[JP1.012] Electron Energy Confinement During HHFW Heating and Current Drive on NSTX

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Electron energy confinement time is measured for several HHFW wavelength configurations by varying the spacing of two Thomson scattering laser pulses relative to modulated pulses of HHFW power. Maintaining discharge equilibrium conditions as constant as possible is essential to provide smooth changes in electron energy with sharp transitions in RF power. Instability influences both the radial profile of the electron energy and the confinement time. Core electron energy confinement times in the range of ~ 15 ms have been observed for the conditions studied. This core confinement is reduced during a sawtooth instability but, while the electron energy is distributed outward by the sawtooth, the bulk electron energy confinement time is essentially unaffected. The radial deposition of energy into the electrons is noticeably more peaked for longer wavelength excitation as is expected theoretically. Quantitative comparisons of the measured electron energy profiles with modeling predictions will be presented for the several regimes studied.

Electron Energy Confinement During HHFW Heating and Current Drive on NSTX

- Goal: Attempt to quantify the electron energy confinement time for HHFW heating on NSTX ant its dependence on antenna phasing
- Outline:
  - Two-laser Thomson scattering method for discerning exponential rise and decay times for RF pulse heating
  - $P_e(0)$ rise and decay times (τ_0) for $k_\phi = 14\ m^{-1}$ (180^o antenna element phasing) and $k_\phi = -7\ m^{-1}$ ($-\ 90^o$ phasing, co-current drive)
  - Effect of instability on $P_e(0)$
  - P_e profiles - radial power deposition
  - Electron energy W_e from integral of P_e over volume defined by EFIT magnetic surfaces
  - W_e rise and decay times (τ_{We}) for $k_\phi = 14\ m^{-1}$ and $-7\ m^{-1}$
    - Implications for RF power to bulk plasma
  - Possible explanations for reduction of power delivered to bulk plasma
    - Edge ion heating
  - Summary

Three data points are sufficient to determine exponential decay properties

- assuming decay conditions (τ and T_F) are constant

$T_e(t) = T_0 - (T_0 - T_F)*(1 - e^{-t/\tau})$

$T1 = T_e(t1)$, $T2 = T_e(t2)$, $T0 = T_0$

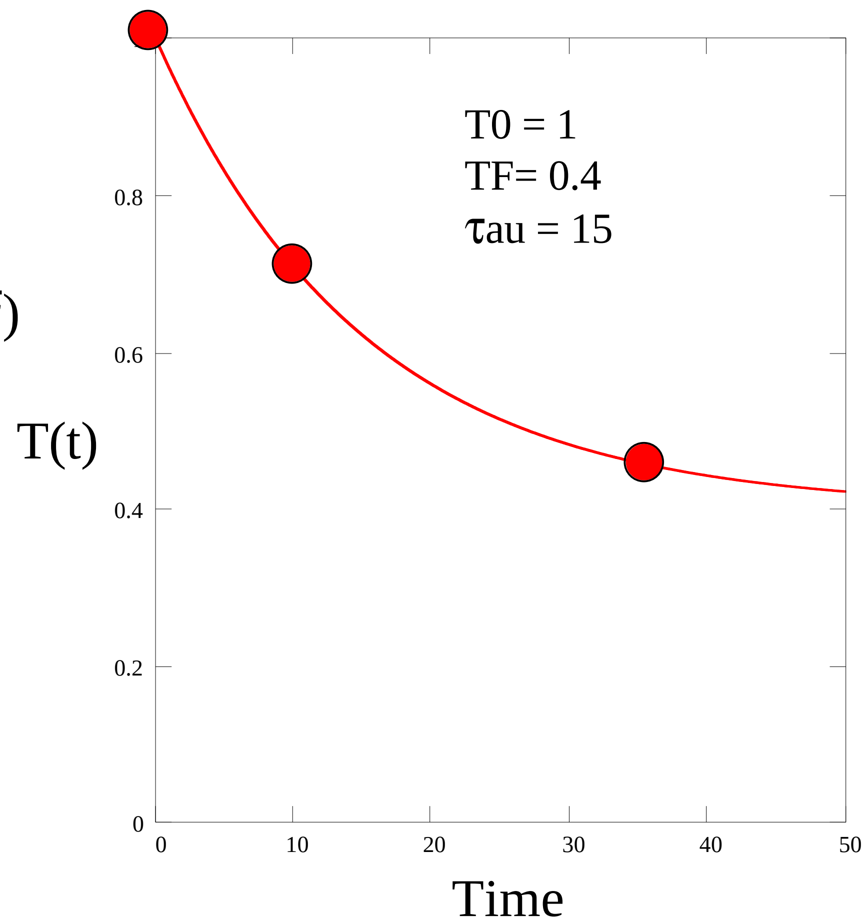
Solve for τ:

$(T0 - T1)/(T0 - T2) = (1 - e^{-t1/\tau})/(1 - e^{-t2/\tau})$

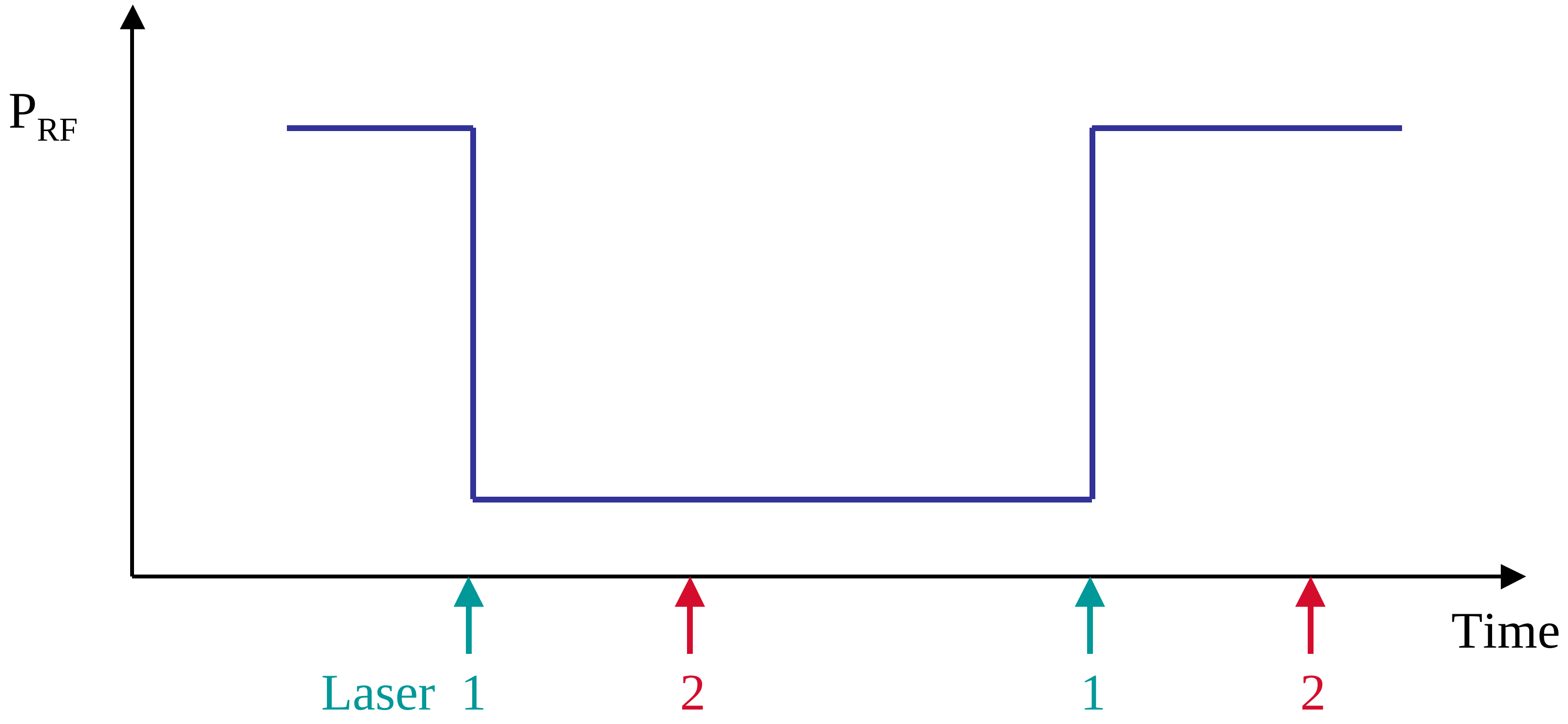
Solve for T_F:

$(T0 - T_F) = (T0 - T2)/(1 - e^{-t2/\tau})$

$$T(t) := T0 - (T0 - TF)\cdot\left(1 - e^{\frac{-t}{Tau}}\right)$$



Experimental Setup



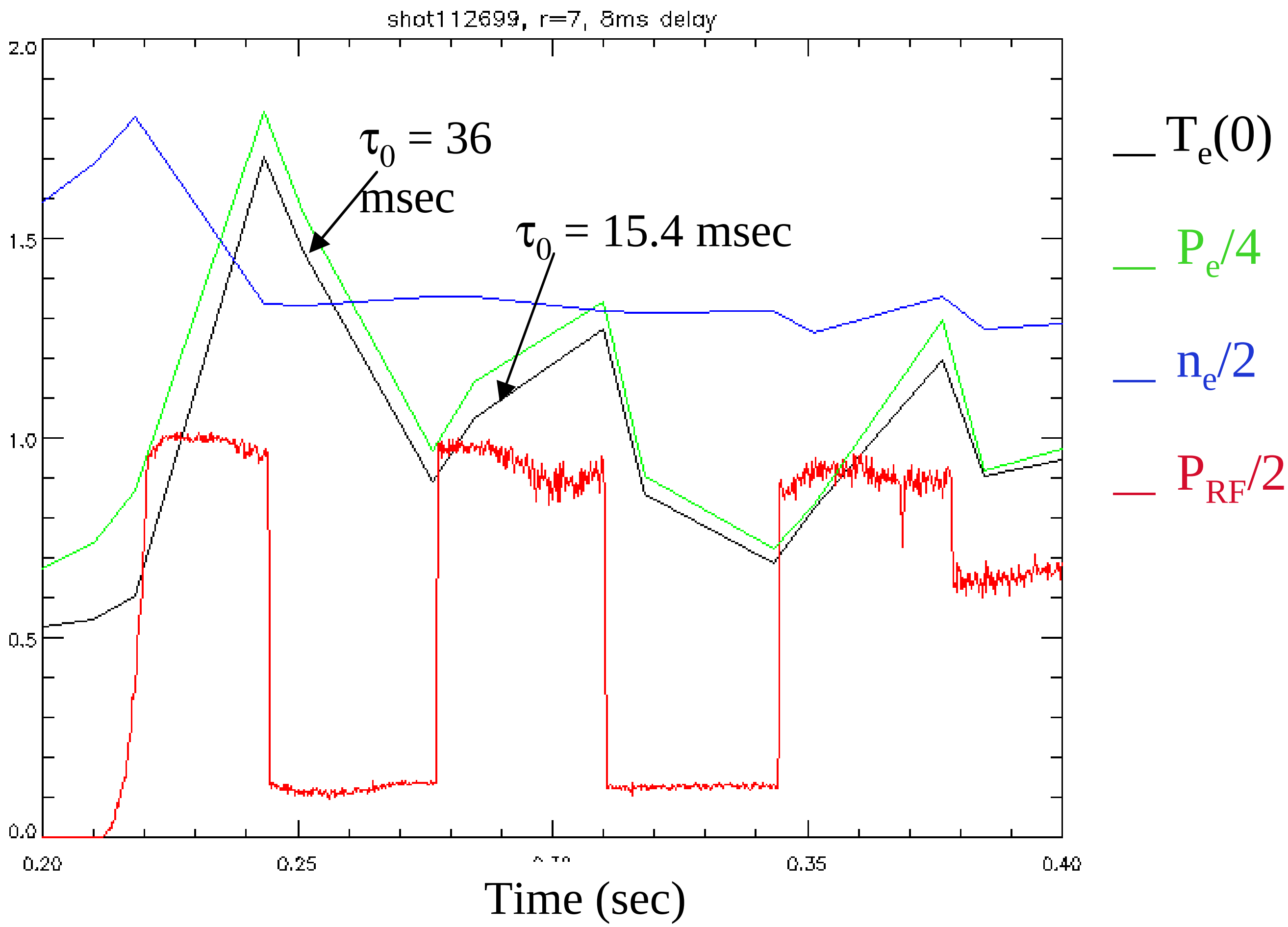
- Laser 2 has an adjustable time delay relative to laser 1
- Laser 1 measurement is extrapolated to the P_{RF} fall (rise) time for value at t_0
- Equilibrium control conditions are held as constant as possible - I_P, B_T, n_e, plasma position, shape

$T_e(r=0)/P_e(0)$ for 14 m^{-1} and -7 m^{-1} Cases versus Time

- Comparisons for decay period after the first RF pulse
  - $k_{||}$ dependence of RF power deposition profile
- Comparisons for rise period during the second RF pulse
  - Effect of profile changes

$T_e(0)$ versus Time for 180° Antenna Phasing - $k_{||} = 14\ m^{-1}$

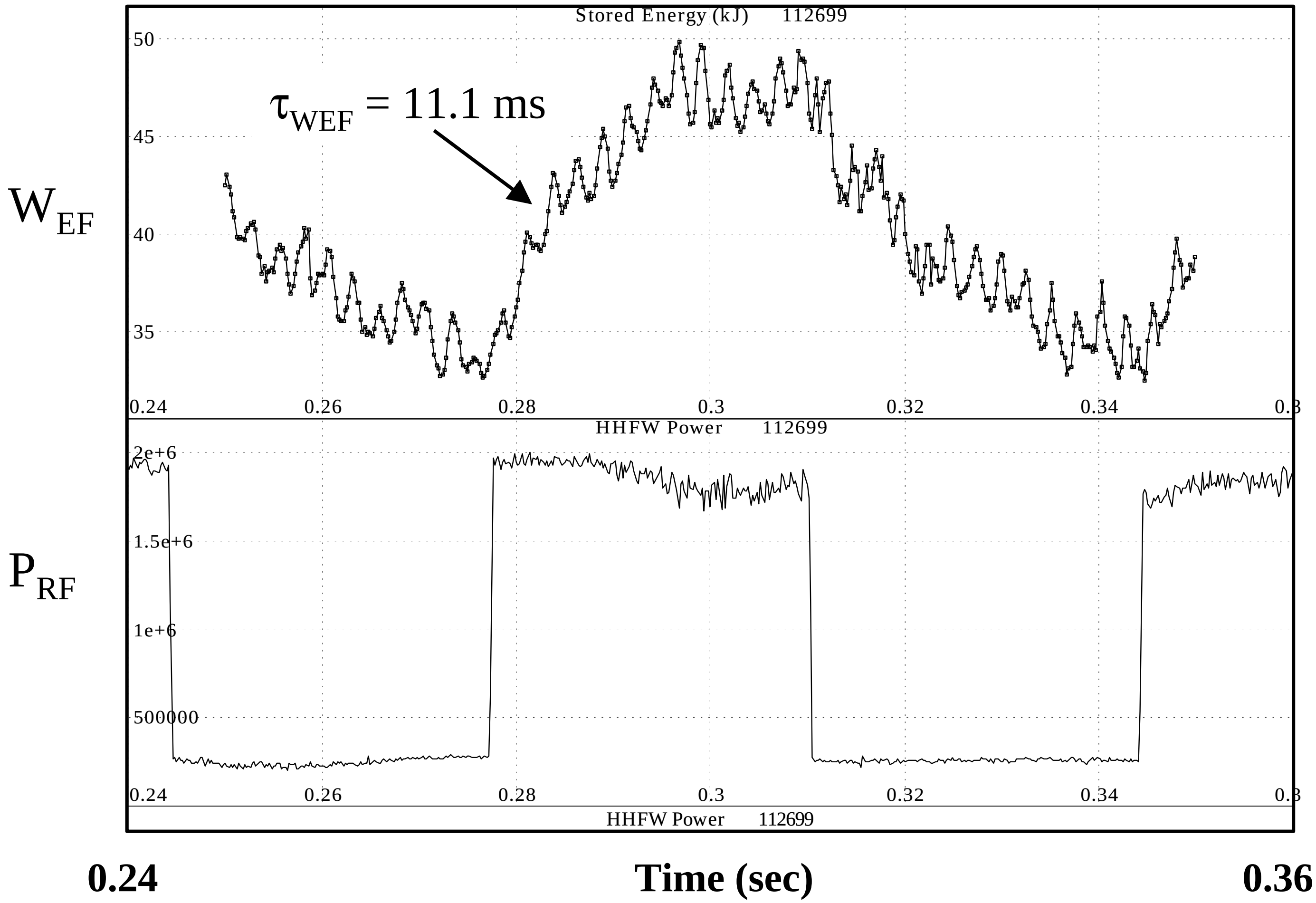
Shot 112699 with 8 ms laser delay (I_P = 0.6 MA, B_T = 0.45 T, Helium)



- The τ_0 = 15.4 msec for the second RF pulse agrees reasonably well with that indicated by EFIT for the total stored energy

Stored Energy vs Time from EFIT for Shot 112699

- $k_{\parallel} = 14\ m^{-1}$

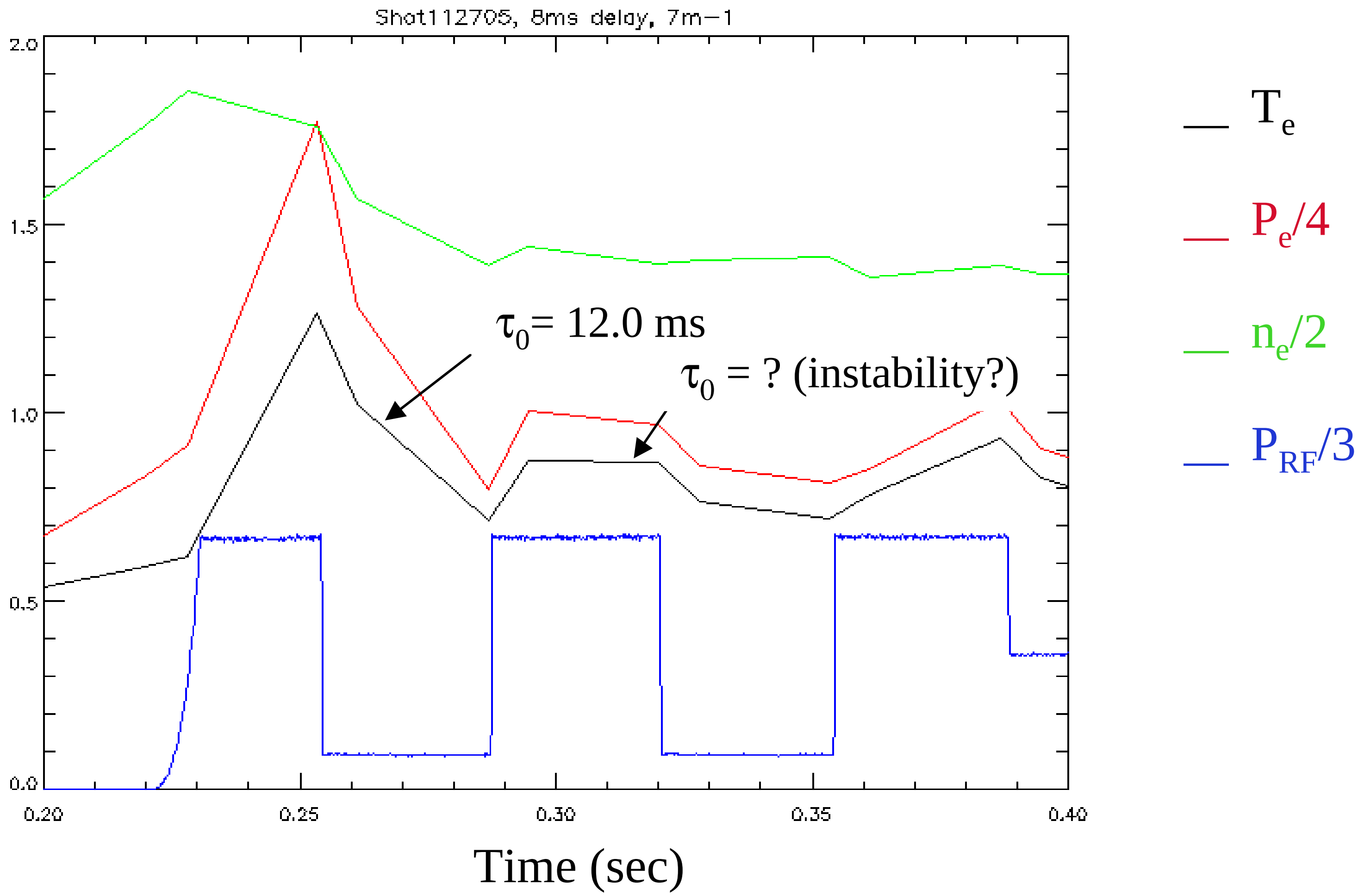


- τ_{WEF} = 11.1 msec compares well with τ_0 =15.4 msec for $T_e(0)$
- Some leveling off of W_{EF} is observed due to a small decrease in P_{RF} and perhaps to instability affecting the energy confinement

$T_e(0)$ versus Time for - 90° Antenna Phasing - $k_{\|} = -7\ m^{-1}$

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

NSTX



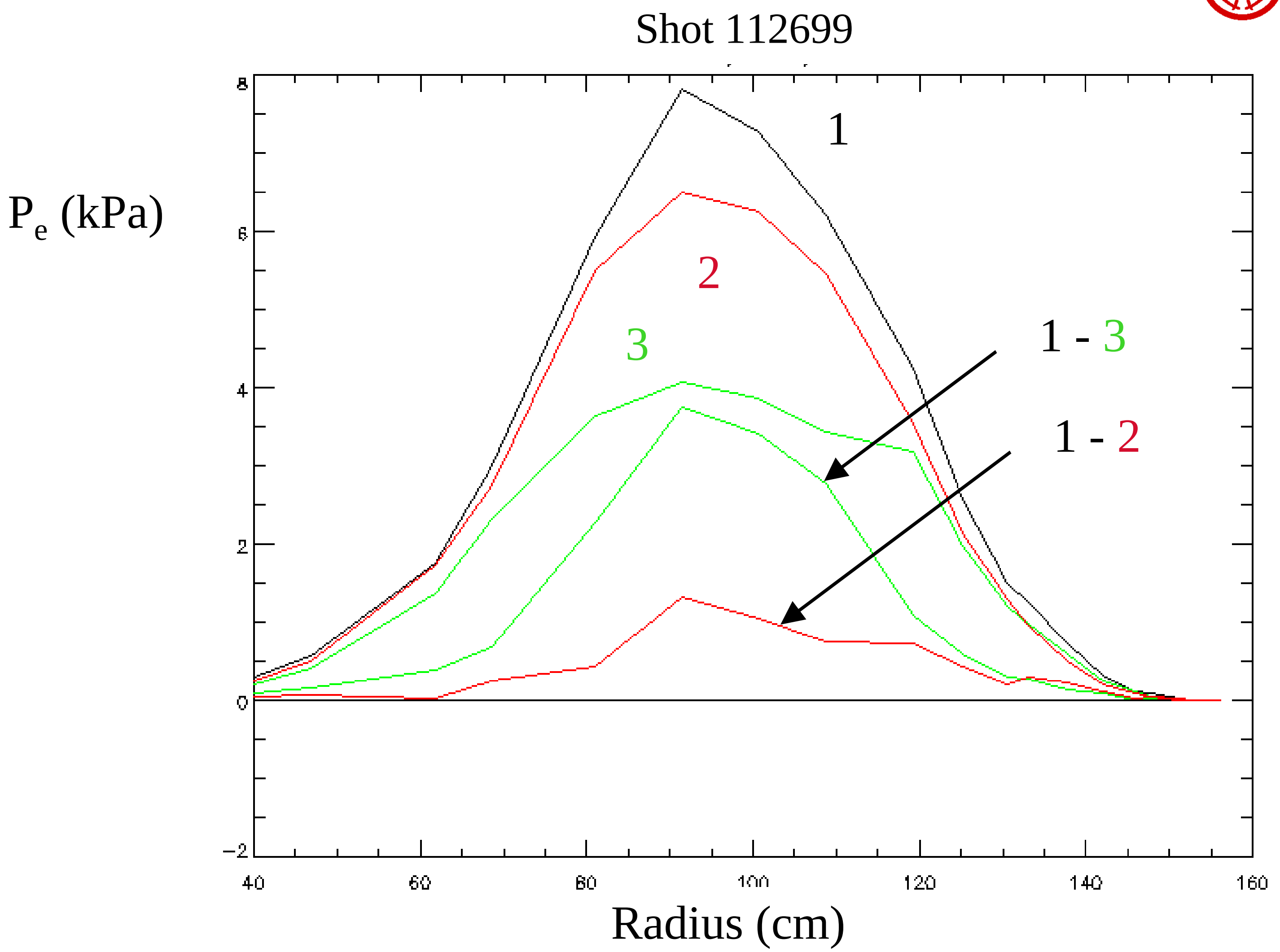
- τ_0 after first pulse is shorter than for 14 m^{-1} case - note n_e decrease
- τ_0 cannot be calculated for the second RF pulse - T_e/P_e profiles are obviously changing

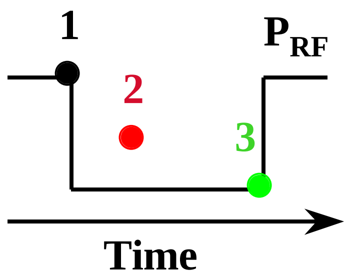
P_e Profiles for 14 m^{-1} and -7 m^{-1} Cases versus Time

- Comparisons for decay period after the first RF pulse
- Comparisons for rise period during the second RF pulse

P_e vs Radius for 14 m^{-1} After First RF Pulse

Laser times(sec) are 1 (0.2433), 2 (0.2513), 3 (0.2767)

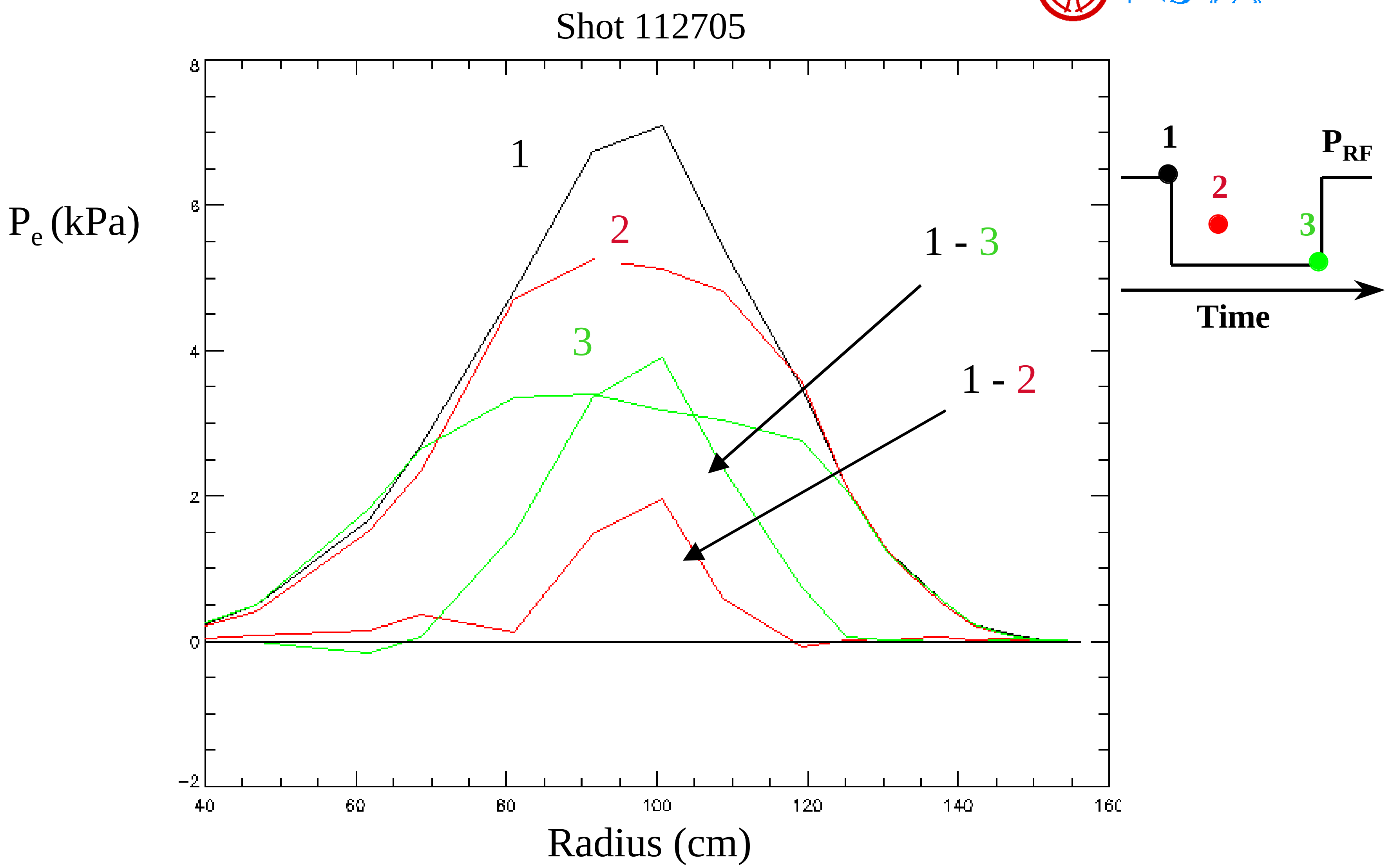




- Electron pressure decay is reasonably symmetric after the first RF pulse

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)

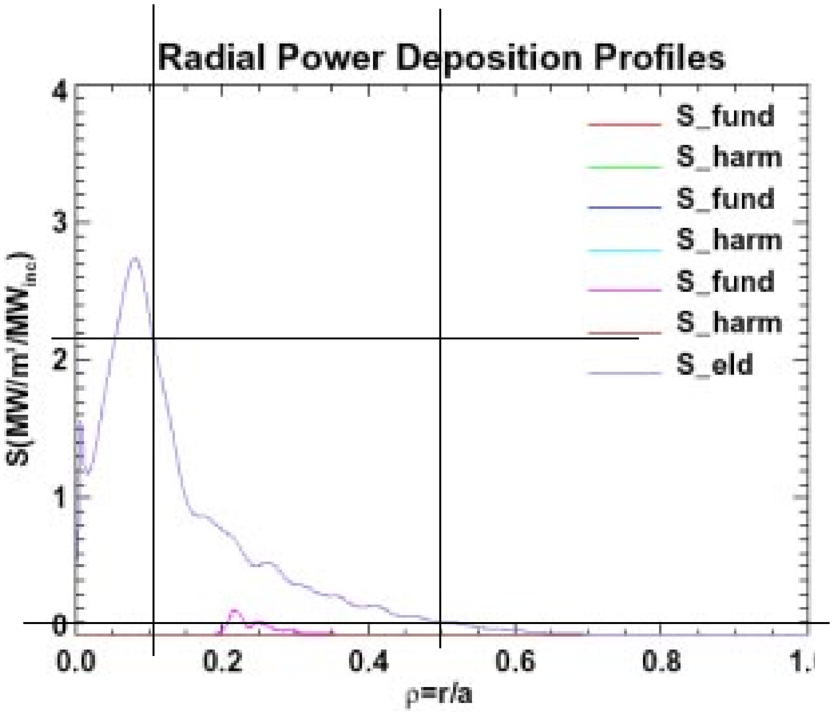


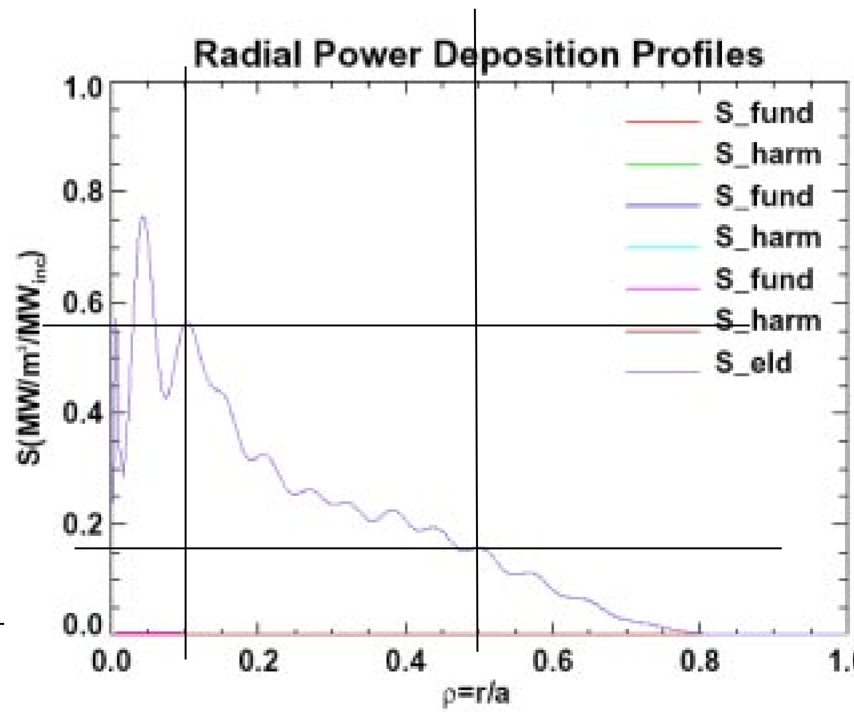
- Electron pressure decay is reasonably symmetric after the first RF pulse but the decay is strongly centralized

P_e profile decay suggests that RF power deposition for -7 m^{-1} is more central than for 14 m^{-1} in agreement with modeling

112705 (-90)

112699 (180)





More central dep

Broader

Toric modeling gives a more central deposition profile for -7 m^{-1}

P_e profile decay suggests that RF power deposition for -7 m^{-1} is more central than for 14 m^{-1} in agreement with modeling

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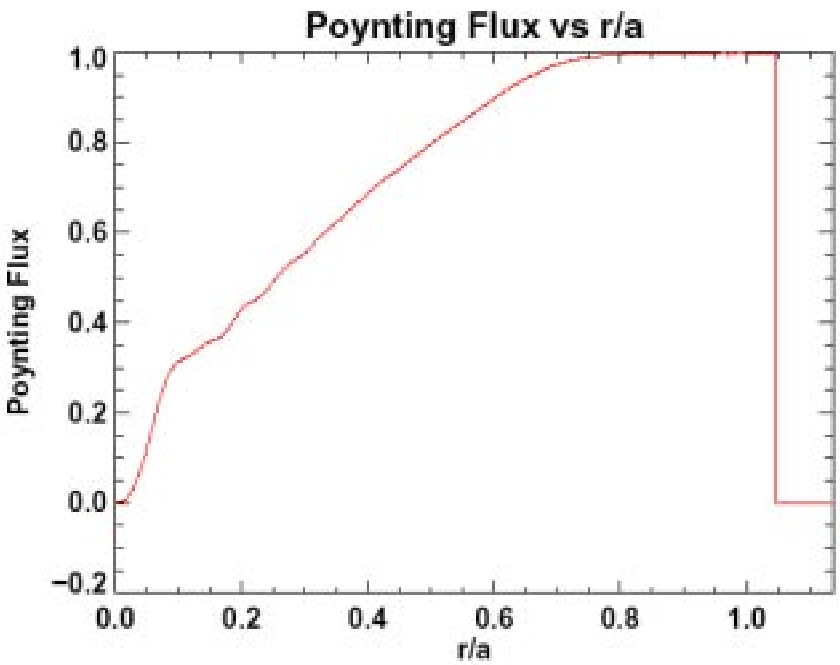
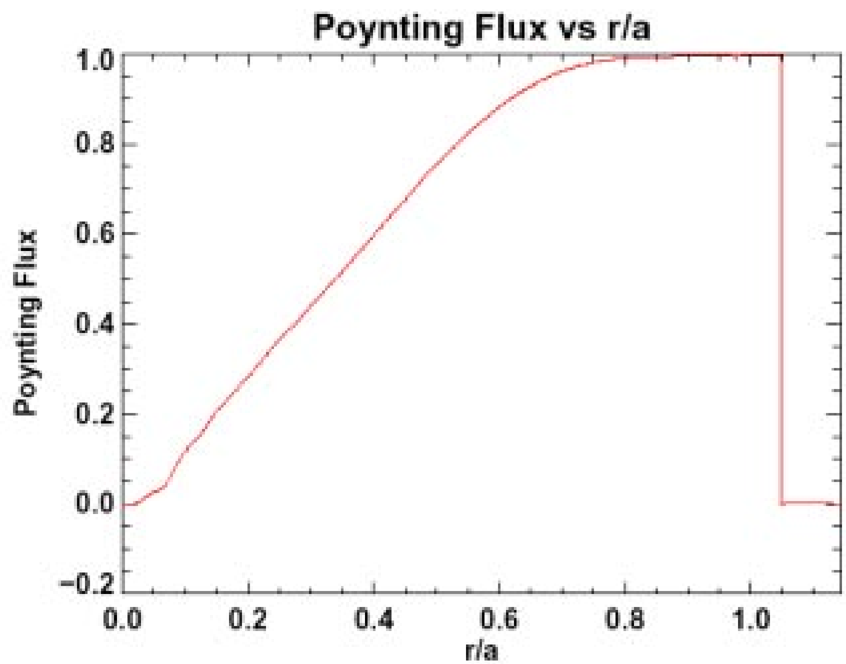
112705: -7m^{-1}



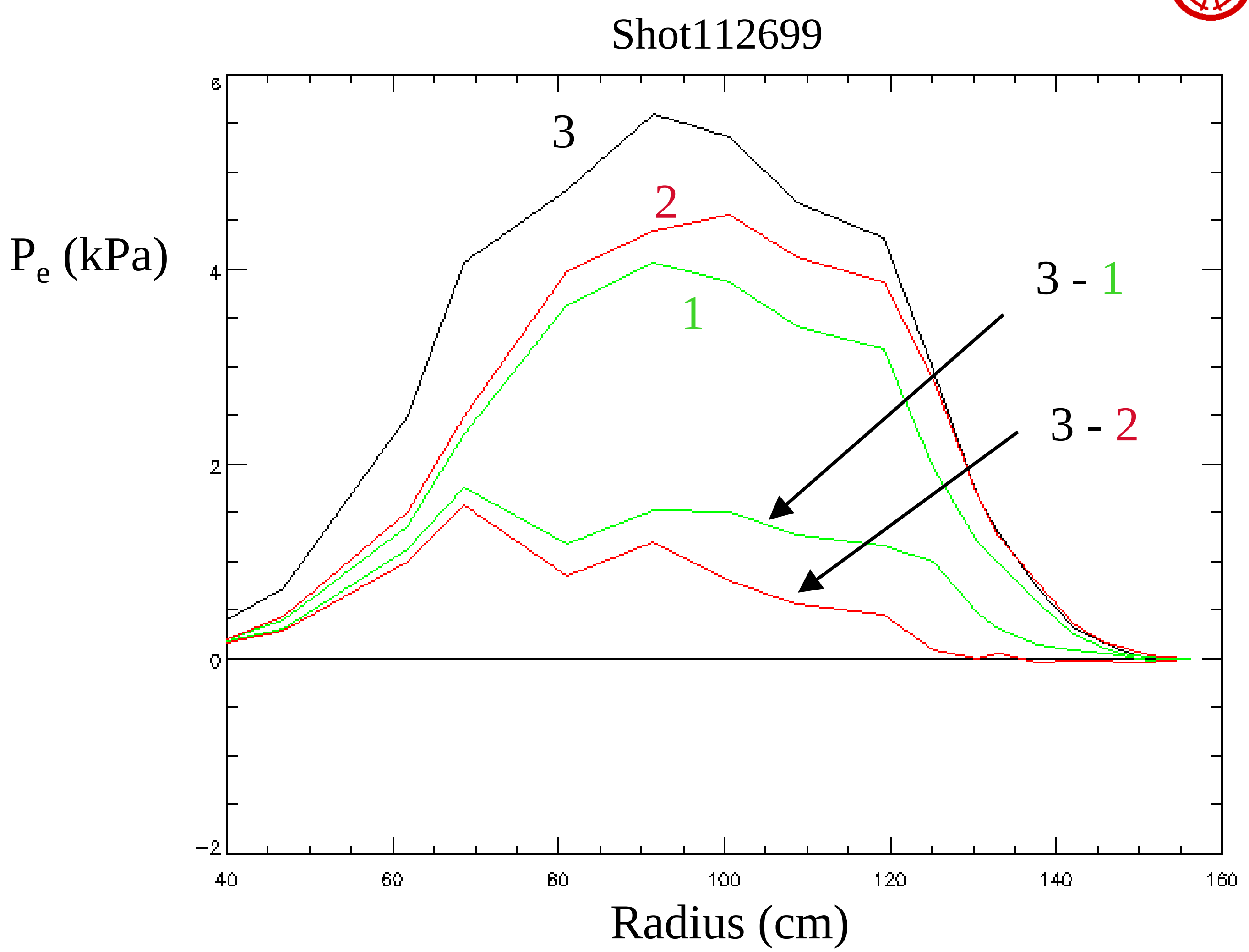
112699: 14m^{-1}

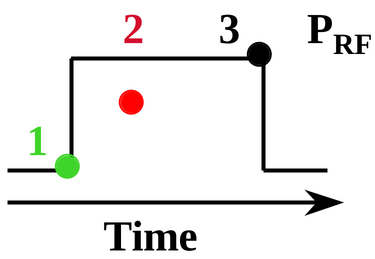


- Toric modeling gives a more central RF power deposition for -7 m^{-1}

P_e vs Radius for 14 m^{-1} for Times for Second RF Pulse

Laser times(sec) are 1 (0.2767), 2 (0.2847), 3 (0.3100)

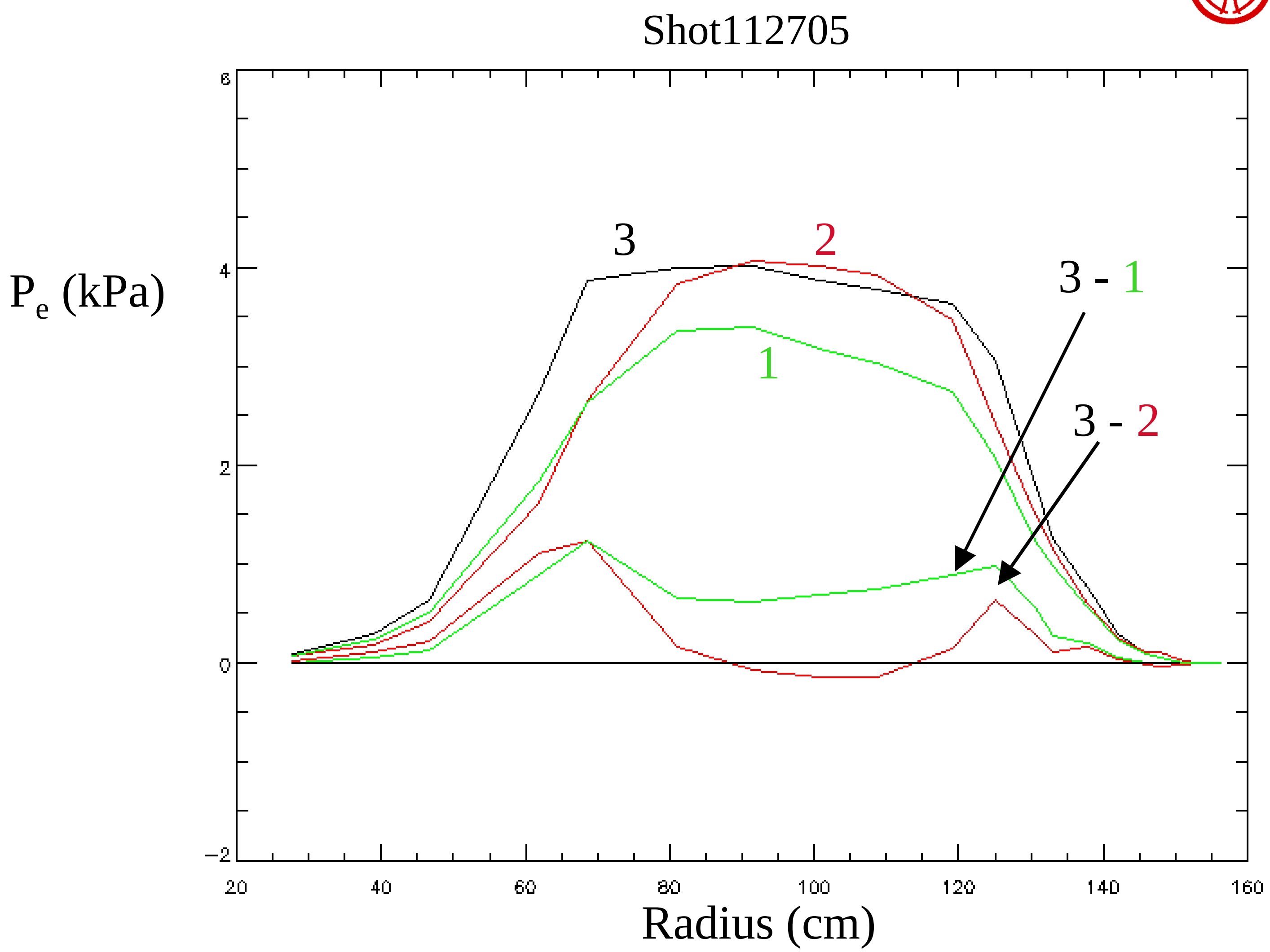


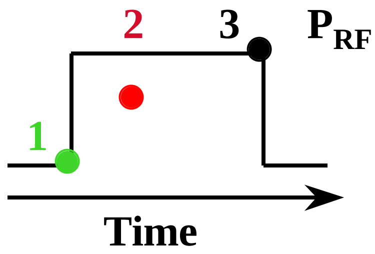


- Electron heating shifts toward the inside during the latter part of the second RF pulse
  - clear that profile shape is changing in time and is affecting the τ_0 calculation

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

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



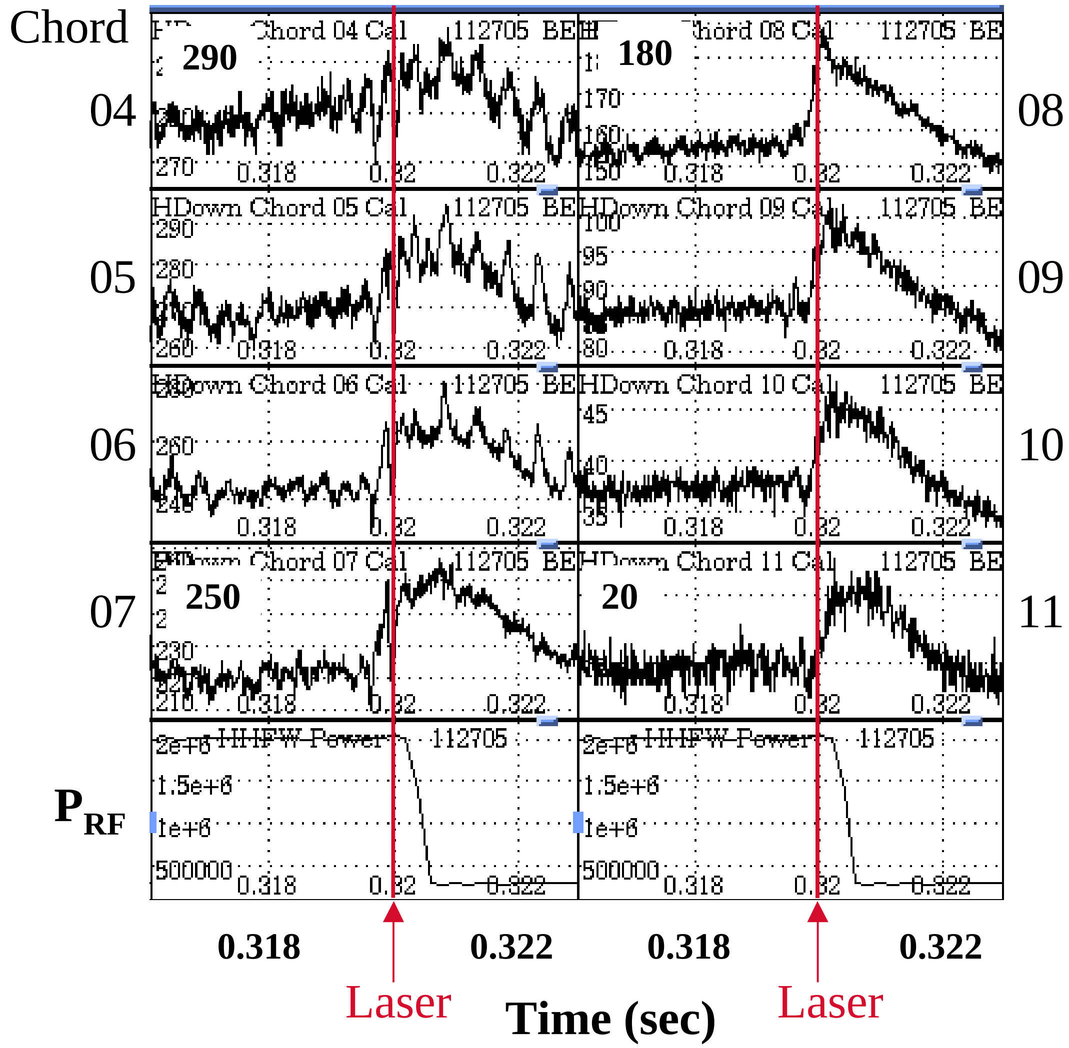


- Electron heating flattens in core and shifts inward during second RF pulse
  - apparently the laser fired during a sawtooth instability at time 3

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

Soft Xray HDown (Shot112705)



14 m^{-1} Has Considerably Less Sawtooth Activity During the Second RF Pulse

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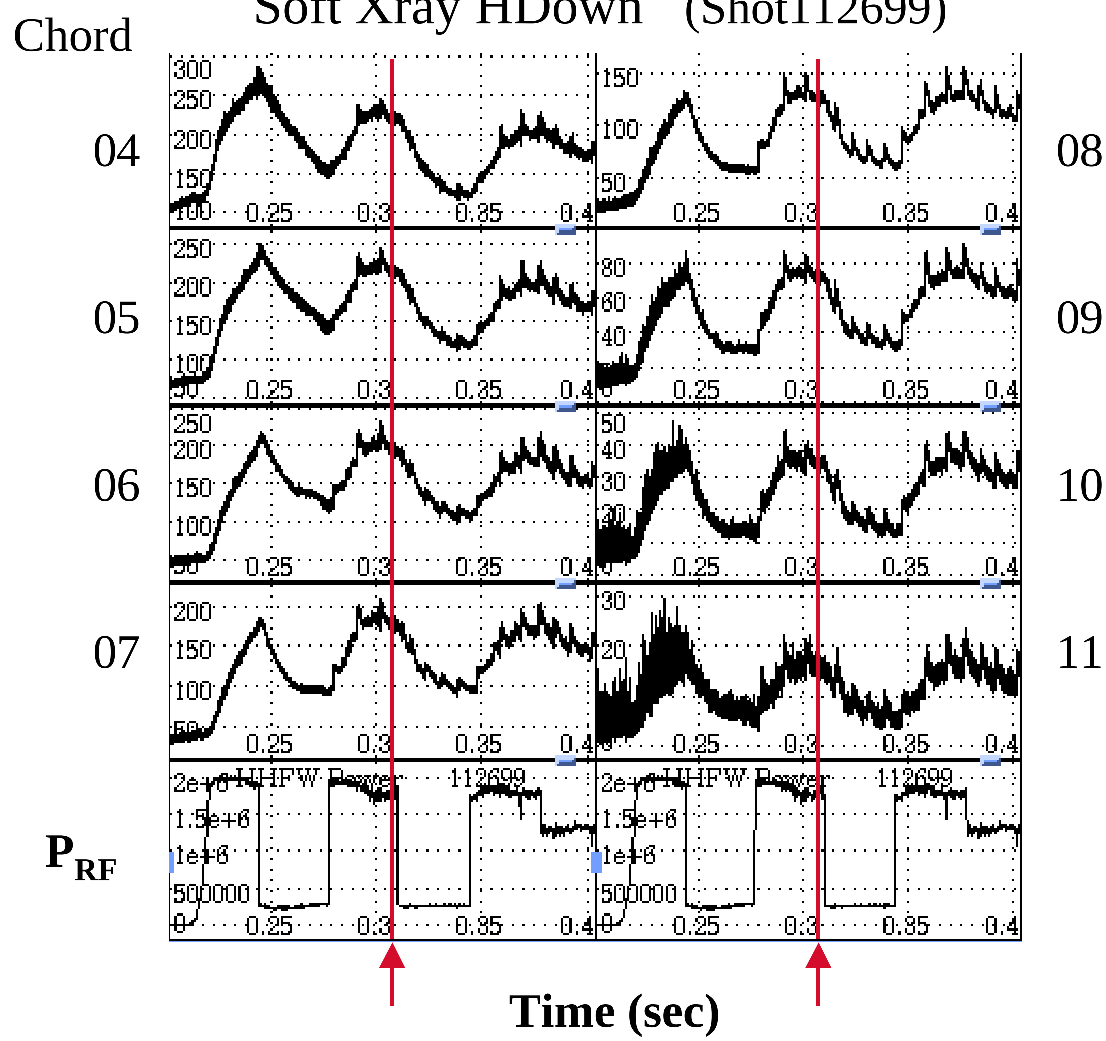
- No sawtooth is observed at laser time 0.310 sec at end of RF pulse

Soft Xray HDown (Shot112699)

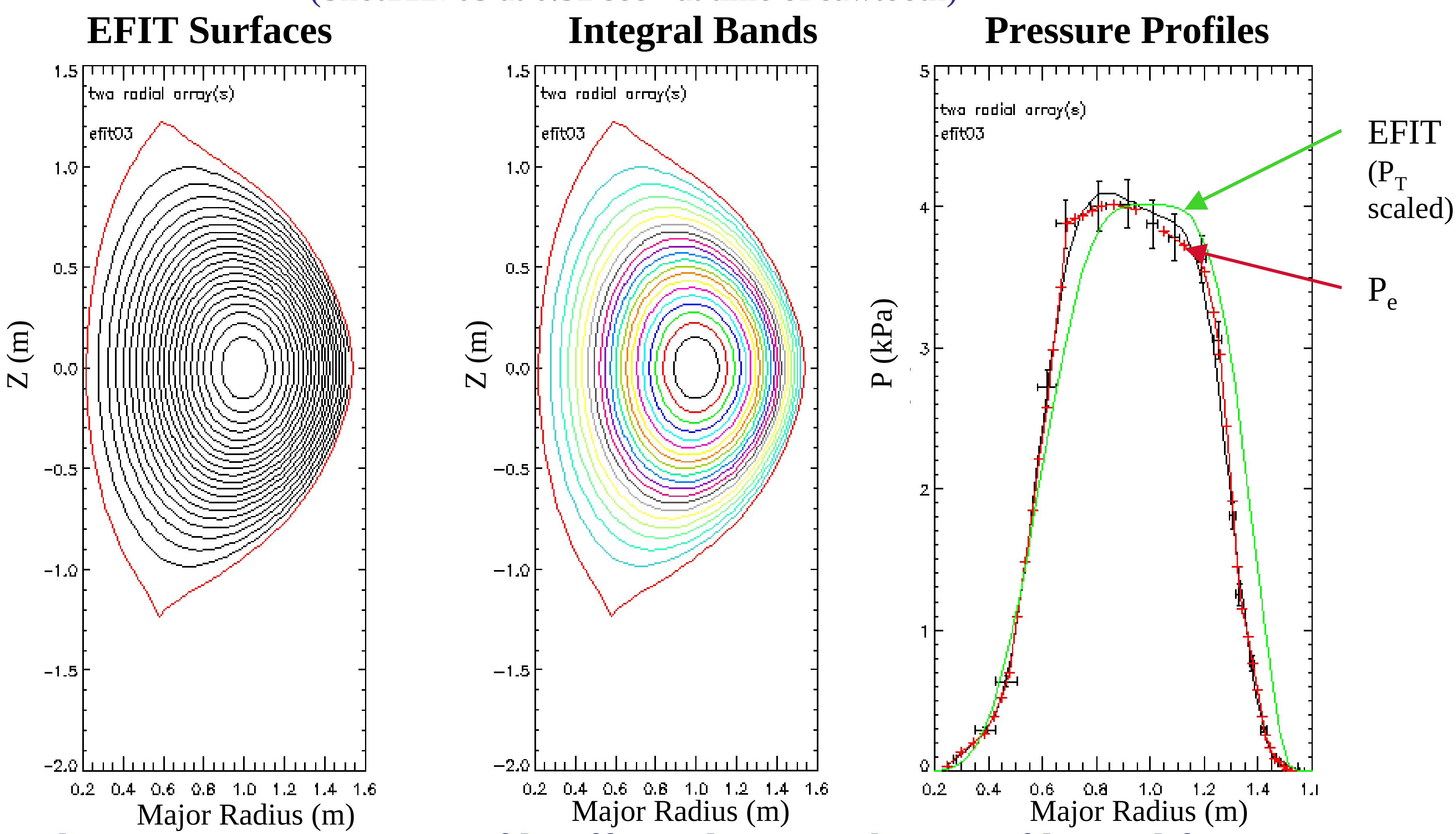


Electron Stored Energy for 14 m^{-1} and -7 m^{-1} Cases

- Integration of P_e over the EFIT magnetic surface defined volumes is used to determine W_e
- Estimate of RF power needed to produce the incremental stored electron energy and its dependence on $k_{||}$ evaluated

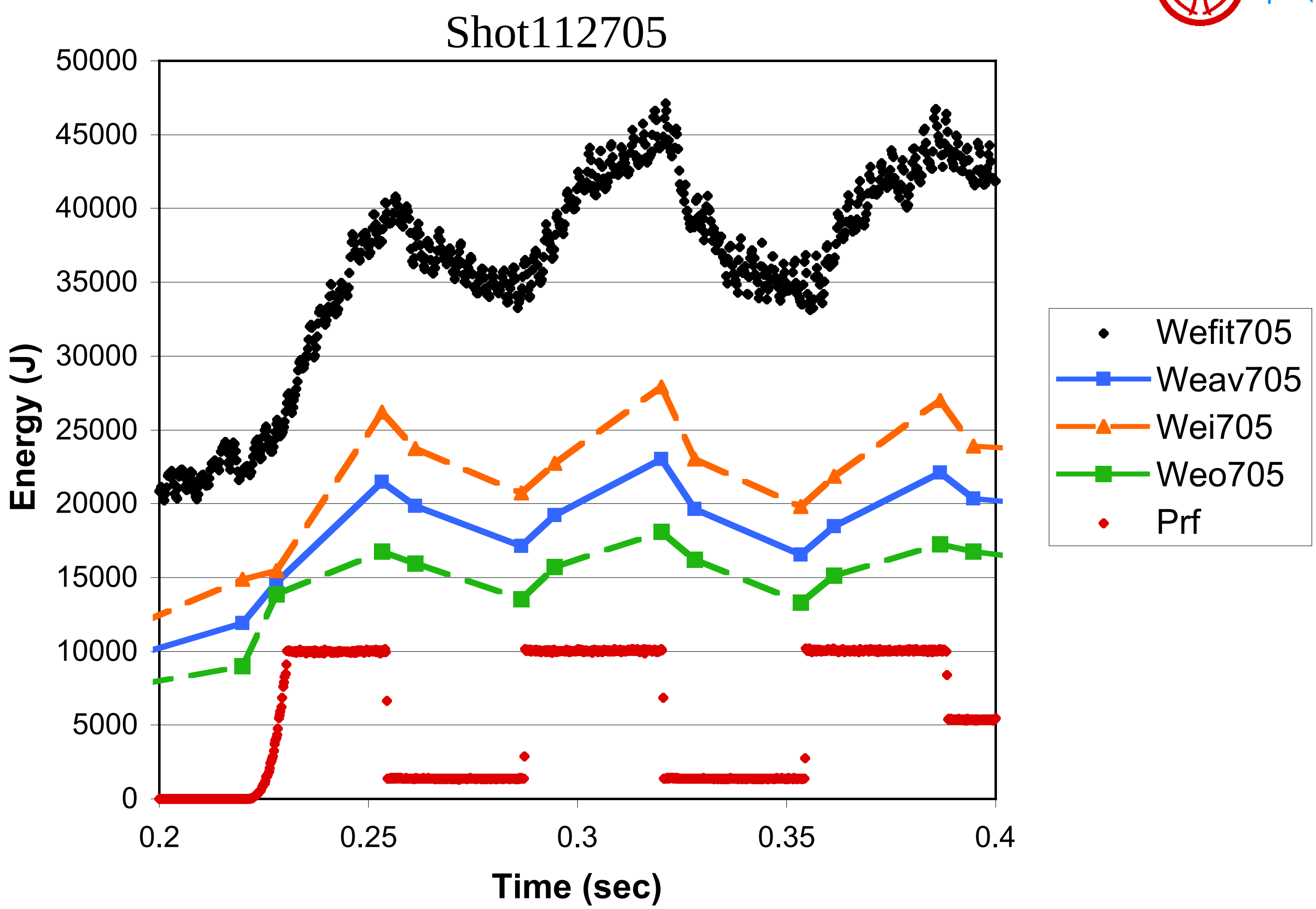
Total electron stored energy is evaluated by integrating $P_e(R)$ over the EFIT magnetic surfaces

(Shot112705 at 0.32 sec - at time of sawtooth)



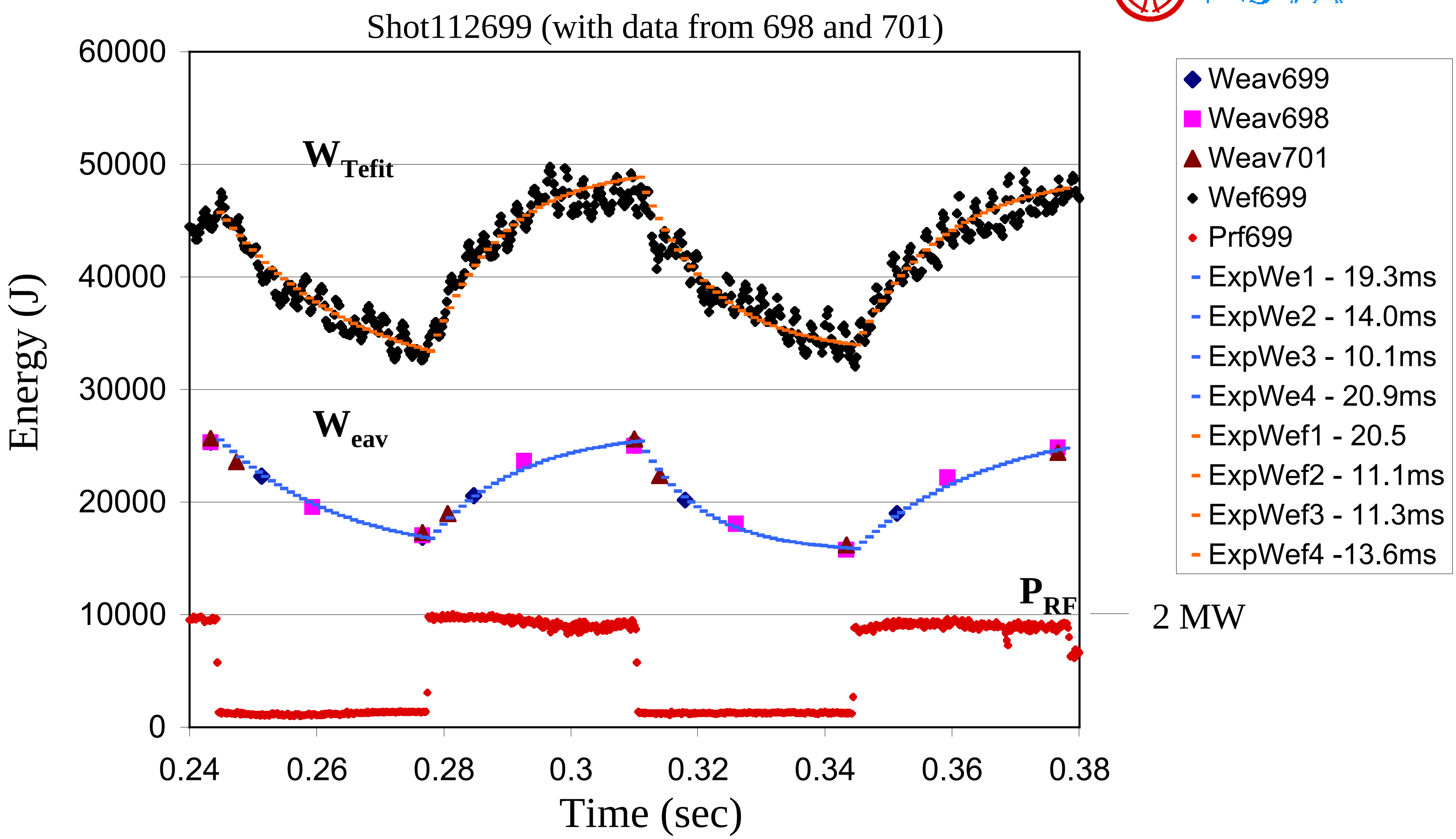
- Thomson scattering P_e profile offset relative to the P profile used for W_{EFIT} is taken into account by integrating over surfaces using separately P_e values inside the EFIT axis (W_{ei}) and outside the EFIT axis (W_{eo}): $W_{eave} = W_{ei} + W_{eo}$

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



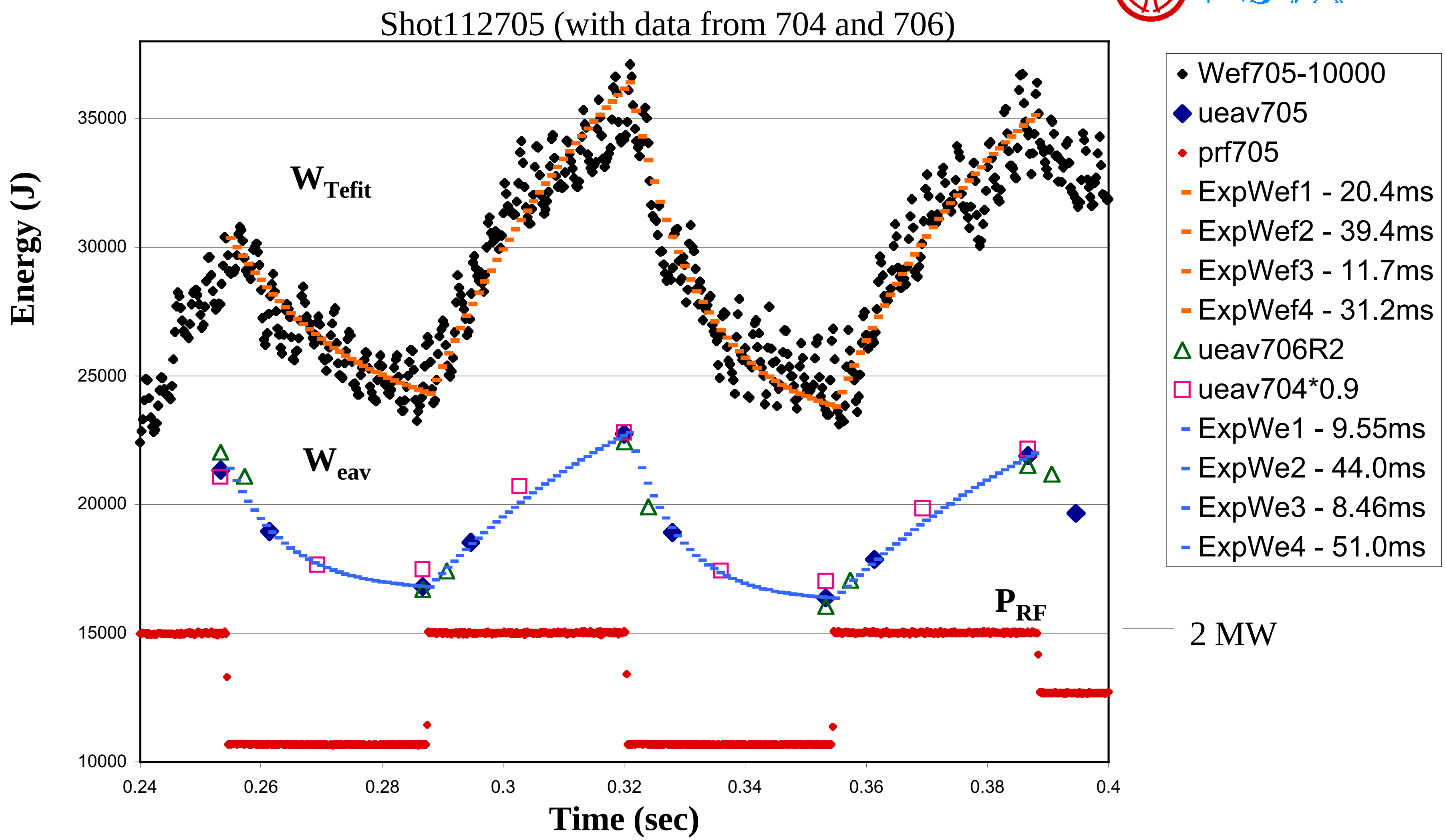
- W_{eav} continues to rise during the second RF pulse suggesting that the sawtooth redistributes energy but does not greatly reduce the total electron energy
- W_{eav} tracks the total energy from EFIT well but is only about half of W_{tefit} instead of the expected value of ~ 2/3 -- the EFIT pressure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

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



- Electron stored energy exhibits an exponential rise and τ_{We} is comparable to the corresponding value τ_{WTefit} for the total stored energy
  (see S. Bernabei et al, JP1.011 for a detailed investigation of total stored energy)

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



- Flattening observed for $P_e(0)$ during second RF pulse is not present for W_{eav}
- The exponential times for both W_{eav} and W_{tefit} are noticeably longer during the RF pulses than during the decay periods

The exponential electron energy curves suggest that a large fraction of the RF power is not deposited in the bulk plasma

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

	ΔW_F(kJ) $\Delta W_e/\Delta W_{EF}$	τ(msec) $\tau_\varepsilon/\tau_{EF}$	P_{RFeff}(MW)	% = $P_{RFeff}/\Delta P_{RF}$
– 14 m^{-1} :				
Second RF Pulse	11.48/19.33	14.0/11.1	0.820/1.74	50/105
Third RF Pulse	11.53/15.98	20.9/13.6	0.552/1.17	34/71
– -7 m^{-1} :				
Second RF Pulse	11.49/22.8	44.0/39.4	0.261/0.579	15/33
Third RF Pulse	11.92/18.0	51.0/31.2	0.234/0.579	13/33

- These power deposition estimates indicate that the RF power reaching the core is considerably reduced for the smaller $k_{||}$ case and that the power sustaining the electron stored energy is roughly half that supporting the total stored energy (see S. Bernabei et al., JP1.011 for a more extensive treatment of the total stored energy)
- 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 $k_{||}$

P_{RF} losses at the edge of the plasma are indicated

- Excitation of surface waves, near field and far field, can cause power deposition in sheaths and in the periphery of the plasma
- An edge radiation diagnostic measures significant ion heating in the plasma which can be attributed to decay wave excitation - see S. Diem et al., JP1.014

RF deposition at the periphery of the plasma can be due to surface wave effects and edge heating

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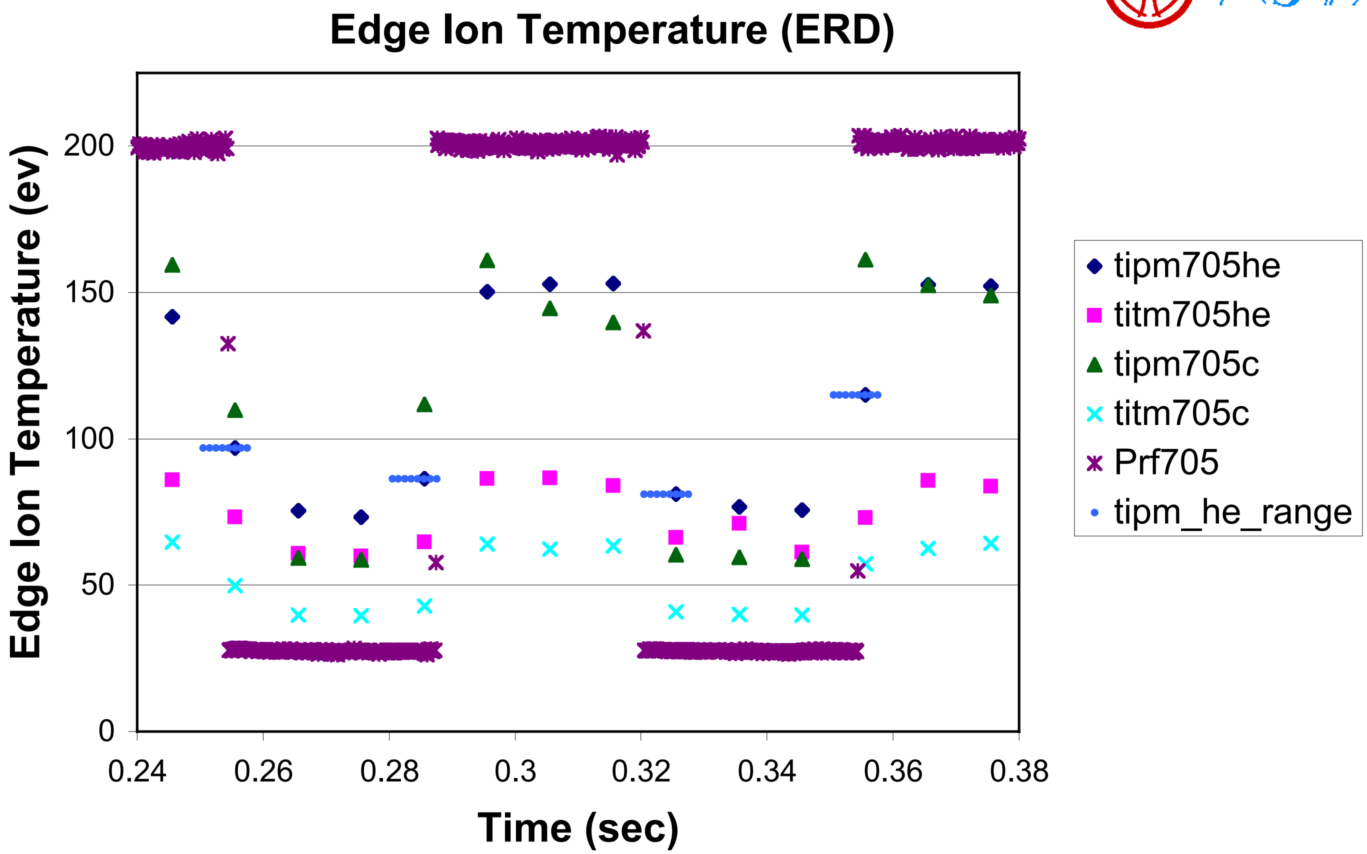

- Edge ion heating via parametric decay waves accounts for a substantial amount of RF power loss - see S. Diem et al., JP1.014
- The edge radiation diagnostic indicates that the helium ion poloidal temperature reaches ~ 150eV and decays very rapidly at the end of an RF pulse - in a msec or less

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 core 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 give 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_{tefit}) well but is only ~ 1/2 of its value instead of the $\geq$ 2/3 level expected for the helium plasma
- The apparent power needed to produce the measured increase in W_e is substantially less than the applied RF power and decreases with $k_{||}$
- 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