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HHFW and EBW Heating and Current Drive 5-Year Research Plan

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For the NSTX National Team

DOE Review of NSTX Five-Year Research Program Proposal
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Outline

- Motivation
- High Harmonic Fast Waves (HHFW)
  - *Research Goals*
  - *Status:*
    - *HHFW System*
    - *Experimental Results*
    - *Theory & Modeling*
  - *5-Year Plan*
- Electron Bernstein Waves (EBW)
  - *Research Goals*
  - *Status:*
    - *Mode Conversion Theory*
    - *Mode Conversion & Coupling Experiments*
    - *Technology Issues*
  - *5-Year Plan*

NSTX National Spherical Torus Experiment

HHFW & EBW Provide Tools for Local Electron Heating and Current Drive in High β, ST Plasmas

- High β scenarios require off-axis CD to complement bootstrap and NBI CD
- On-axis RF CD is also required for solenoid-free current ramp-up and steady-state operation
- Lower hybrid and conventional ECCD cannot be used in high β ST plasmas, where $\omega_{pe} >> \omega_{ce}$
- HHFW in high β plasmas have strong single pass electron absorption, so potential for desired off-axis deposition
- EBW propagate in an ST plasma & are strongly absorbed at EC resonances; potentially allowing local EBWH & EBWCD

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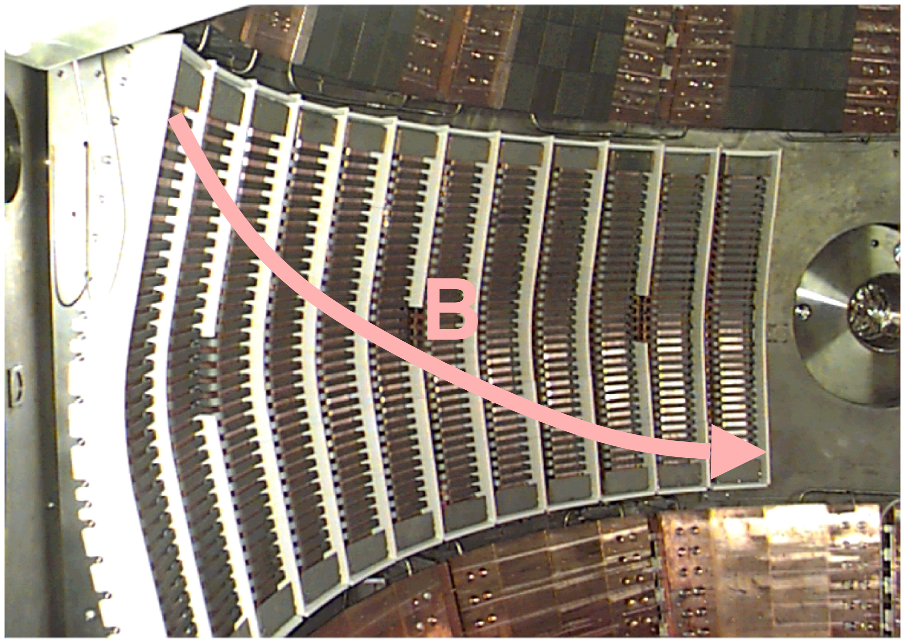
High Harmonic Fast Waves (HHFW)

HHFW 5-Year Research Goals

- HHFW-assisted current ramp-up
- Pressure profile modification
- HHFW CD-assisted discharge sustainment
- Use HHFW, with other tools, for $\tau_{pulse} > \tau_{skin}$ operation

Status of HHFW Research

Flexible High Power HHFW Heating and CD System Operational on NSTX

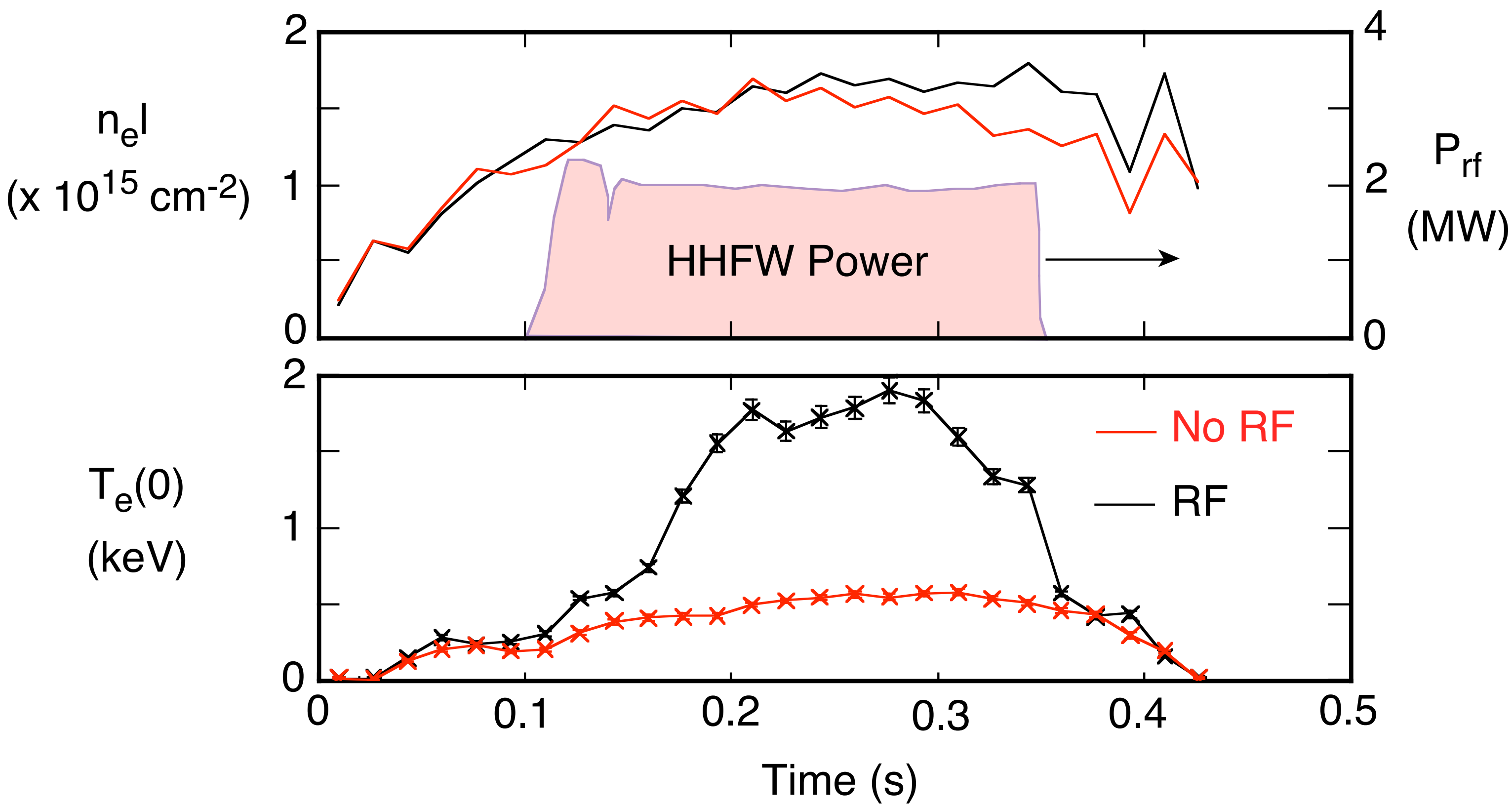


- Uses TFTR ICRF hardware
- f = 30 MHz, ω/Ω_D = 9-13
- 6 MW from 6 transmitters
- Pulse length up to 5 s
- 12 Element antenna
- Active phase control
- $k_T = \pm$ (3-14) m^{-1}
  - *variable during shot*

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

P. Ryan, *et al., Fus. Eng. & Design,* **56-57**, 1395 (2001)

HHFW Primarily Heats Electrons when $T_i < 2$ keV, as Expected from Theory



- No evidence for direct thermal ion heating
- HHFW heats ions when $T_i \geq 2$keV and $\square_i$ significant
- Confinement generally consistent with ITER scalings

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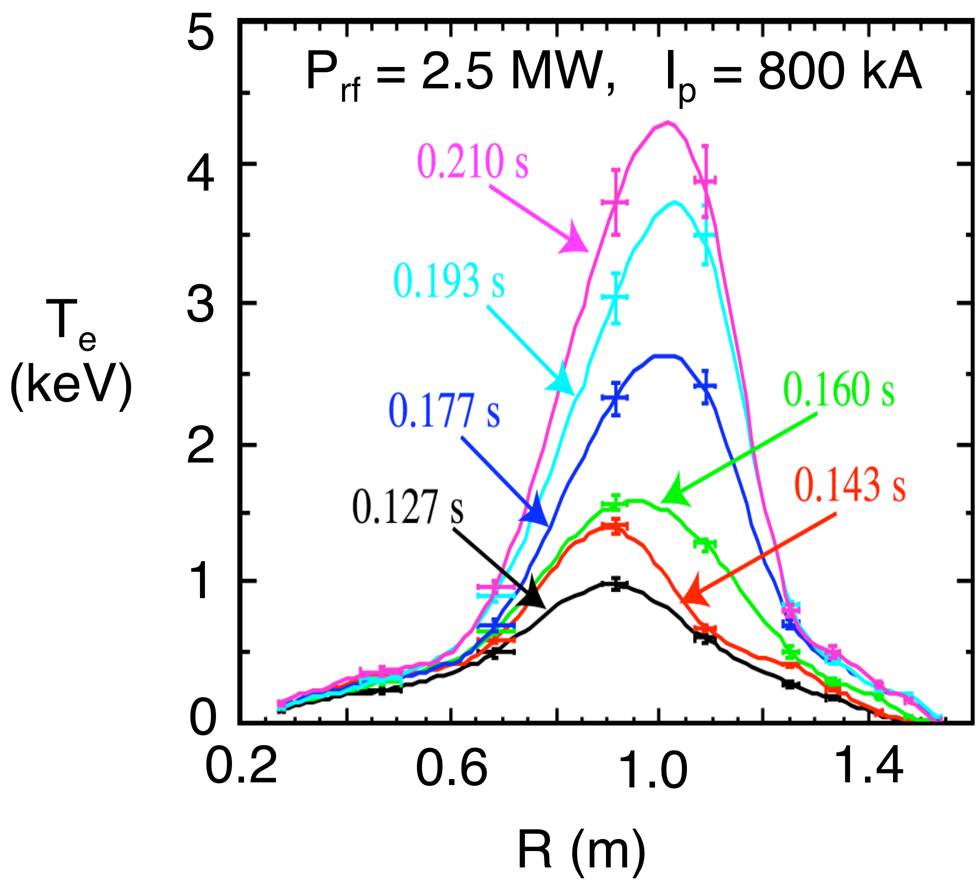
Some HHFW-Heated Discharges Exhibit Internal Transport Barrier Behavior



- 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 with time in the central region

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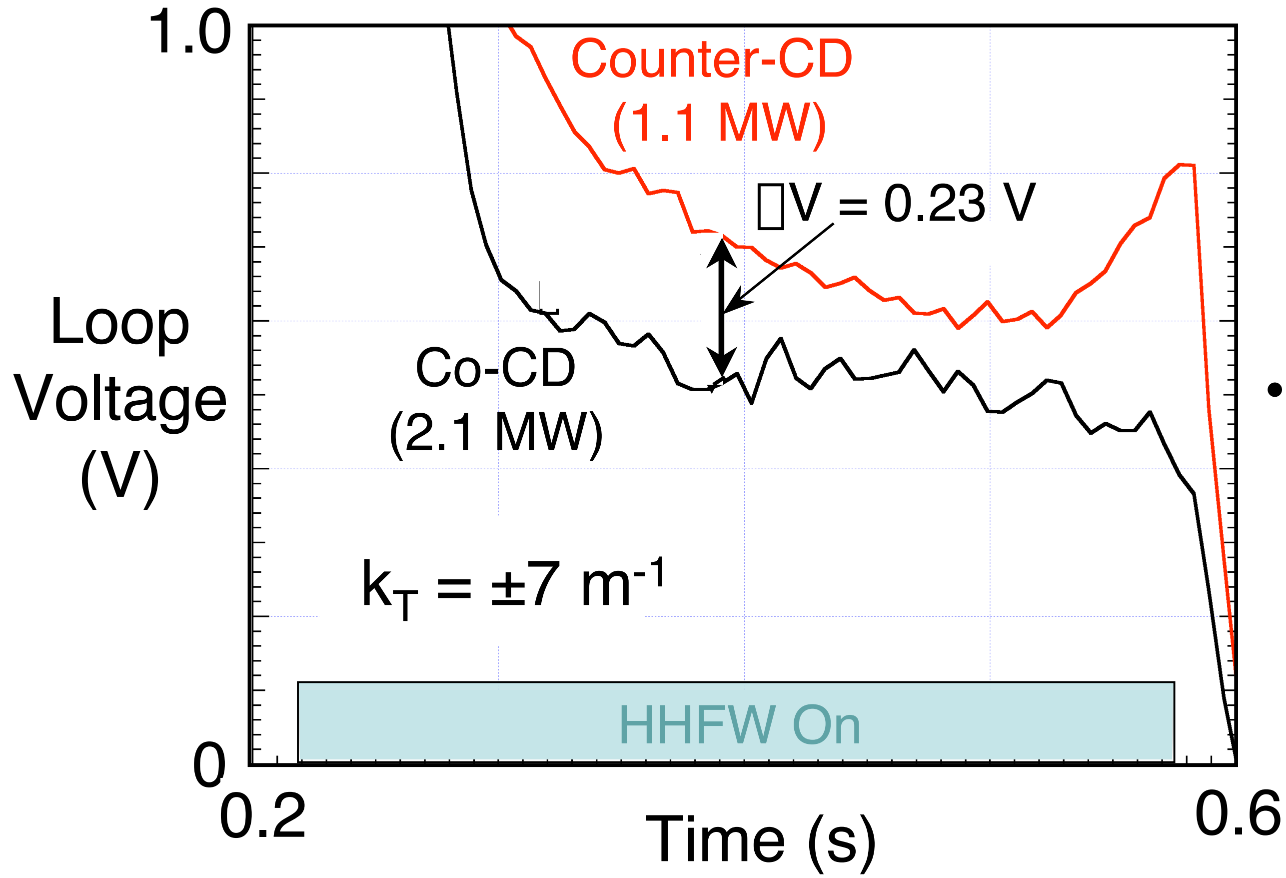
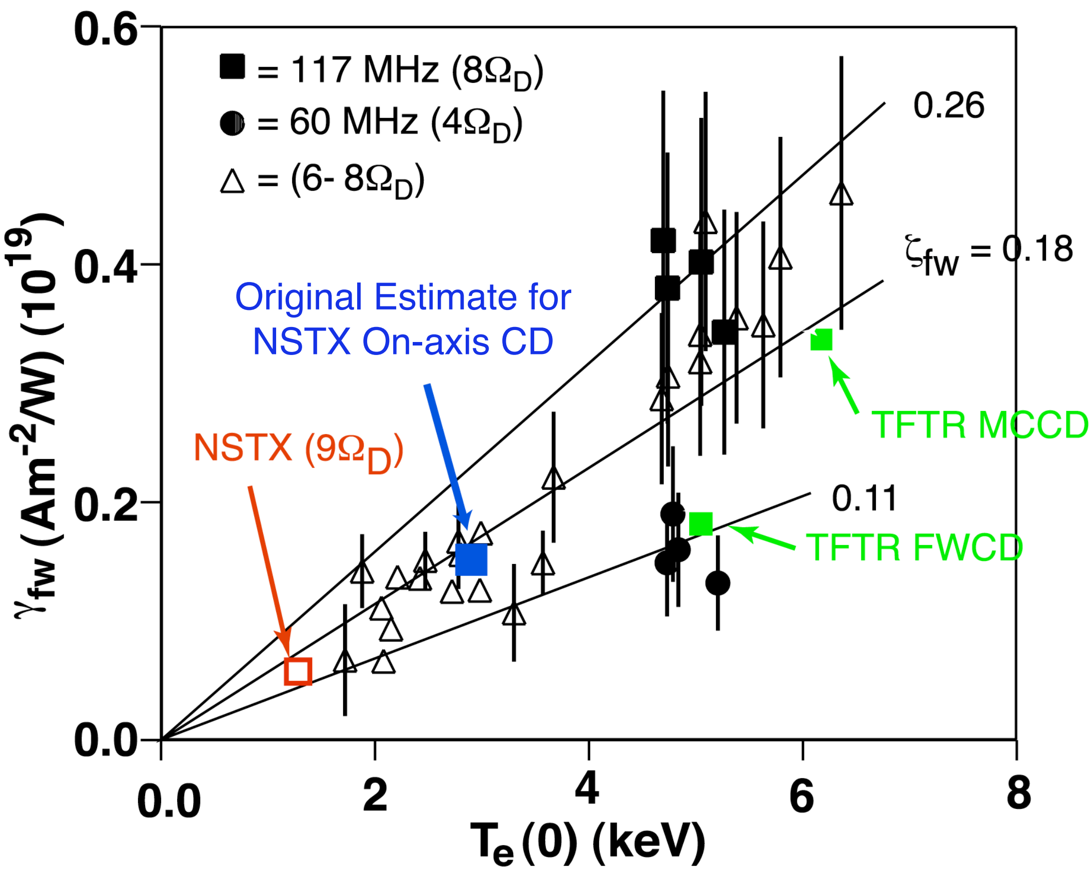
Less Loop Voltage to Maintain I_P With Co Phasing; Magnetics Analysis Estimates I_{cd} = 110 kA (0.05 A/W)



- Plasmas matched for central T_e

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

HHFW CD Efficiency Consistent with DIII-D & TFTR CD; But Significant Off-Axis HHFW CD not Expected

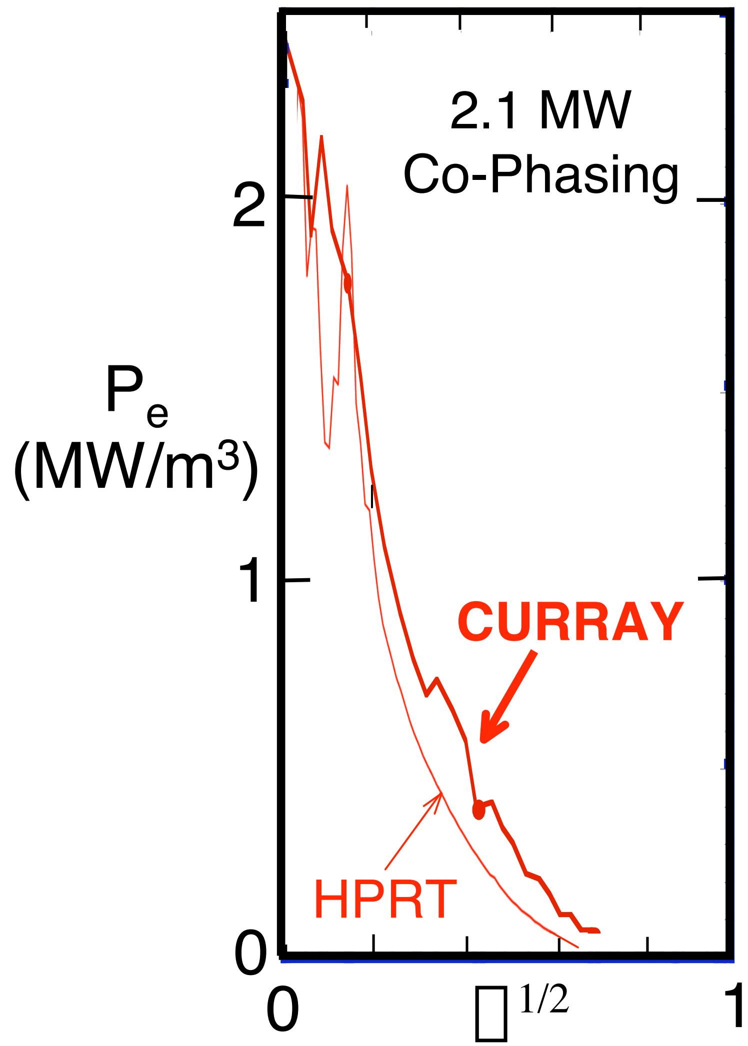


- More RF power & improved confinement regime should increase T_e to meet original estimate for on-axis HHFW CD

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

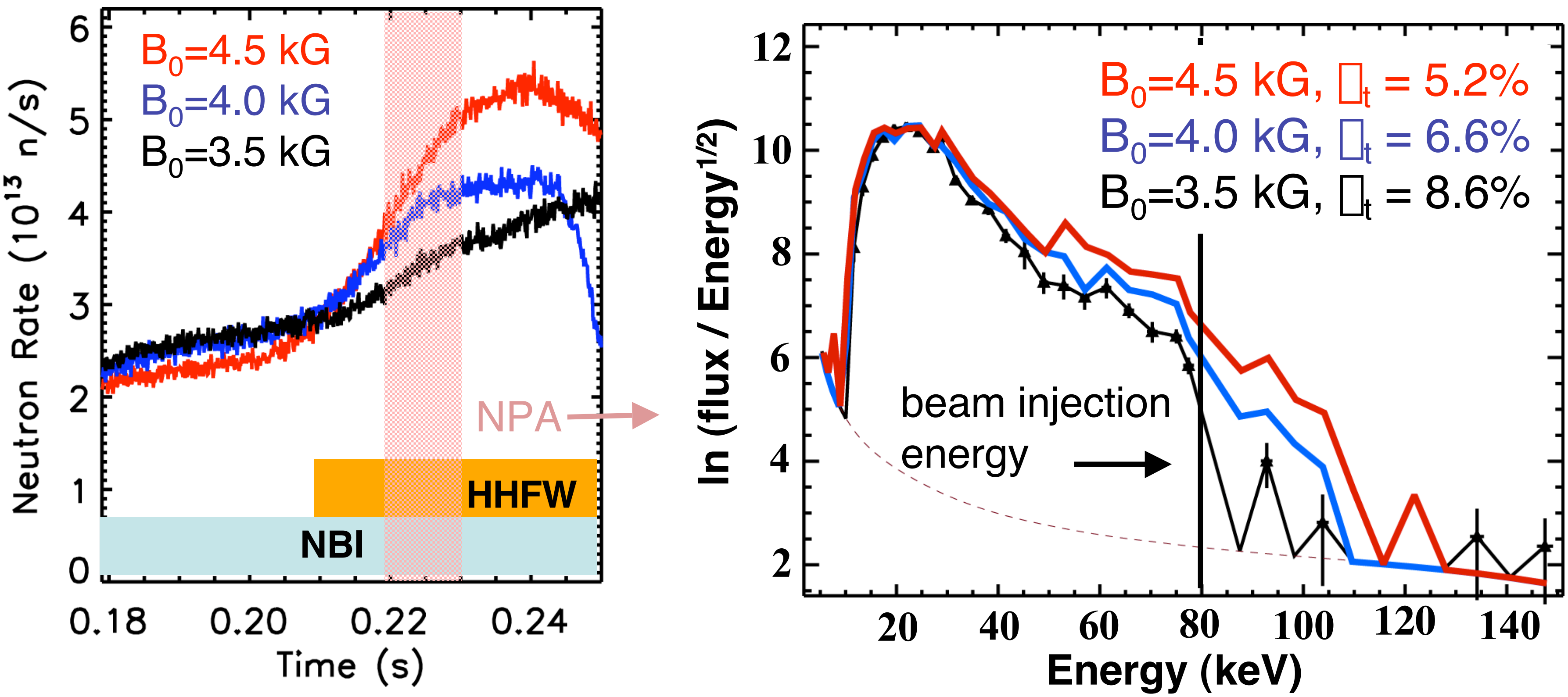
- Present results are for on-axis HHFW CD
- Trapping can significantly reduce off-axis CD efficiency:
  - *High □ may reduce trapping*

Codes Predict Strong Electron Damping, as Seen in Experiments



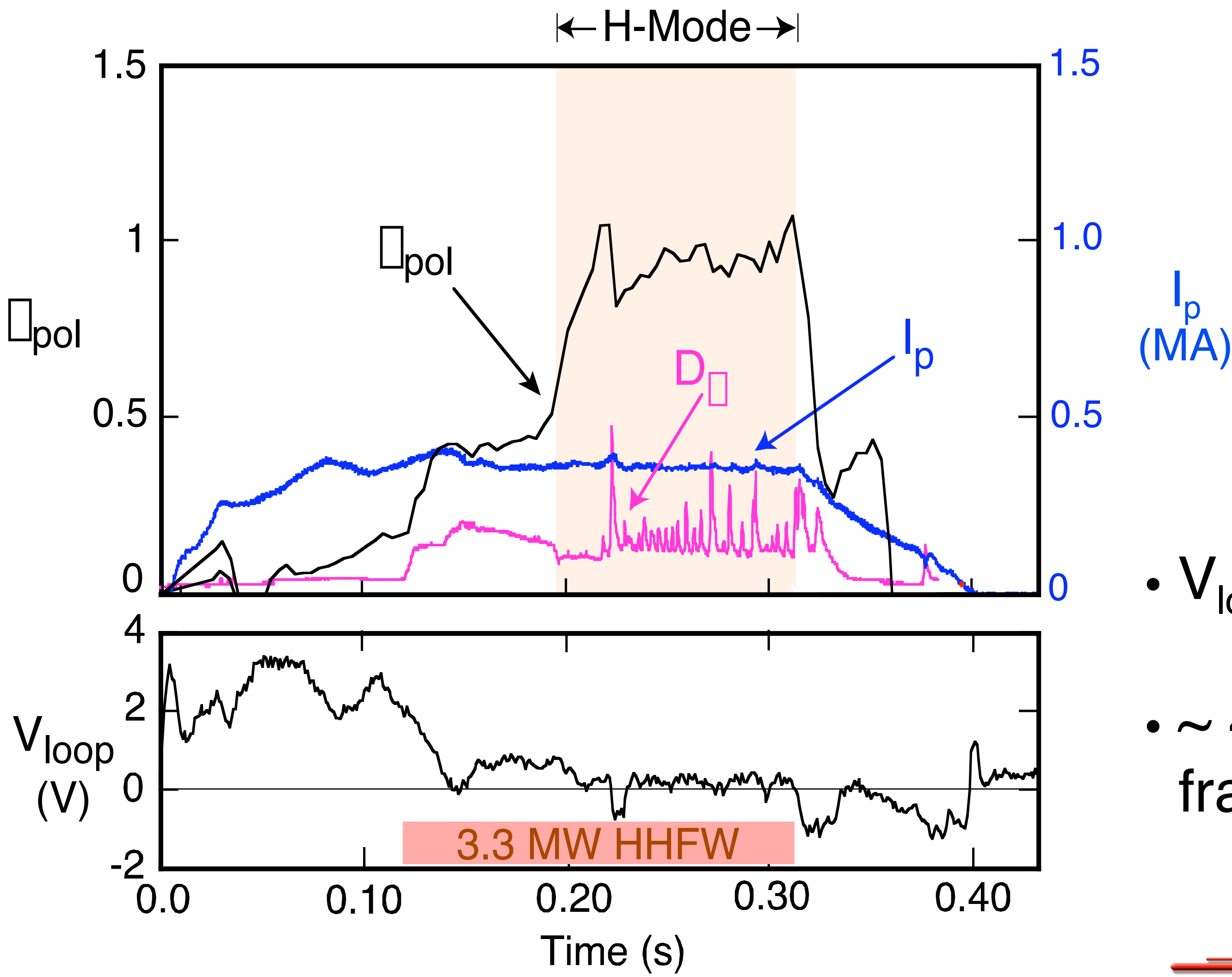
- Good agreement between ray tracing codes (CURRAY, HPRT)
- Full-wave codes predict similar deposition to ray tracing:
  - *Full-wave kinetic models predict no significant mode conversion*
  - *More modeling needed to determine if mode conversion important at higher B and/or ion □*

Evidence Seen for HHFW Interactions with Energetic Beam Ions, as Predicted



- Tail reduced at lower B, higher β:
  - *- Larger β promotes greater off-axis electron absorption reducing power available to central fast ion population*

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



- $V_{loop} \sim 0$
- ~ 40% bootstrap fraction

HHFW 5-Year Research Plan

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

- Plan has five major components:

  - *Dependence of coupling on plasma configuration & density*

  - *Heating & coupling with NBI and profile modification*

  - *HHFW current drive studies*

  - *Solenoid-free plasma startup*

  - *Technical performance improvements*

Dependence of Coupling on Plasma Configuration & Density

2004:

- *Investigate thermal ion heating; use H-mode plasmas & new X-ray crystal T_i diagnostic*

- *Vary inner & outer gaps in double null discharge; previously only studied in limiter and lower single null plasmas*

- *Study effect of varying density on heating efficiency over a wider range of density*

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Heating & Coupling with NBI & Profile Modification

2004:

- *Modify internal inductance with early heating; reduce volt-sec consumption & increase q(0)*
- *HHFW heating efficiency with strong NBI; study dependence on target □ and density*
- *HHFW H-mode access*

2005-6:

- *Feedback control of HHFW heating at high □ to broaden electron pressure profile*

HHFW Current Drive Studies

2004-5:

- *Measure J(R) with motional stark effect (MSE) diagnostic*
- *Dependence of CD efficiency on RF power, density, temperature and antenna phasing*

2006:

- *Study reduction in off-axis CD efficiency due to trapping and possible increase in CD efficiency at high □*

2007-8:

- *Feedback antenna phasing on MSE J(R) & rtEFIT*
- *HHFW with full feedback control of antenna phase using MSE LIF system for real time J(R), & P(R)*

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Solenoid-Free Plasma Startup

2004-5:

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

2006-7:

- *HHFW handoff to NBI during current ramp up*

2007-8:

- *Minimize flux consumption with HHFW to enable long pulse, high β, non-inductive plasmas*

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Technical Performance Improvements

2004-5:

- *Continue dedicated experiments to elucidate HHFW antenna power limits & reliability issues; recent modifications increased voltage limit by ~ 40%*

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

Electron Bernstein Waves (EBW)

EBW May Allow Highly Localized Heating & Current Drive in ST Plasmas

- EBW propagate & are strongly absorbed at EC resonances in ST plasma; potentially allowing local EBWH & EBWCD

- Electromagnetic waves can couple to EBW via two mode conversion processes:

  X-B Conversion: X-mode launch perpendicular to B field couples to EBW when L_n is short at the upper hybrid resonance (UHR)

  O-X-B Conversion: Near-circular polarization launch at oblique angle to B field couples to EBW when angle set to make $\square_p$ and $\square_L$ cutoffs coincide

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EBW 5-Year Research Goals

- Demonstrate efficient coupling to EBW via X-B and O-X-B conversion
- Control spatial location where EBWs damp and heat electrons; optimize J(R) for High β operation
- Test EBW-assisted non-inductive current startup, alone, or in combination with HHFW and/or CHI
- Test suppression of neoclassical tearing modes with EBW current drive
- Plan to install ~ 1 MW of RF source power by 2006, increasing to ~ 4 MW by 2008

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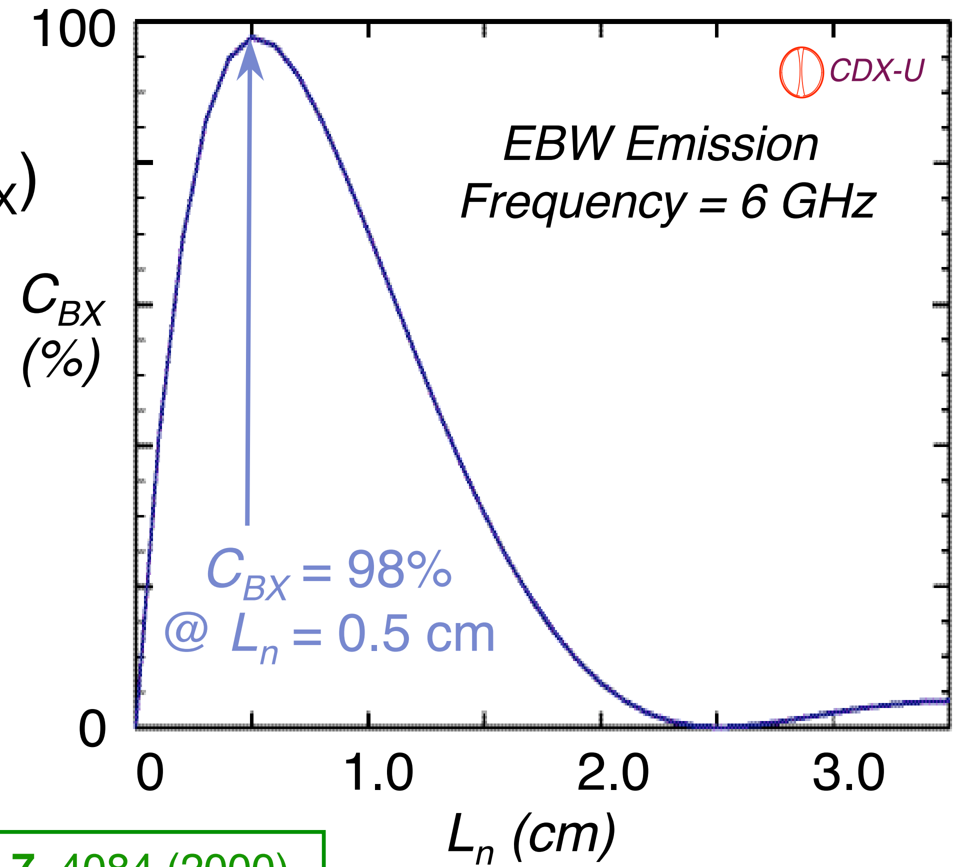
Status of EBW Research

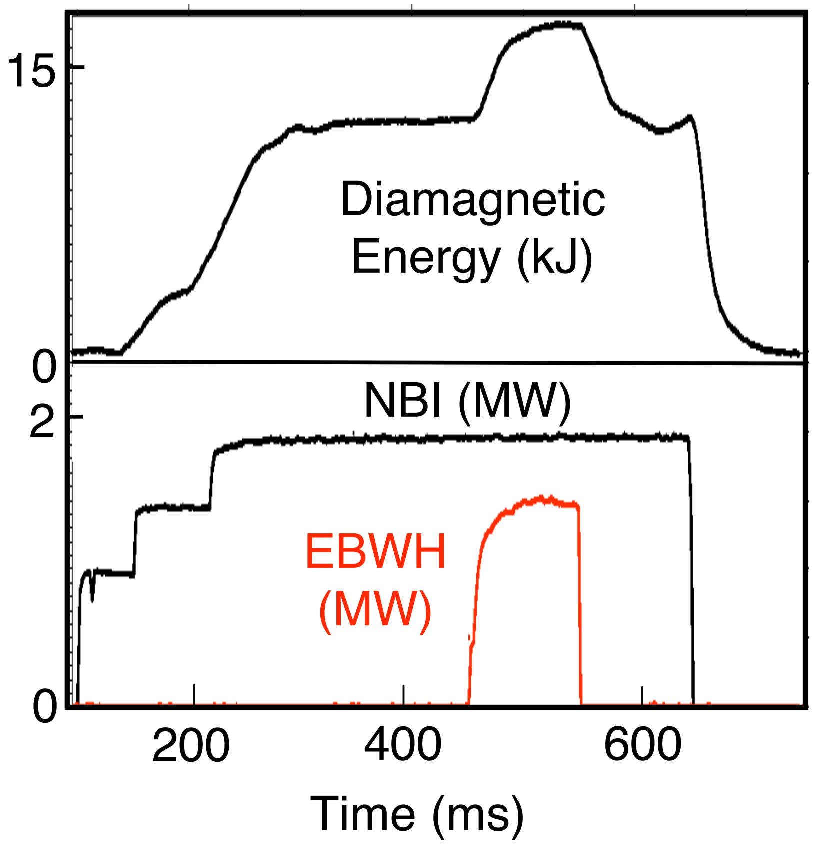
EBW Emission Experiments on CDX-U and NSTX Focused on Maximizing B-X Conversion in Scrape Off Layer

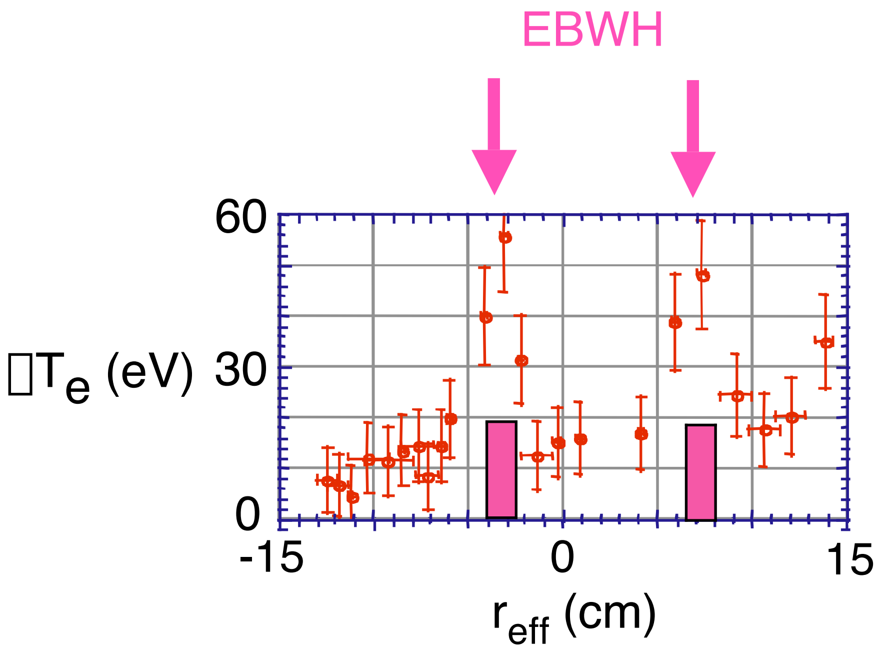
- EBW to X-mode conversion efficiency (C_{BX}) very sensitive to L_n:
- B-X emission evaluates efficiency of X-B process for heating and CD



A.K. Ram & S.D. Shultz, *Phys. Plasmas,* **7**, 4084 (2000)
A.K. Ram, *et al.*, *Phys. Plasmas,* **9**, 409 (2002)

Local O-X-B Heating Demonstrated on W-7AS Stellarator



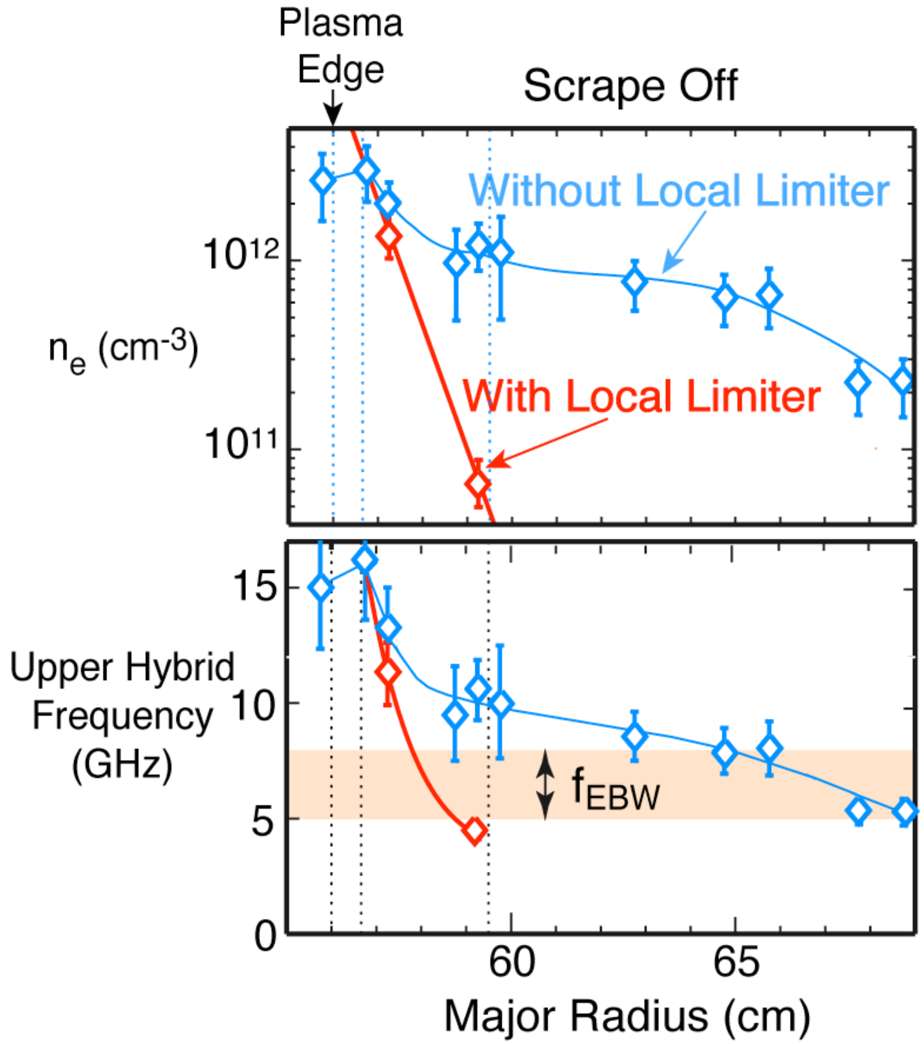


- T_e increased from 270 to 310 eV with 1.5 MW EBWH over ~ 3 cm radius

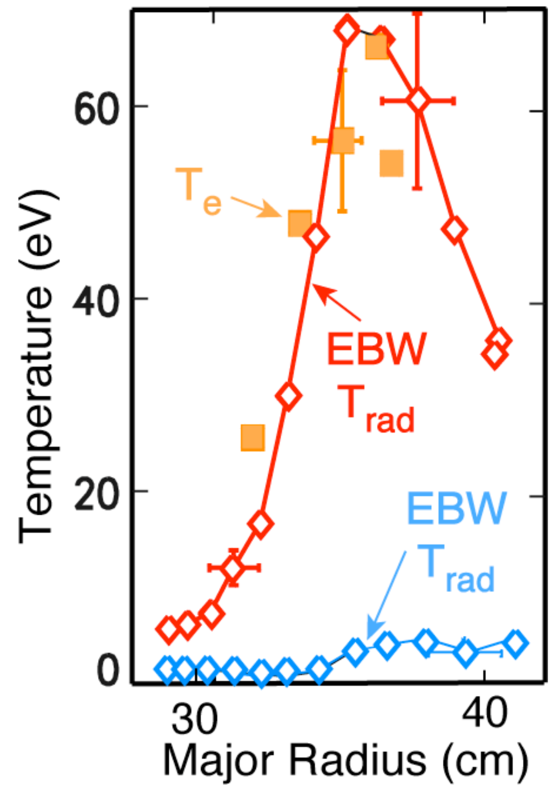
H.P. Laqua, *et al.*, *Phys. Rev. Lett.* **78**, 18 (1997)

W7-AS

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



B. Jones *et al.*,
Phys. Rev. Lett. **90**, 165001 (2003)



CDX-U

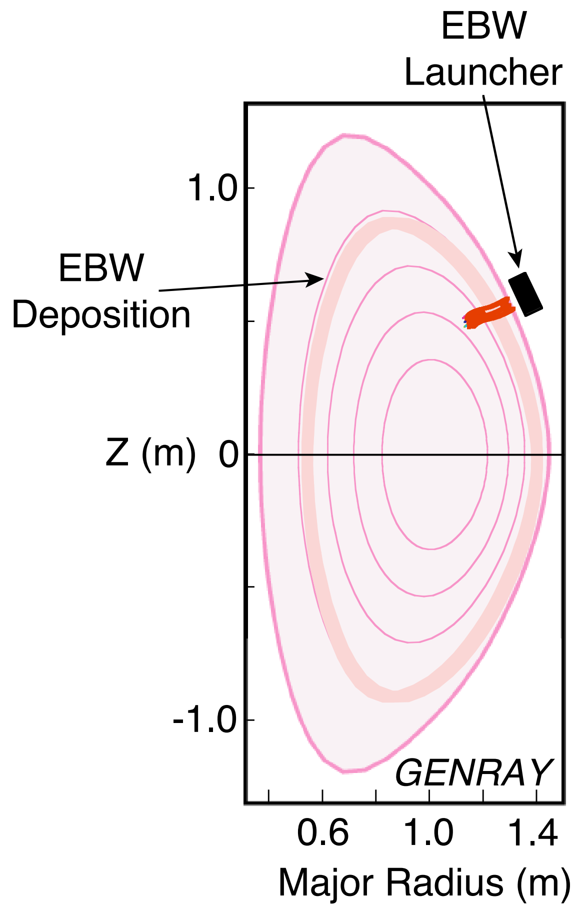
Need C_{BX} > 80% for Viable EBW Heating & CD System

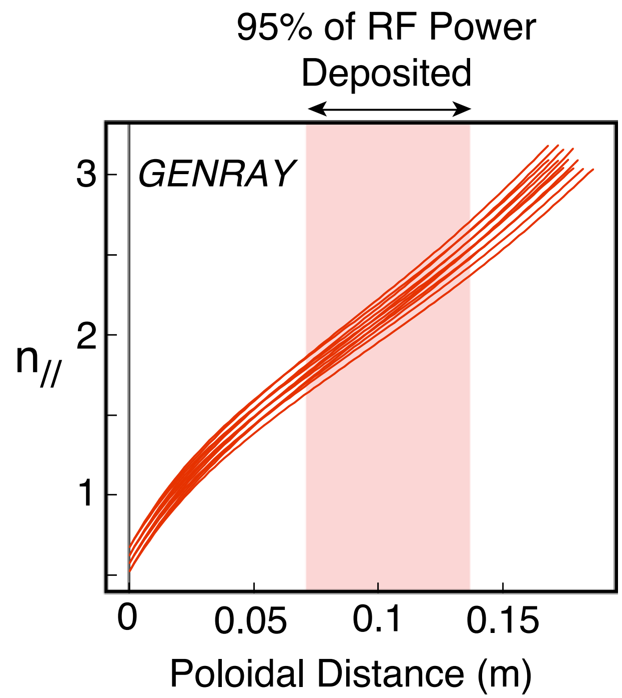
- C_{BX} < 5% for L-Mode and 10-15% for H-Mode on NSTX in 2001
- Experiment on NSTX using HHFW antenna tiles to shorten L_n last year achieved $C_{BX} \leq 50\%$
- Next year, demonstrate C_{BX} > 80% on NSTX using installed antenna with optimized local limiter
- Also, installed B-X-O antenna on NSTX for EBW emission measurements next year
- Collaboration begun with MAST O-X-B heating experiments

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

- Fully non-inductive, $\beta \sim 40\%$ plasma requires ~ 150 kA externally driven current between r/a = 0.4 and 0.8
- NTM's may grow at q = 1.5 and q = 2 surfaces located between r/a = 0.3 and 0.5, in high β plasma
- EBW heating and CD being modeled with GENRAY ray tracing & CQL3D Fokker-Planck codes
- Recent modeling results indicate EBWCD in NSTX is dominated by Okhawa CD at r/a > 0.3; increases with r/a

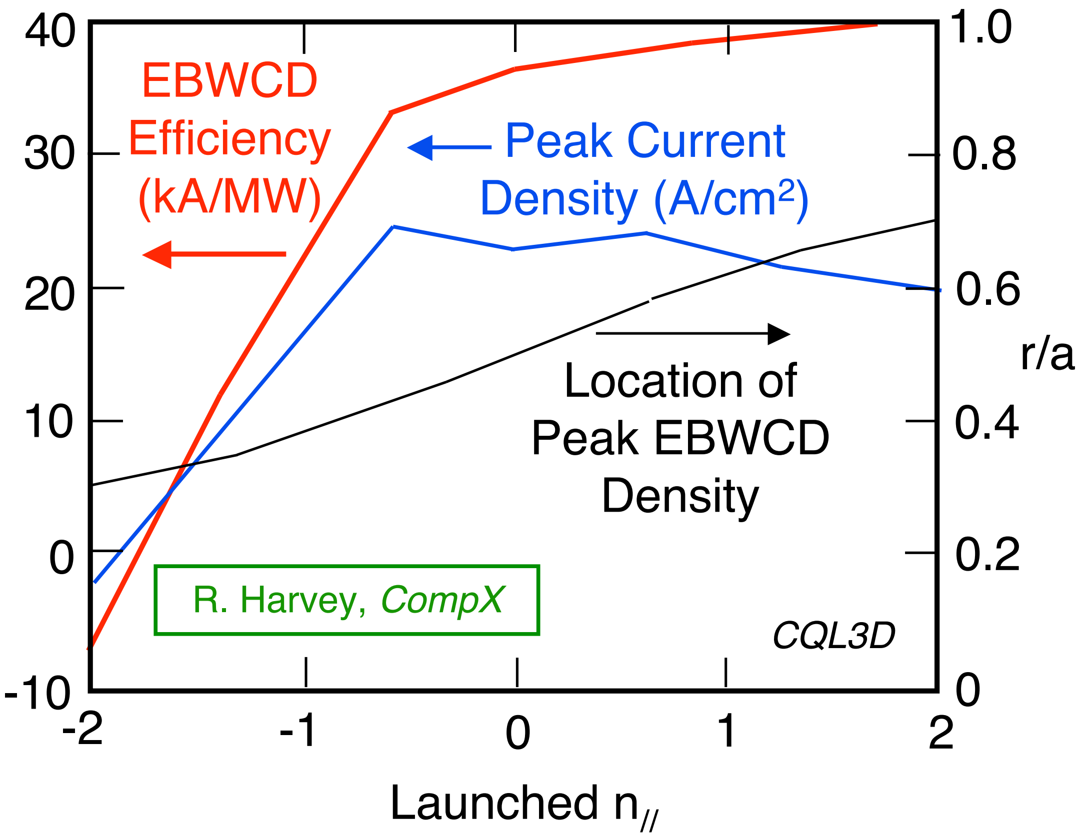
Placing EBW Launcher Well Above or Below Midplane Produces Large $n_{//}$ Shifts Needed for Efficient EBWCD





15 GHz RF launched at 65° above mid-plane, with $0.5 < n_{//} < 0.7$ into β = 30% NSTX equilibrium

Radial Location of EBWCD is Highly Localized and can be Varied by Changing Launched $n_{//}$



- Positive current results from Okhawa CD
- Plan ~ 4 MW at RF source power to get > 100 kA ; efficiency increases with r/a
- Normalized CD efficiency, $\square_{ec}$ = 0.4, compares favorably to ECCD

1 MW of 15 GHz RF launched at 65^o above mid-plane, into □ = 30% NSTX equilibrium

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Status of EBW RF Technology

- NSTX plasmas require fundamental EBW RF source frequencies ~ 15 GHz
- No long pulse, high power sources in this frequency range
- MIT proposes 1 MW tube design with ~ 50% efficiency; requires 18-24 month development:
  - *Will issue cost & schedule quote this year*
- MIT tube design has TE02 output, TE02 to HE11 converter design already available from GA
- Use low-loss corrugated HE11 transmission line, also available from GA

Design Requirements for EBW RF Launcher

- More modeling needed to define design requirements for launcher
- Need well defined $n_{//}$ spectrum, good focusing and some beam steering
- Use steerable focusing mirror launcher
- Polarization control by grooved mirror
- May use local limiter and/or localized gas puffing to steepen L_n at mode conversion layer:
    - *to improve X-B tunneling*
    - *widen O-X-B angular launch window*

NSTX National Spherical Torus Experiment

EBW 5-Year Research Plan

EBW Research in 2003

- *Complete GENRAY/CQL3D scoping study for NSTX; including modeling of EBW-assisted plasma startup*
- *Theoretically determine importance of relativistic effects in EBW propagation & damping; may need to include in scoping study*
- *Estimate threshold for driving edge parametric instabilities*
- *Complete conceptual design for EBW launcher*
- *Request quote for ~ 1 MW gyrotron*
- *MAST begins testing O-X-B heating*

EBW Research in 2004-5

- *Obtain ≥ 80% B-X and/or B-X-O conversion on NSTX*
- *Complete design of the EBW heating and current drive system*
- *Include radial transport effects in CQL3D modeling of EBW current drive*

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EBW Research in 2006

- *Complete installation of 1 MW EBW system*
- *Demonstrate EBW heating with ~ 1 MW RF source*
- *Look for evidence of RF-driven parametric instabilities*
- *Study spatial control of electron heating*
- *Look for suppression of NTMs*

EBW Research in 2007-8

- *Begin experiments with 4 MW EBW system*
- *Demonstrate plasma current generation & control*
- *Study plasma EBW startup*
- *Investigate NTM suppression by EBWCD*

HHFW and EBW Heating and Current Drive Provide Critical Tools Supporting NSTX Research

HHFW:

- Heating and current drive for plasma startup and sustainment studies
- Powerful heating for high □ and high □ plasma sustainment studies

EBW:

- Heating and current drive for startup and sustainment studies
- Neoclassical Tearing Mode control
- Heating and current profile control for high □ sustainment studies

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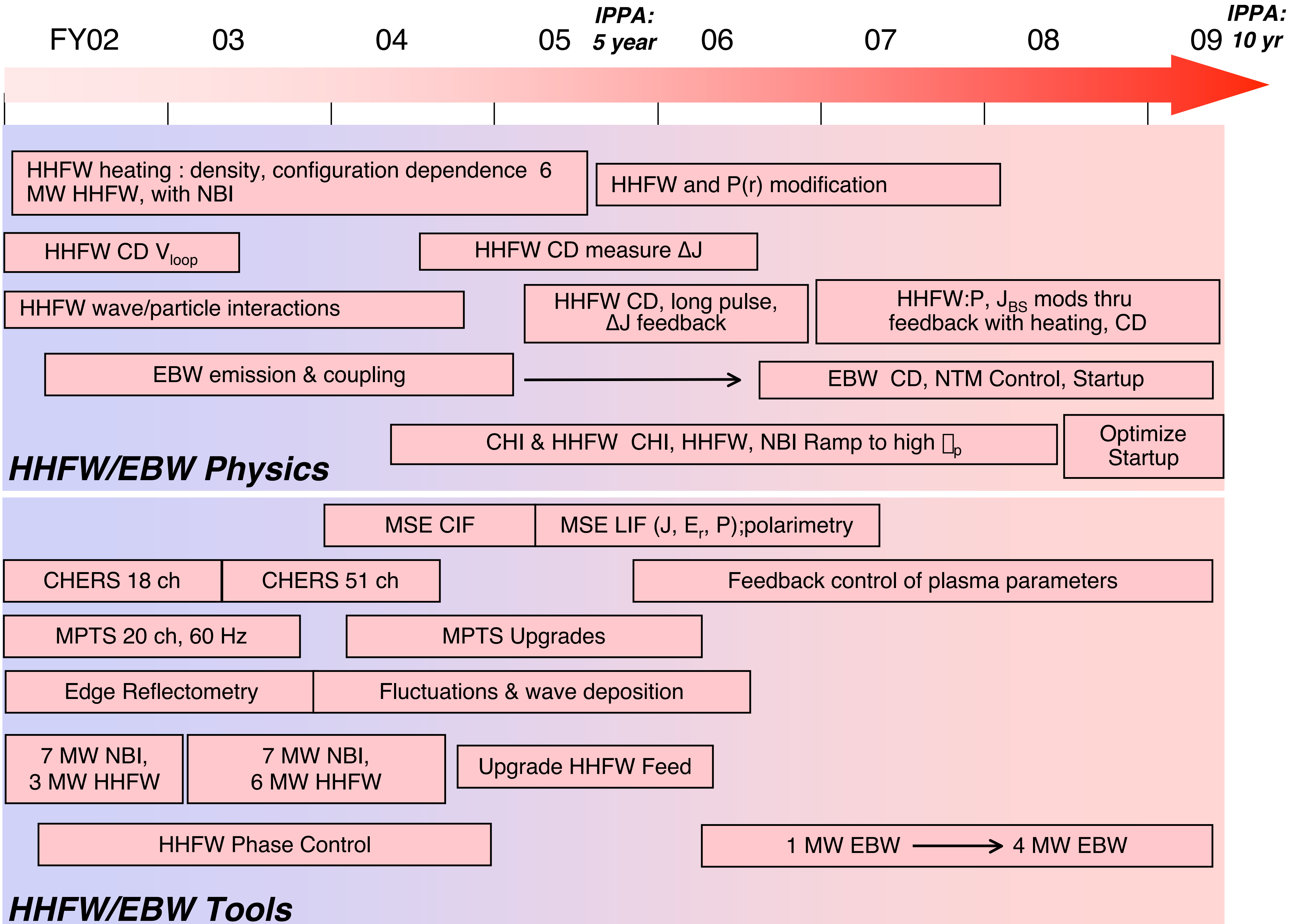
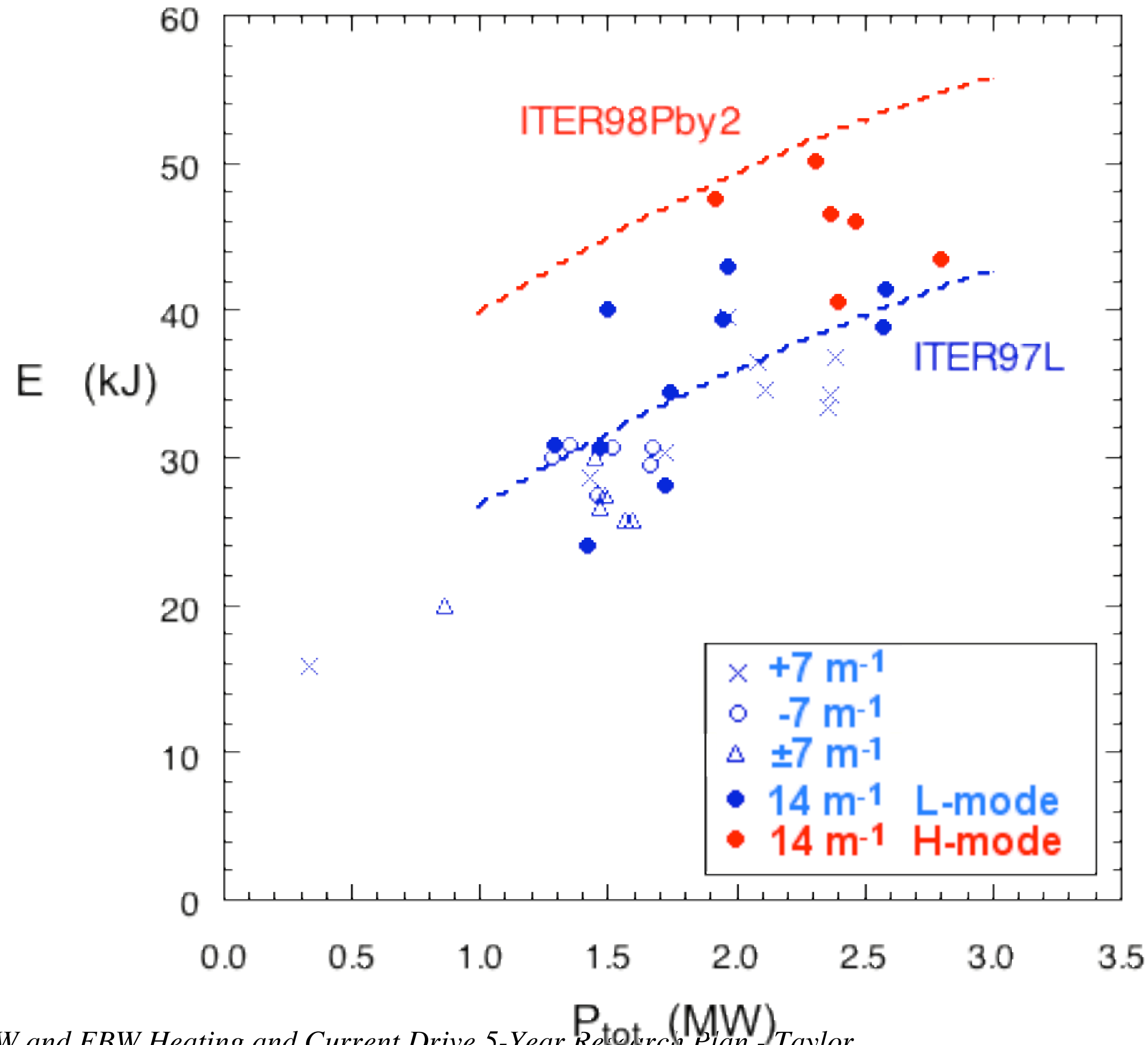

FY02
03
04
05
IPPA:
5 year
06
07
08
09
IPPA:
10 yr
HHFW heating : density, configuration dependence 6 MW HHFW, with NBI
HHFW and P(r) modification
HHFW CD V_{loop}
HHFW CD measure ΔJ
HHFW wave/particle interactions
HHFW CD, long pulse, ΔJ feedback
HHFW:P, J_{BS} mods thru feedback with heating, CD
EBW emission & coupling
EBW CD, NTM Control, Startup
CHI & HHFW CHI, HHFW, NBI Ramp to high □p
Optimize Startup
HHFW/EBW Physics
MSE CIF
MSE LIF (J, E_r, P);polarimetry
CHERS 18 ch
CHERS 51 ch
Feedback control of plasma parameters
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 Phase Control
1 MW EBW
4 MW EBW
HHFW/EBW Tools

Backup Slides

HEATING WITH HHFW FOLLOWS PREDICTIONS OF CONVENTIONAL SCALING



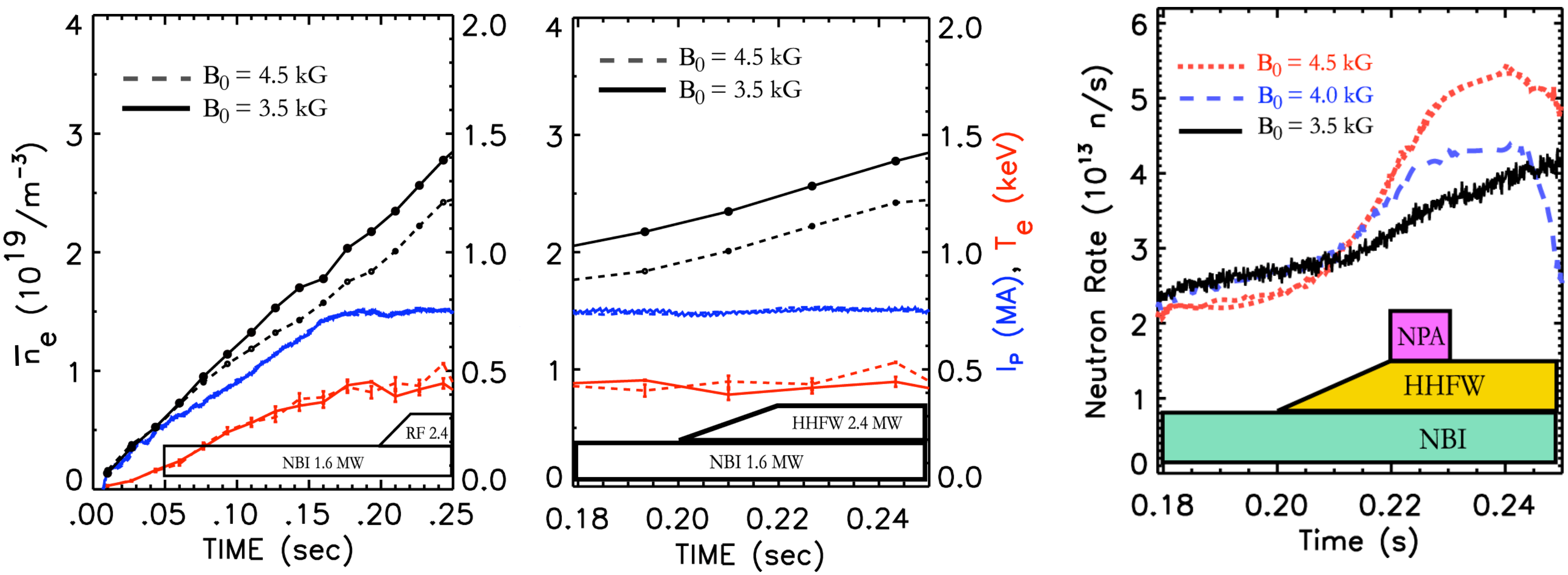
I_p= 500 kA
B_T= 4.5 kG
$<n_e>$ =1.5 x10^{19} m^{-3}

H mode defined by appearance of edge pedestal

P.M. Ryan

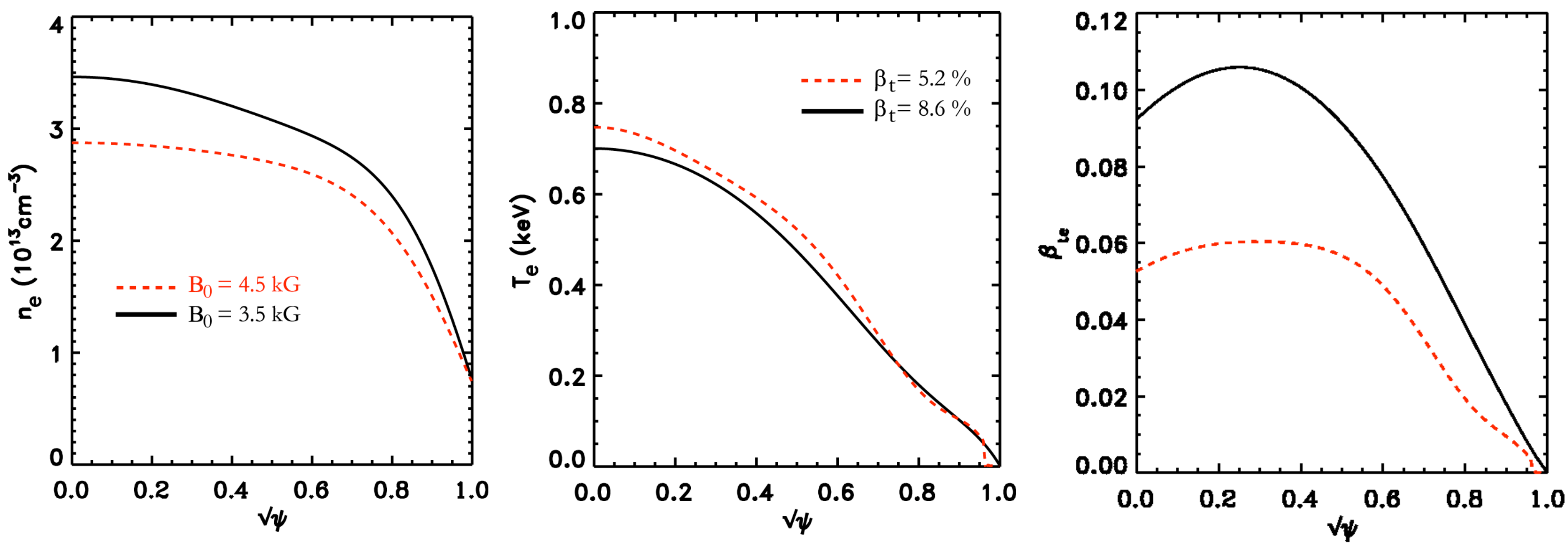
D.W. Swain

Time trace for n_e and T_e at high and low B



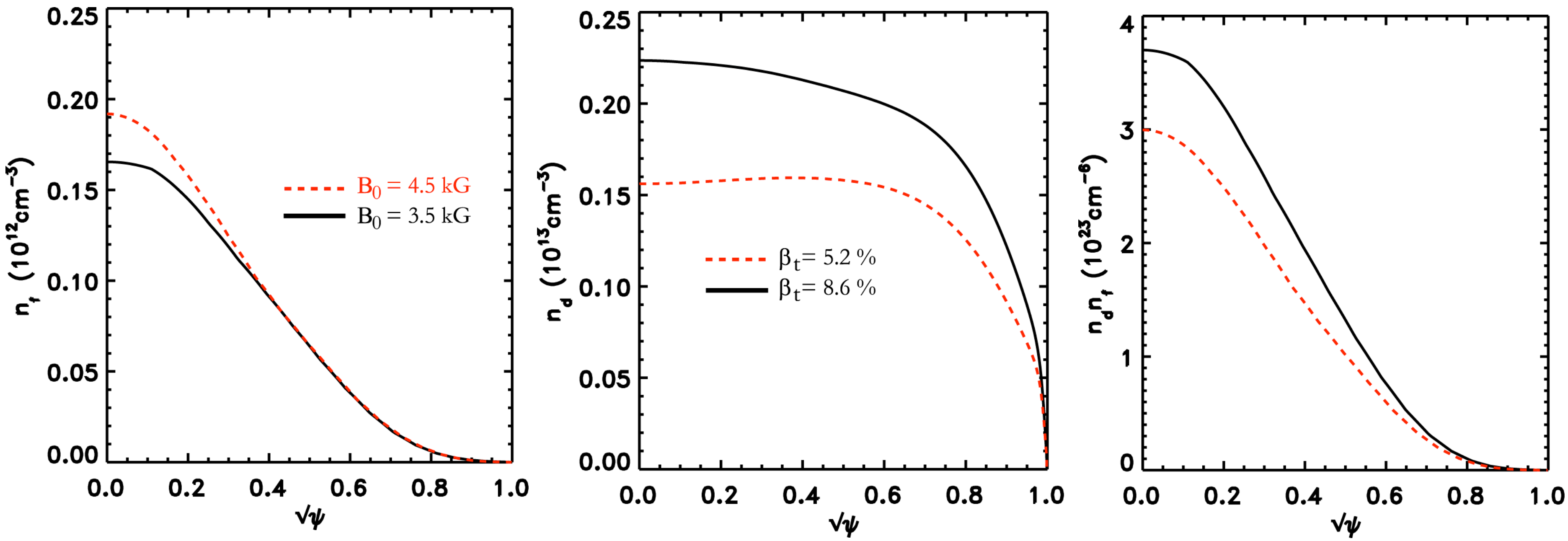
- Lower B, higher β_t shot has same current, similar T_e as low β_t
- $\bar{n}_e$ after NBI turn-on somewhat larger at lower B
- Neutron rate before RF turn-on larger at lower B

n_e,T_e, β_{te} profiles at high and low B, t = 235 ms



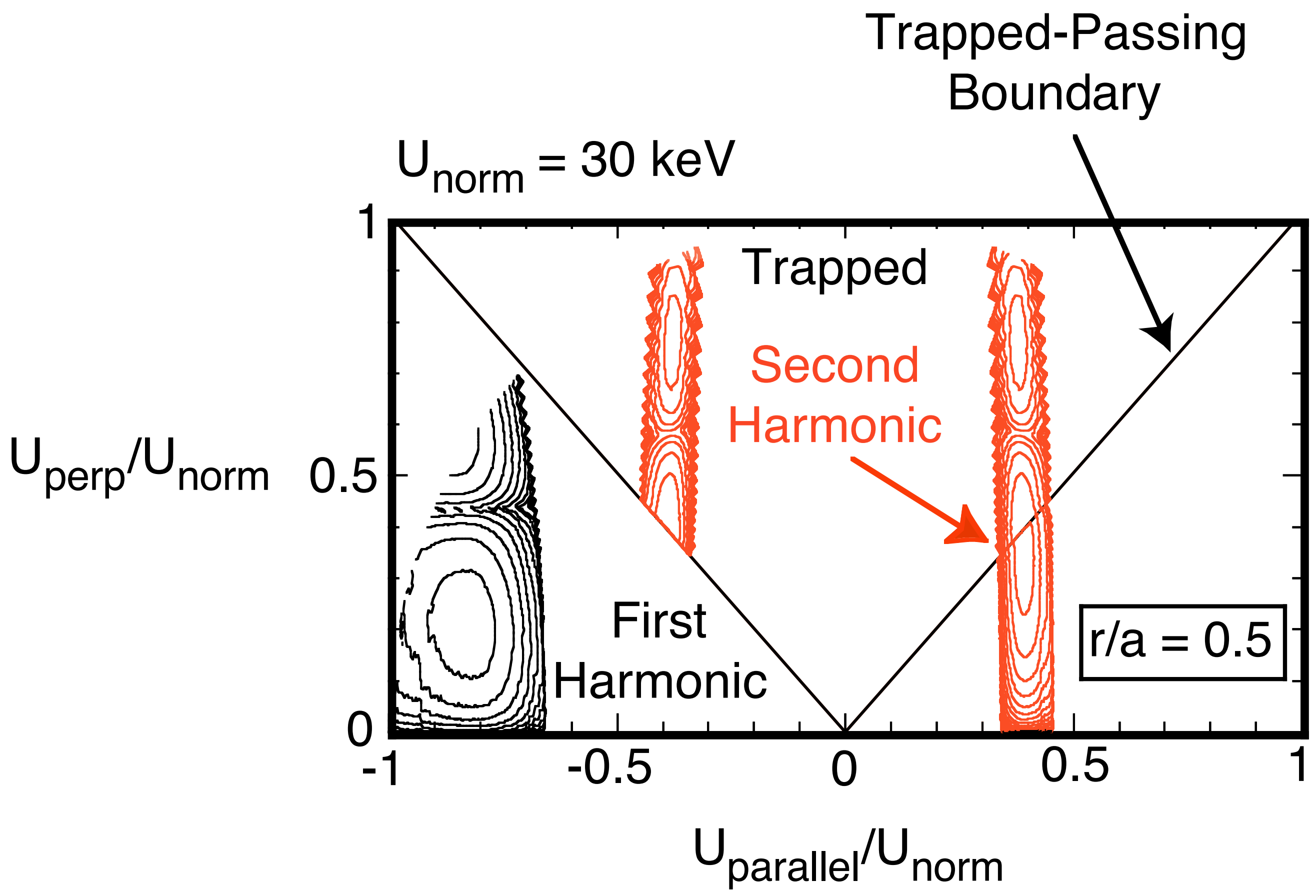
- n_e profile difference evident
- Midplane β_{te} profile difference far more prominent

n_d, n_f, profiles at high and low B, t = 235 ms



- Using measured Z_{eff} and TRANSP, n_{fast} and n_d determined
- Neutron rate n_d □ n_f, consistent with trace before RF
- RF-induced enhancement would be stronger if densities equal

Peak Diffusion in Vicinity of Trapped-Passing Boundary Enables Strong Ohkawa Current Drive



15 GHz RF launched at 65º above mid-plane, with $0.5 < n_{//} < 0.7$ into = 30% NSTX equilibrium

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