NSTX

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HHFW Heating Properties for H-mode Plasmas in NSTX

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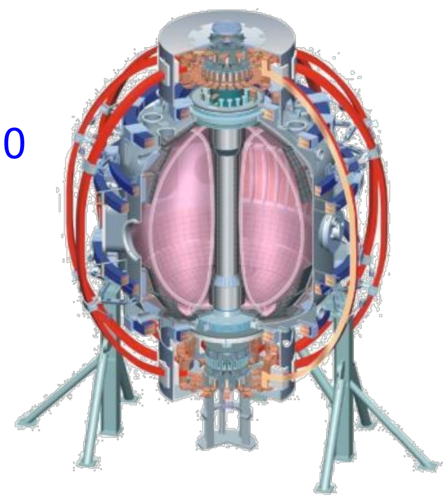

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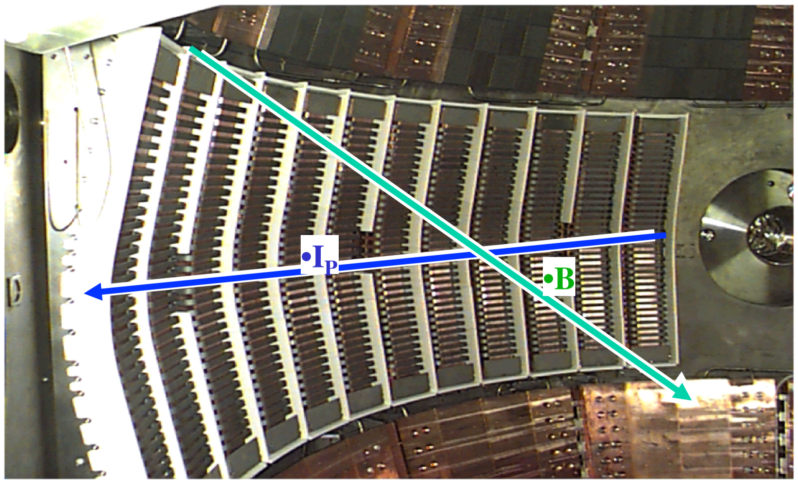
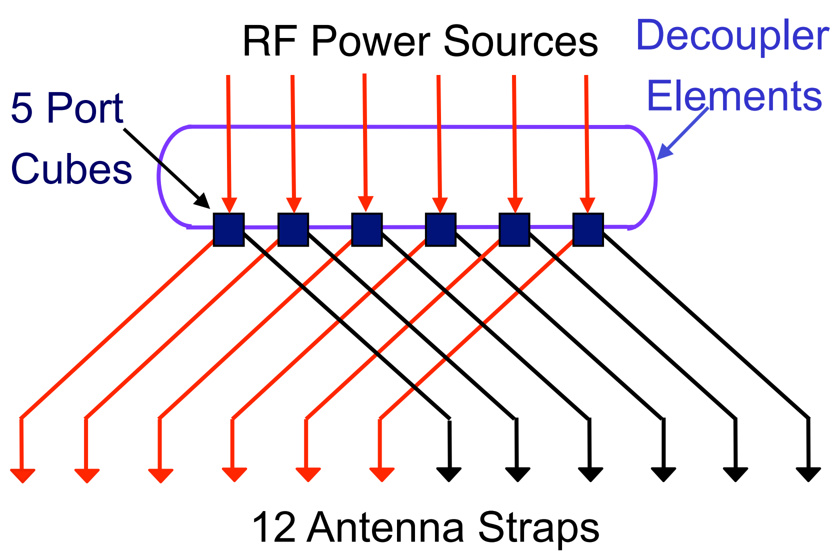
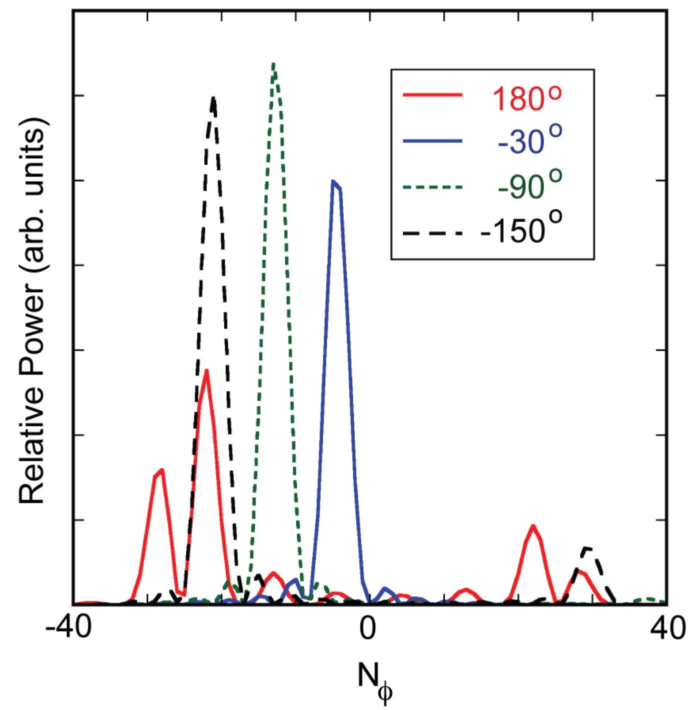
NSTX HHFW antenna has well defined spectrum, ideal for studying dependence of heating on antenna phase



HHFW antenna extends toroidally 90°





- Phase between adjacent straps easily adjusted between 0° to 180°

- Large B pitch affects wave spectrum in plasma core

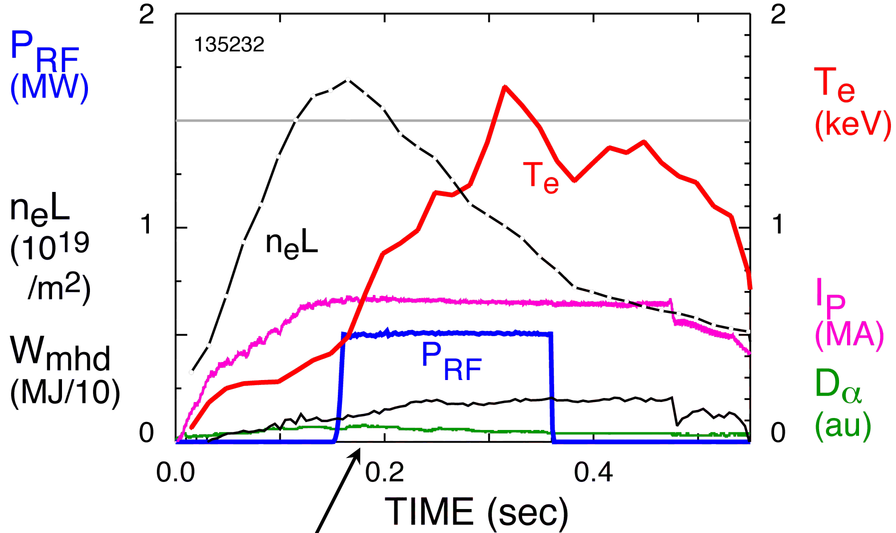
HHFW heating properties for H-mode plasmas in NSTX

Outline:

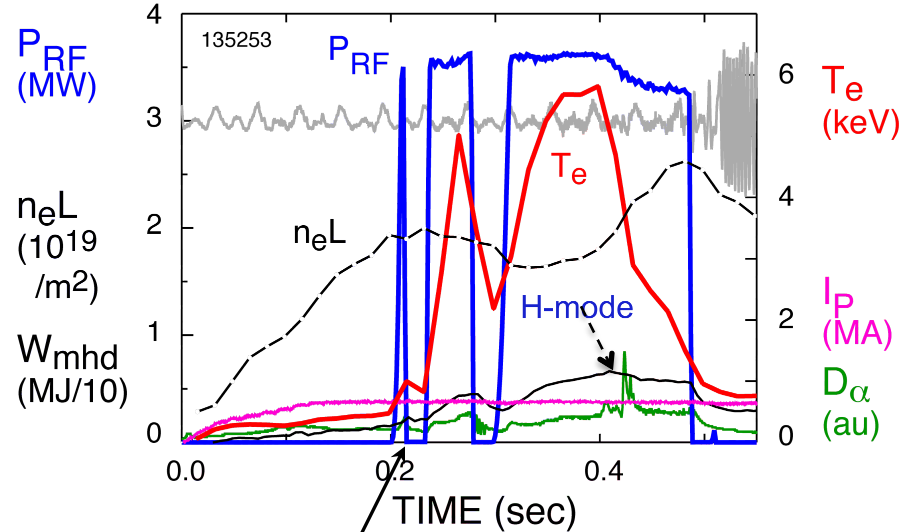
- Operation at higher power and with ELMs with upgraded, conditioned antenna
- H-mode with NBI and HHFW
  - RF ‘hot’ zone on the bottom divertor plate
    - Increased edge deposition with ELMs
  - Effect of ELMs on core heating
  - ELM heat deposition with fast IR camera
- H-mode with HHFW alone
  - Effect of ELMs on core heating
  - Sustained stored energies with programming of P_{RF} down to ~ 1.4 MW in the ELM-free-like H-mode regime
  - Very narrow ELM heat deposition with fast IR camera

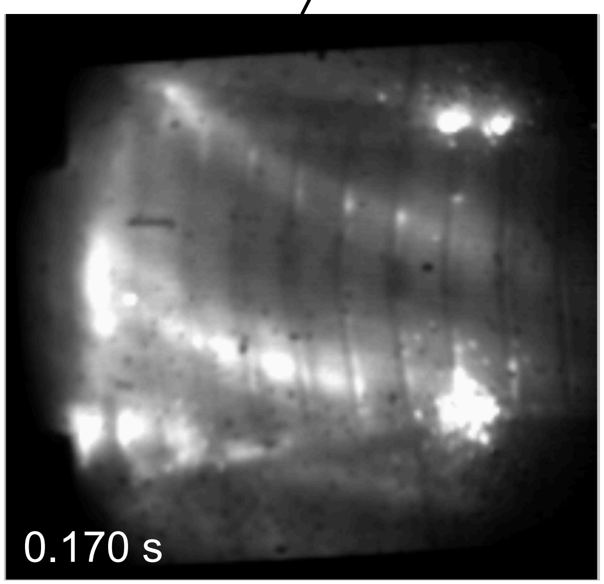
Plasma conditioning of the upgraded HHFW antenna has resulted in operation up to 3.7 MW

Plasma Conditioning: 0.5 MW – no arc



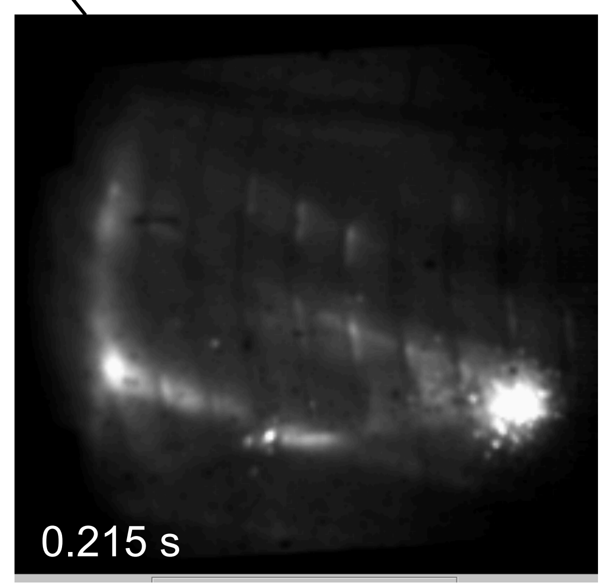
3.7 MW – 2 arcs





- Lithium sputtering from outside of antenna can cause arcs if material (dust) enters faraday shield enclosure

- RF power is not limited by RF voltage on antenna but the limit appears to be an induced RF current effect – i.e, an RF current limit



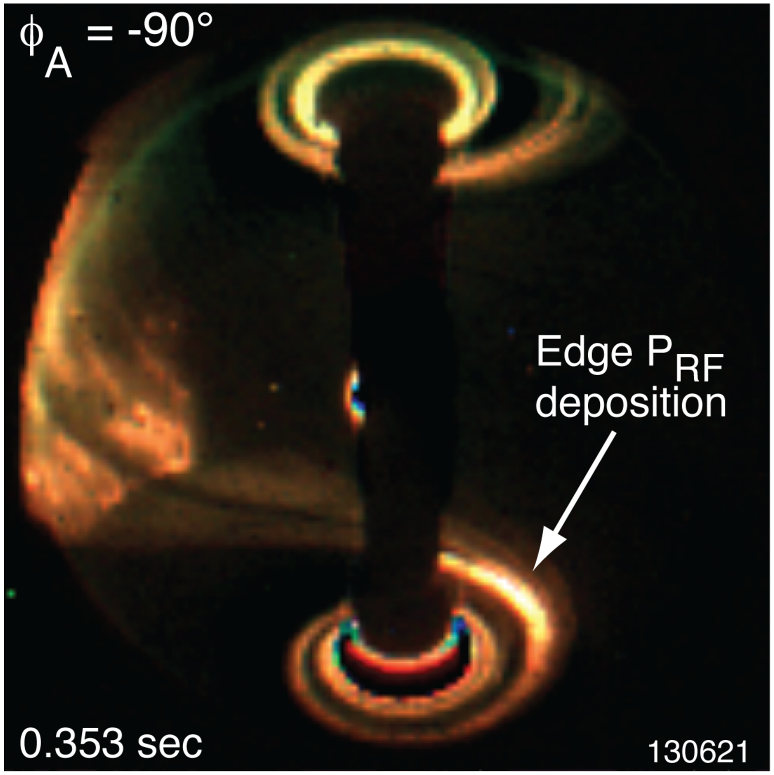
Operation in H-mode with HHFW+NBI
- Effect of ELMs on core and edge heating

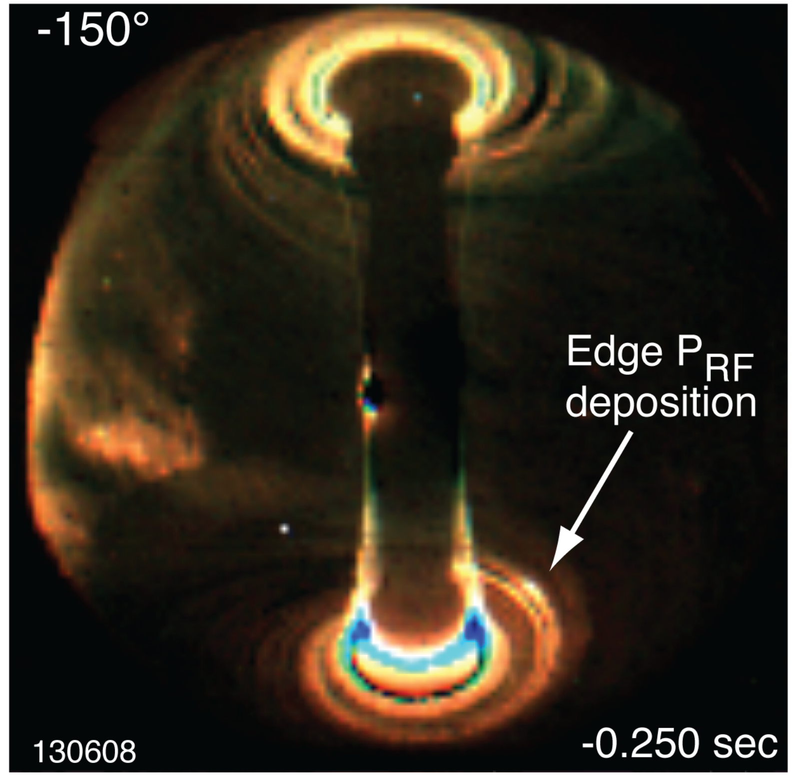
Summary of results to be presented:

- H-mode HHFW power coupling with type I ELMs compared to ELM-free case in deuterium
- Losses in scrapeoff region to the outer divertor RF heated zone enhanced with ELMs
  - Apparently due to increased edge density effect on edge RF power deposition
- ELM energy deposition peaked around outer divertor strike radius and may contribute little to the RF hot zone

Fast waves propagating in the SOL are heating the tiles of the outer divertor plate

ELM-free H-mode, P_{RF} ~ 1.8 MW, P_{NB} = 2 MW, I_P = 1 MA, B_T = 5.5 kG, D_2





- "Hot" region is much more pronounced at -90° than at -150°
  - Edge power loss is greater at -90°
  - Also, suggests fields move away from wall at -150° along with the onset density for perpendicular wave propagation
- IR camera measurements indicate hundreds of kW are deposited in the "hot" region

Study of RF heating of the outer divertor plates versus magnetic field pitch and antenna phase for ELMy case

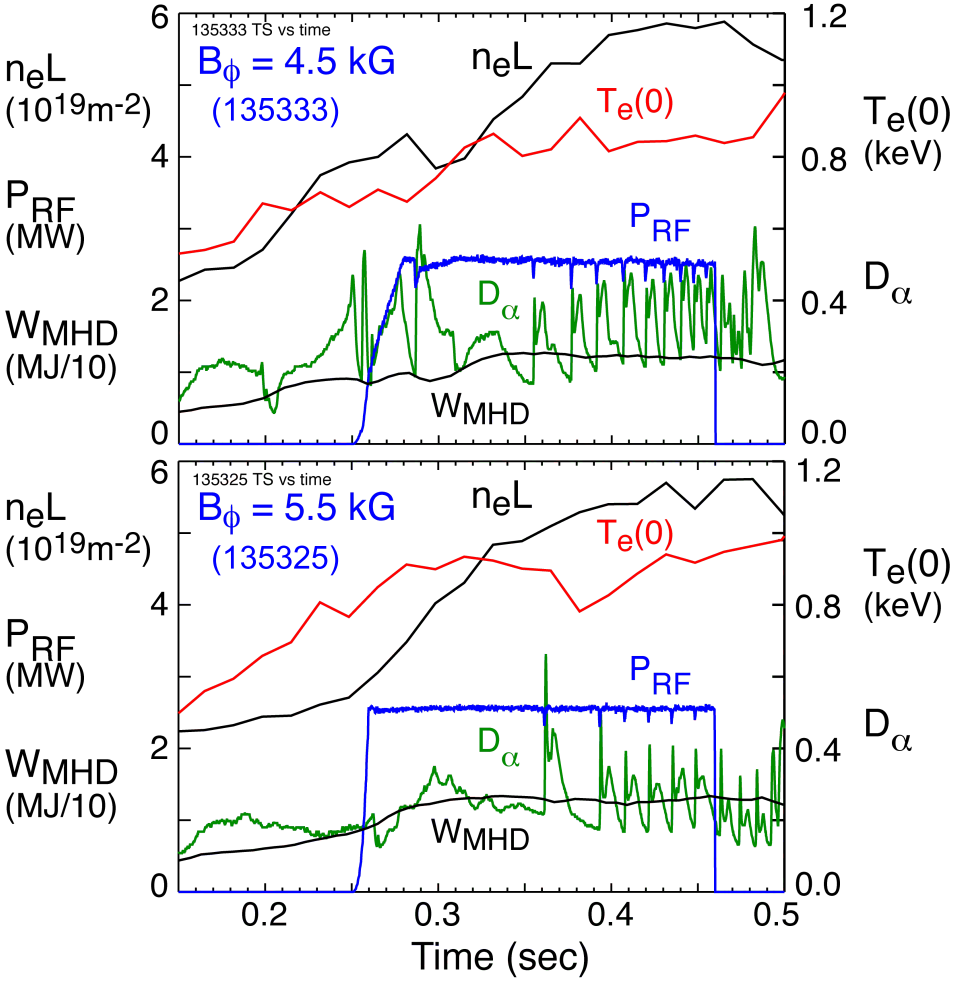
- ELMing discharges studied for I_P = 0.8 MA, P_{NB} = 2 MW versus:

B_ϕ and	ϕ_A	Shot #
5.5 kG	-90°	135325
4.5 kG	-90°	135333
4.5 kG	-150°	135337
5.5 kG	-150°	135339

- Powered through ELMs without arcs for these cases

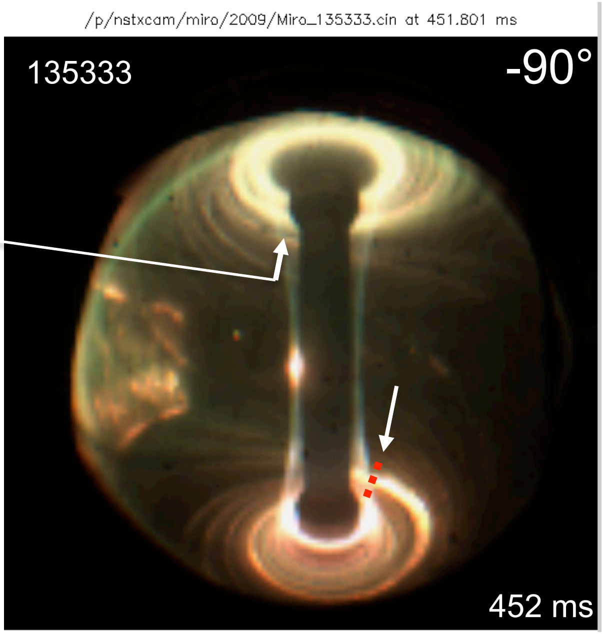
- Edge power loss is increased with higher density and ELMing activity

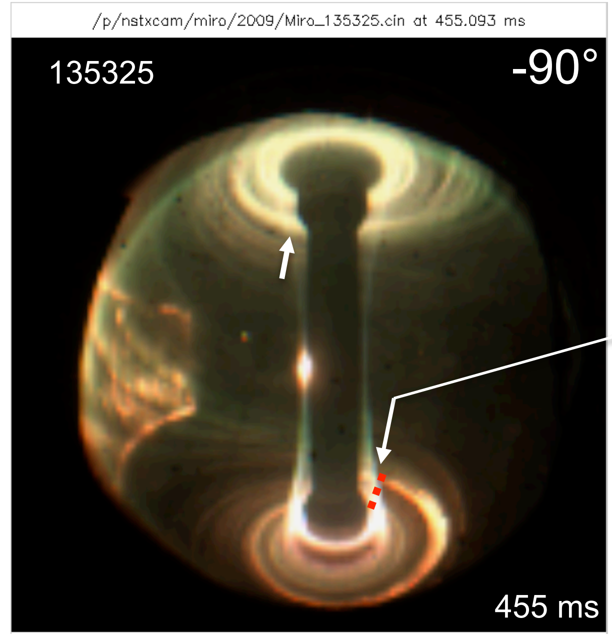
ϕ_A = -90° discharge parameters



RF heated pattern on lower divertor plate follows the magnetic pitch

Bay G IR view



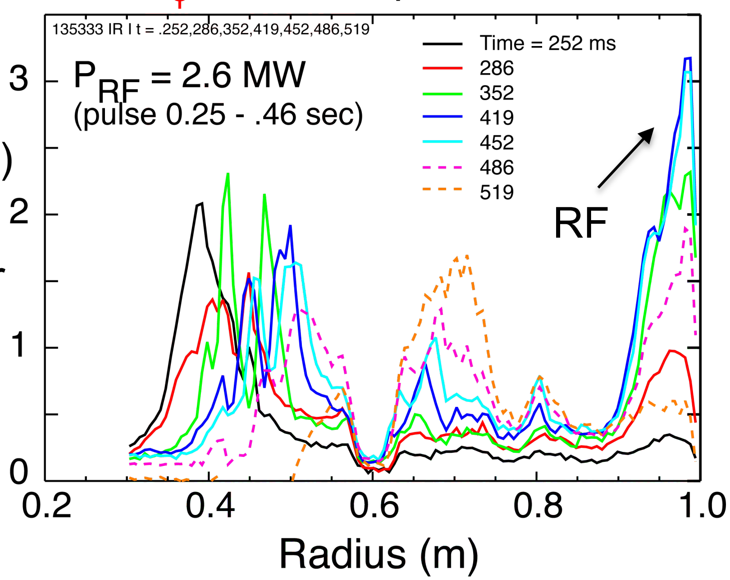


Bay I IR view

B_ϕ = 4.5 kG, I_P = 0.8 MA

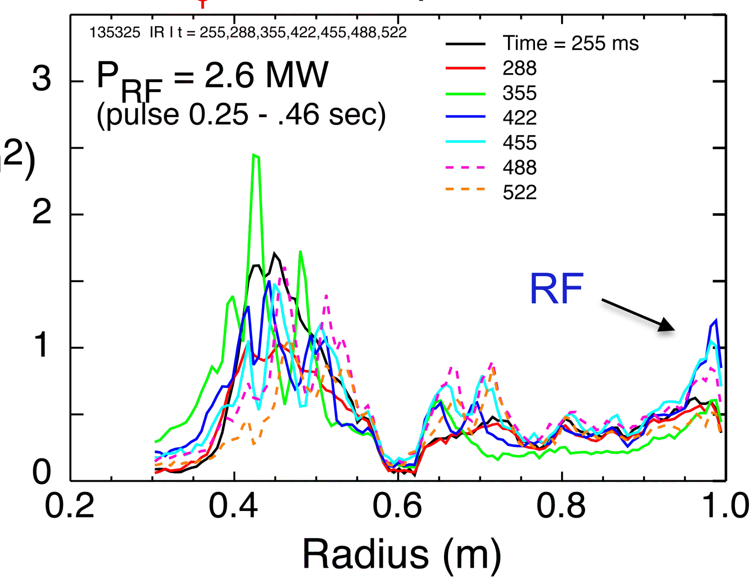
Q (MW/m^2)

(Heat flux on divertor plate at Bay I)

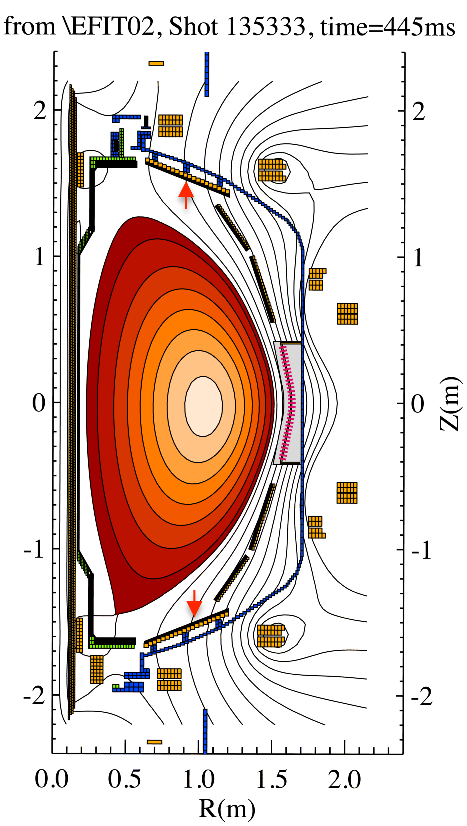


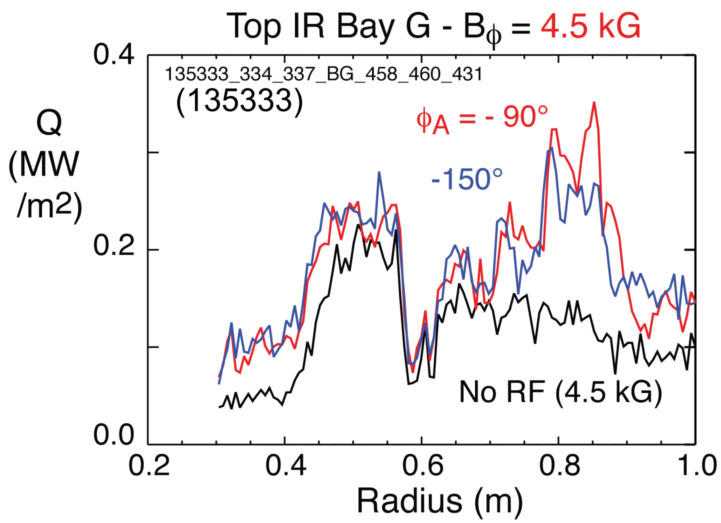
B_ϕ = 5.5 kG, I_P = 0.8 MA

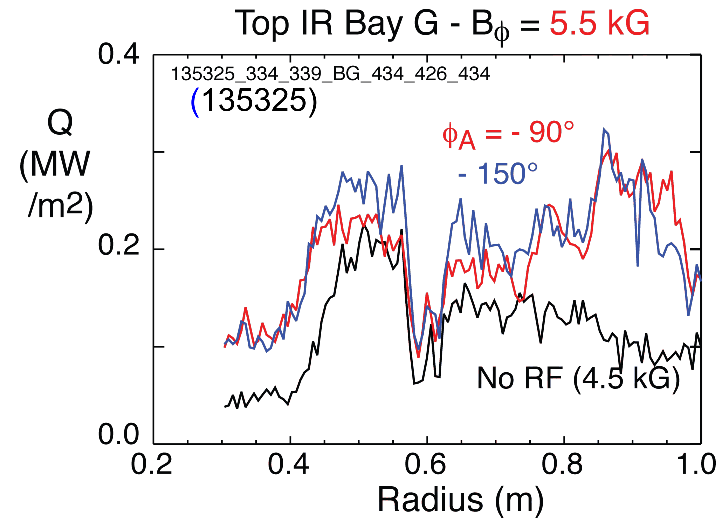
Q (MW/m^2)

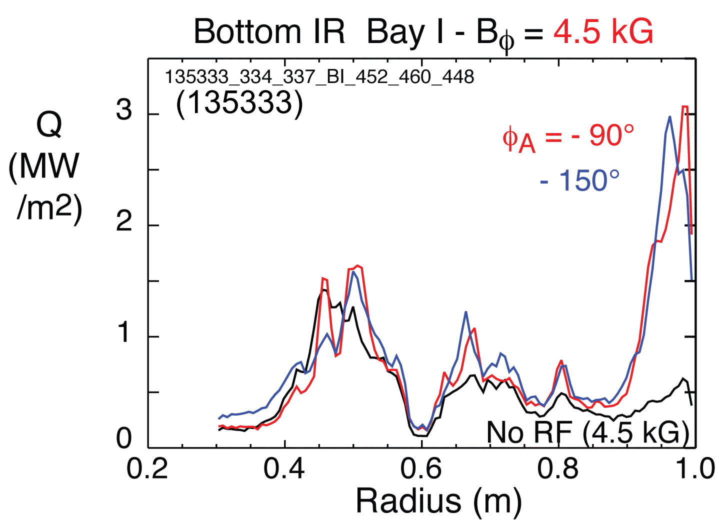


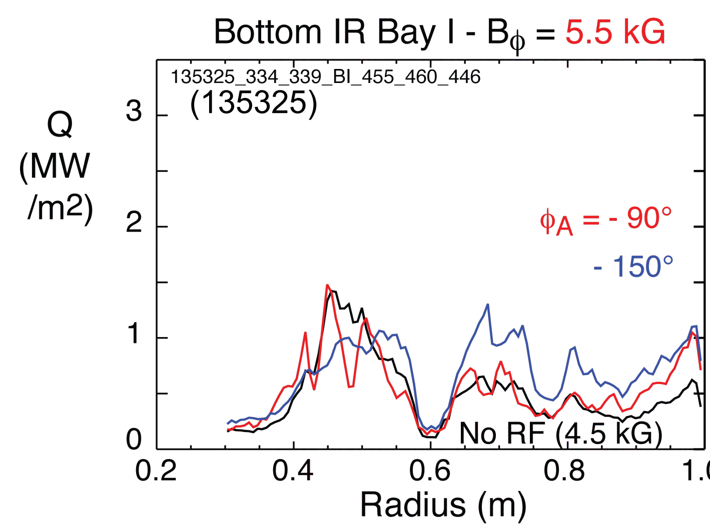
Location of heat zone has significant dependence on field pitch at lower and upper divertor plates







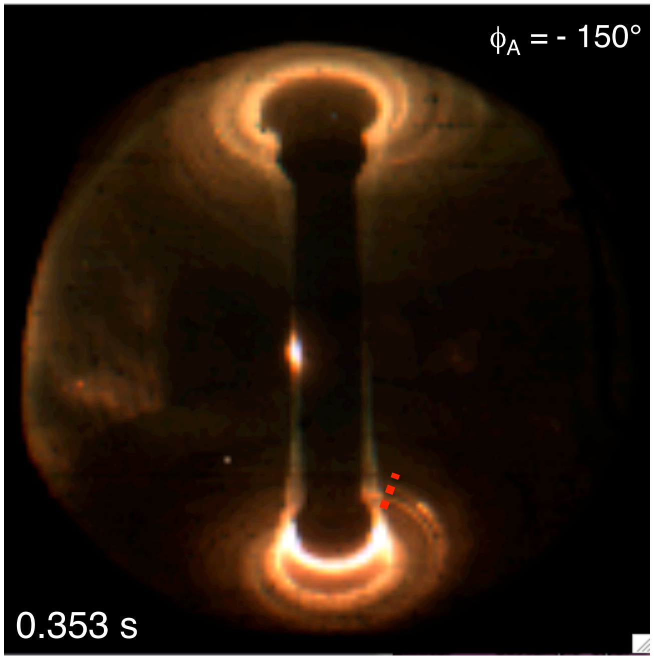




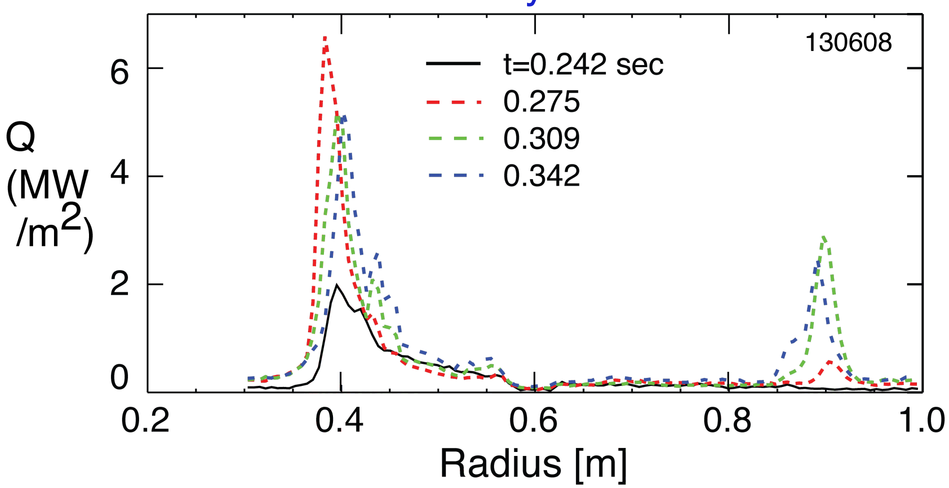
- ~ 8 cm shift outward with reduced field pitch
- Also, possibly a small shift with phase

Heating on outer divertor plate is more intense with ELMs with same field pitch (P_{RF} = 1.9 MW)

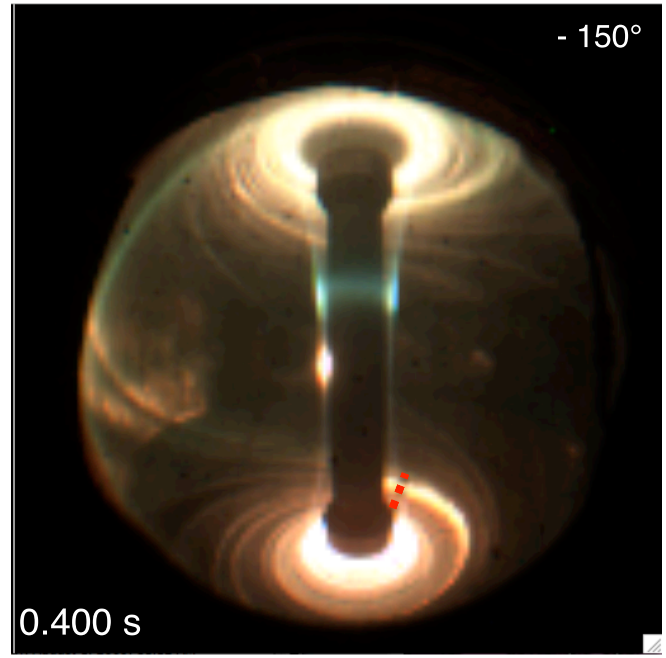
130608 ELM free – 5.5 kG, 1 MA



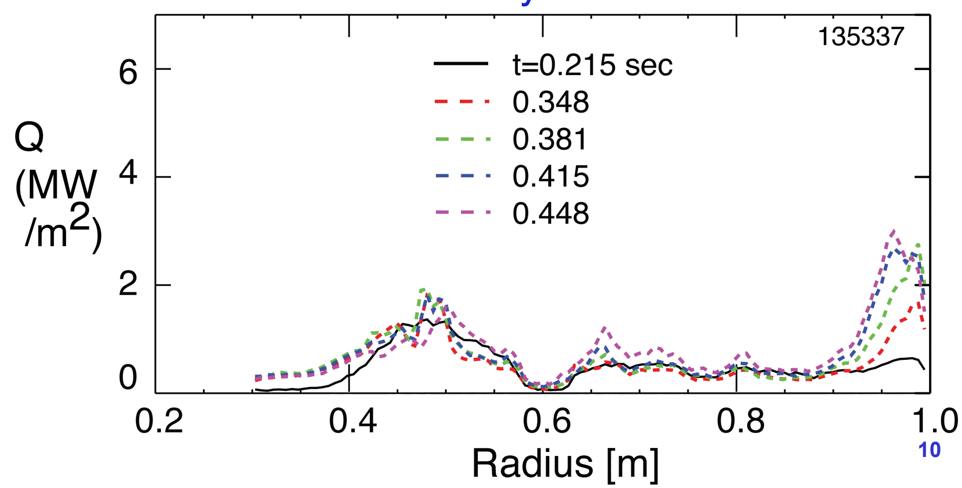
IR Bay I



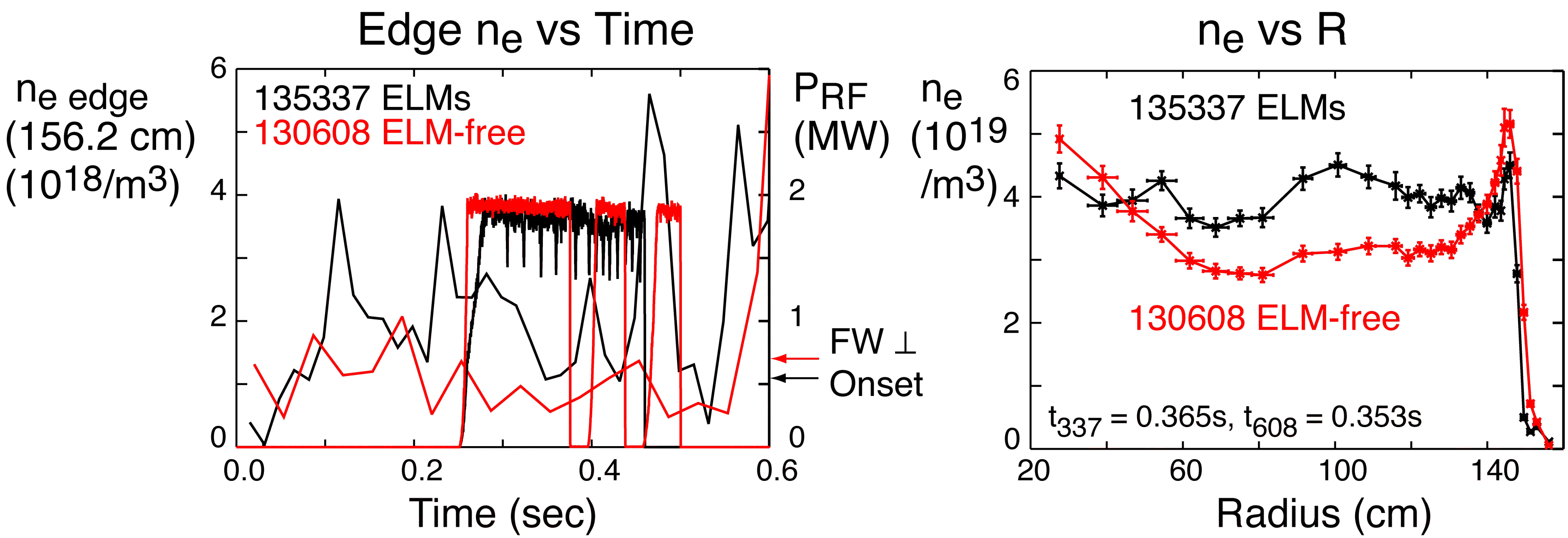
135337 with ELMs – 4.5 kG, 0.8 MA



IR Bay I

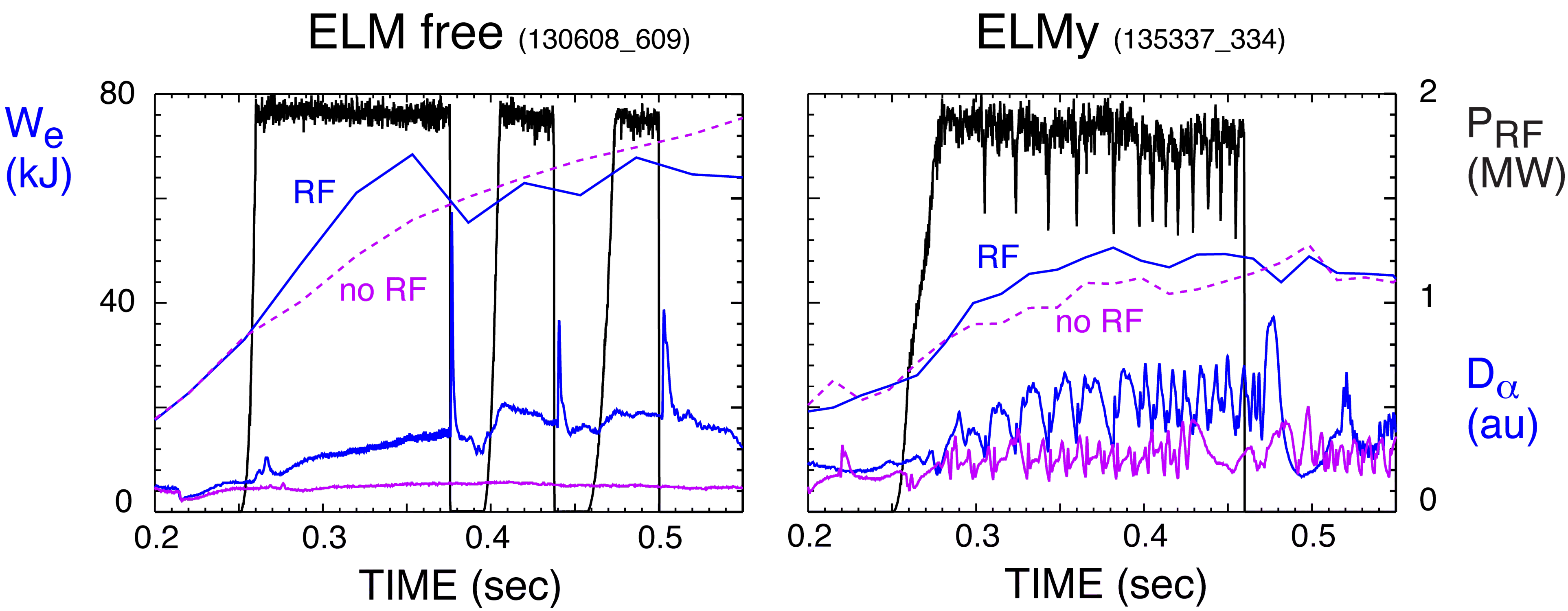


Higher edge loss with ELMs is consistent with higher edge density with ELMs



- Thomson scattering indicates that the edge density relative to the onset density for perpendicular propagation is greater with ELMs
  - consequently the FW perpendicular propagation begins closer to the antenna with ELMs
- ELMs reduce the energy confinement as well

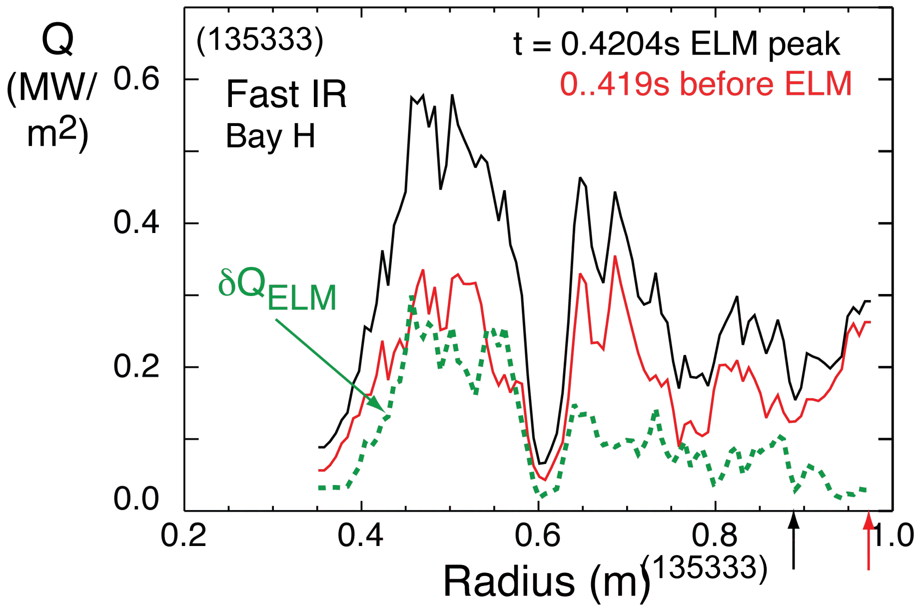
ELMs reduce RF plasma heating by ejecting energy (as for NB) as well as by producing higher edge density

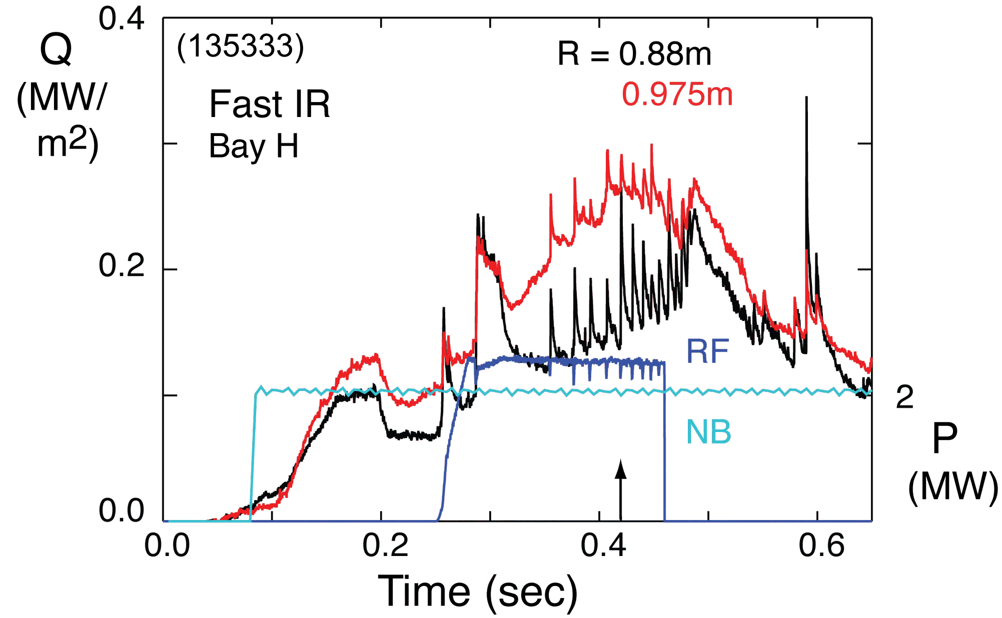


- ΔW_e and ΔW_{tot} for shot 135337 with ELMs are reduced by ~ 50% relative to shot 130608 ELM free case
- D_α indicates increased power deposition to divertor region with ELMs

ELMs do not appear to enhance HHFW edge loss to divertor directly

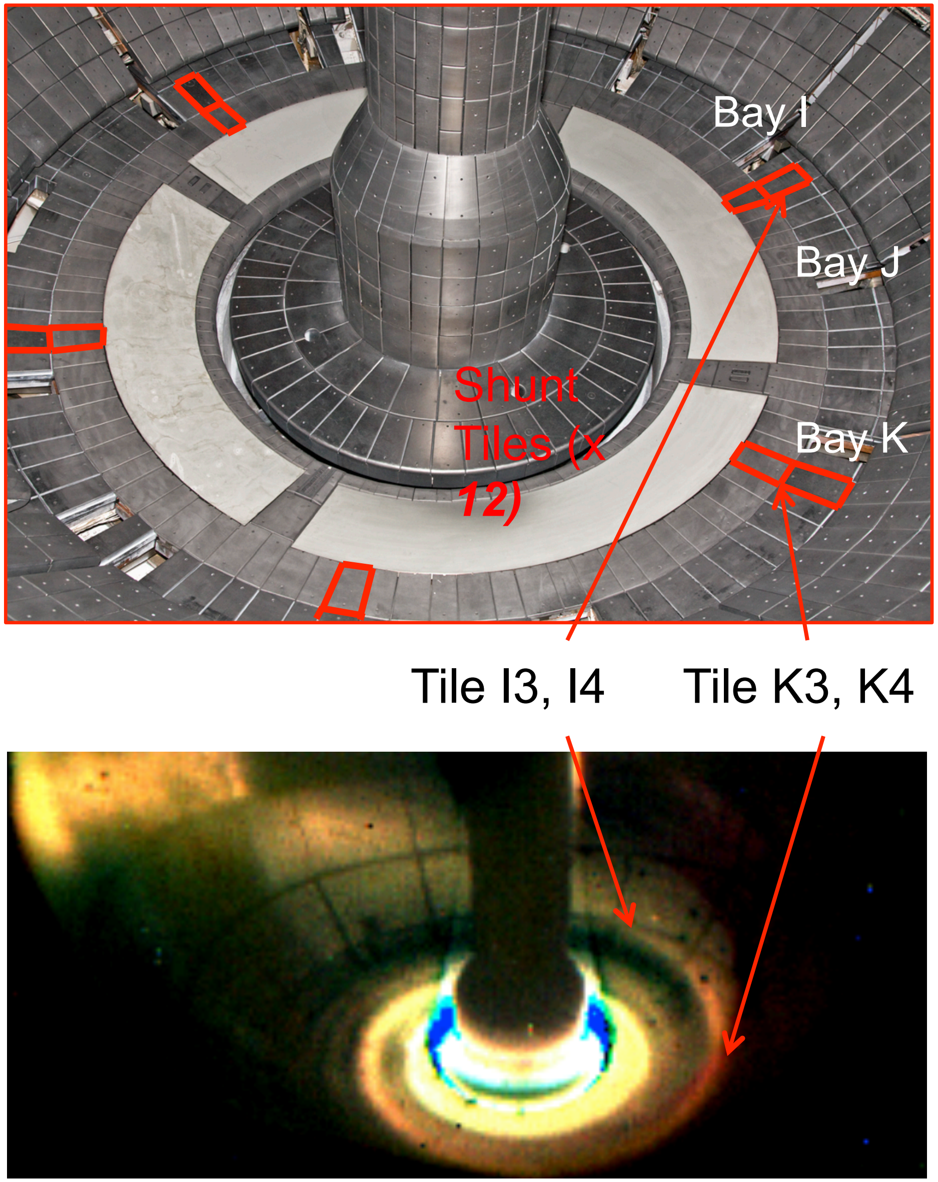
Fast IR at Bay H with antenna phase ϕ_A = -90°, B_T = 4.5 kG, I_P = 0.8 MA





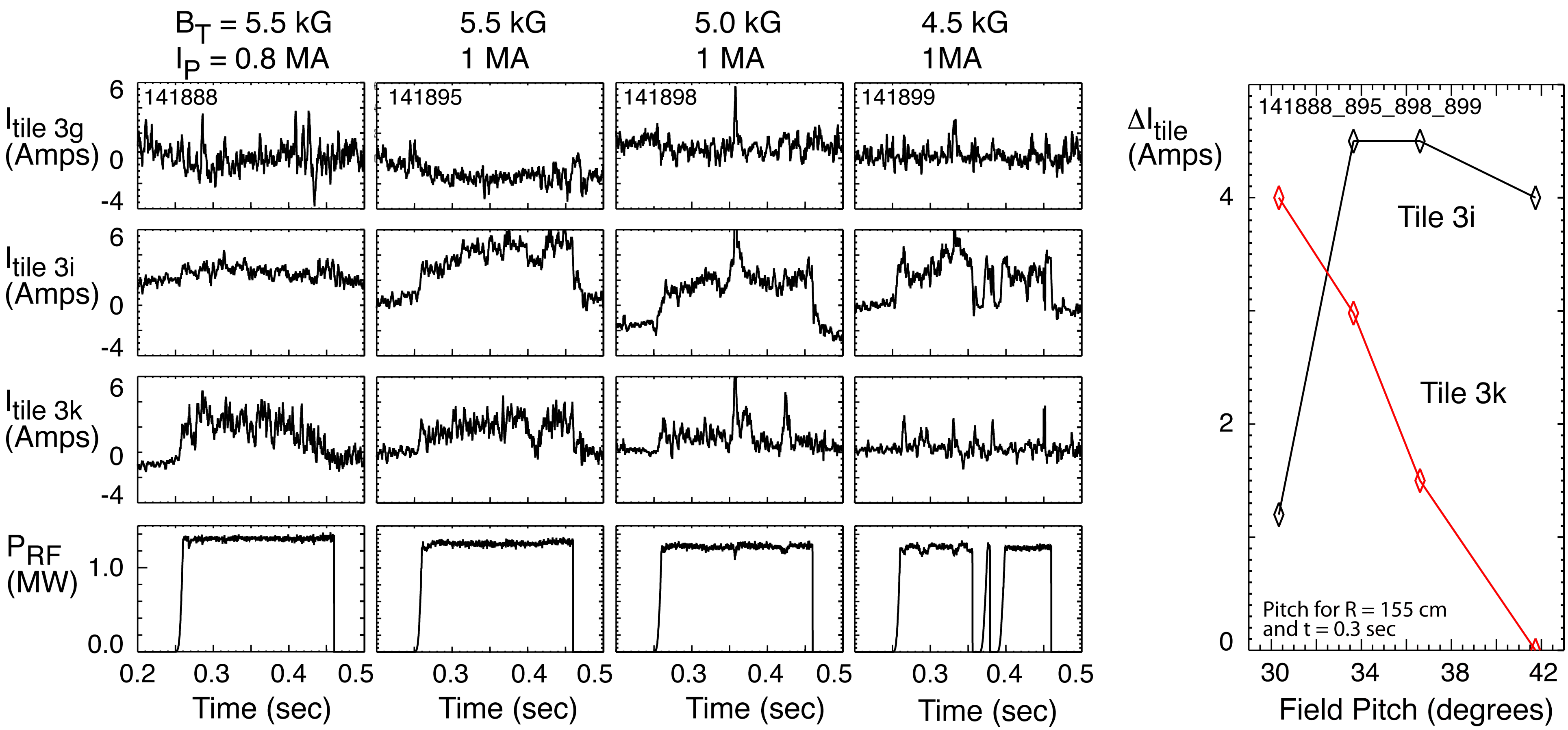
- Key question: does ELM contribute significant heat in the primary RF heated divertor zone?
  - *Probably not*
- Fast IR camera shows ELM heat deposition peaked at outer strike radius – falling to a low value towards the RF heated zone (R ~ 1.1 m)
- Experiments have begun to determine the ELM effect on the primary RF edge heating zone at Bay H at higher magnetic field pitch (e.g., 4.5 kG, 1 MA)

Divertor tile currents are used to track presence of RF fields (sheath) and driven currents



- Tiles in row 3 and 4 of divertor plate are instrumented with Rogowski sensors
- Bay I and K tiles are in line with “hot” zone for RF edge deposition

Divertor tile currents in row 3 show movement of RF hot zone across tiles as magnetic field pitch is increased



- $\Delta I_{tile\ 3k}$ decreases and $\Delta I_{tile\ 3i}$ increases as magnetic field pitch increases and RF spiral hot zone moves toward the center stack

Operation in H-mode with HHFW alone - Effect of ELMs on core heating and energy deposited on the outer divertor plate

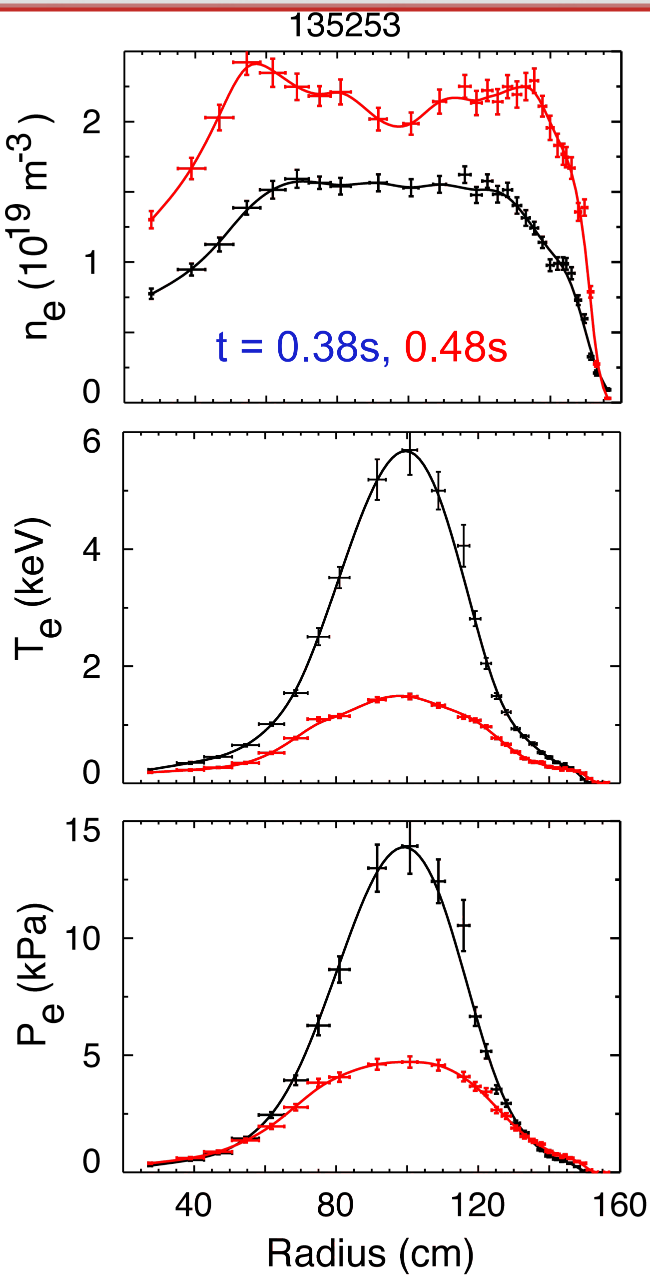
Summary of results to be presented for helium plasmas with an antenna phase of ϕ_A = -90° throughout:

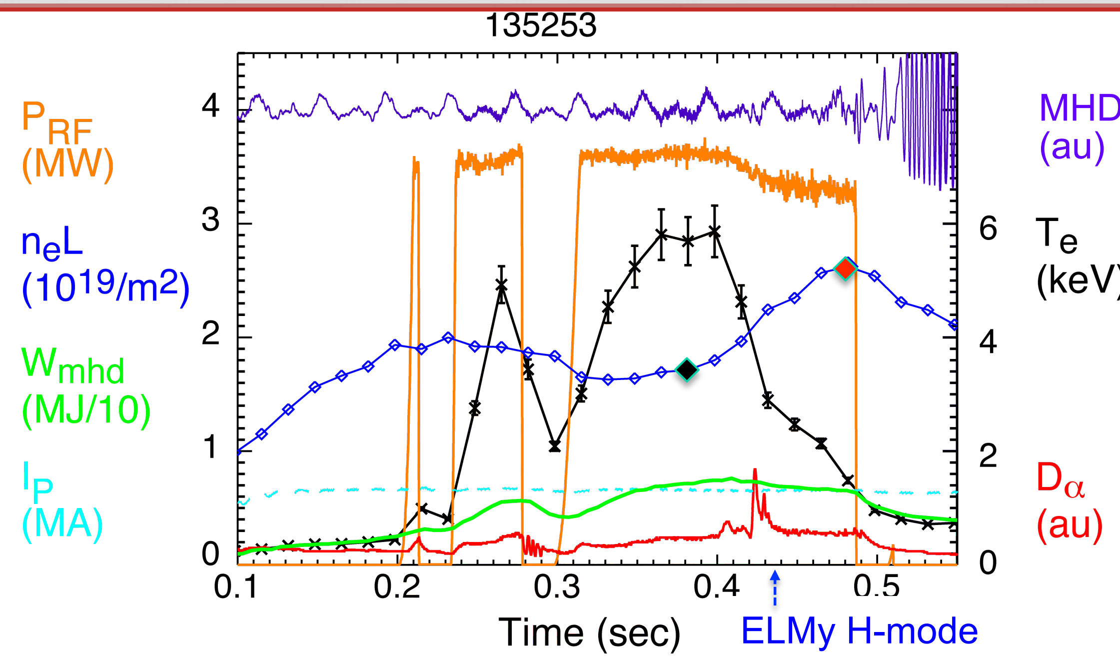
– Heating for ELM-free-like and Elmy H-mode conditions for helium plasmas
  - ELMs cause large increase in energy deposited to the divertor
  - Programming power to delay ELMs maintains core stored energy

– Losses in scrapeoff region to the outer divertor RF heated zone may be enhanced with ELMs
  - Due to increased edge density and edge density gradient during ELMs

– ELM energy deposition is strongly peaked around outer divertor strike radius and probably ELM contributes little direct deposition in the RF hot zone

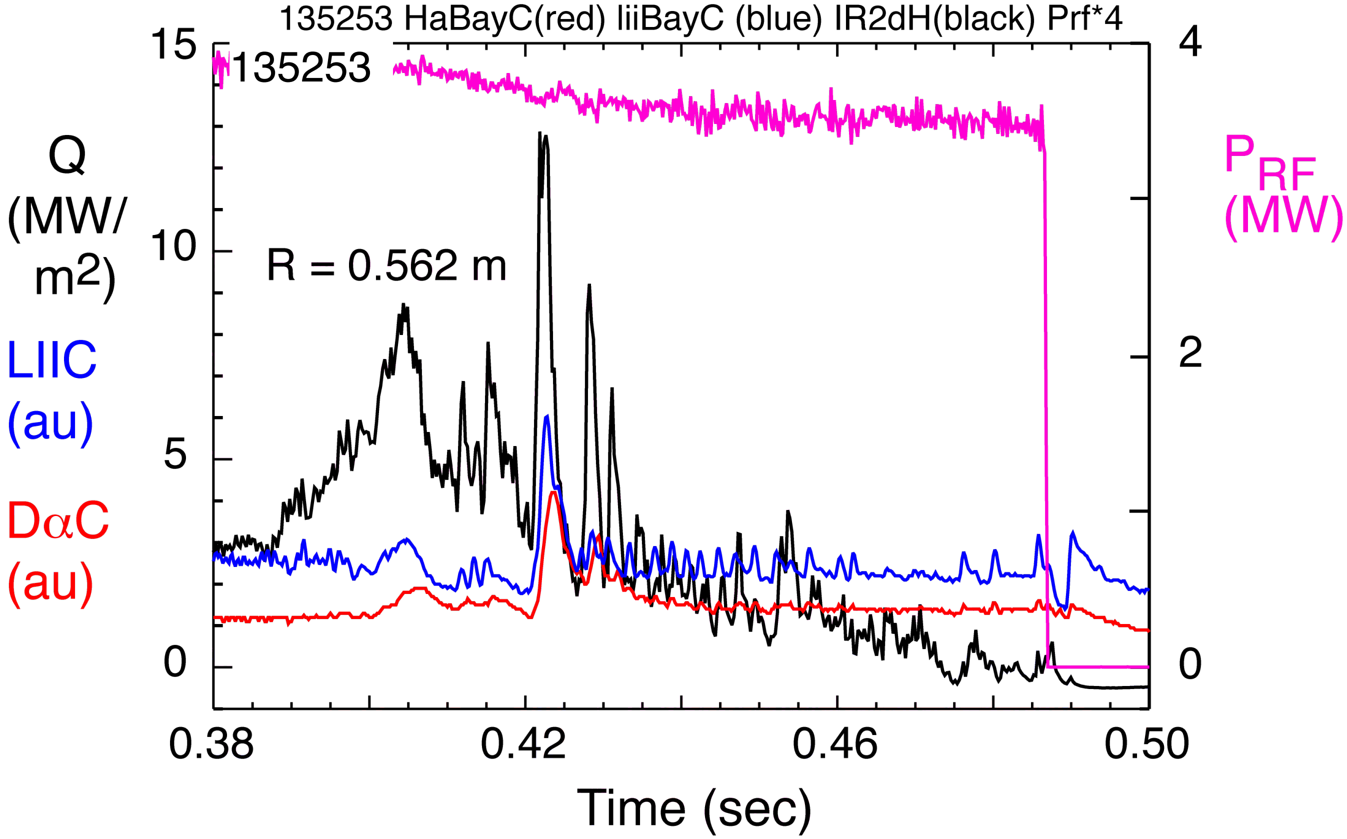
RF-only H-mode Thomson scattering characteristics





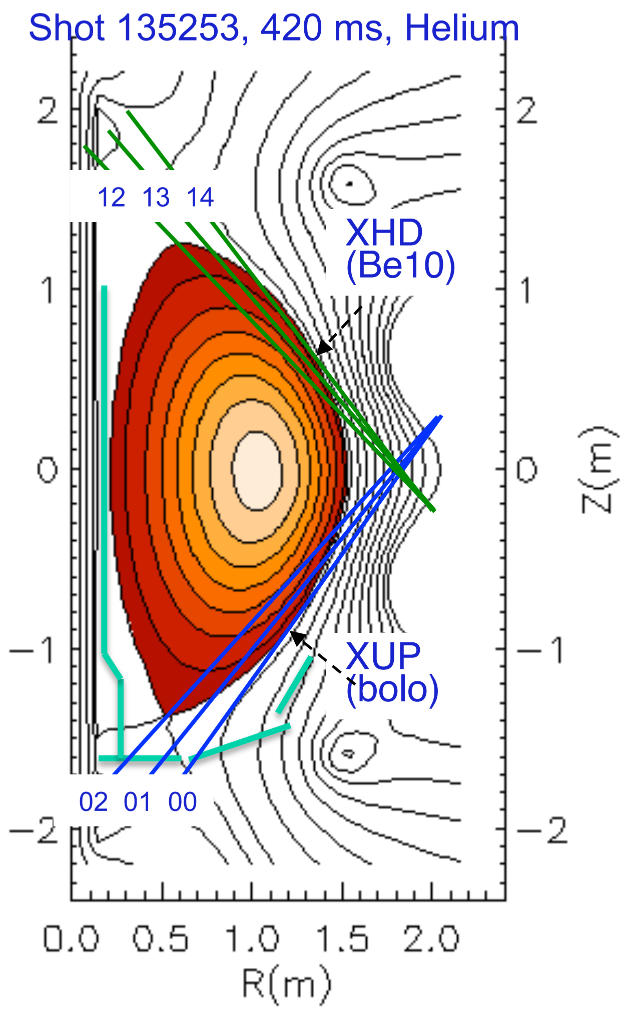
- Transition to ELMy H-mode is accompanied by:
  - Steepening of edge density gradient
  - D_α indication of large ELMs
  - Drop off of $T_e(0)$
  - Increase in reflected RF power

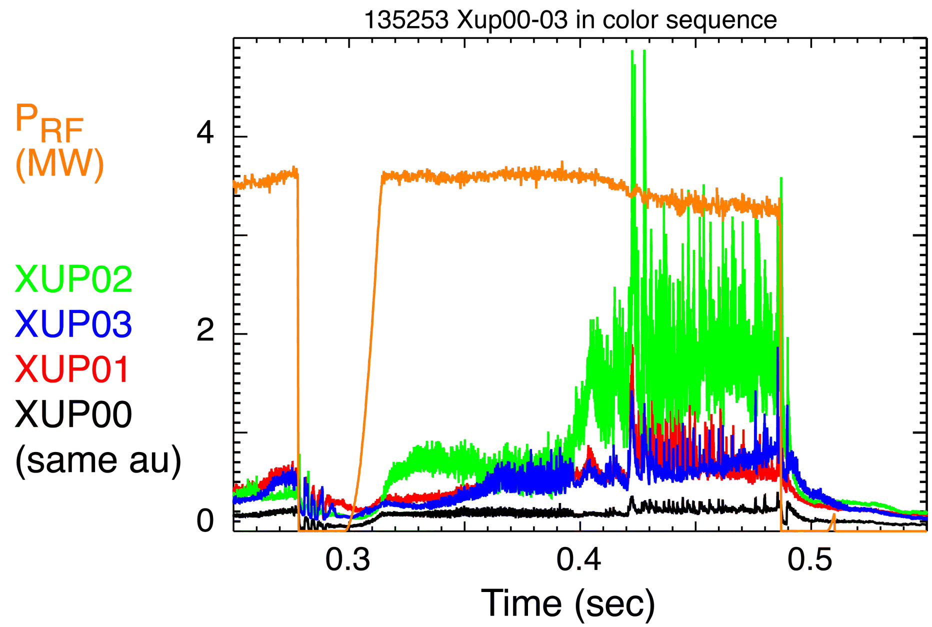
ELMs are measured on fast IR at Bay H, D_α at Bay C, and LiI at Bay C

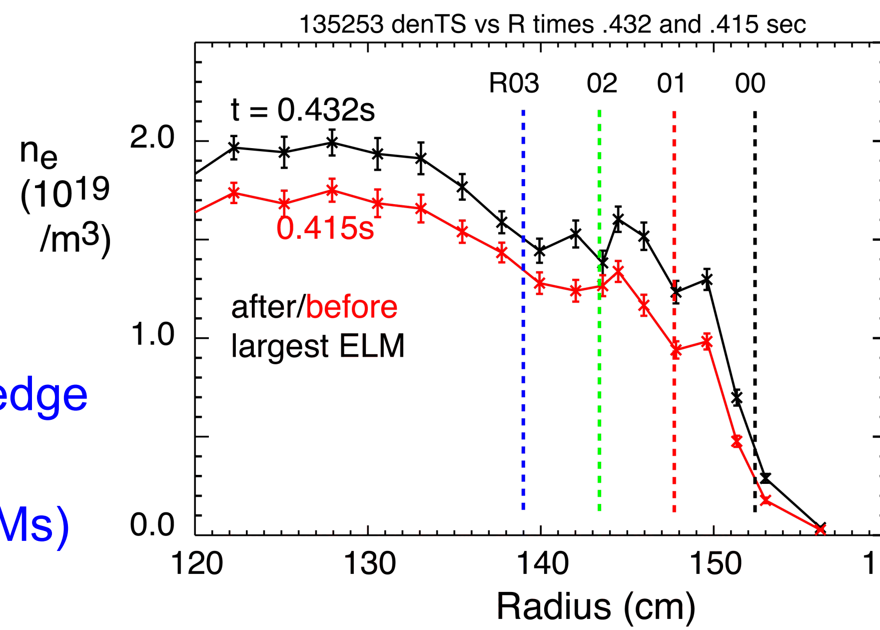


- The Bay H fast IR heat deposition measurement, Q, clearly shows the ELM heat deposition on the lower divertor plate at R = 0.562 m (divertor strike radius)
- Small effect of ELM is evident on the net RF power
- ELMs are located away from the antenna

ELM effect on soft X-ray (bolo) signals peaks inside the last closed flux surface

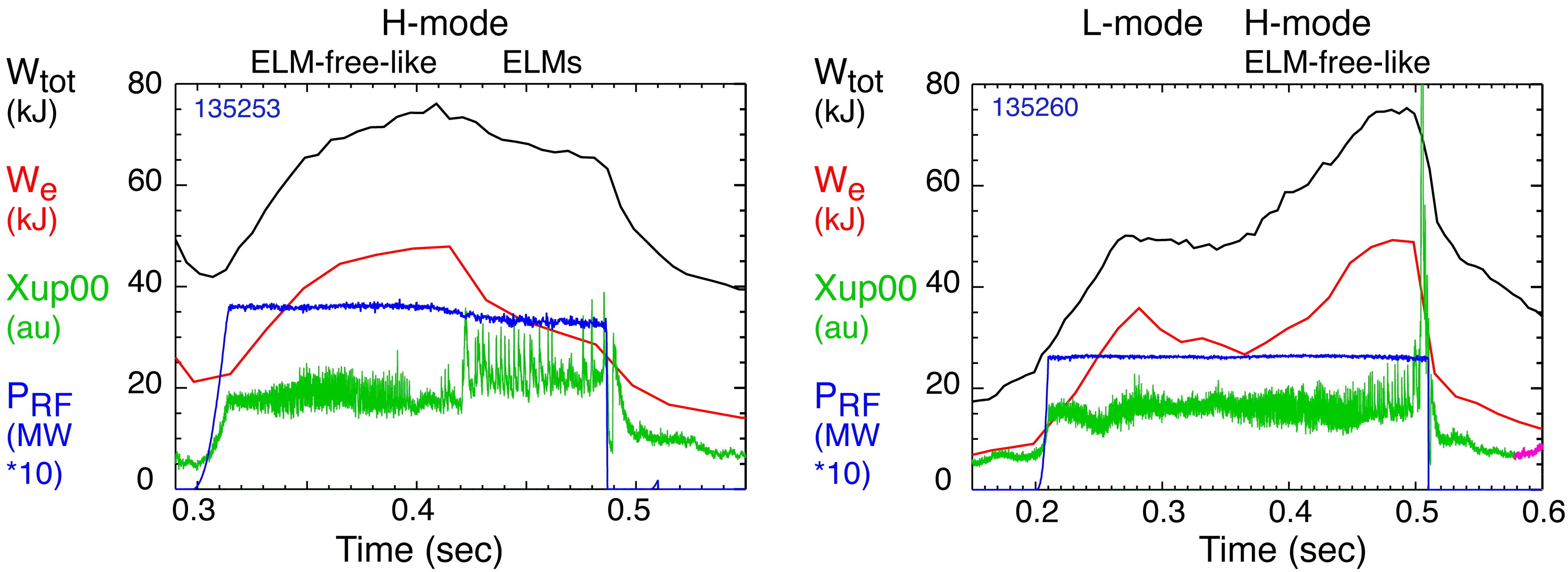






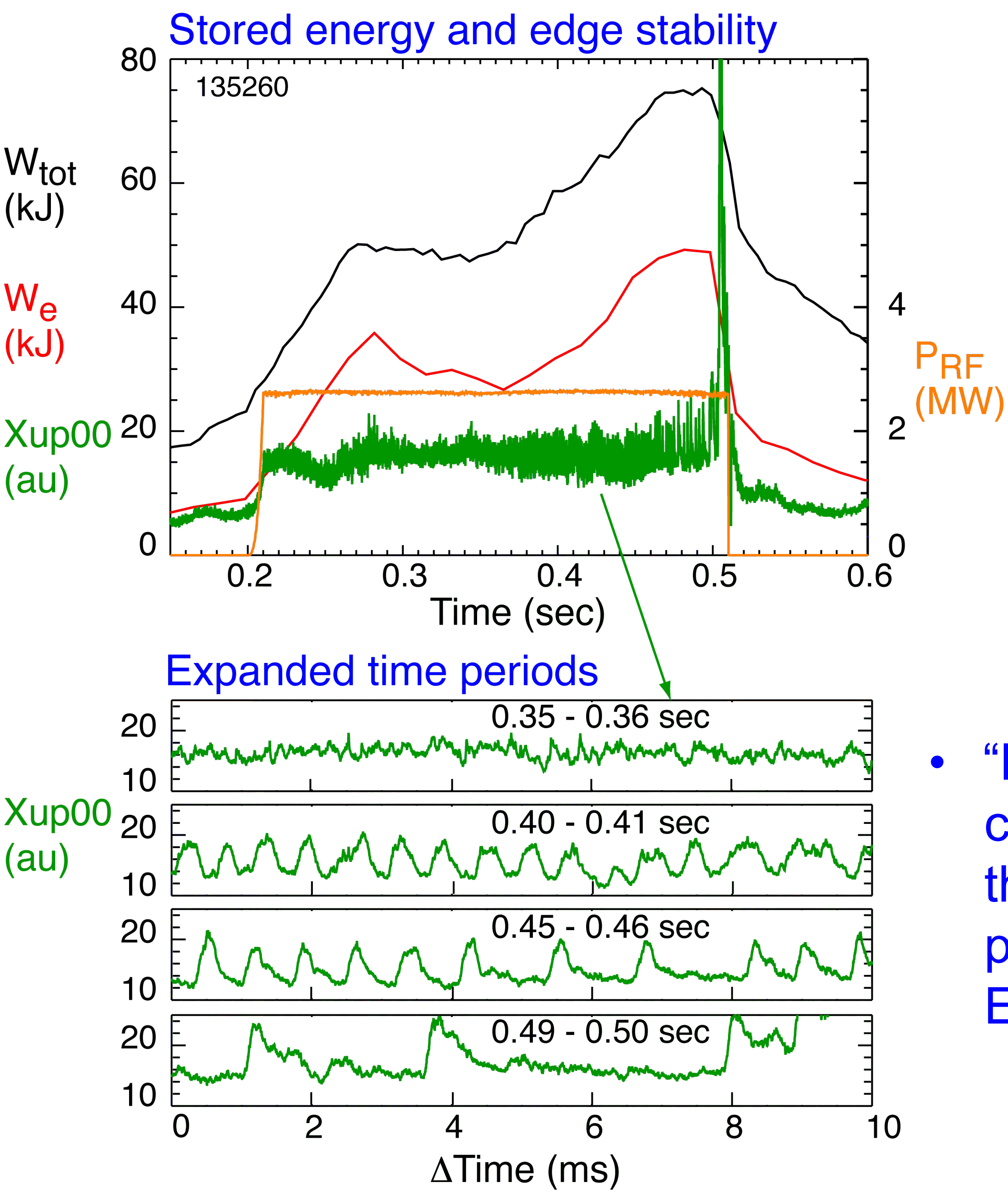
- Xup (bolo) peaks strongly on third cord into edge of plasma - at top of pedestal or at X-point
- ELM-free-like (oscillations followed small ELMs) H-mode is evident prior to 0.39 sec

ELMs reduce heating efficiency for the RF H-mode as for the NB H-mode case



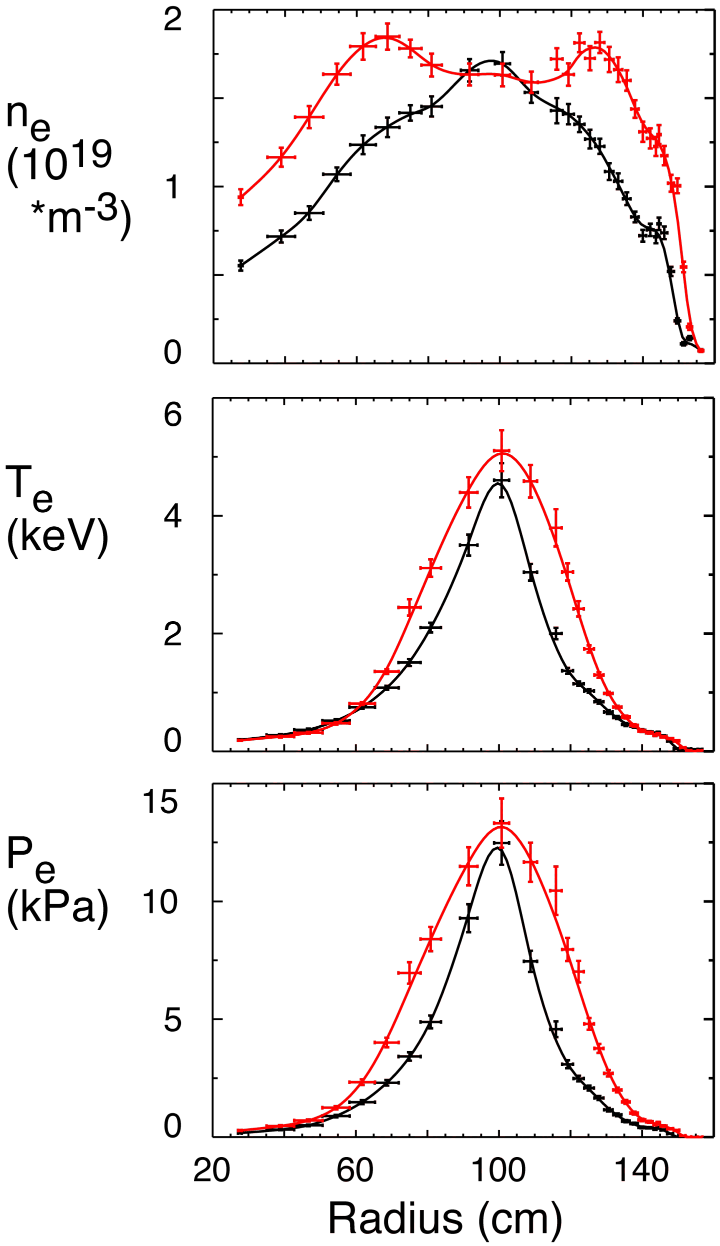
- At P_{RF} = 3.7 MW ELM-free-like transition to ELMy H-mode results in greatly reduced stored energies W_{tot} and W_e
- At P_{RF} = 2.7 MW L-mode slowly transitions to ELM-free-like H-mode and stored energies increase accordingly
- Large ELM at end of the 2.7 MW RF pulse strongly reduces the stored energies

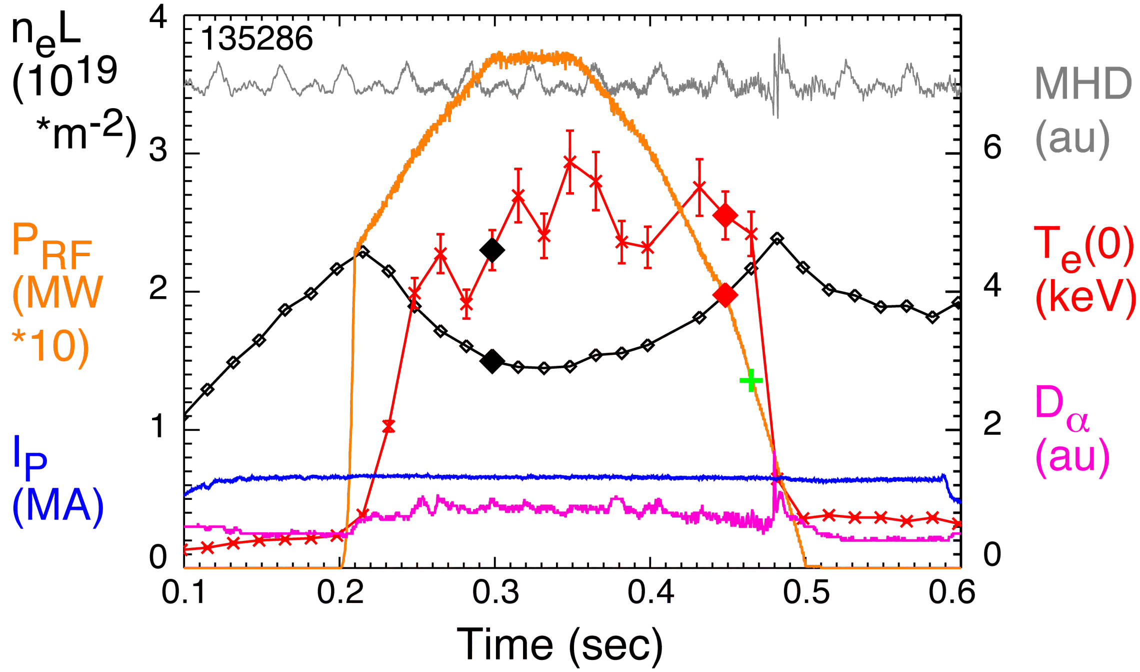
Stored energy increase period is accompanied by edge oscillations and small ELMs



- "ELM-free-like" period is characterized by edge oscillations that peak on top of density pedestal and are followed by small ELMs

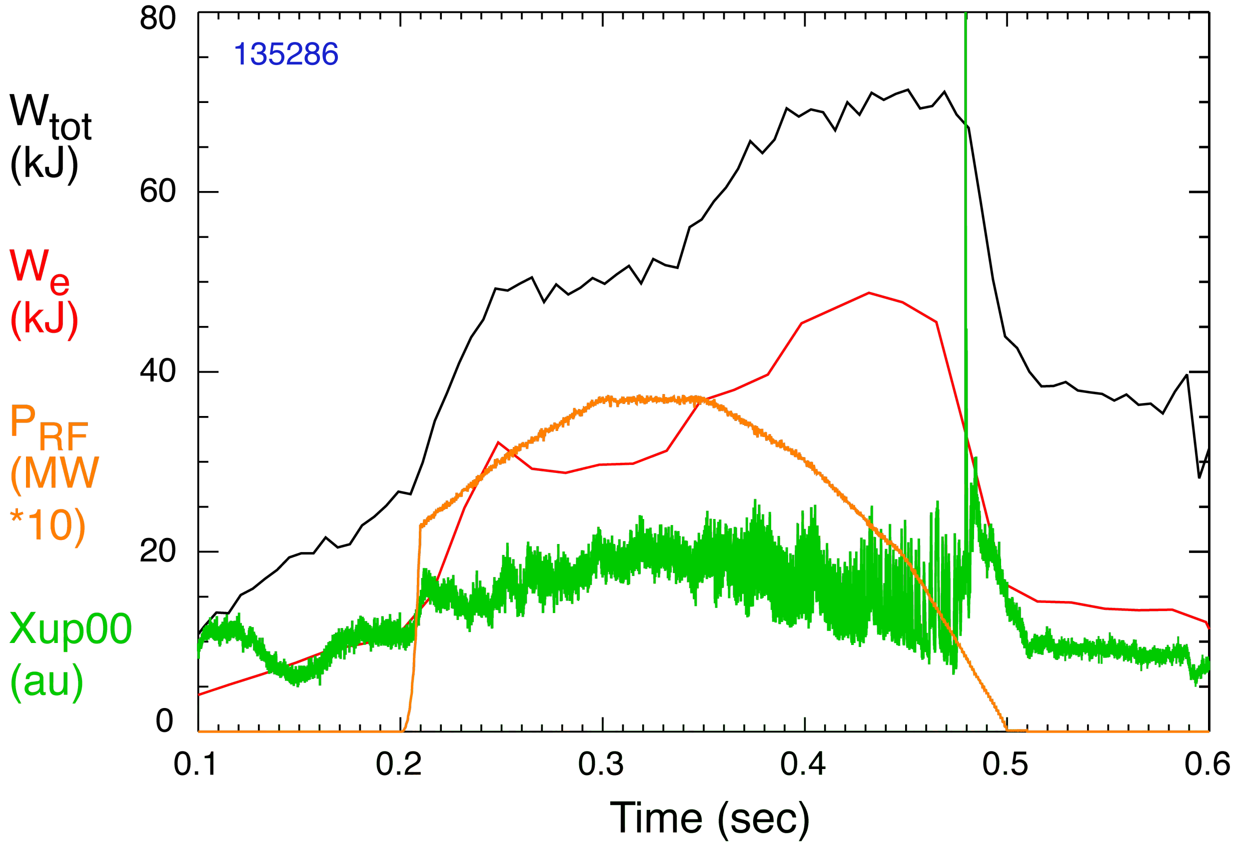
Slow fall of P_{RF} results in sustainment of high $T_e(0)$ and core electron heating even down to P_{RF} < 1.4 MW





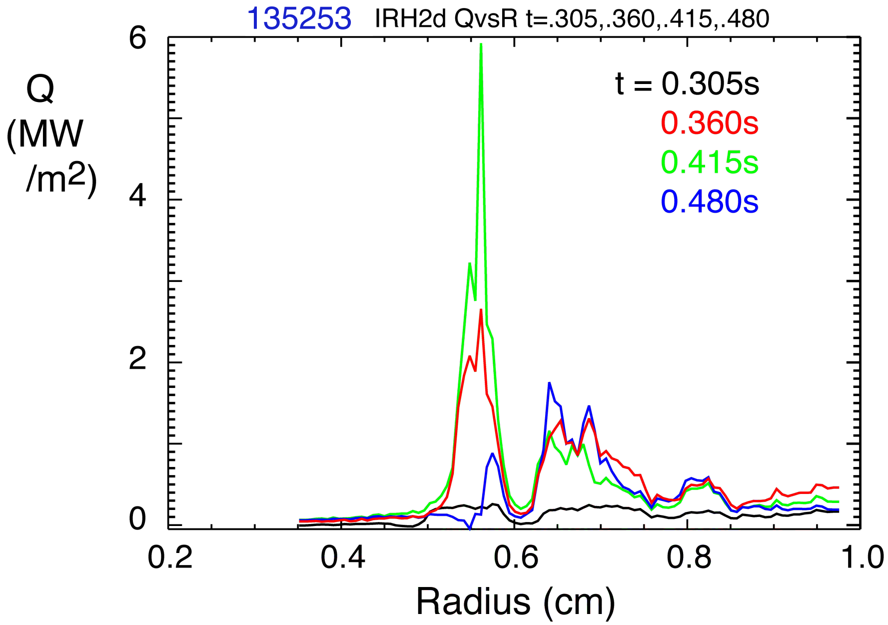
- Slow transition to H-mode from L-mode as power is ramped to 3.7MW
- During slow ramp down of P_{RF}, the core temperature is maintained and broadened in radius even down to 1.36 MW
- Large ELM at even lower power strongly reduces the stored electron energy and marks the transition back to the L-mode

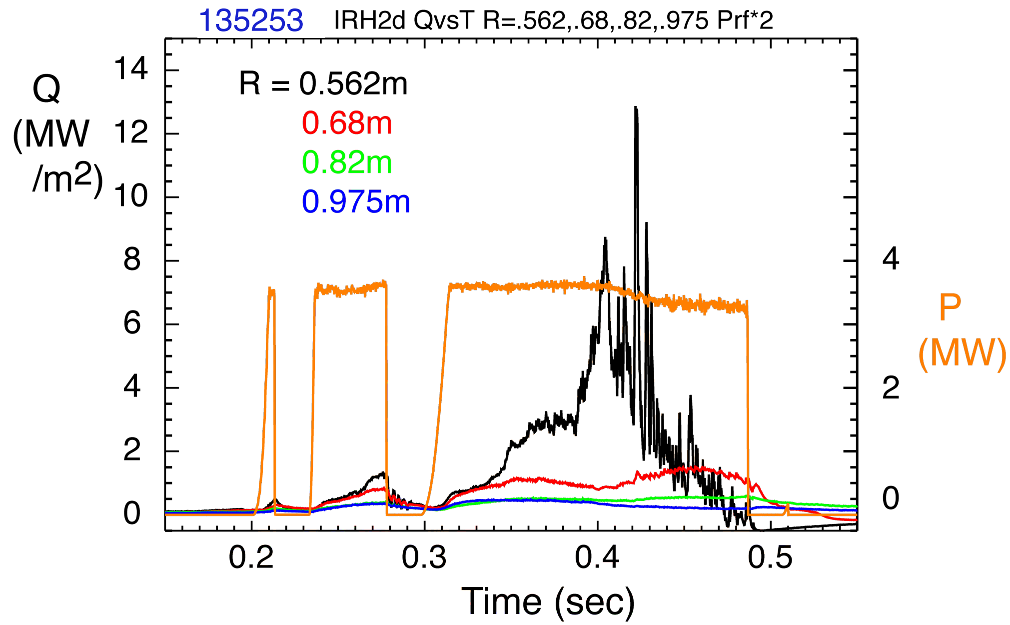
Stored energies increase during the fall of P_{RF} in ELM-free-like H-mode period

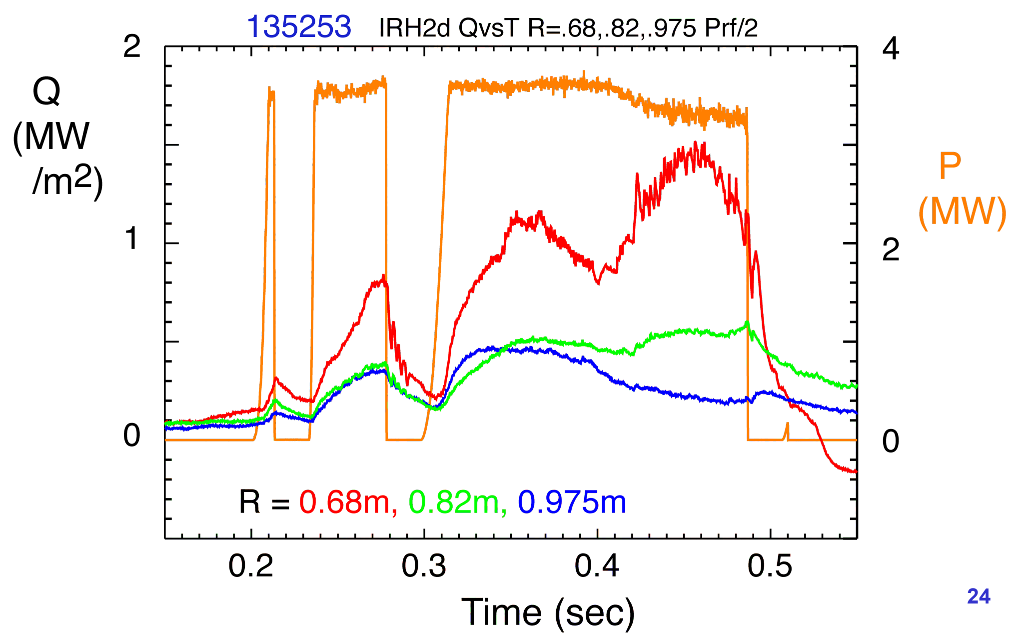


- Both W_{tot} and W_e begin to increase just prior to the end of the 3.7 MW flat top of the RF power waveform
- Both stored energies attain values during the RF power ramp down comparable to the previous levels shown for 3.7 MW and 2.7 MW flat RF power pulses
- Evidently in ELM-free-like H-mode operation little power is needed to sustain the stored energies (a strong change in radial transport is indicated)

Fast IR at Bay H clearly shows time response of heating on bottom divertor plate

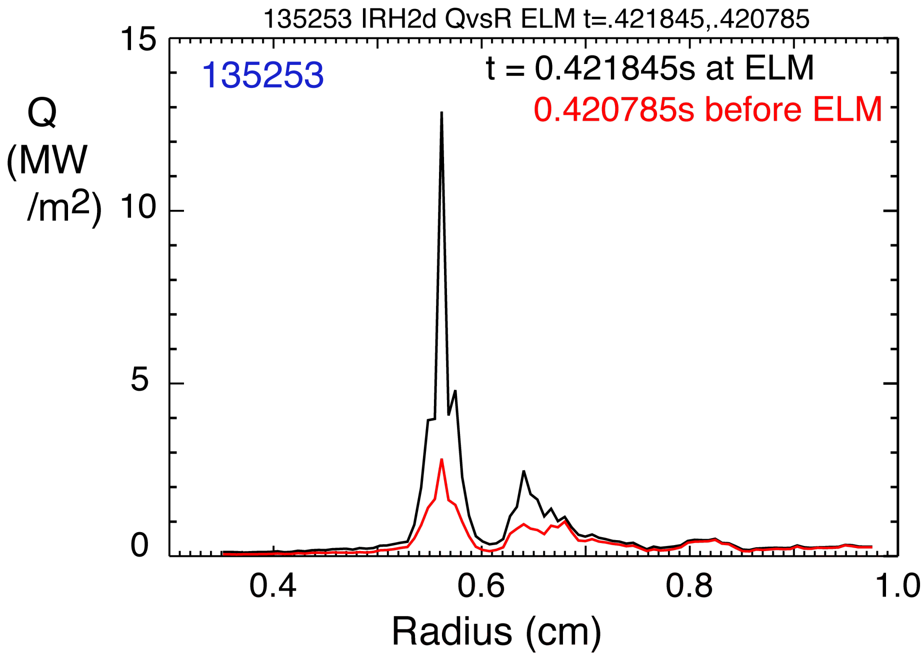


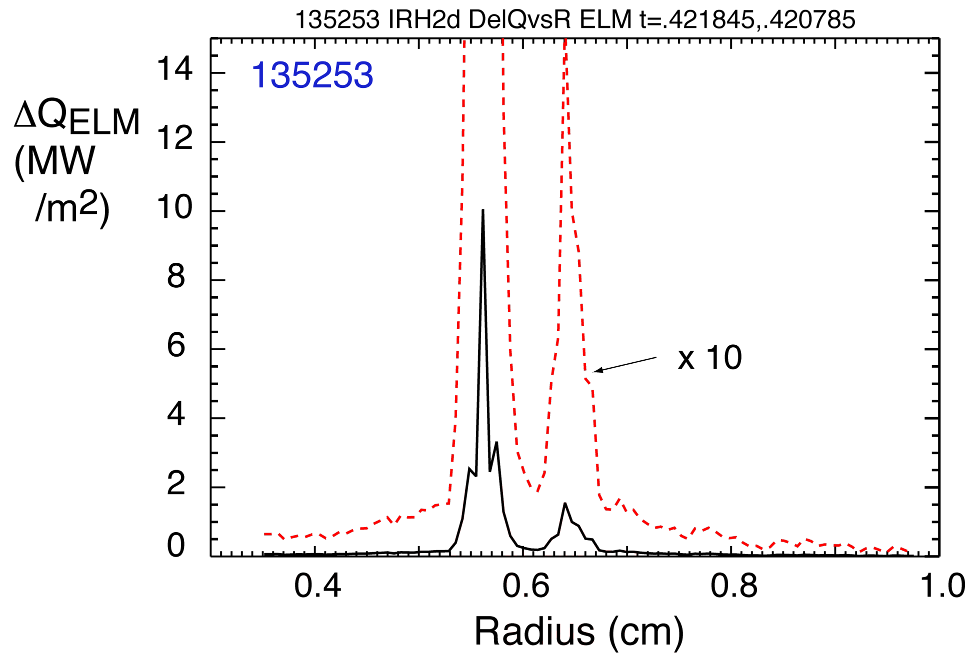




- Heating at the strike radius increases strongly with transition to ELMy H-mode
- Transition in RF heating at larger R is evident for t > ~ 0.4s

RF produced ELM deposits most of its energy in the vicinity of the outer divertor strike radius

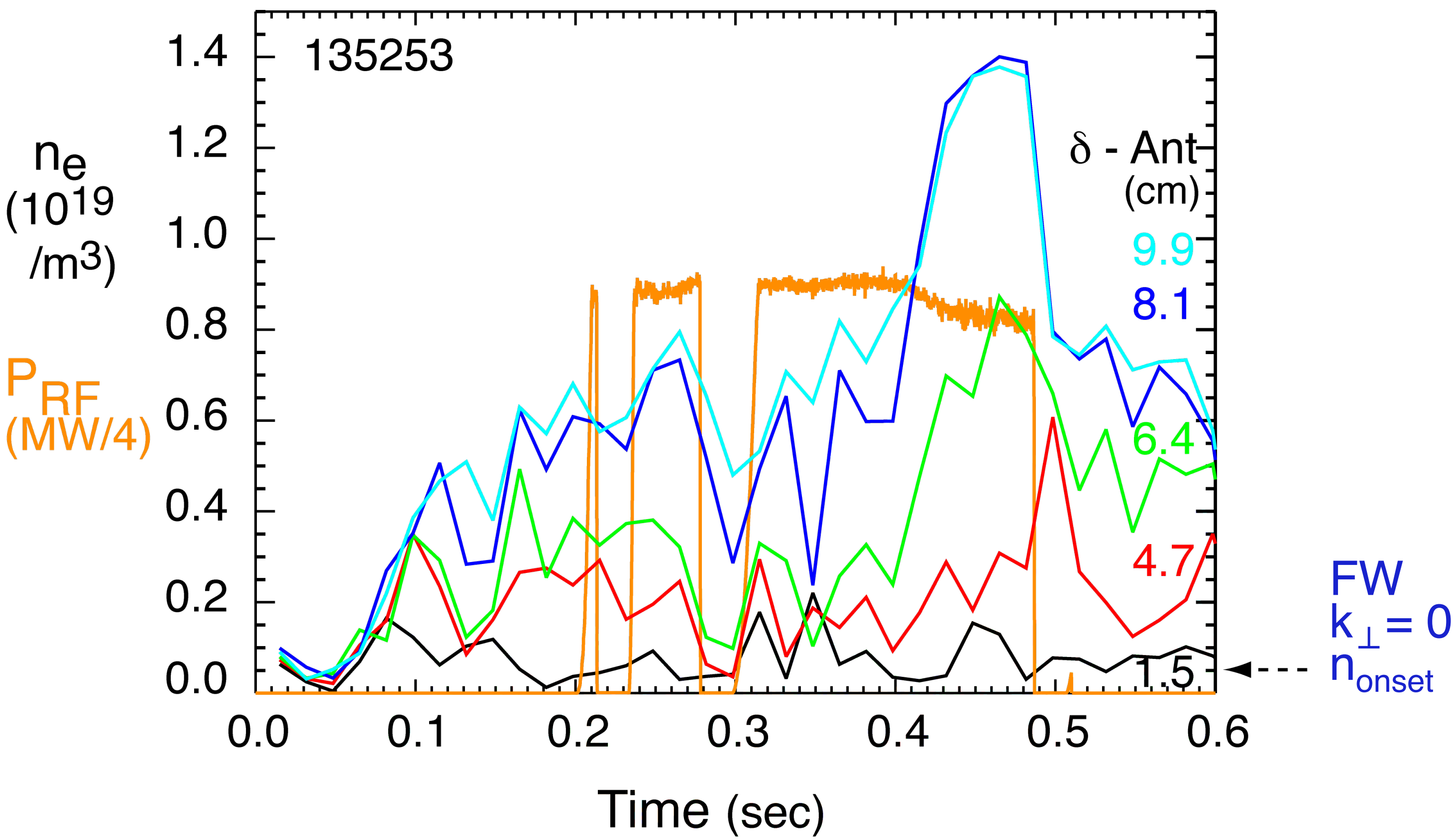




- Very little ELM heat is deposited away from the strike point in absence of energetic beam ions
- ELM deposition has very small effect on RF coupling

What causes core electron heating to decrease strongly during the Elmy H-mode?

- Strong expulsion of energy by ELMs is clear from previous data
- Edge RF power deposition may increase after transition to H-mode as well
  - Edge density increase due to ELMs?
  - Steepening of density gradient may enhance edge loss to wall/divertor tiles and antenna face



Summary

- ELMs enhance edge RF power losses in scrapeoff region to the outer divertor RF heated zone in the NBI + RF case and probably for the RF-only case
  - ➢ Apparently due to increased edge density and possibly increased edge density gradient effects on edge RF power deposition during ELMs
- ELM energy deposition is peaked around the outer divertor strike radius and may contribute little to the RF hot zone
  - ➢ Elms cause a large increase in energy deposited to the divertor peaked around the outer divertor strike radius
  - ➢ ELM-induced energy deposition is much more peaked near the outer divertor strike radius in RF-only case, perhaps due to absence of fast-ions from NBI
- Programming RF power reduction to delay ELMs maintained core stored energy in RF-only case
  - ➢ Elevated total and electron stored energies obtained for ELM-free-like conditions at 3.7 MW and maintained for P_{RF} ramps down to 1.36 MW
  - ➢ Transport properties in the ELM-free-like RF H-mode regime appear to support significant stored energies with significantly reduced RF core heating power