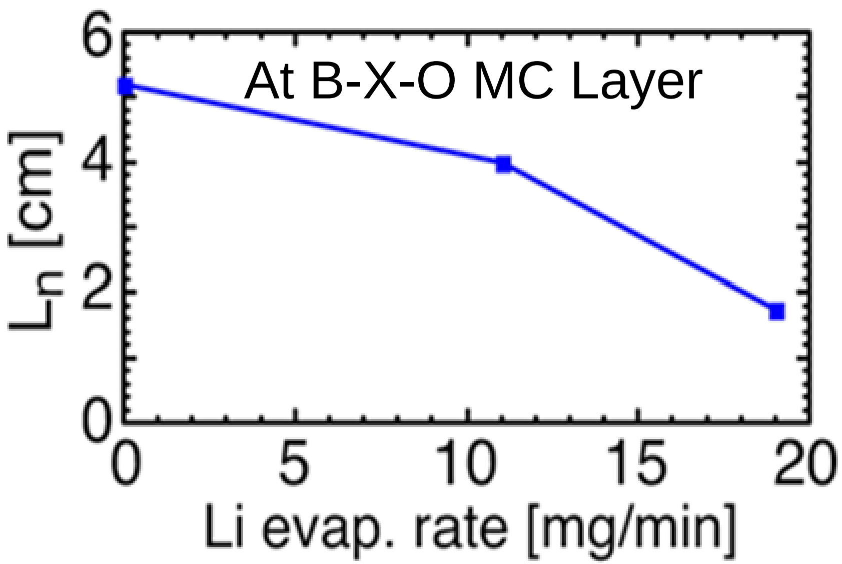
- In FY08 increase EBW coupling in H-mode with more Li, test if integrated Li is important

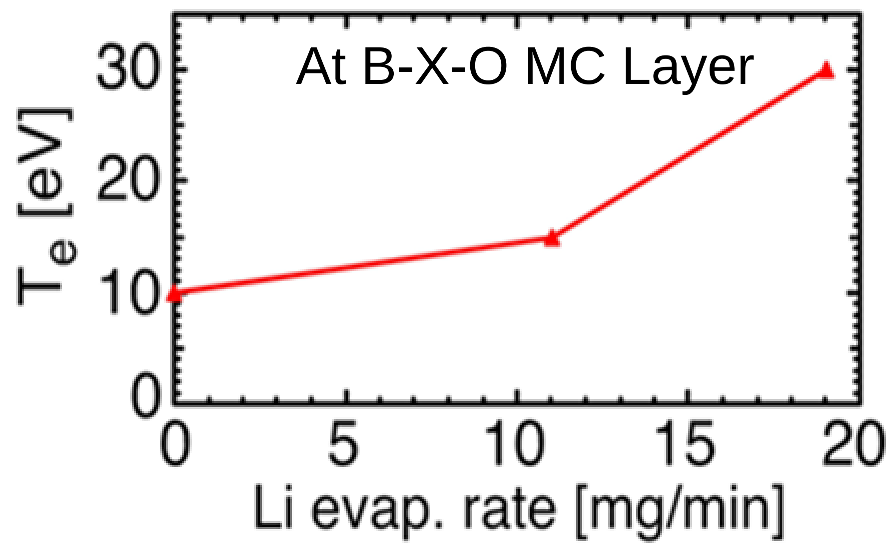
PAC21-38



Lithium Evaporation Increases T_e and Reduces L_n Near the B-X-O Mode Conversion Layer, Located in Scrape Off

NSTX





- f_{ce} & $2f_{ce}$ B-X-O mode conversion (MC) layer typically in plasma scrape off, R = 144-151 cm
- T_e increased from 10-30 eV with addition of Li
  - Simulation predicts EBW collisional damping significant for T_e< 20 eV
  - Ongoing theory/modeling collaborations with Josef Preinhaelter (Prague), Bob Harvey (CompX) & Abhay Ram (MIT)

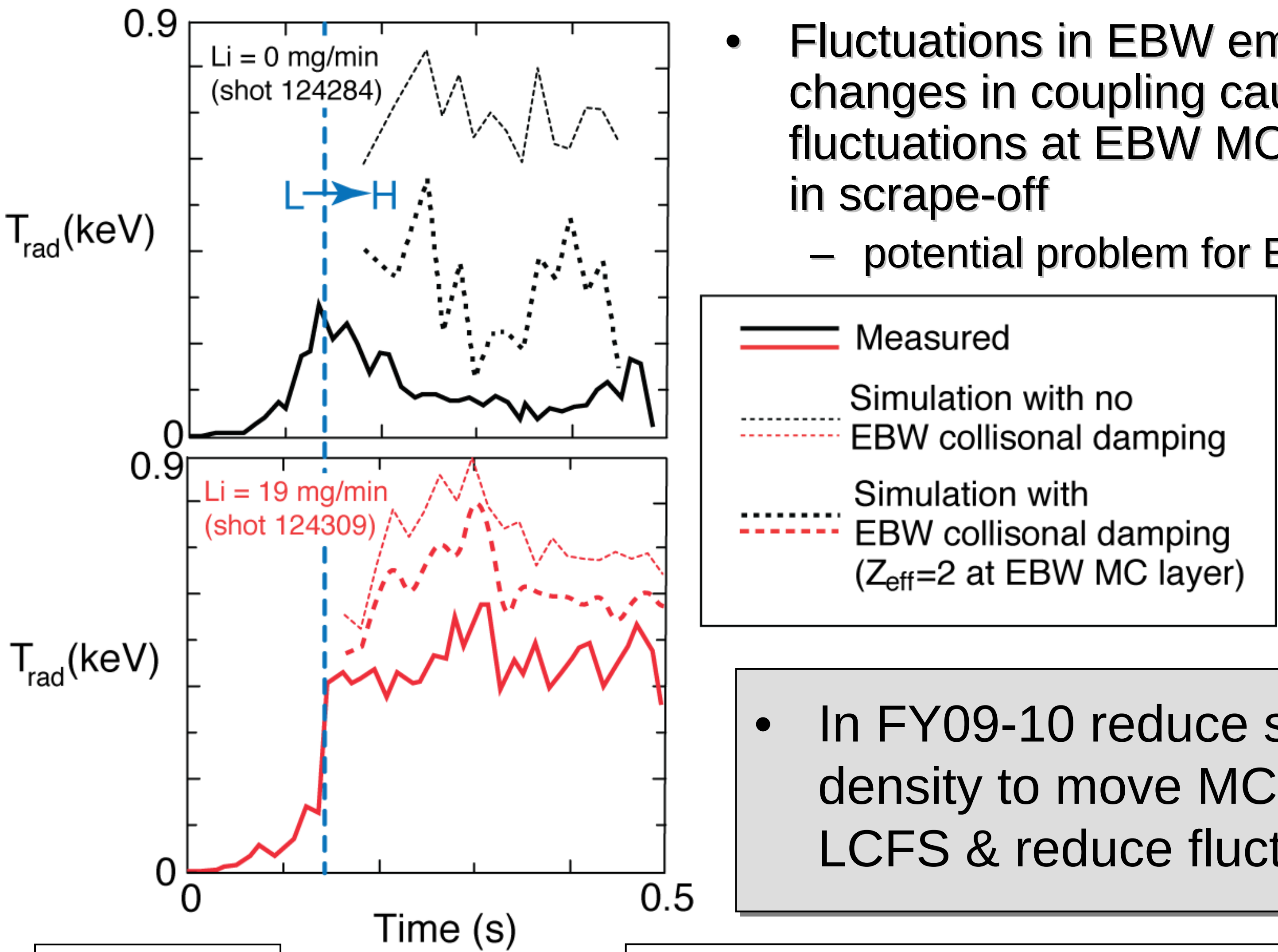
PhD Thesis

PAC21-38

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

EBW Emission Simulations* of H-Mode Shots Predict Much Less EBW Collisional Damping for Shot With Li

NSTX



- Fluctuations in EBW emission due to changes in coupling caused by n_e fluctuations at EBW MC layer located in scrape-off
  - potential problem for EBWH coupling

- In FY09-10 reduce scrape off density to move MC inside LCFS & reduce fluctuations

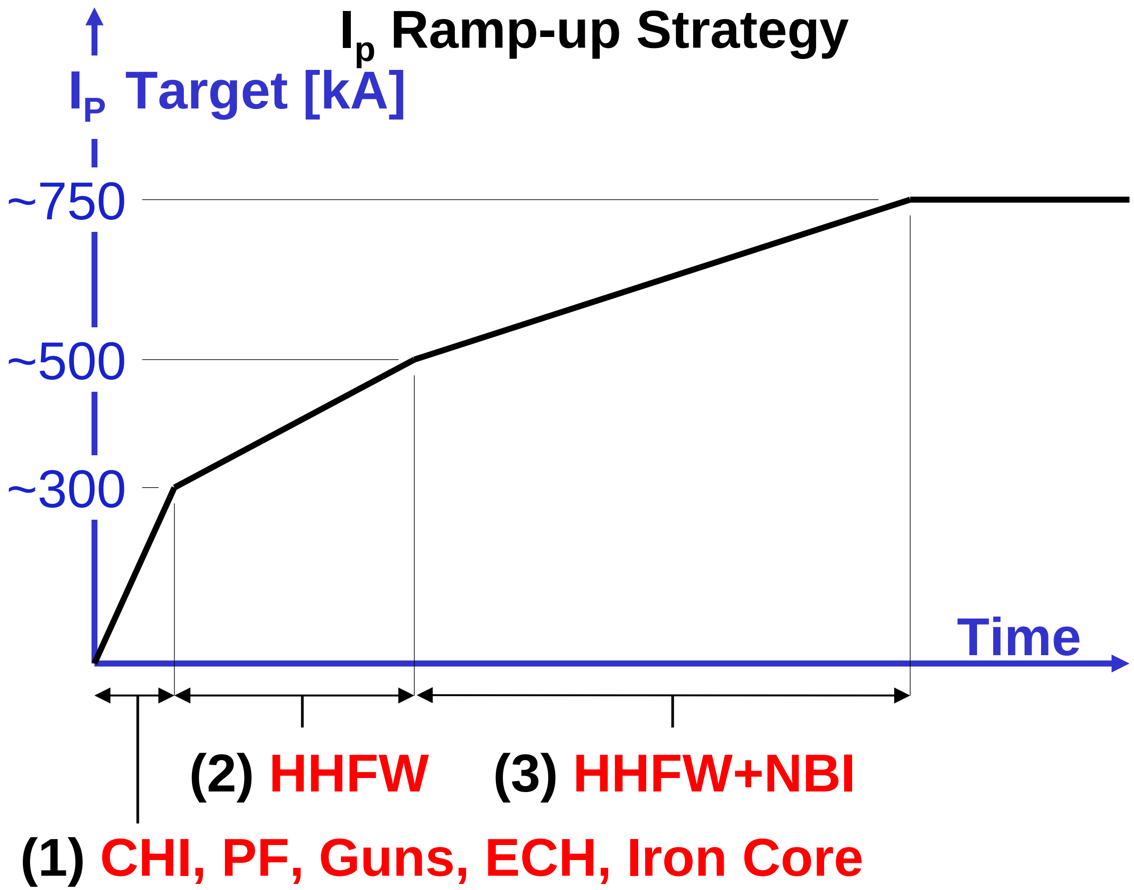
PAC21-38

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

28 GHz ECH Not in FY09-10 Base Budget, But Can Use Small Amount of OH Instead to Simulate Iron Core

NSTX

NSTX Start-up & I_p Ramp-up Strategy



Start-up/Ramp-up Requirements

(1→2) I_P, T_e, RF coupling must be sufficiently high for HHFW to be absorbed

(2) Sufficiently high P_{RF}, τ_E must be achieved for I_P overdrive using BS and HHFW current drive

(2→3) Sufficiently high I_P needed to absorb NBI, high P_{HEAT}, τ_E, β_P needed for current overdrive

EBW Research Plan for FY08-10

NSTX

FY08:

- Optimize EBW emission coupling in H-mode with Li evaporation:
  - Assess effect of integrated Li
- Collaborate with MAST on 28 GHz startup experiments

PAC21-11

FY09:

- Continue coupling studies on NSTX & collaboration with MAST:
  - Explore low density plasmas on NSTX with EBW MC inside LCFS
- Begin installation 350 kW 28 GHz ECH system

FY10:

- 28 GHz ECH-assisted startup & preionization experiments
- If no incremental funding for 28 GHz ECH in FY09-10, can use small amount of OH instead to simulate iron core:
  - Also expand collaboration with MAST on ECH-assisted startup & EBWH
- * Note: Plan element assuming 10% increment over the base funding

EBW Research Plan for FY11-13

NSTX

FY11:

- Install second 350 kW 28 GHz gyrotron for ECH-assisted startup with up to 700 kW

FY12:

- Install EBW launcher
- EBW coupling studies & on-axis heating

FY13:

- 700 kW core & off-axis heating studies (benchmark deposition codes)
- Without incremental funding in FY11-13 on- & off-axis EBW heating could be pursued through an expanded collaboration with MAST

* Note: Plan element assuming 10% increment over the base funding

PAC21-37

Summary

HHFW:

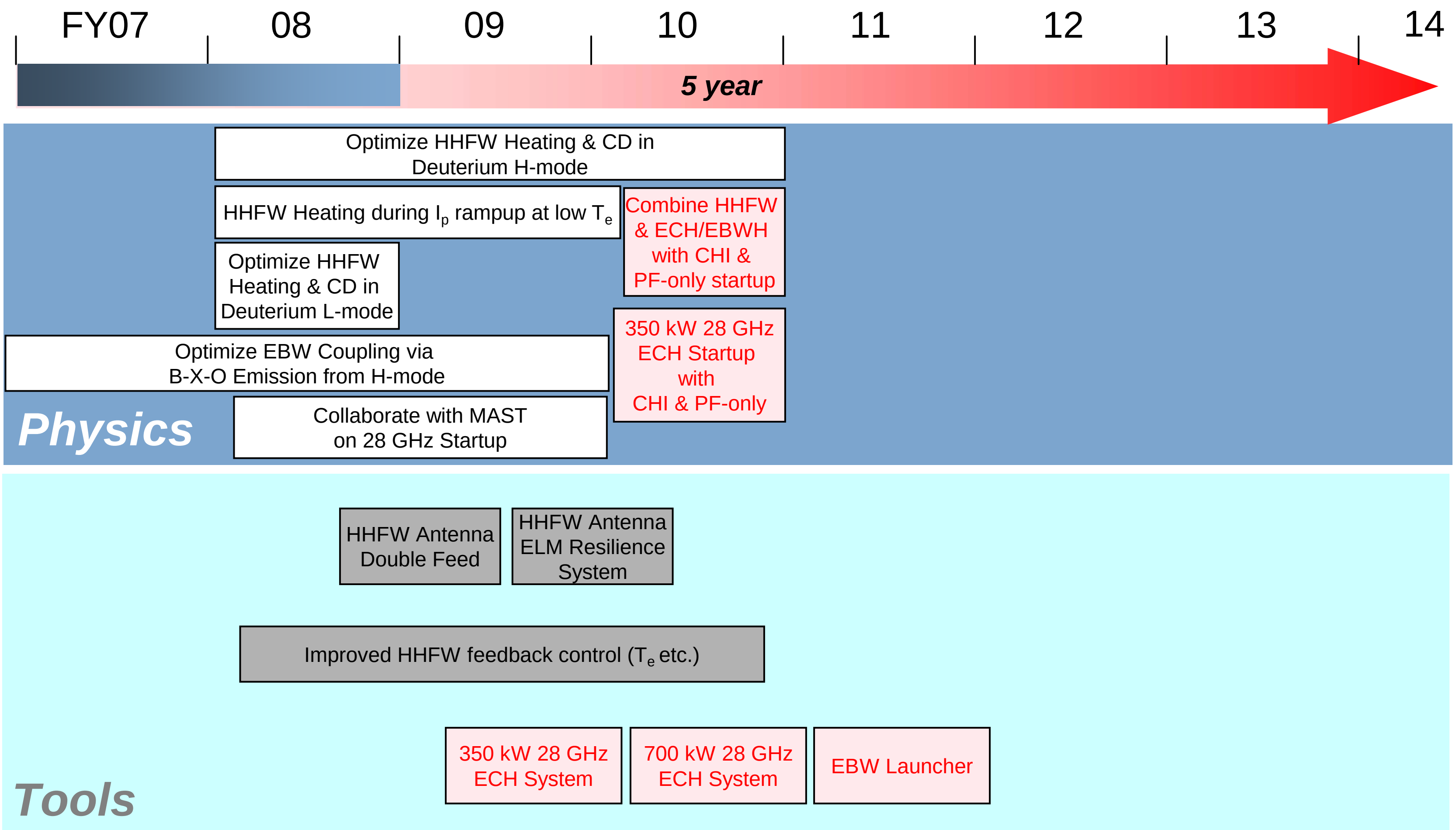
- Improved heating with CD phasing, with & without NBI, in He L-mode at $B_t(0)$ = 5.5 kG by lowering edge n_e to reduce edge losses
- Clear evidence of on-axis HHFW CD from MSE measurements, consistent with TORIC & AORSA full wave code predictions
- FY08 CD experiments will use longer heating pulses at higher power, and $B_t(0)$ = 5.5 kG L- and H-mode deuterium plasmas
- Deuterium experiments will assess the effect of Li on HHFW coupling

EBW:

- Coupling from H-modes increased from 10% to 65% at 18 GHz & from 10% to 50% at 28 GHz by adding Li evaporation to reduce EBW collisional damping at EBW MC layer
- FY08 EBW experiments focus on increasing coupling from H-mode by adding more Li evaporation & will assess importance of integrated Li

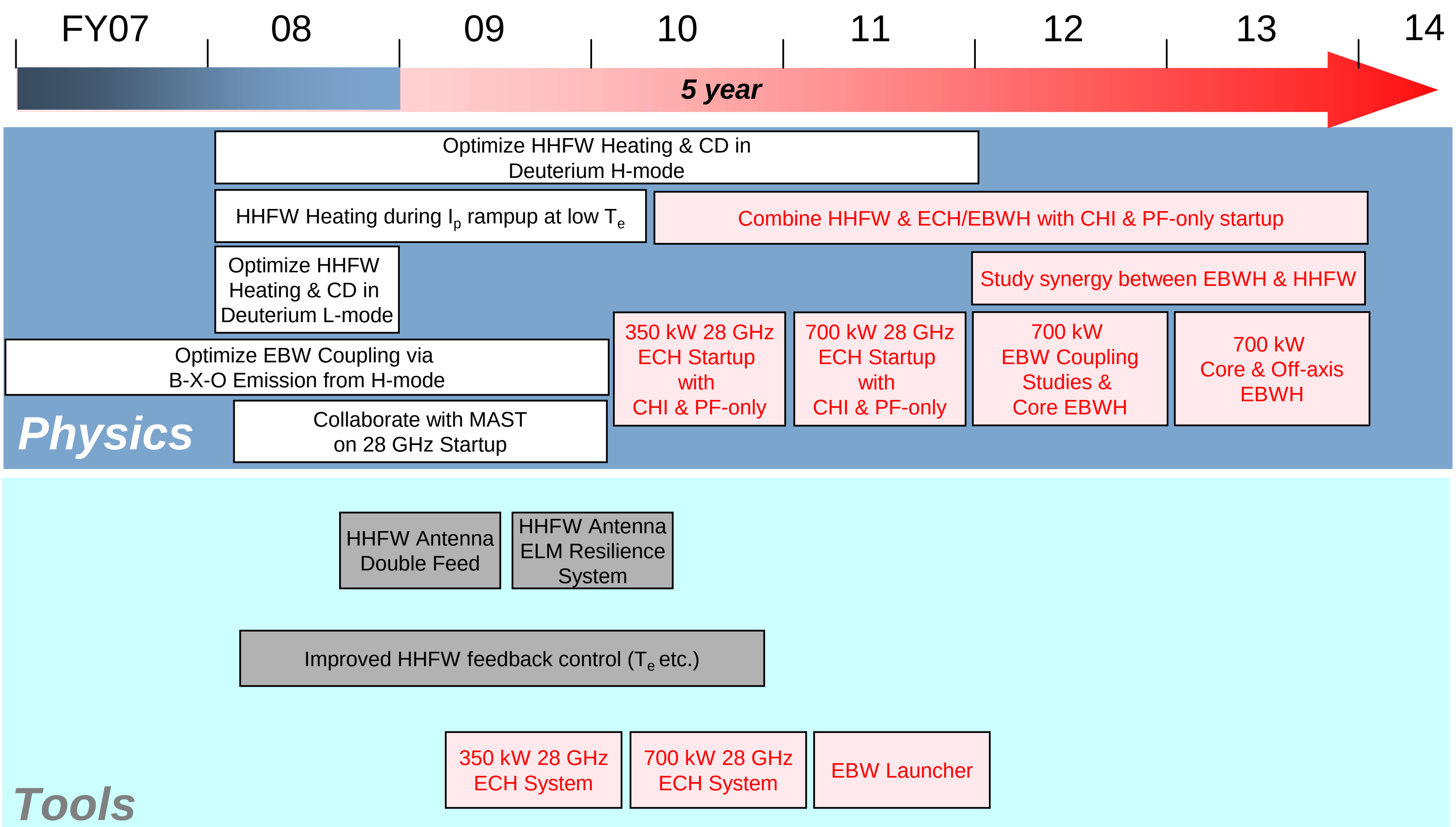
Backup Slides

Timeline for NSTX HHFW & EBW Research (Assuming NSTX does not run beyond FY10)



= Plan element assuming 10% increment over base funding in FY09-10

Timeline for NSTX HHFW & EBW Research



= Plan element assuming 10% increment over base funding in FY09-13