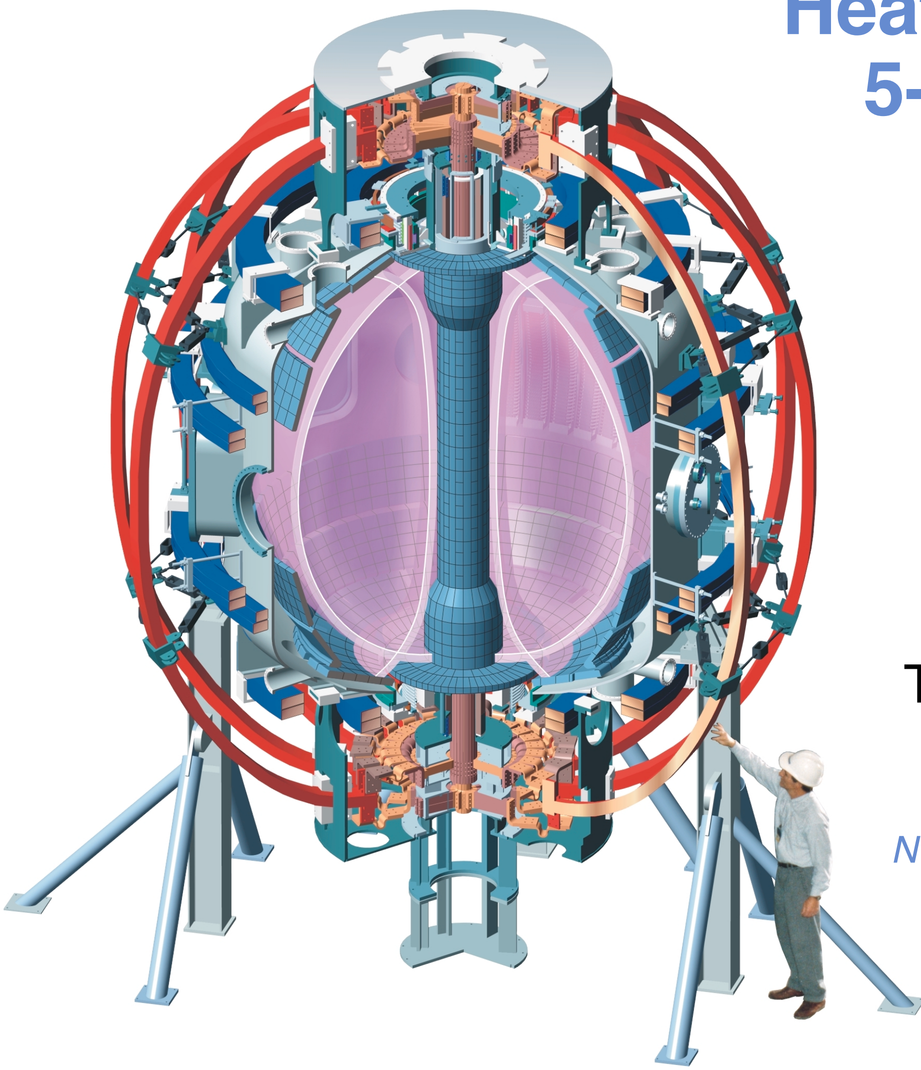
NSTX Wave-Particle Physics, Heating and Current Drive 5-Year Research Plan



presented

by

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and

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NSTX 5-Year Research Plan Review Meeting
December 12-13, 2002

NSTX
NATIONAL SPHERICAL TORUS EXPERIMENT

Outline

High Harmonic Fast Waves (HHFW)

- 5-Year Research Goals
- Research Status:
  - *HHFW System*
  - *Experimental Results*
  - *Theory & Modeling*
- 5-Year Research Plan

Electron Bernstein Waves (EBW)

- 5-Year Research Goals
- Research Status:
  - *Mode Conversion Theory*
  - *Mode Conversion & Coupling Experiments*
  - *Technology Issues*
- 5-Year Research Plan

HHFW Research

HHFW Provide a Tool for Electron Heating & Current Drive in High β, ST Plasmas

- ST's need auxiliary current drive (CD)
- High β plasma makes Lower Hybrid and conventional electron cyclotron CD (ECCD) impossible
- HHFW in high β plasmas has strong single pass absorption on electrons

  - *can allow off-axis deposition*

HHFW 5-Year Research Goals

- HHFW 5-year research objective to provide heating & CD tools to supplement OH

- Enable preliminary assessment of ST performance
  - *HHFW-assisted startup*
  - *Pressure profile modification*
  - *HHFW CD-assisted discharge sustainment*

- 10-Year goal to use HHFW, with other tools, for $\tau_{pulse} > \tau_{skin}$ operation

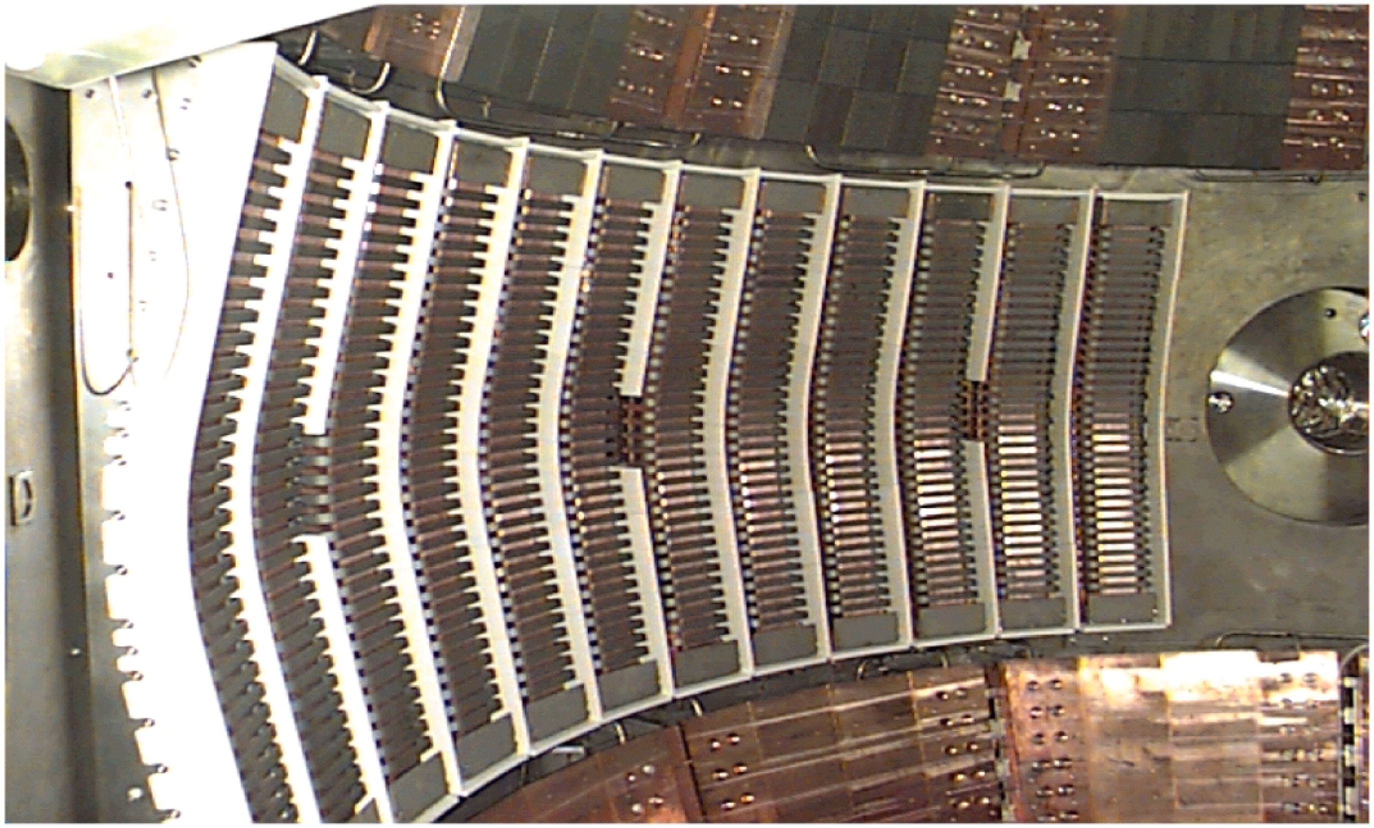
Status of HHFW Research

Flexible System for High Power HHFW has been Installed on NSTX

- Utilizes TFTR ICRF transmitters & transmission line
- 30 MHz frequency corresponds to ω/Ω_D = 9-13
- 6 MW total power from 6 transmitters for up to 5 s
- 12 Element antenna with active phase control allows wide range of wave spectra

  - $k_T = \pm$ (3-14) m^{-1}
  - *can be varied during shot*

HHFW 12 Element Antenna Array Provides Good Spectral Selectivity



- Digital phase feedback system sets phase between straps
- Antenna utilizes BN insulators to minimize RF sheaths

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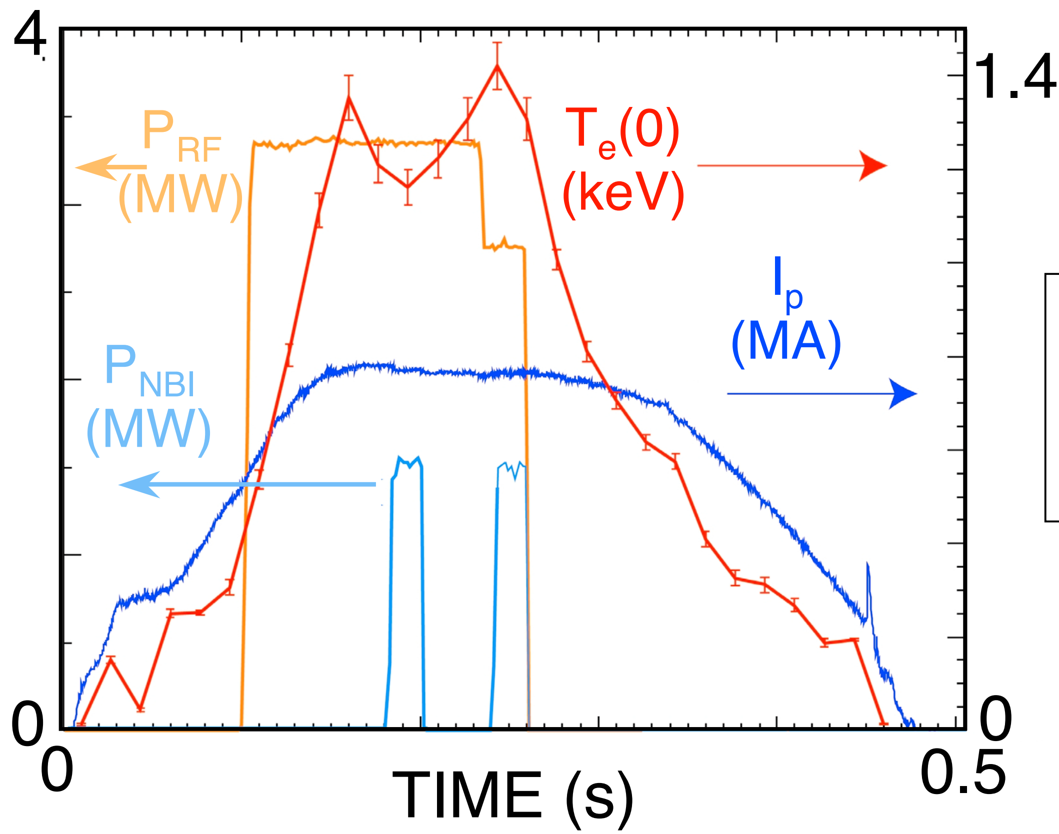
HHFW Primarily Heats Electrons in NSTX, as Expected from Theory

- For non-NBI NSTX plasmas HHFW deposits all its power into electrons
  - *No experimental evidence for direct thermal ion heating*
  - *HHFW does heat NBI ions*

- Energy confinement on NSTX follows conventional scaling predictions when heat is applied via the electron channel

- Improved electron energy confinement has been observed

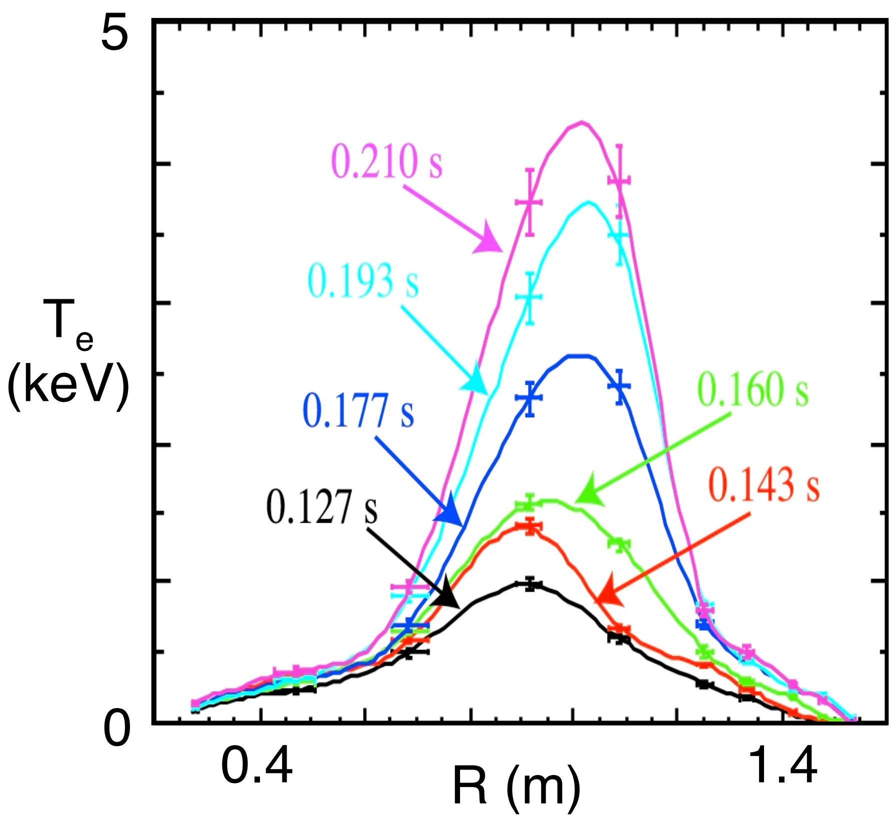
HHFW Provides Strong Electron Heating



B = 0.44 T
$\mathbf{k}_T$ = 14 m^{-1}
n_{e0} = 4.0x10^{19} m^{-3}

- Confinement consistent with predictions of standard scaling *[L-Mode: ITER97L, H-Mode ITER98Pby2]*

Some HHFW-Heated Discharges Display Behavior of Internal Transport Barrier



P_{rf} = 2.5 MW

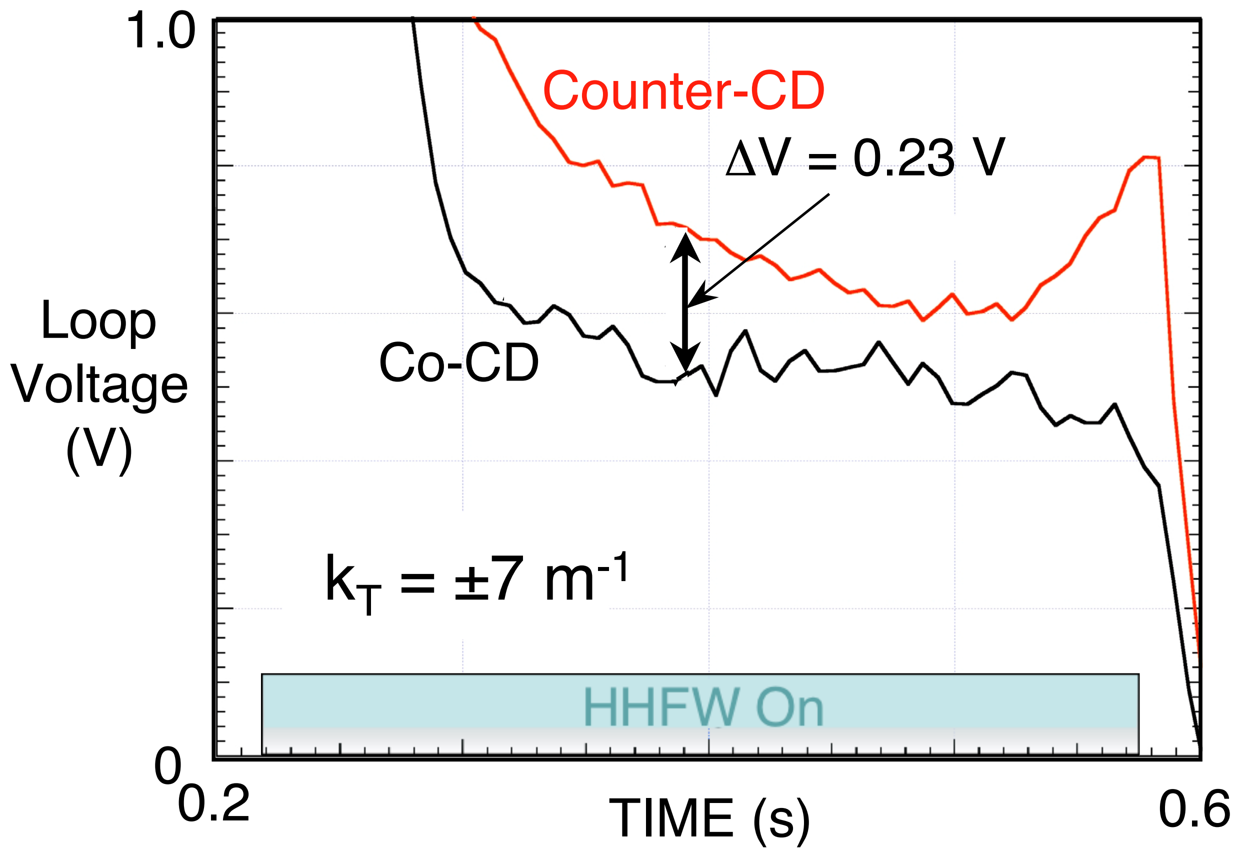
I_p = 800 kA

- T_e increases strongly inside half radius
- Density profile doesn't show change
- T_i (0) rises with T_e(0)
- χ_e progressively decreases in the central region

Differences in Loop Voltage with Directed Spectra Consistent with HHFW CD

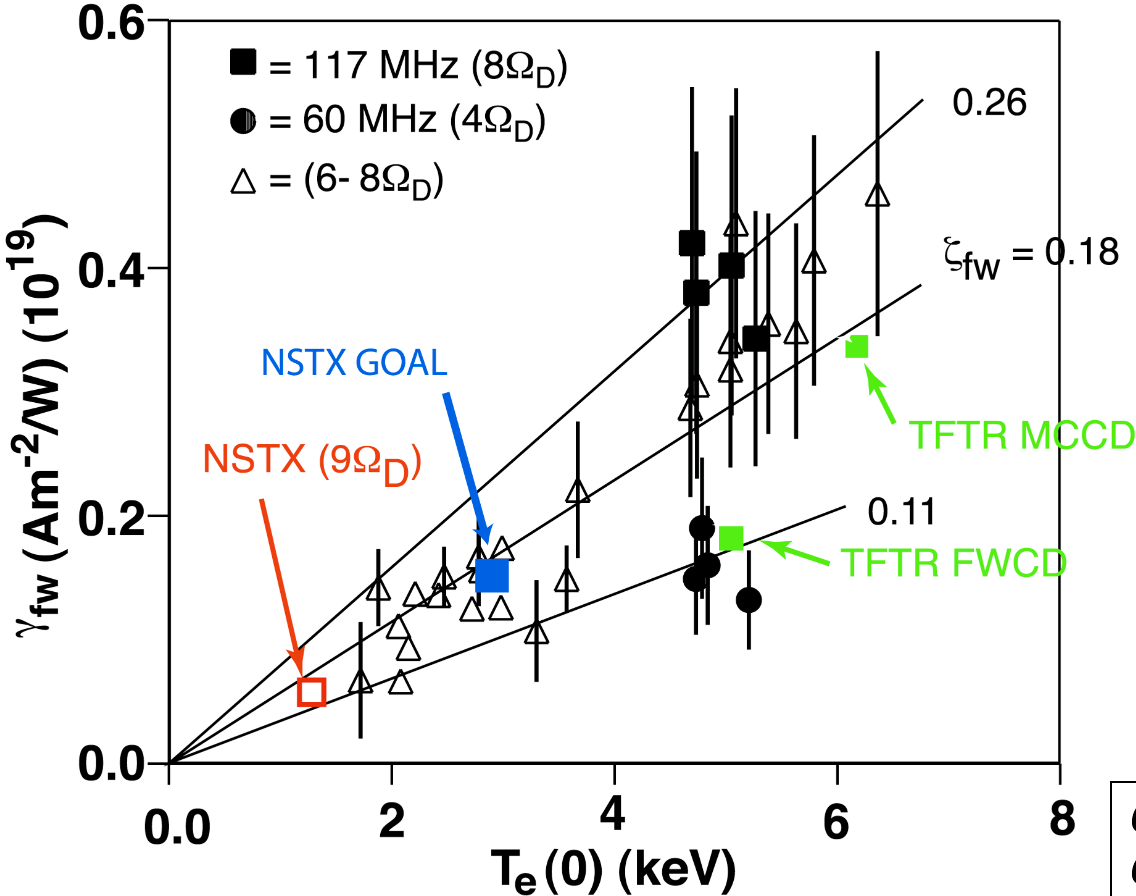
- Experiment performed at low electron β and current to maximize effect of HHFW CD on loop voltage
- Compare discharges with wave phased ± (3-7) m^{-1}
- Adjust power levels and fueling to match density and temperature profiles
- Loop voltage differences seen when no central MHD (sawteeth, m=1)
- Driven current inferred from analysis of magnetic signals comparable to theoretical predictions

Less Loop Voltage to Maintain I_P With Co Phasing; Magnetic Signal Analysis Estimates I_{cd} = 110 kA (0.05 A/W)



- TORIC I_{cd} = 95 kA (0.05 A/W)
- CURRAY I_{cd} = 162 kA (0.08 A/W)

CD Efficiency Consistent with DIII-D & TFTR CD Experiments

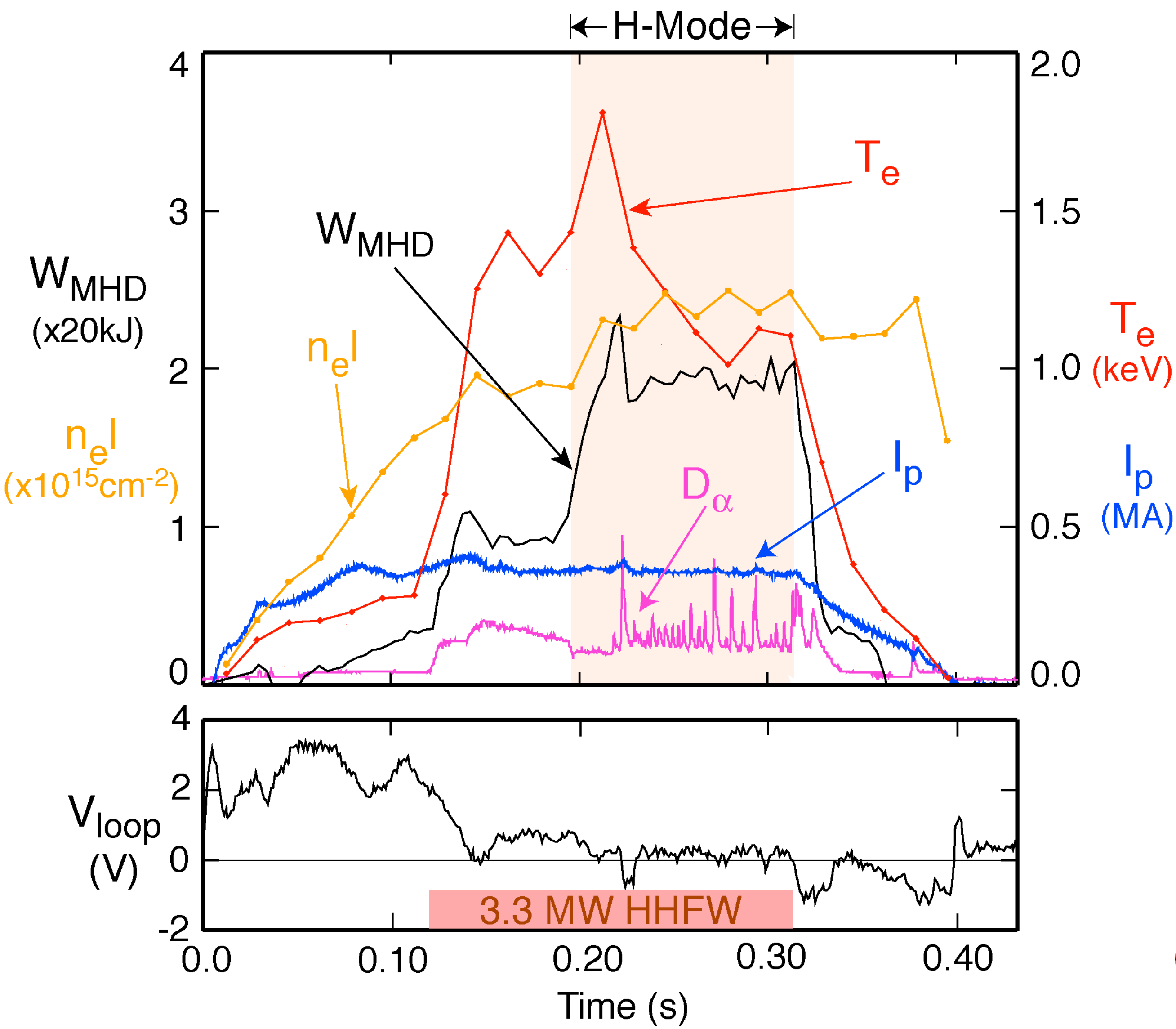


- Operation at increased T_e required to meet NSTX goals:
  - *More RF power and improved confinement regime should allow this*

C. Petty et al., Plasma Physics and Controlled Fusion ***43*** *(2001) 1747*

- Trapping significantly reduces HHFW-driven current:
  - *Diamagnetic effects at high β may reduce trapping*

High β Poloidal H-Mode Plasmas Provide Excellent Candidate for Long Pulse Sustainment



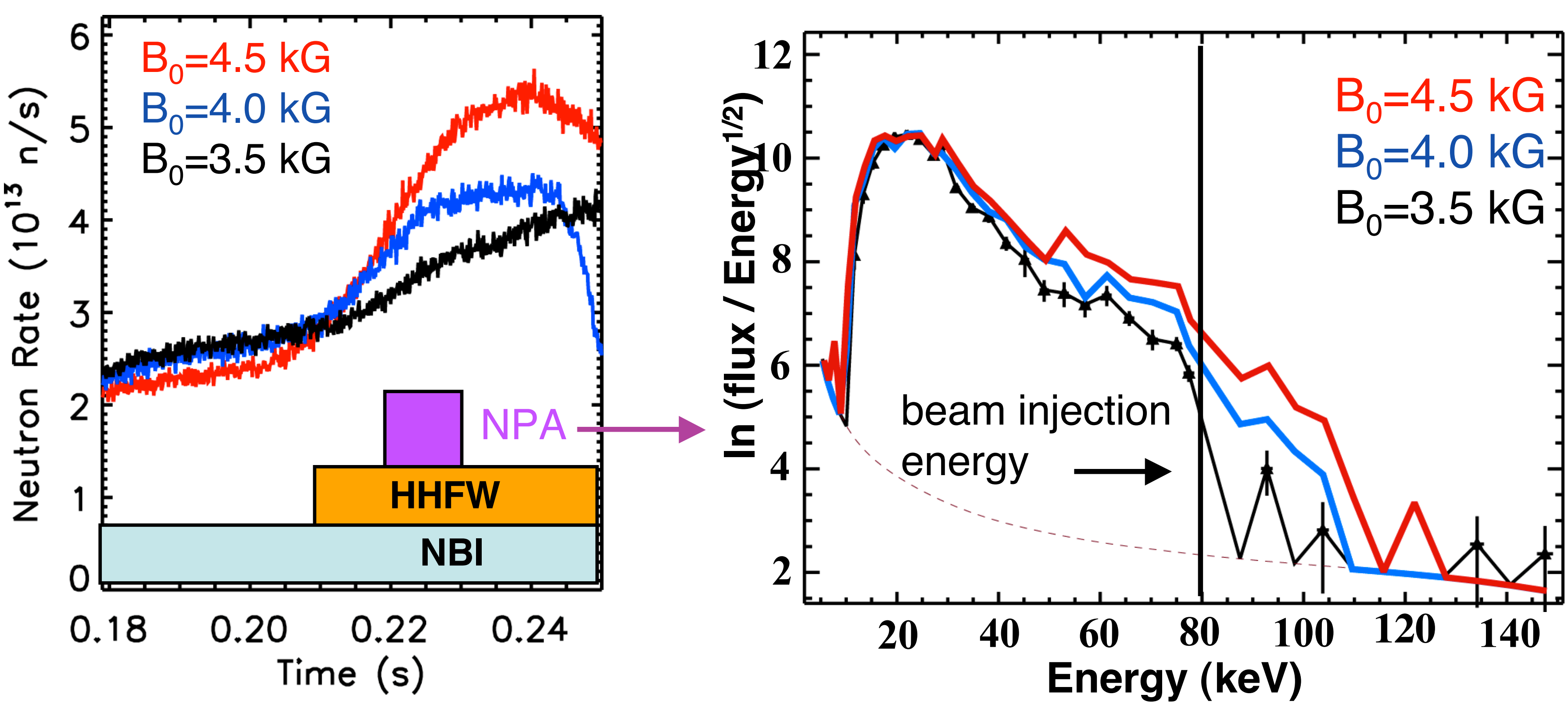
- V_{loop} ~ 0
- ~ 40% bootstrap fraction

Evidence of HHFW Interaction with Fast Ions, as Predicted

- Damping on beam ions may reduce CD efficiency
- At high harmonic numbers (N ≥ 9) ion damping can be important due to large $k_\perp \rho_i$
  - *On NSTX $k_\perp \rho_i \sim 10$ for 80 keV beam ion*
  - *Damping maximum at ~ 35 keV for N = 9*
- Neutral particle analyzer shows fast ion tail build-up during NBI + HHFW and decay after NBI turn-off
  - *D^+ tail extends to 130 keV*
  - *Tail saturates in time during HHFW*

NSTX National Spherical Torus Experiment

Tail Reduced at Lower B, Higher β



- Larger β_e promotes greater off-axis electron absorption reducing power available to centralized fast ion population

Further Code Development Needed to Model Interaction Between HHFW and Fast Neutral Beam Ions

- 1-D METS code generalized to model wave propagation and absorption with significant non-thermal population
- Initial results indicate that beam distribution can be approximated by Maxwellian with same average energy
- Effect of beam anisotropy to be evaluated in 2003
- 2-D non-Maxwellian effects could also be important, may need to generalize 2-D codes to include non-Maxwellian species in dielectric tensor operator

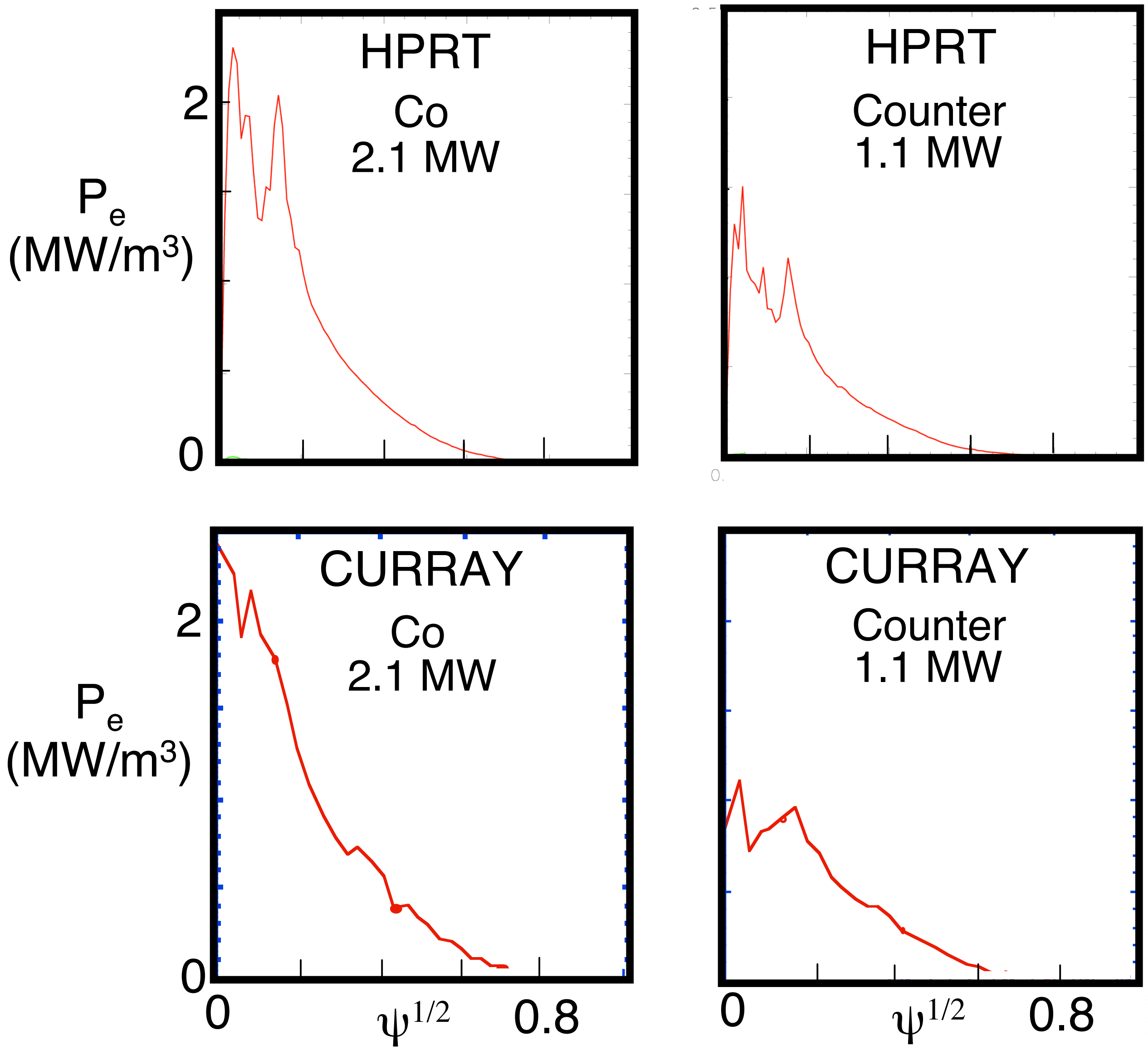
Modeling HHFW in NSTX Shows Electron Absorption Dominates; IBW Conversion Not Significant

- METS 1-D and AORSA 2-D all-order codes show no excitation for short wavelength modes in present NSTX plasmas

- Further numerical studies needed to determine if IBW conversion is important at higher B fields and/or higher ion β

- WKB ray tracing codes may be applicable due to:
    - absence of significant IBW conversion
    - wavelength < equilibrium gradient scalelength

Excellent Agreement Between Ray Tracing Codes for HHFW Current Drive Experiments



- AORSA & TORIC predict similar deposition to ray tracing codes

HHFW 5-Year Research Plan

HHFW 5-Year Research Plan Focused On Evaluating the Effectiveness of HHFW as an ST Research Tool

- HHFW research plan has five major components:
  - *Study dependence of HHFW coupling on plasma configuration & density*
  - *Explore HHFW coupling with neutral beam heating*
  - *Investigate CD and wave-particle interactions*
  - *Develop solenoid-free plasma startup*
  - *Improve technical performance of the HHFW system*

Study Dependence of HHFW Coupling on Plasma Configuration & Density

2003-4:

- *Explore coupling into double null discharge and vary inner and outer gaps; previously studied limiter and single null*
- *Study effect of increasing density on heating efficiency*
- *Density control will be explored over a wider range due to improved fueling & wall conditioning*

Explore HHFW Coupling with Neutral Beam Heating

2003-4:

- *Modify internal inductance with early heating; reduce volt-sec consumption and increase q(0)*
- *HHFW heating efficiency in presence of strong neutral beam injection; dependence on target β and density*
- *Study HHFW H-mode access*

2005-6:

- *Initial feedback control of HHFW heating to maintain J(R) & P(R); study off-axis deposition at high β to broaden electron pressure profile*

Investigate CD and Wave-Particle Interactions - I

<u>2003</u>:

- *Operate HHFW reliably at higher power levels, with improved high voltage antenna feed*

<u>2004</u>:

- *Measure J(R) with motional stark effect (MSE) diagnostic*

<u>2005-6</u>:

- *Investigate dependence of CD efficiency on RF power, density, temperature and antenna phasing*
- *Explore reduction in off-axis CD efficiency due to trapping and possible increase in CD efficiency due to diamagnetic effect at high* β

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Investigate CD and Wave-Particle Interactions - II

2006:

- *Feedback antenna phasing on MSE J(R) & rtEFIT*

2007-8:

- *HHFW with full feedback control of antenna phase using MSE LIF system to obtain real time J(R) & P(R)*

Develop Solenoid-Free Plasma Startup

2004-5:

- *Couple HHFW into Coaxial Helicity Injection (CHI) startup*
- *HHFW heating with CHI to develop bootstrap current*
- *HHFW CD phasing with CHI for direct current drive*
- *HHFW handoff to NBI*

2006-8:

- *HHFW-assisted ramp to high β_{pol}*
- *Use HHFW to optimize flux consumption in high performance plasmas*

Improve Technical Performance of HHFW System

2003-4:

- *Dedicated experiments to elucidate HHFW antenna power limits & reliability issues*

2005:

- *Possibly modify HHFW antenna to be double-end fed; reduces voltage for same power & removes hard ground*

2006:

- *If asymmetry in launch spectrum remains a problem for CD may tilt antenna straps*

EBW Research

EBWs May Enable Local Heating, Current Drive and $T_e(R,t)$ Measurements on ST Plasmas

- Electron cyclotron heating, CD and radiometry not viable for spherical torus (ST) plasmas, where $\omega_{pe} >> \omega_{ce}$

- EBWs propagate when $\omega_{pe} >> \omega_{ce}$ and strongly absorb at EC resonances, allowing EBW heating, CD and radiometry in STs

- Local EBW heating and CD are potentially important for non-inductive startup and MHD suppression in an ST

- EBWs can couple to electromagnetic waves near the upper hybrid resonance (UHR) that surrounds ST plasmas

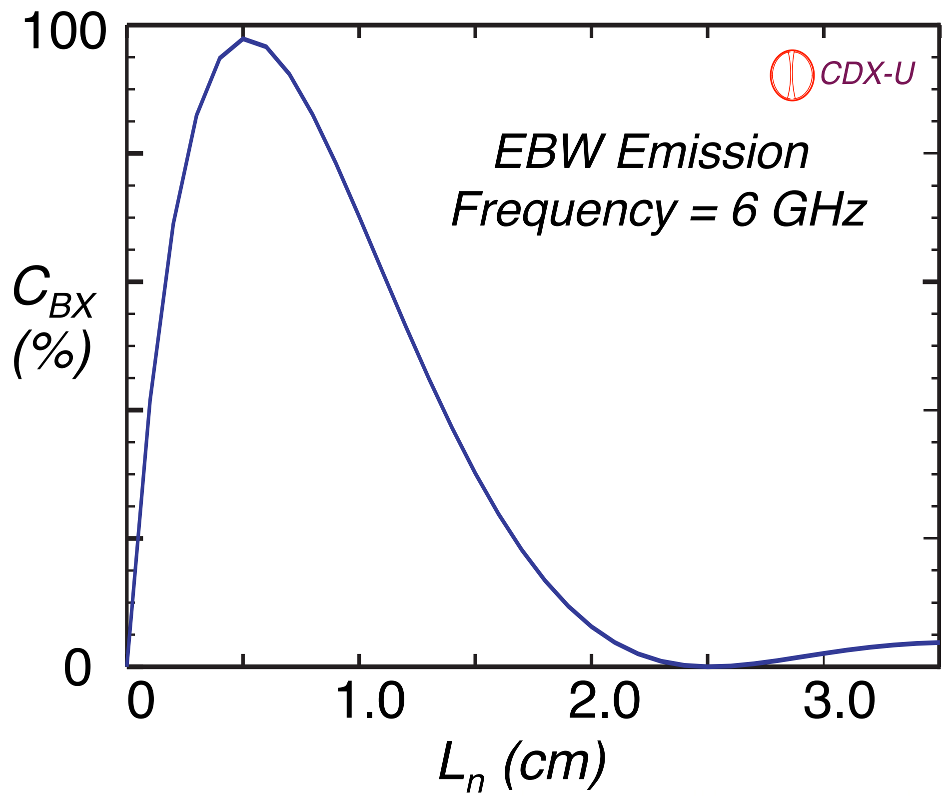
EBW 5-Year Research Goals

- 5-year research program has four goals:
  - *Demonstrate efficient coupling of X-mode or O-mode waves to EBWs*
  - *Control spatial location where EBWs damp and heat electrons*
  - *Test EBW-assisted non-inductive current startup, alone or in combination with HHFW and/or CHI*
  - *Test suppression of neoclassical tearing modes with EBW heating and/or current drive*
- Plan to install ~ 1 MW by 2006, ~ 3 MW by 2007

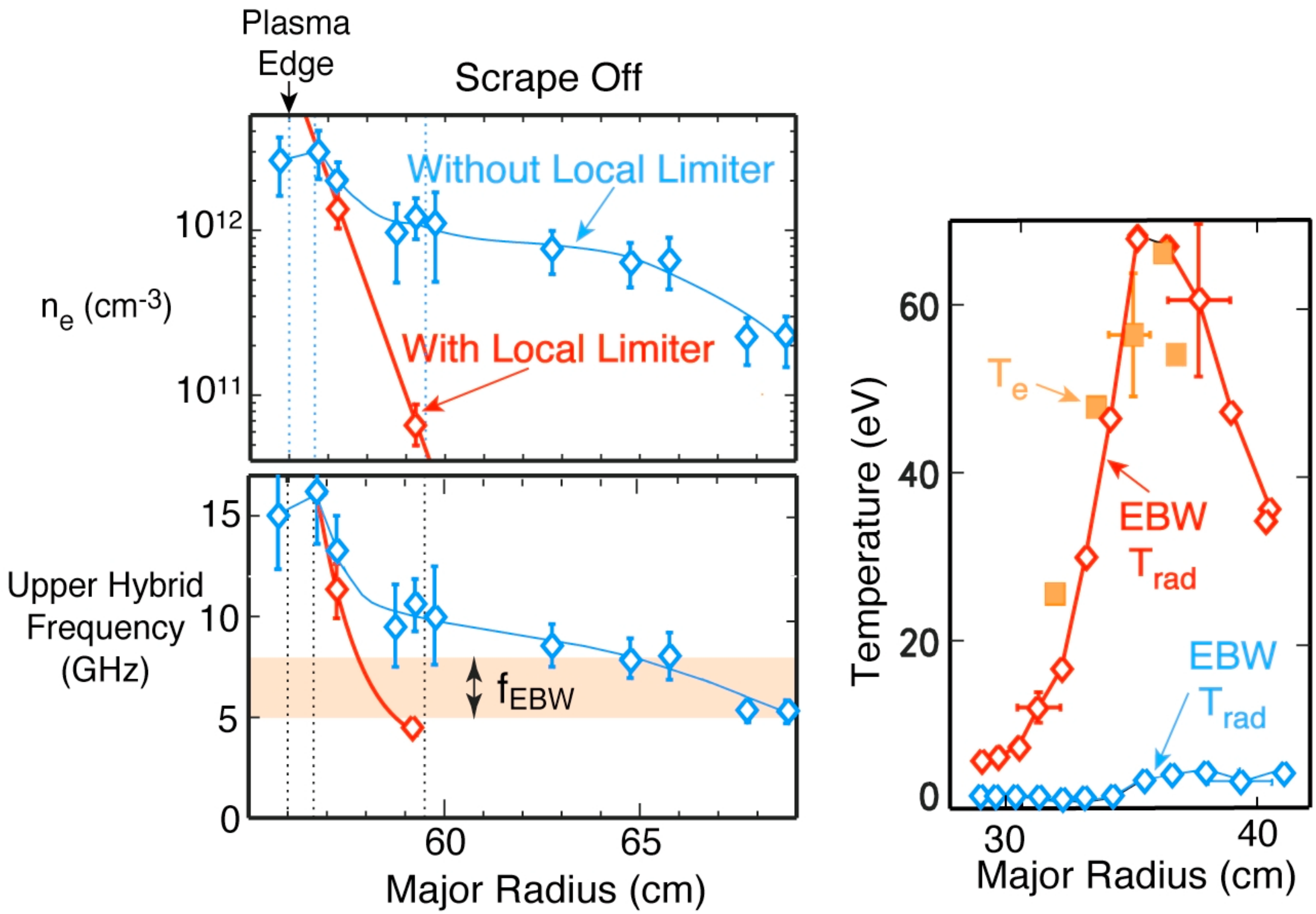
Status of EBW Research

EBW Experiments on CDX-U and NSTX Have Focused on Maximizing EBW Conversion to X-Mode (B-X)

- If L_n is short at the UHR, EBW can tunnel to the fast X-mode: *EBW to X-mode conversion efficiency (C_{BX}) very sensitive to L_n*
- Measurement of B-X emission evaluates the efficiency of the X-B process for heating and CD
- Mode conversion to the O-mode (B-X-O) also possible; studied on W-7AS and MAST



On CDX-U, Limiter Shortened L_n to 0.7cm, Increasing C_{BX} to > 95%, in Good Agreement with Theory



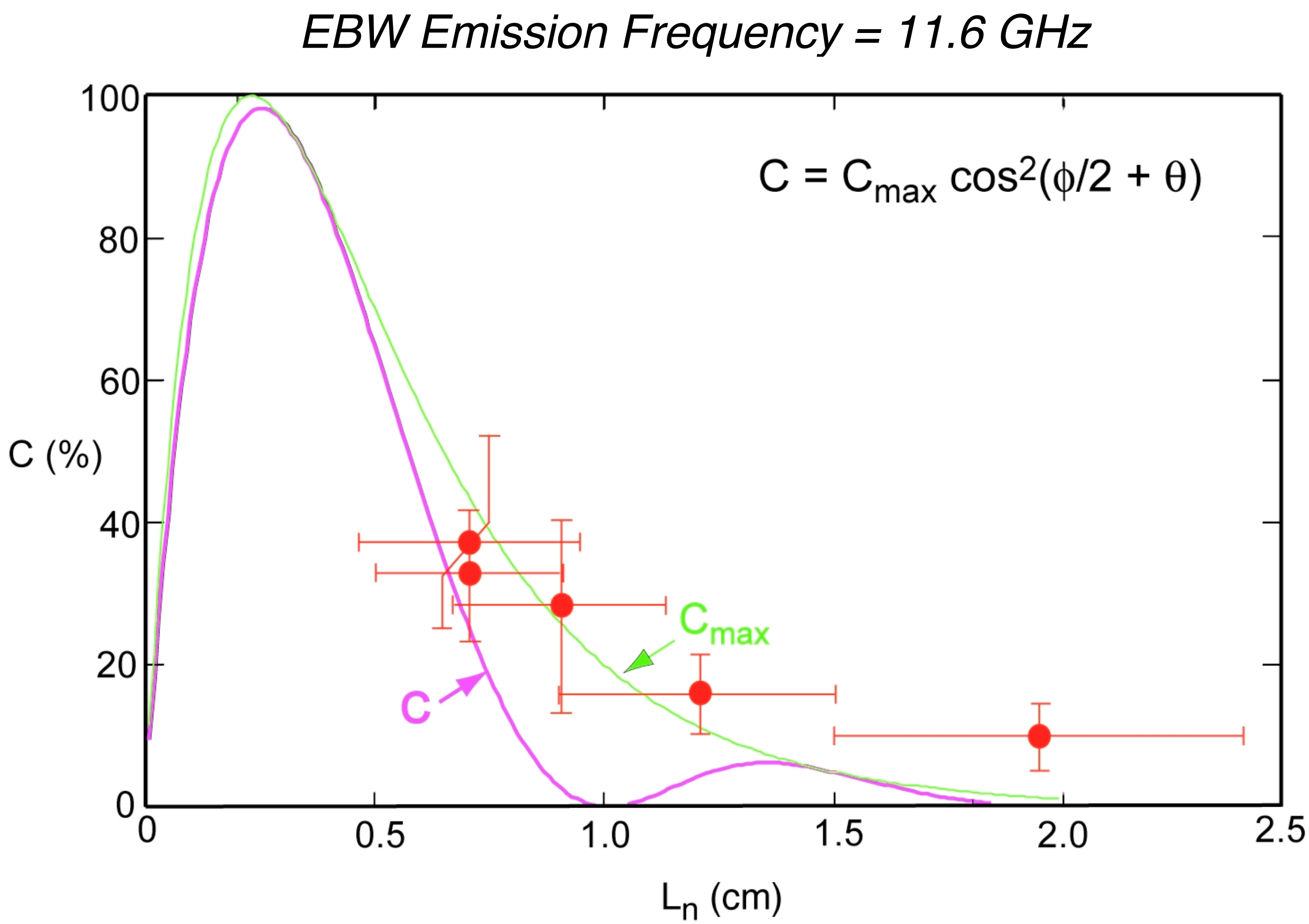
CDX-U

Need C_{BX} > 80% for Viable EBW Heating and CD System on NSTX

- Measured $C_{BX} < 5\%$ for NSTX L-Mode plasmas, 10-15% during H-Modes
- Reproduce CDX-U experiments with local limiter on NSTX next year, for both B-X and B-X-O conversion
- Results from experiment on NSTX using HHFW antenna tiles to shorten L_n this year were very encouraging:

  - achieved $C_{BX} \leq 50\%$

C_{BX} Increased from 10% to 50% as L_n Shortened from 2 to 0.7 cm, Agreeing with Theory



- Will attempt similar experiment with O-Mode antenna next year

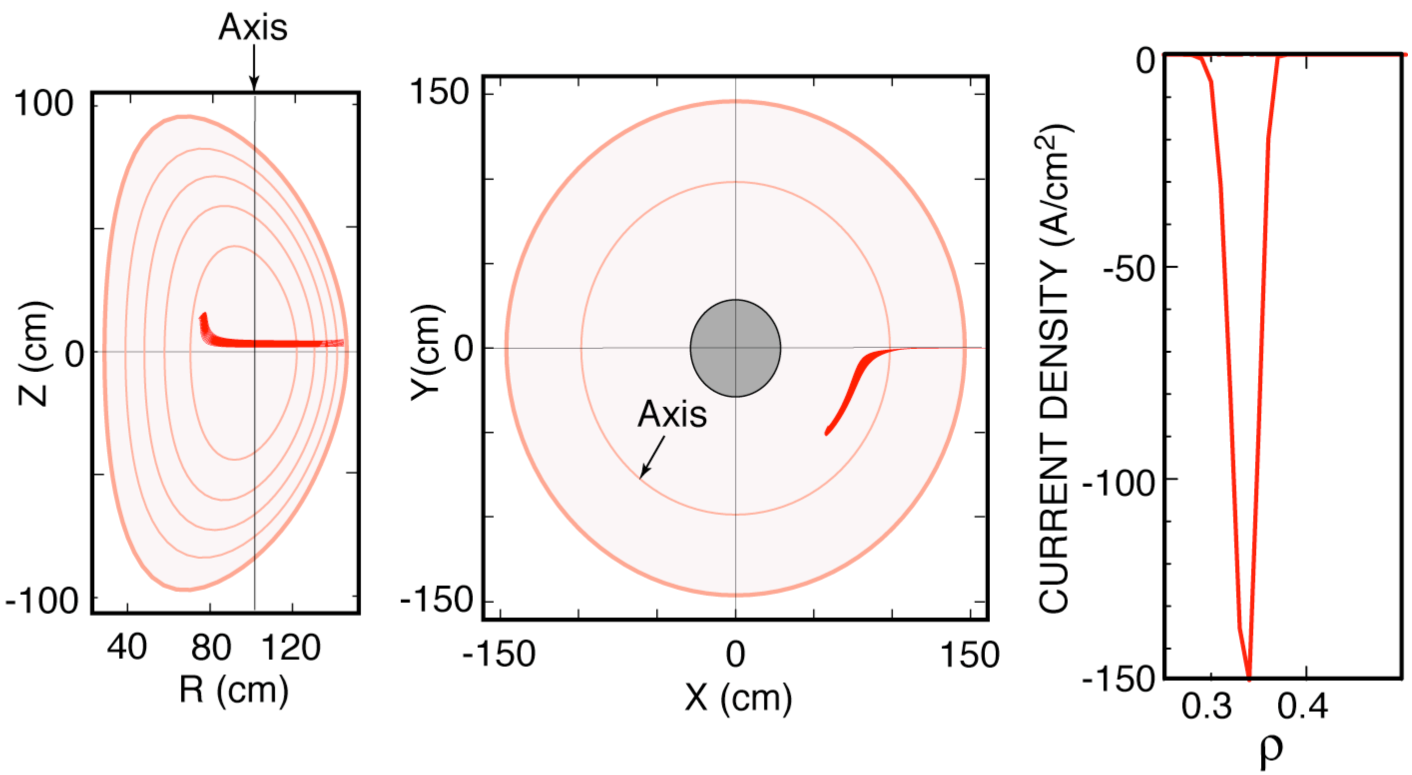
EBW Heating and CD May Optimize Equilibrium for High β Plasmas by Suppressing MHD

- Trapped particle effects make high field side (HFS) EBW power deposition more attractive
- Greatest access to HFS for fundamental EBW frequencies
- EBW heating and current drive modeling with GENRAY ray tracing and CQL3D bounce-averaged Fokker-Planck codes

In β ~ 20% NSTX Plasma, EBWCD Efficiency Comparable to ECCD and Very Localized

1 MW 14.5 GHz RF at 5° above mid-plane, $-0.1 < n_{//} < 0.1$

CD efficiency = 0.065 A/W, $n_{eo} = 3x10^{19}\ m^{-3}$, T_{eo} = 1keV



- CD localization supports requirements for NTM suppression

Status of EBW RF Source Technology

- Focus NSTX program is B_o ~ 0.4-0.5 T plasma operation requiring fundamental EBW RF source at ~ 15 GHz
- No long pulse, high power ~ 15 GHz sources
- Four 28 GHz, 350 kW, CW gyrotrons at ORNL might be retuned to operate at 15.3 GHz (~ 200kW/tube)
  - Retuning needs to be tested
  - Provides only ~ 800 kW with four tubes
- Prefer to develop new megawatt level ~ 15 GHz tube;
  - MIT proposes 800 kW tube with ~ 50% efficiency
  - MIT estimates 18-24 month development
  - Need to issue request for cost & schedule quote in early 2003

Design Requirements for EBW RF Launcher

- EBW launcher design presently undefined
- Need well defined $n_{//}$ spectrum, good focusing and some beam steering
- Use either focusing mirrors or phased 4-8 element array
- Polarization control by external waveguide or grooved mirrors
- Use local limiter to steepen L_n at the mode conversion layer for both X-B and O-X-B launch

EBW 5-Year Research Plan

EBW Research in 2003

- Complete GENRAY/CQL3D scoping study for NSTX
- GENRAY/CQL3D modeling of EBW startup
- Determine importance of relativistic effects in EBW propagation & damping, and edge parametric instabilities
- Complete conceptual design for EBW antenna
- Request quote for ~ 1 MW, 15 GHz tube
- MAST to test O-X-B heating

EBW Research in 2004-5

- Obtain ≥ 80% B-X and/or B-X-O conversion on NSTX
- Complete design of 1-3 MW, 15 GHz EBW heating and current drive system
- Include radial transport effects in CQL3D modeling of EBW current drive
- Begin install of 1 MW, 15 GHz heating system

EBW Research in 2006

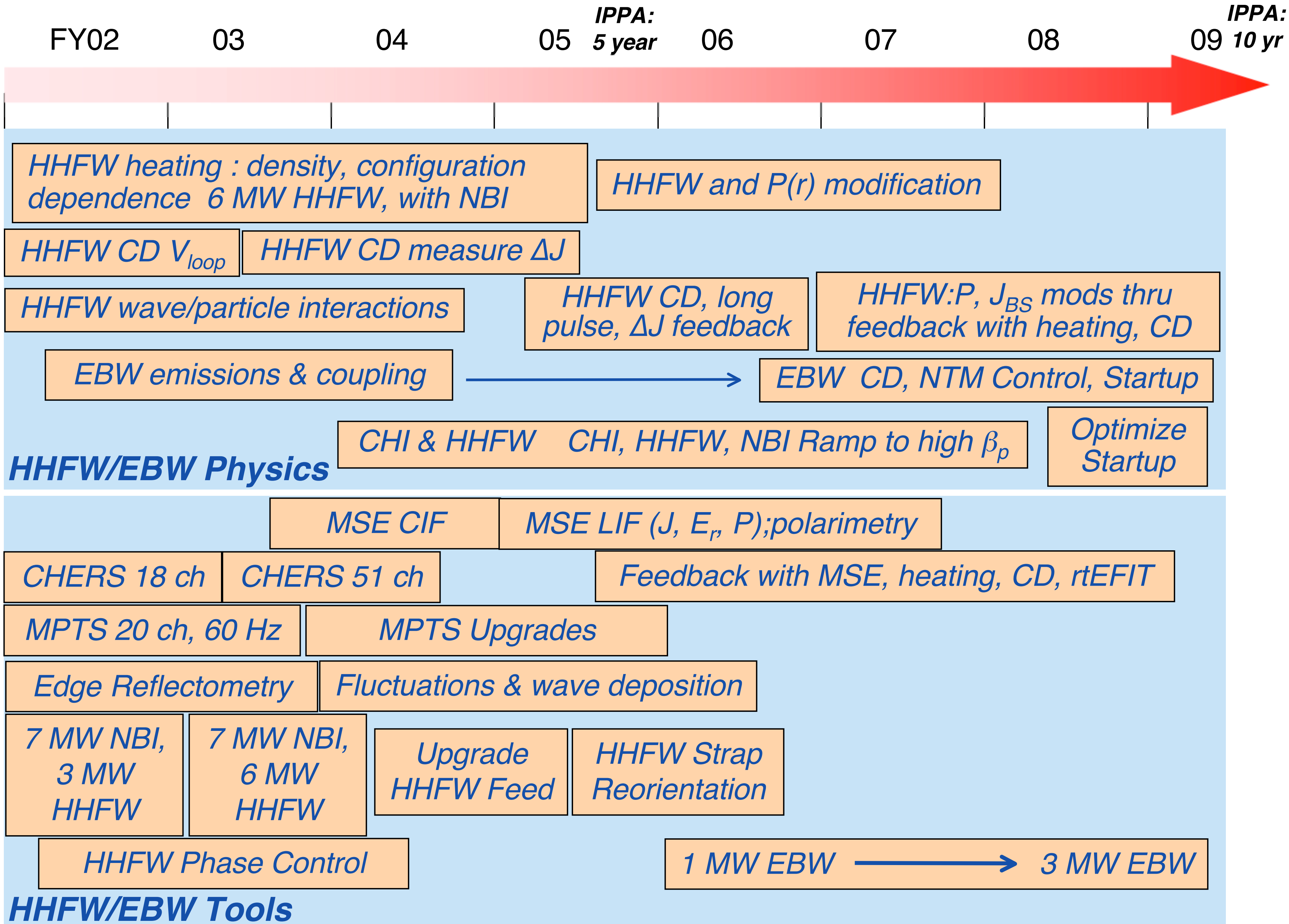
- Complete installation of 1MW, 15 GHz EBW heating and CD system
- Demonstrate coupling to EBW's with ~ 1 MW, 15 GHz
- Study spatial control of electron heating by EBWs

EBW Research in 2007-8

- Begin experiments with 1-3 MW, 15 GHz
- Demonstrate plasma current generation & control
- Study plasma EBW startup
- Investigate NTM suppression by EBW heating and/or CD

HHFW and EBW Heating and CD Can Provide Tools to Enable Solenoid-Free ST Operation at High β

- Strong HHFW electron heating seen, initial evidence for HHFW CD and interaction between HHFW and NBI ions observed
- 5-year goal to demonstrate HHFW-assisted startup, pressure profile modification and HHFW CD-assisted sustainment
- > 95 % B-X conversion attained on CDX-U, ~ 50% so far on NSTX; plan to obtain > 80% conversion on NSTX
- Modeling indicates efficient localized, off-axis, EBW CD is possible on NSTX
- Install ~ 1 MW EBW system by 2006, ~ 3 MW in 2007; 5-Year goal to test EBW startup and NTM suppression


FY02
03
04
05
IPPA: 5 year
06
07
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IPPA: 10 yr
HHFW heating : density, configuration dependence 6 MW HHFW, with NBI
HHFW and P(r) modification
HHFW CD V_{loop}
HHFW CD measure ΔJ
HHFW wave/particle interactions
HHFW CD, long pulse, ΔJ feedback
HHFW:P, J_{BS} mods thru feedback with heating, CD
EBW emissions & coupling
EBW CD, NTM Control, Startup
CHI & HHFW
CHI, HHFW, NBI Ramp to high β_p
Optimize Startup
HHFW/EBW Physics
MSE CIF
MSE LIF (J, E_r, P);polarimetry
CHERS 18 ch
CHERS 51 ch
Feedback with MSE, heating, CD, rtEFIT
MPTS 20 ch, 60 Hz
MPTS Upgrades
Edge Reflectometry
Fluctuations & wave deposition
7 MW NBI, 3 MW HHFW
7 MW NBI, 6 MW HHFW
Upgrade HHFW Feed
HHFW Strap Reorientation
HHFW Phase Control
1 MW EBW
3 MW EBW
HHFW/EBW Tools