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NSTX

Spectral Effects on Fast Wave Core Heating and Current Drive

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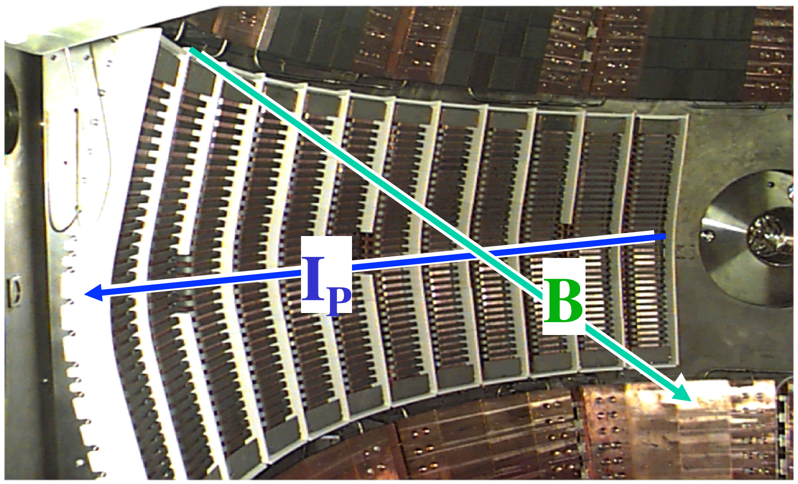
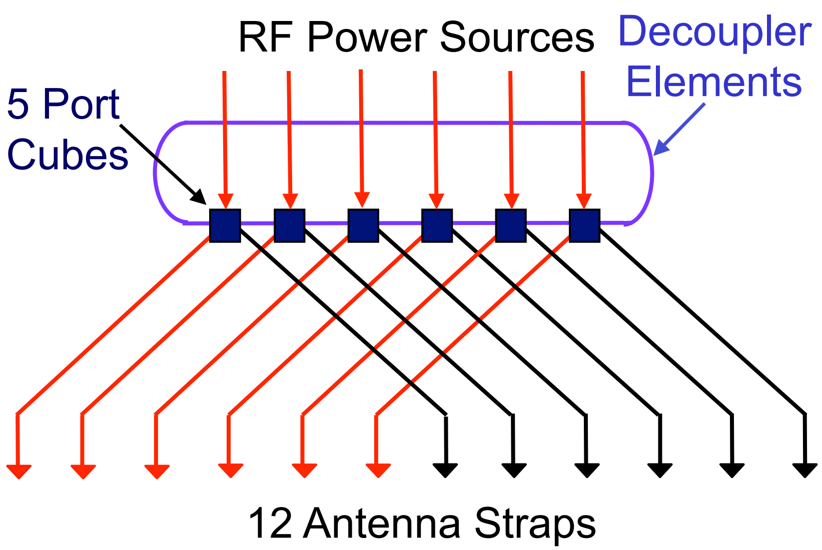
Overview

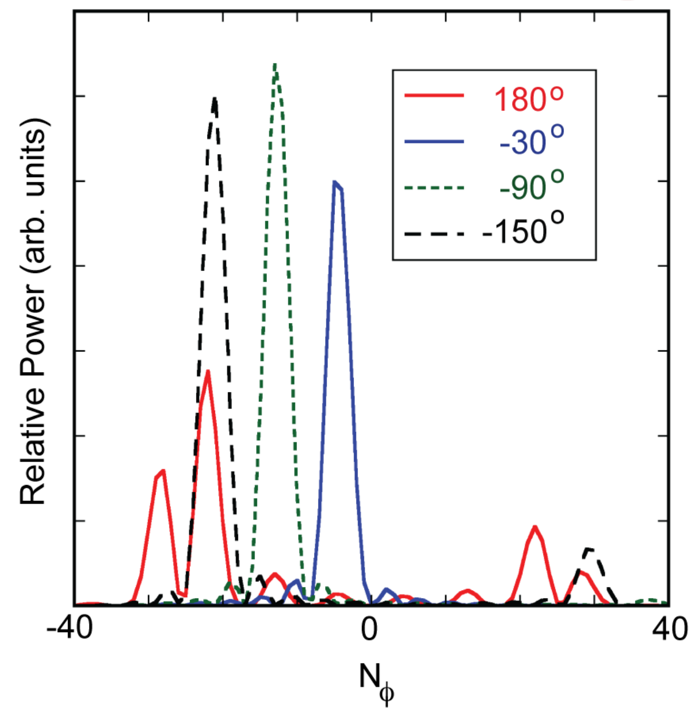
- ***Motivation:***
  - Efficient rf heating and current drive required in ST devices and ITER
  - Experiments on tokamaks and NSTX found core heating efficiency degraded for low launched parallel wave numbers, $k_{//}$
- ***Approach:***
  - Study dependence of core high harmonic fast wave (HHFW) heating efficiency on antenna phase, magnetic field, and edge density in NSTX
- ***Conclusions:***
  - Results show core heating efficiency improves when fast wave propagation begins away from the launcher and wall
  - Careful tailoring of edge density profile may be important in ITER
  - Initial MSE measurements of HHFW-driven currents consistent with numerical simulations

NSTX HHFW antenna has well defined spectrum, ideal for studying dependence of heating on antenna phase



HHFW antenna extends toroidally 90°





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

Strong "single pass" absorption ideal for studying competition between core heating and edge power loss

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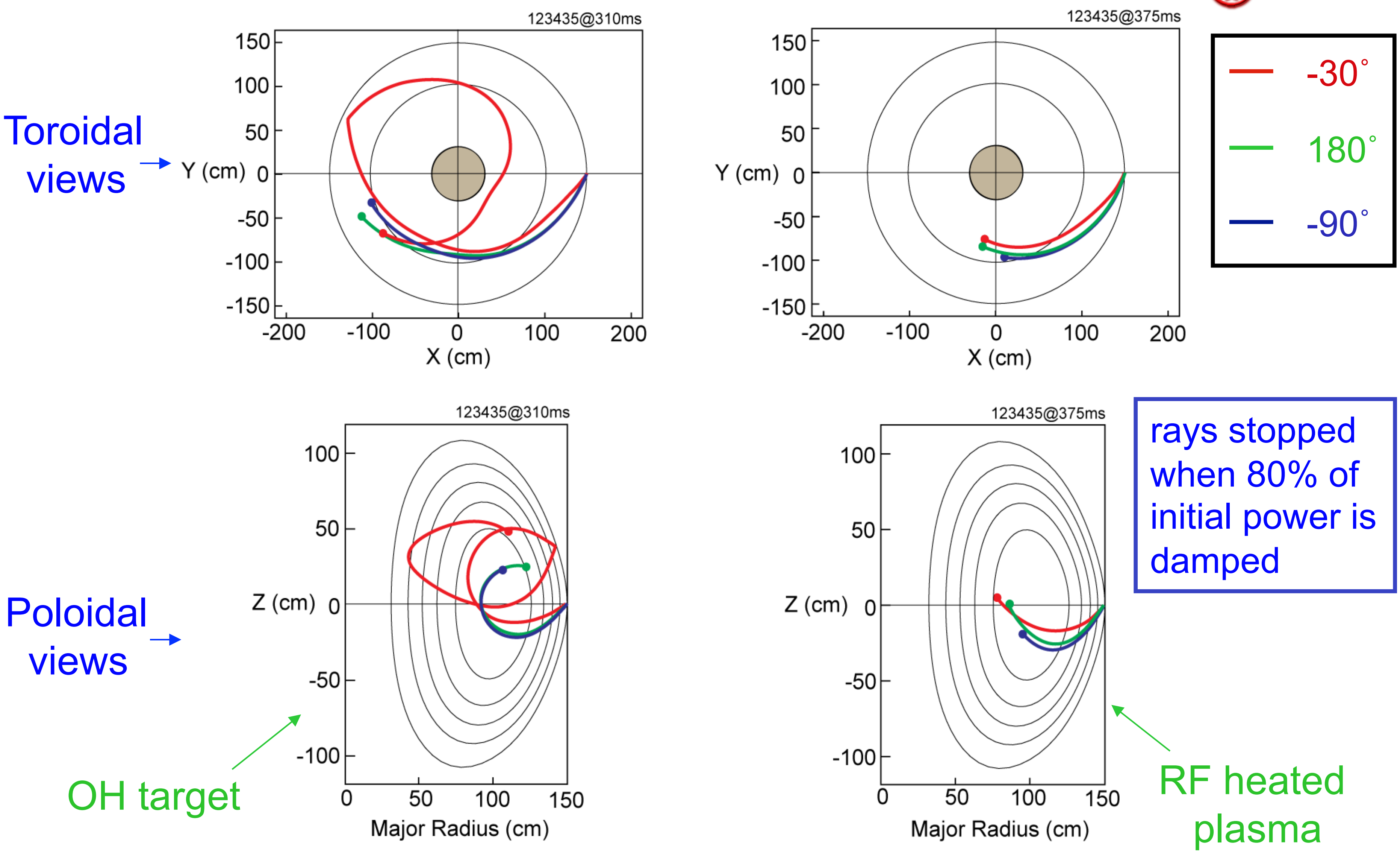

Dependence of heating efficiency on antenna phase has been studied using RF power modulation

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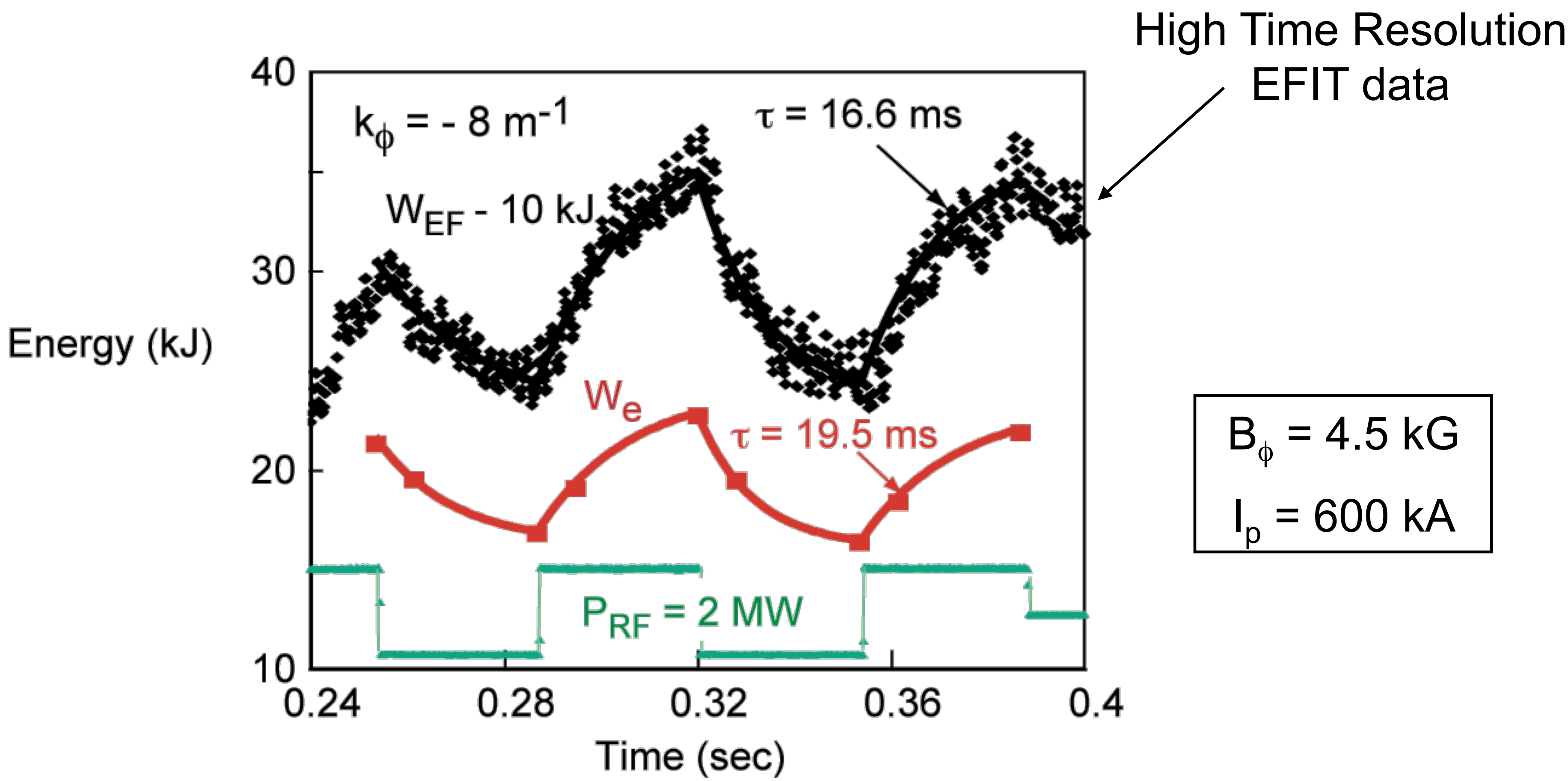

B_ϕ = 4.5 kG
I_p = 600 kA

Electron and Total Stored Energy exhibit exponential rise, with $\tau_{We} \sim \tau_{WEF}$

HHFW heating efficiency determined via power modulation

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- 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

Heating efficiency for $k_{//}$ = 8 m^{-1} increased substantially as B_T increased from 0.45 T to 0.55T

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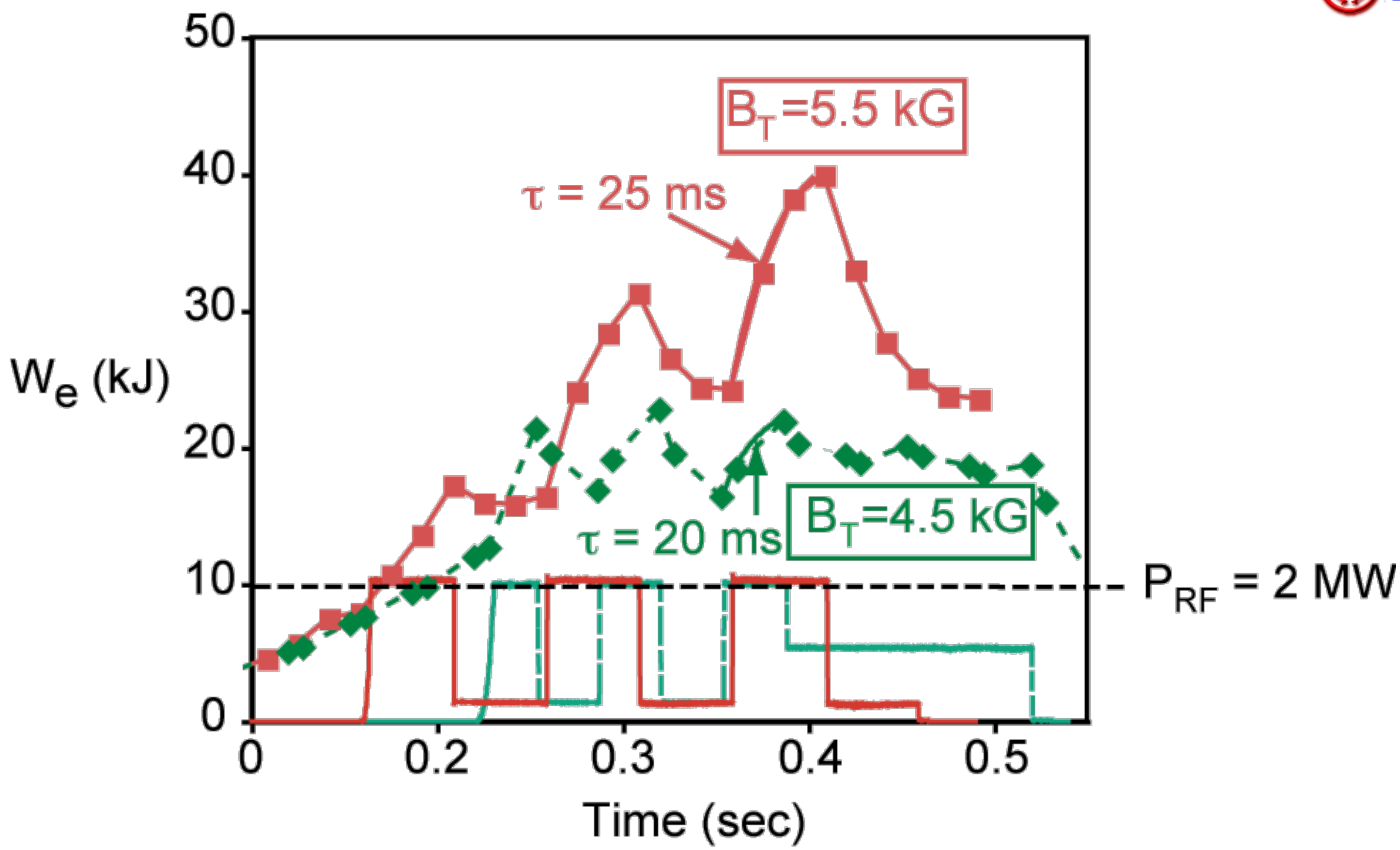

- ΔW_e for B_T = 0.55 T is ~ twice value for 0.45 T over same time interval
- RF power deposition to electrons increases from ~ 22% to ~ 40% at higher B_T, total efficiency increases from ~ 44% to ~ 65%

Improved heating at $k_{||} = -8\ m^{-1}$ *not due* to reduced edge heating from parametric decay instability (PDI)

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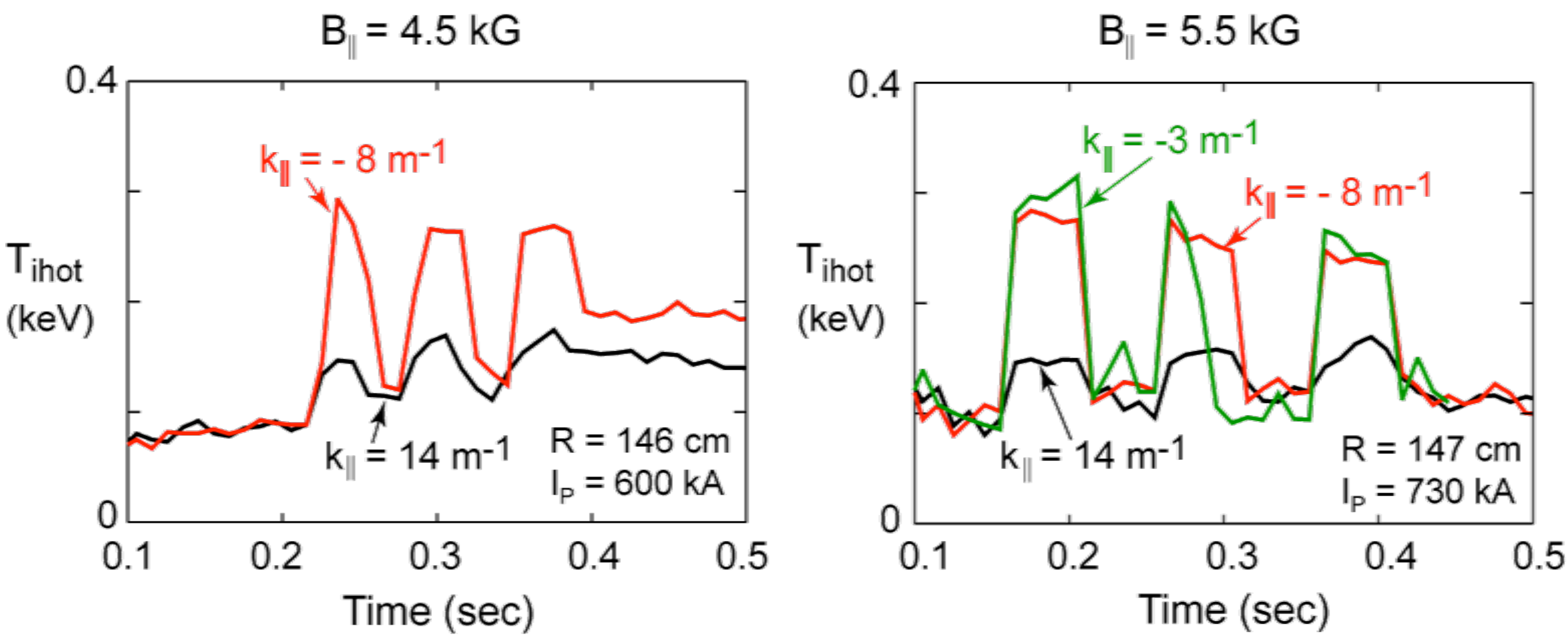
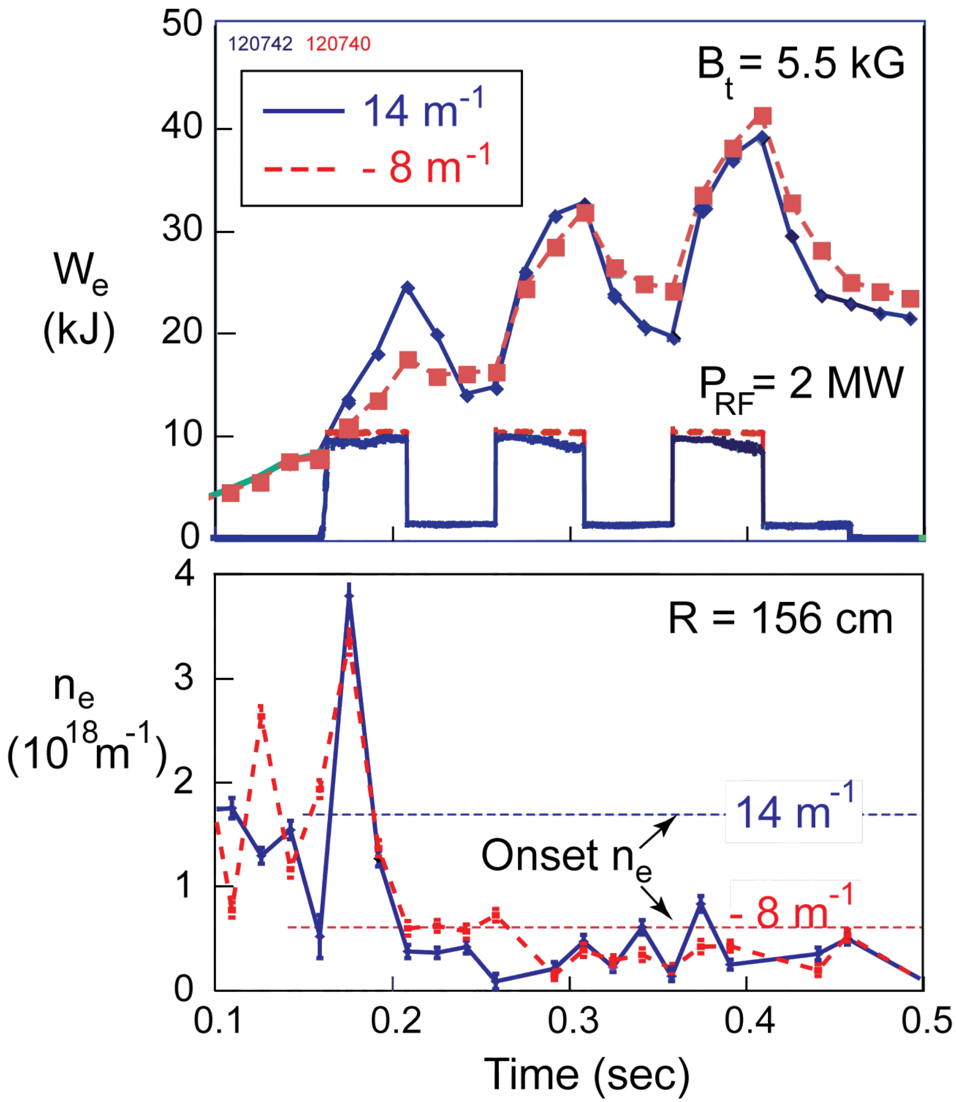
Edge ion heating as a measure of PDI losses



- Edge ion heating comparable at 0.45T and 0.55T with $k_{||} = -8\ m^{-1}$
- PDI edge heating similar at $k_{||} = -3\ m^{-1}$ and $-8\ m^{-1}$ ⇒ suggests other surface wave losses and reduced core damping account for decrease in heating efficiency

Edge power loss increases when perpendicular propagation onset density is near antenna/wall



- 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

Degradation of heating efficiency at lower $k_{||}$ likely due to HHFW propagation too close to launcher / wall

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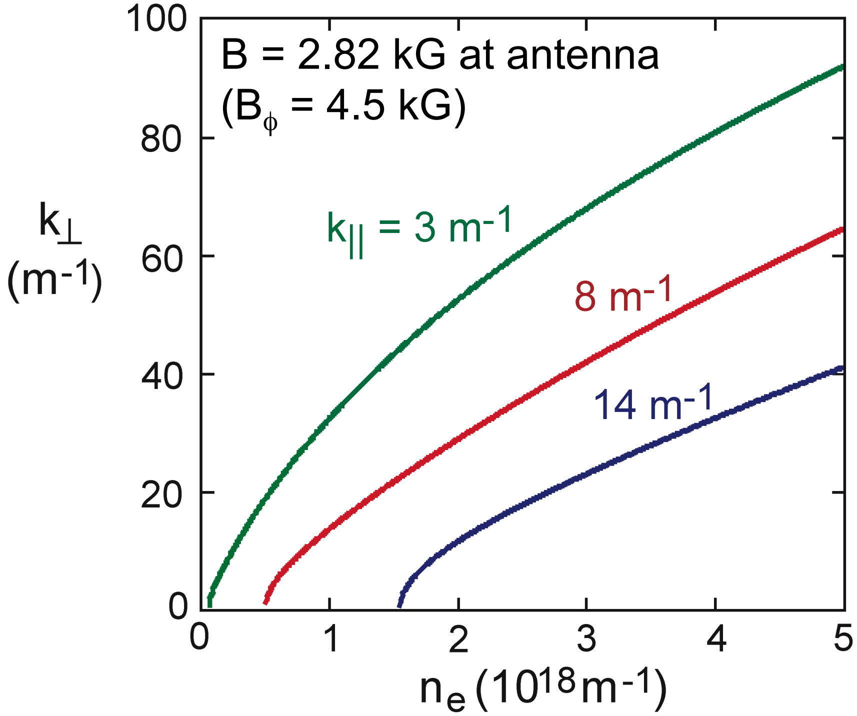
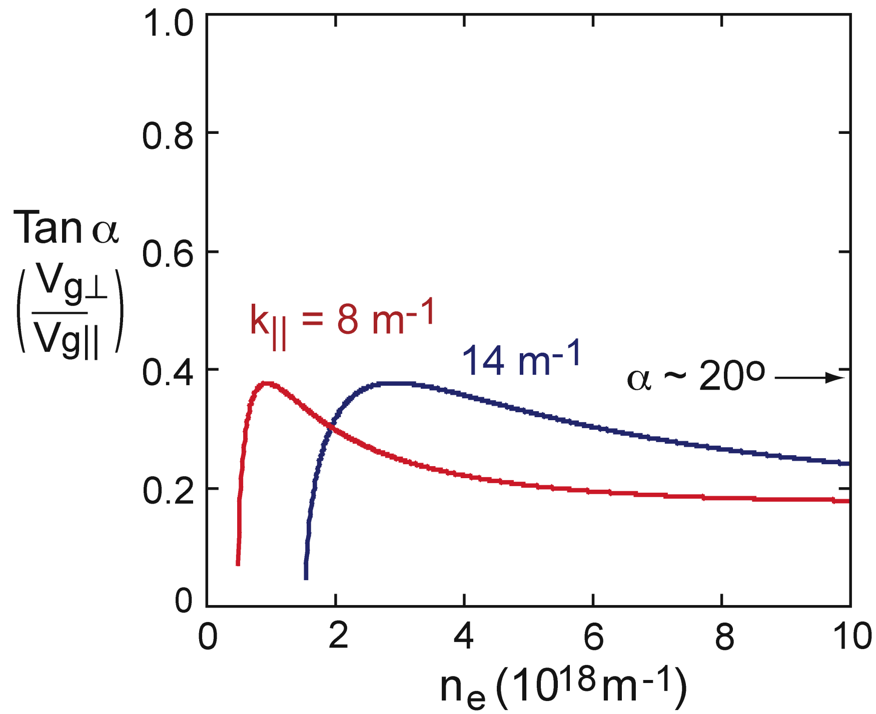
Propagating $k_\perp$ vs density at antenna B



Angle of ray to B vs density

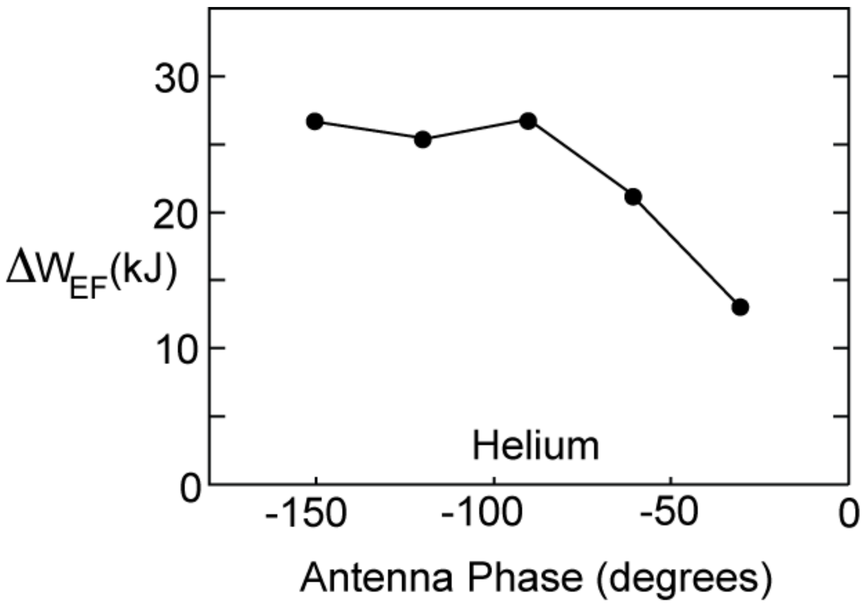


Onset density is $\propto B^*k_{||}^2/\omega$

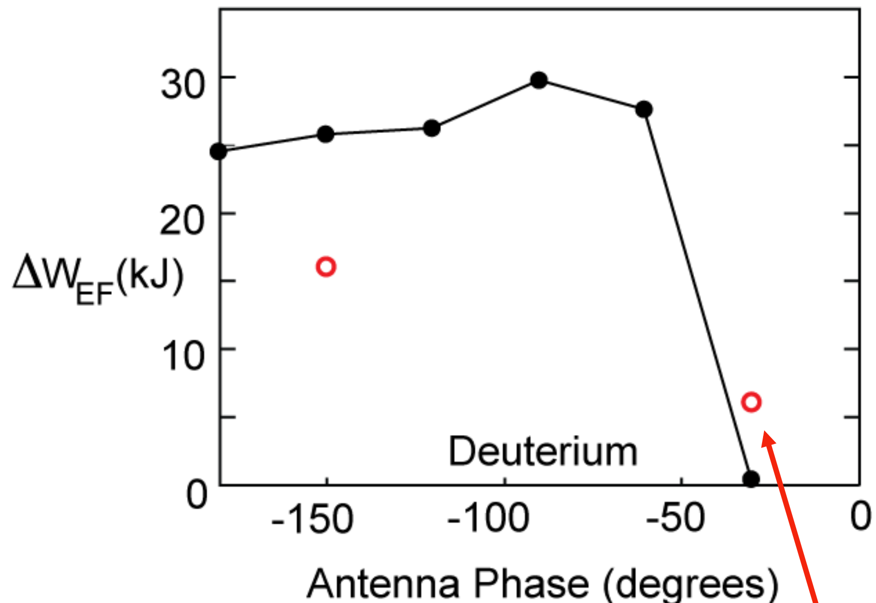
- Propagation is very close to wall at $k_{||} = 8\ m^{-1}$, on wall at $k_{||} = 3\ m^{-1}$
- Losses in surface should be higher for lower $k_{||}$
- Propagation angle relative to B much less than for lower harmonic case
- Increasing B should move onset farther from antenna, increasing heating

RF-induced increase in electron stored energy comparable in Helium and D plasmas

P_{rf} ~ 1.8 MW in He-4 plasmas
(~ 230 ms duration)

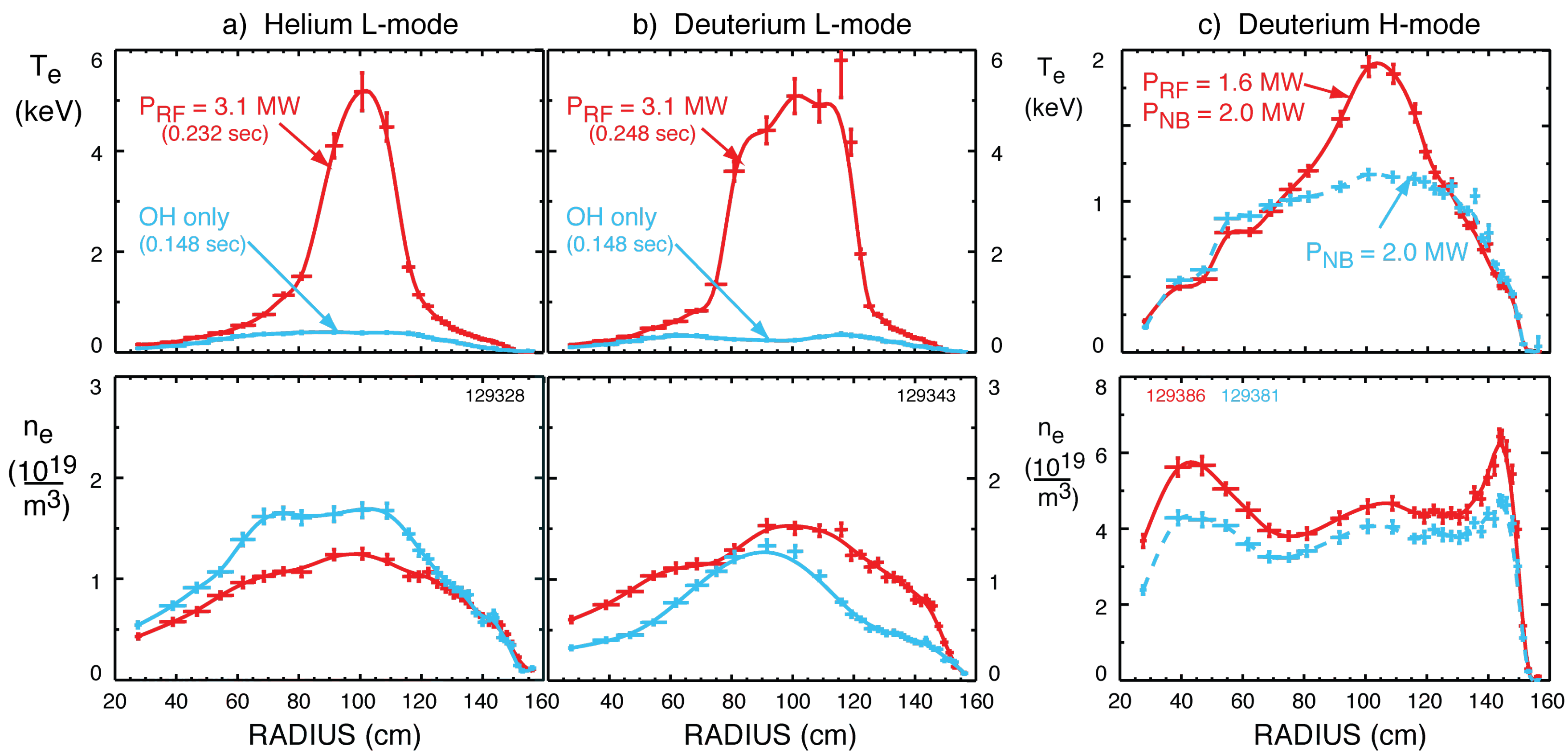


P_{rf} ~ 1.1 MW in D plasmas
(~230 ms duration)



Noticeable increase in ΔW_{EF} with -30° phasing in D plasmas with Li edge conditioning, even with shorter rf duration (67 ms)

Improved HHFW Heating is Being Used to Support Transport Studies



- $T_e(0)$ of ~ 5 keV produced to support high k scattering study of small scale turbulence (ETG mode?) in He and D_2
- Core electron heating of NB deuterium H-mode to support study of core electron transport (no HHFW heating observed prior to control of edge density)

NSTX results indicate surface wave damping could be important for ITER ICRF heating

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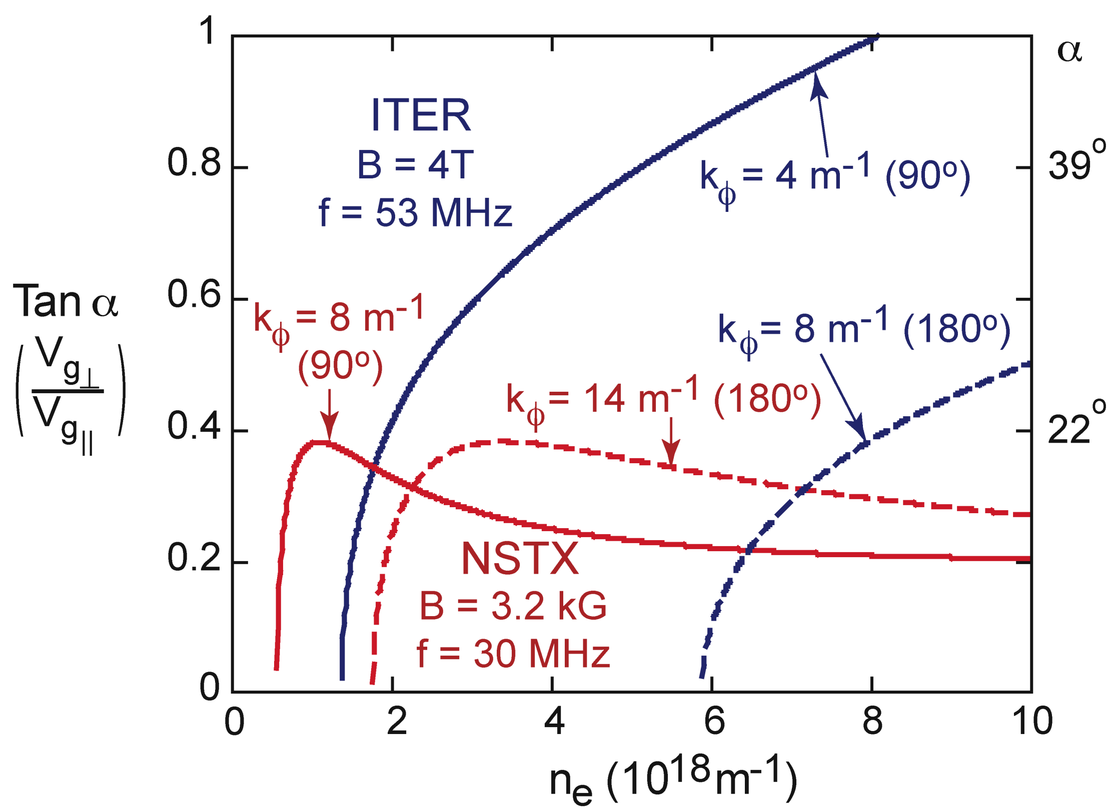
Angle of wave propagation relative to B



- $k_\phi \sim 4\ m^{-1}$ at 53 MHz for CD phasing in ITER
- 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)

Edge loss mechanisms need to be identified experimentally and included in advanced RF codes

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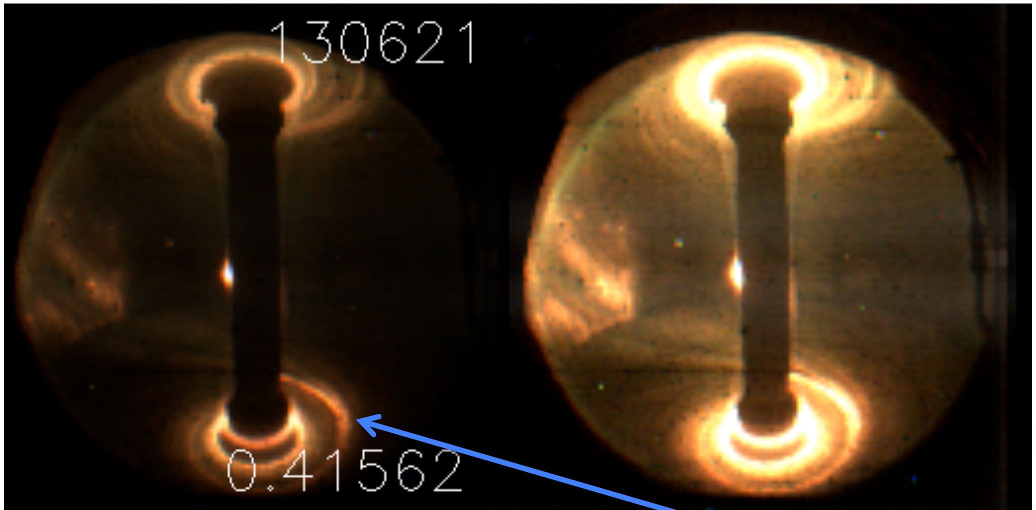
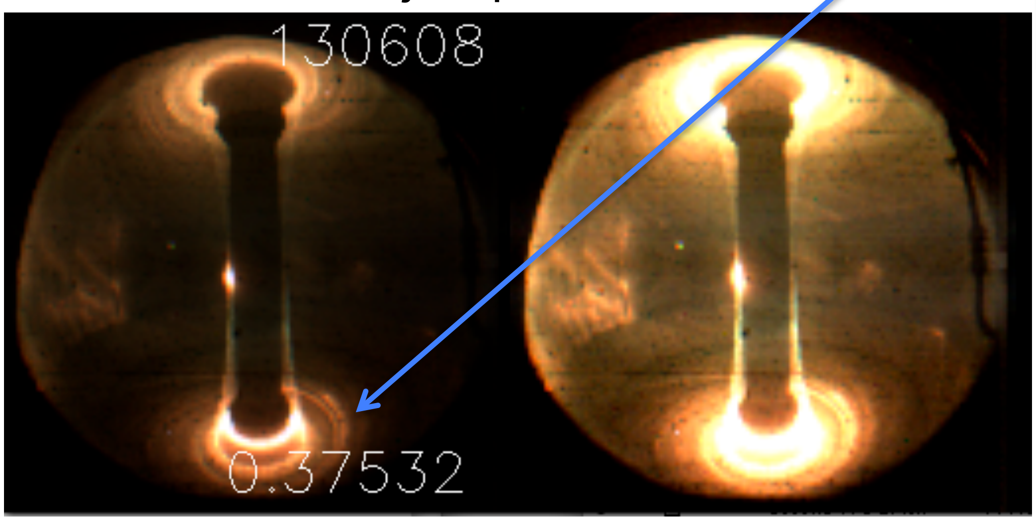
- Searching for edge RF power loss processes on NSTX:
  - Collision effects
  - Sheath effects
  - PDI effects
  - Antenna reactive field losses
  - Propagating FW losses
  - Non-toroidally symmetric, localized losses
  - Etc.
- Diagnostic tools on NSTX include:
  - edge reflectometer
  - edge CHERS
  - probes for PDI effects
  - cameras for visible and IR light
  - etc.

RF Effect Seen Outside Divertor Strike-point

Phase = - 90° just prior to arc before elm



Phase = - 150° just prior to arc before elm



Searching for edge RF power loss processes

P_{RF} ~ 1.8 MW, I_P = 1 MA, P_{NB} = 2 MW

- RF interaction is localized toroidally
- Appears to be linked with antenna along field lines
- Intensity may be dependent on phase dies away after RF is removed
  - decay in 15 – 20 msec

Next campaign

- Need to measure heating with infrared camera and thermocouples to deduce RF power lost
- Need RF power and phase scans to see if power lost correlates with observed heating efficiency

Current Drive studies with MSE diagnostic have begun with more efficient heating at k_ϕ = - 8 m^{-1}

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- MSE measurements of CD use 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 -90° antenna phase (k_ϕ = - 8 m^{-1})

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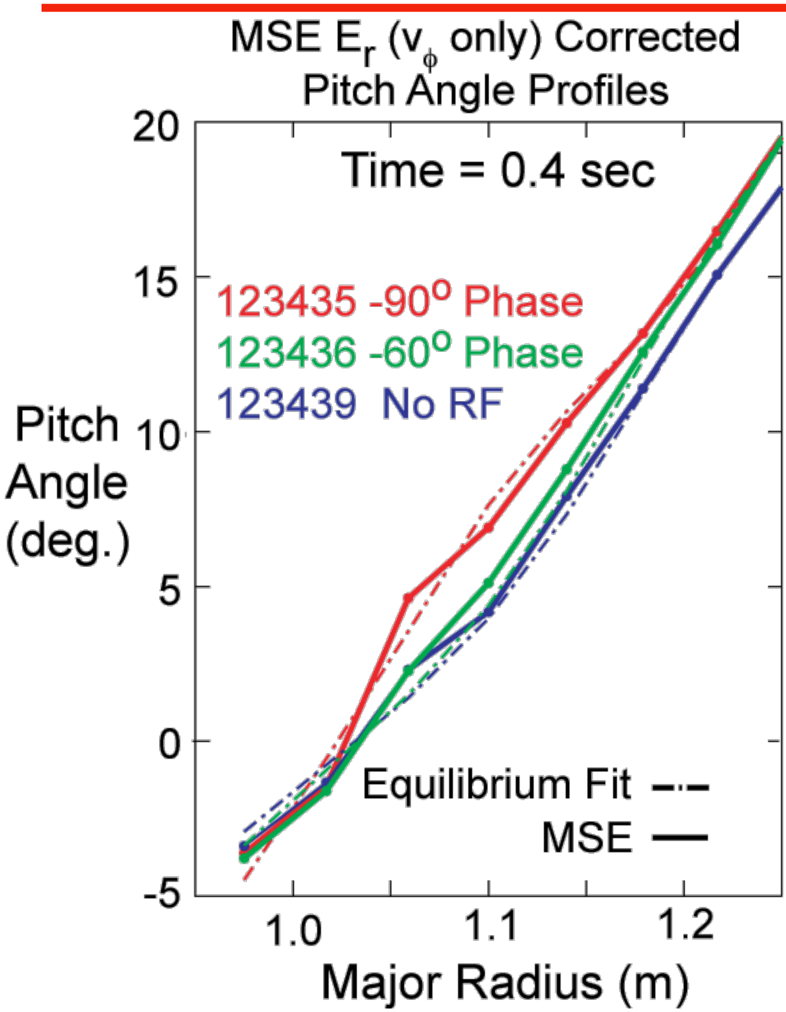
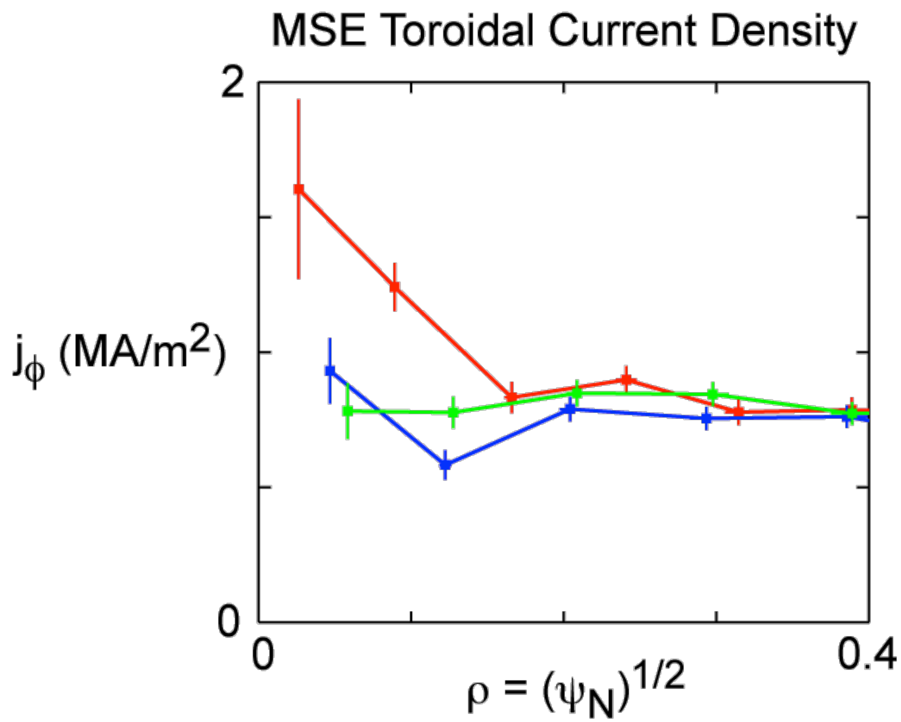
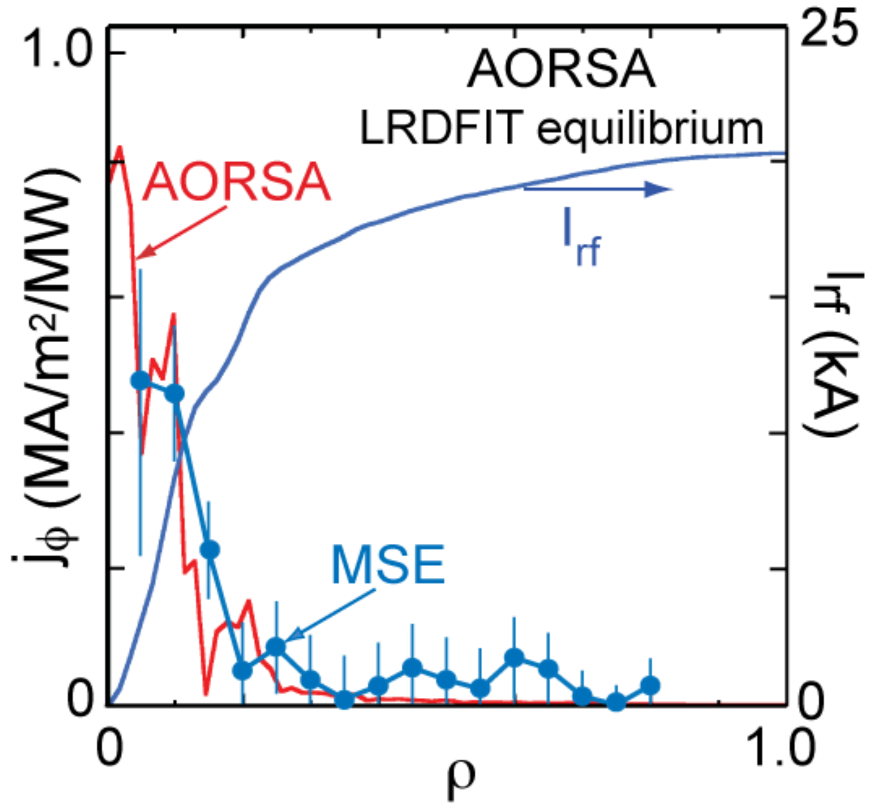




- Difficult to fit equilibrium reconstruction curves to MSE fine structure in core
- j_ϕ obtained directly from the MSE pitch angles using LRDFIT magnetic surfaces

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

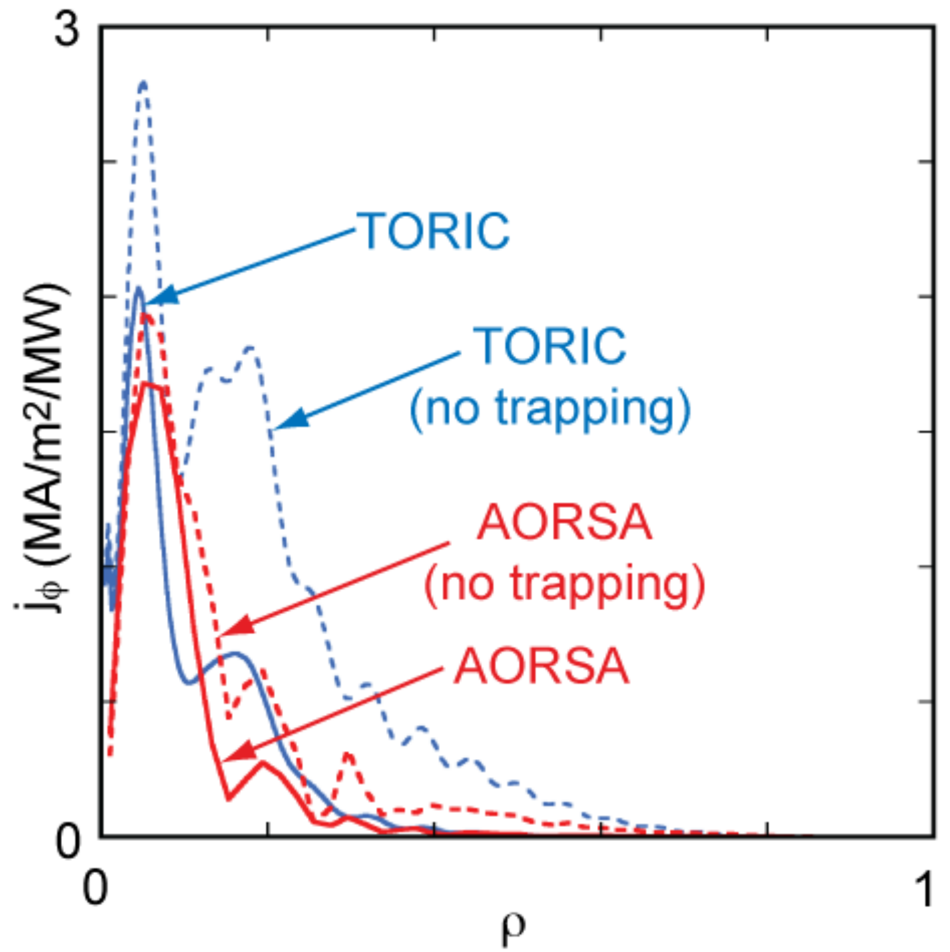
Measured current drive at - 90° antenna phase (k_ϕ = - 8 m^{-1}) peaks in the core, consistent with modeling



MSE profile normalized assuming 1.2 MW of HHFW absorbed in plasma

AORSA prediction used full toroidal spectrum and Ehst-Karney approximation, including trapping effects

Modeling indicates that trapping effects limit the driven currents to the core, consistent with MSE measurements



AORSA and TORIC comparisons using a single toroidal mode number (N_{tor} = 12) at peak of the launched spectrum are remarkably similar

Modeling must include the full power spectrum of launched waves for quantitative agreement with MSE

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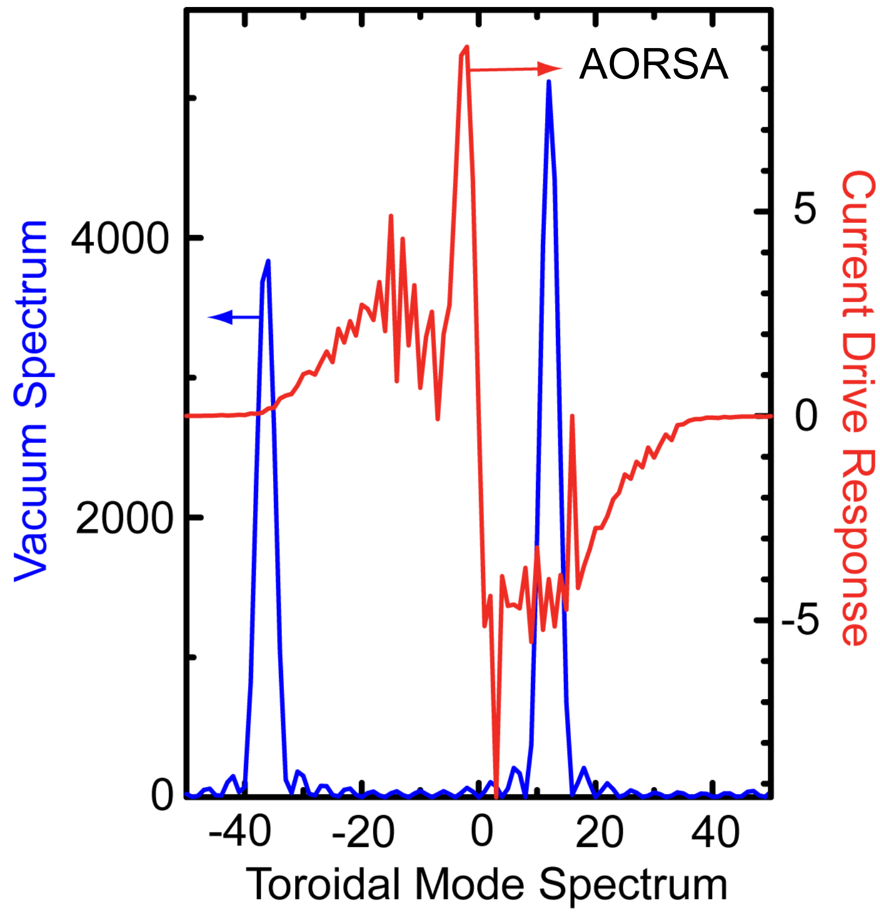
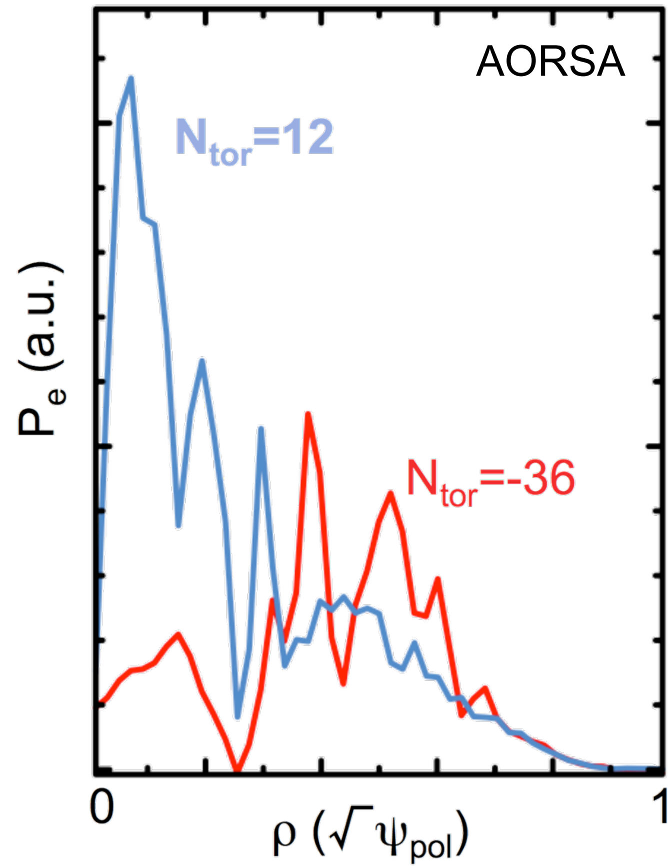
Driven Current Spectrum



Power Deposition Profile



Ehst-Karney:

$$J_{rf} \propto P_e$$

Current driven on the back lobe is localized well off-axis and lost due to trapping effects

Comparisons between MSE and modeling improve when equilibrium fit is constrained by MSE measurements

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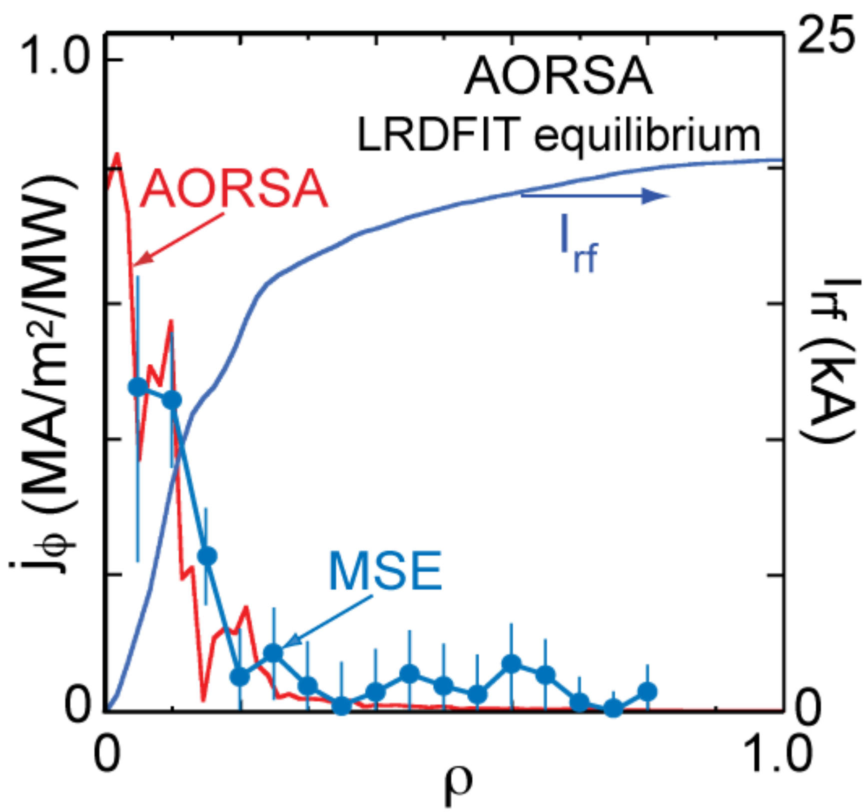
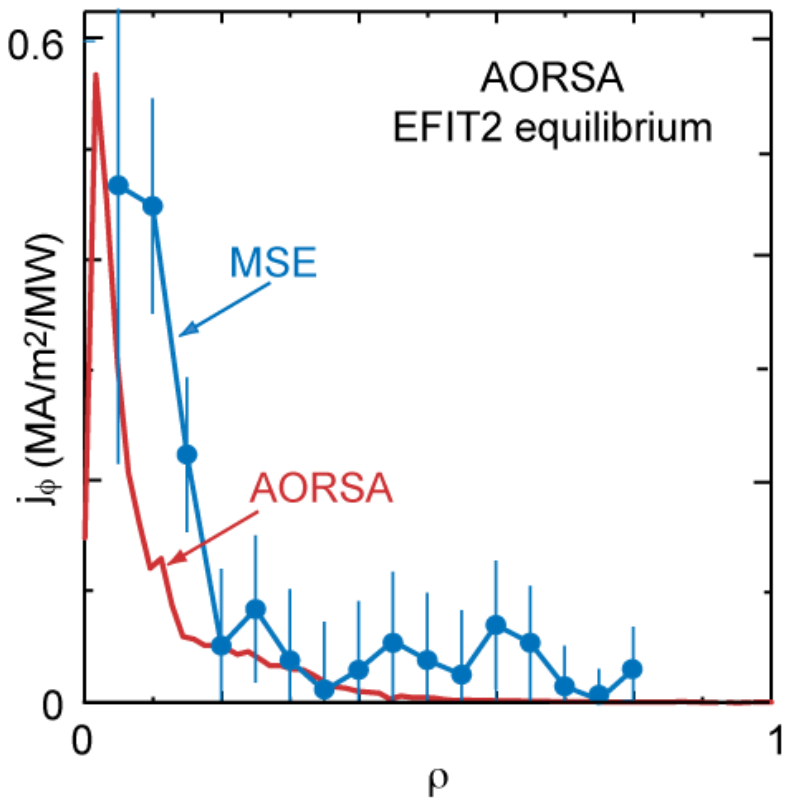


LRDFIT uses MSE data, as well as magnetics and kinetic profiles



EFIT2 uses magnetics and kinetic profiles

3D Codes using full toroidal spectrum being extended to include surface damping and CD effects

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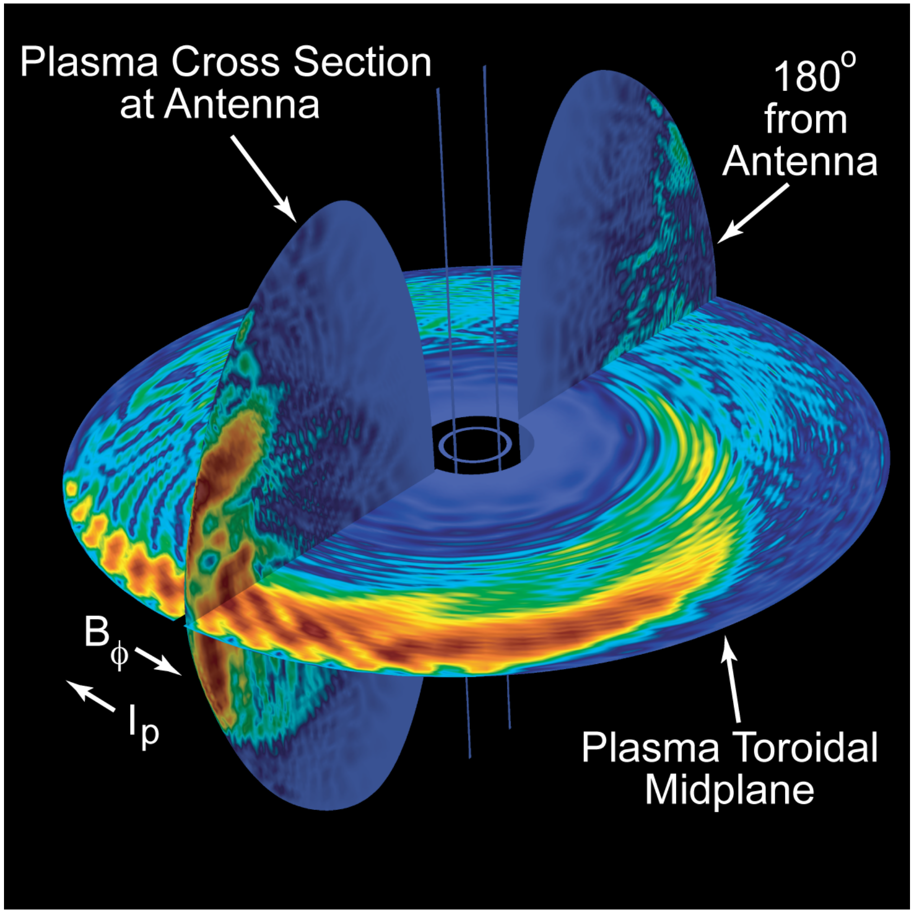
AORSA $|E_{RF}|$ field amplitude for -90° antenna phase case with 101 n_ϕ



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

Conclusions

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- Degradation of heating efficiency occurs when the onset density for FW propagation is exceeded too close to the antenna / wall
  - dramatic increase in core heating efficiency observed at higher B_ϕ & lower edge n_e for -90° CD phasing (k_ϕ = - 8 m^{-1})
  - rf losses in the plasma edge are a function of k_ϕ & edge density
  - ⇨ *Effect could be important for ITER since wave number is relatively low for some heating/CD scenarios*
- Initial MSE measurements are consistent with simulations from the AORSA and TORIC codes
  - 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, including the total launch spectrum, the effect of high B pitch at antenna, and the back EMF (time-dependent effects).