Exploration of High Harmonic Fast Wave Heating on NSTX

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OUTLINE

- Role and Characteristics of High Harmonic Fast Wave (HHFW) heating
- Technical Application on NSTX
- Electron Heating and Confinement Results
- Current Drive Experiments
- Interaction with Fast Ions
- Future Work
- Summary

HHFW HEATING PROVIDES A TOOL FOR ELECTRON HEATING AND CURRENT DRIVE

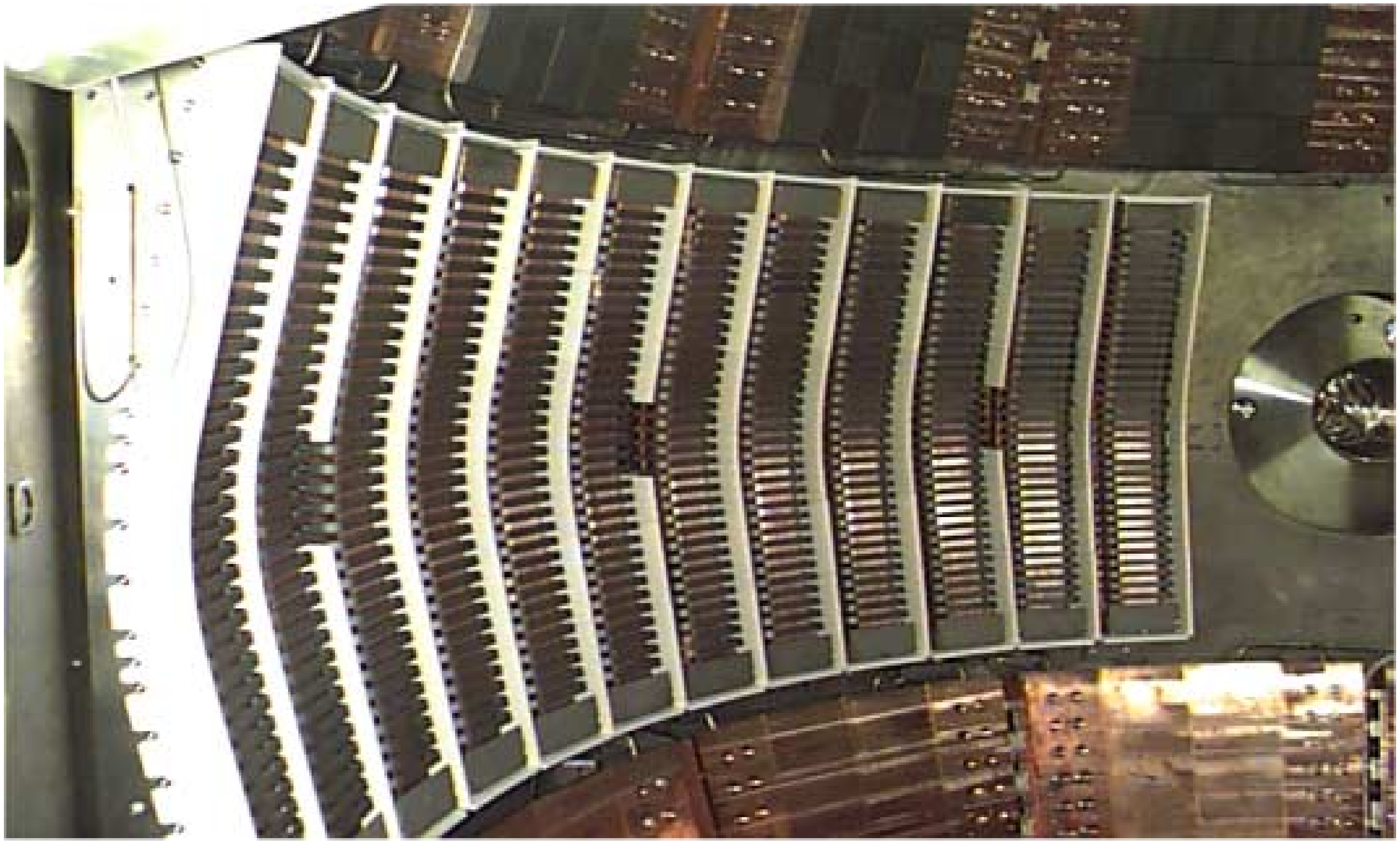
- ST's need auxiliary current drive (CD)
- High beta plasma makes Lower Hybrid and conventional Electron Cyclotron CD impossible
- HHFW in high beta plasmas has strong single pass absorption on electrons
  - Can allow off-axis deposition

FLEXIBLE SYSTEM FOR HIGH POWER HHFW HAS BEEN INSTALLED ON NSTX

- Utilizes TFTR ICRF system
- 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

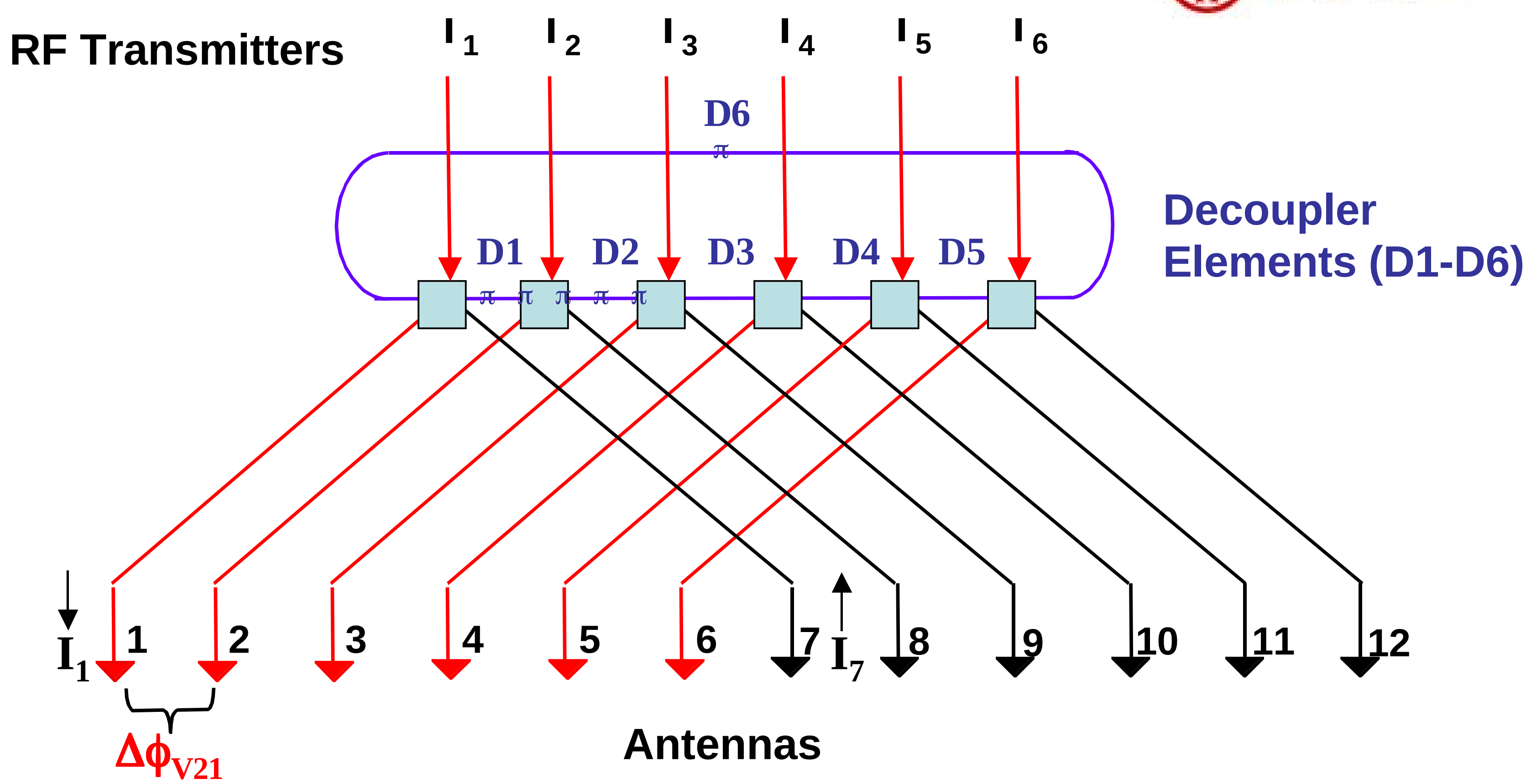
HHFW 12 ELEMENT ANTENNA ARRAY PROVIDES GOOD SPECTRAL SELECTIVITY

NSTX



- Antenna takes up almost 90° toroidally
- Utilizes BN insulators to minimize rf sheaths

DIGITAL PHASE FEEDBACK CONTROL SYSTEM SETS THE PHASE BETWEEN ANTENNA 1-6



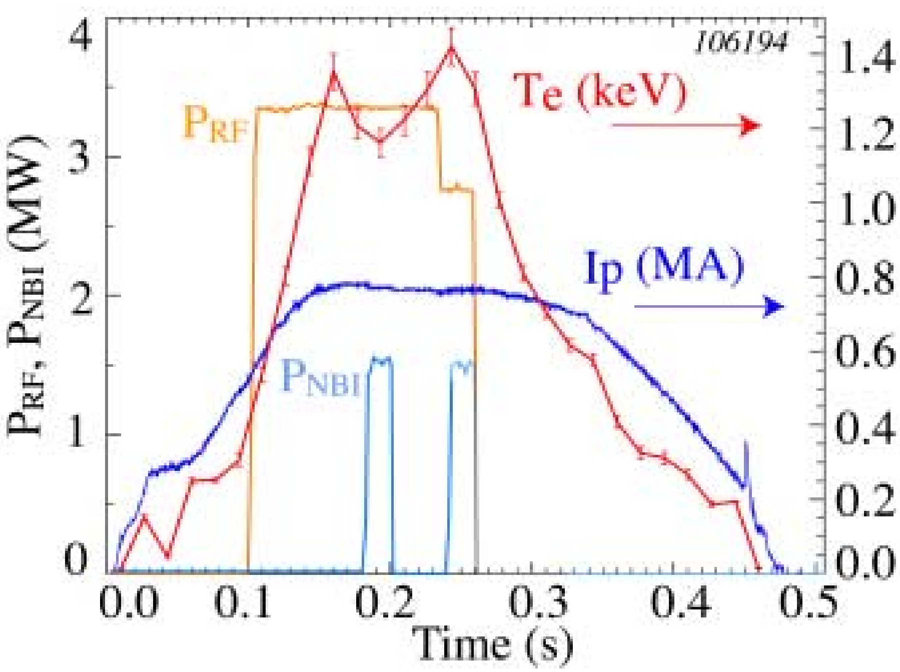
- Decouplers compensate for large mutual coupling between elements allowing phase control
- I^{th} and i^{th} + 6 antenna currents hard wired out of phase

HHFW HEATS ELECTRONS IN NSTX, AS EXPECTED FROM THEORY

- For typical NSTX plasmas HHFW deposits all its power into electrons
  - No evidence of 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

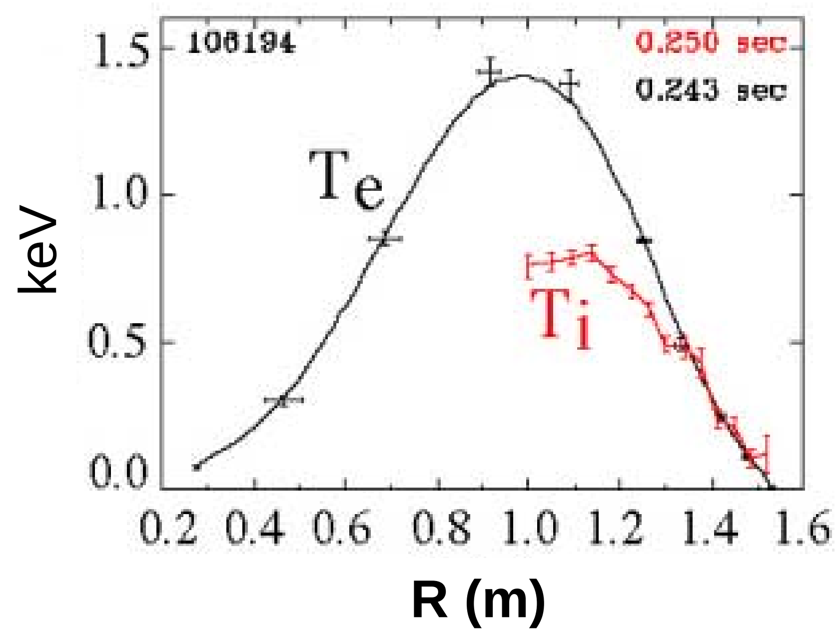
HHFW PROVIDES STRONG ELECTRON HEATING

He Discharge



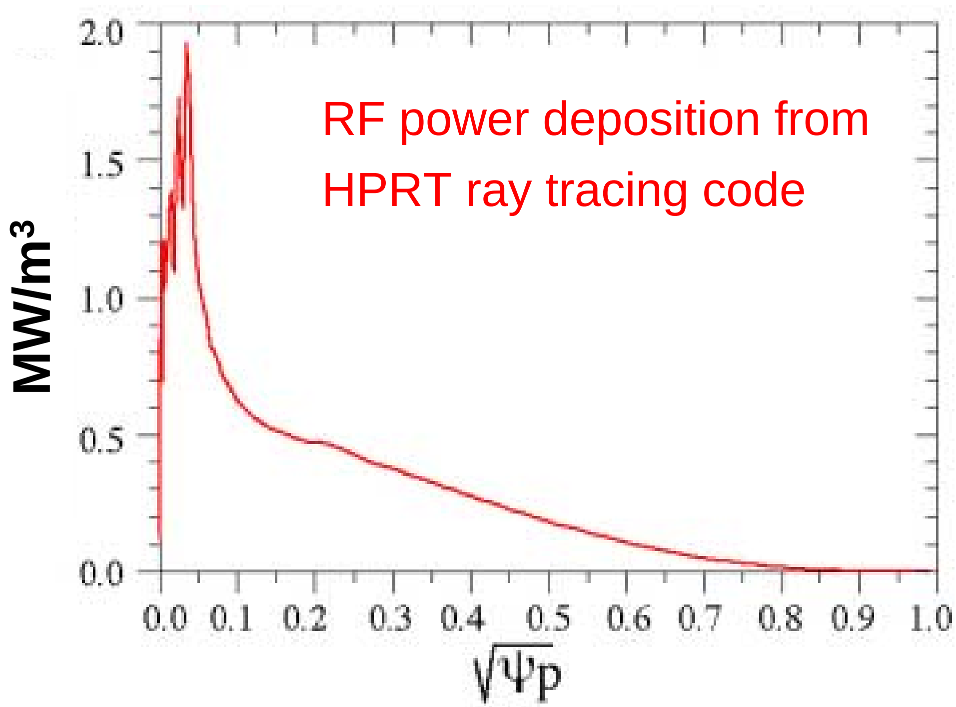
NOTE LOW INTIAL T_e

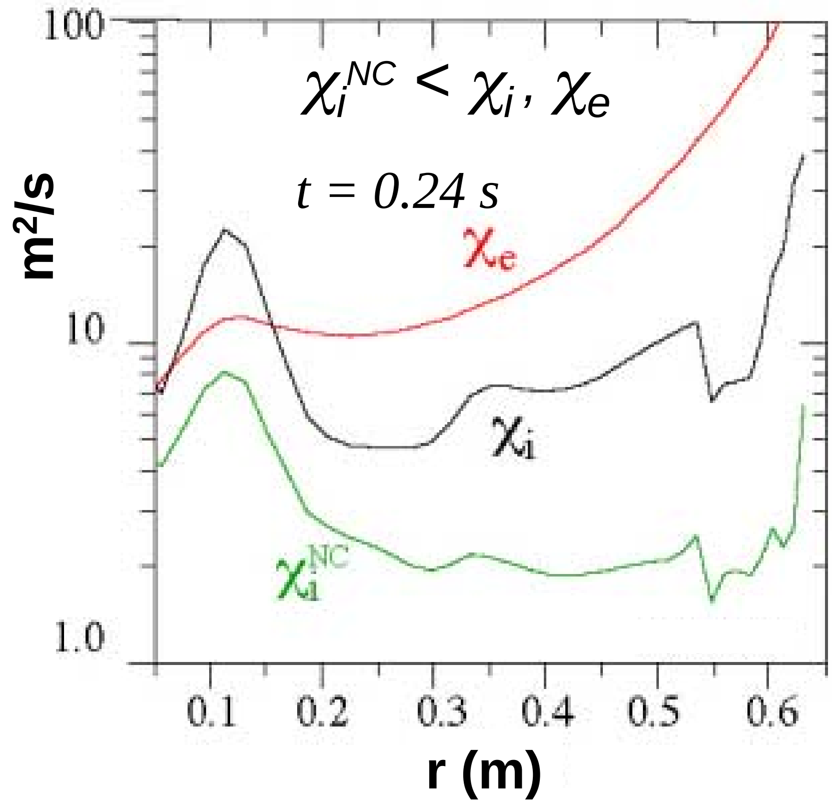
$T_e > T_i$



- B = 0.44 T
- $\mathbf{k}_T$ = 14 m^{-1}
- n_{e0} = 4.0 x 10^{19} m^{-3}

BOTH ELECTRONS AND IONS EXCEED NEOCLASSICAL IN HHFW HEATED PLASMAS

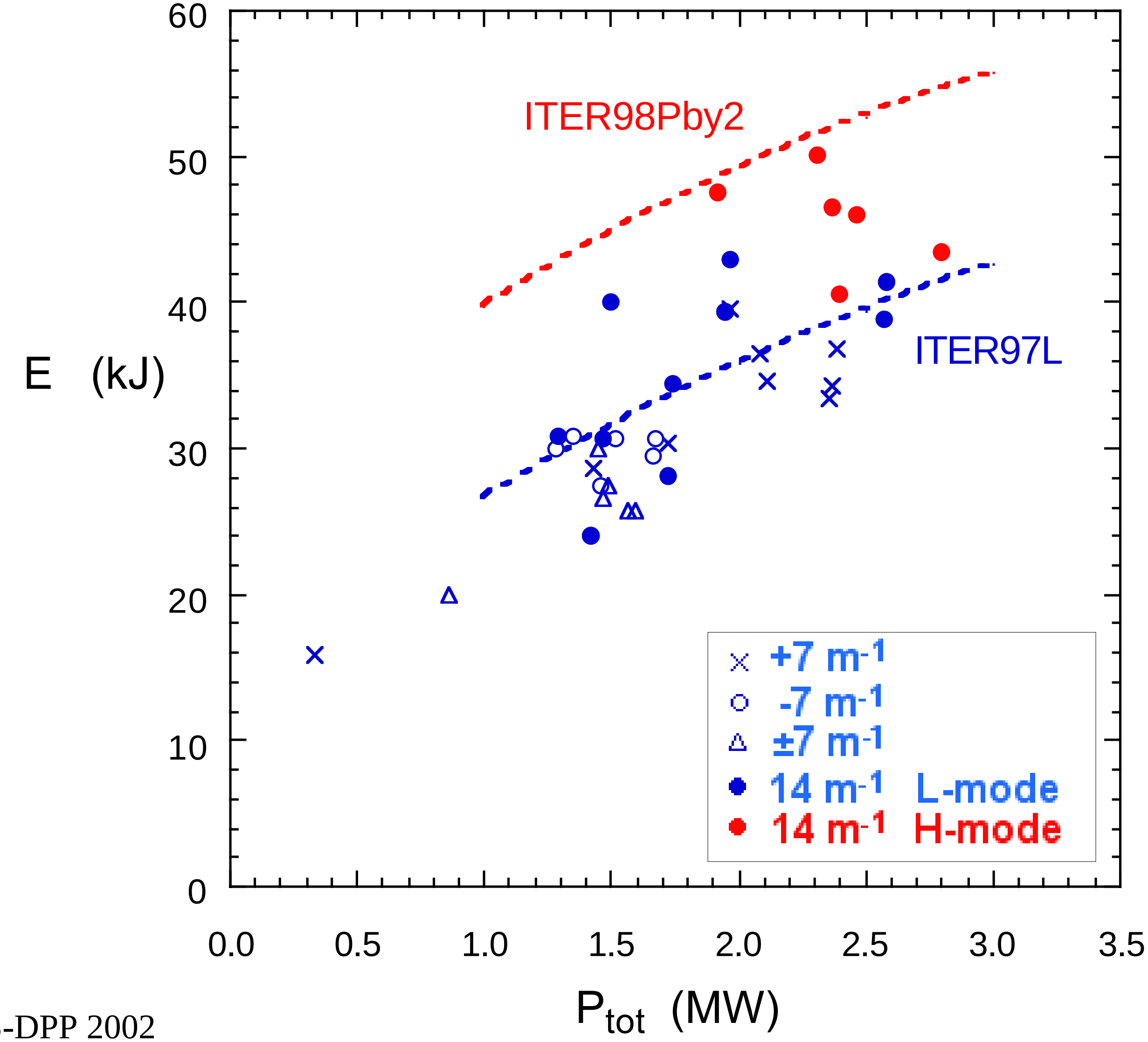




- Consistent with transport from Trapped Electron Modes
  - –Calculated to dominate in NSTX regime

Increasing χ_e with radius unlike NBI heating

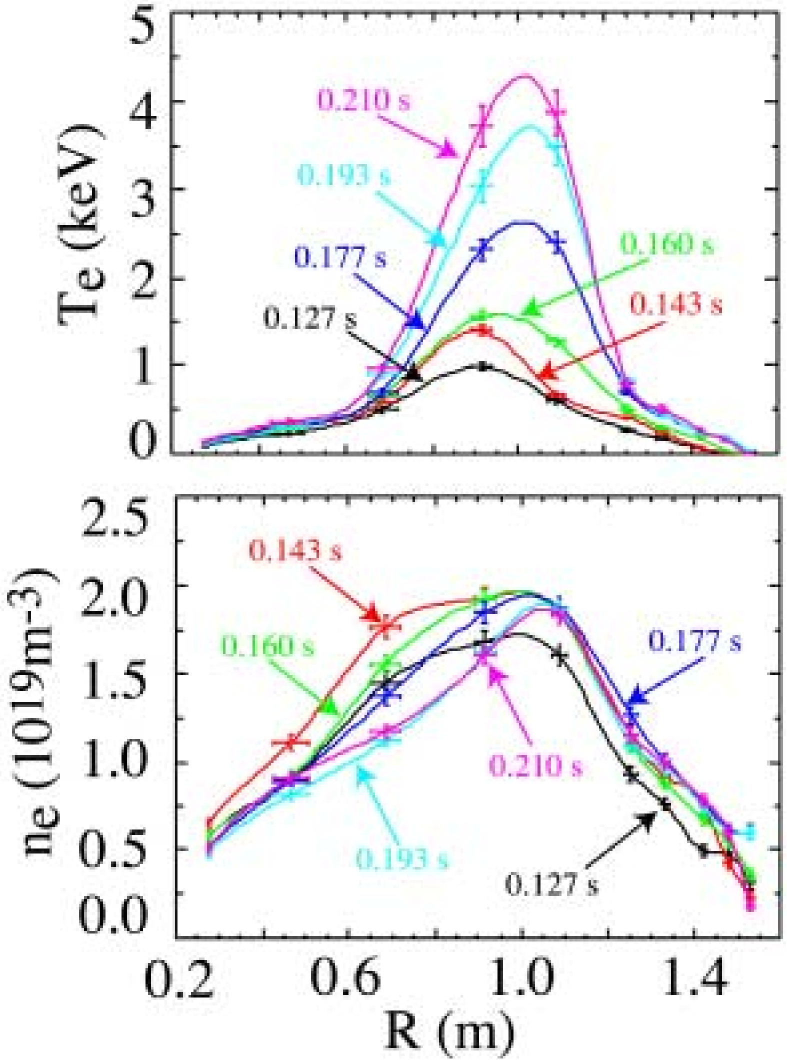
HEATING WITH HHFW FOLLOWS PREDICTIONS OF CONVENTIONAL SCALING



I_p= 500 kA
B_T= 4.5 kG
$\langle n_e \rangle$ =1.5 x10^{19} m^{-3}

H mode defined by appearance of edge pedestal

SOME HHFWDISCHARGES DISPLAY BEHAVIOR OF INTERNAL TRANSPORT BARRIER



T_e increases strongly inside half radius

Density profile doesn't show change

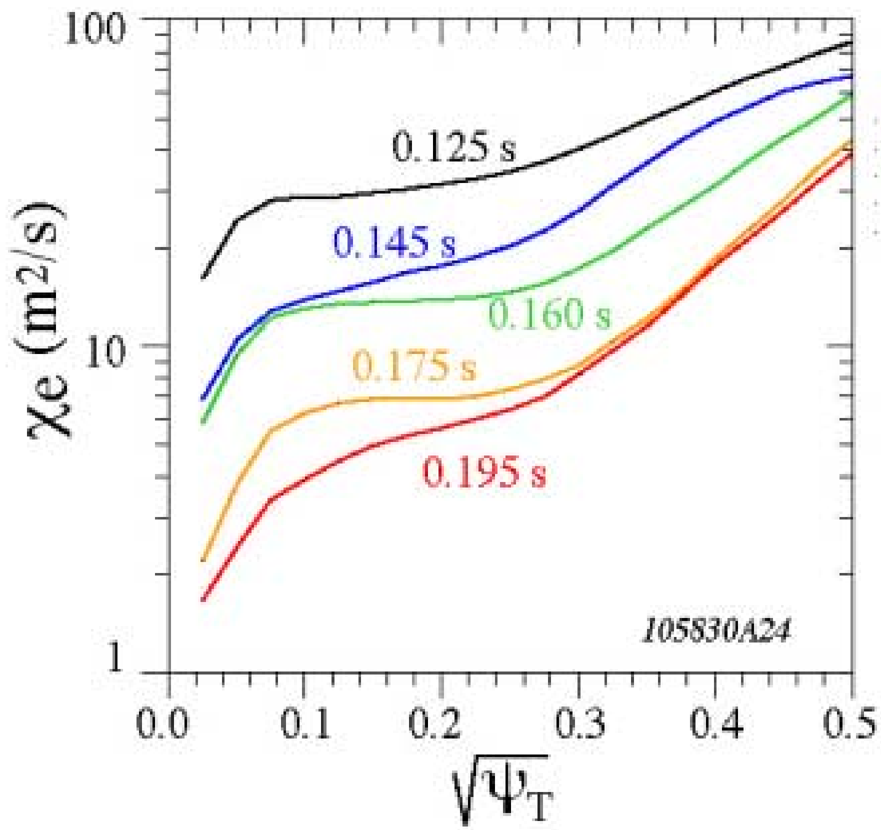
T_i(0) rises with T_e increase

Prf = 2.5 MW

Ip = 800 kA

INCREASE IN T_e CORRESPONDS TO DECREASE IN χ_e

- χ_e progressively decreases in the central region
- Power deposition from ray tracing
- $T_{io}(t)$ obtained from X-ray crystal spectrometer

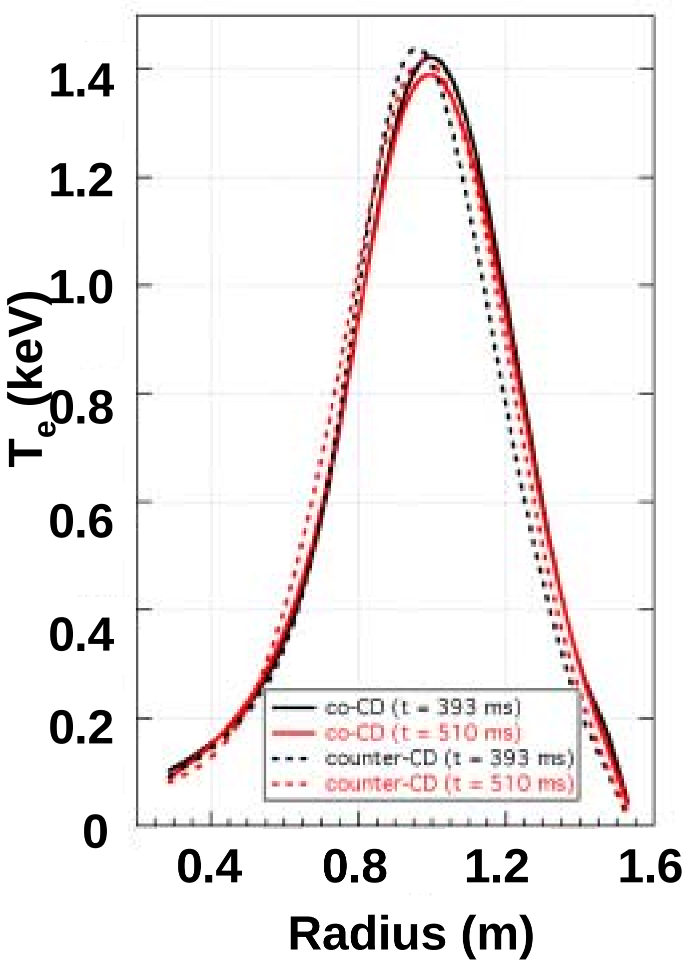


DIFFERENCES IN LOOP VOLTAGE WITH DIRECTED SPECTRA ARE CONSISTENT WITH CURRENT DRIVE

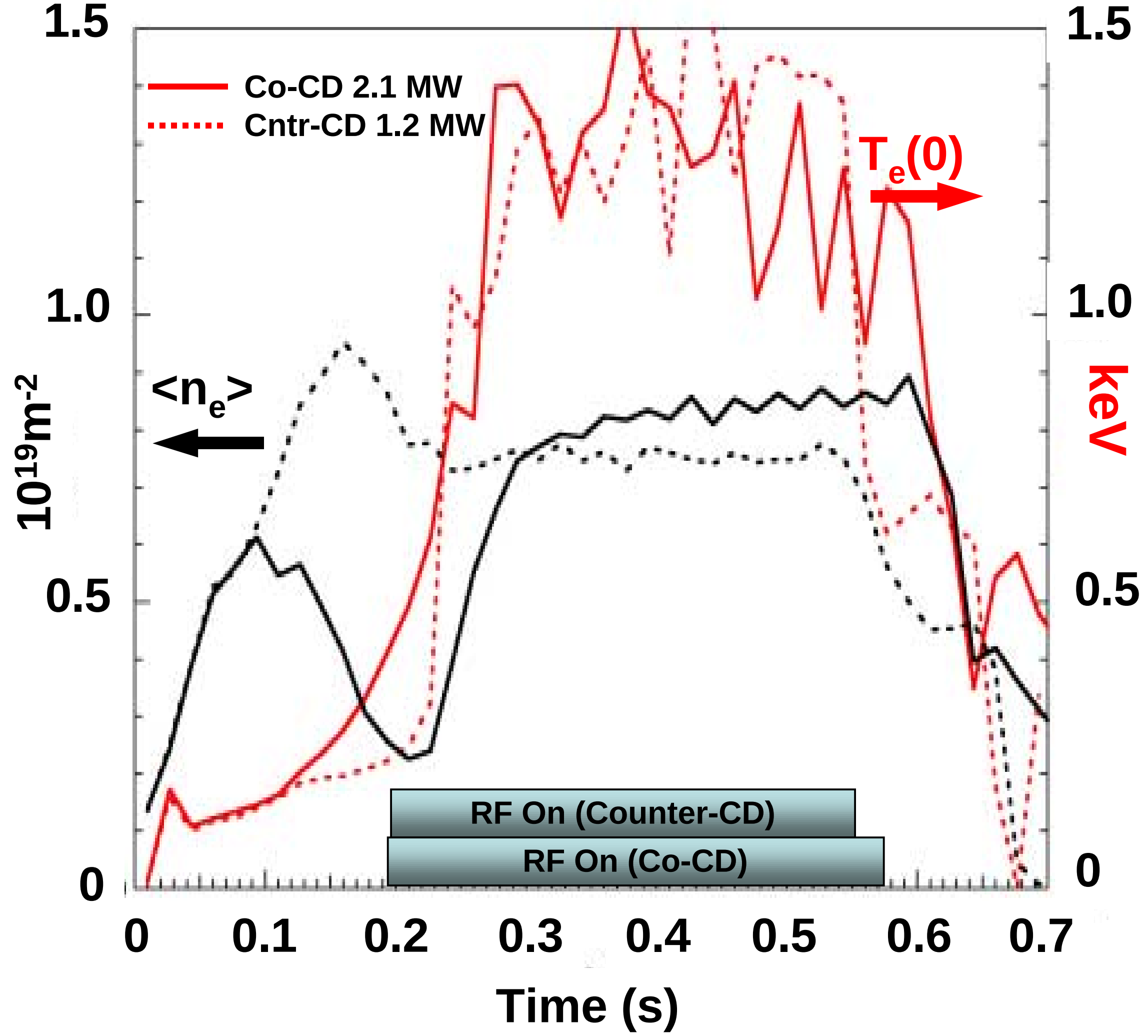
- Experiment performed at low electron beta and low current to maximize effect of rf current drive on loop voltage
- Compare discharges with wave phased ± (3-7) m^{-1}
- Adjust power levels and fueling to match density and temperature profiles
- Loop voltage differences seen in the absence of central MHD (sawteeth, m=1)
- Amount of driven current inferred from circuit analysis of magnetic signals is comparable to theoretical predictions

ELECTRON PARAMETERS MADE COMPARABLE BY ADJUSTING POWER AND FUELING

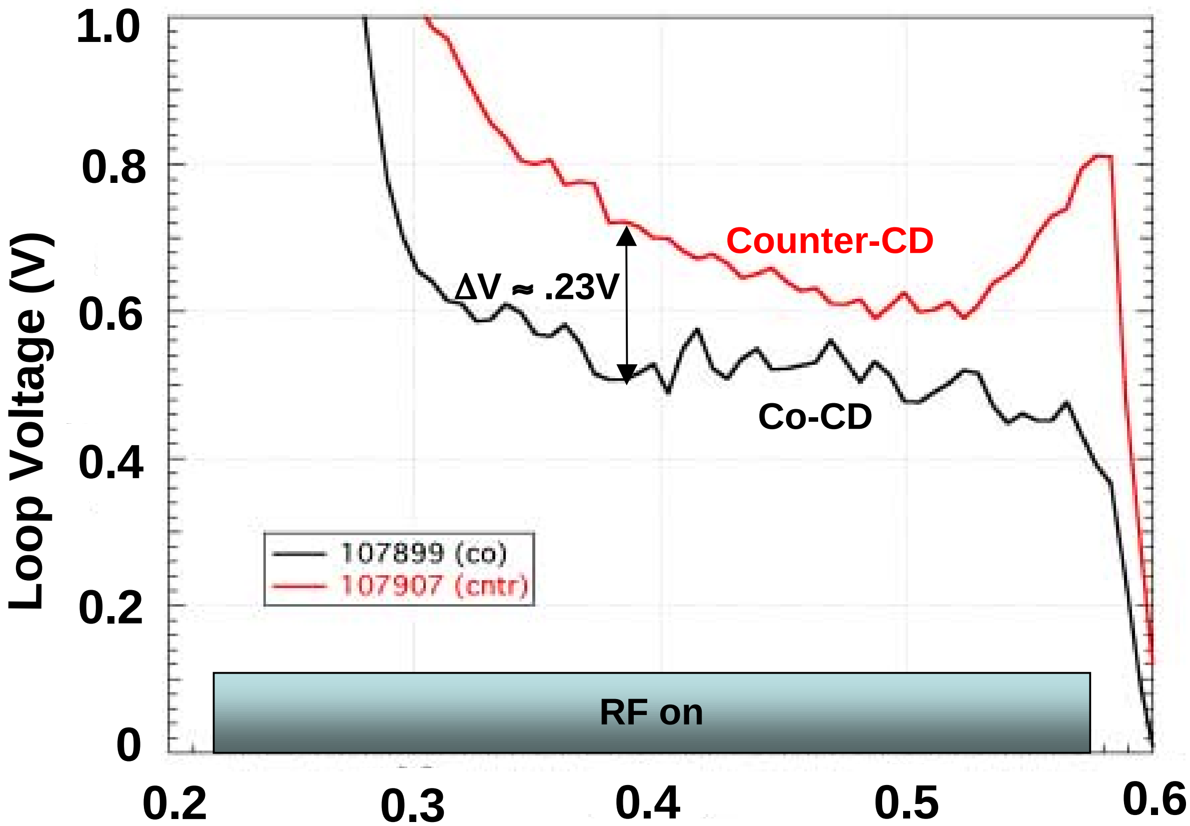
Temperature profiles matched throughout discharges



I_P = 500 kA, B_T = 4.5 kG



LESS LOOP VOLTAGE REQUIRED TO MAINTAIN I_P WITH CO PHASING



$k_T = \pm 7\ m^{-1}$

Internal inductance is similar for the two cases and ΔV is not caused by dl_i/dt

Also seen at faster phasing - $k_T = \pm(3, 5)\ m^{-1}$

CURRENT DRIVE MODELING ANALYSIS AND CODE PREDICTIONS IN ROUGH AGREEMENT

Circuit analysis (0D): $I_P = (V - 0.5 * I_P * dL_i/dt)/R_P + I_{BS} + I_{CD}$

(Assumes steady state, R_P and I_{BS} (pressure profiles) independent of array phasing, $I_{CD} \propto P_{RF}/n_e$)

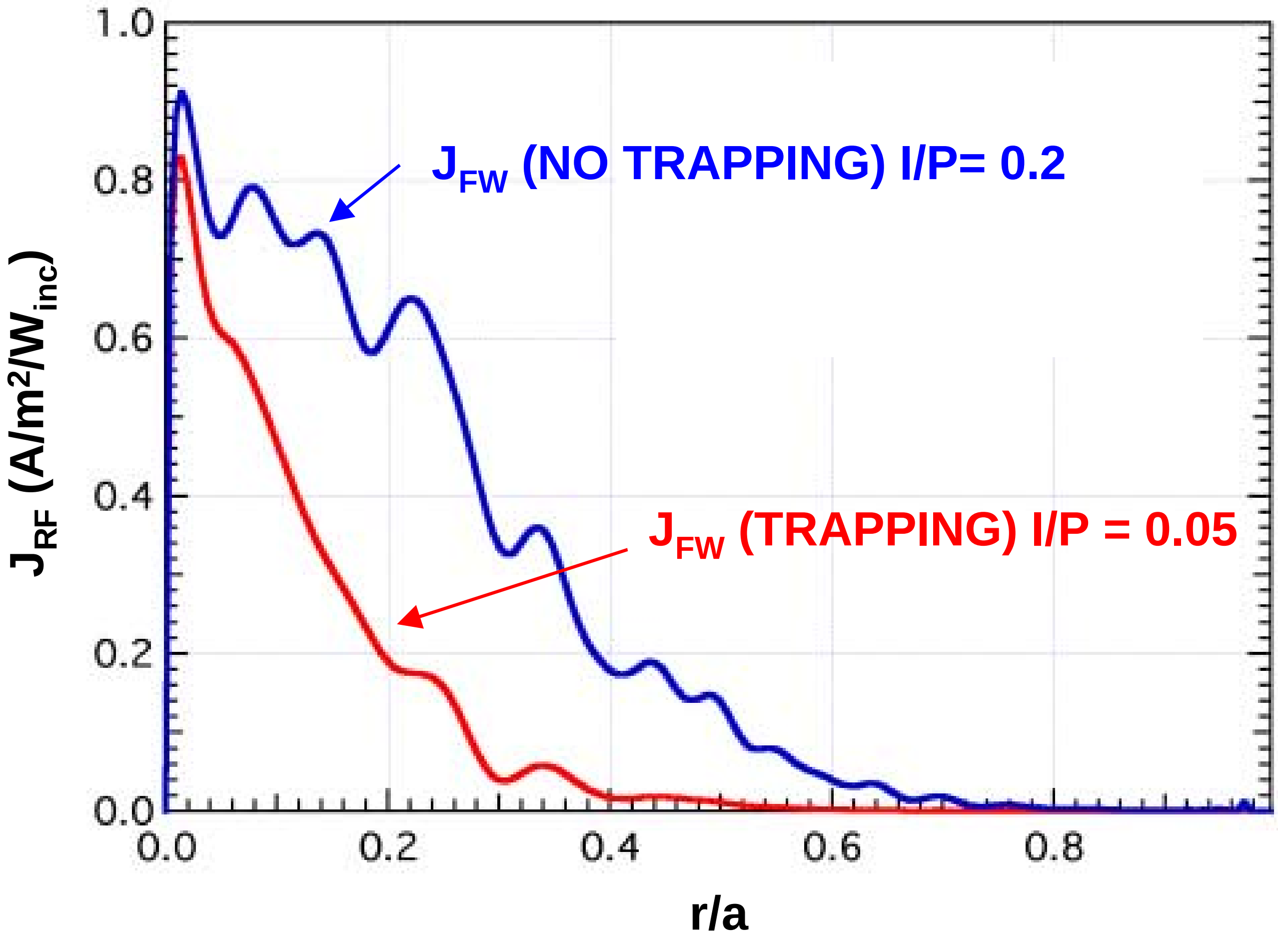
- ➢ **$I_{CO} \approx$ 110 kA (0.05 A/W)**

Codes - Calculated electron power absorption profiles are coupled to the Ehst-Karney parameterization of the adjoint solution for current drive efficiency to obtain current density profiles

- **TORIC**: Full wave ICRF field solver $[(k_\perp \rho_i)^2 << 1]$
  - ➢ **$I_{CO} \approx$ 96 kA (0.05 A/W)**
- **CURRAY**: Ray tracing code (all orders in $k_\perp \rho_i$)
  - ➢ **$I_{CO} \approx$ 162 kA (0.08 A/W)**

TRAPPING SIGNIFICANTLY REDUCES DRIVEN CURRENT

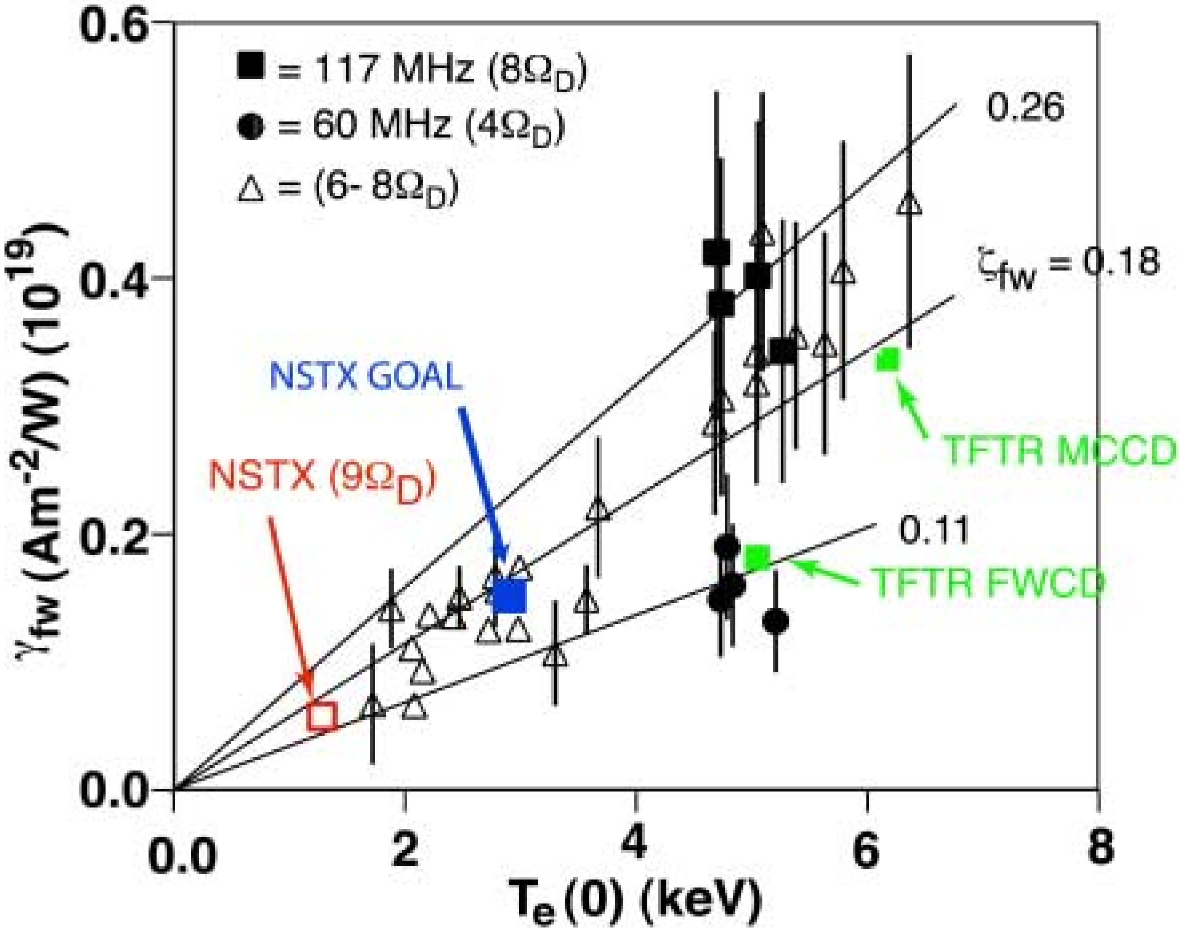
Calculated Driven Current Density Profiles



TORIC CALCULATION FOR NSTX CO CD SHOT

- **The "no trapping" profile is indicative of the power deposition profile**
- **Diamagnetic effects at high beta may reduce trapping**

HHFW CURRENT DRIVE CONSISTENT WITH D-IIID AND TFTR CD EXPERIMENTS



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

Operation at increased Te required to meet NSTX goals
Increased Power and improved confinement regime should allow this

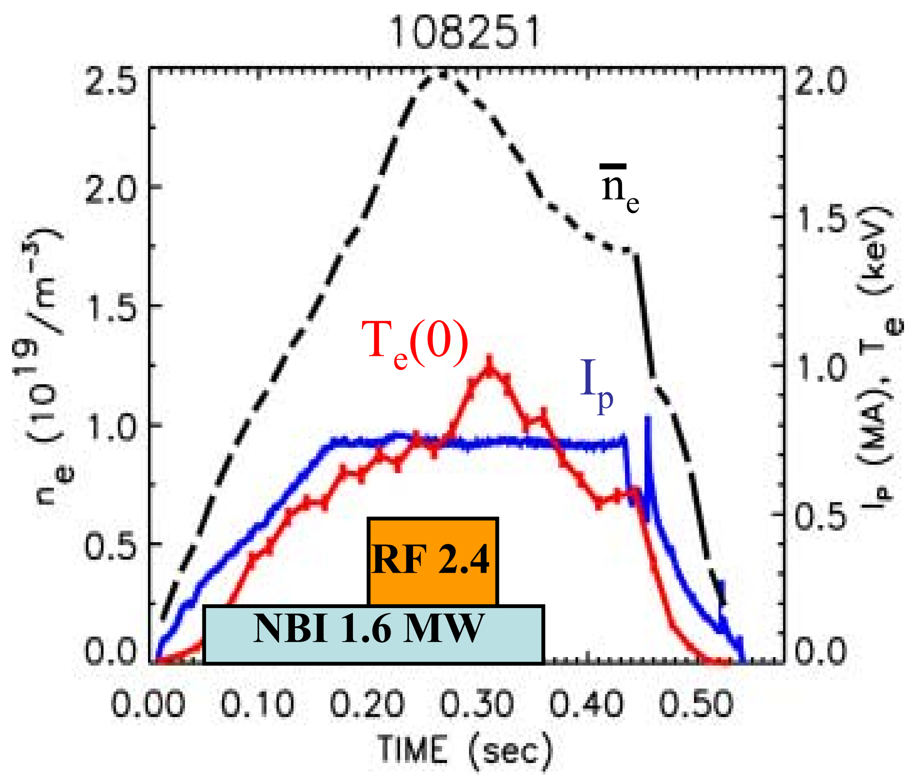
HHFW PREDICTED TO INTERACT WITH FAST IONS

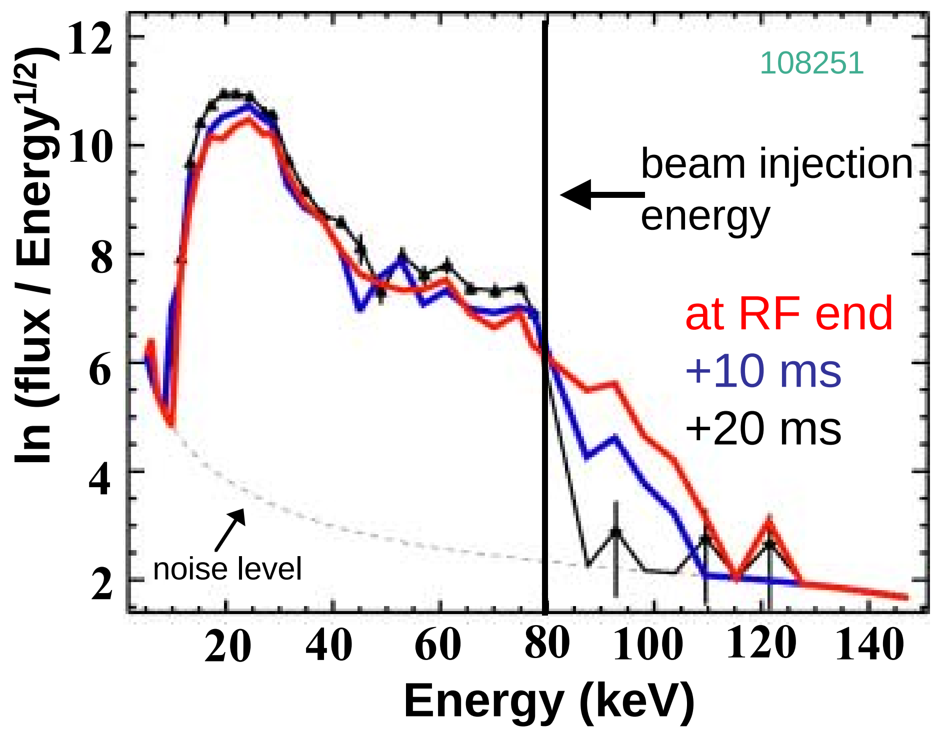
- Damping on beam ions may reduce current drive efficiency
- At high harmonic numbers ($n \geq 9$) ion damping can be important due to large $k_\perp \rho_i$
  - On NSTX $k_\perp \rho_i \sim 10$ for 80 keV beam ion
  - Damping maximum when $\lambda = (k_\perp \rho_i)^2/2 \sim n^2/3$

    $\sim$ 35 keV for n=9

NEUTRAL PARTICLE ANALYZER SHOWS FAST ION TAIL BUILD-UP AND DECAY

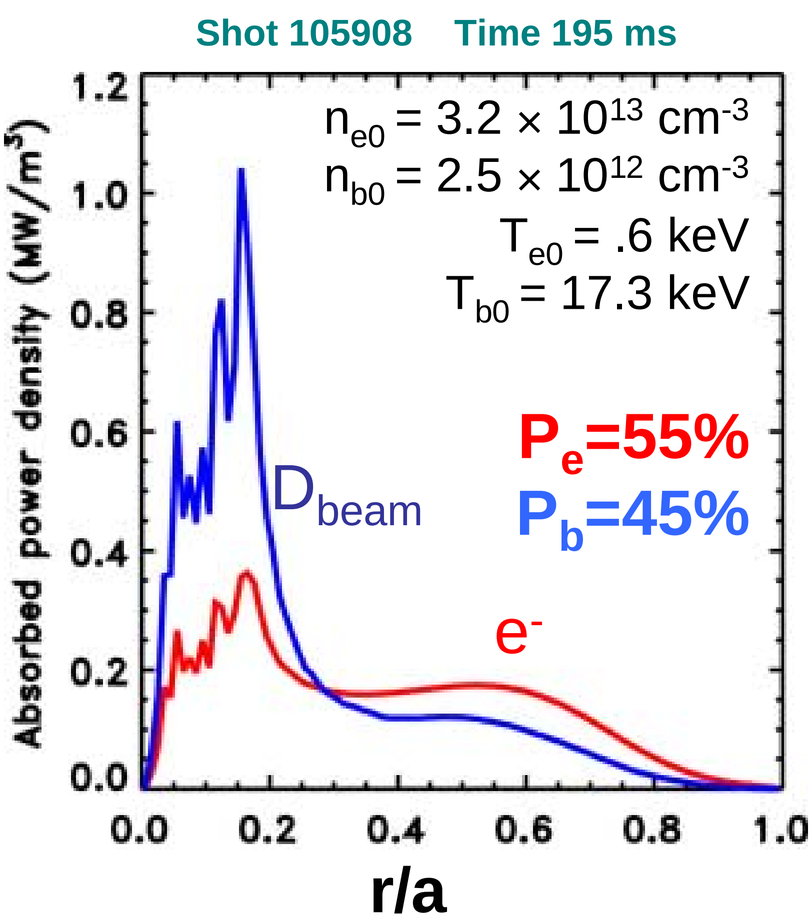
- D^+ tail extends to 130 keV
- Tail saturates in time during HHFW





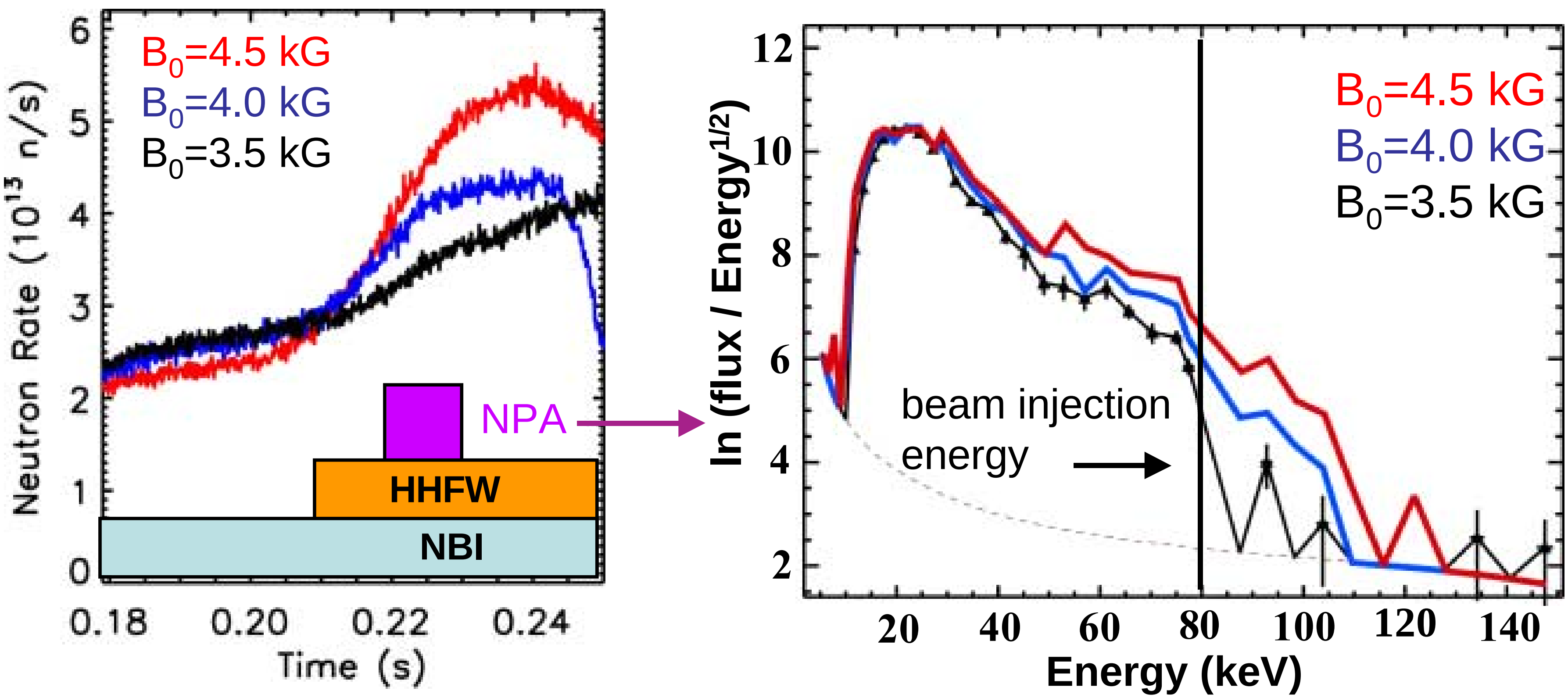
- Tail decays on collisional time scale

RAY TRACING PREDICTS SIGNIFICANT ION ABSORPTION - COMPETITIVE WITH ELECTRONS



- HPRT computes hot plasma absorption over cold ion/hot electron ray path
- 25 rays used
- TRANSP output used as input for fast ion temp and density distribution
- Fast ions dominate central absorption, electrons further off-axis
- $T_{i,th}$ = 2 T_e (XCS), no thermal ion absorption

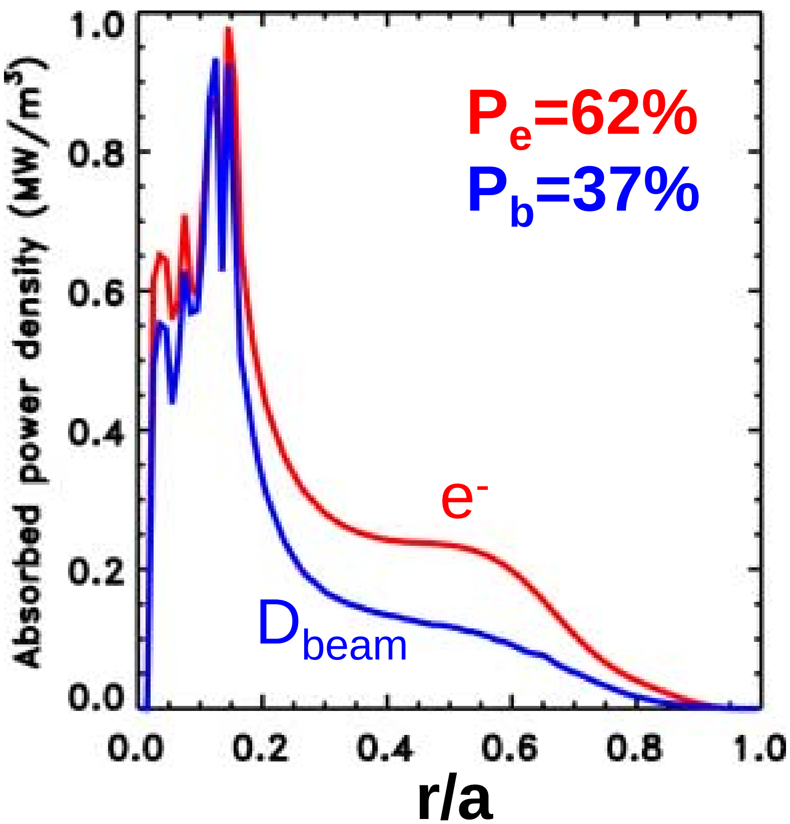
TAIL REDUCED AT LOWER B, HIGHER β



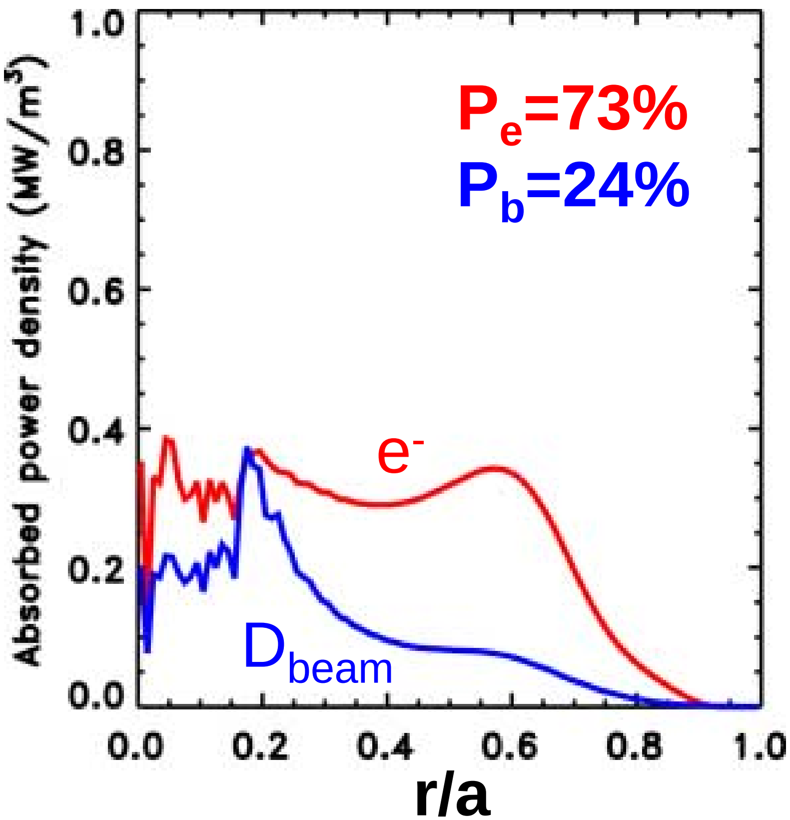
- Larger β_e promotes greater off-axis electron absorption reducing power available to centralized fast ion population

OBSERVATION OF REDUCED FAST ION ABSORPTION AT HIGHER β IS CONSISTENT WITH THEORY

β_t=5%, B_0=4.5 kG



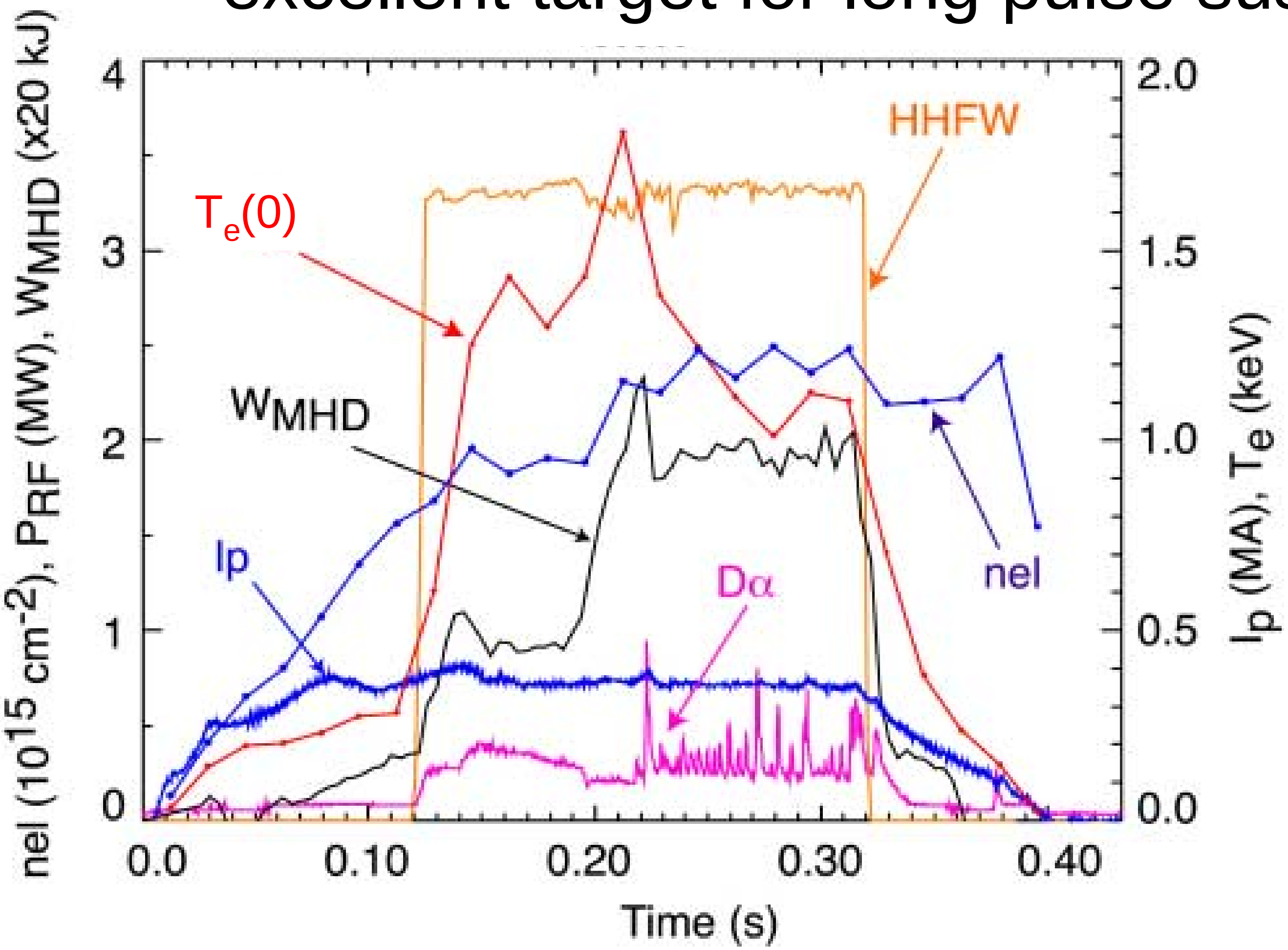
β_t=9%, B_0=3.5 kG



- Lower on-axis absorption for lower B, higher β predicted

FUTURE WORK INCLUDES EXTENDING RF CURRENT DRIVE TO LONG PULSE SUSTAINMENT

- High beta poloidal H-mode plasmas provide excellent target for long pulse sustainment



β_p =1

I_{BS}/I_P = 0.4

q(0) rises

l_i drops

k_T = ±14 m^{-1}

SUMMARY

- HHFW PROVIDES MEANS OF ELECTRON HEATING ON NSTX
  - Confinement consistent with predictions of standard scaling
  - Improved confinement regime observed

- INITIAL EVIDENCE OF CURRENT DRIVE
  - Driven current is consistent with modeling and previous FWCD experiments
  - Increased Te needed to achieve NSTX goals
    - Improved confinement regime
    - Higher power

- INTERACTION BETWEEN HHFW AND NBI IONS OBSERVED
  - Ion interaction decreases with increasing electron beta