Electron Stored Energy/Energy Confinement Indication of HHFW Surface Power Deposition on NSTX

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Additional Thomson scattering measurements of the electron energy confinement time during and following HHFW pulses for both heating and current drive antenna phasing are being carried out on NSTX in order to confirm the earlier conclusion that the power delivered to the core plasma is reduced considerably for the current drive phasing case as contrasted to the heating phasing case. This result occurs even though the radial deposition of energy into the electrons in the core plasma is noticeably more peaked for current drive phasing (longer wavelength excitation) relative to that for heating phasing (shorter wavelength excitation) as is expected theoretically. Thus it indicates that surface/peripheral damping processes play a more important role for current drive phasing. Many processes are possibly contributing to this "surface" power loss – surface wave excitation, RF sheath dissipation, and parametric decay wave excitation to name a few. Evidence of parametric decay wave heating has been obtained but does not appear to account fully for the difference between the two phasings. The possible contribution of collisional damping of surface waves to the surface power loss will be explored.

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- Goal: Continue the investigation of HHFW power deposition into the electrons on NSTX as a function of antenna spectra - determine surface power deposition and possible contributing causes
- Outline:
  - Two-laser Thomson scattering method for discerning exponential rise and decay times for RF pulse heating
  - $P_e(r=0,t)$ sensitivity to instabilities and profile evolution
  - Electron energy $W_e(t)$ from integral of $P_e(r,t)$ over volume defined by EFIT magnetic surfaces
  - W_e rise and decay times (τ_0, τ)
    - for $k_\phi = 14\ m^{-1}$ (180^o antenna element phasing)
    - and for $k_\phi = -7\ m^{-1}$ (-90^o phasing, co-current drive)
  - Implications for RF power to bulk plasma
  - Possible magnetic sheer effect on surface damping (co vs counter CD phasing)
  - Possible processes contributing to the reduction of power delivered to bulk plasma
    - Edge ion heating via parametric decay, surface waves, high radial mode numbers, Bernstein (parasitic) wave excitation, reactive current collision and sheath losses
  - Summary

Three data points are sufficient to determine exponential decay properties

- assuming decay conditions (τ and W_F) are constant

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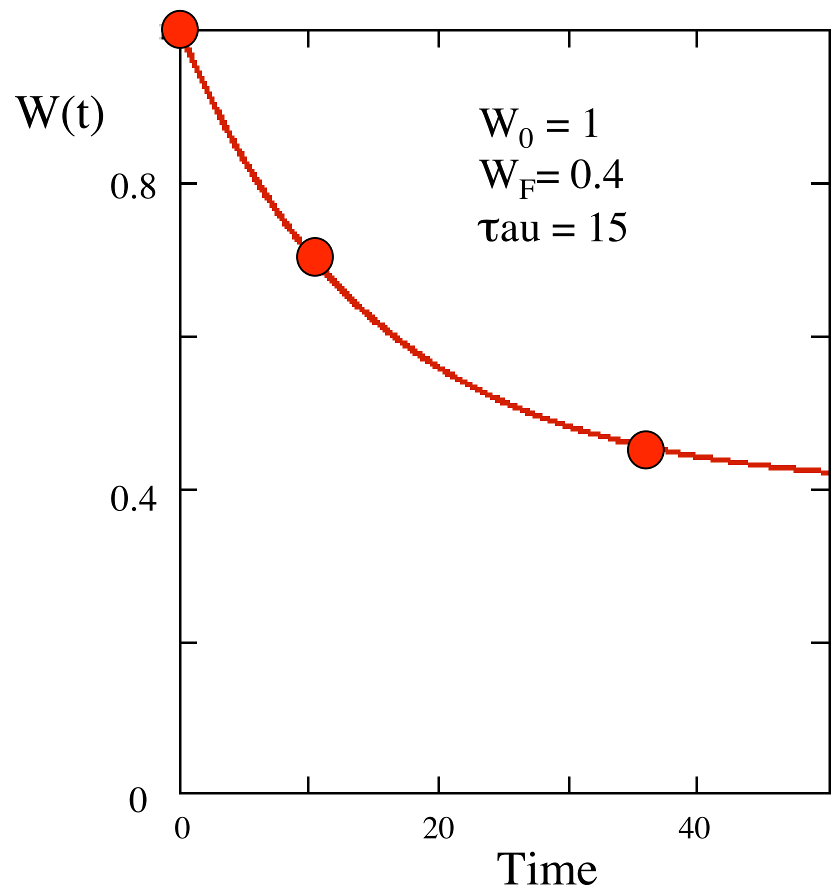
$W_e(t) = W_0 - (W_0 - W_F)*(1 - e^{-t/\tau})$

$W1 = W_e(t1)$, $W2 = W_e(t2)$, $W0 = W_0$

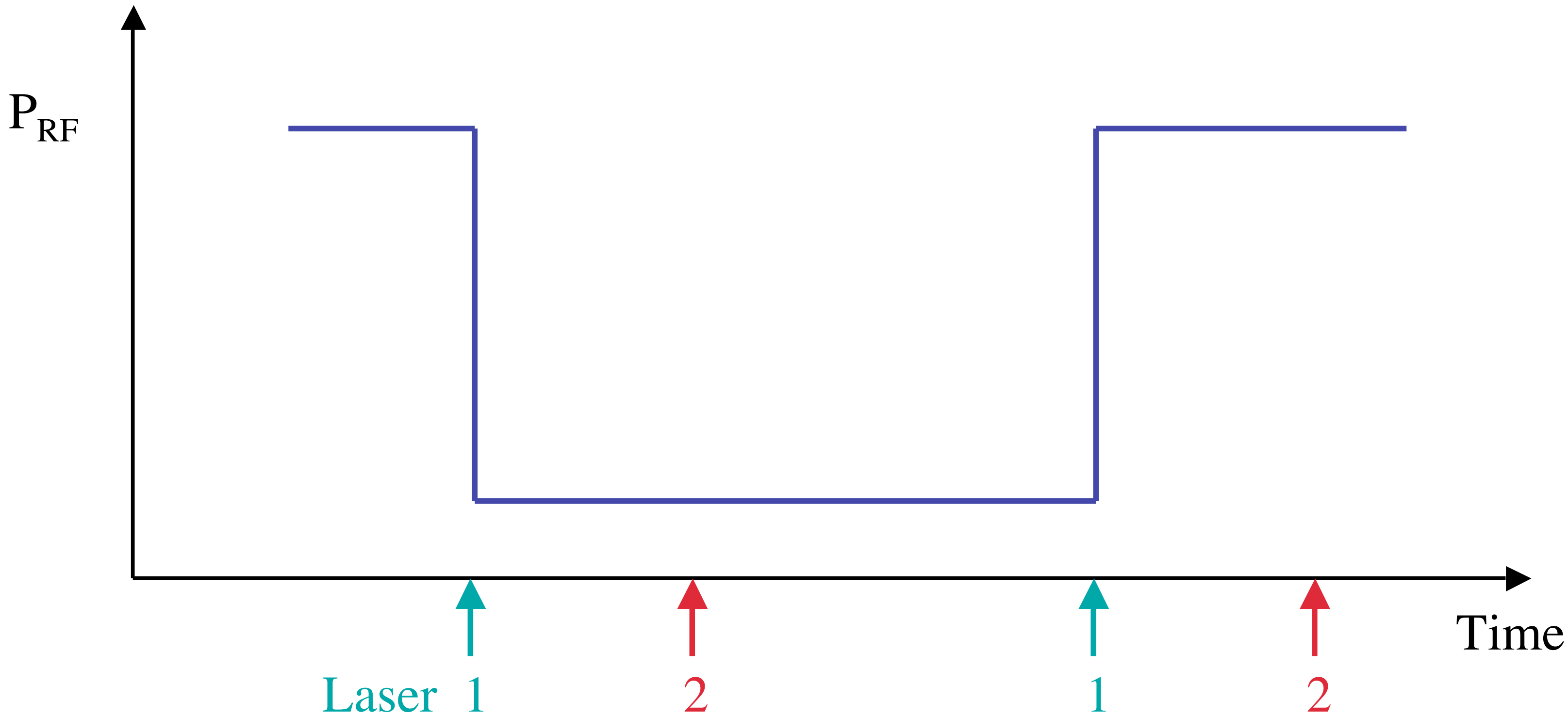
Solve for τ:
$(W0 - W1)/(W0 - W2) = (1 - e^{-t1/\tau})/(1 - e^{-t2/\tau})$

Solve for W_F:
$(W0 - W_F) = (W0 - W2)/(1 - e^{-t2/\tau})$

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



Experimental Setup



- Laser 2 has an adjustable time delay relative to laser 1
- Laser 1 measurement is extrapolated to the P_{RF} fall (rise) time for value at t_0
- Equilibrium control conditions are held as constant as possible - I_P, B_T, n_e, plasma position, shape

CENTRAL ELECTRON PRESSURE TIME RESPONSE AFFECTED BY PROFILE EVOLUTION AND INSTABILITY

P_e(r=0) versus Time for - 90° Antenna Phasing (k_ϕ = -7 m^{-1}) Shows Clear Effect of Instability

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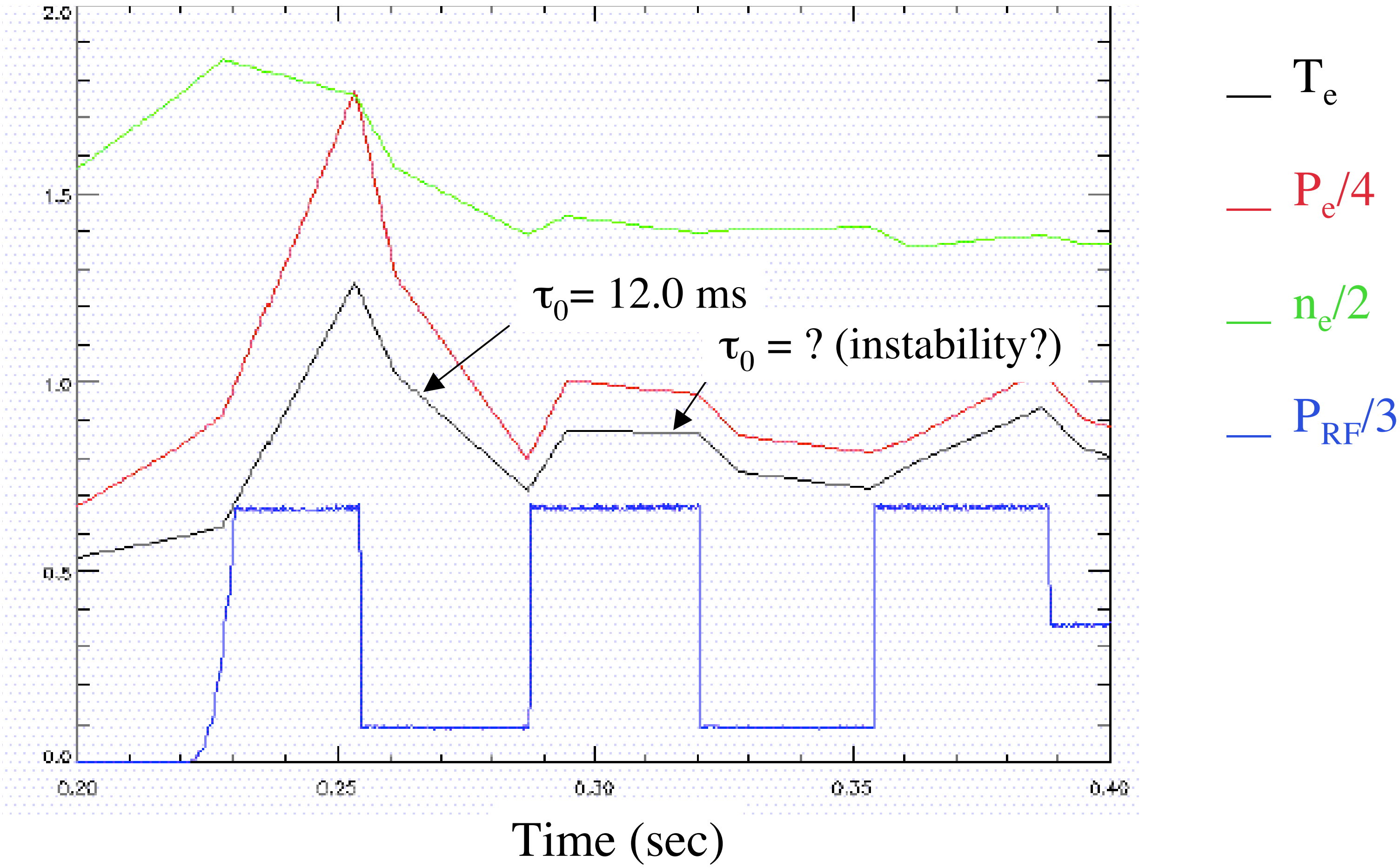
Shot 112705 with 8 ms laser delay (I_P = 0.6 MA, B_T = 0.45 T, Helium)



- τ_0 cannot be calculated for the second RF pulse - P_e profiles are obviously changing in time

P_e vs Radius for -7 m^{-1} After First RF Pulse

Laser times(sec) are 1 (0.2533), 2 (0.2613), 3 (0.2867)

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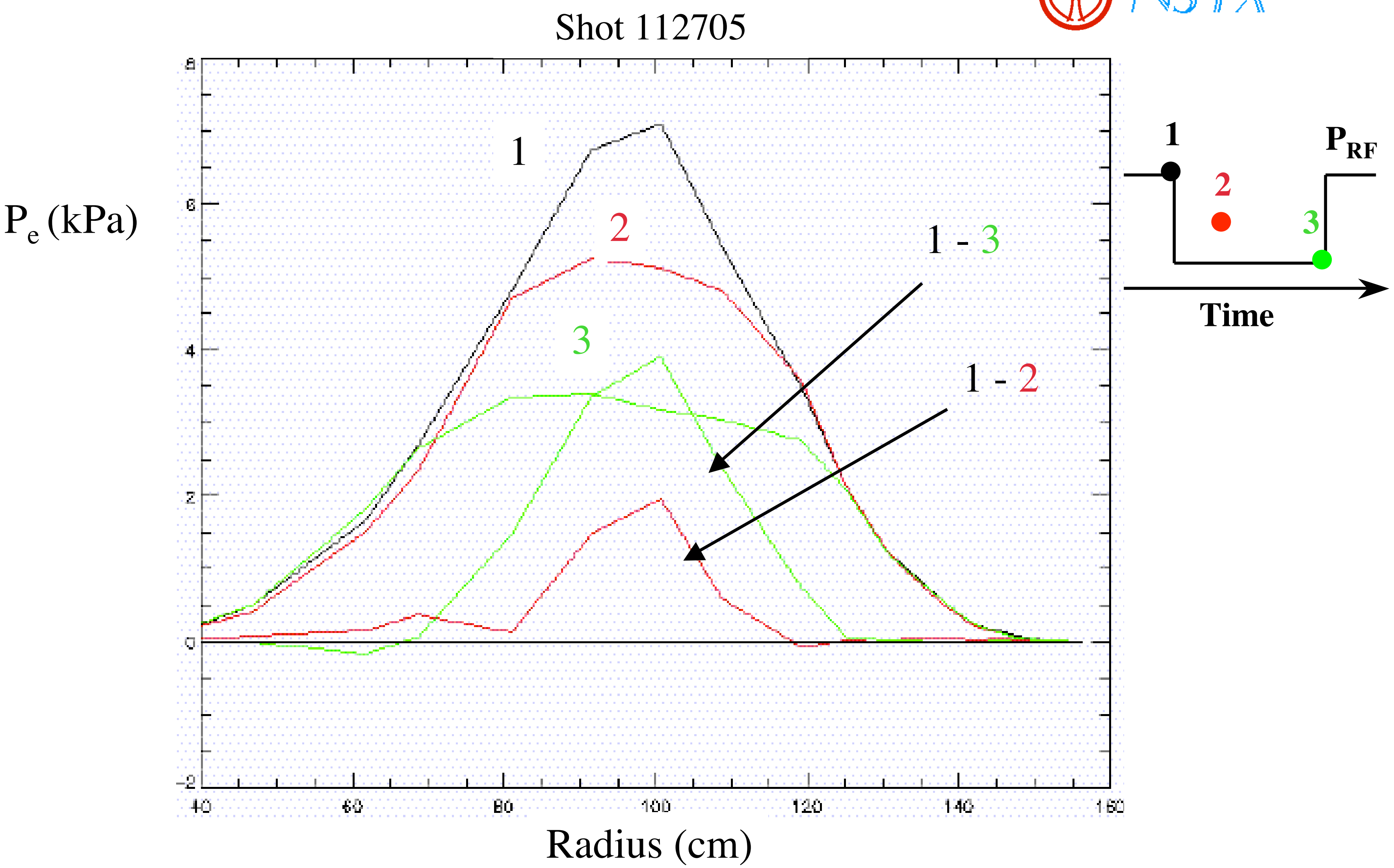
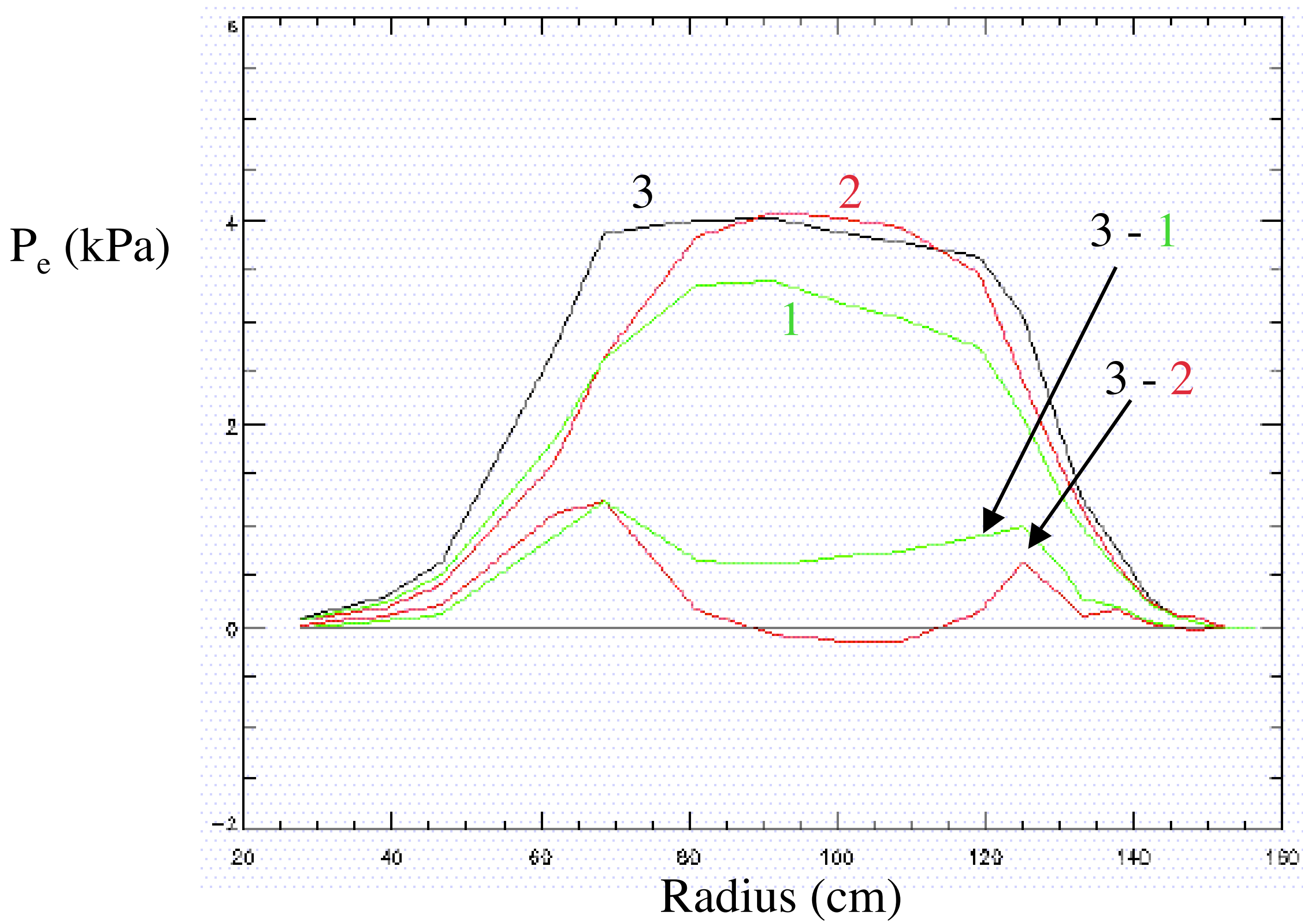


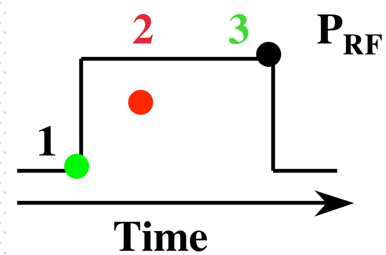
- Electron pressure decay is reasonably symmetric after the first RF pulse and the decay(heating) is strongly centralized as expected for $k_\phi = 7m^{-1}$

P_e vs Radius for -7 m^{-1} for 3 Times for Second RF Pulse

Laser times(sec) are 1 (0.2867), 2 (0.2947), 3 (0.3200)

Shot112705



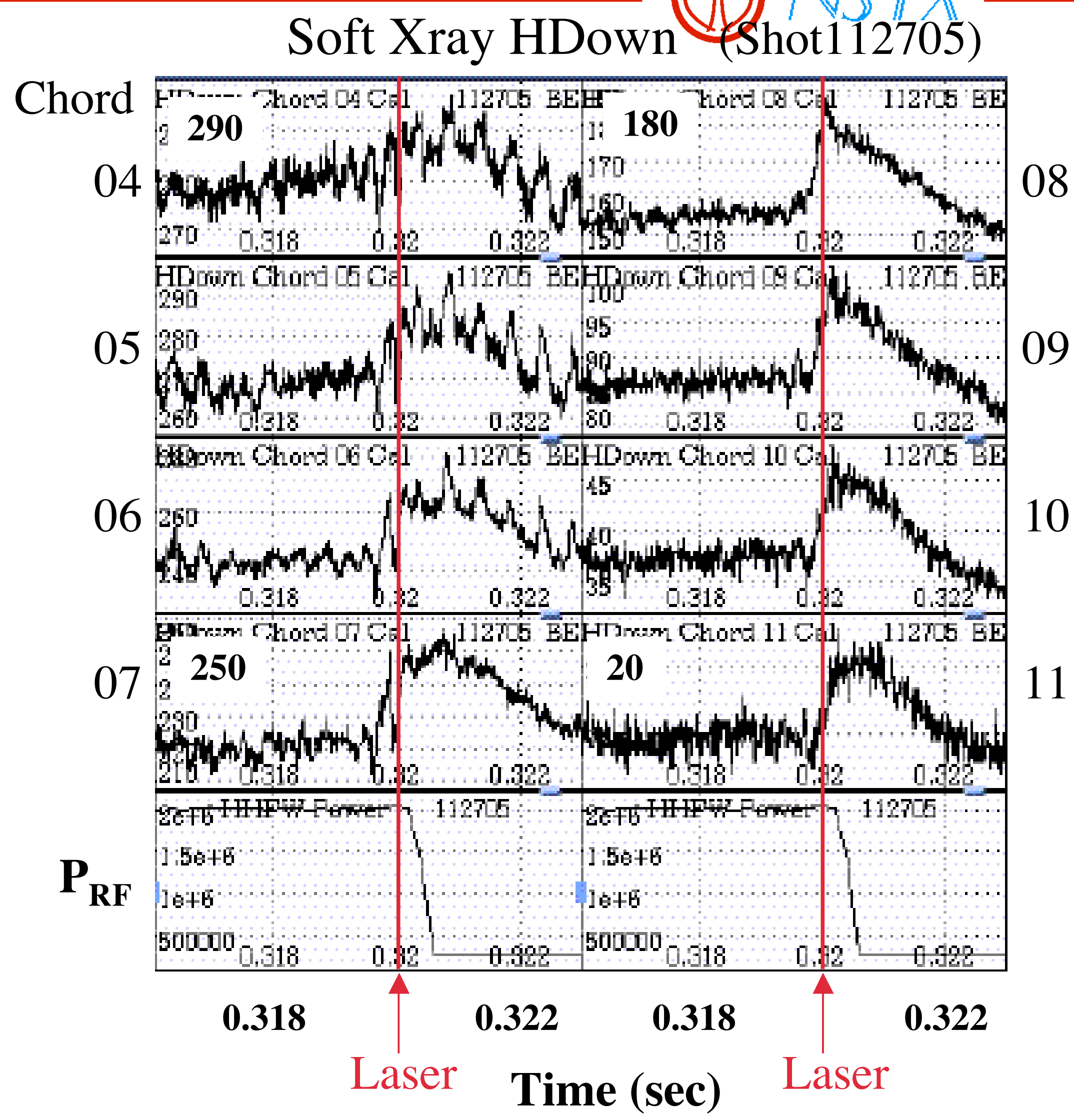


- Electron heating flattens in core and shifts inward during second RF pulse
    - the laser fired during a sawtooth instability at time 3

Presence of Sawtooth at Laser Time 3 is Evident on Soft Xray Chord Array

- Spread of profile peaks at chord 8 off-axis at the time of the laser - 0.320 sec (0.2 ms after crash)

- Thus it is required that the total stored electron energy integrated over the plasma volume be evaluated to take into account profile effects



$W_e(t)$ Obtained by Integrating $P_e(r,t)$ Over the Plasma Volume is Used to Ameliorate Profile Effects

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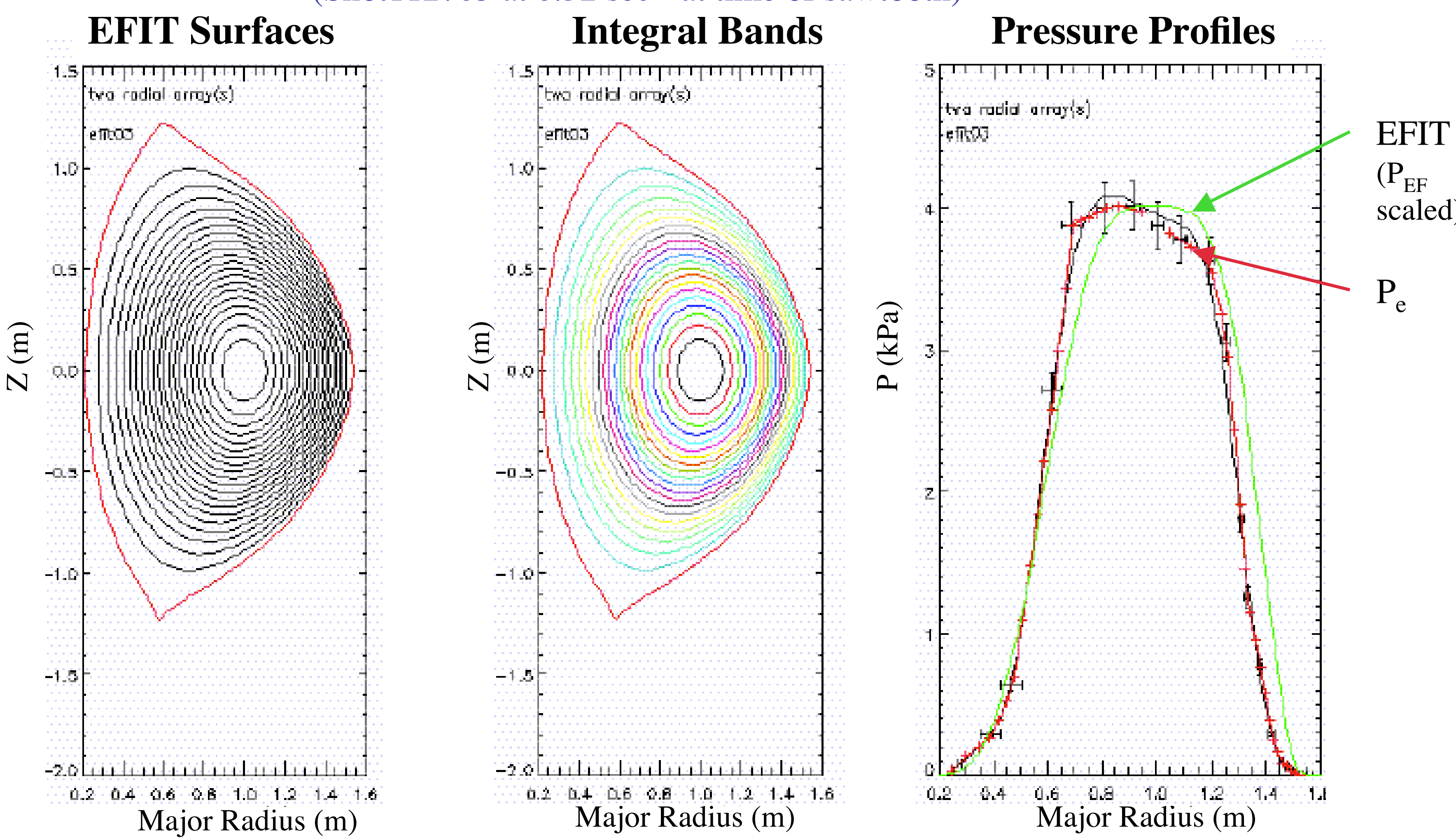
- Estimate of RF power needed to produce the incremental stored electron energy and its dependence on k_ϕ evaluated

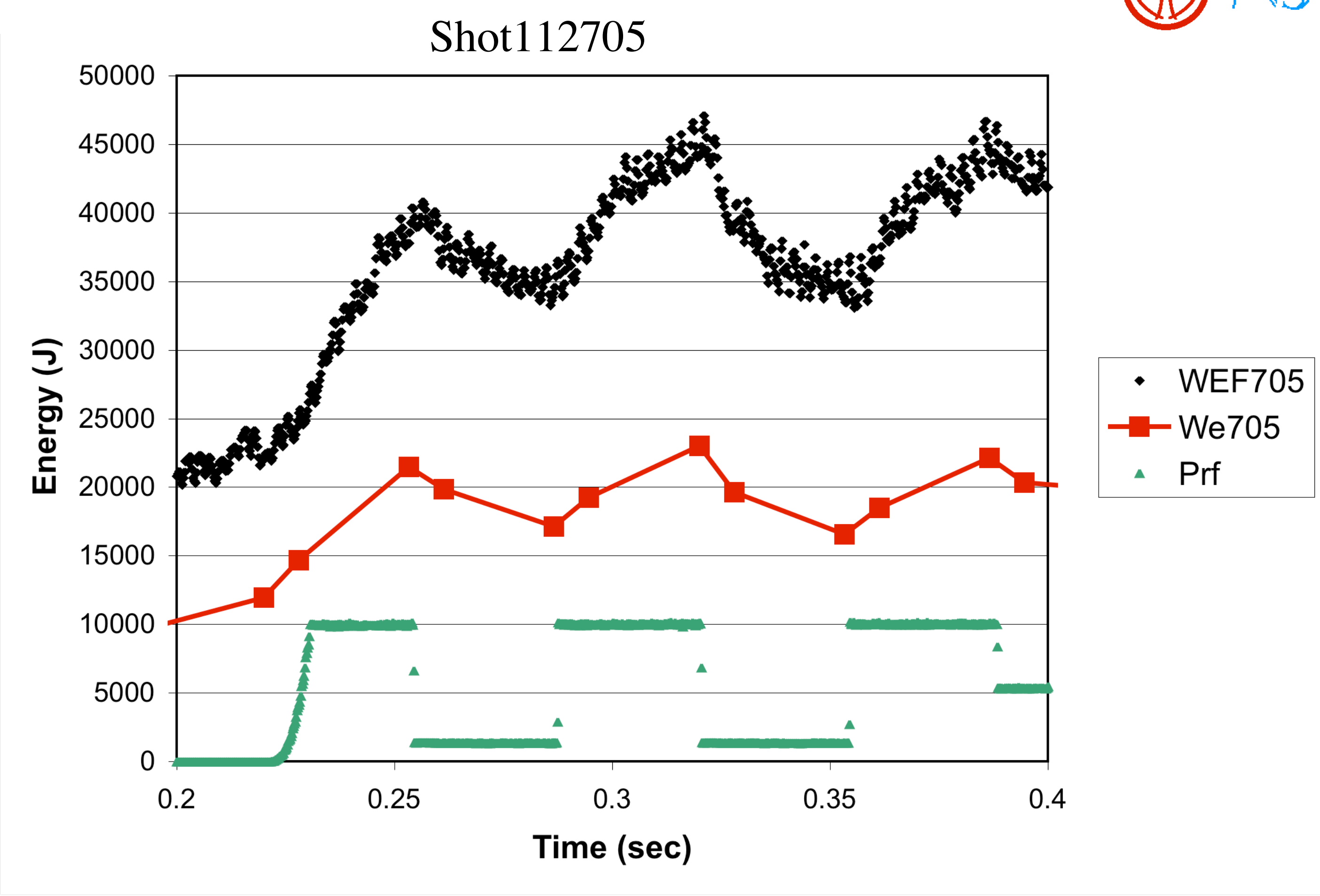
Total electron stored energy is evaluated by integrating $P_e(R)$ over the EFIT magnetic surfaces

(Shot112705 at 0.32 sec - at time of sawtooth)



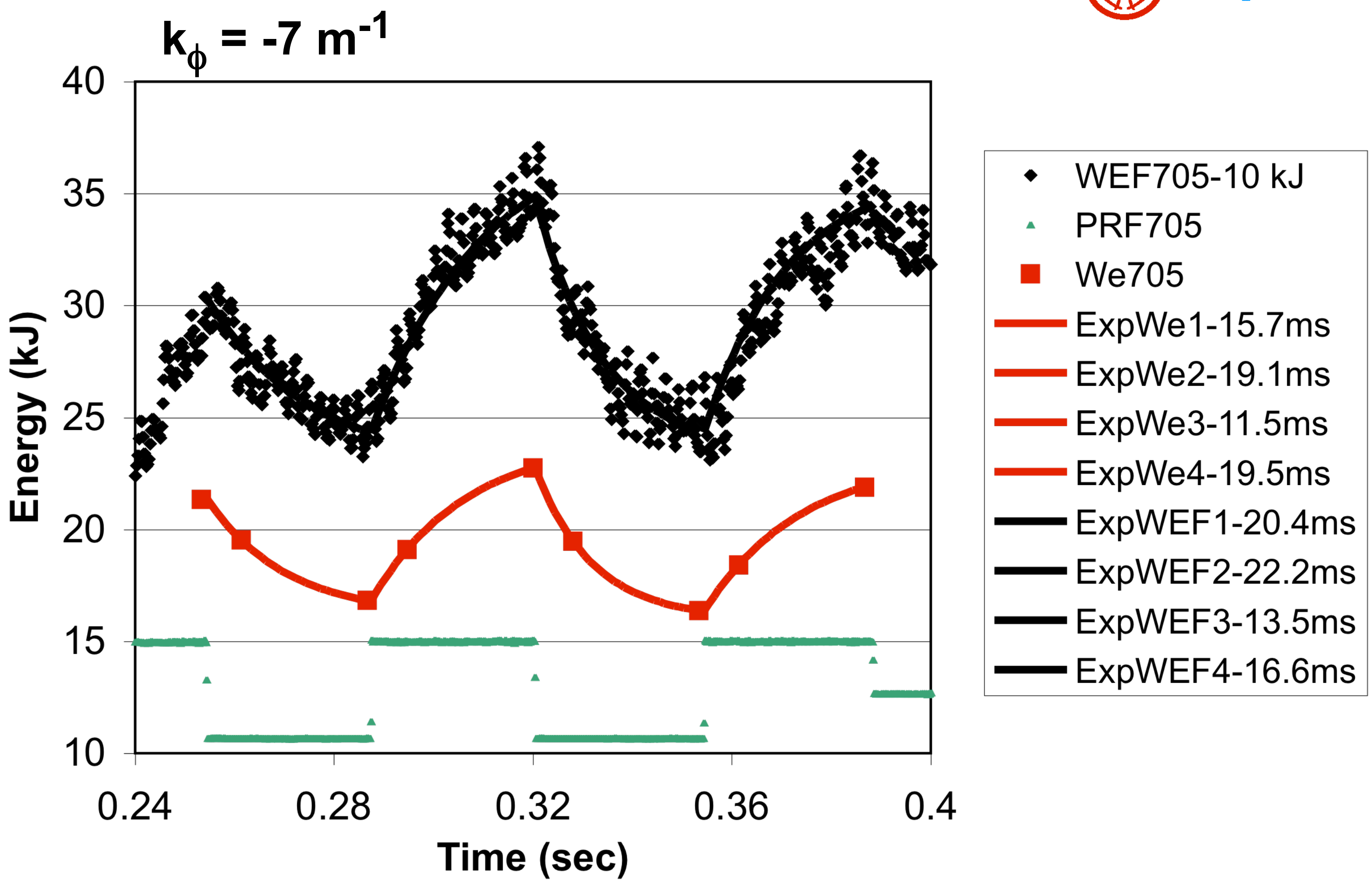
- Thomson scattering P_e profile offset relative to the P profile used for W_{EFIT} is taken into account by integrating over surfaces using separately P_e values inside the EFIT axis (W_{ei}) and outside the EFIT axis (W_{eo}): $W_e = W_{ei} + W_{eo}$

Total electron energy from integration of P_e over EFIT surface volumes for -7 m^{-1}



- W_e continues to rise during the second RF pulse suggesting that the sawtooth redistributes energy but does not greatly reduce the total electron energy
- W_e tracks the total energy from EFIT well but is only about half of W_{EF} instead of the expected value of ~ 2/3 -- the EFIT pressure profile is broader than that for P_e

Electron Stored Energy and τ Values Evaluated for -7 m^{-1}



- Flattening observed for $P_e(0)$ during second RF pulse is not present for W_{eav}
- Electron stored energy exhibits an exponential rise and τ_{We} is comparable to the corresponding value τ_{WEF} for the total stored energy

Electron Stored Energy and τ Values Evaluated for 14 m^{-1}

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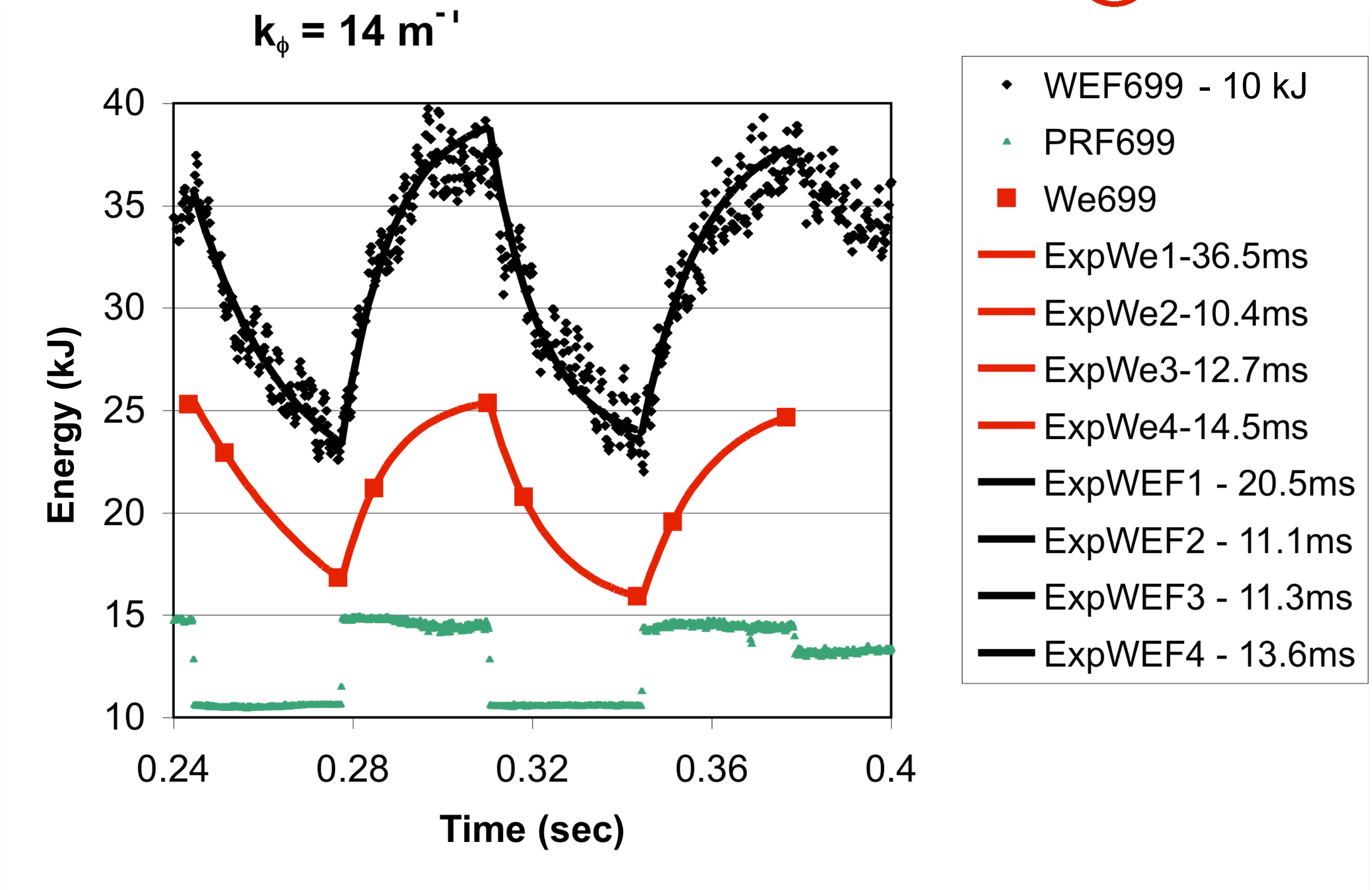

- Electron stored energy exhibits an exponential rise and τ_{We} is comparable to the corresponding value τ_{WEF} for the total stored energy for k_ϕ = 14 m^{-1} as well

Power to Core Plasma Estimated from W_e/τ

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Estimate of RF power needed to produce the measured incremental stored electron energy and its dependence on k_ϕ evaluated

P_{RF} LOSSES AT EDGE OF PLASMA ARE INDICATED

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- An estimate for the power required to give the observed stored energy during the RF pulses is obtained from $\Delta W_{eF}/\tau_{We}$ where ΔW_e is the difference in the final W_e values with and without the RF pulse - similarly for W_{EF}:

	ΔW_F(kJ) $\Delta W_{eF}/\Delta W_{EFF}$	τ(msec) $\tau_\varepsilon/\tau_{EF}$	P_{RFDep}(MW) $P_{RFDepe}/P_{RFDepEF}$	$\eta = P_{RFDep}/\Delta P_{RF}$ (%) η_e/η_{EF}
– 14 m^{-1} :				
Second RF Pulse	15.1/19.4	10.4/11.1	1.45/1.75	84/101
Third RF Pulse	10.6/16.0	12.7/13.6	0.834/1.18	48/68
– -7 m^{-1} :				
Second RF Pulse	7.9/15.1	19.1/22.2	0.413/0.680	24/39
Third RF Pulse	7.2/12.6	11.5/16.6	0.626/0.759	36/44

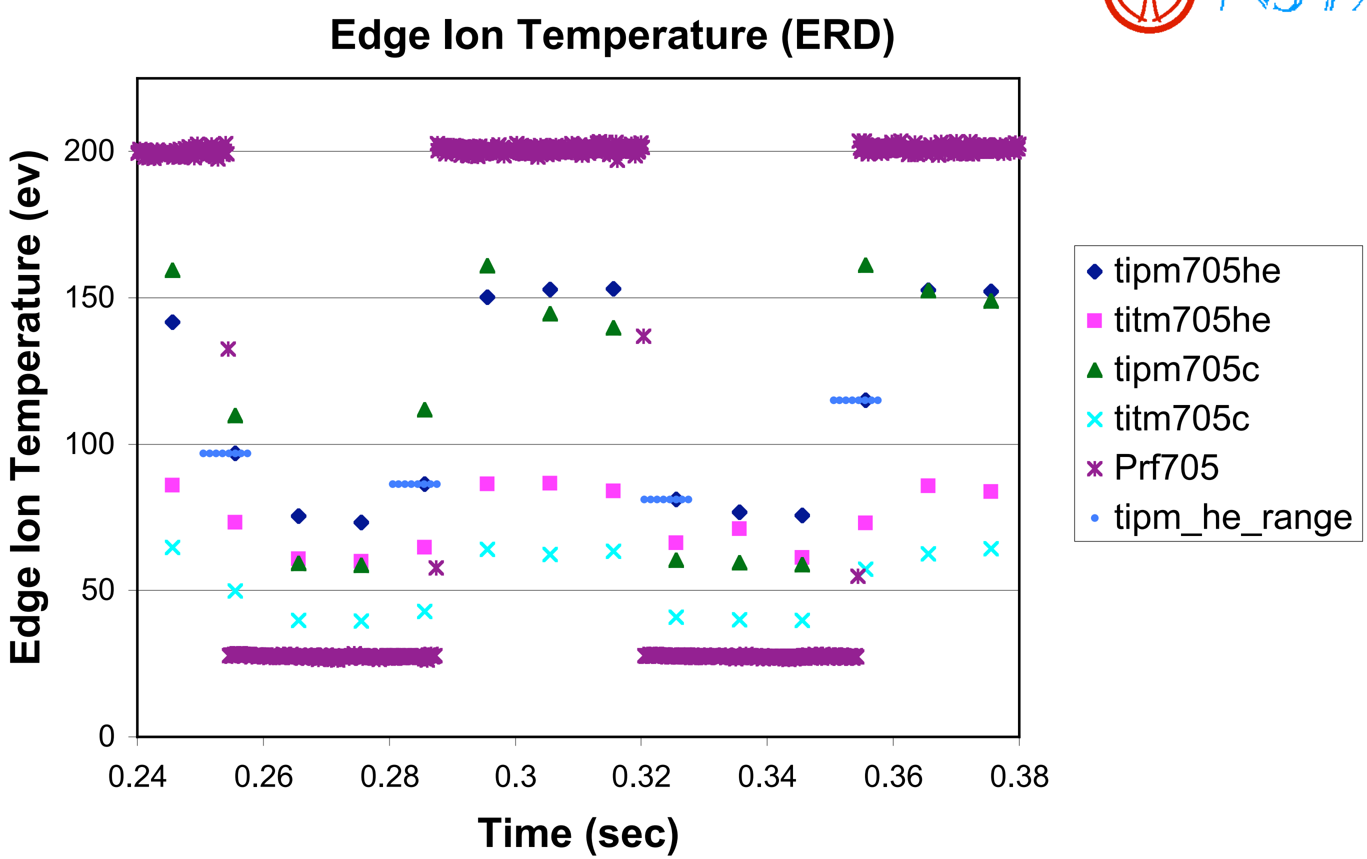
- These power deposition estimates indicate that the RF power reaching the core is considerably reduced for the smaller k_ϕ case and that the power sustaining the electron stored energy is roughly 3/4th that supporting the total stored energy ($\eta_e \div \eta_{EF}$)
- These estimates suggest that considerable power is being lost in the surface of the plasma where the energy confinement is low

  - the RF power loss is apparently significantly greater for the lower k_ϕ

Possible Loss Processes in Edge Plasma

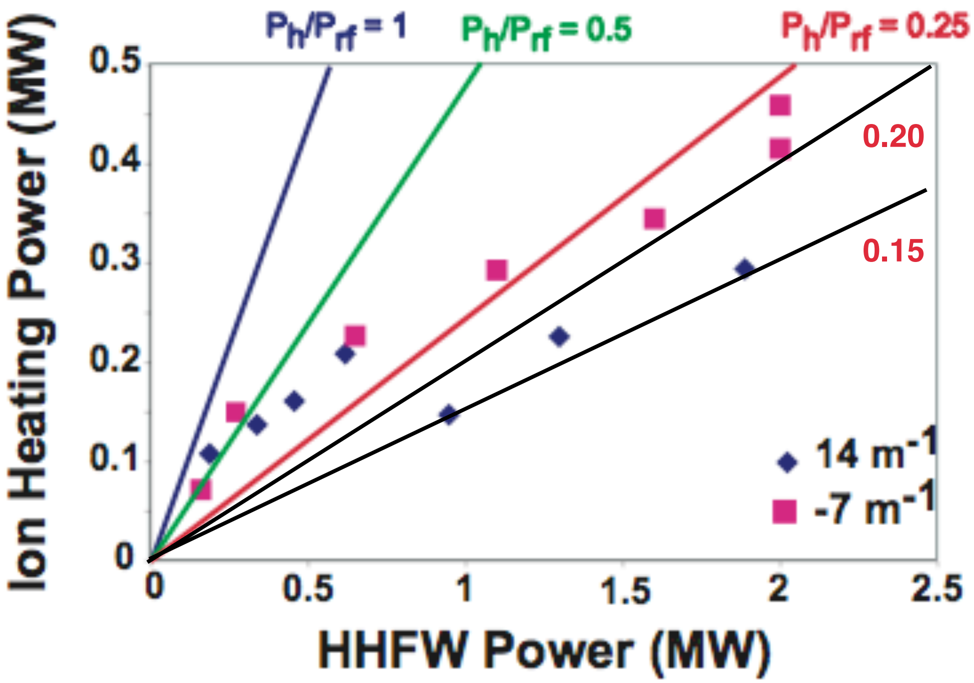
- Ion heating through parametric decay
- Excitation of surface waves, near field and far field, can cause power deposition in sheaths and through collisions in the periphery of the plasma
  - Magnetic pitch angle (shear) effects
  - Surface waves (propagating along field)
  - Reactive waves (evanescent along field)

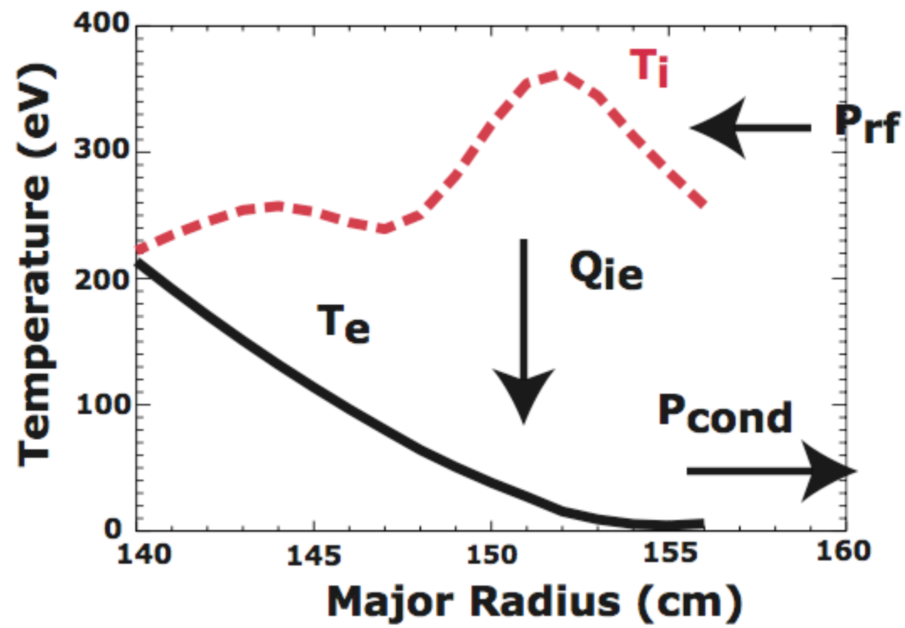
Substantial RF heating of the edge helium ions is measured with the edge radiation diagnostic



- The edge radiation diagnostic indicates that the helium ion poloidal temperature reaches ~ 150eV and decays very rapidly at the end of an RF pulse - in a msec or less

Significant RF Power is Required to Sustain the Large Temperature Difference between the edge ions and electrons





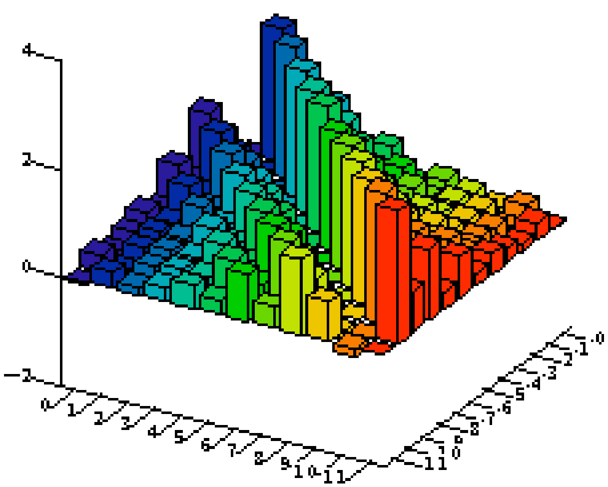
- Edge ion heating via parametric decay waves accounts for a substantial amount of RF power loss which increases somewhat with wavelength - 16%/23% loss for 14 m^{-1}/-7 m^{-1}

T.M. Biewer et al., Physics of Plasmas 12 (2005) 056108

Magnetic shear is calculated to affect antenna loading and possibly affects surface power deposition

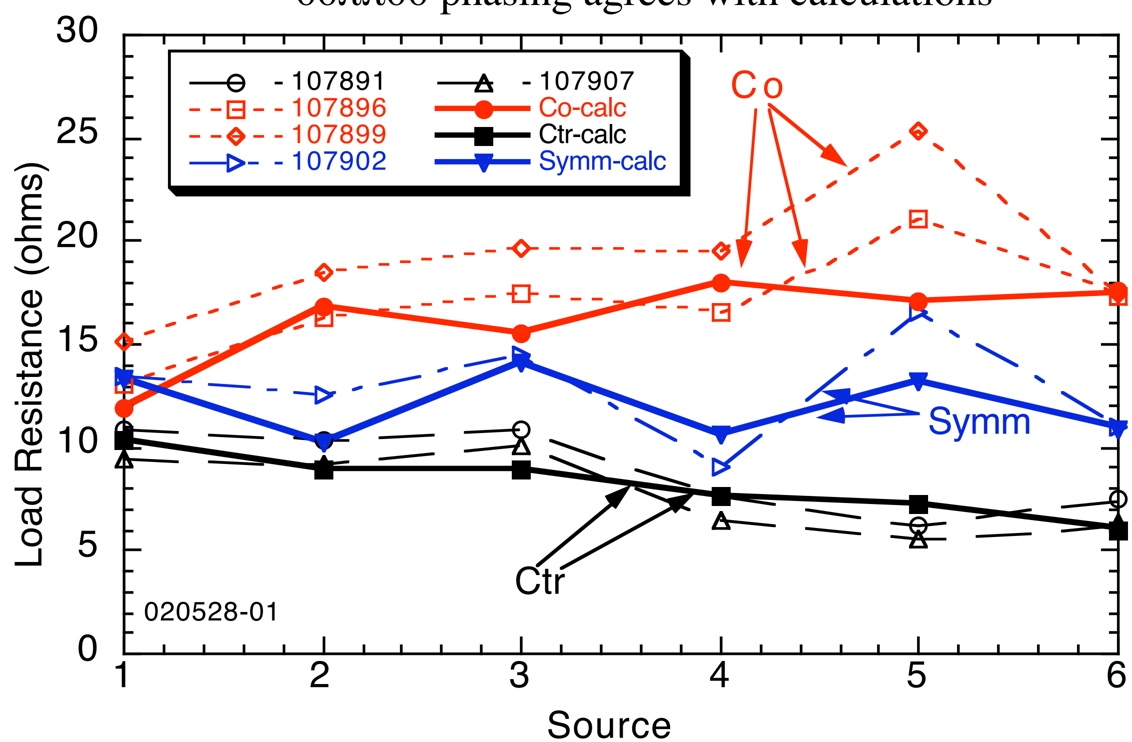
- Loading of antennas with co-CD phasing is ≈ twice the loading with ctr-CD
- Asymmetry caused by pitch angle of magnetic field in front of antenna.
  - RANT3D/GLOSI used to calculate 12x12 impedance matrix of antennas
  - 12-strap, 6-loop circuit model used to calculate load resistance R_{load}
  - Calculations in good agreement with measured loading

- 12x12 impedance matrix from RANT3D (Im part, diag. term suppressed) shows asymmetry



- * R_{load} = value of resistance terminating 50-Ω line that gives measured refl. coeff.

- Measured load resistance R_{load}* for co-, counter-, and 00ππ00 phasing agrees with calculations



D. Swain et al., EPS02

Core Heating Made Equal for Co and Counter CD for Current Drive Experiments By Adjusting P_{RF} and Gas Feed

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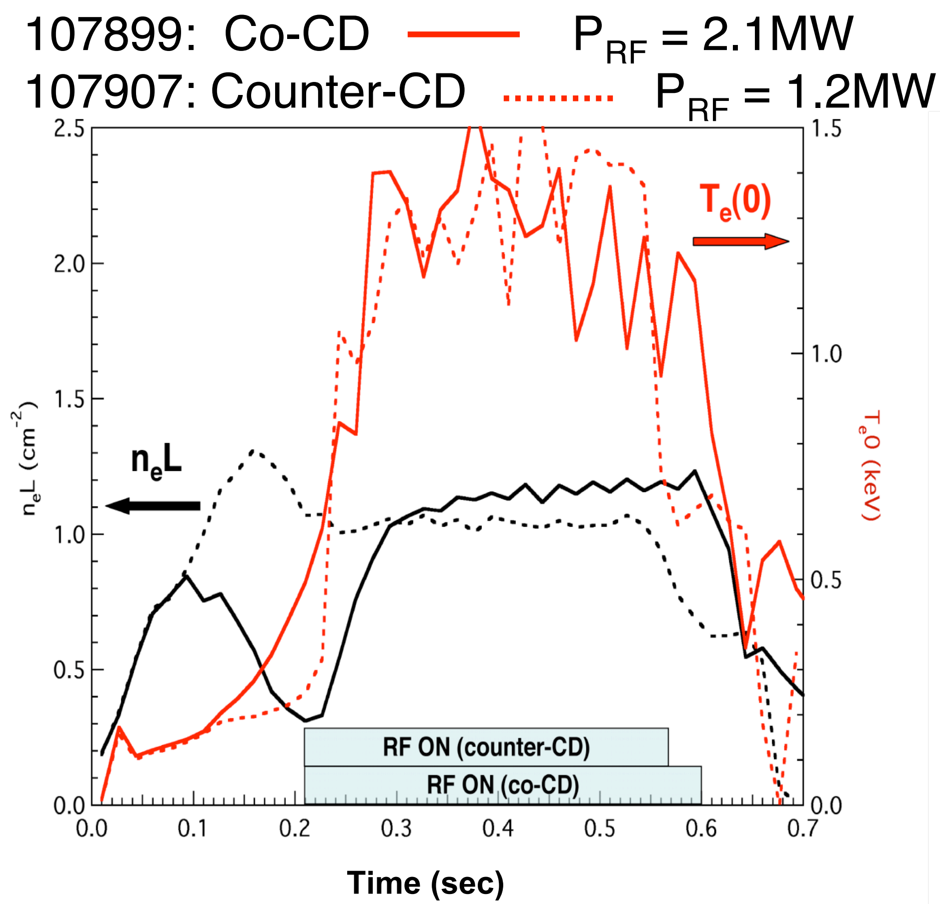
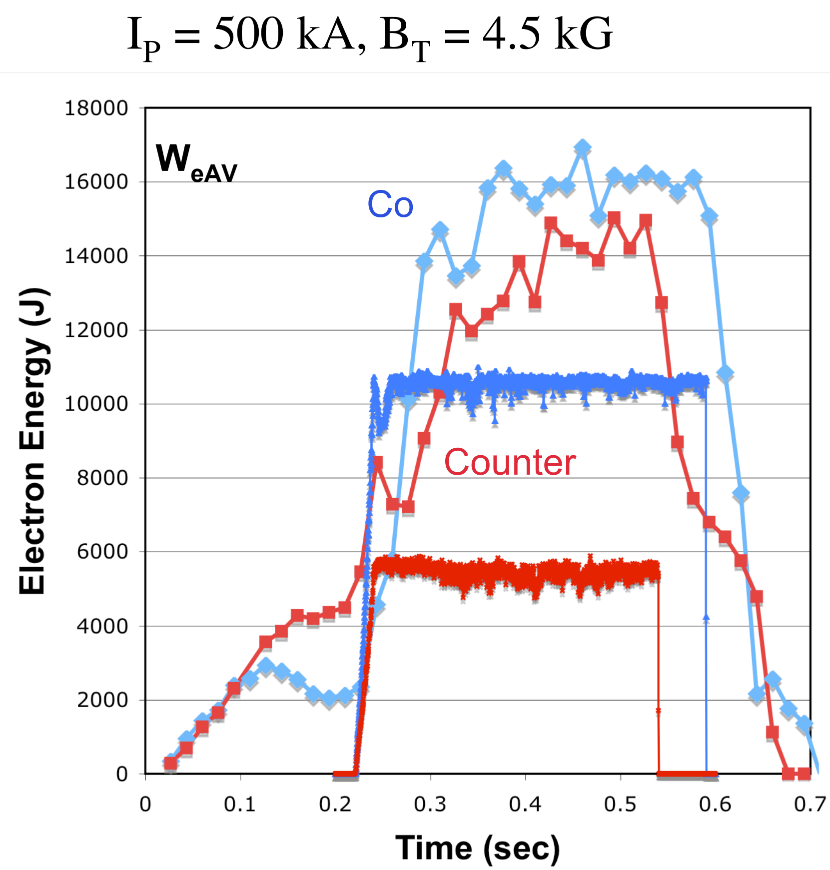




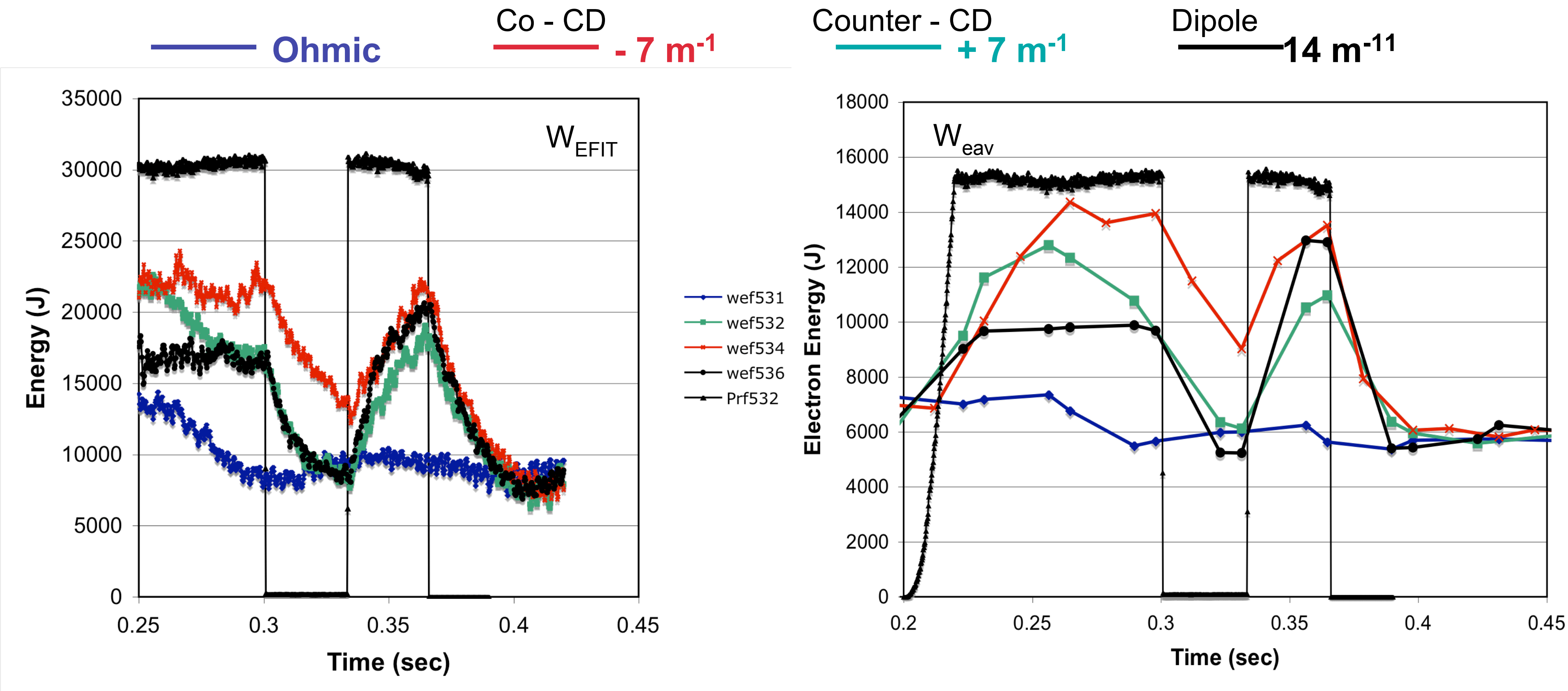
- Core heating efficiency ~ 2x higher in the counter CD case
- Suggests that extra loading in the co-CD case could be due to surface waves

J. Hosea et al., APS02; P. Ryan et al., IAEA02

Attempt to Evaluate Effect of Phase/k_ϕ at Lower Shear

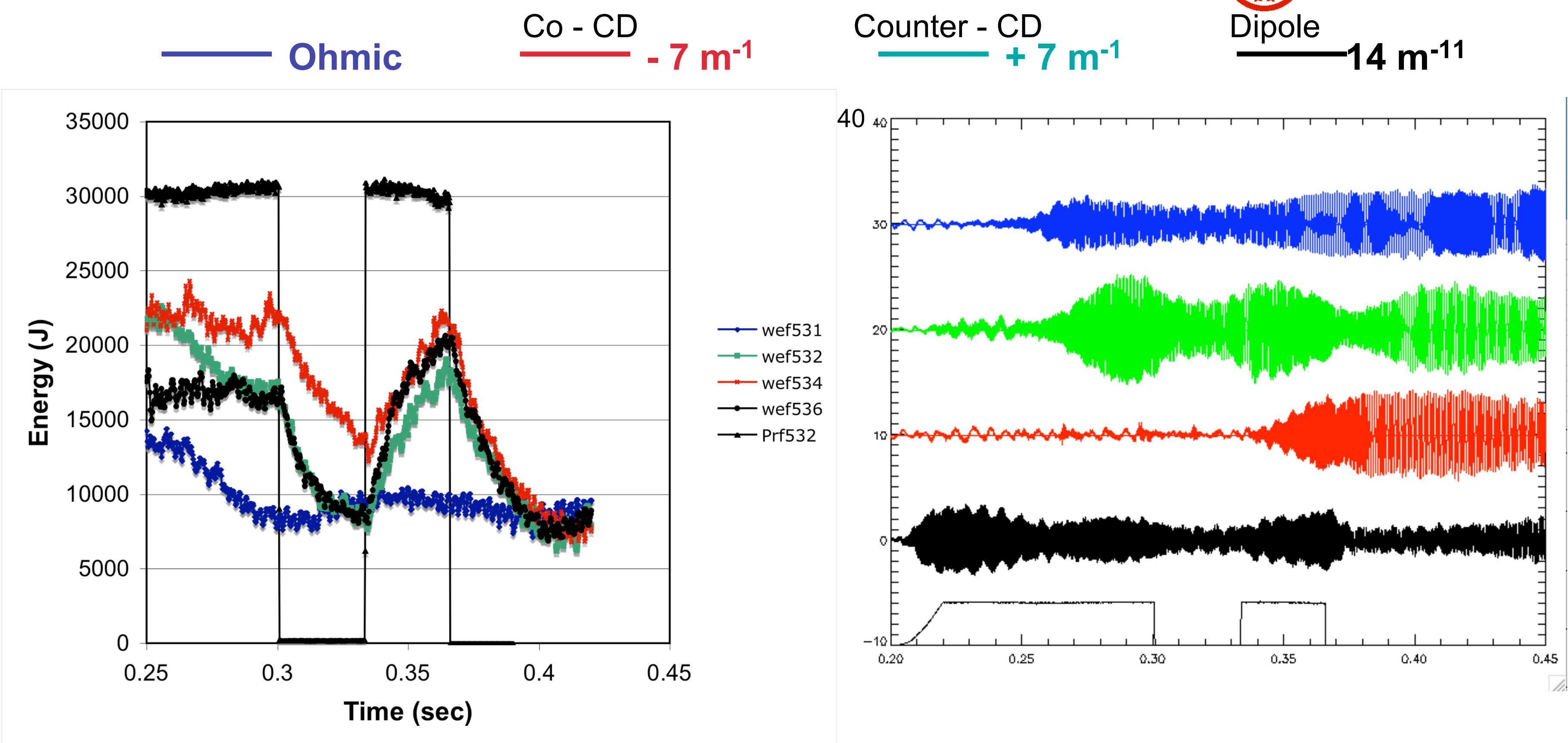
I_P = 300 kA, B_T = 4.5 kG, P_{RF} = 2 MW

NSTX



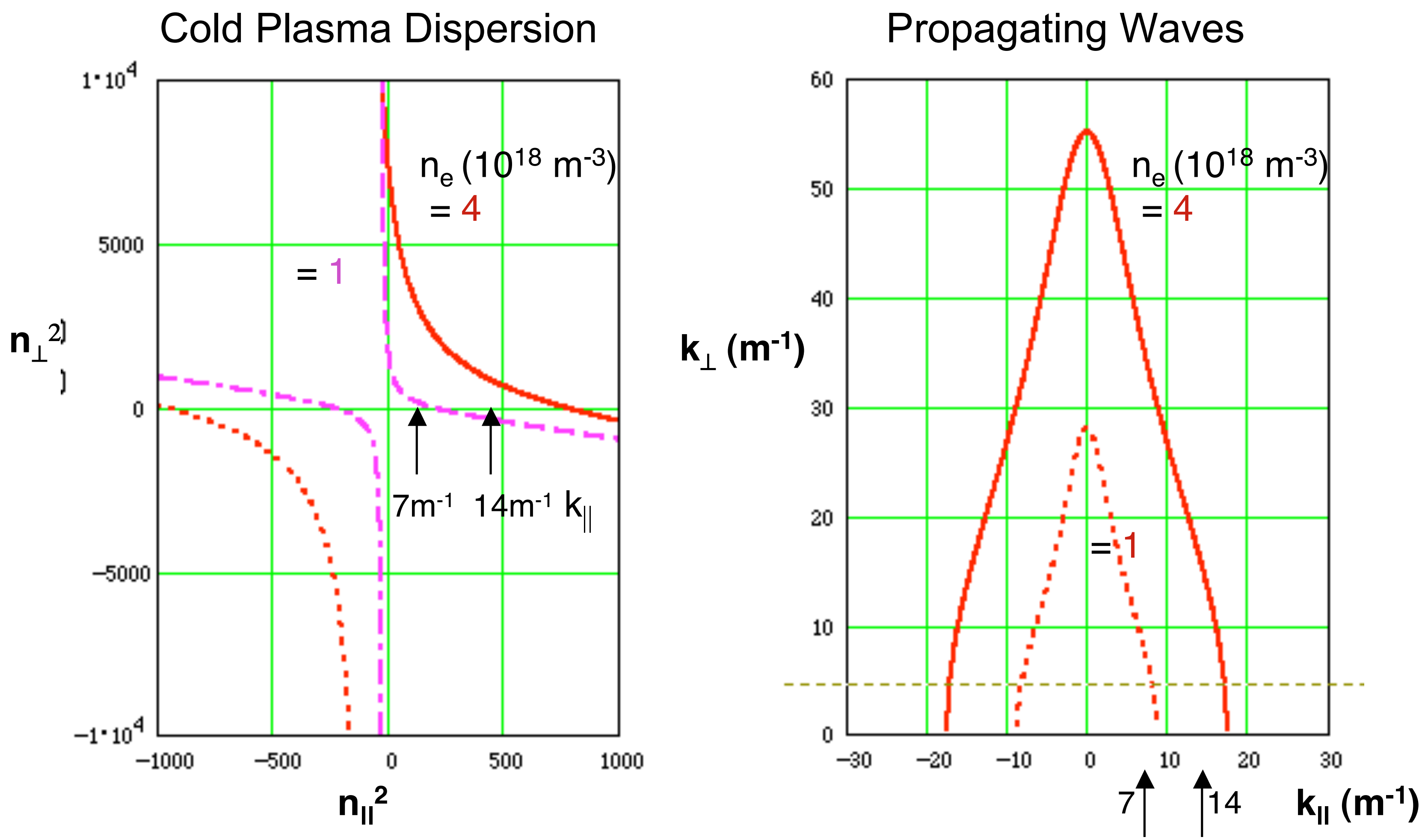
- Electron energy tracks EFIT stored energy well
- Rise and decay τ_{EF} values for second pulse are similar for -7 m^{-1} and +7 m^{-1} as are the ΔW values
- The τ values for 14 m^{-1} are smaller and $\Delta W/\tau$ appears to be larger as before
- However, MHD instability is affecting stored energy for this 300 kA case

Variable MHD Activity Affects Stored Energy Comparison for this Lower Shear Case ($I_P = 300$ kA, $B_T = 4.5$ kG, $P_{RF} = 2$ MW)



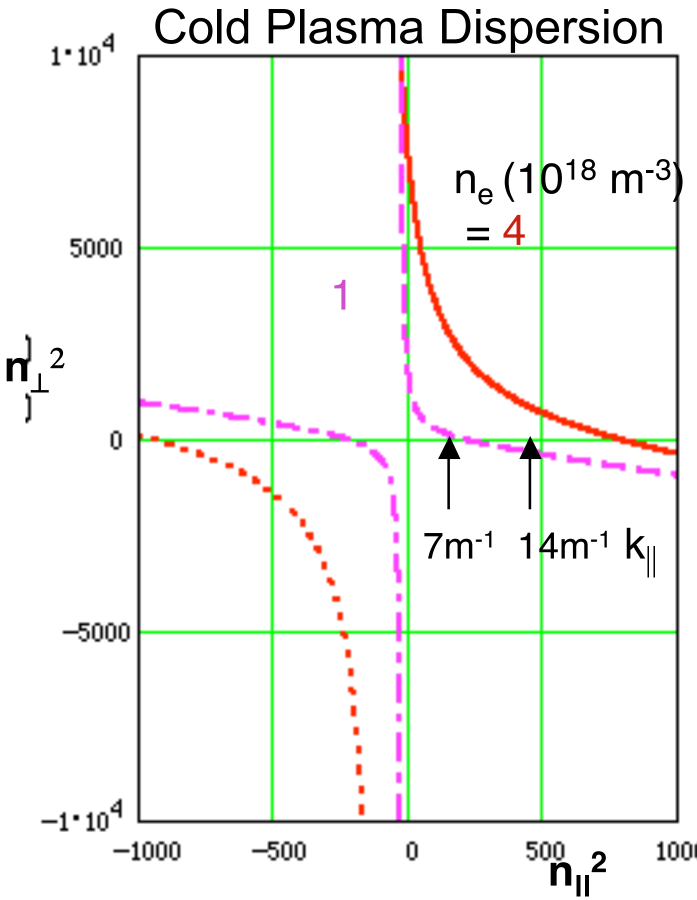
- MHD reduces stored energy
- Quantitative comparisons versus k_ϕ are not possible under variable MHD conditions
- Future experiments will pursue conditions for quantitative comparisons

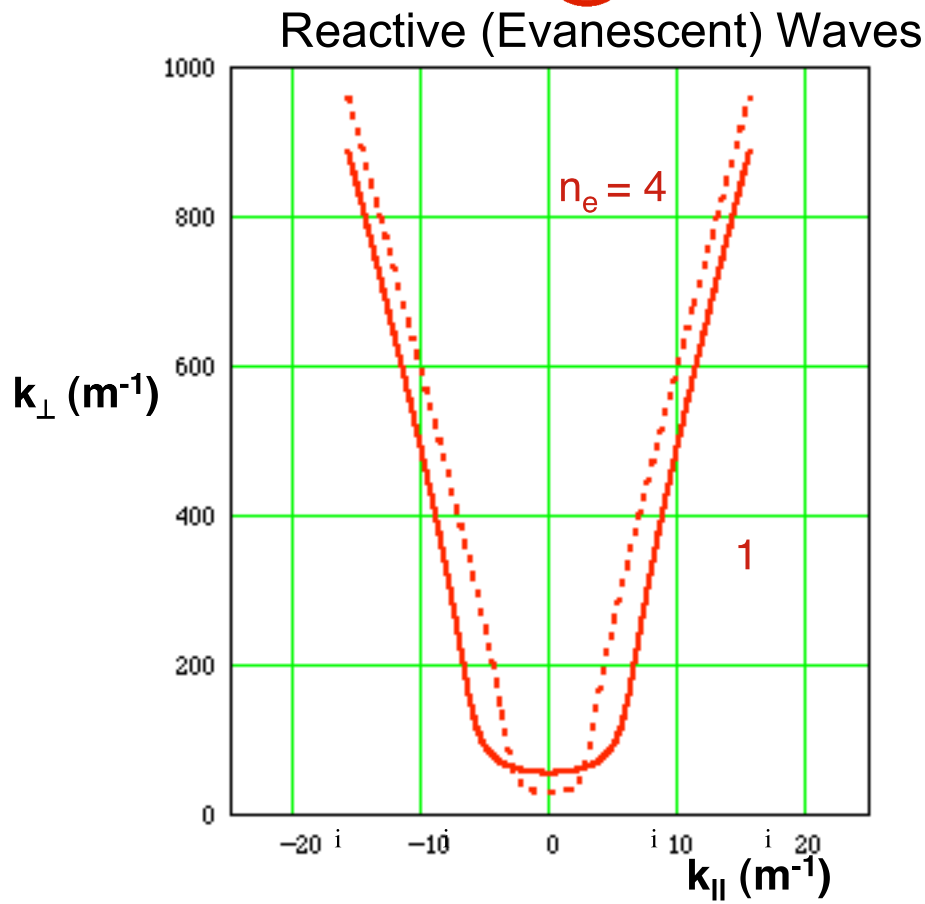
Wave propagation in the surface plasma is enhanced at lower $k_{||}$



- Fast Waves propagate at lower density and reach much higher $k_\perp$ at a given density for lower $k_{||}$
- "Surface wave" fields are enhanced at lower $k_{||}$ and should contribute to greater power loss through parametric decay, sheath damping and collisions

Radially propagating reactive waves support currents induced in the plasma





- Reactive waves are strongly localized in the plasma surface and may contribute to surface damping through collisions and sheaths
- Low values of Im($k_{||}$) correspond to long evanescent lengths in the toroidal direction - these can be cancelled with proper location and phasing of antenna elements - 90^o phasing cancels less well

Summary

- The use of two multi-pulse lasers, one delayed in time relative to the other, and both synched with RF power pulses has permitted an evaluation of the electron energy confinement time
- The axial confinement measurement is influenced strongly by profile changes - especially the large central changes due to the sawtooth instability
- Integration of the Thomson scattering P_e profile over the plasma volumes defined by the EFIT magnetic surfaces gives the total stored electron energy W_e
  - this is not strongly affected by the profile changes caused by the sawtooth instability
- W_e tracks the total energy from EFIT (W_{EF}) well but is ~ 1/2 of its value instead of the ≥ 2/3 level expected for the helium plasma — although ΔW_e is ~ 3/4 ΔW_{EF} as expected
- The apparent power needed to produce the measured increase in W_e is substantially less than the applied RF power and decreases with k_ϕ
- RF power loss mechanisms at the periphery of the plasma are evidently in play: effects of excited surface waves which do not propagate into the core of the plasma and the direct heating of ions by parametric decay waves are both key paths for RF power deposition in sheath regions and in the low confinement periphery of the plasma
- Further study is required to quantify the dominant processes that contribute to the surface power deposition