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Program & Plans for EBW and HHFW Research on NSTX

Joel Hosea & Gary Taylor
For the NSTX Team

21st NSTX Program Advisory Committee Meeting
(PAC-21)
January 17-19, 2007

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EBW and HHFW Heating and Current Drive are Important Elements for Attractive ST and Component Test Facilities



⇒ With NBI for non-inductive current drive

⇒ Without NBI for startup to produce conditions suitable for NBI

- Strategy for startup is proposed in response to PAC-19 request

Considerable progress made in FY06:

EBW

- Shown viable for L-mode at fundamental (f_{ce}) emission frequencies
 - *However, low second harmonic ($2f_{ce}$) EBW emission measured for L-mode*
- Also, observed very low EBW emission for H-mode at f_{ce} & $2f_{ce}$
 - *Understanding emission in H-mode is principle goal for 2007*

HHFW

- Dramatic increase in core heating efficiency at higher B_t & lower edge n_e
- Edge loss effects similar to those observed at lower ICRF harmonics (ITER relevant)
- Efficient heating maintained in presence of NBI heating
 - *Sets stage for current drive studies with MSE in FY07*

Results & Plans for EBW Research

EBW Research Goals for FY07-09



FY07:

- Study H- & L-Mode coupling physics with improved diagnostics
- Investigate behavior of EBW coupling on plasma shape, z , I_p etc.
- Compare to EBE simulation with kinetic model EBW collisional damping

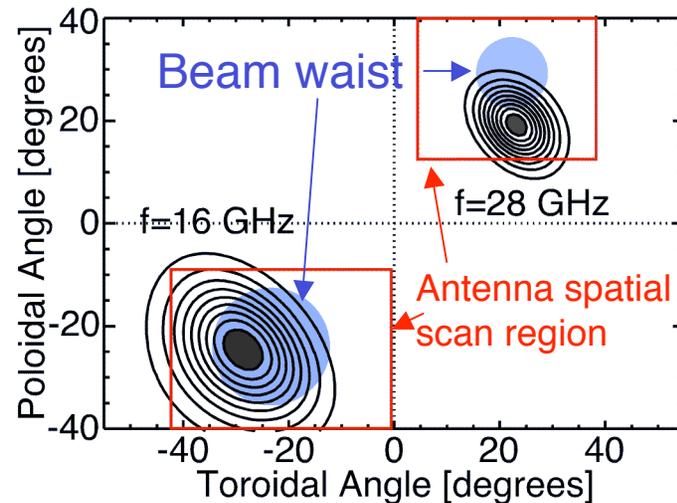
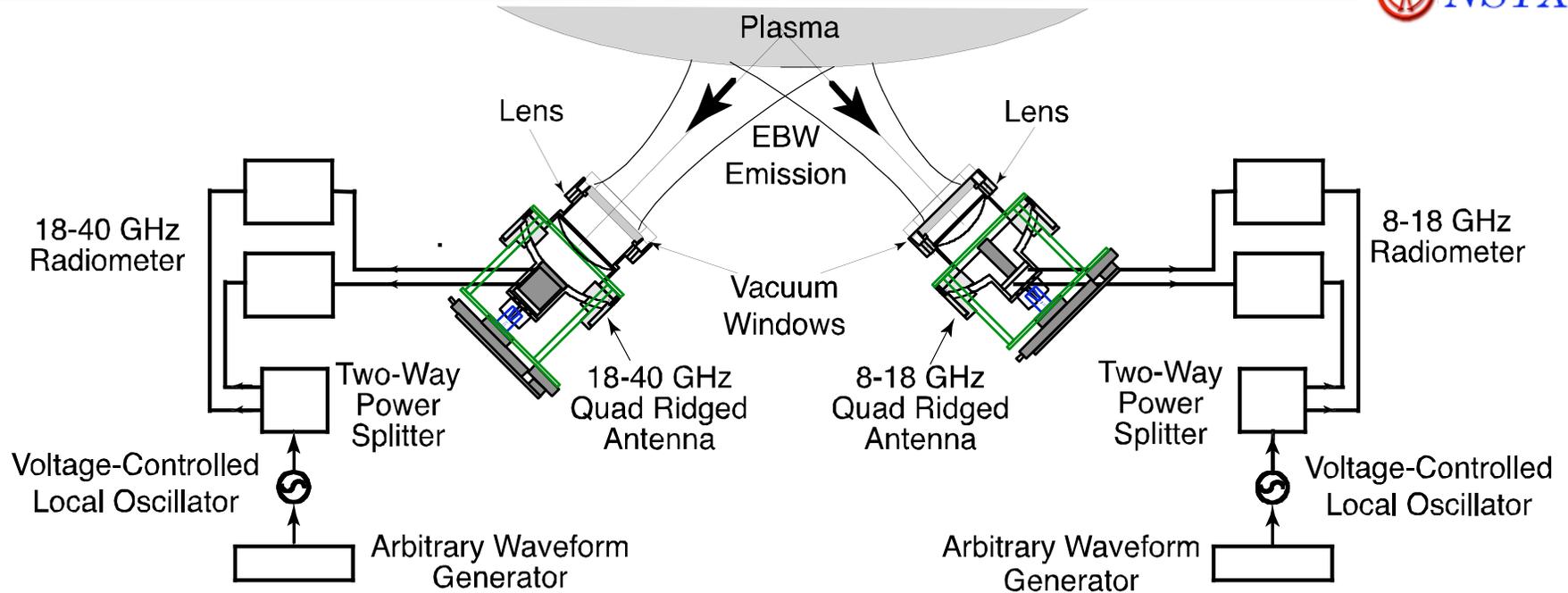
FY08:

- Continue optimization EBE studies
- Install ~ 200 kW 28/15.3 GHz ECH/EBWH system (pending review)

FY09:

- ECH/EBW expts. with CHI & PF-only startup at 100 - 200 kW

New Remotely Steered Antennas Provided Angular Mapping of B-X-O Emission Window during 2006

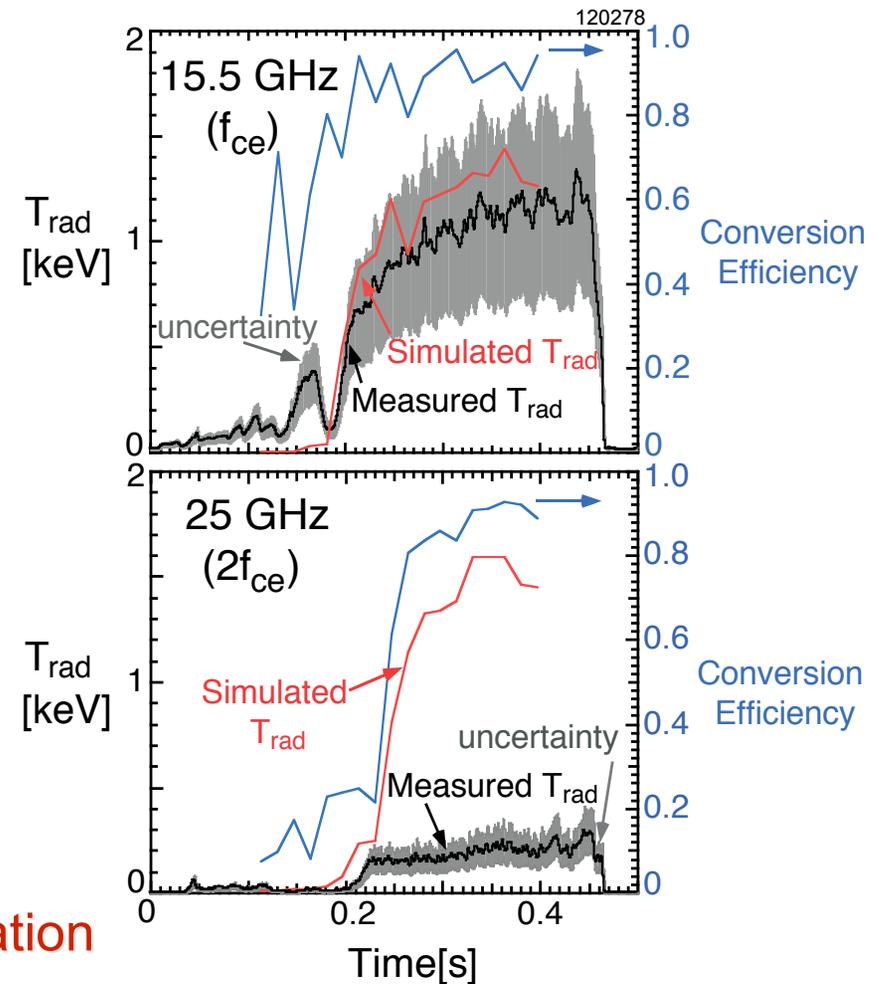
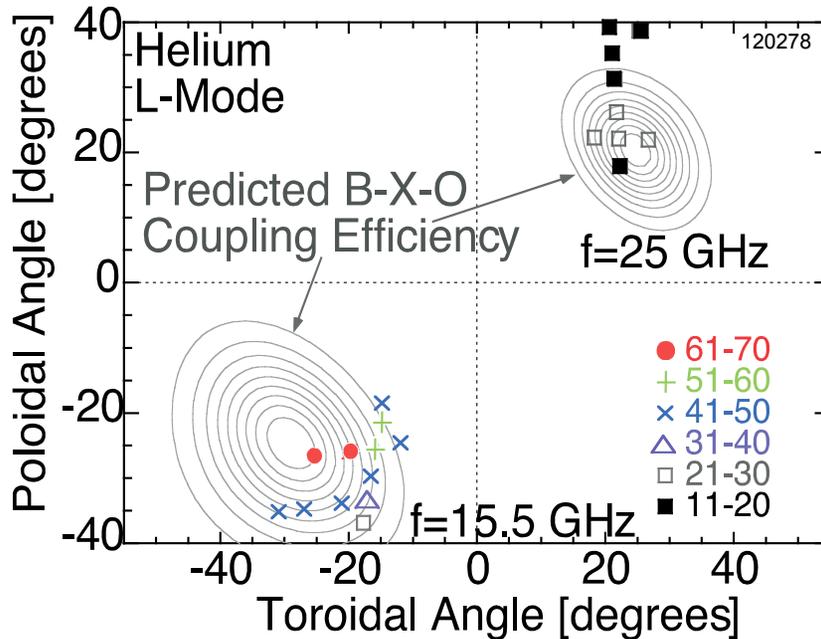


• $\pm 10^\circ$ scan in poloidal & toroidal directions

L-Mode B-X-O Emission Data from 2006 Run Agrees Well With Modeling at f_{ce} , but not $2f_{ce}$



- Measure $70 \pm 20\%$ f_{ce} coupling, but only $\sim 25 \pm 10\%$ $2f_{ce}$ coupling
- EBW emission simulation predicts $\sim 90\%$ coupling at f_{ce} & $2f_{ce}$

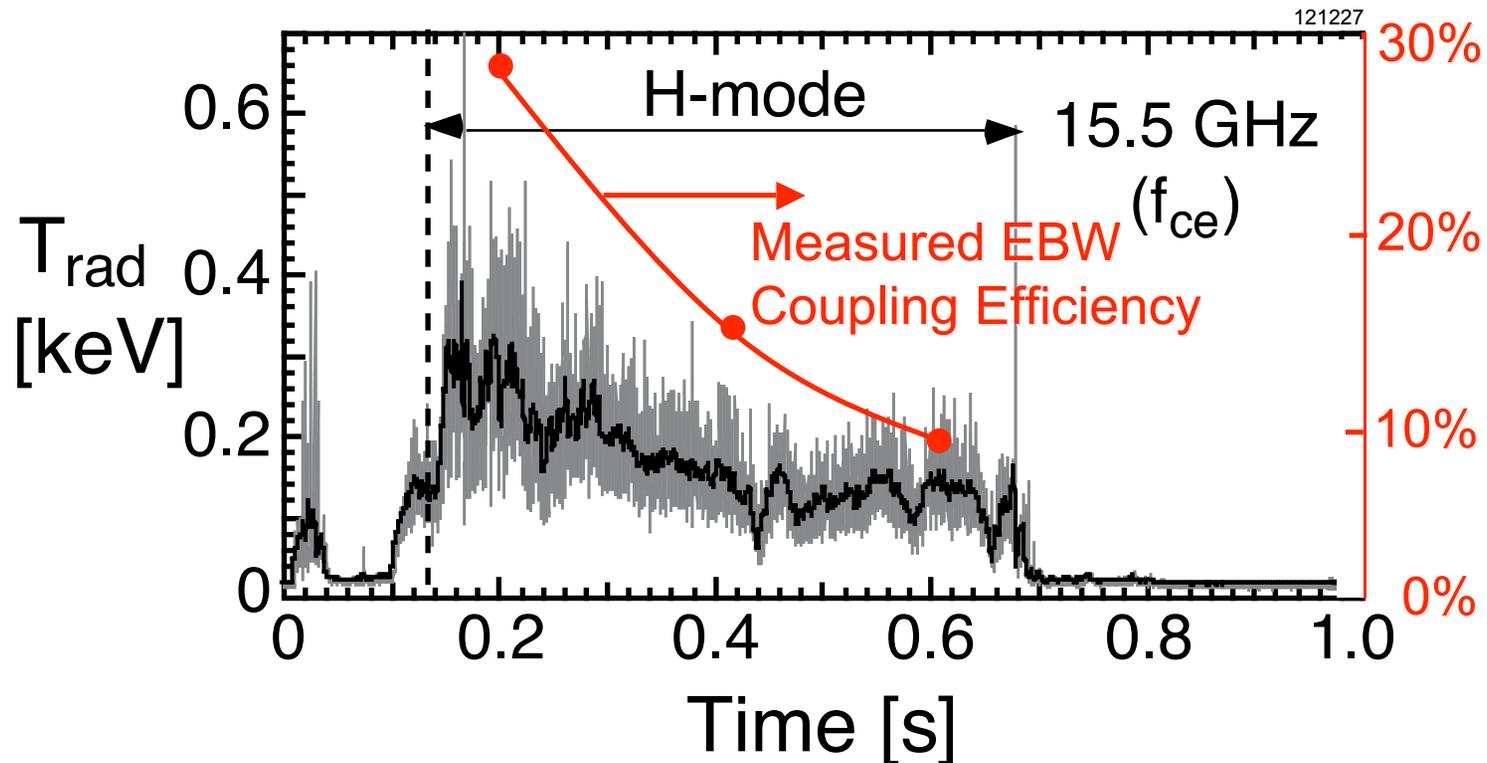


- Possible causes:
- large Doppler broadening effects resulting in off-axis damping
 - EBW damping at conversion layer
 - problems with EBW emission simulation

Very Low B-X-O Emission Measured During H-Mode Plasmas



- < 30% B-X-O coupling from H-mode plasmas
- Coupling falls throughout H-mode phase



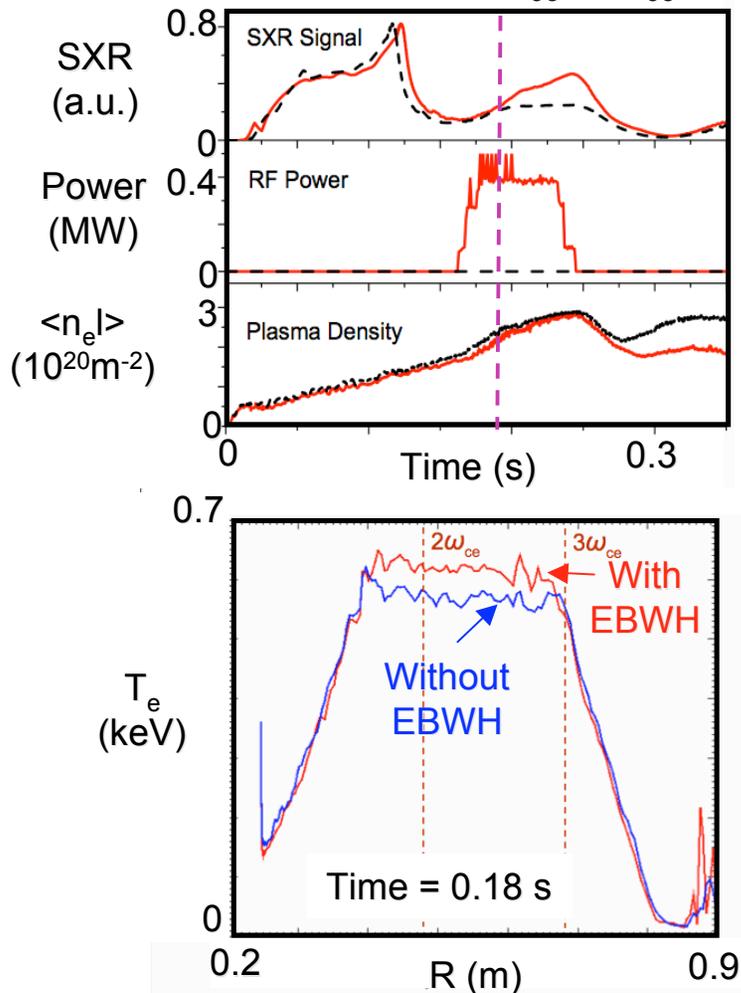
- Possible causes - collisional damping, edge bootstrap current, refraction
- EBW emission research contributing to PhD thesis

EBW Heating via B-X-O Coupling Recently Demonstrated on MAST & TCV



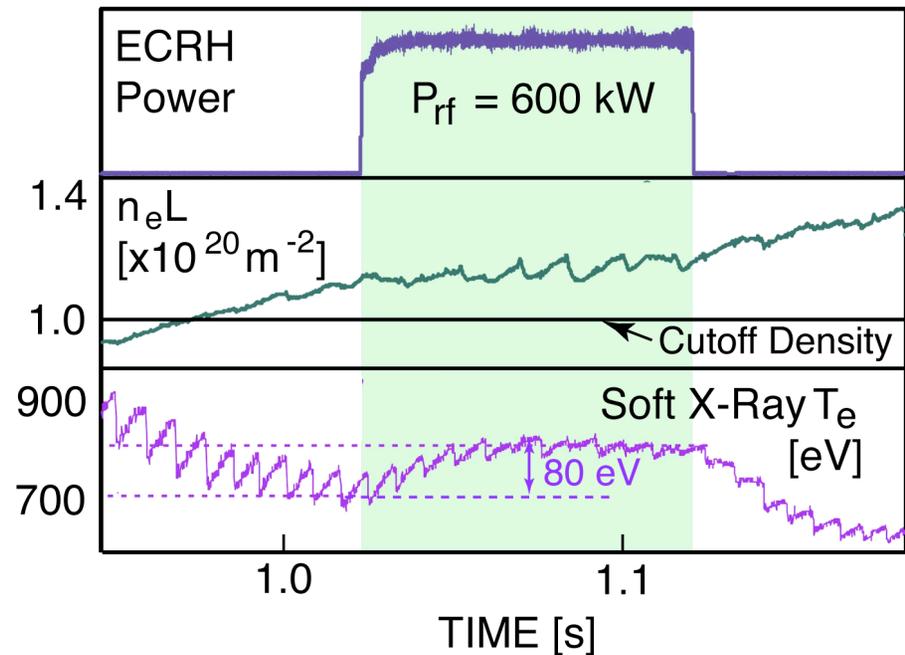
MAST

Compressed High Density H-Mode
 $f = 60 \text{ GHz } (2f_{ce} \text{ \& } 3f_{ce})$



TCV

$B_t(0) = 1.5 \text{ T}, f = 82.7 \text{ GHz } (2f_{ce})$



EBW Diagnostic Upgrades Implemented to Improve Study of B-X-O Coupling Physics in 2007



- Sweep range of EBW radiometers increased:
12-18 GHz & 24-32 GHz → 8-18 GHz & 18-36 GHz
- Improved angular coverage & tighter focusing for remotely-steered EBW antennas
- Gas injector installed near EBW antennas to investigate effect of collisions on B-X-O coupling
- Wide acceptance angle ($>80^\circ$) 8-18 GHz antenna on midplane

2007 EBW Expts to Elucidate Low EBW Coupling in H-mode & Disagreement with Simulation in L-Mode



- Study dependence of EBW coupling on plasma shape, z , I_p etc....
- Low T_e at B-X-O conversion layer may cause EBW damping:
 - *local gas puffs & Li conditioning to modify edge T_e & n_e at conversion layer to change collisionality*
- Investigate EBW emission behavior at L-H & H-L transition
- Bootstrap current at H-mode pedestal can change field pitch at UHR moving B-X-O emission window outside acceptance angle:
 - *Wide angle antenna to look for EBE outside acceptance angle*

Enhance NSTX EBW Experimental Research Through Modeling & Collaboration



- MAST collaboration: 28 GHz start-up/ramp-up experiments (*Jan 2007*)
- Benchmarking BANDIT and CQL3D/GENRAY EBW ray tracing and current [CompX/Ioffe Inst./MAST] (*Jan 2007*)
- Include kinetic model of EBW mode conversion in GENRAY [CompX/MIT] and EBE simulation code [Prague IPP]
- 2-D EBW mode conversion modeling [MIT]
- Model EBW-HHFW synergy - probably weak - PAC-19 action item [CompX]
- δf PIC simulation of EBW mode conversion to look for nonlinear EBW self-interaction [U. Colorado]

200 kW ECH/EBWH Proposed for Non-Solenoid Start-up & EBWH Tests Into I_p Flat Top in 2008-9

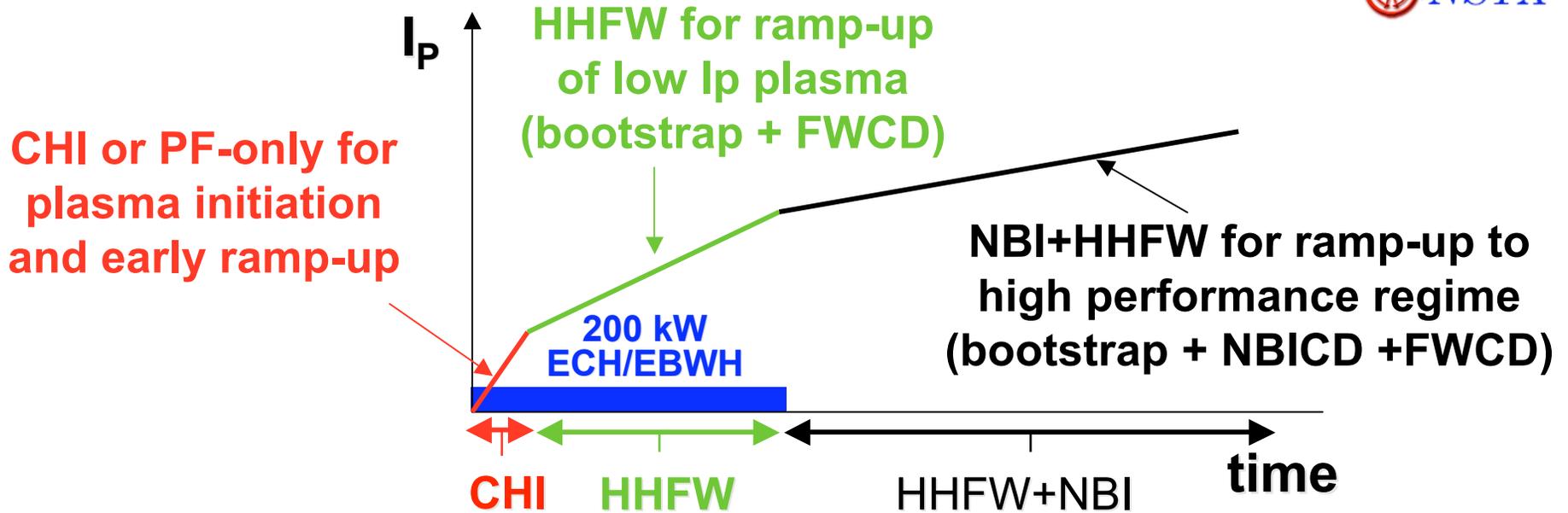


- ORNL proposing ~200 kW ECH/EBWH system (pending review)
 - Heating for CHI & PF-only start-up plasmas
 - Provide ~ 100 eV start-up plasma for effective HHFW heating to support ECH/EBWH/CHI transition to HHFW current ramp-up
 - Conduct low power EBW coupling & heating during I_p flat top
- System can be operational at 28 & 15.3 GHz for FY09 run campaign
 - Modest development and testing (e.g. verify 15.3 GHz operation)
- 28 GHz $2f_{ce}$ on-axis ECRH at $B_o = 0.55$ T when $n_e(0) < 9 \times 10^{18} \text{ m}^{-3}$
- ~ 20% per pass ECRH absorption for $n_e(0) \sim 2 \times 10^{18} \text{ m}^{-3}$, $T_e(0) \sim 20$ eV CHI plasma

ECH Resonance Locations on NSTX
 $R = 0.85$ m, $r = 0.62$ m, $B_o = 0.55$ T

Frequency/ Harmonic #	Resonant Field (T)	Major Radius (m)	Normalized Minor Radius	Critical Density $\times 10^{18} \text{ m}^{-3}$
28 GHz/fund	1	0.47	-0.61	9.2
→ 2nd	0.5	0.94	0.14	9.2 ←
3rd	0.33	1.41	0.9	9.2
15.3 GHz/fund	0.55	0.86	0.02	2.7

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



ECH needed for preionization and early heating

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

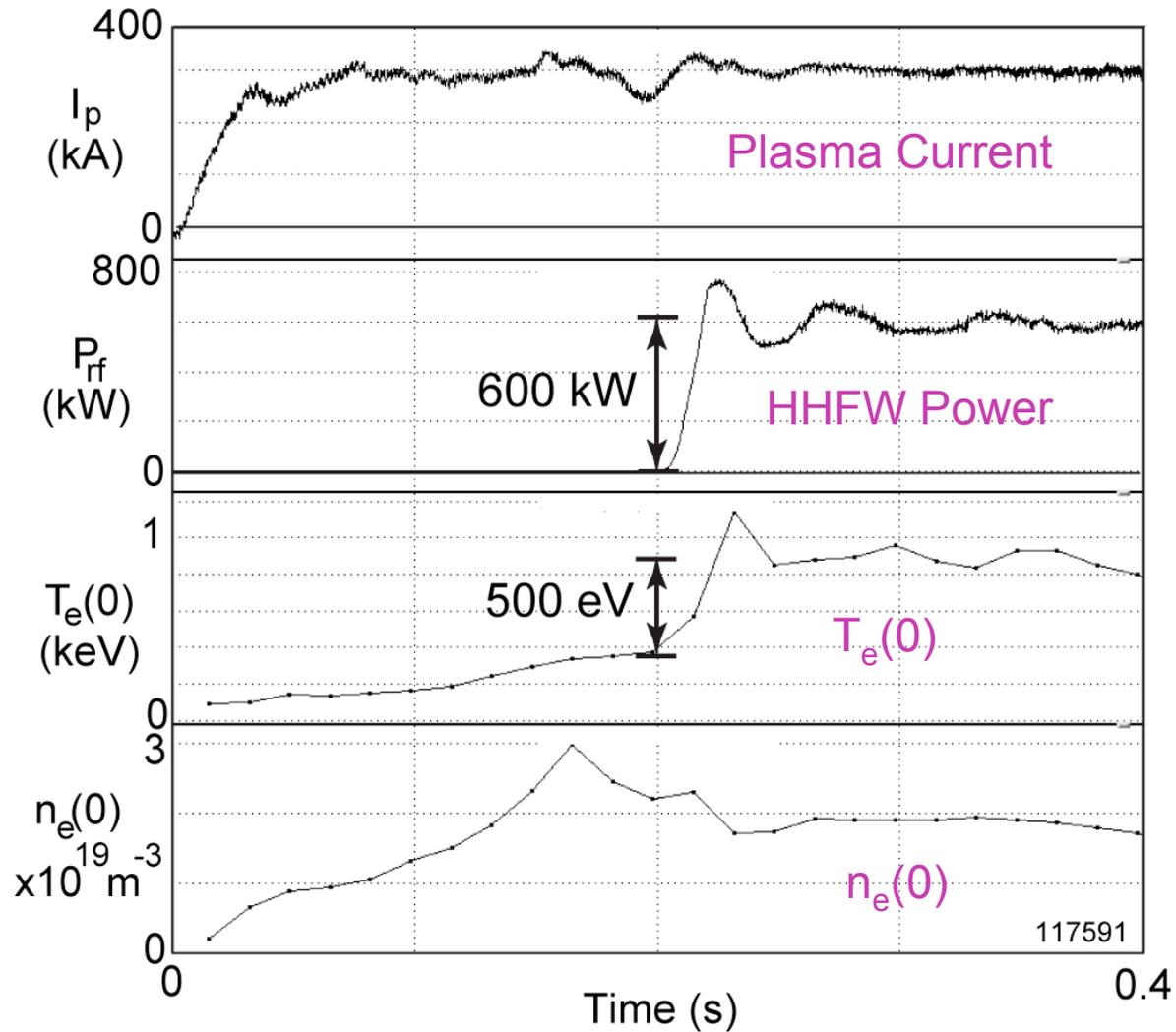
METS Single-Pass Modeling Estimates

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

ECRH can create n_e , T_e for adequate HHFW absorption



Low I_p , n_e , T_e HHFW Supports ~ 100 kW EBWH being Detectable



Results & Plans for HHFW Research

HHFW Research Goals for FY07-09



FY07-08:

- Establish coupling and heating physics - compare with theory that includes edge loss mechanisms - collisions, sheaths, PDI, turbulence (ITER relevant)
- Optimize current drive at high field
 - *With and without neutral beam injection*
- Explore coupling/heating of CHI plasma and simulated CHI/ECH plasma (ohmic plasma with low current and T_e)

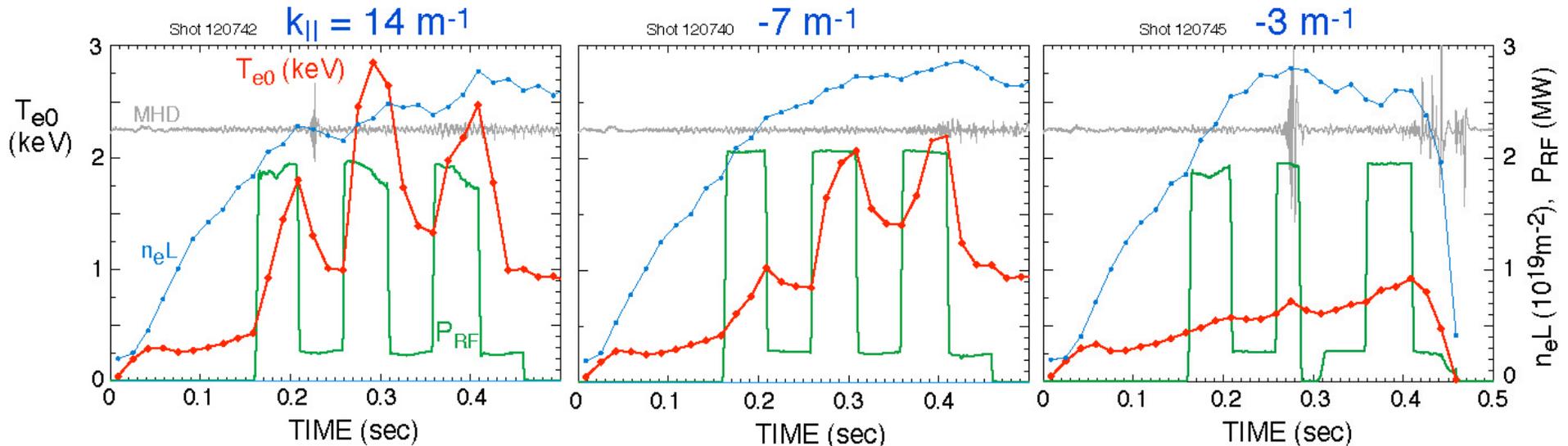
FY09:

- Establish startup scenarios with CHI + ECH
- Begin HHFW antenna feed upgrade to enhance coupled power by a factor > 2 (under incremental budget)
- Incremental milestone to characterize & optimize edge plasma-HHFW interactions

HHFW Propagation and Damping Physics Studied vs B_T and Antenna $k_{||}$ in 2006

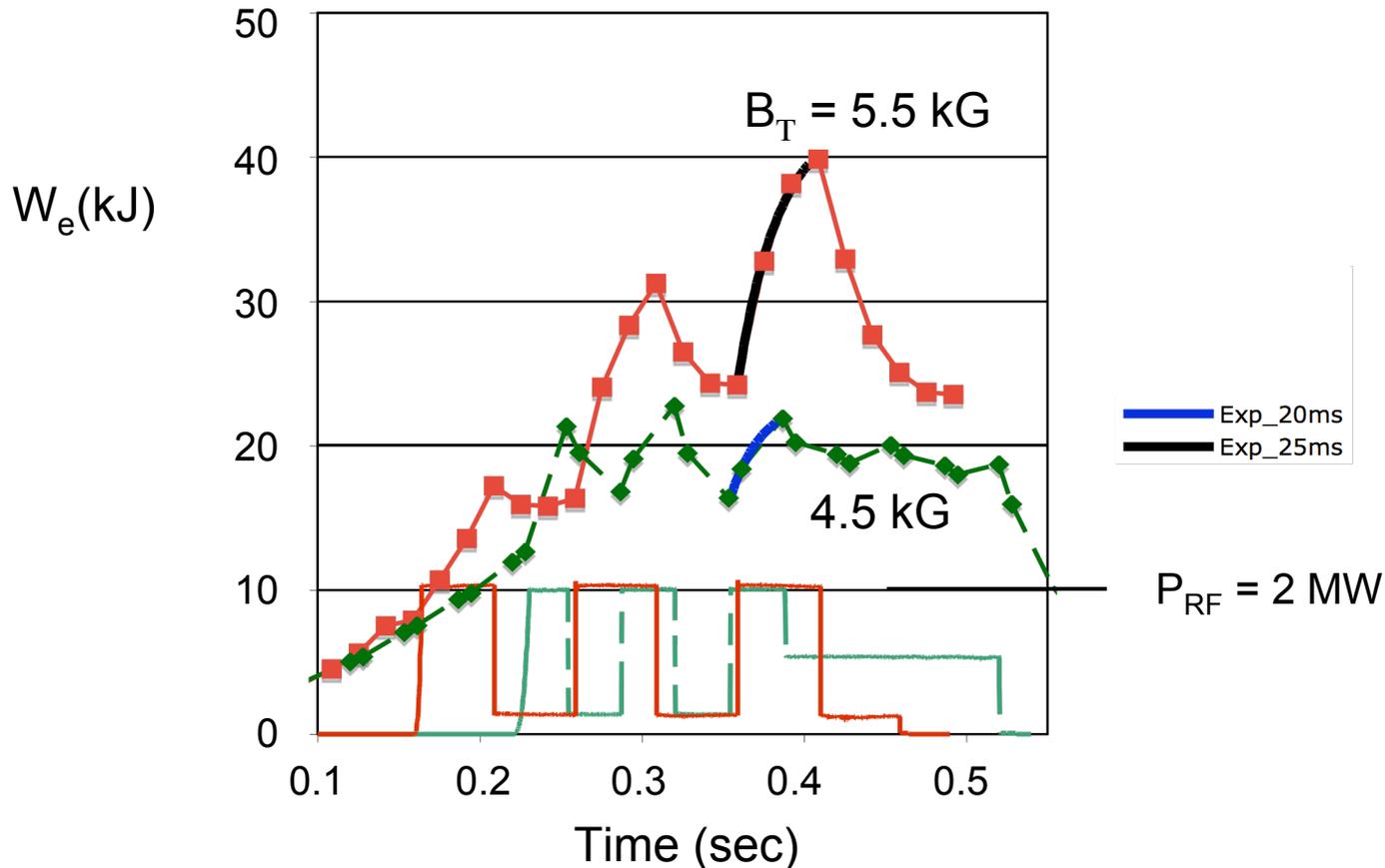


Electron heating for $B_T = 5.5$ kG, $I_p = 720$ kA



- Clear strong dependence on $k_{||}$ – almost no heating at $k_{||} = -3 \text{ m}^{-1}$
- Heating at $k_{||} = -7 \text{ m}^{-1}$ comparable to $k_{||} = 14 \text{ m}^{-1}$
- Heating at $k_{||} = -7 \text{ m}^{-1}$ for first RF pulse about half that for $k_{||} = 14 \text{ m}^{-1}$
 - edge density during the first RF pulse is well above onset value for fast wave perpendicular propagation
- Ray tracing and full wave simulations of 3D global wave structure underway

ΔW_e for $k_{\parallel} = -7 \text{ m}^{-1}$ Increased Substantially as B_T Increased from 4.5 kG to 5.5 kG



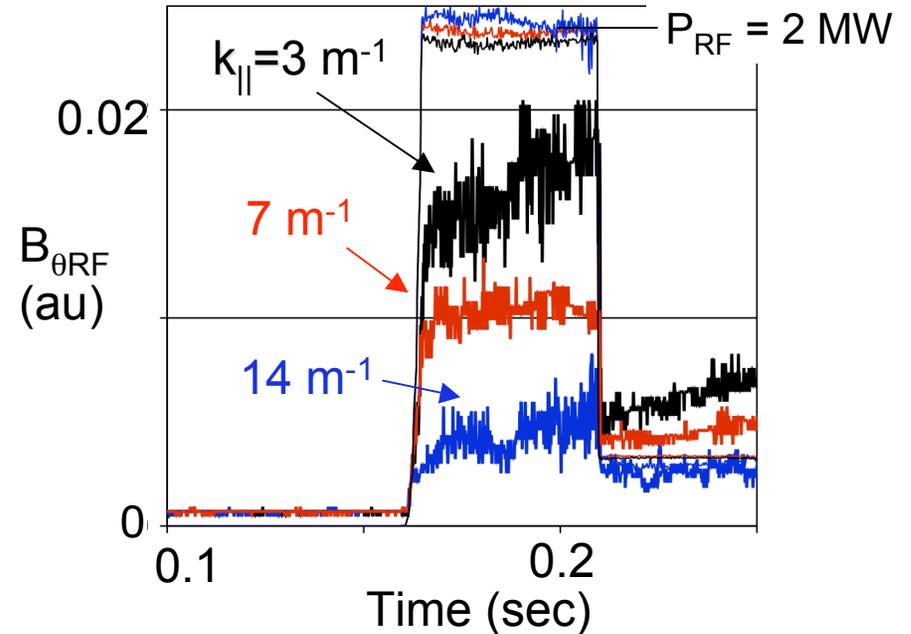
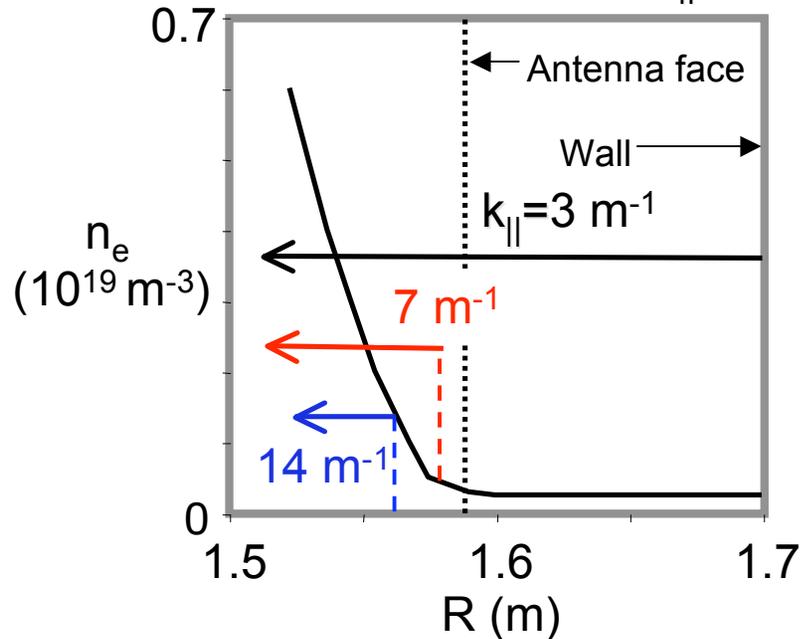
- ΔW_e for $B_T = 5.5 \text{ kG}$ is ~ 2 times the value for 4.5 kG over same time interval
- RF power deposition to **electrons** increases from $\sim 22\%$ to $\sim 40\%$ at the higher B_T and **total** efficiency increases from $\sim 44\%$ to $\sim 65\%$

Fast Wave Propagation at Lower n_e for Lower k_{\parallel} Appears to Contribute Strongly to Power Losses in Edge Regions



Perpendicular wave propagation onset in edge regions - $n_{onset} \propto B * k_{\parallel}^2$

RF far surface fields vs k_{\parallel}
- probe on opposite side from antenna



- Propagation close to wall at $k_{\parallel} = 7 \text{ m}^{-1}$, on wall at $k_{\parallel} = 3 \text{ m}^{-1}$
 \Rightarrow *Losses in surface should be higher for lower k_{\parallel}*
- RF probe signals are a strong function of k_{\parallel}
 \Rightarrow *structure & sheath losses should increase going from 14 m^{-1} to 3 m^{-1}*
- Increasing B should push onset further from antenna and increase heating
- RF SciDA developing models to quantify edge fields and sheath losses

Higher Core Coupling Efficiency Sets Stage for CD Experiments in FY07-08



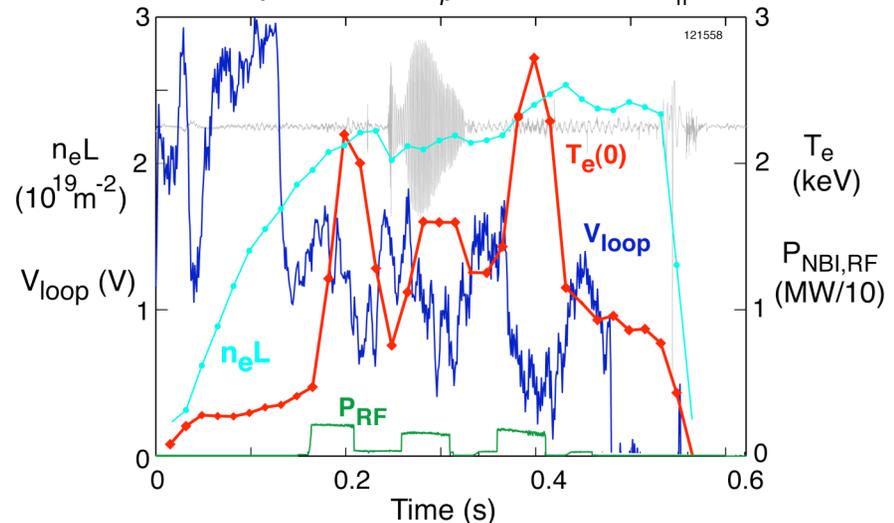
- Repeat earlier V_{loop} comparisons at $k_{||} = \pm 7 \text{ m}^{-1}$ for same P_e profiles

⇒ with observed higher efficiency, more HHFW-CD expected at 5.5 kG

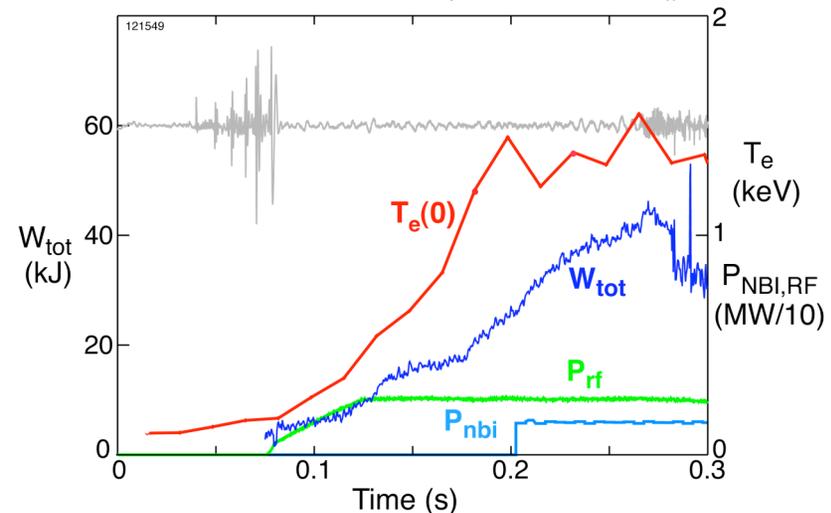
- Direct MSE measurement of HHFW-CD planned

⇒ Initial test of HHFW with 70 kV suggests that an MSE measurement of HHFW-CD may be viable at high B_T

Helium, $B_t = 5.5 \text{ kG}$, $I_p = 0.72 \text{ MA}$, $k_{||} = -7 \text{ m}^{-1}$



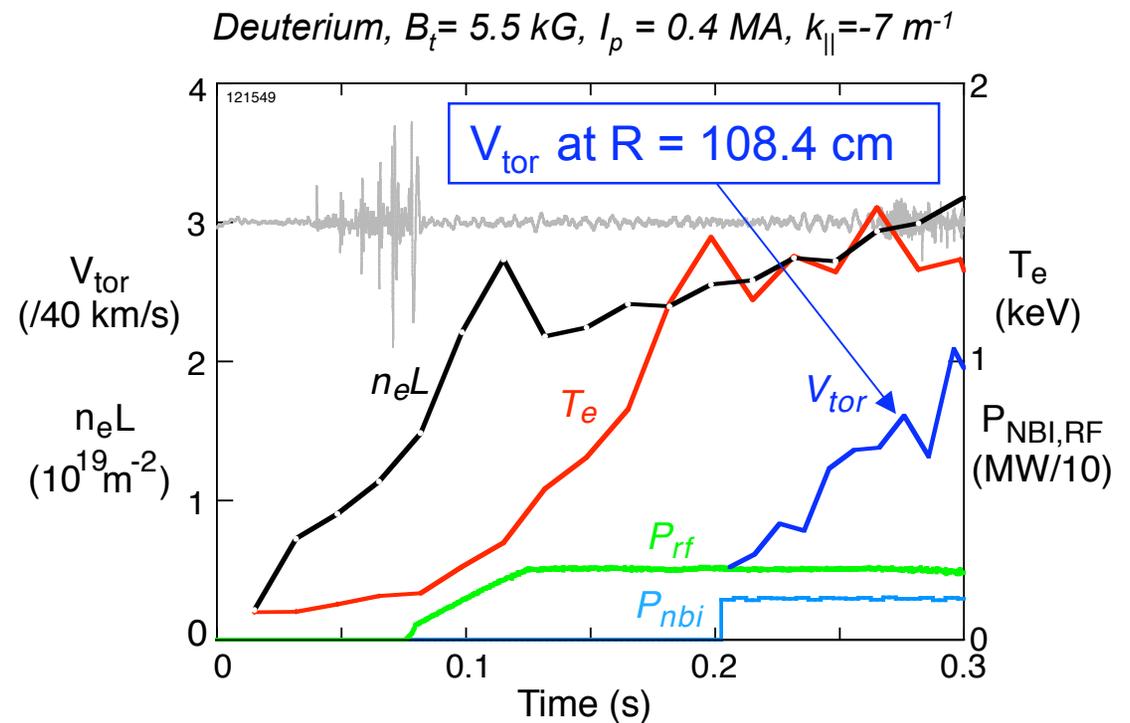
Deuterium, $B_t = 5.5 \text{ kG}$, $I_p = 0.4 \text{ MA}$, $k_{||} = -7 \text{ m}^{-1}$



Successful HHFW Operation with NB Permits Measurement of Rotation with HHFW



- Initial rotation measurement made in FY06 run
- Need to scan the measurements vs RF power and k_{\parallel} to determine the rotation properties
- Supports ITPA studies on plasma rotation with no external momentum input (TP-6.1)



HHFW Theory & Modeling Support Provided by Multi-Institutional Collaboration



- Previous studies focused on HHFW propagation and absorption in plasma core
- Current research priorities include:
 - 3D reconstruction of HHFW fields and power flow, including collisional loss
[CompX, MIT, ORNL, PPPL]
 - Benchmarking of TORIC / TOPICA against NSTX data
[MIT, RF SciDAC, PPPL]
 - Development of PIC code simulation of wave dynamics in edge regions
[TechX / RF SciDAC]
 - Development of edge sheath boundary conditions for wave codes
[Lodestar, ORNL / RF SciDAC]
 - Investigation of possible HHFW to slow wave mode conversion
[PPPL, RF SciDAC]
 - Self-consistent simulation of HHFW interactions with energetic ions
[RF SciDAC]
 - Installation of HHFW modules in TRANSP for time-dependent analysis
[CompX, MIT, and PPPL]

Proposed FY07 Waves-ET Experiments



Priority	Experiment	ST	Tor. Sci.	ITPA
1	HHFW Current Drive at High B_t	x	x	
1	HHFW Power Balance Optimization at High B_t	x	x	
1	EBW Coupling at 8-40 GHz for H-Mode Plasmas	x	x	
1	EBW Coupling at 8-40 GHz for L-Mode Plasmas	x	x	
2	HHFW + NBI Rotation	x	x	x
2	Absorption of HHFW on Beam Ions	x	x	
2	13 m^{-1} HHFW CD Phasing	x	x	