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Recent Improvements in Fast Wave Heating in NSTX

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In collaboration with

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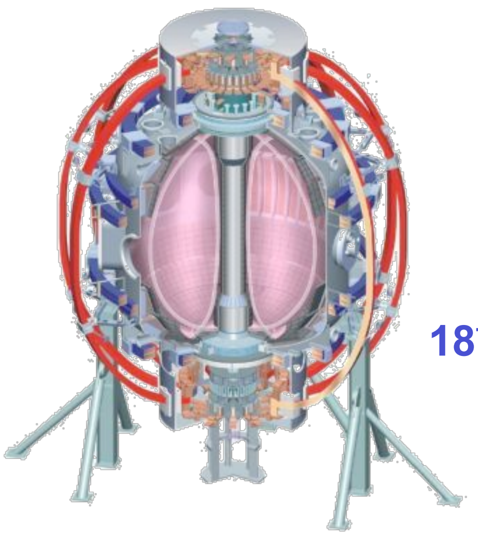

18th Conference on RF Power in Plasmas
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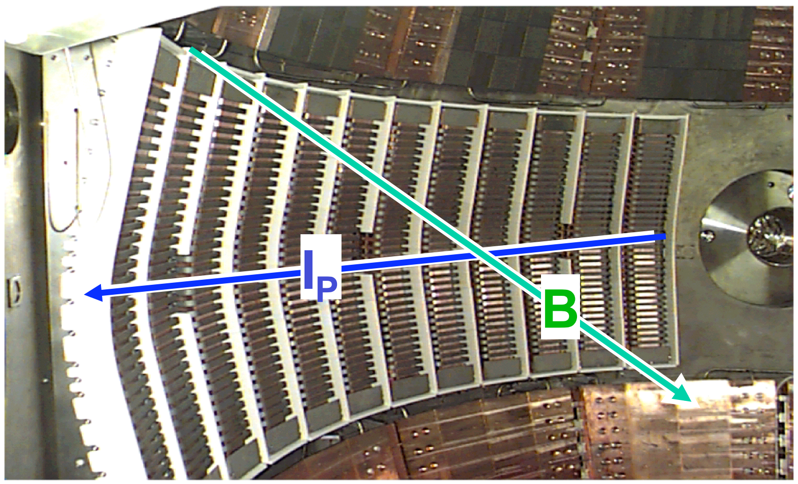
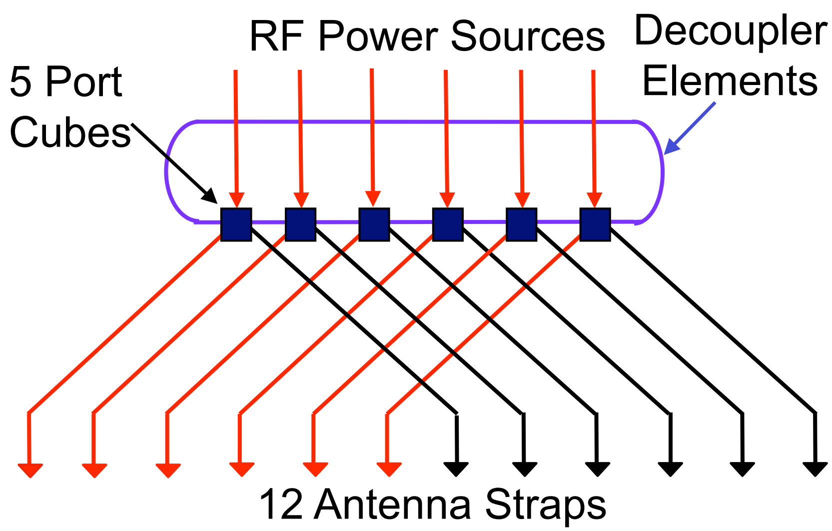
Abstract

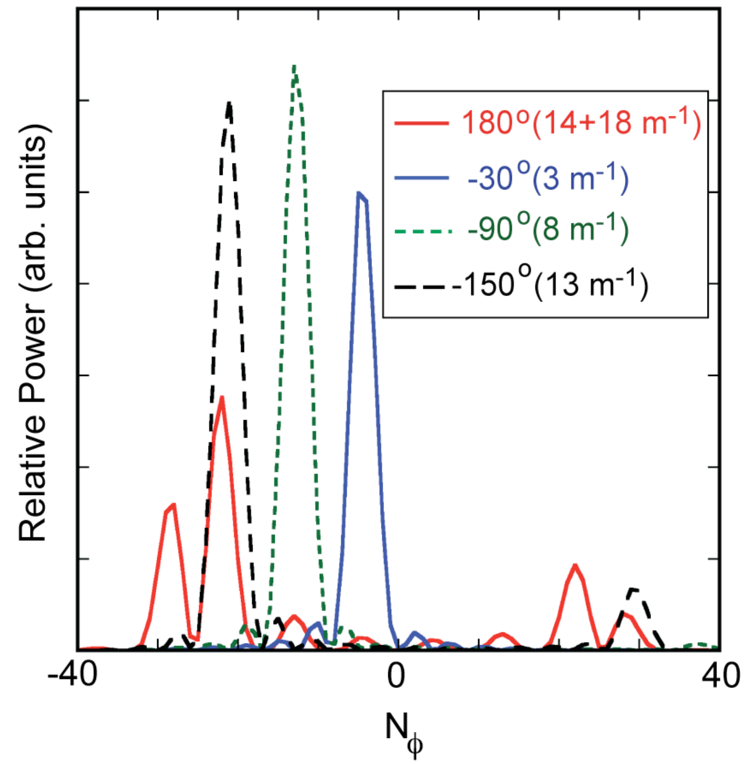
Recent improvements in high-harmonic fast wave (HHFW) core heating in NSTX are attributed to using lithium conditioning, and other wall conditioning techniques, to move the onset density for fast wave propagation further from the antenna. This has resulted in the first observation of HHFW core electron heating in deuterium plasma at a launched toroidal wavenumber, $k_\phi = -3\ m^{-1}$, NSTX record core electron temperatures of 5 keV in helium and deuterium discharges and, for the first time, significant HHFW core electron heating of deuterium neutral-beam-fuelled H-mode plasmas. Also, $k_\phi = -8\ m^{-1}$ heating of the plasma start-up and plasma current ramp-up has resulted in significant core electron heating, even at central electron densities as low as ~ $4 \times 10^{18}\ m^{-3}$.

NSTX HHFW Antenna Has Well Defined Spectrum, Ideal for Studying Phase Dependence of Heating



HHFW antenna extends toroidally 90º

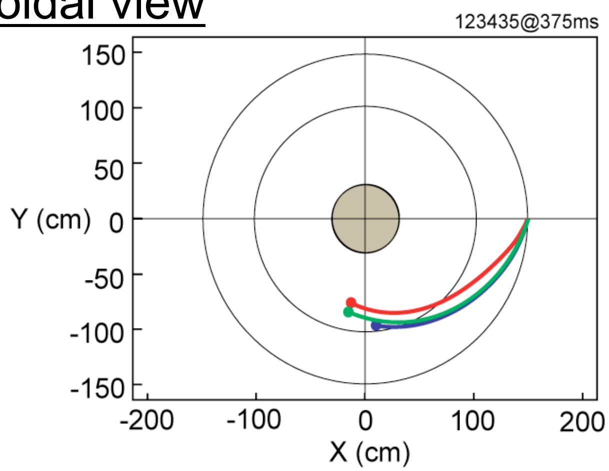




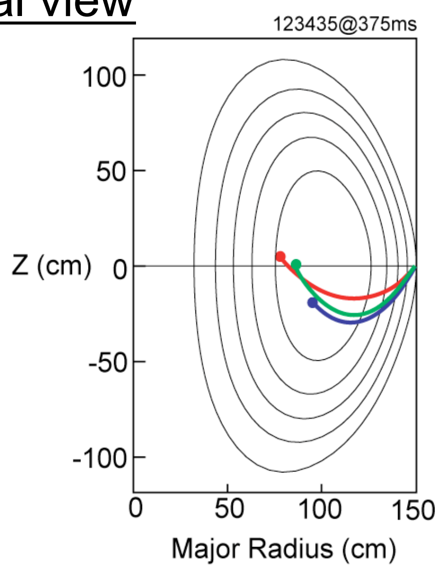
- Straps in each loop fixed at 180º out of phase
- Phase between adjacent loops easily adjusted between 0º to 180º
- Large B pitch affects wave spectrum in plasma core

Strong "Single Pass" Fast Wave Absorption Ideal for Studying Core Heating Versus Edge Power Loss

GENRAY: Toroidal view



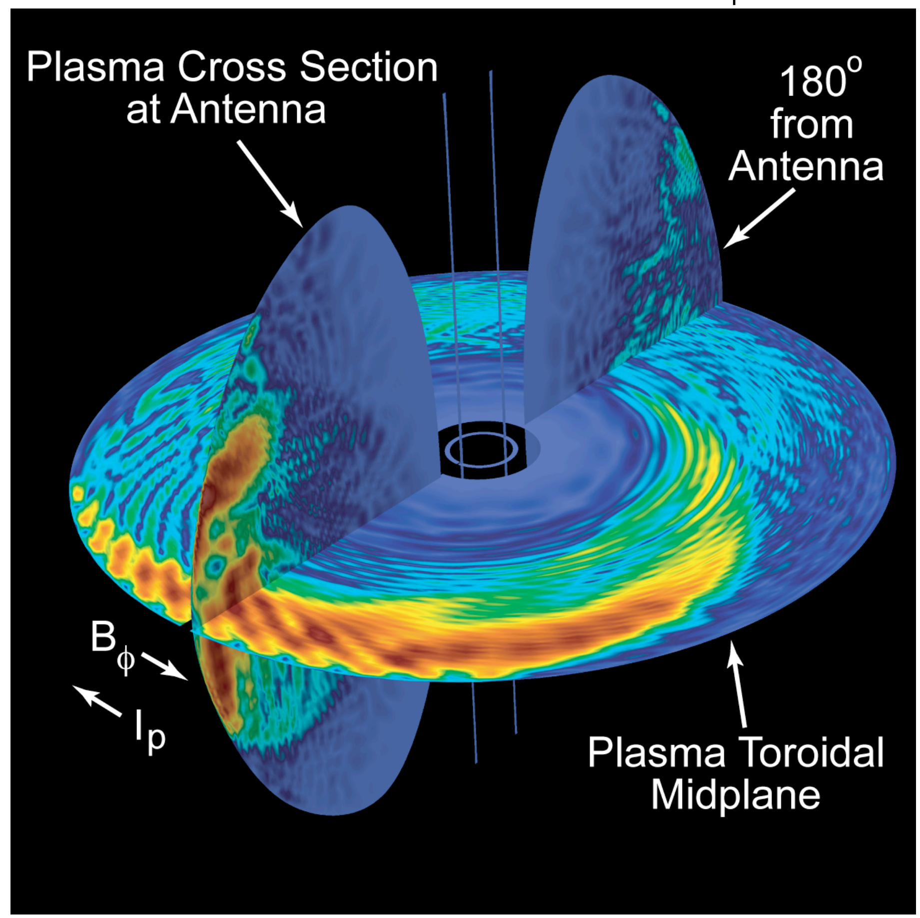
Poloidal view



$\Delta\phi = -30^\circ$
$\Delta\phi = 180^\circ$
$\Delta\phi = -90^\circ$

Rays stopped when 80% of RF power is damped

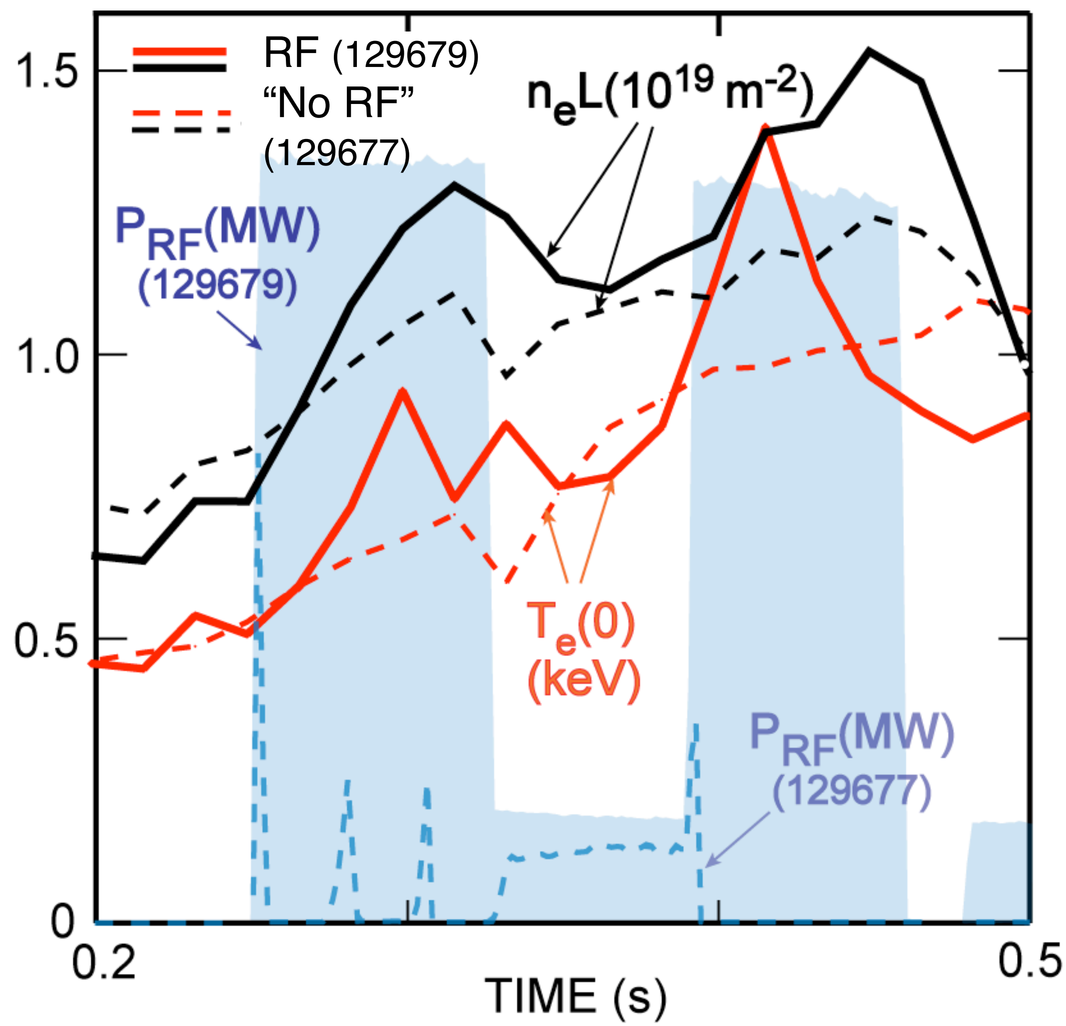
AORSA: $|E_{RF}|$ field amplitude for $\Delta\phi = -90^o$ antenna phase & 101 n_ϕ modes



- Edge power loss occurs in the vicinity of the antenna, no multi-pass damping

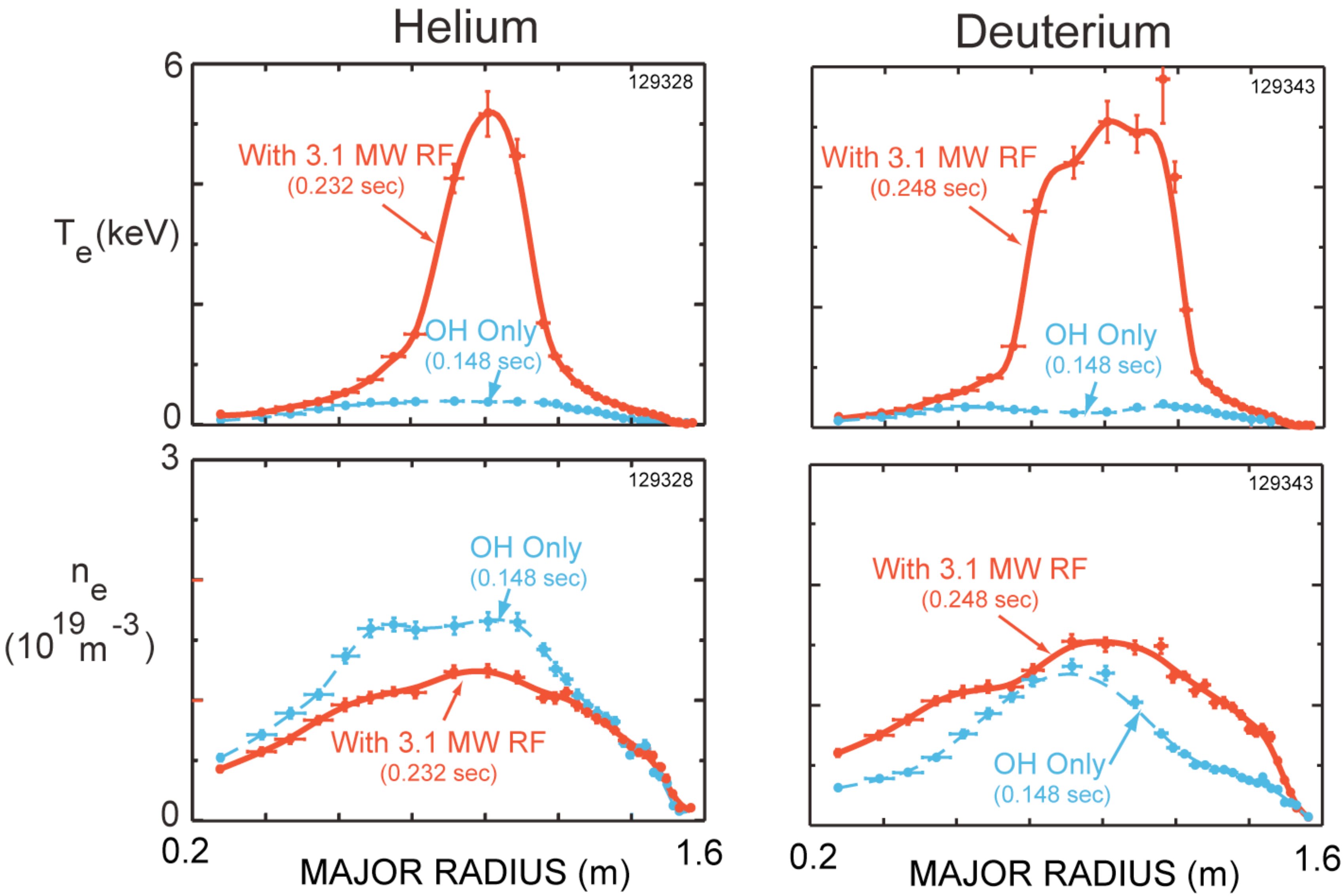
Improved HHFW Heating of L-Mode Plasmas

Electron Heating in Deuterium Plasma at $k_\phi = 3\ m^{-1}$ Seen Only After Lithium Wall Conditioning

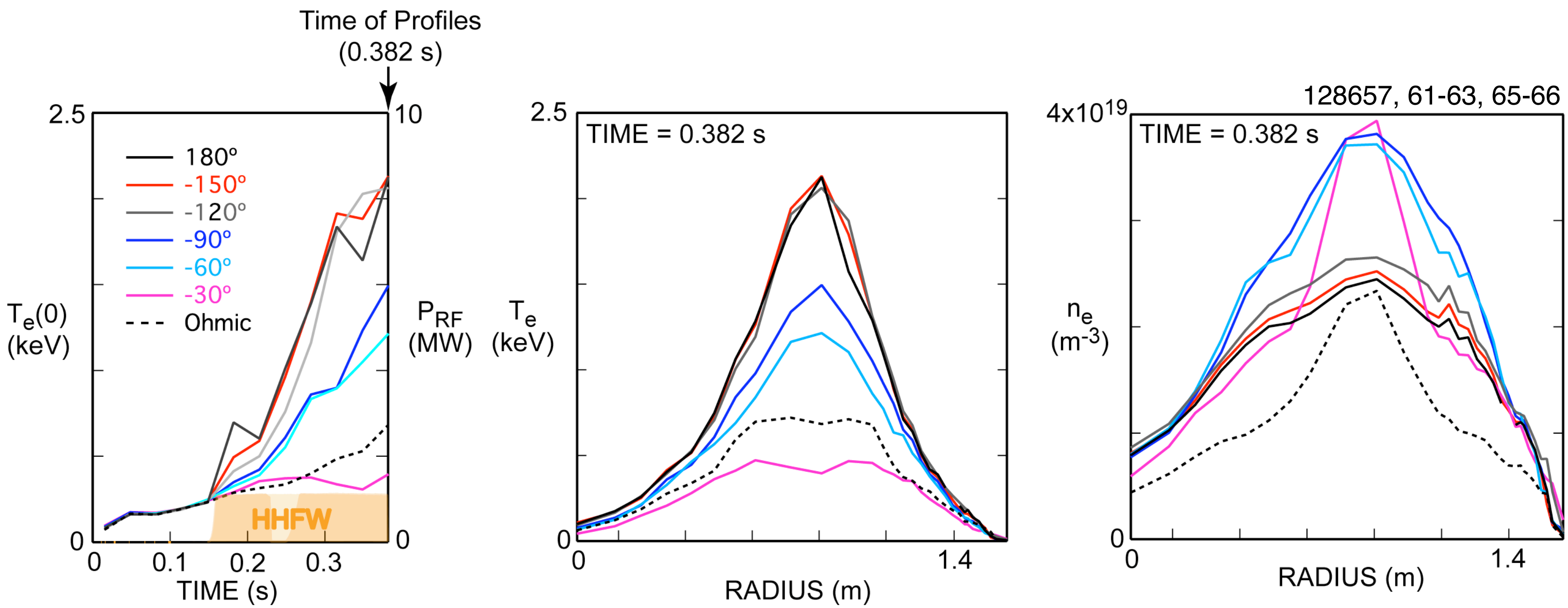


- First observation of core heating in deuterium plasmas for $k_\phi = 3\ m^{-1}$ ($\Delta\phi = -30^\circ$)
- Lithium evaporation rate of 20 mg/min used to reduce edge density

D and He Plasmas Heated to NSTX Record $T_e(0) \sim 5$ keV with 3.1 MW of $k_\phi = -8\ m^{-1}$ HHFW



Strong Dependence of HHFW Heating on k_ϕ in L-mode Deuterium Plasmas



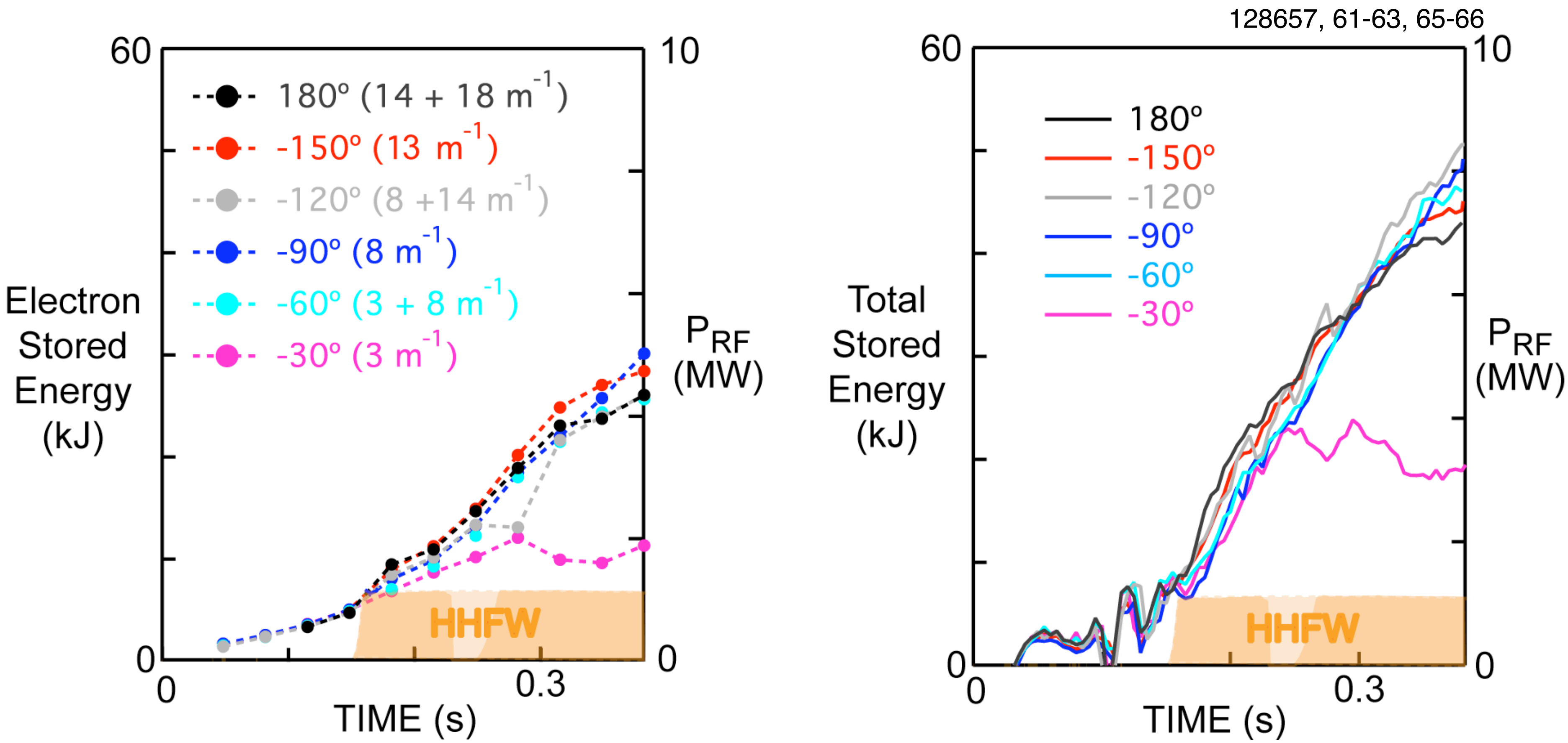
Central T_e heating rate faster for higher k_ϕ antenna phasings

Higher k_ϕ antenna phasings lead to centrally peaked $T_e(R)$

Lower k_ϕ antenna phasings increase $n_e(0)$

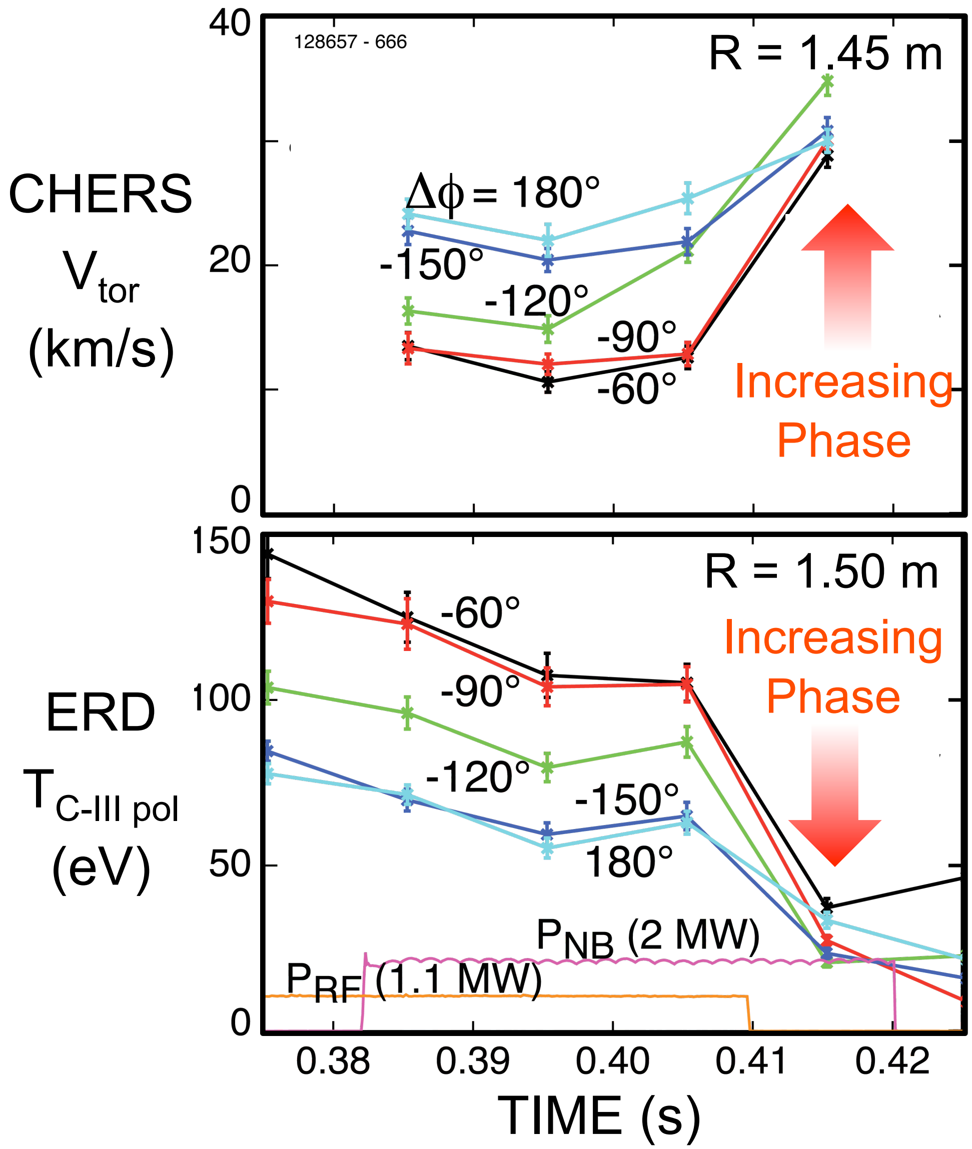
- Array phase scanned from -180° to -30°, in 30° increments
- $n_e(R)$ behavior in D plasmas comparable to He plasmas

k_ϕ Dependence of HHFW Heating Efficiency in Deuterium Similar to Helium Plasmas



- Heating efficiency drops for $|\Delta\phi| < 60°$ due to high edge density and MHD

Edge Toroidal Velocity Decreases with Antenna Phase as Edge Ion Energy Increases



- Correlation between increase in edge toroidal velocity (V_{tor}) & decrease in edge C-III poloidal temperature ($T_{C\text{-}III\ pol}$) suggests ion loss or trapping is affecting rotation

- V_{tor} returns to approximately the same value after RF turn off
  – energetic ions decay about 2 ms after the RF turns off

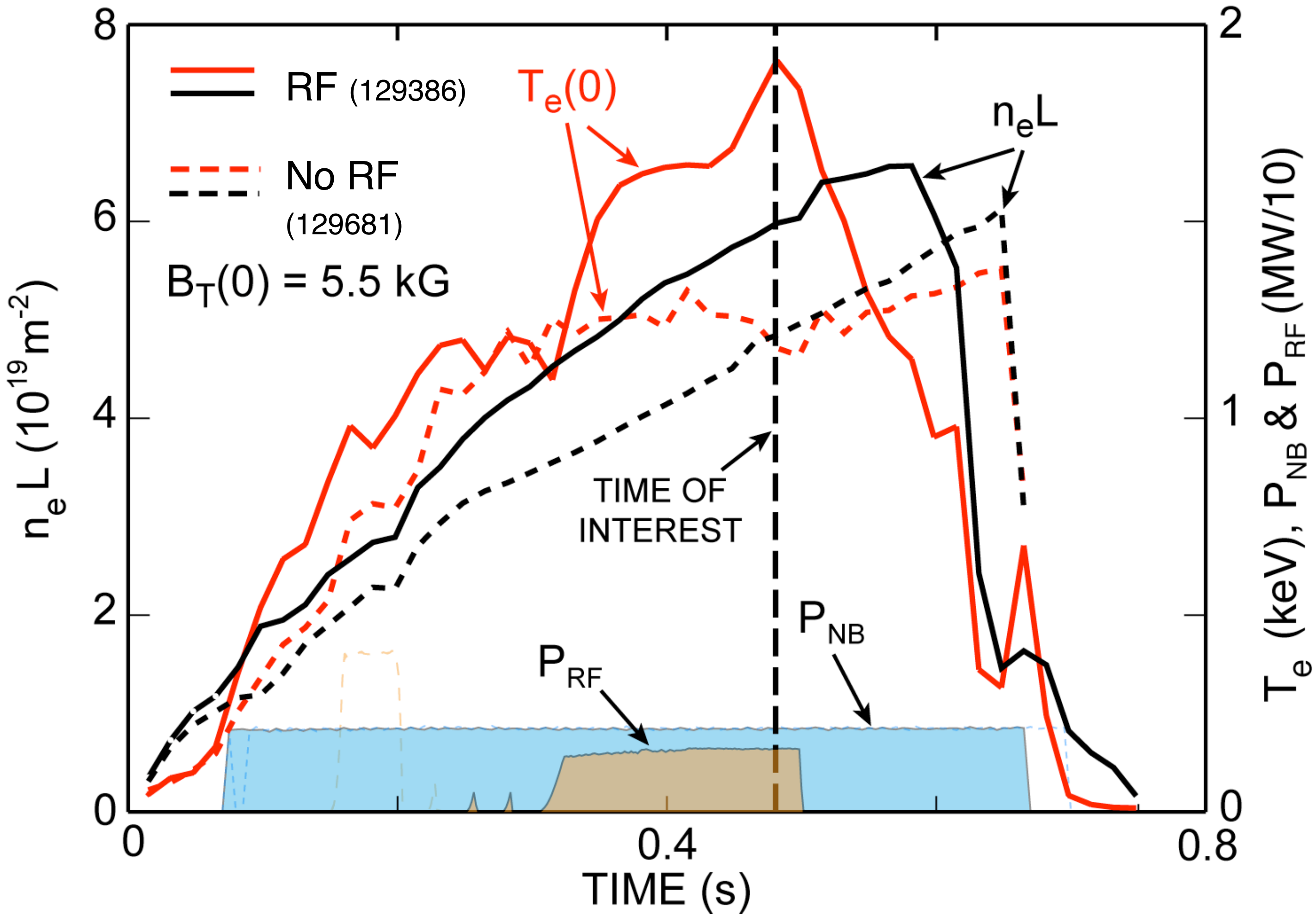
HHFW Heating of Deuterium NBI H-Mode Plasmas

HHFW Coupling and Heating in H-mode Plasmas

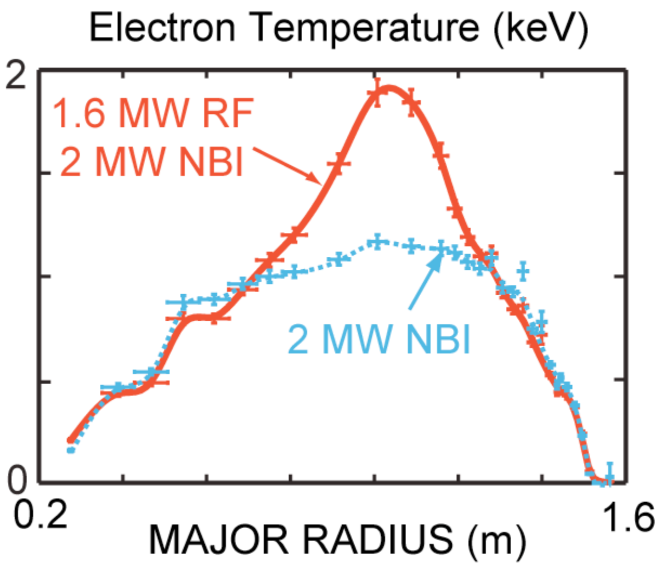
- Initial experiments show dependence of heating efficiency on k_ϕ is similar to L-mode
  - Degradation of heating at $\Delta\phi$ = -90° (k_ϕ = -8 m^{-1}) relative to $\Delta\phi$ = -150° (k_ϕ = -13 m^{-1})
- Major edge power loss channel observed
  - Losses from scrape off layer in front of antenna to outer divertor plate linked along magnetic field lines
- Strong edge pressure gradient appears to lead to large type I ELMs at both antenna phases
  - Arcs occur prior to excursion of divertor D_α light in both cases
- Transmitter trips are caused by arcs, not by increased reflection coefficient from ELMs
  - Can couple RF power during an ELM in the absence of an arc
  - Time derivative of reflection coefficient can be used to discriminate between ELMs and arcs

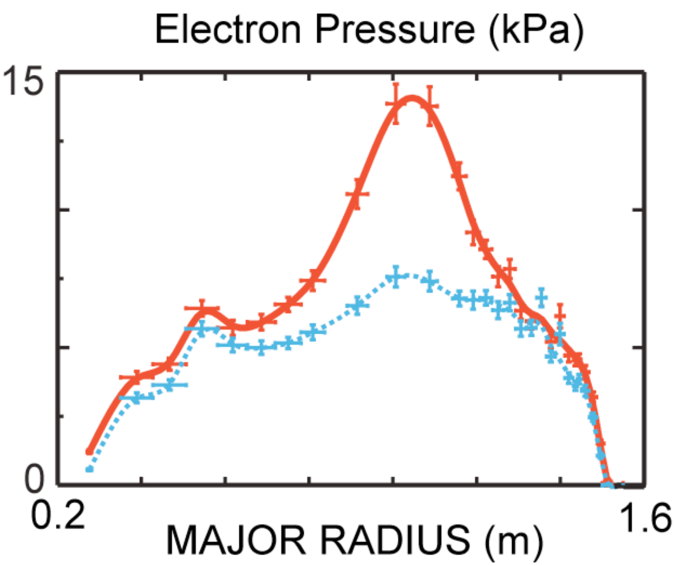
First Significant HHFW Heating of Core Electrons During NBI-Fuelled Deuterium H-mode Plasmas

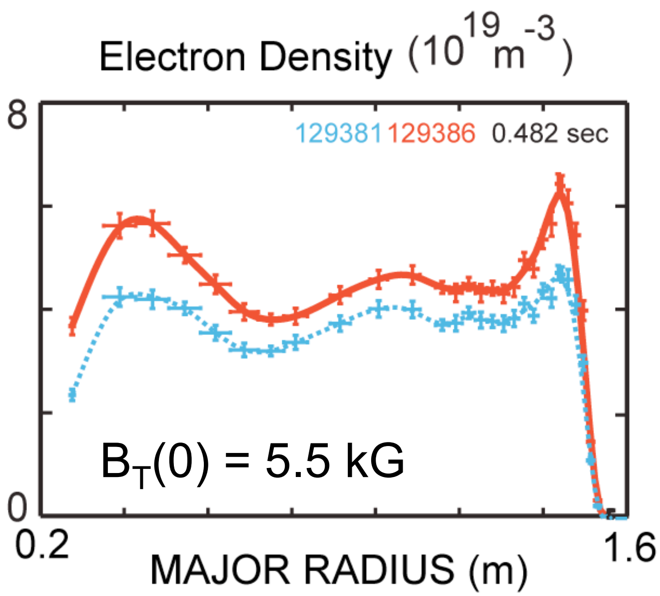
- Previously, HHFW did not heat core of deuterium NBI H-mode plasma at $B_T(0)$ = 4.5 kG and without benefit of lithium conditioning



$T_e(0)$, $P_e(0)$ Increased when 1.6 MW of $\Delta\phi = 180^o$ ($k_\phi = 14\ m^{-1} + 18\ m^{-1}$) RF Coupled to D NBI Plasma

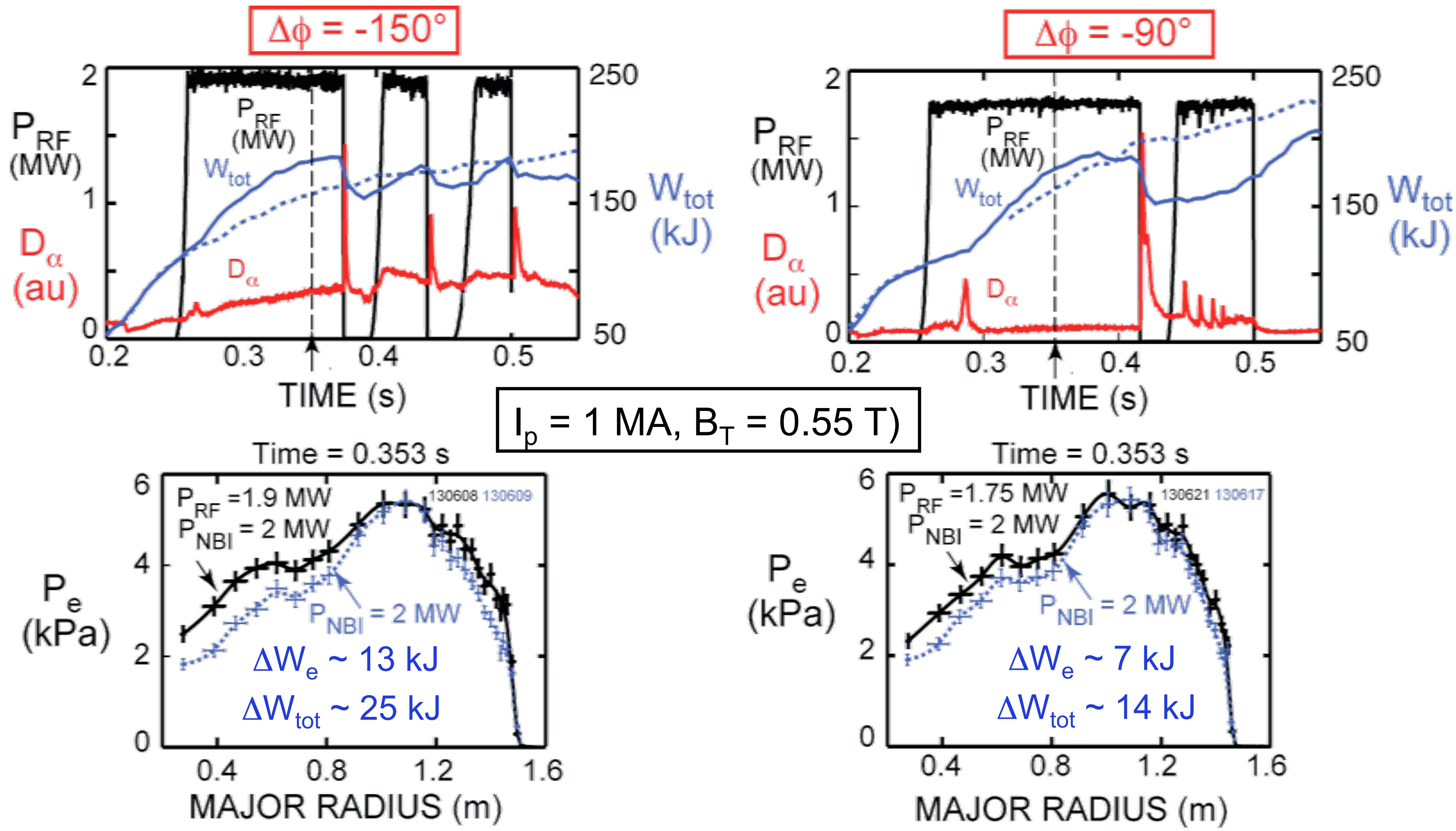






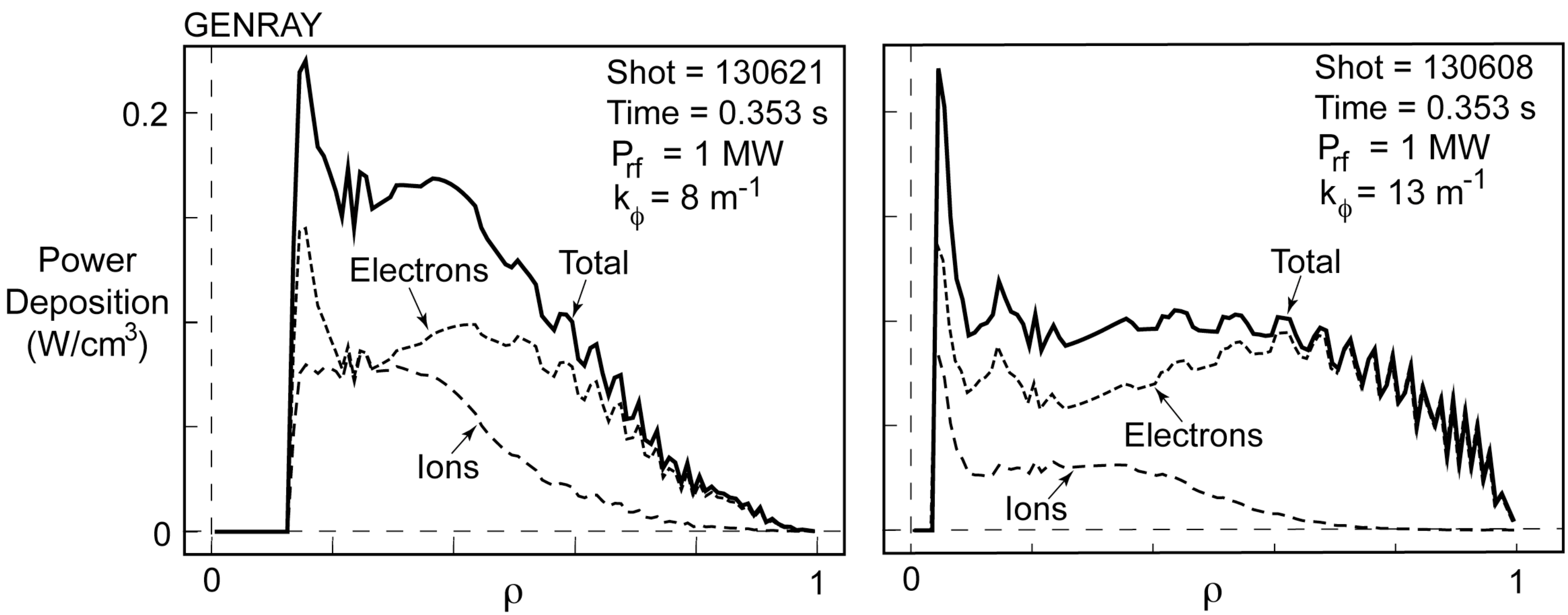
- Experiments starting to study HHFW coupling into deuterium H-modes

Heating of Deuterium H-mode Plasmas Less Efficient at Lower Antenna Phase/Lower k_ϕ



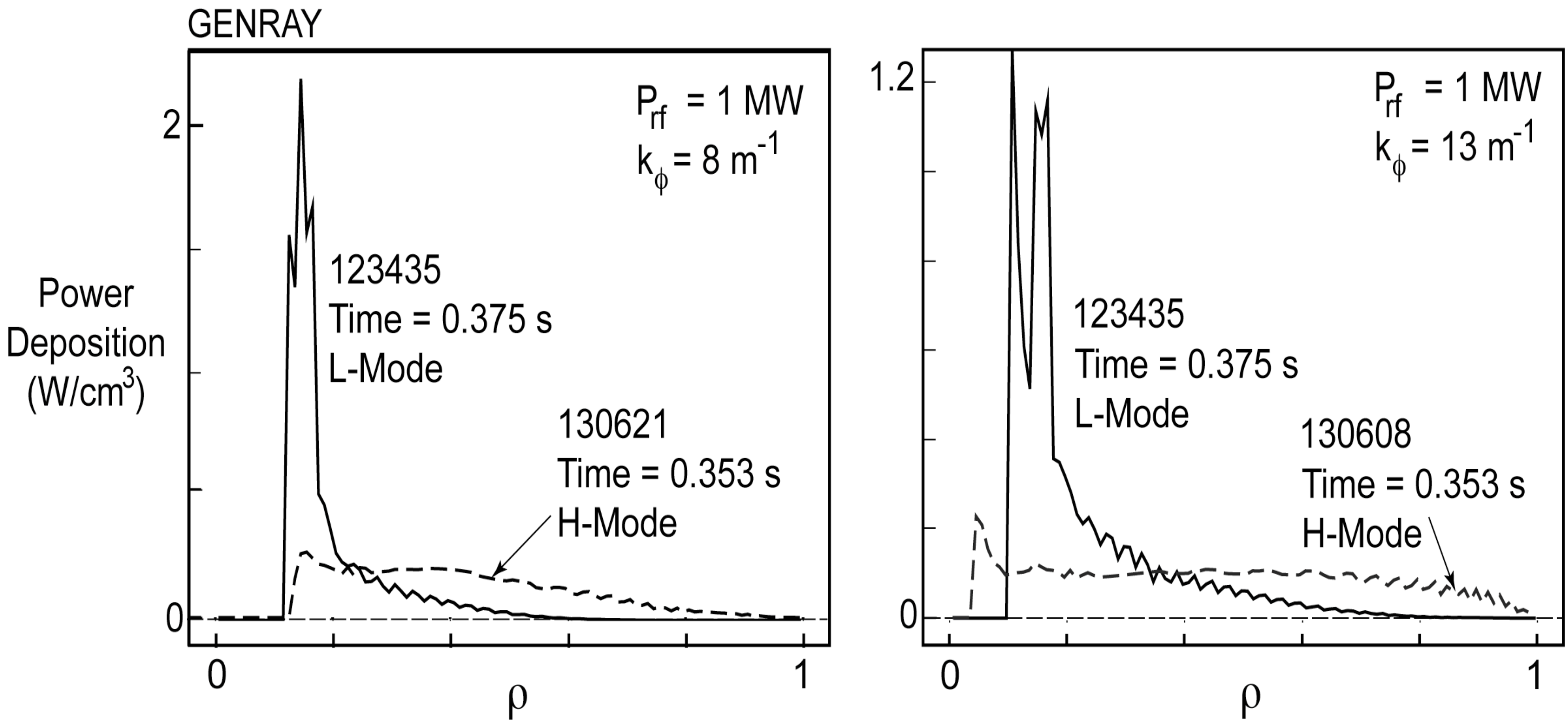
- $\tau_{\Delta Wtot}$ ~ 20 ms gives η_{eff} ~ 66%, 40% for $\Delta\phi$ -150°, -90°, respectively
- P_{RF} losses coupled to edge are ~ 0.7 MW, 1.1 MW for $\Delta\phi$ = -150°, -90°

Narrower RF Power Deposition at Lower k_ϕ in NBI H-Mode Plasmas



- RF power deposition on slowing NBI ions in core, particularly at lower k_ϕ
- Deposition to slowing NBI ions decreases as density rises through RF heating pulse *[B. LeBlanc, Poster A-30, this conference]*

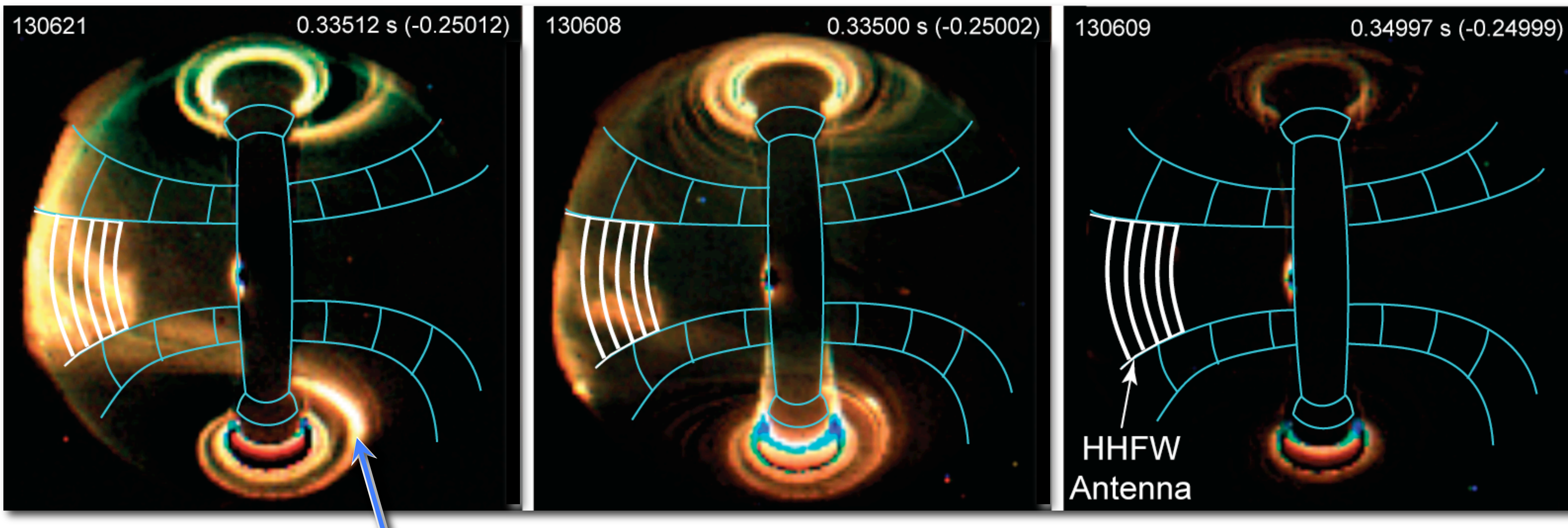
Much Broader RF Power Deposition in NBI H-Mode Compared to L-Mode, at both k_ϕ = 8 and 13 m^{-1}



Stronger Interaction Along Field Line at Lower Phase/Longer Wavelength

P_{rf} = 1.8 MW, P_{nbi} = 2 MW, I_p = 1 MA, B_T = 5.5 kG

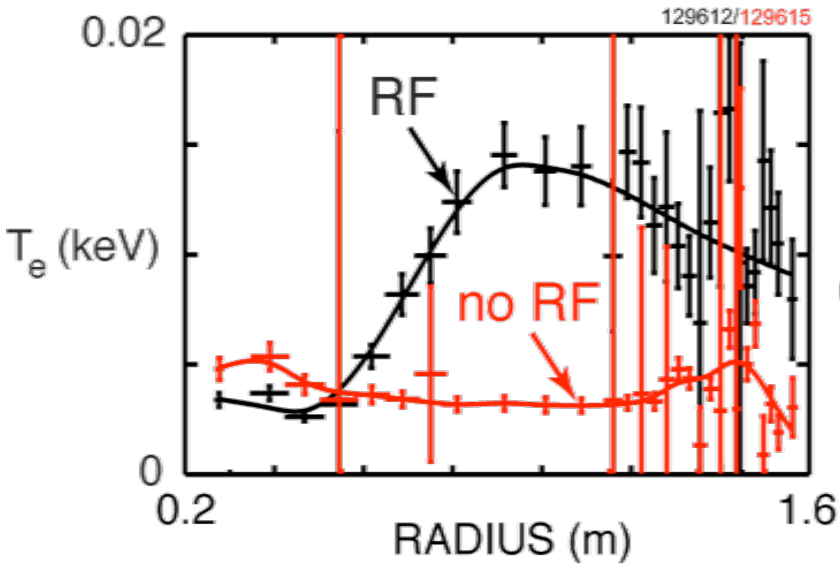
$\Delta\phi$ = - 90° | $\Delta\phi$ = - 150° | No RF

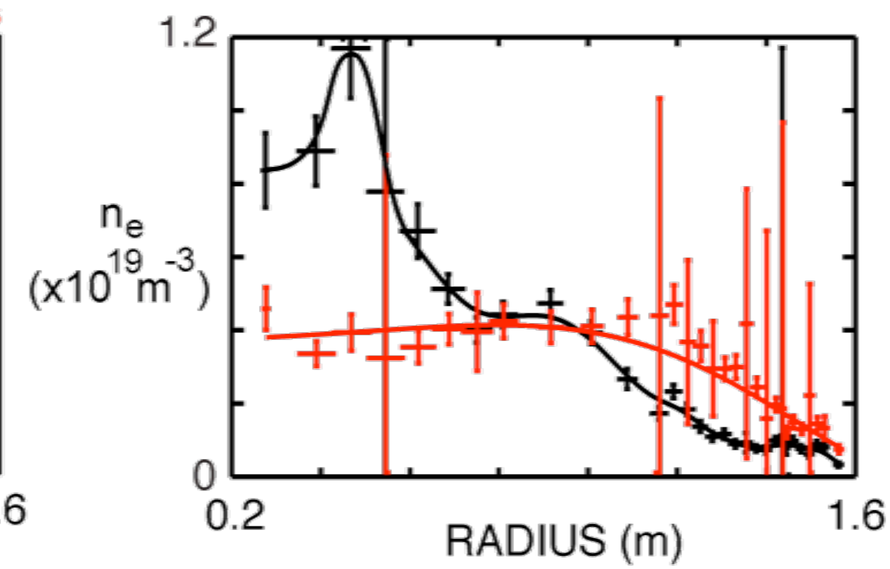


- "Hot" region in outboard divertor much more pronounced at $\Delta\phi$ = -90° than $\Delta\phi$ = -150° *[J. Hosea, Talk I-6, this conference]*
  - Linked with region in front of HHFW antenna along field lines
  - Intensity is dependent on phase, dies away after RF turns off, in ~ 20 ms for $\Delta\phi$ = -90° and 8 ms for $\Delta\phi$ = -150°

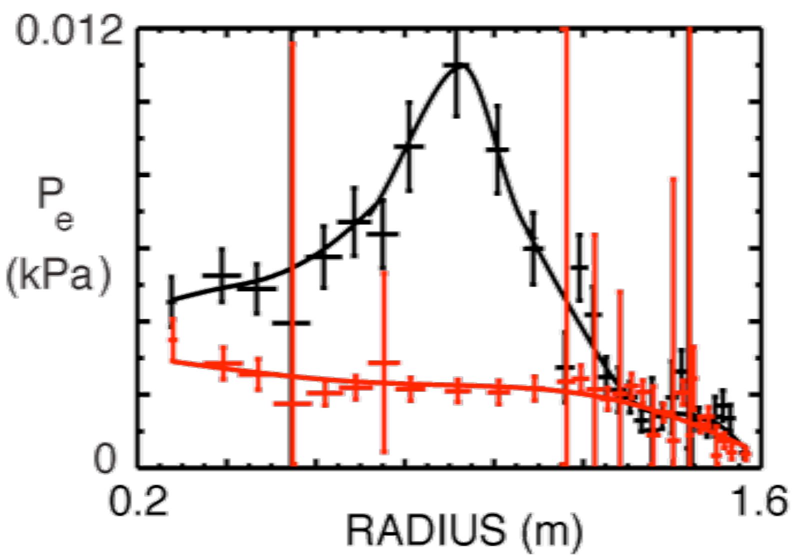
HHFW Heating of Deuterium Start-up & Current Ramp-up

Core Electron Heating Observed when ~ 550 kW of HHFW Power Coupled into CHI Start-up Plasma





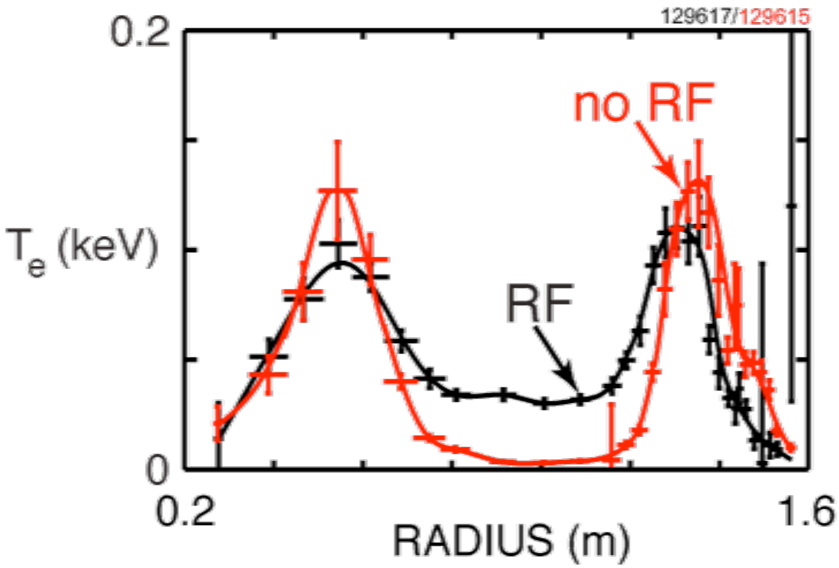
Time = 20 ms

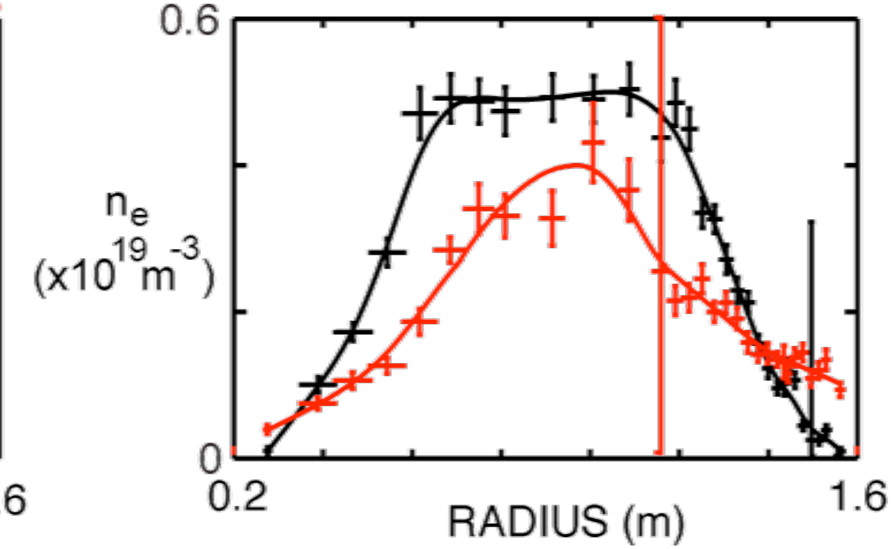


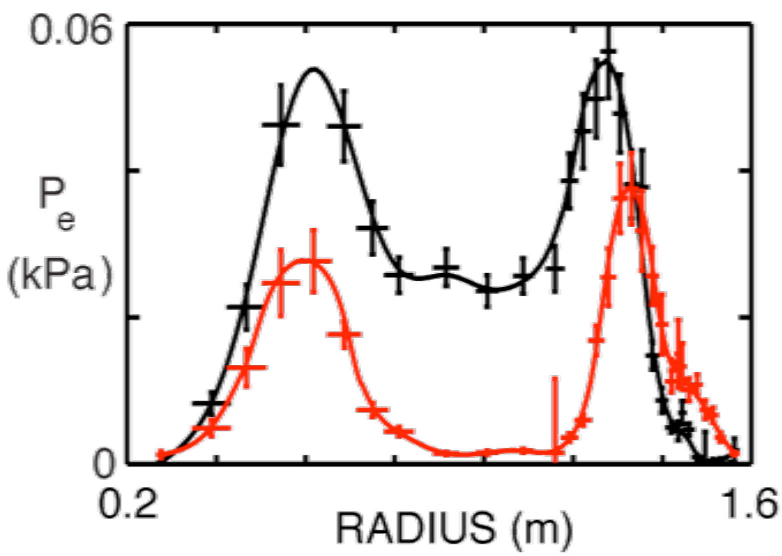
- P_{rf} ~ 550 kW from 10 to 22 ms increased $T_e(0)$ from ~3 to ~15 eV

k_ϕ = -8 m^{-1} Heating

P_{rf} ~ 550 kW from 18 to 64 ms Increased $T_e(0)$ from ~ 3 to ~ 33 eV





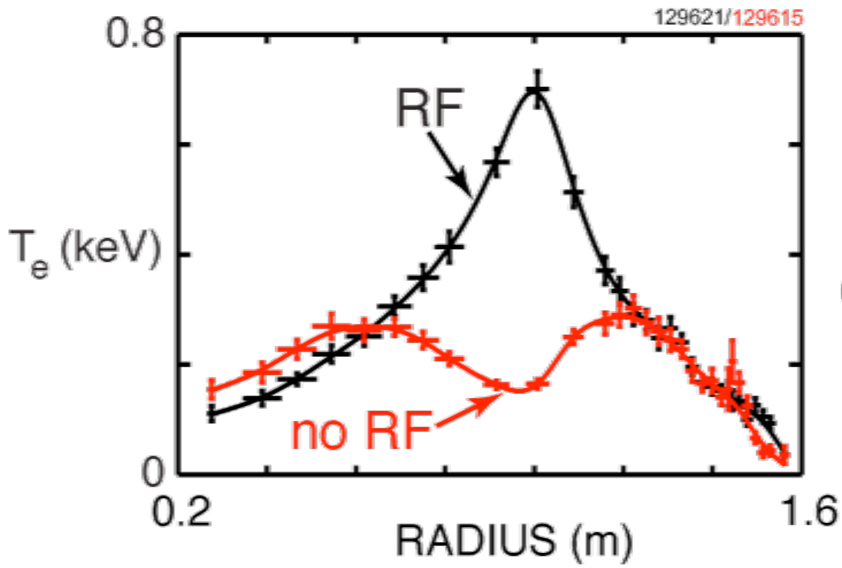


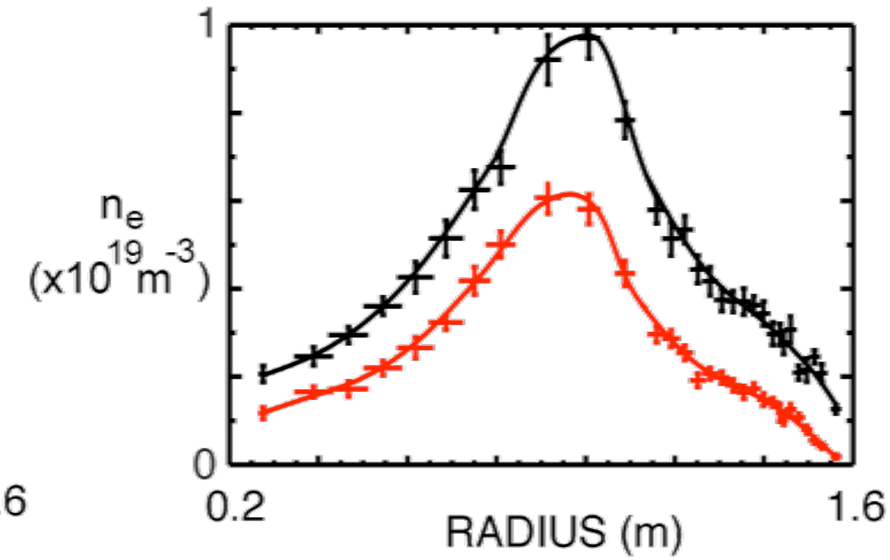
Time = 53 ms

- HHFW coupled from 18 to 64 ms
- T_e , P_e profiles remained hollow during HHFW heating pulse

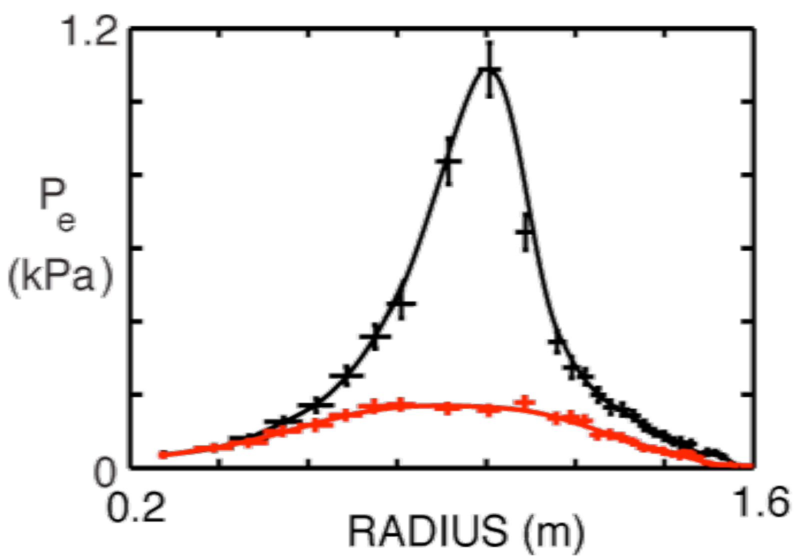
k_ϕ = -8 m^{-1} Heating

HHFW Experiments Later in I_p Ramp-up Show Good Core Electron Heating in D_2 with CD Phasing





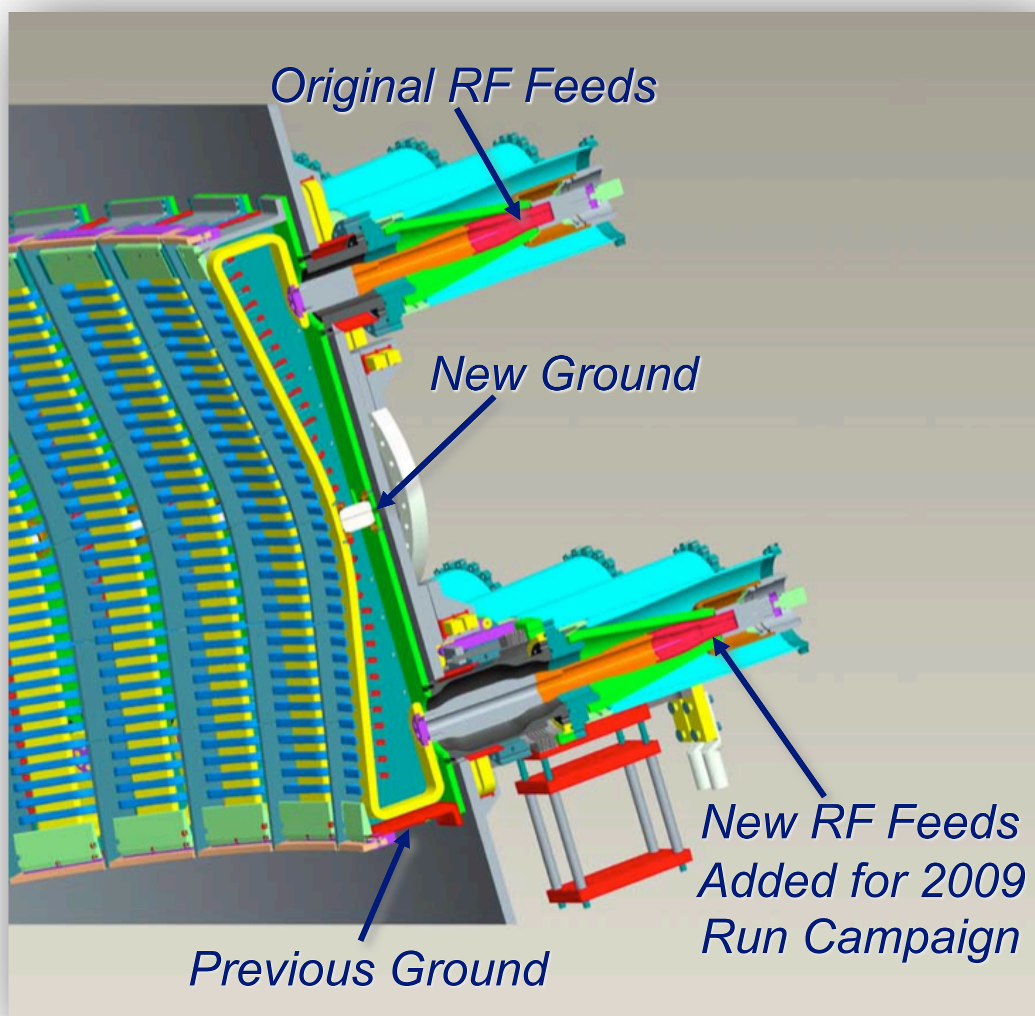
Time = 120 ms



- $T_e(0)$ increased from ~140 eV to ~ 700 eV at $n_e(0)$ ~ 6 $x10^{18}$ m^{-3} and ~ 9 $x10^{18}$ m^{-3}, respectively

k_ϕ = -8 m^{-1} Heating

HHFW System Upgrades in 2009-11 Should Double Coupled Power & Increase Resilience to ELMs



- 2009 double-feed upgrade shifts ground from end to strap center
- Lower strap voltage for given strap current:
  - Doubles power per strap for same plasma load
  - Permits larger plasma-antenna gap (lower load)
- ELM resilience upgrades & better outer gap control planned for 2010-2012 allow better coupling into H-mode & I_p ramp-up

Improved Core Electron Heating Achieved in L-Mode & H-Mode through Edge Conditioning

- Efficient electron heating achieved in L-mode for wide range of k_ϕ by keeping wave propagation onset away from antenna/wall
  - $k_\phi < 5\ m^{-1}$ core heating in D_2 required lithium wall conditioning
  - NSTX record $T_e(0) \sim 5$ keV with ~ 3 MW of $k_\phi = -8\ m^{-1}$ heating in D_2 & He plasmas

- First significant core electron heating of D_2 NBI fuelled H-mode

- Experiments with $k_\phi = -8\ m^{-1}$ heated D_2 CHI start-up & OH I_p ramp-up show core electron heating at $n_e(0) \sim 4\text{-}8 \times 10^{18}\ m^{-3}$

- HHFW system upgrades in 2009-11 permit higher power, and more reliable operation