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NSTX

High Harmonic Fast Wave Heating Efficiency Enhancement and Current Drive at Longer Wavelength on NSTX

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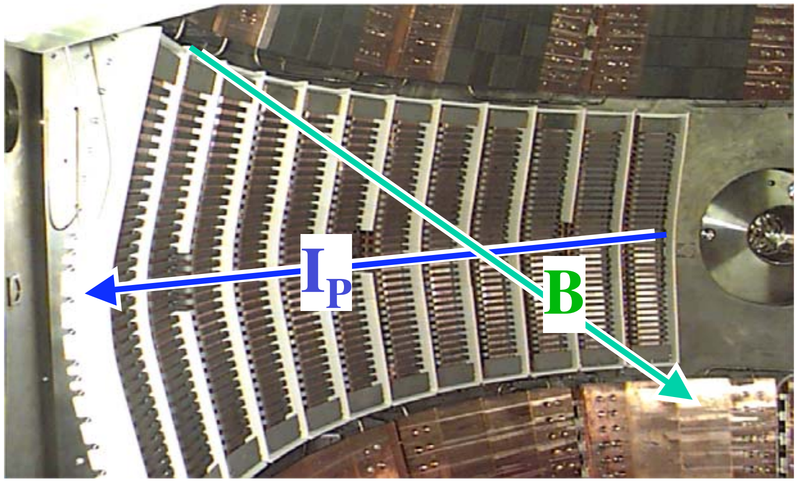
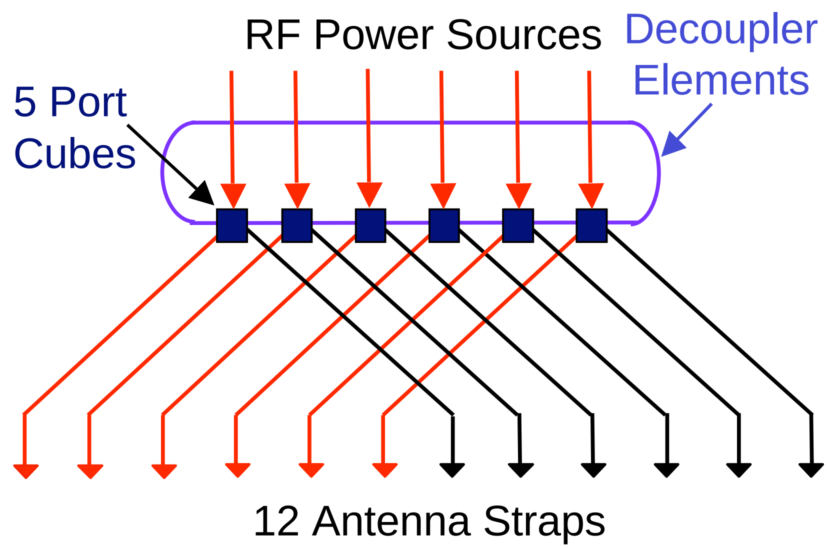
HHFW Heating & Current Drive (CD) being Developed for Non-Inductive Startup, I_p Ramp-Up and to Sustain High β

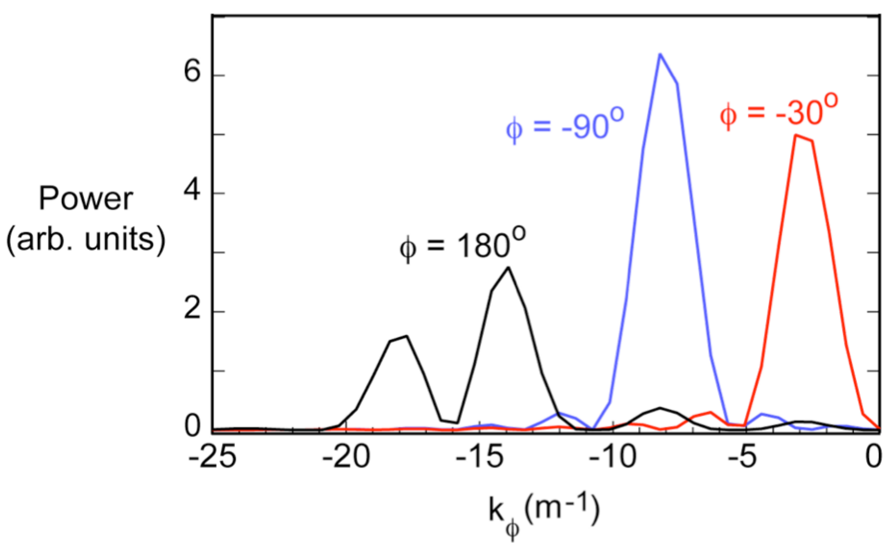
- Explore strong dependence observed for heating on B and k_ϕ
  - Heating efficiency for CD phasing (ϕ = -90^o between adjacent antenna strap currents, or k_ϕ ~ - 8 m^{-1}) improves markedly at higher B :
    - *Due to a reduced surface FW wave damping, not to reduced parametric decay instability (PDI) heating*
  - Heating efficiency still falls off for $|k_\phi|$ < 8 m^{-1} (|antenna phase| < 90^o) where surface wave losses dominate reduced core damping
- Surface FW damping for ITER IC CD phasing could be important
- Initial motional Stark effect (MSE) diagnostic study of HHFW CD carried out under conditions of improved heating efficiency

NSTX HHFW Antenna Toroidal Spectrum Well Controlled for Studying Antenna Phase Effects



HHFW antenna extends toroidally 90°





- Phase between adjacent straps easily adjusted between 0° to 180°
- Large B pitch affects wave spectrum in plasma core

HHFW Heating Efficiency Determined via Power Modulation

- RF power deposited in plasma core evaluated by modulating RF power and fitting rise and fall of the stored energy with exponential functions:

$$W(t) = W_0 - (W_0 - W_F)*(1 - e^{-t/\tau})$$

  - $P_{RFdep} = \Delta W_F/\tau$
  - Heating efficiency is $P_{RFdep}/\Delta P_{RFpulse}$

- W_{EF} , total stored energy, from magnetic equilibrium reconstruction
- W_e , electron stored energy, from integrating Thomson scattering $P_e(r)$ profile over volumes defined by magnetic equilibrium reconstruction

Electron and Total Stored Energy Exhibit Exponential Rise, with $\tau_{We} \sim \tau_{WEF}$

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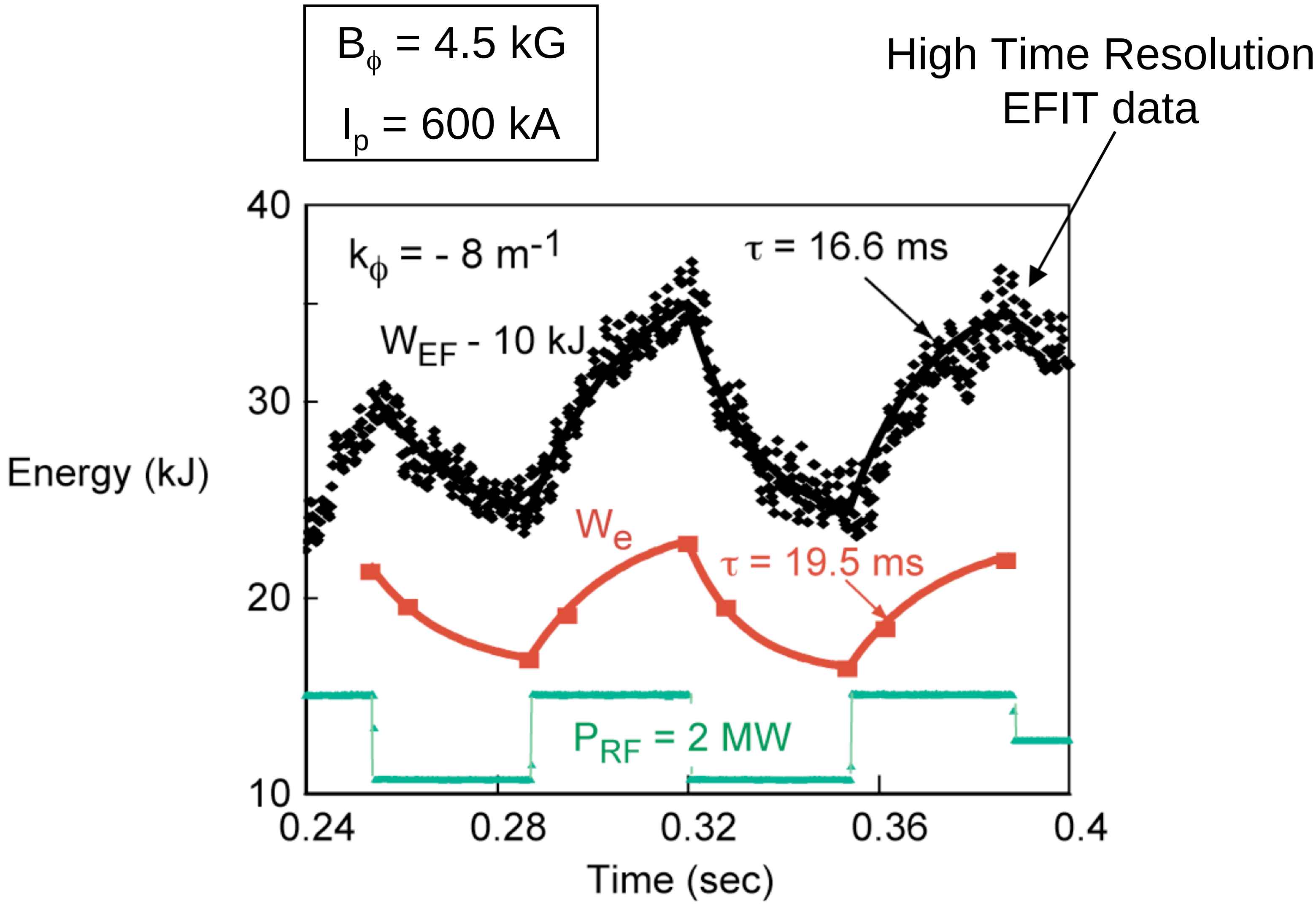

Heating Efficiency at B_ϕ = 4.5 kG Strongly Reduced at Lower k_ϕ

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- Heating Efficiency [$P_{RFdep}/\Delta P_{RF}$] (for third pulse on previous slide):

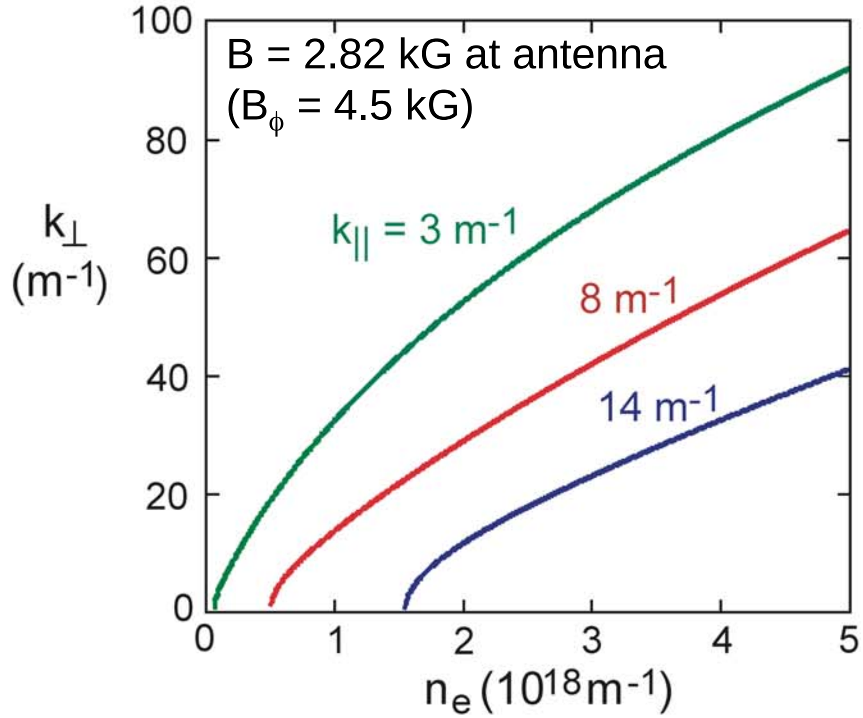
k_ϕ (m^{-1})	Electrons	Total
14	48%	68%
- 8	22%	44%

- RF power reaching core considerably reduced for smaller k_ϕ (longer wavelength):
  - Shows surface loss is strong function of wavelength
- Edge spectroscopy measures strong edge ion heating via parametric decay, but not strongly dependent on k_ϕ:
  - For P_{RF} = 2 MW, 16% loss at k_ϕ = 14 m^{-1} & 23% loss at k_ϕ = - 8 m^{-1}

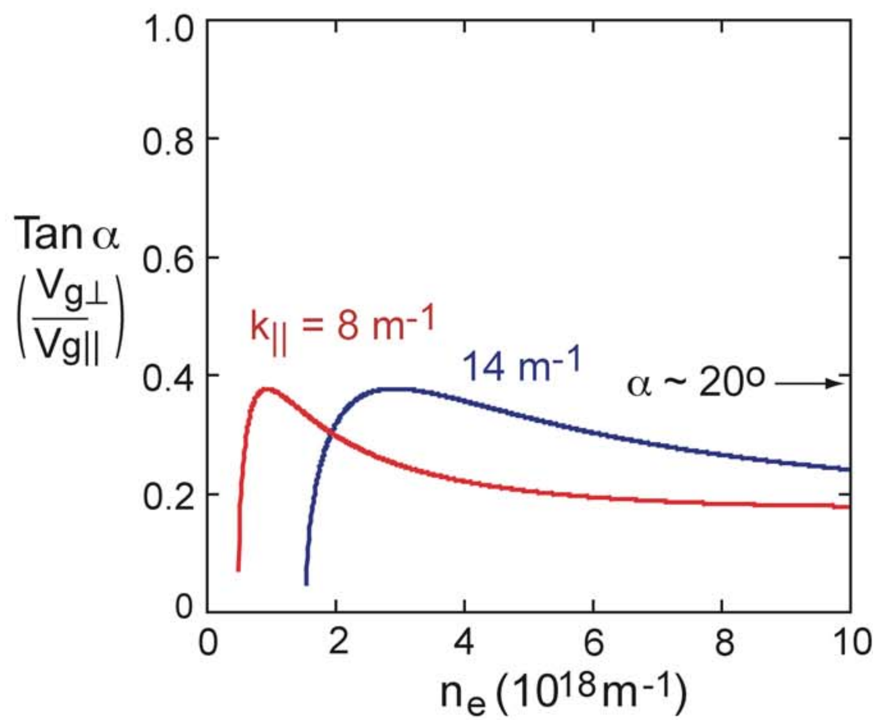
    [Biewer, T. M. et al. *Physics of Plasmas* **12**, 056108 (2005)]
- Other loss mechanisms present; leading candidate, explored here, is surface wave damping on antenna/wall surfaces

Surface FW Propagation Supports Surface Loss at Lower $k_{||}$

Propagating $k_\perp$ vs density at antenna B



Angle of ray to B vs density



Onset density is $\propto B^* k_{||}^2/\omega$

- Propagation is very close to wall at $k_{||} = 8\ m^{-1}$, on wall at $k_{||} = 3\ m^{-1}$
- Losses in surface should be higher for lower $k_{||}$
- Propagation angle relative to B much less than for lower harmonic case
- Increasing B should move onset farther from antenna, increasing heating

Heating Efficiency for $k_{||}$ = - 8 m^{-1} Increased Substantially as B_ϕ Increased from 4.5 kG to 5.5 kG

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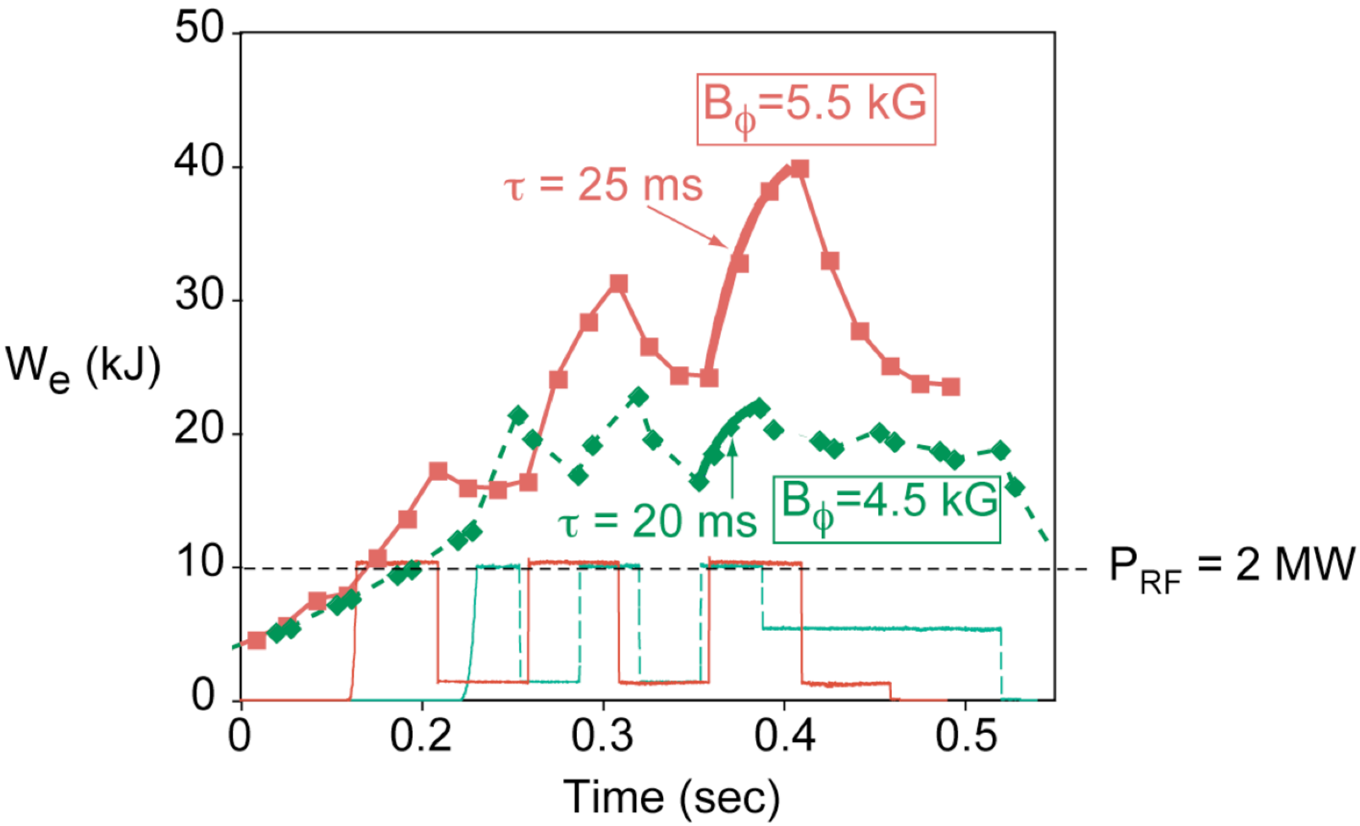

- ΔW_e for B_ϕ = 5.5 kG is ~ 2 times the value for 4.5 kG over same time interval
- RF power deposition to electrons increases from ~ 22% to ~ 40% at higher B_ϕ, total efficiency increases from ~ 44% to ~ 65%

HHFW Electron Heating Greatly Improved at k_ϕ = - 8 m^{-1}, Remains Poor at Lower k_ϕ

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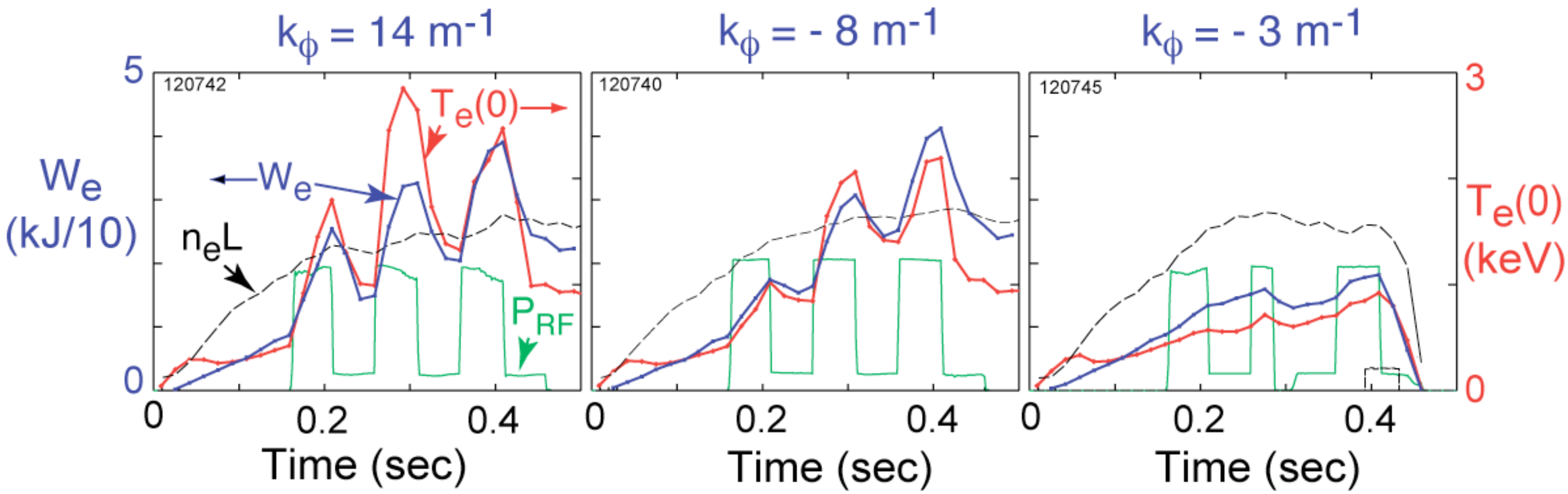
Electron heating for B_ϕ = 5.5 kG, I_P = 720 kA, P_{RF} = 2 MW



- Clear strong dependence on k_ϕ – almost no heating at k_ϕ = - 3 m^{-1}
- Heating at k_ϕ = - 8 m^{-1} comparable to k_ϕ = 14 m^{-1} for last two RF pulses but about half that for k_ϕ = 14 m^{-1} for the first RF pulse

Edge Power Loss Increases When Perpendicular Propagation Onset Density is Near Antenna/Wall

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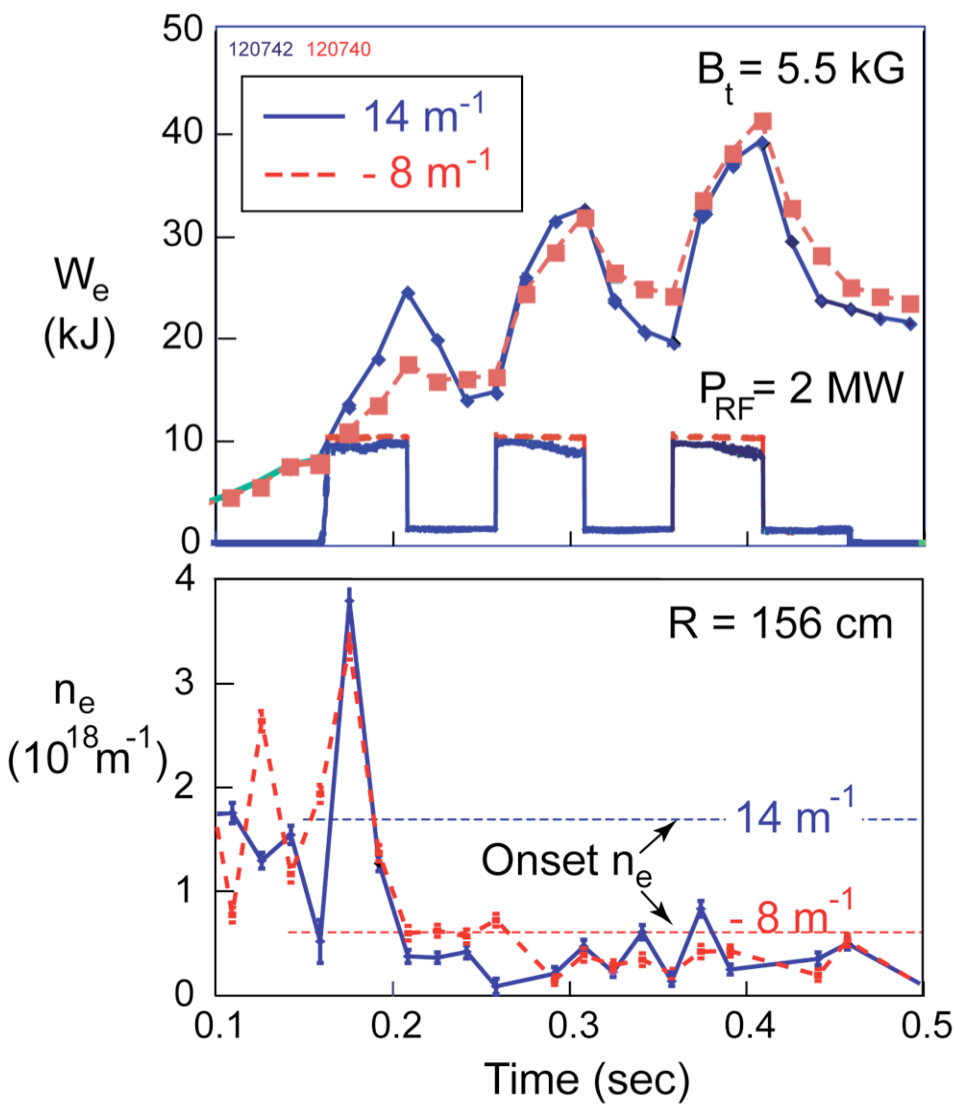

- ΔW_e at - 8 m^{-1} about half ΔW_e at 14 m^{-1} for the first pulse
- ΔW_e at - 8 m^{-1} and 14 m^{-1} comparable for the last two RF pulses
- Density in plasma edge is high for first pulse and low for last two pulses
- Edge density affects heating when above onset density close to antenna, consistent with surface wave propagation near antenna/wall contributing to RF losses

Improved Heating Efficiency at k_ϕ = - 8 m^{-1} Not Due to Reduced Parametric Decay Instability (PDI) Edge Heating

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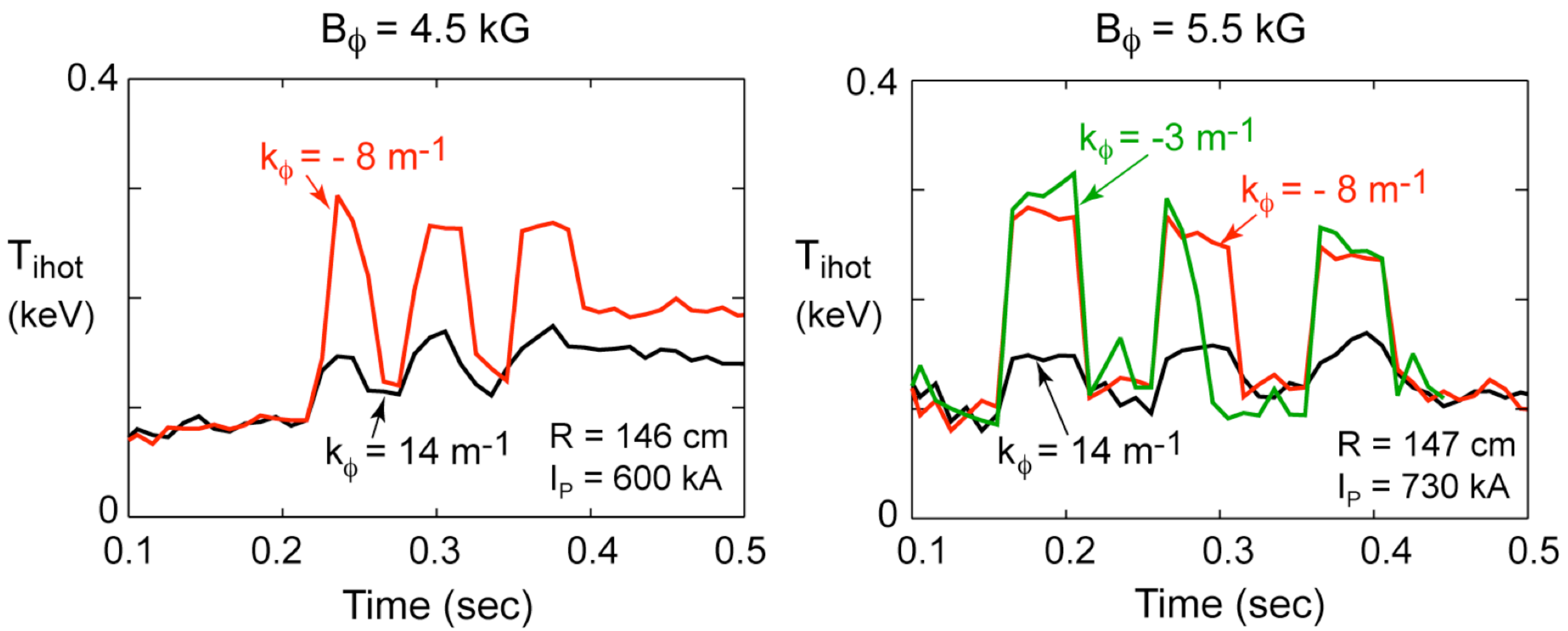
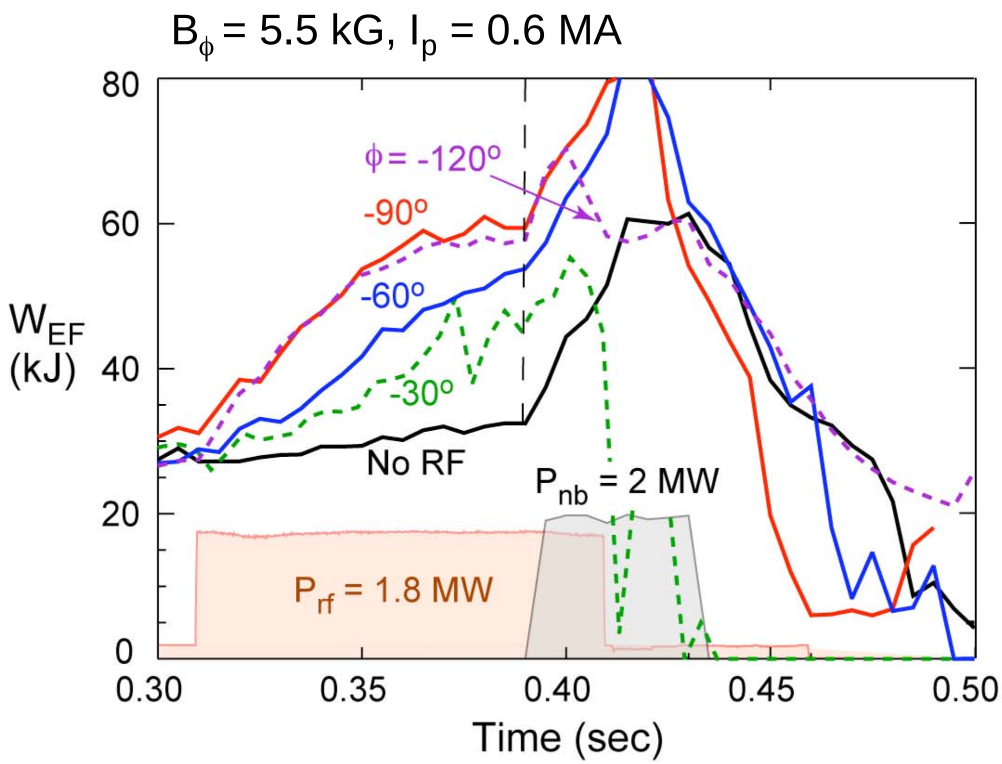
Edge helium ion heating as a measure of PDI losses

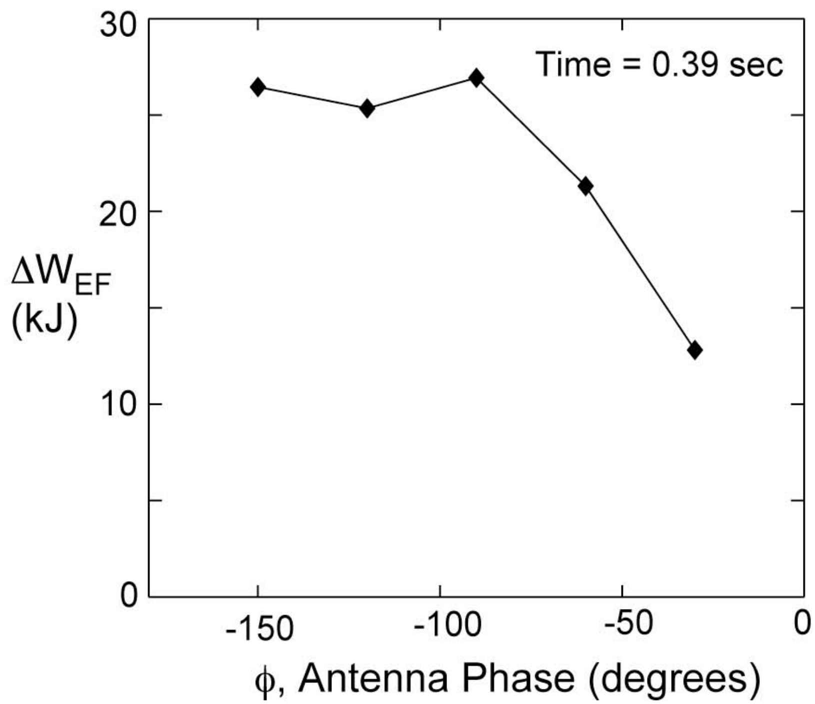


- No significant change in edge ion heating with increased B_ϕ at k_ϕ = - 8 m^{-1}
- PDI edge heating similar at k_ϕ = - 3 m^{-1} and - 8 m^{-1}, suggests surface wave losses and reduced core damping account for decrease in heating efficiency

Heating Efficiency at B_ϕ = 5.5 kG Decreases for $\phi < -90^o$ ($k_\phi < -8\ m^{-1}$)

- Heating efficiency at strap-to-strap antenna phase, $\phi = -30^o$ approximately half the efficiency at $\phi = -90^o$





Profile Dependence on Antenna Phase (ϕ) Suggests RF Modifies Transport

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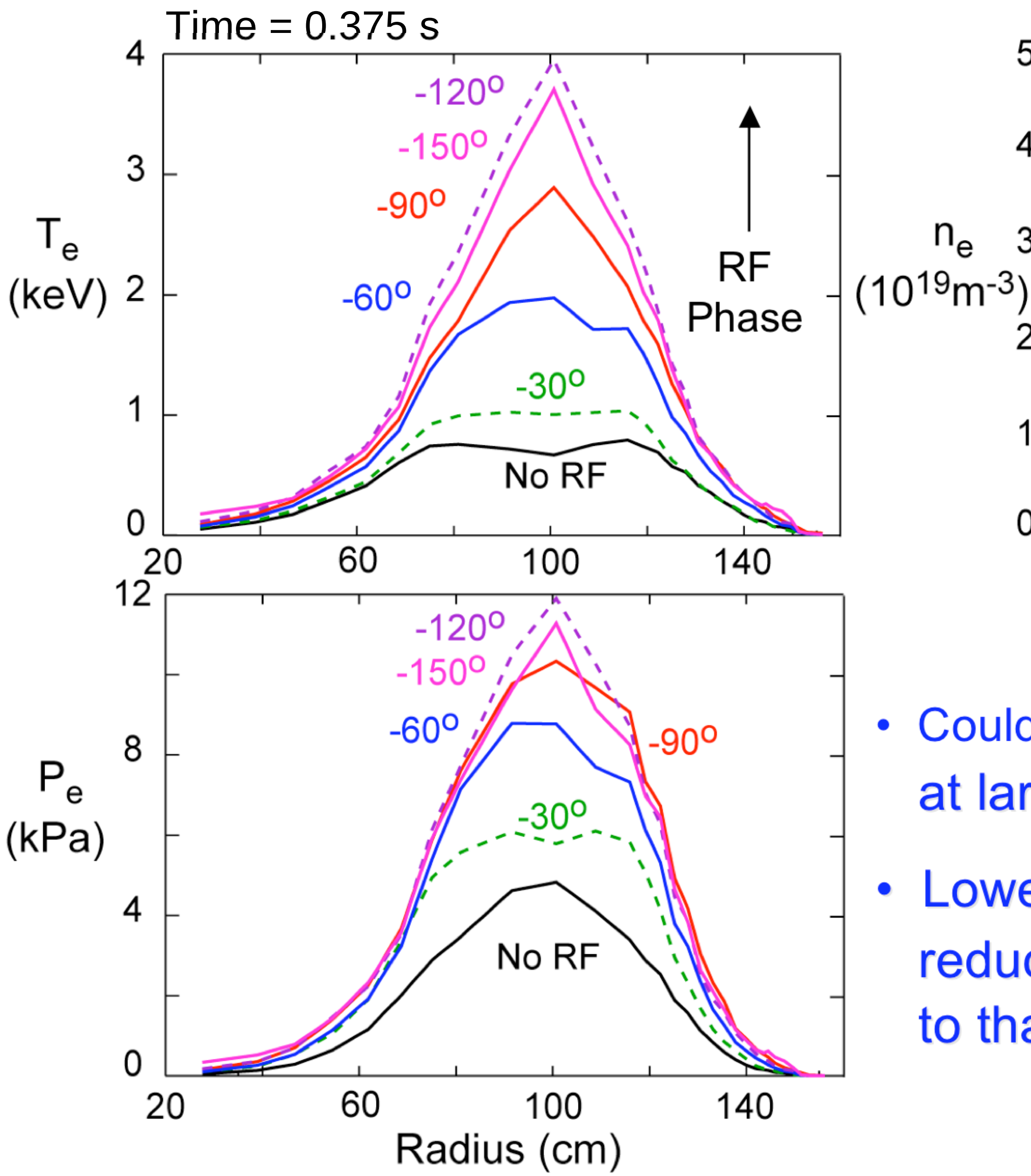
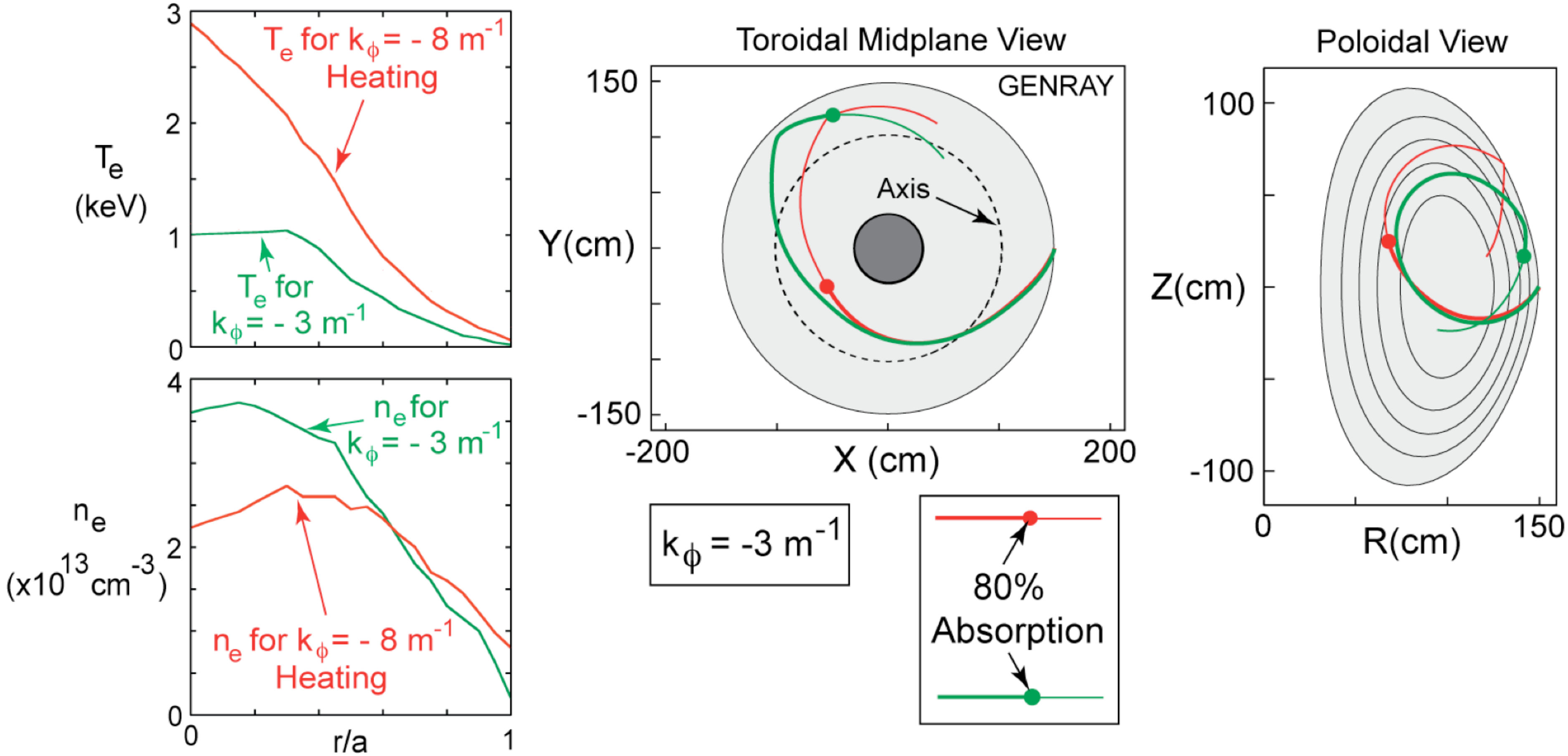


- Could result from reactive current effects at large B pitch
- Lower $T_e(0)$ at ϕ = - 30° (k_ϕ = - 3 m^{-1}) reduces single pass damping relative to that at ϕ = - 90° (k_ϕ = - 8 m^{-1})

Ray Tracing Predicts k_ϕ = -3 m^{-1} Wave Damping Stronger in Higher T_e Plasma Produced by k_ϕ = -8 m^{-1} Preheating



- Wave passes through core away from inner wall
  - k_ϕ = -3 m^{-1} single pass damping is high ~ 70%
  - With k_ϕ = -8 m^{-1} profiles, -3 m^{-1} singles pass damping is > 90%

k_ϕ = -3 m^{-1} Heating is Improved by k_ϕ = -8 m^{-1} Preheating, But $T_e(0)$ Not Sustained Due to Surface Damping

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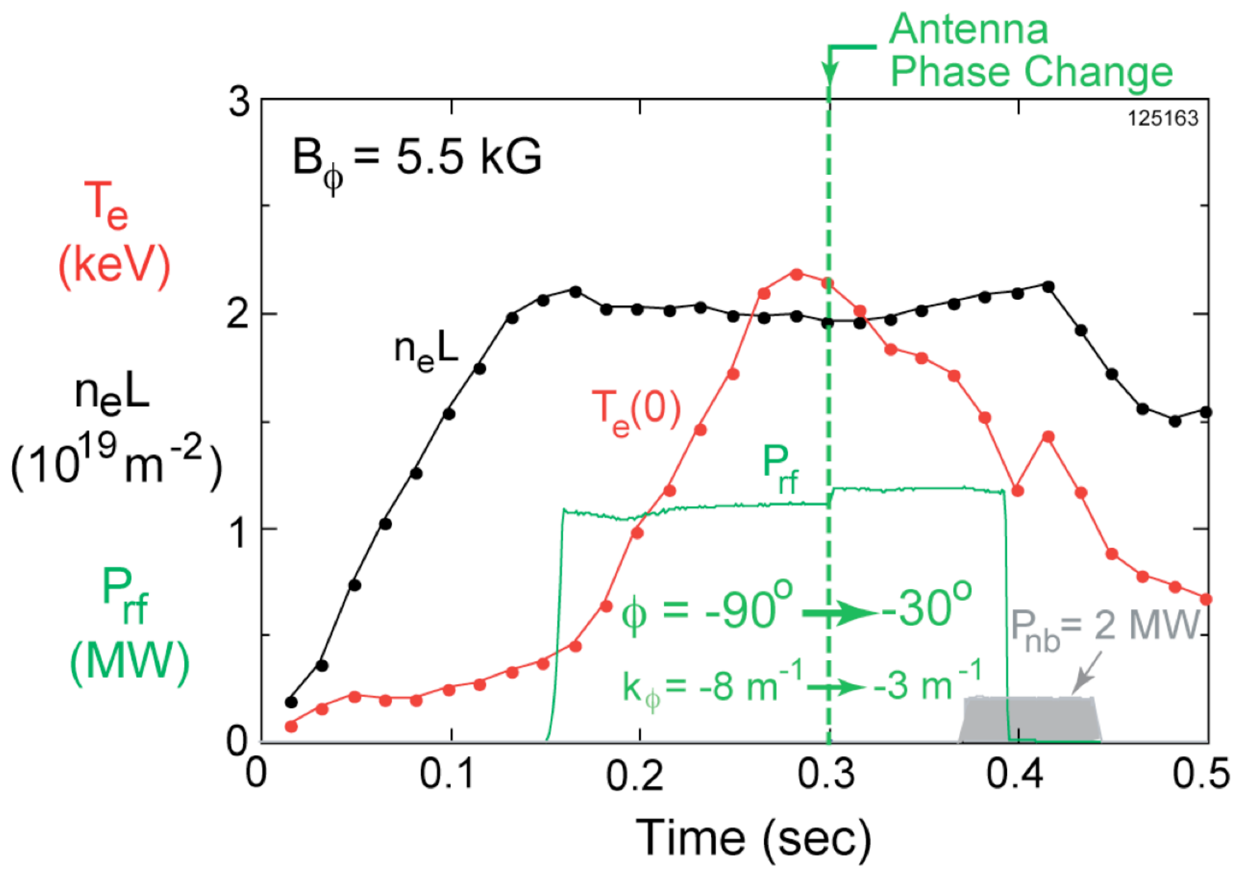

- Phase change from -90^o to -30^o during RF pulse provides $T_e(0)$ = 2.2 keV single pass damping target for the k_ϕ ~ - 3 m^{-1} wave
- Surface wave loss still dominates and $T_e(0)$ falls to level with only k_ϕ ~ - 3 m^{-1}

NSTX Results Indicate Surface Wave Damping Could be Important for ITER ICRF Heating

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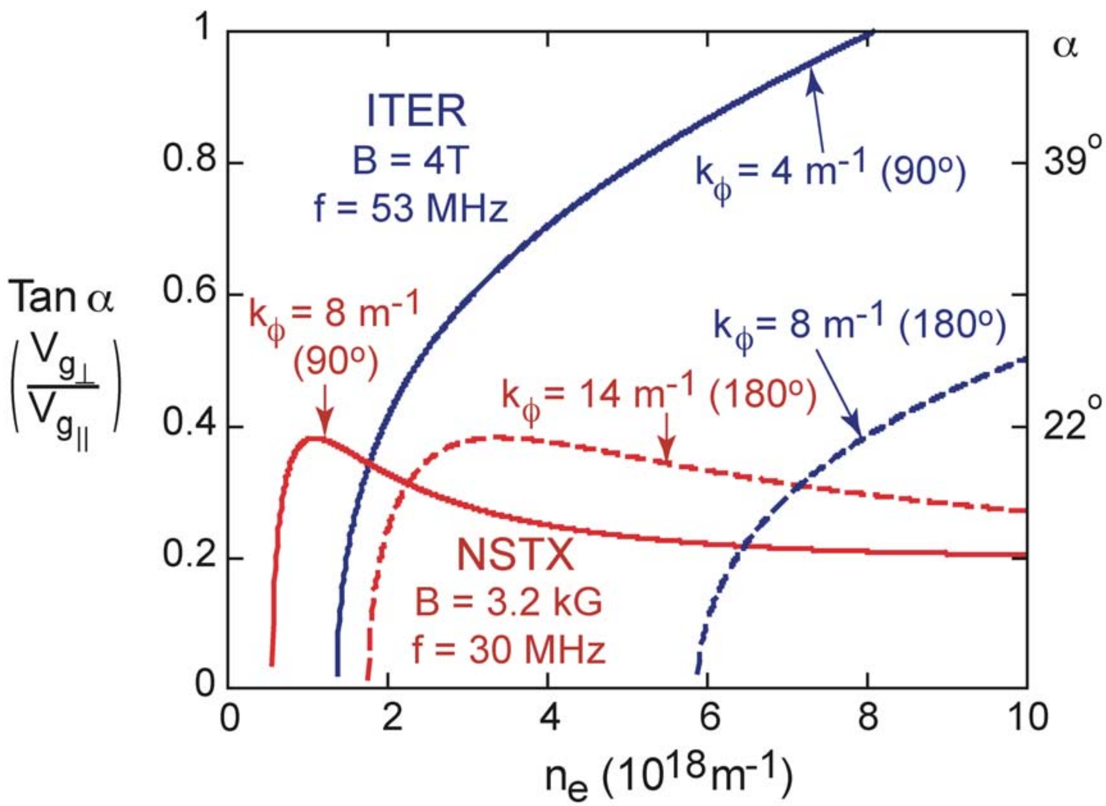
Angle of wave propagation relative to B



- $k_\phi \sim 4\ m^{-1}$ at 53 MHz for CD phasing
- Propagation onset density is relatively low: $\sim 1.4 \times 10^{18}\ m^{-3}$
- For scrape off density above onset density, surface wave damping should be significant

- Surface wave damping on TFTR could have caused the serious antenna heating observed with $k_\phi \Rightarrow \sim 0\ m^{-1}$ (0° between antenna straps)

MSE Current Drive Studies Have Begun with More Efficient Heating at $k_\phi = - 8\ m^{-1}$

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- MSE measurements of CD using a 90 kV "diagnostic" neutral beam at P_{NB} = 2 MW
- Measurements provided in 10 ms time intervals
- First time slice used to measure the RF-driven j profiles
- Linear extrapolation in time suggests perturbation to j profile by P_{NB} not large in first 10 ms for cases where W_{EF} increases linearly in time

MSE Results Show Clear Change in Core Field Pitch Angle for -90º Antenna Phase (k_ϕ = - 8 m^{-1})

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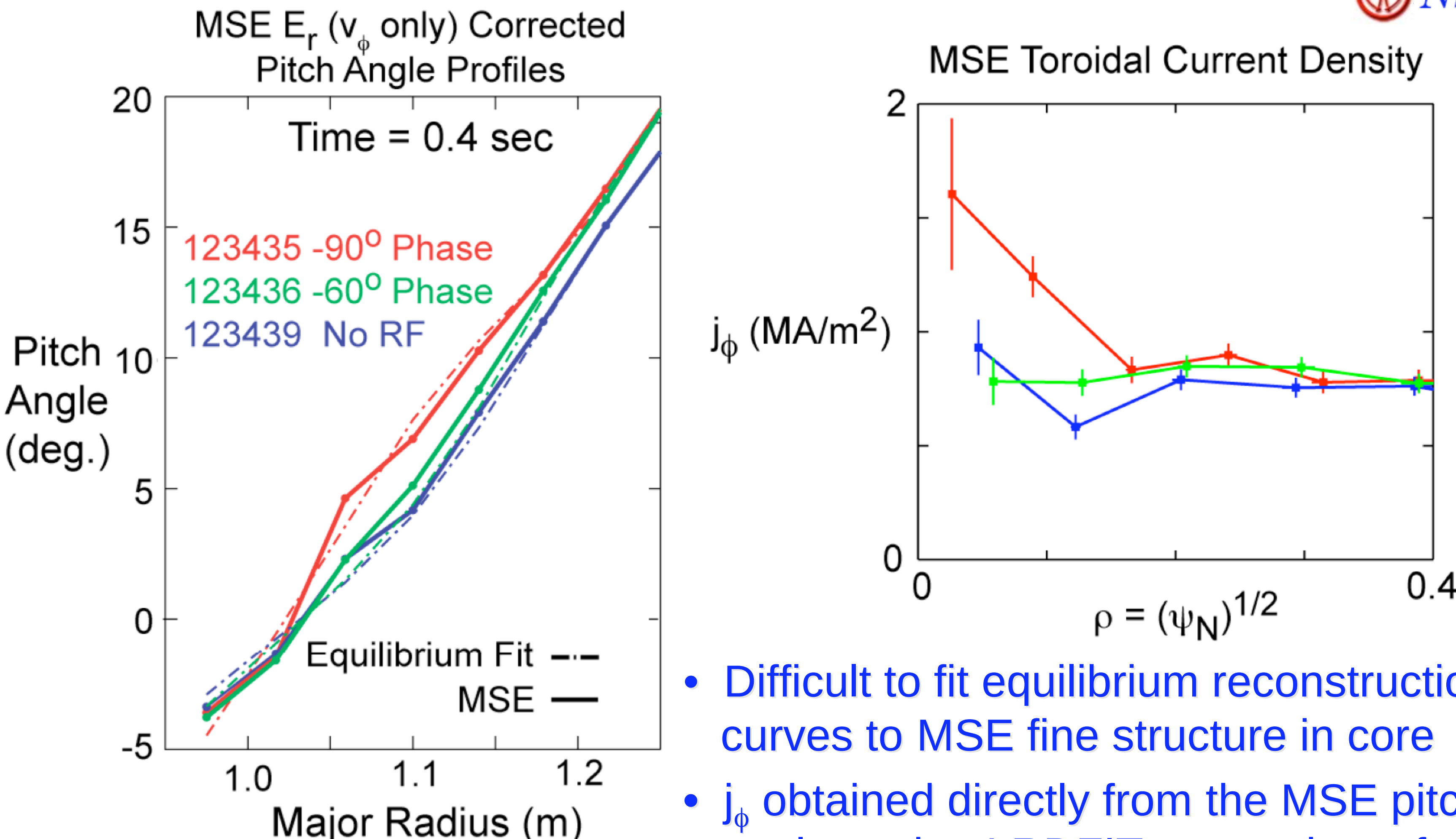
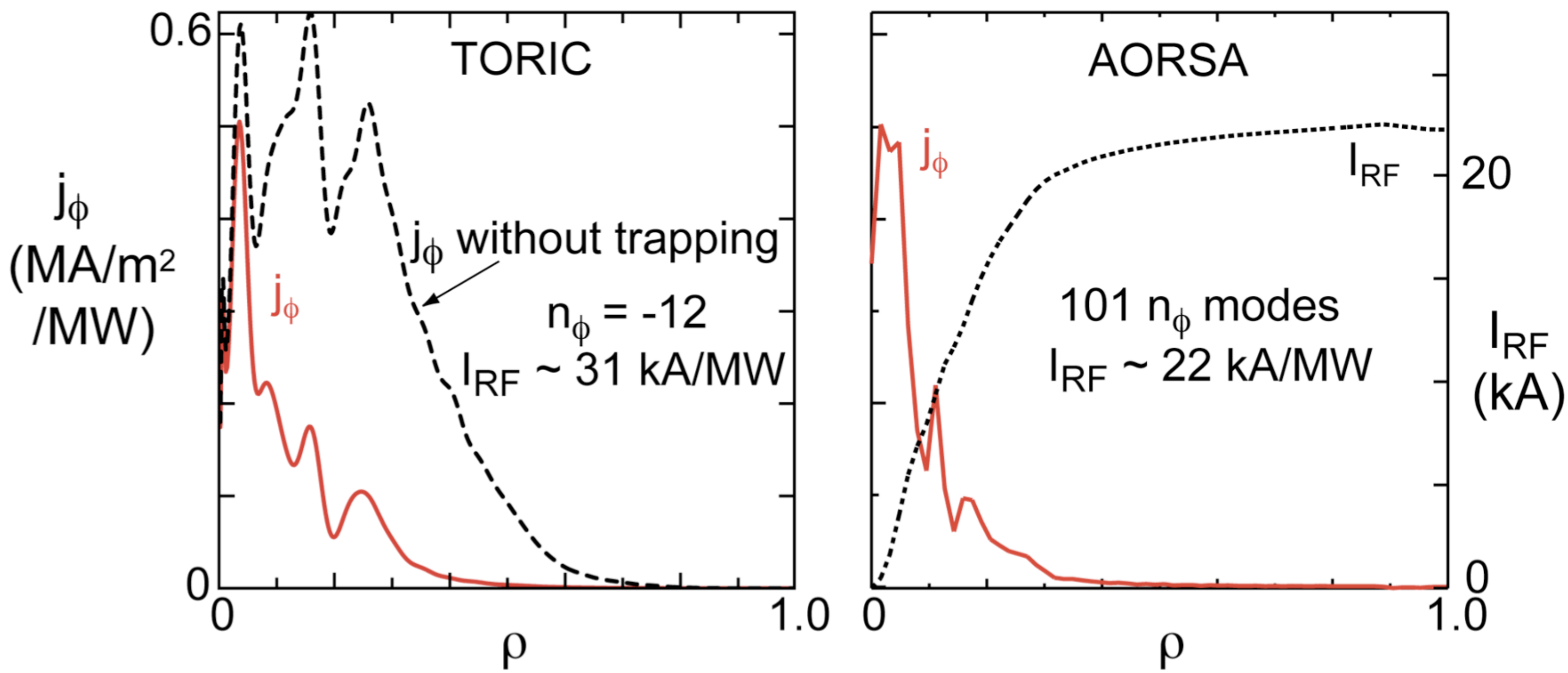


- Difficult to fit equilibrium reconstruction curves to MSE fine structure in core
- j_ϕ obtained directly from the MSE pitch angles using LRDFIT magnetic surfaces

- Integral over j_ϕ peak for -90º phase indicates ~ 15 kA of RF CD relative to no RF case inside R = 1.2 m, ~ 5 kA relative to - 60º phase

Current Drive at - 90° Antenna Phase (k_ϕ = - 8 m^{-1}) Predicted to Peak in Core

Full wave code predictions for j_ϕ



- j_ϕ peaks up for $\rho = (\psi_N)^{1/2} < 0.2$ and AORSA peaks more
- TORIC code predicts ~ 37 kA at 1.2 MW (65% heating efficiency)
- AORSA 2D code predicts ~ 26 kA - ~ 2 x measured value vs No RF
- AORSA includes counter CD spectrum as well

3D Codes Using Full Toroidal Spectrum Being Developed to Include Surface Damping, Core Damping and CD Effects

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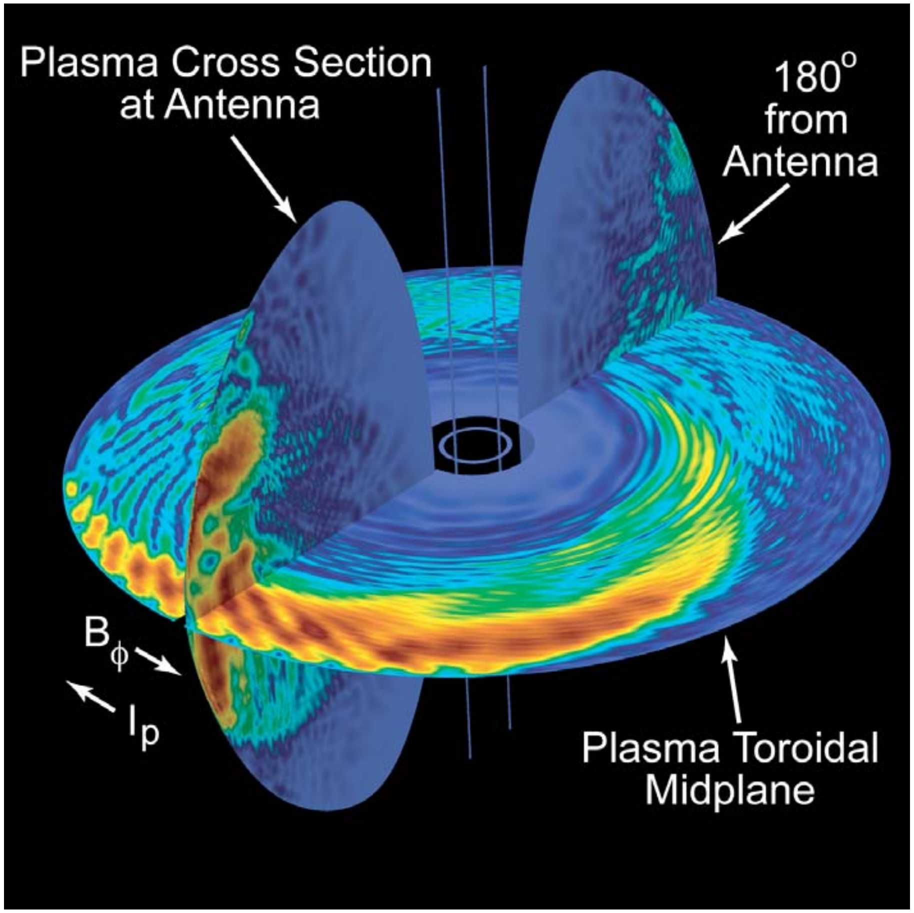
AORSA $|E_{RF}|$ field amplitude for -90^o antenna phase case with 101 n_ϕ



- Waves propagate around plasma axis in + B_ϕ direction
  - similar to GENRAY rays
- Wave fields very low near inner wall
- SciDAC project extending codes to include edge loss mechanisms
- NSTX is good platform for benchmarking advanced RF codes

Conclusions

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- RF losses in the plasma edge are function of k_ϕ & edge density
  - dramatic increase in core heating efficiency observed at higher B_ϕ & lower edge n_e for -90° CD phasing (k_ϕ = - 8 m^{-1})
  - losses are consistent with the onset density for FW perpendicular propagation being exceeded too close to antenna/wall

  ⇨ *Effect could be important for ITER since wavenumber is relatively low for some heating/CD scenarios*
- Initial MSE measurements suggest I_{RF} is ≤ 1/2 that predicted by TORIC and AORSA
  - trapped electron effects are strong in the low aspect ratio NSTX
  - higher RF power for longer pulse length required to make more definitive measurements
- Ongoing RF SciDAC work is important for studying edge loss processes and to provide accurate CD estimates which include total launch spectrum along with effect of high B pitch at antenna

Other Presentations at this Meeting on HHFW

Monday afternoon:

- CO3.002 E. Mazzucato Turbulence fluctuations
- CO3.003 H. Yuh Internal transport barriers

Tuesday afternoon:

- JP8.023J. B. Parker GENRAY analysis

Thursday morning:

- TP8.070D. R. Smith Electron gyroscale fluctuations
- TP8.074L. F. Delgado-Aparicio Multi-energy SXR array measurements
- TP8.101P. M. Ryan HHFW heating and CD progress