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Program & Plans for EBW and HHFW Research on NSTX

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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

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⇒ 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

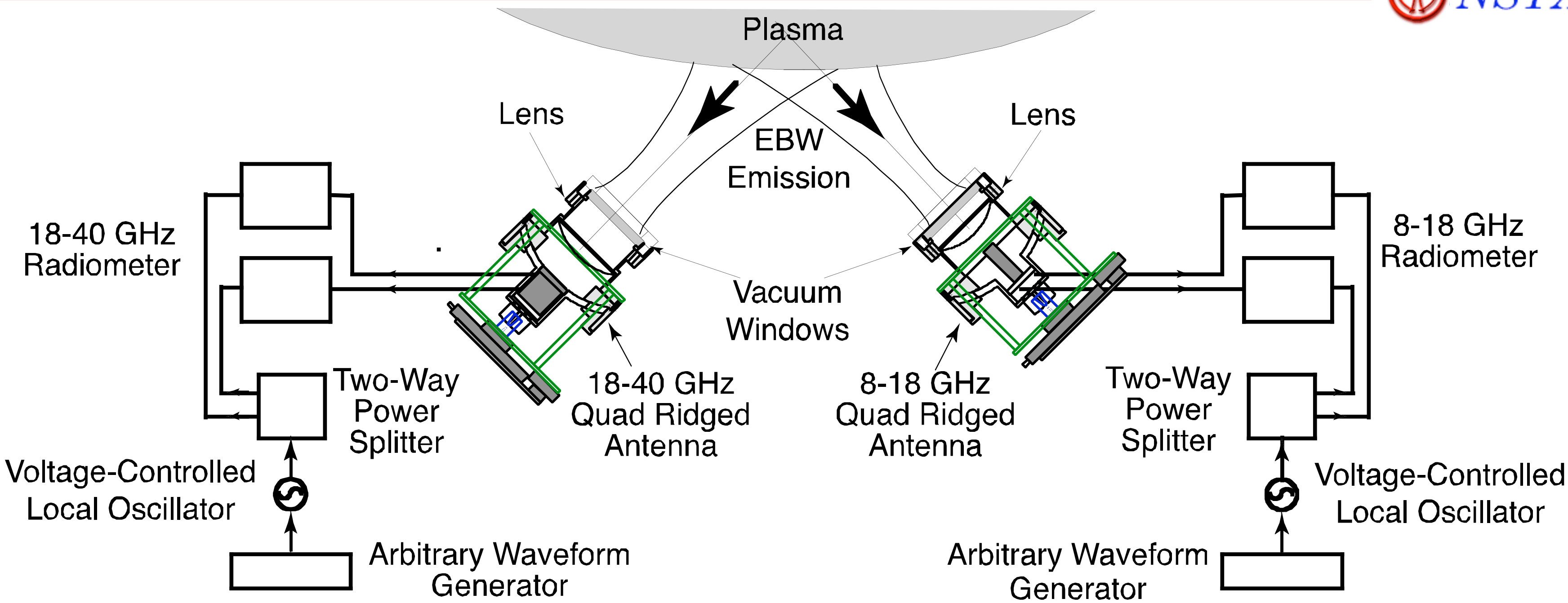
FY08:

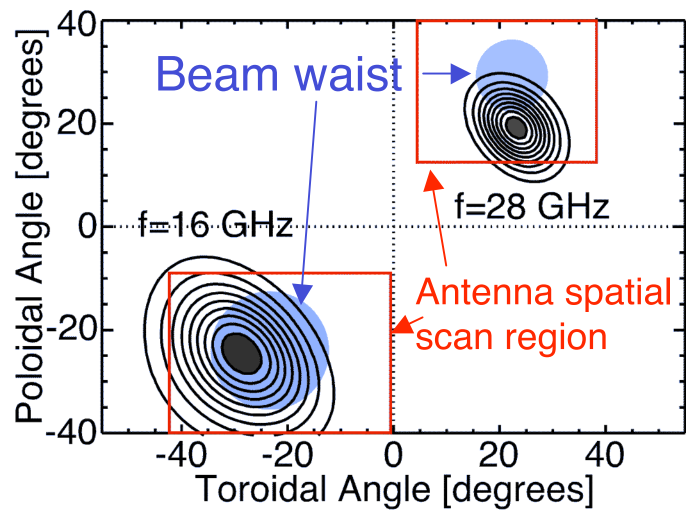
- Continue optimization EBE studies
- Install ~ 200 kW 28/15.3 GHz ECH/EBWH system (pending review)

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

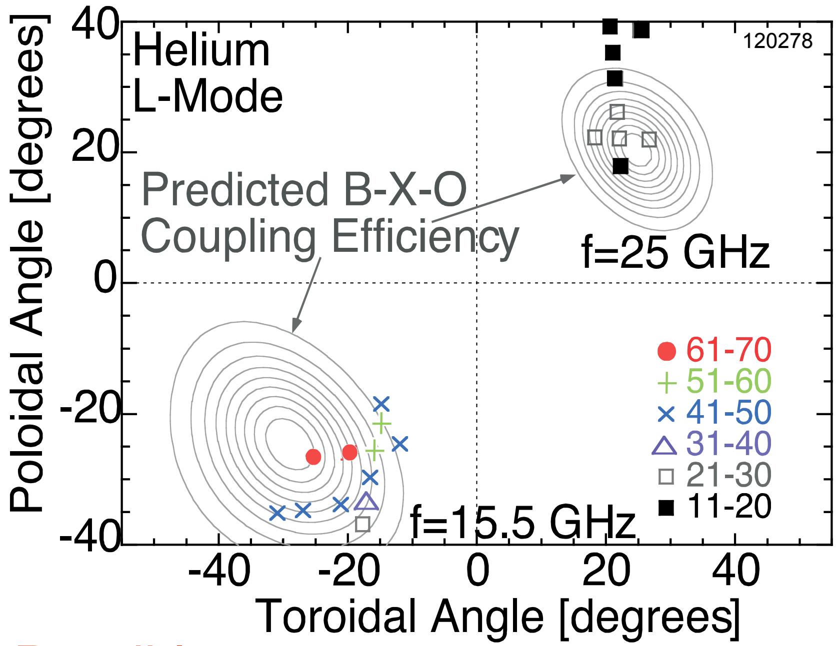


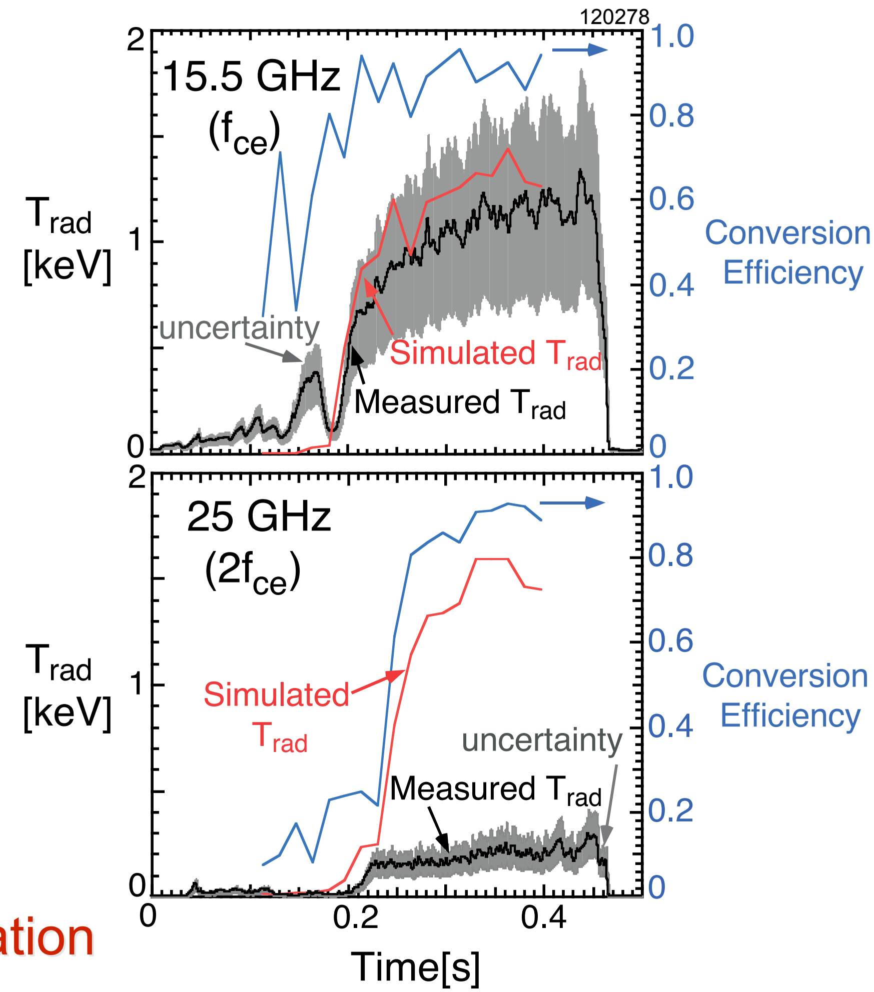


- *±10° scan in poloidal & toroidal directions*

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

- Measure 70 ± 20% f_{ce} coupling, but only ~ 25 ± 10% $2f_{ce}$ coupling
- EBW emission simulation predicts ~ 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

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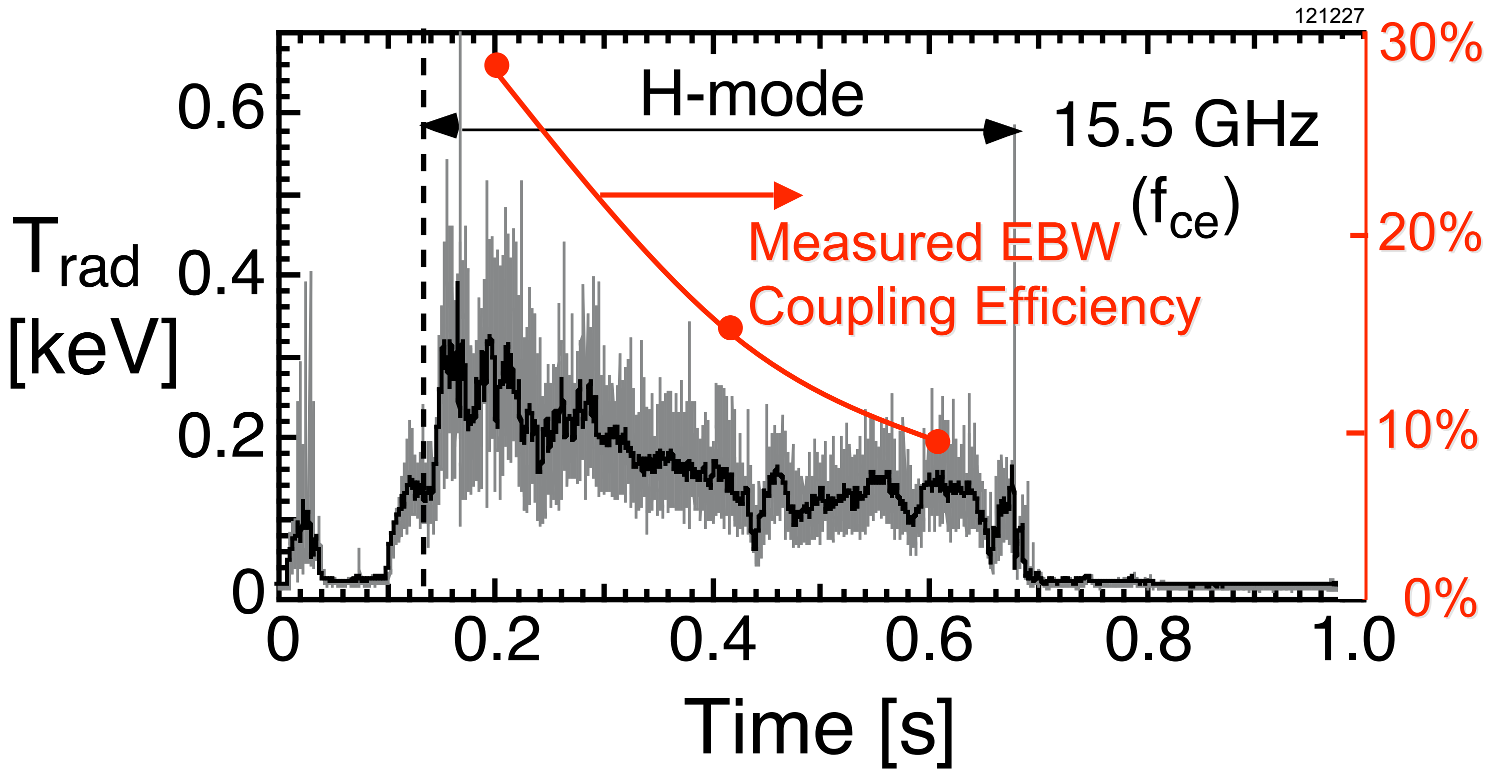
- < 30% B-X-O coupling from H-mode plasmas
- Coupling falls throughout H-mode phase



→ 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

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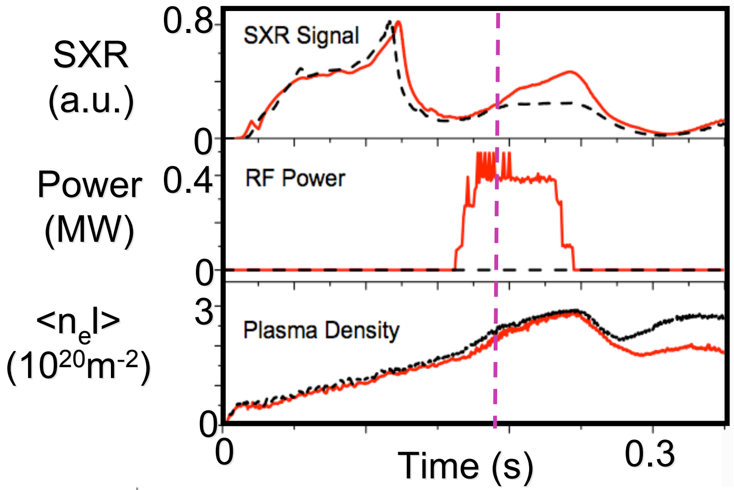
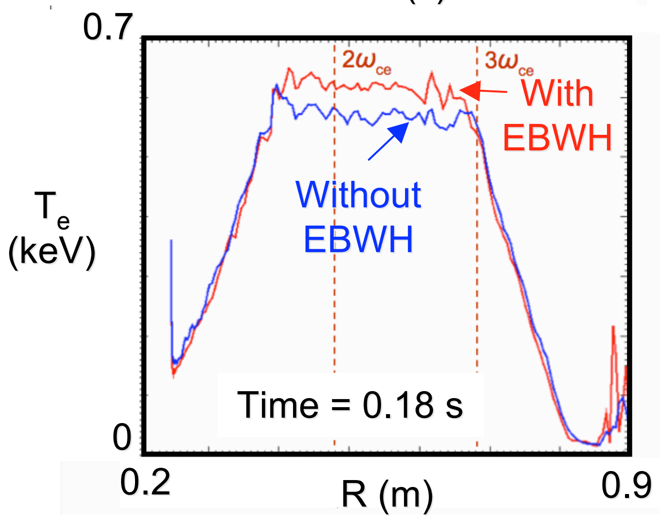
MAST

Compressed High Density H-Mode

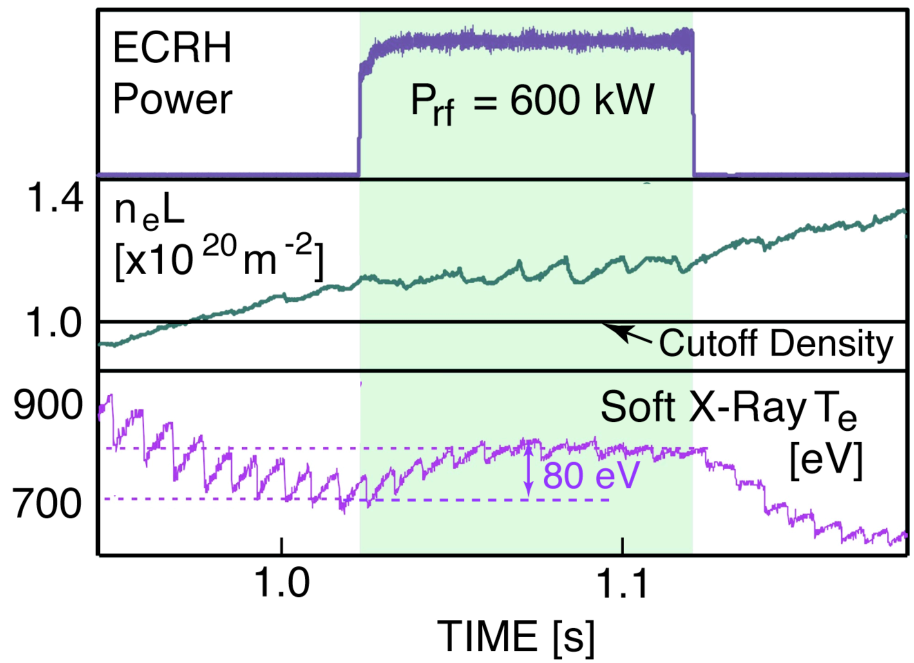
f = 60 GHz ($2f_{ce}$ & $3f_{ce}$)





TCV

$B_t(0)$ = 1.5 T, f = 82.7 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^o) 8-18 GHz antenna on midplane

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

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- 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

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- 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

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- 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 $n_e(0) < 9\times10^{18}$ m^{-3}
- ~ 20% per pass ECRH absorption for $n_e(0) \sim 2\times10^{18}$ 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 $\times10^{18}$ 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

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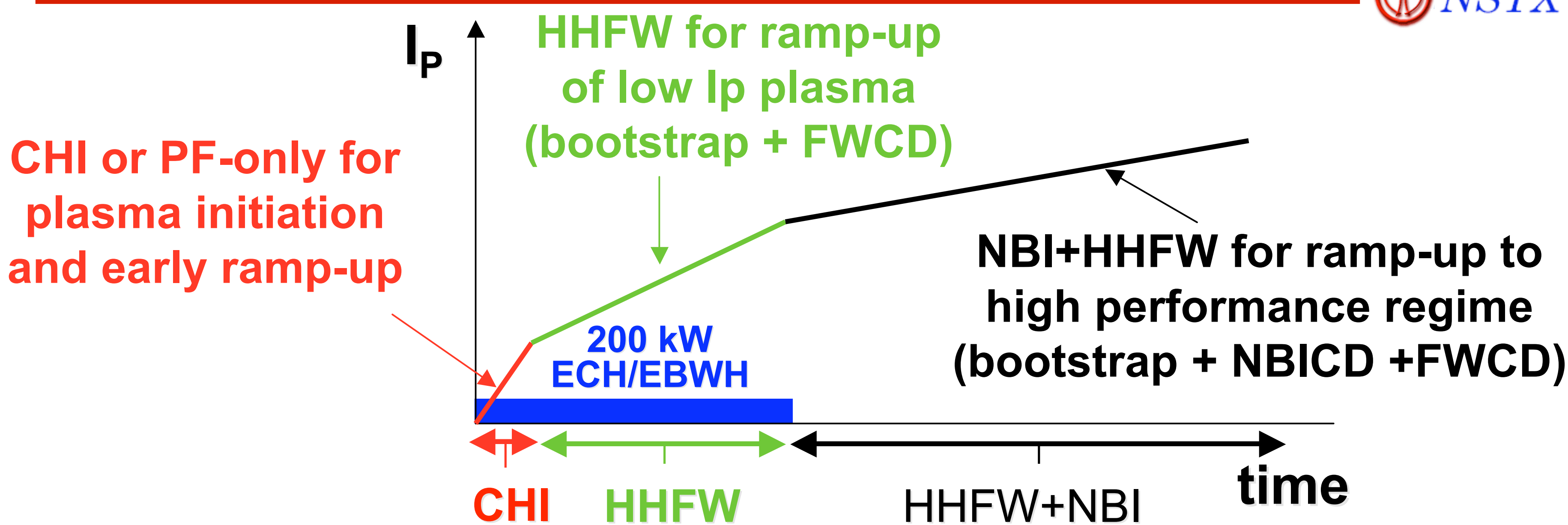

ECH needed for preionization and early heating

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

ECRH can create n_e, T_e for adequate HHFW absorption →

METS Single-Pass Modeling Estimates

$T_e(0)$	$n_e(0)$	% HHFW absorbed
100 eV	$5x10^{18}m^{-3}$	2%
100 eV	**$9x10^{18}m^{-3}$**	**~10%**
300 eV	$9x10^{18}m^{-3}$	~30%

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

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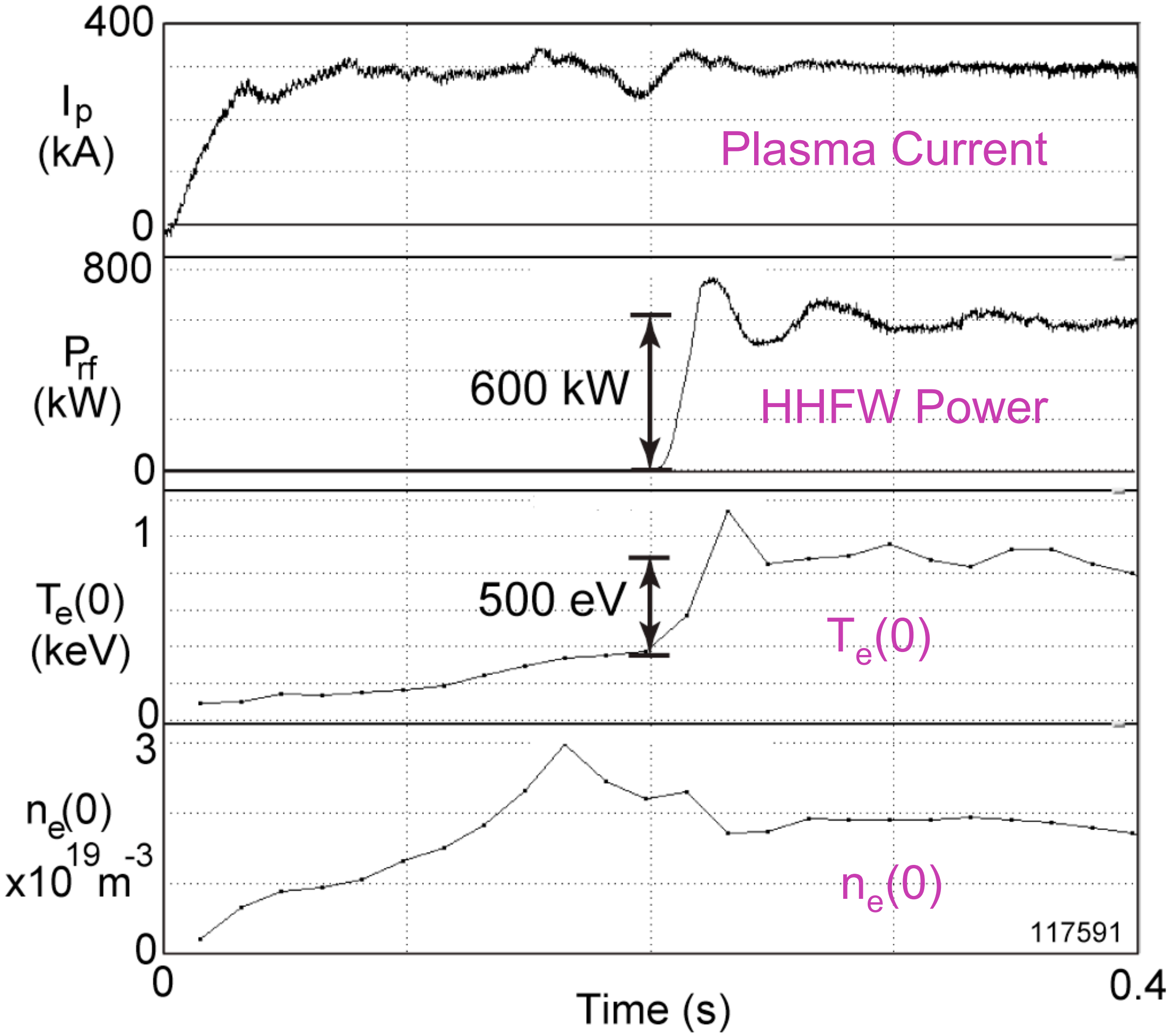

Results & Plans

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

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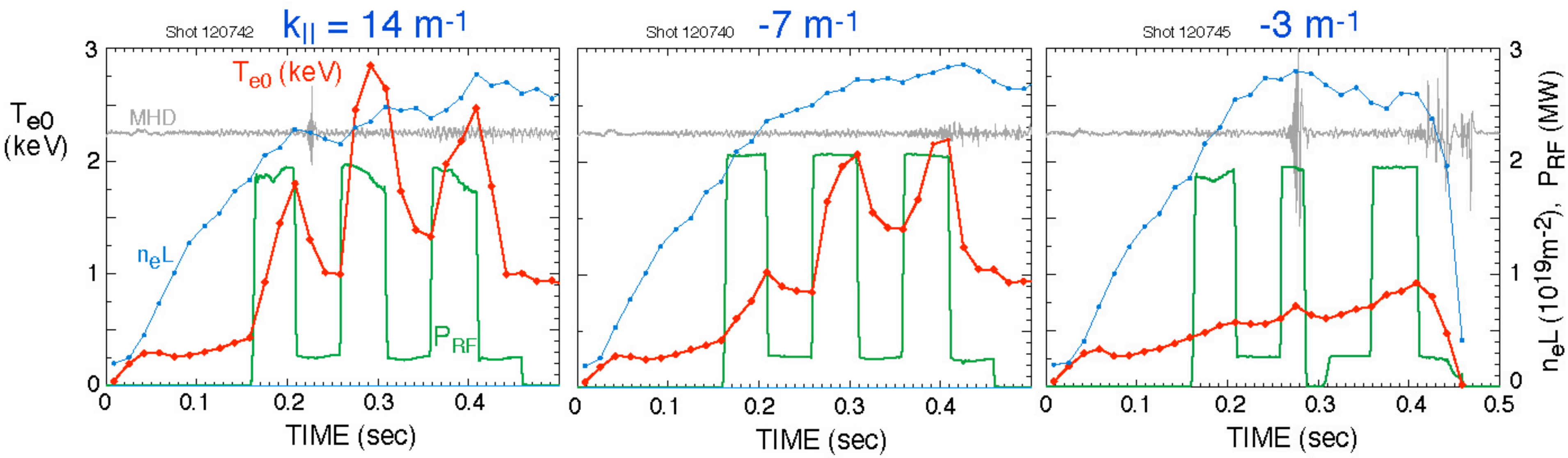
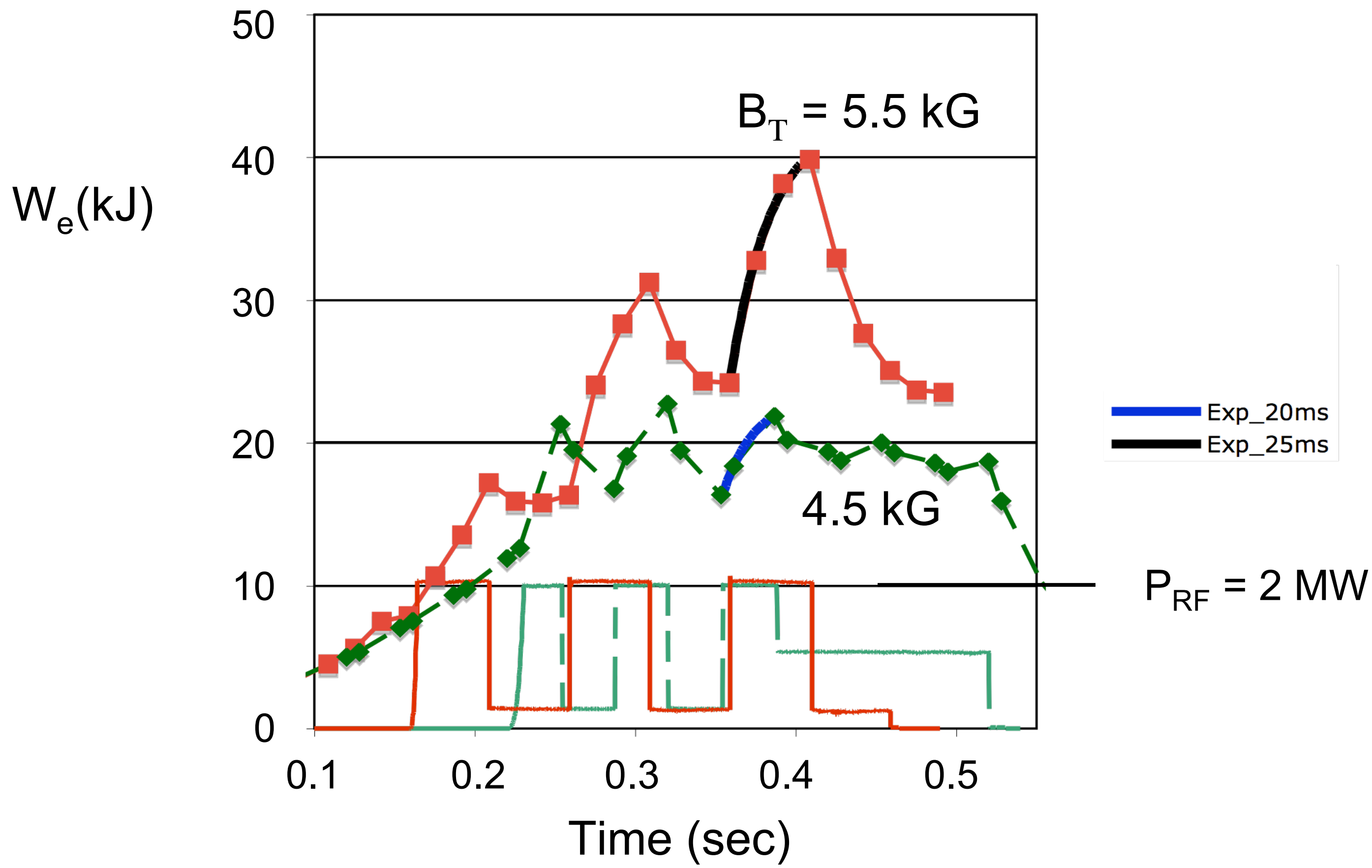
Electron heating for B_T = 5.5 kG, I_P = 720 kA



- Clear strong dependence on $k_{||}$ – almost no heating at $k_{||}$ = - 3m^{-1}
- Heating at $k_{||}$ = -7m^{-1} comparable to $k_{||}$ = 14 m^{-1}
- Heating at $k_{||}$ = -7 m^{-1} for first RF pulse about half that for $k_{||}$ = 14m^{-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 $k_{||}$ = -7 m^{-1} Increased Substantially as B_T Increased from 4.5 kG to 5.5 kG



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

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

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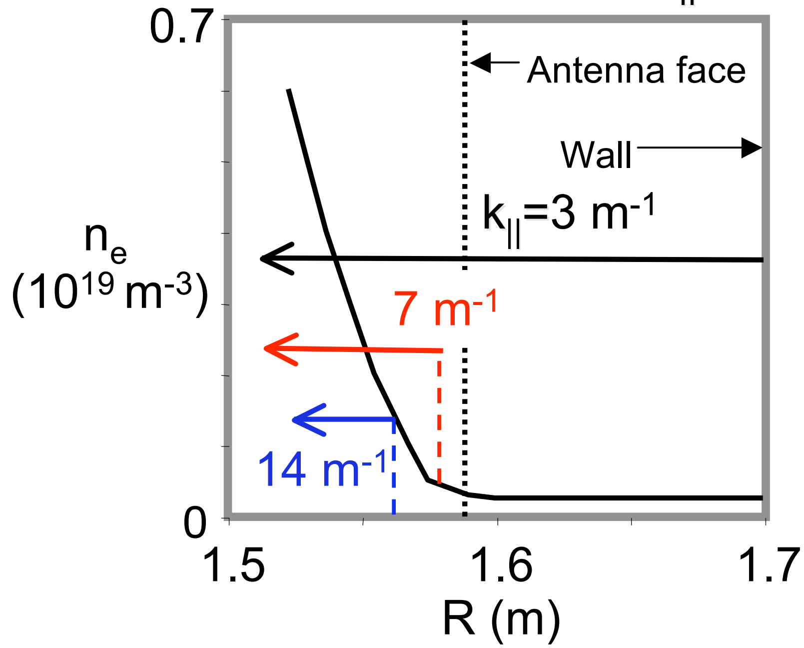
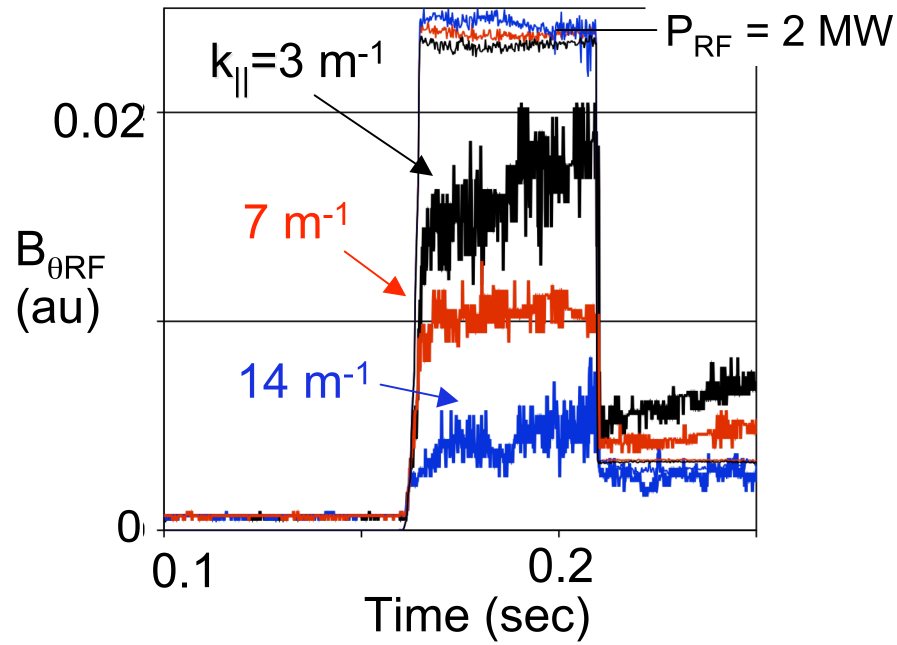
Perpendicular wave propagation onset in edge regions - $n_{onset} \propto B^* k_{||}^2$



RF far surface fields vs $k_{||}$
- *probe on opposite side from antenna*



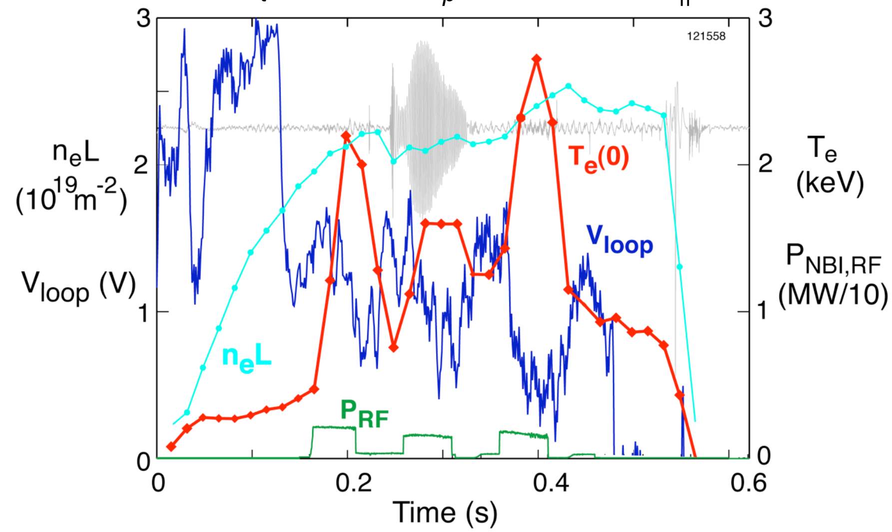
- Propagation close to wall at $k_{||}$ = 7 m^{-1}, on wall at $k_{||}$ = 3 m^{-1}
  - ⇒ *Losses in surface should be higher for lower $k_{||}$*
- RF probe signals are a strong function of $k_{||}$
  - ⇒ *structure & sheath losses should increase going from 14 m^{-1} to 3 m^{-1}*
- Increasing B should 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 $k_{||} = \pm 7\ m^{-1}$ for same P_e profiles

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

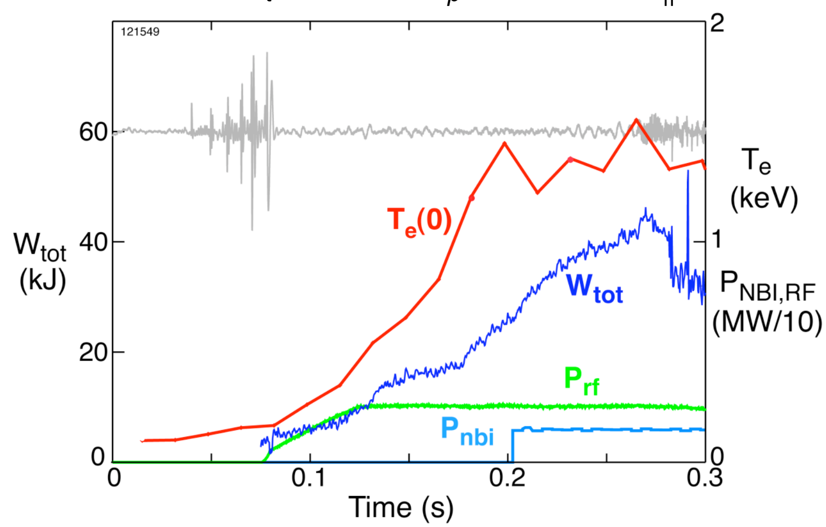
Helium, B_t= 5.5 kG, I_p = 0.72 MA, $k_{||}$=-7 m^{-1}



- 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

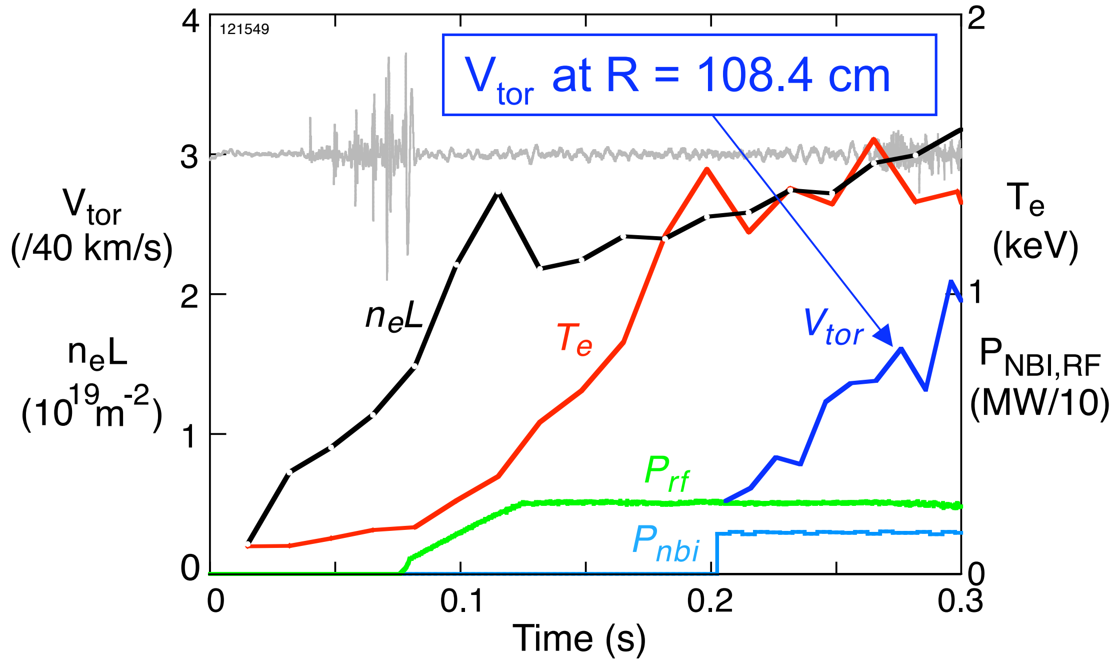
Deuterium, B_t= 5.5 kG, I_p = 0.4 MA, $k_{||}$=-7 m^{-1}



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 $k_{||}$ to determine the rotation properties
- Supports ITPA studies on plasma rotation with no external momentum input (TP-6.1)

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



HHFW Theory & Modeling Support Provided by Multi-Institutional Collaboration

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- 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	