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HHFW Heating Properties for H-mode Plasmas in NSTX

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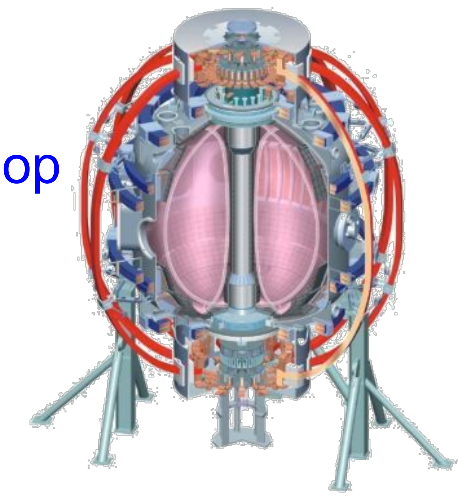

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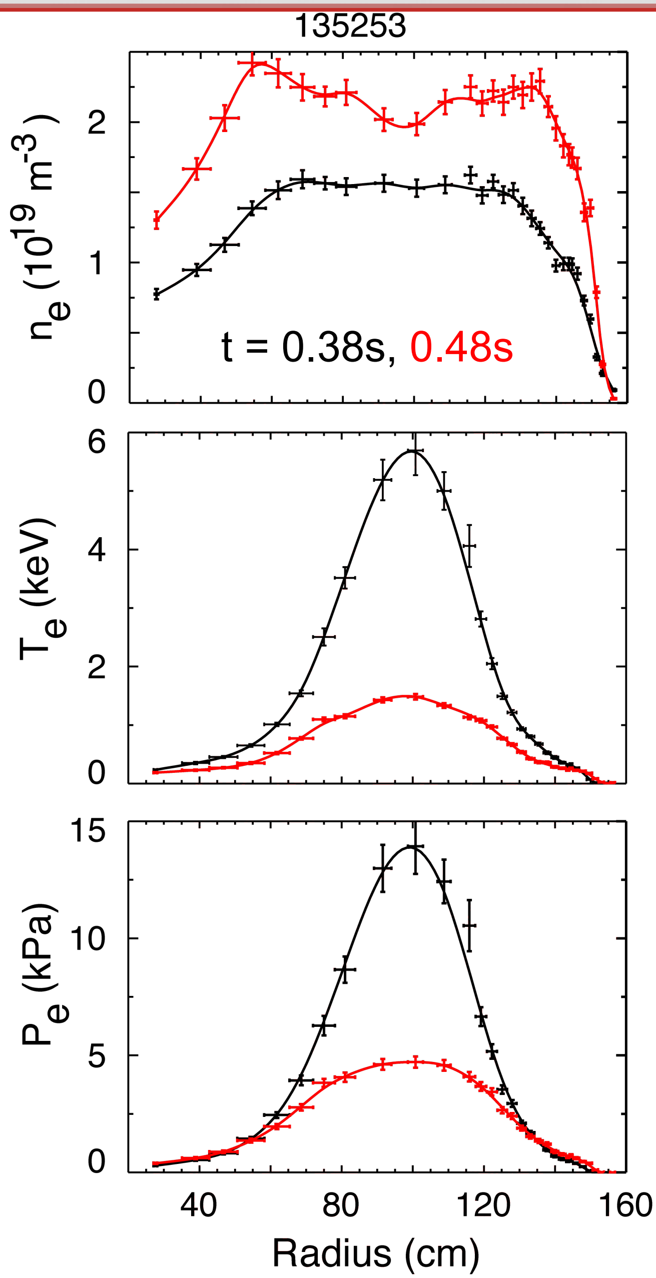
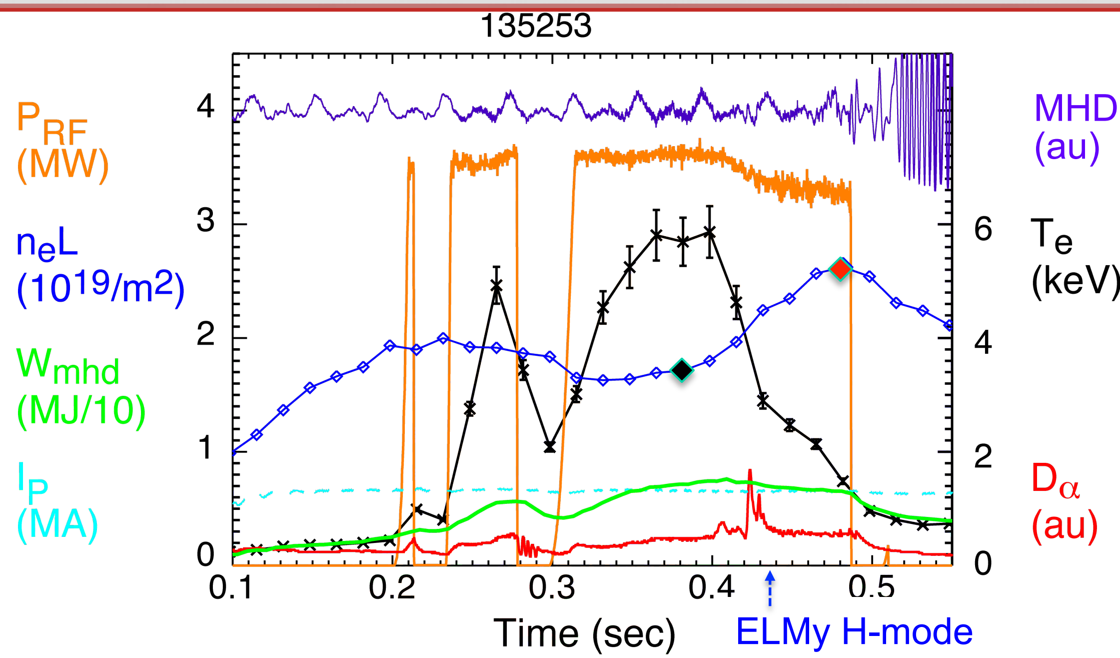
HHFW heating properties for H-mode plasmas in NSTX

Outline:

- 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
    - Stored energy apparently saturated - I.e., transport increases with power
    - High-k scattering measurements indicate increase in ETG power spectrum with RF power
  - Very narrow ELM heat deposition around strike radius with fast IR camera
- H-mode with NBI and HHFW
  - Broader ELM heat deposition around strike radius with fast IR camera
  - Divertor tile currents found to track position of RF “hot” zone associated with edge power loss

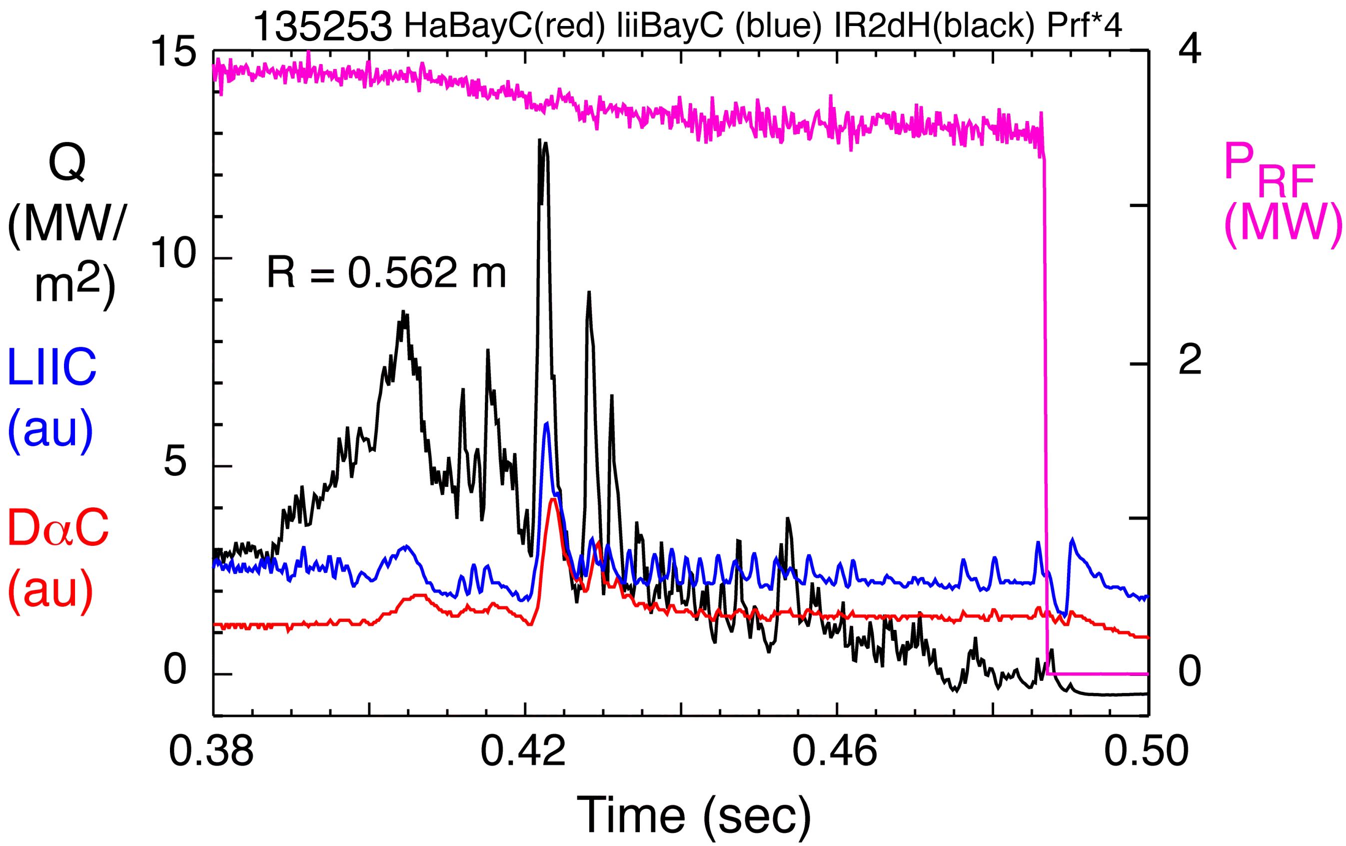
RF-only H-mode Thomson scattering characteristics





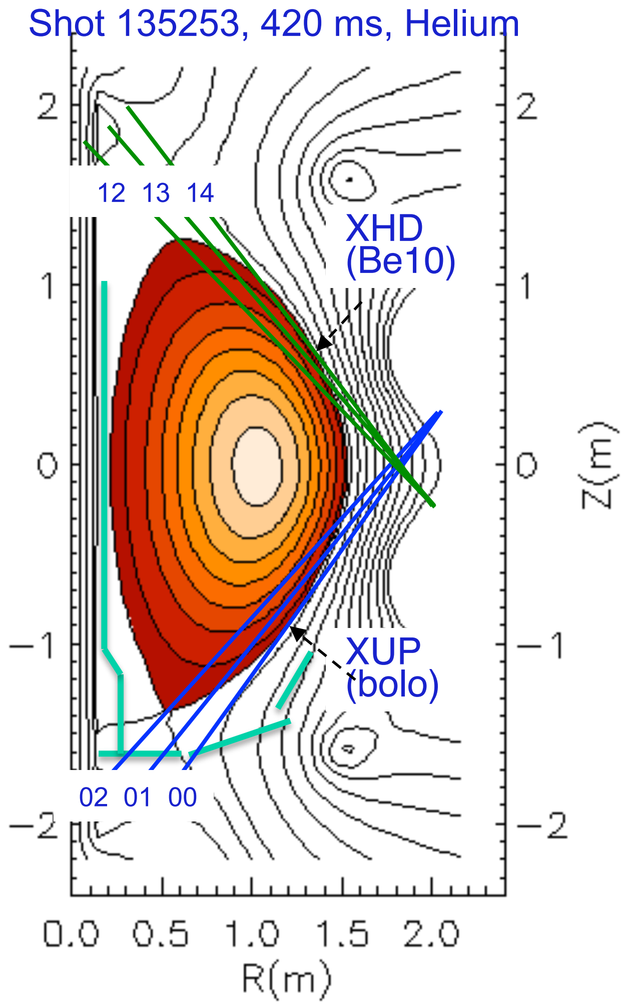
- Transition to ELMy H-mode is accompanied by:
  - Steepening of edge density gradient
  - D_α indication of large ELMs
  - Drop off of $T_e(0)$
  - Increase in reflected RF power
  - Strong decrease in electron stored energy

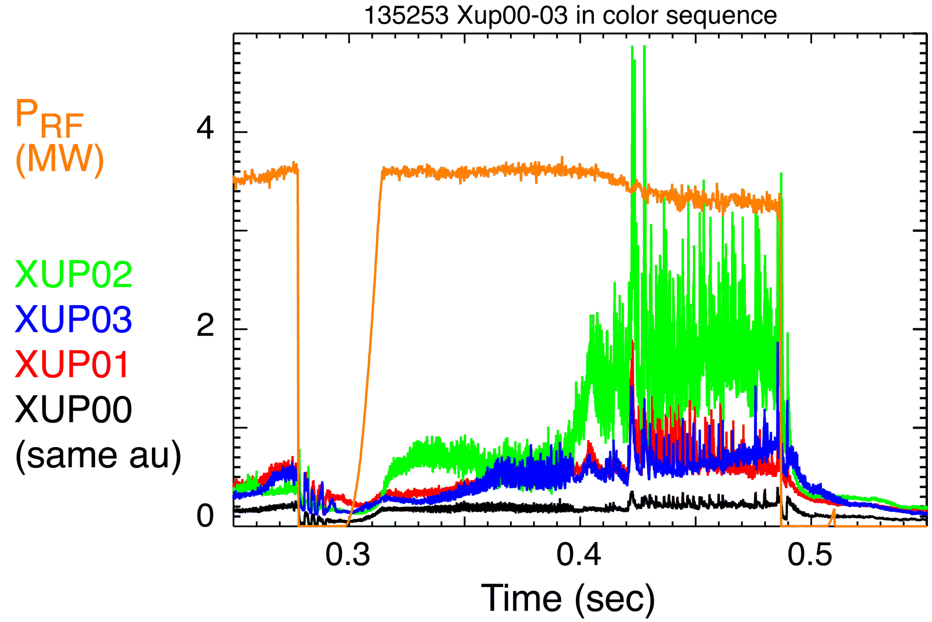
ELM heat deposition at the outer strike radius is very large as measured with the fast IR camera at Bay H

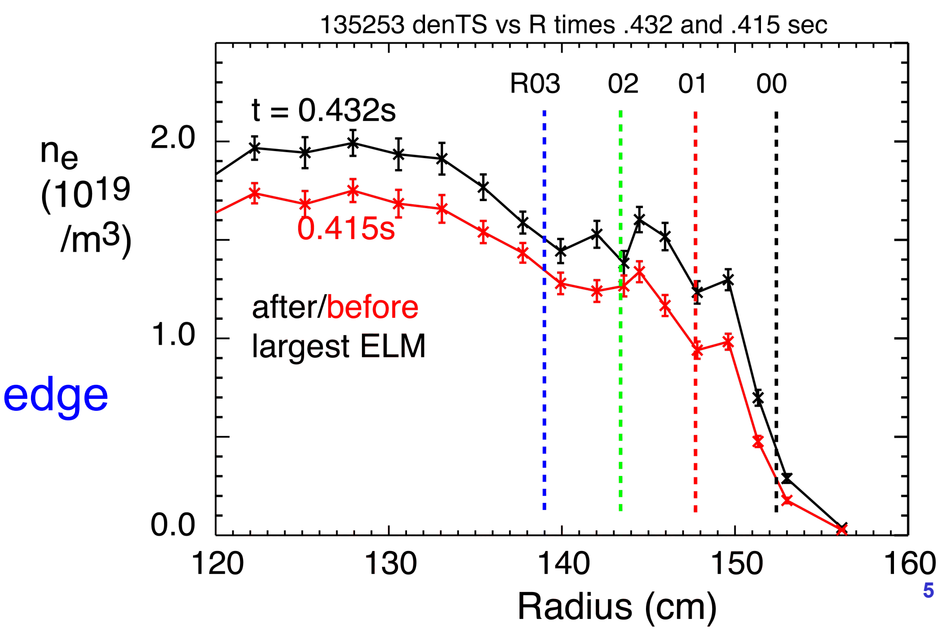


- The Bay H fast IR heat deposition measurement, Q, clearly shows the ELM heat deposition on the lower divertor plate at R = 0.562 m (divertor strike radius)
- Small effect of largest ELM is barely evident on the net RF power
  - ELMs are located away from the antenna

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

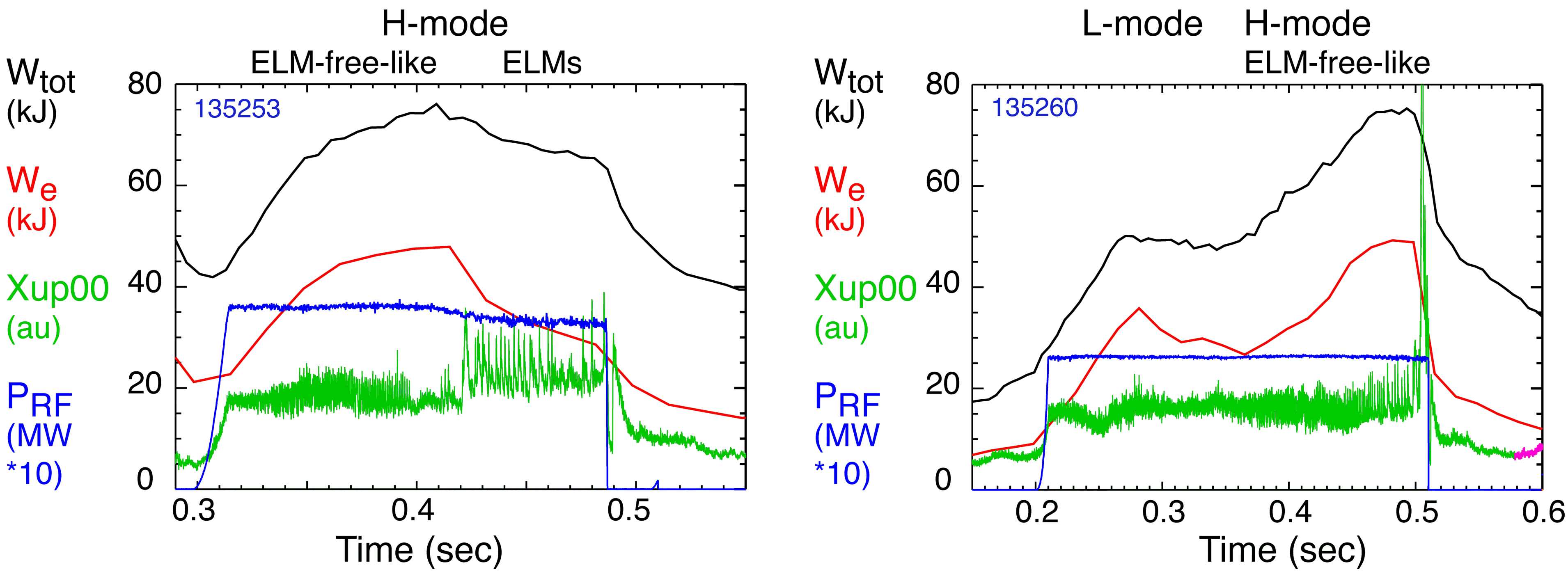






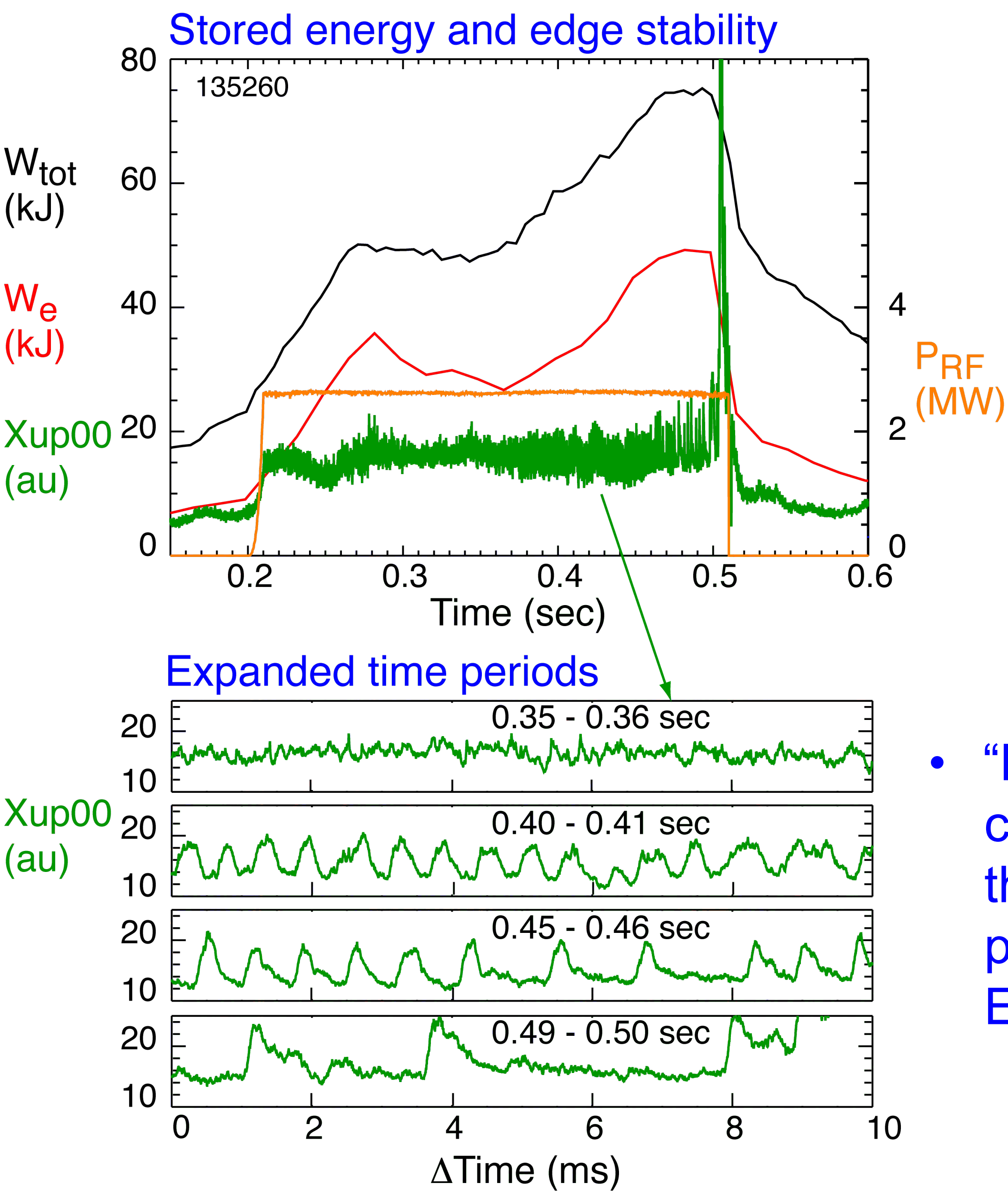
- Xup (bolo) peaks strongly on third cord into edge of plasma - at top of pedestal (or at X-point)
- ELM-free-like (oscillations followed by small ELMs) H-mode is evident prior to 0.39 sec

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



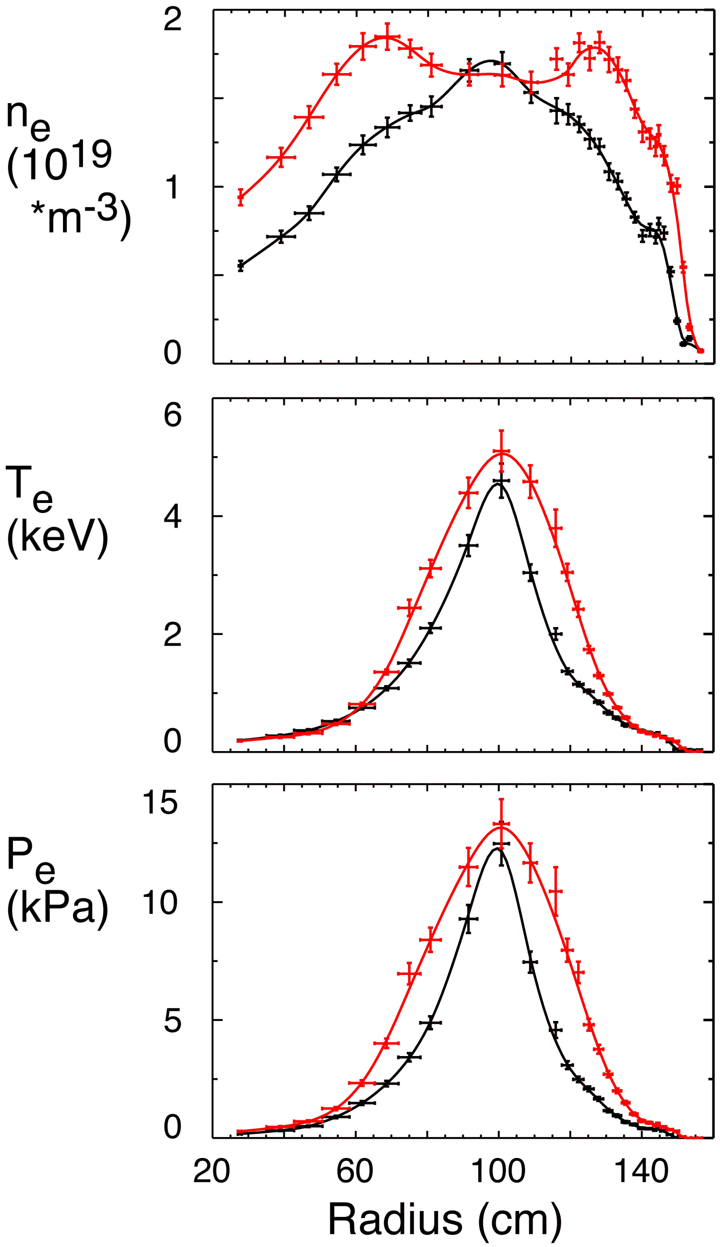
- At P_{RF} = 3.7 MW ELM-free-like transition to ELMy H-mode results in greatly reduced stored energies W_{tot} and W_e
- At P_{RF} = 2.7 MW L-mode slowly transitions to ELM-free-like H-mode and stored energies increase accordingly
- Large ELM at end of the 2.7 MW RF pulse strongly reduces the stored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

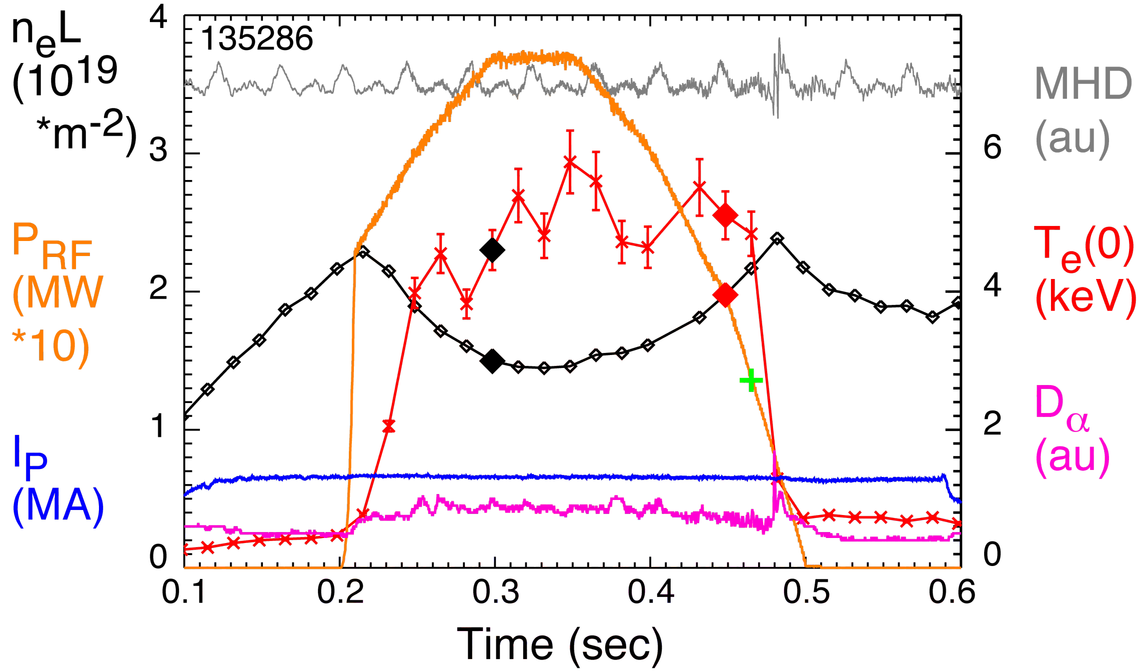
Stored energy increase period is accompanied by edge oscillations and small ELMs



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

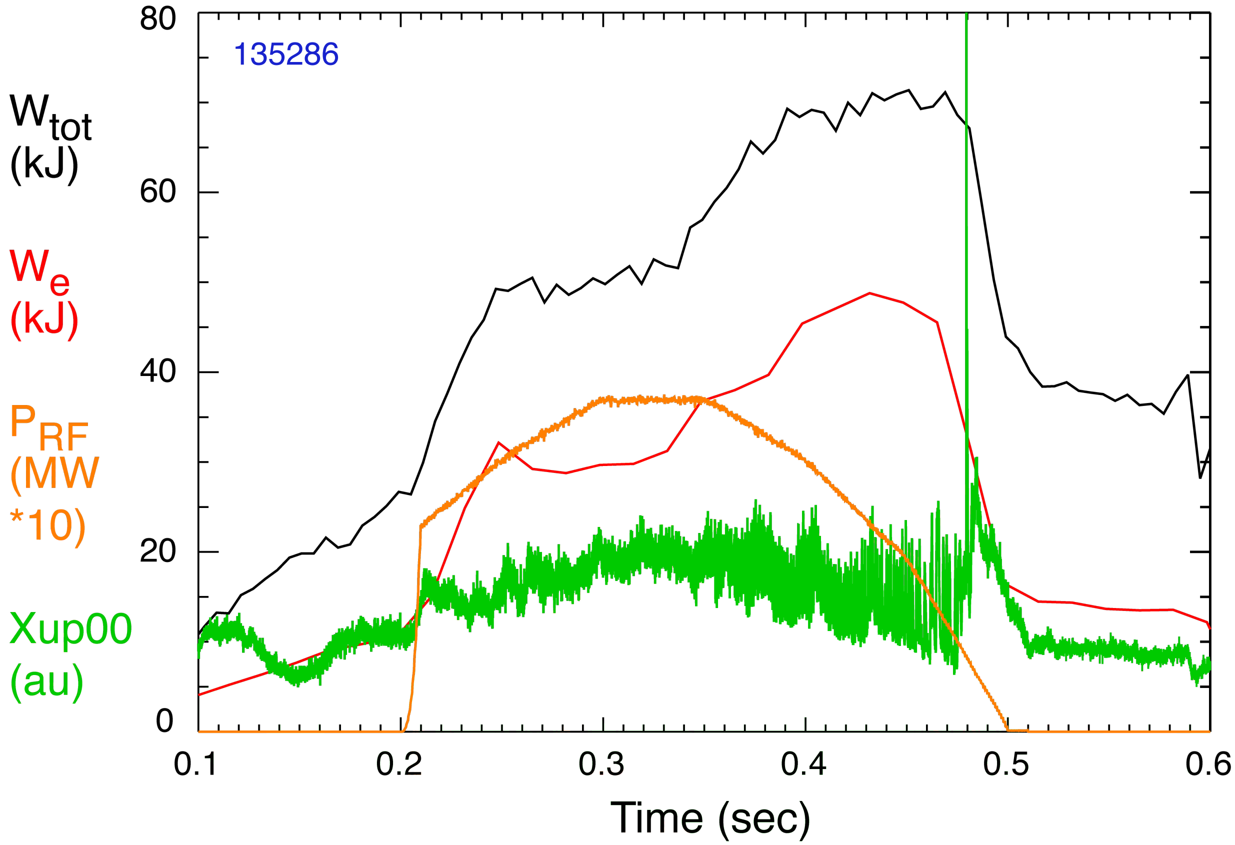
Slow fall of P_{RF} results in sustainment of high $T_e(0)$ and core electron heating even down to P_{RF} < 1.4 MW





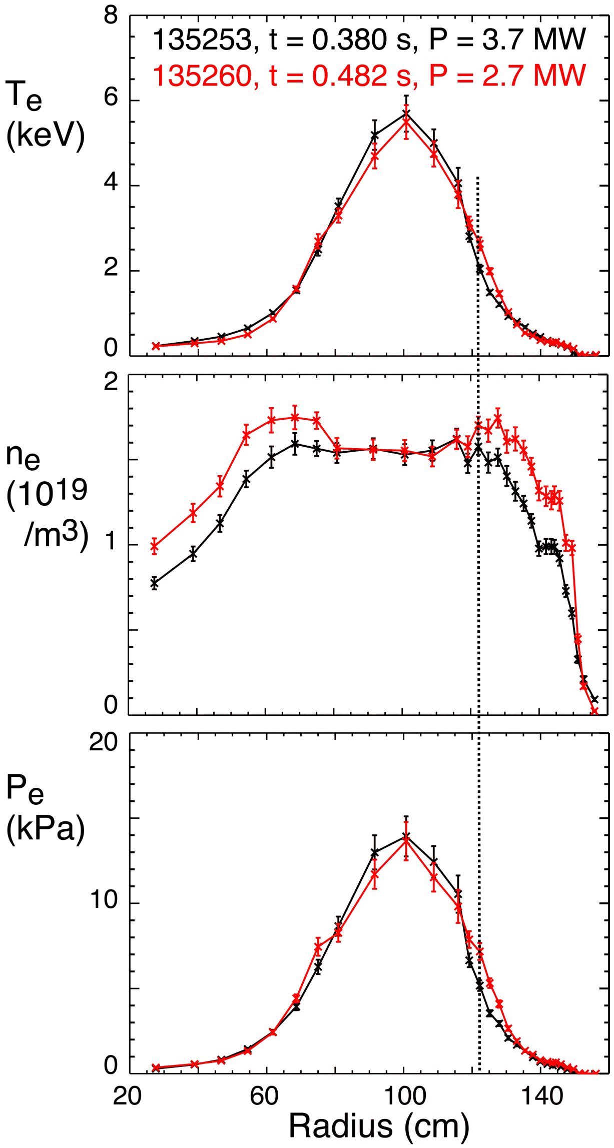
- Slow transition to H-mode from L-mode as power is ramped to 3.7MW
- During slow ramp down of P_{RF}, the core temperature is maintained and broadened in radius even down to 1.36 MW
- Large ELM at even lower power strongly reduces the stored electron energy and marks the transition back to the L-mode

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



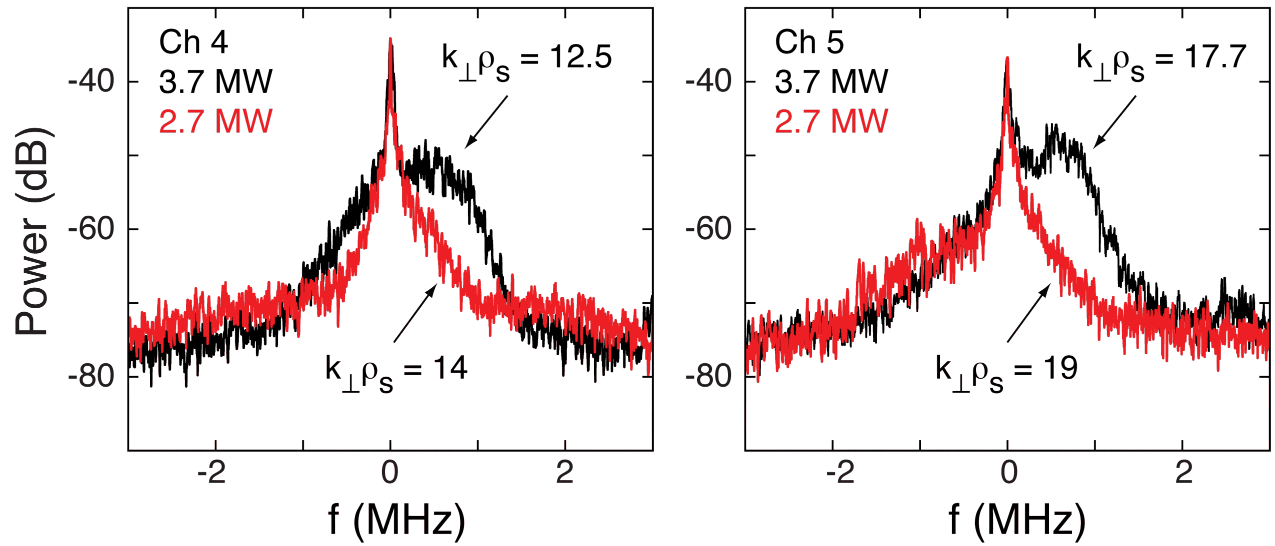
- Both W_{tot} and W_e begin to increase just prior to the end of the 3.7 MW flat top of the RF power waveform
- Both stored energies attain values during the RF power ramp down comparable to the previous levels shown for 3.7 MW and 2.7 MW flat RF power pulses
- Evidently in ELM-free-like H-mode operation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

Initial high-k scattering measurements indicate that ETG turbulence increases with RF power



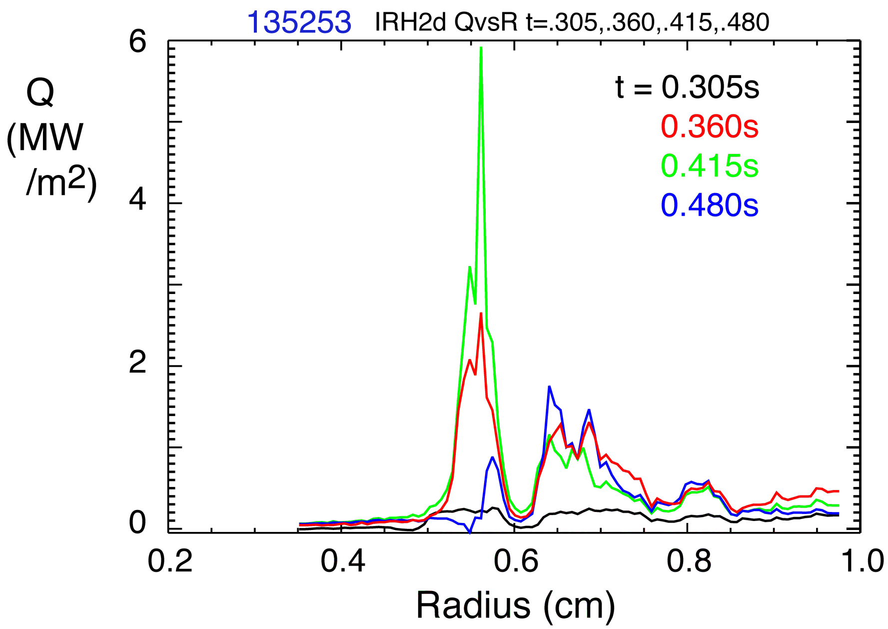
High-k scattering spectra vs RF power

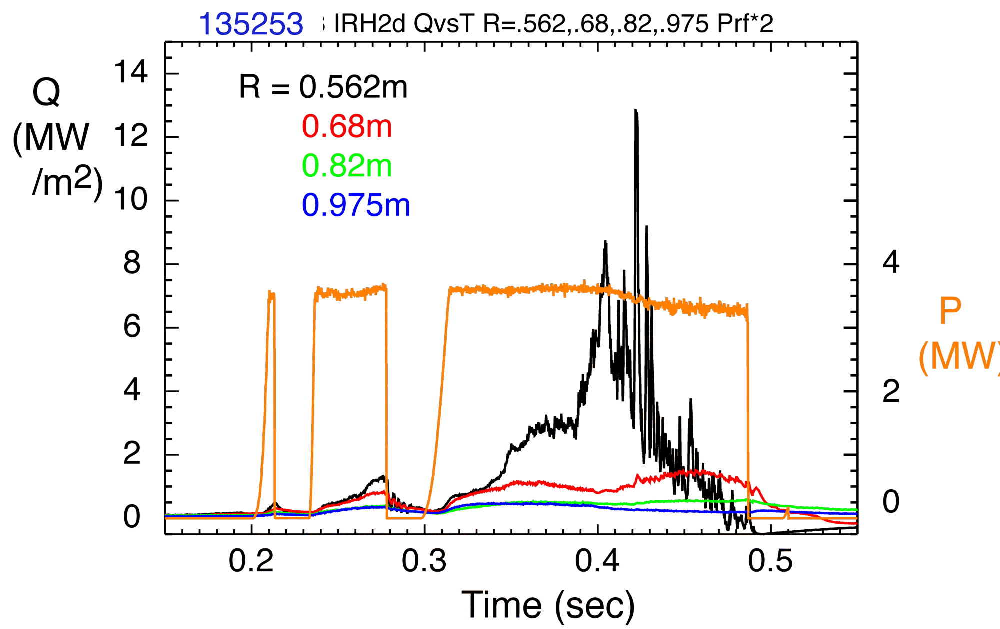
Comparison for 135253, t = 0.38 s and 135260, t = 0.482 s



- Increase in ETG turbulence may cause the observed saturation of stored energy with increasing RF power

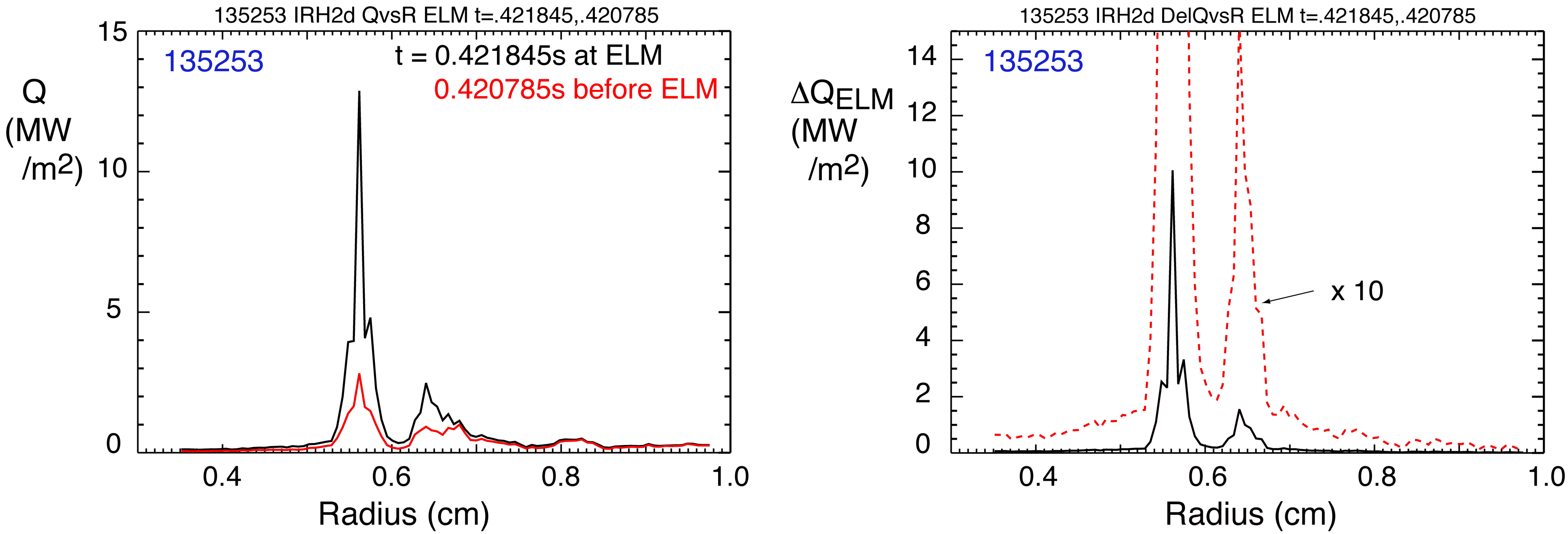
Fast IR at Bay H clearly shows time response of heating on bottom divertor plate





- Heating at the strike radius increases strongly with transition to ELMy H-mode
- Fast IR (Bay H) shows ELM energy deposition on lower divertor plate to be localized near the outer strike radius – 0.562 m

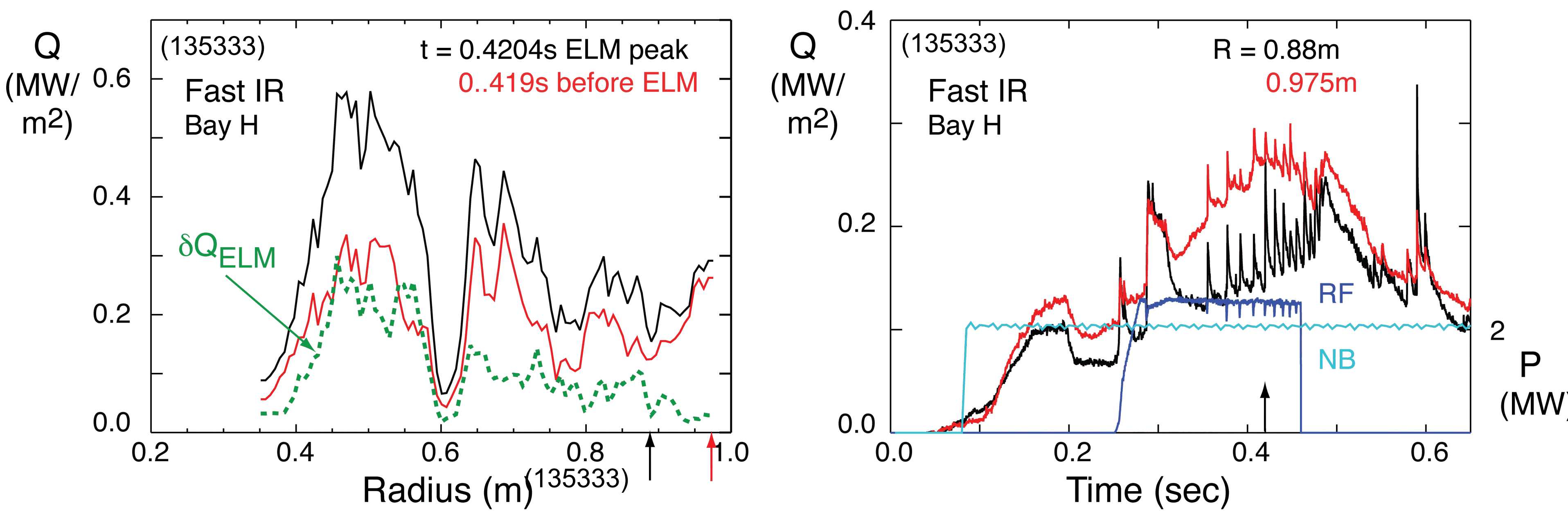
RF produced ELM deposits most of its energy in the vicinity of the outer divertor strike radius



- 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 edge heating "hot" zone (>1.2 m)

ELM power deposition about the strike radius is broader for the NBI + HHFW ELMy H-mode

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

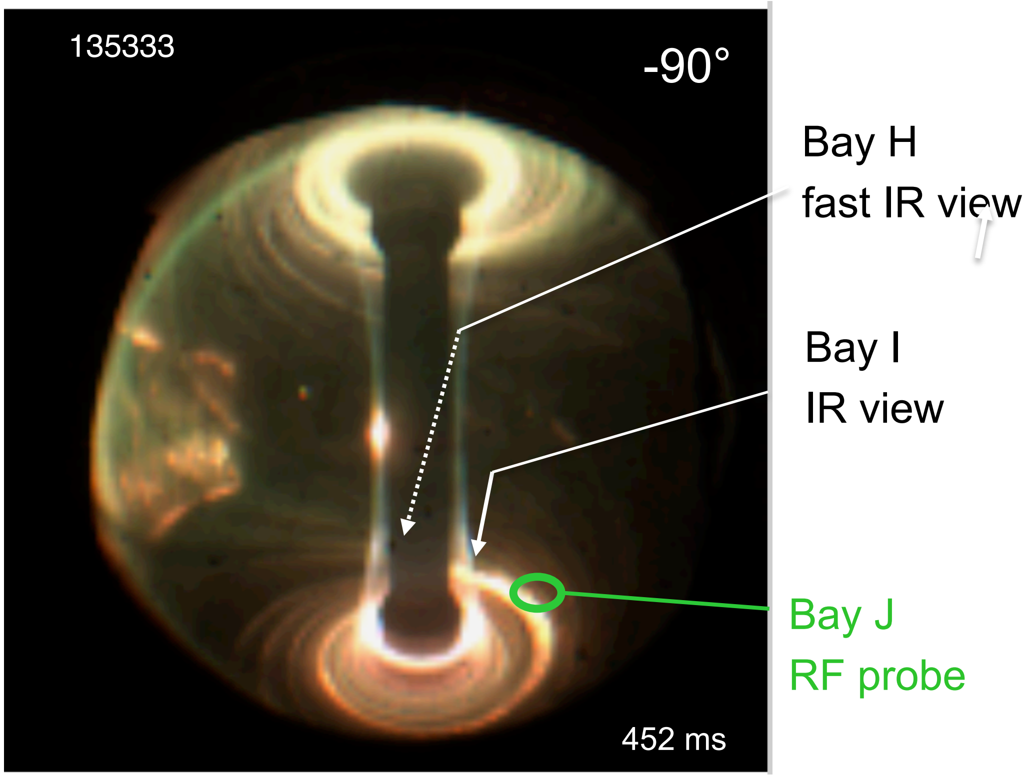


- Fast IR camera shows ELM heat deposition peaked at outer strike radius – falling gradually to a low value towards the RF heated zone (R ~ 1.1 m)
- Experiments have begun to determine the ELM effect on the primary RF edge heating zone at Bay H at higher magnetic field pitch (e.g., 4.5 kG, 1 MA) – effect would appear to be small

Experimental studies have begun to determine the properties of the RF interaction at the “hot” zone

It is important to determine if surface waves are delivering RF power to the divertor vs direct currents being driven in the near field of the antenna

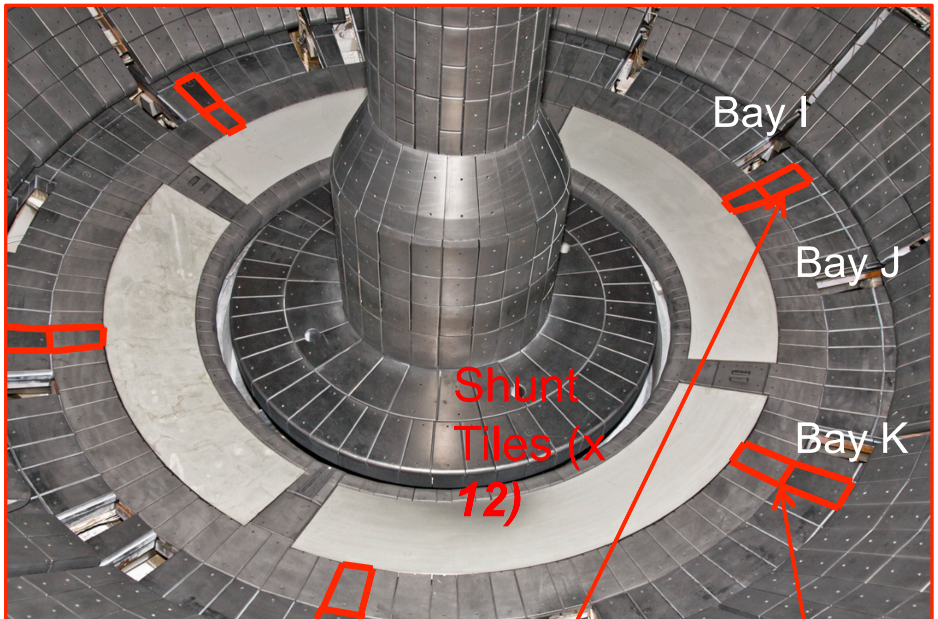
– for benchmarking codes that allow projections of this effect to ITER



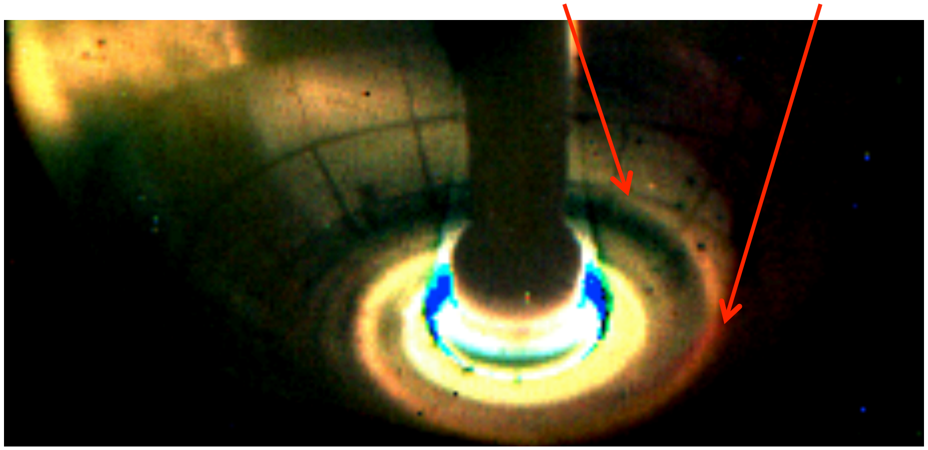
B_ϕ = 4.5 kG, I_P = 0.8 MA

- IR cameras locate the heat deposition radially
- Divertor tile currents can be used to indicate RF surface wave effects

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

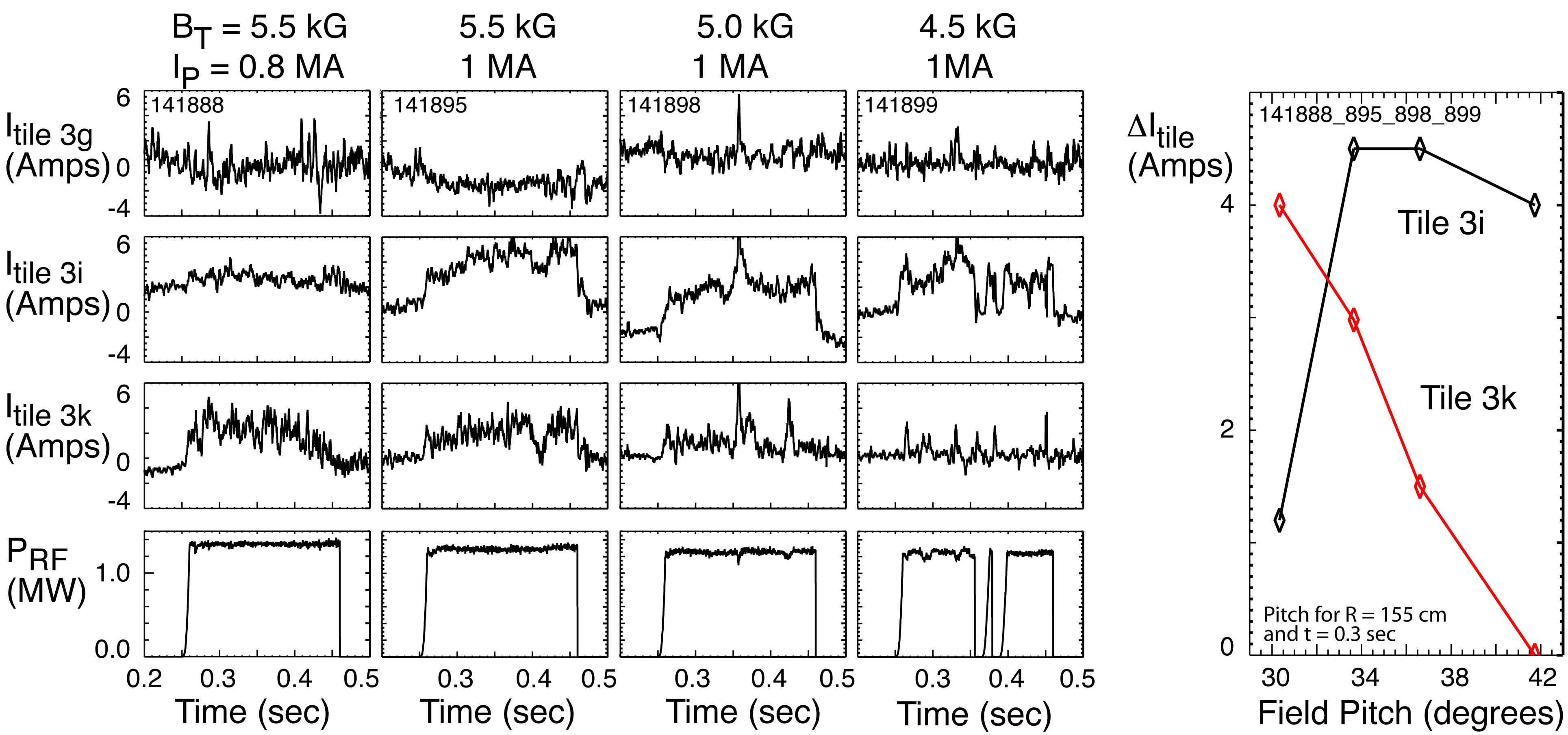


Tile I3, I4 Tile K3, K4



- 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

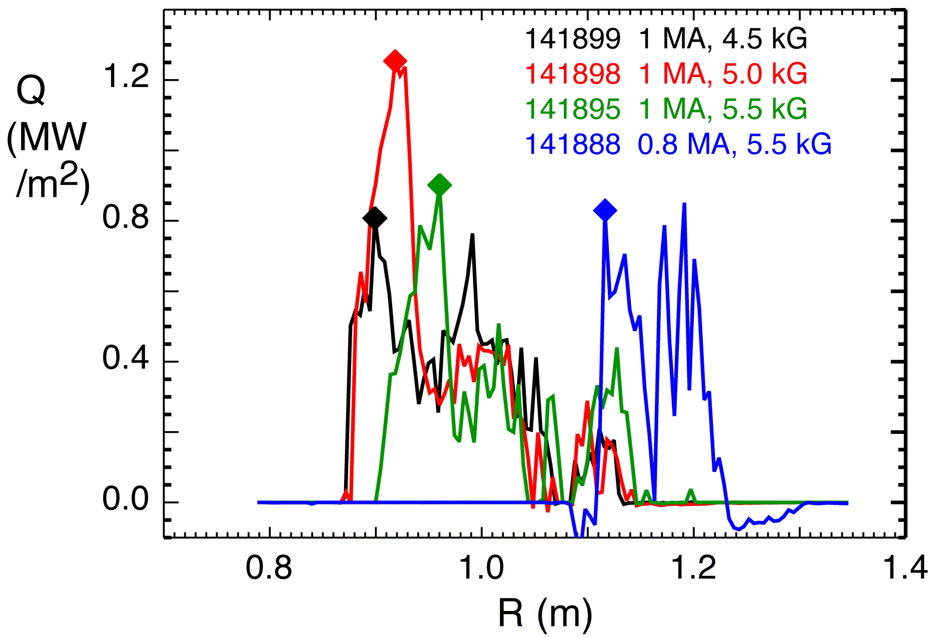
Divertor tile currents in row 3 show movement of RF hot zone across tiles as magnetic field pitch is increased



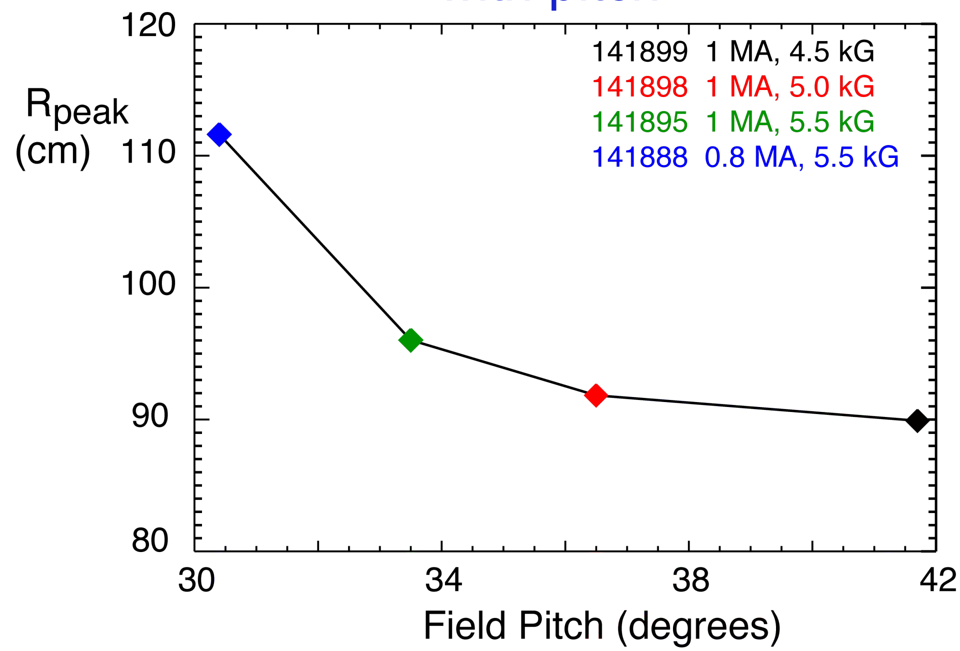
- $\Delta I_{tile\ 3k}$ decreases and $\Delta I_{tile\ 3i}$ increases as magnetic field pitch increases and RF spiral hot zone moves toward the center stack

Tile currents in row 3 are consistent with RF hot zone movement measured with the fast IR camera at Bay H

Fast IR at Bay H vs field pitch
for t = 0.450 sec



Shift of RF hot zone
with pitch



- Movement of RF hot zone with magnetic field pitch is relatively fast in the lower pitch range but slows considerably in the higher pitch range

Significant results

- 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, apparently due to absence of fast-ions from NBI
    - Important contrast between electron and ion dominated heating regimes
- 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 elevated stored energies with significantly reduced RF core heating power
    - Increased level of ETG turbulence evident at higher power may enhance transport
    - Modeling is needed to balance RF power deposition and transport properties
- Investigation of interaction of the RF edge drive with the outer divertor plate has begun
  - Tile currents track well with the location of the RF "hot" zone
  - RF "hot" zone moves toward the center post with increasing magnetic field pitch