NSTX

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SOL Properties of HHFW electron heating generated H-modes in NSTX

J. C. Hosea, R. E. Bell, A. Diallo, S. Gerhardt, M. A. Jaworski, G. J. Kramer, B. P. LeBlanc, R. J. Perkins, C. K. Phillips, L. Roquemore, G. Taylor, J. R. Wilson, *PPPL*, J.-W. Ahn, T. K. Gray, R. Maingi, A. McLean, P. M. Ryan, *ORNL*, S. Sabbagh, *Columbia U.*, and the NSTX Team

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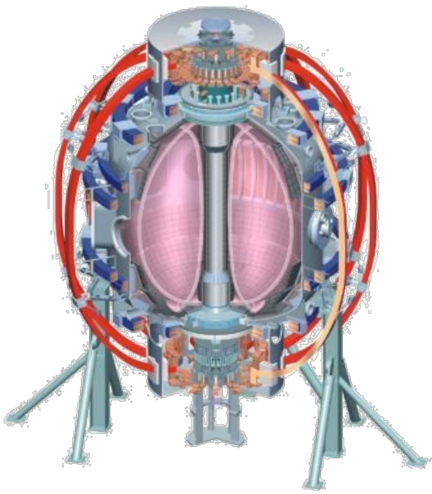
54th Annual Meeting APS Division of Plasma Physics

Providence, Rhode Island

October 29 – November 2, 2012



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Work supported by USDOE Contract No. DE-AC02-09CH11466

Abstract

In neutral beam generated H-modes, it has been shown that high harmonic fast wave power lost to the divertor regions flows along the magnetic field lines passing in front of the antenna [1]. Here we extend this power flow study to the case of HHFW generated H-modes [2]. Using the field strike point spiral from the Spiral code as a guide, it is found that for comparable launched RF powers the power loss in the outer scrape off layer (SOL) is generally much less for the HHFW generated H-mode case. Also, much of the heating in the lower divertor region is at/near the outer vessel strike radius as expected for low RF power loss in the SOL. The dependence of the loss at the outer vessel strike radius on the possible presence of ETG turbulence will be discussed. Also, Langmuir probe characteristics for moderate RF power showing the effects on the floating potential and ion saturation current upon moving the outer vessel strike radius past the probes will be presented and related to the EFIT02 and LRDFIT04 equilibrium representations to help specify the best equilibrium for the Spiral code field line mappings.

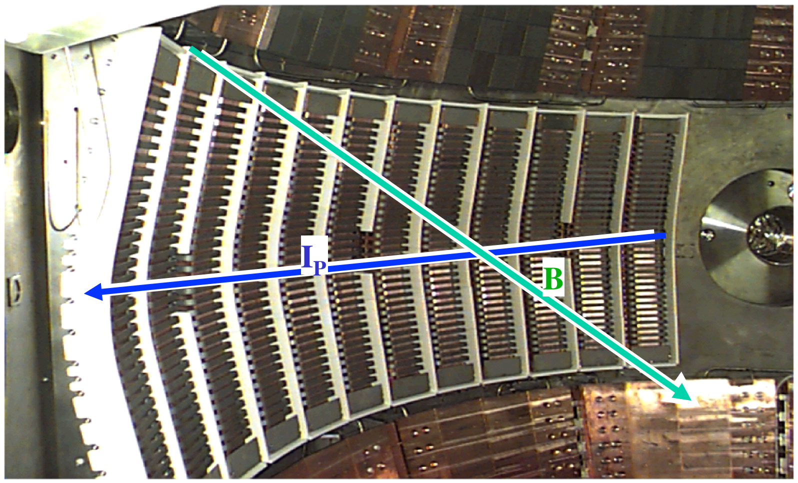
1. R. Perkins et al., PRL **109**, 045001 (2012).
2. J. Hosea et al, EPS Conference Proceedings (Strasbourg 2011) paper P2-098.

Introduction

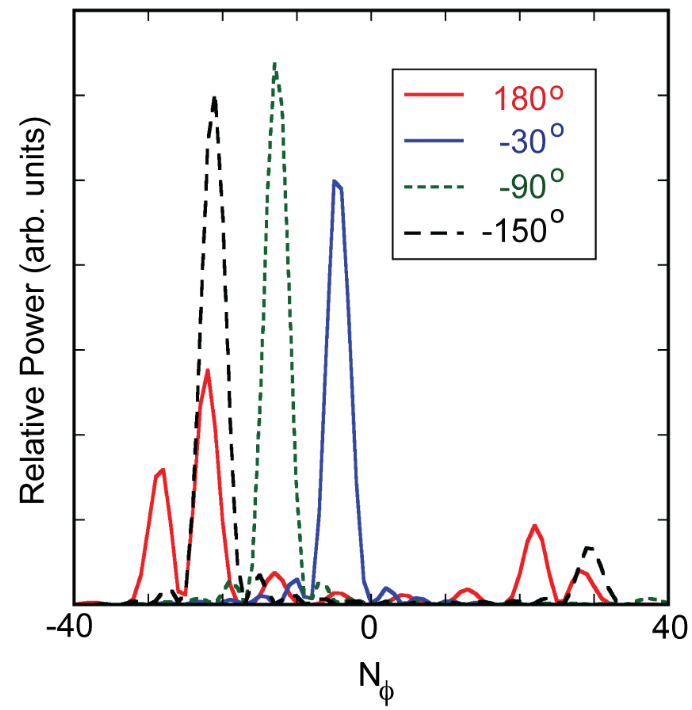
Outline

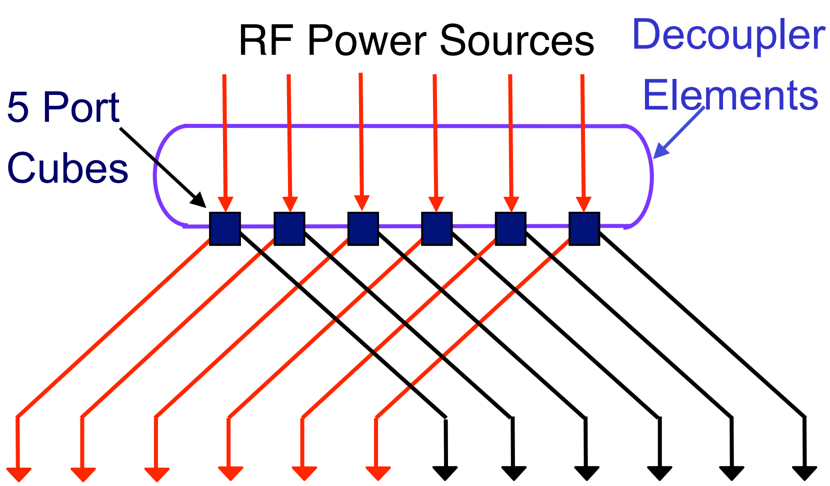
- HHFW only H-modes are observed for P_{RF} ≈ 2.5 MW and above
- Properties of HHFW generated ELMs
  – ELMs reduce RF plasma heating by ejecting energy (as for NB)
  – Fast IR heat flux measurements indicate that ELM heat flux deposition to the lower divertor region peaks very strongly at the outer strike radius
    - ➢ Much more strongly than for comparable NBI+HHFW conditions
  – Outer strike radius is most accurately located with LRDFIT04 relative to EFIT02 – this agrees with probe measurements
- RF heat deposition on divertor regions during the ELM-free-like H-mode phase
  – Spiral code predictions for the RF heat deposition location on the lower divertor appears to be less accurate than for the NB + HHFW H-mode case
  – The upper divertor heat deposition is well matched by the LRDFIT04 Spiral analysis
  – RF power deposited on the divertors appears to small
- Stored energy is saturated during the ELM-free-like H-mode phase
  – Apparently due to turbulence but heating effect on divertor is difficult to separate out

NSTX HHFW antenna has well defined spectrum – 12 straps are driven in pairs by 6 sources that are decoupled



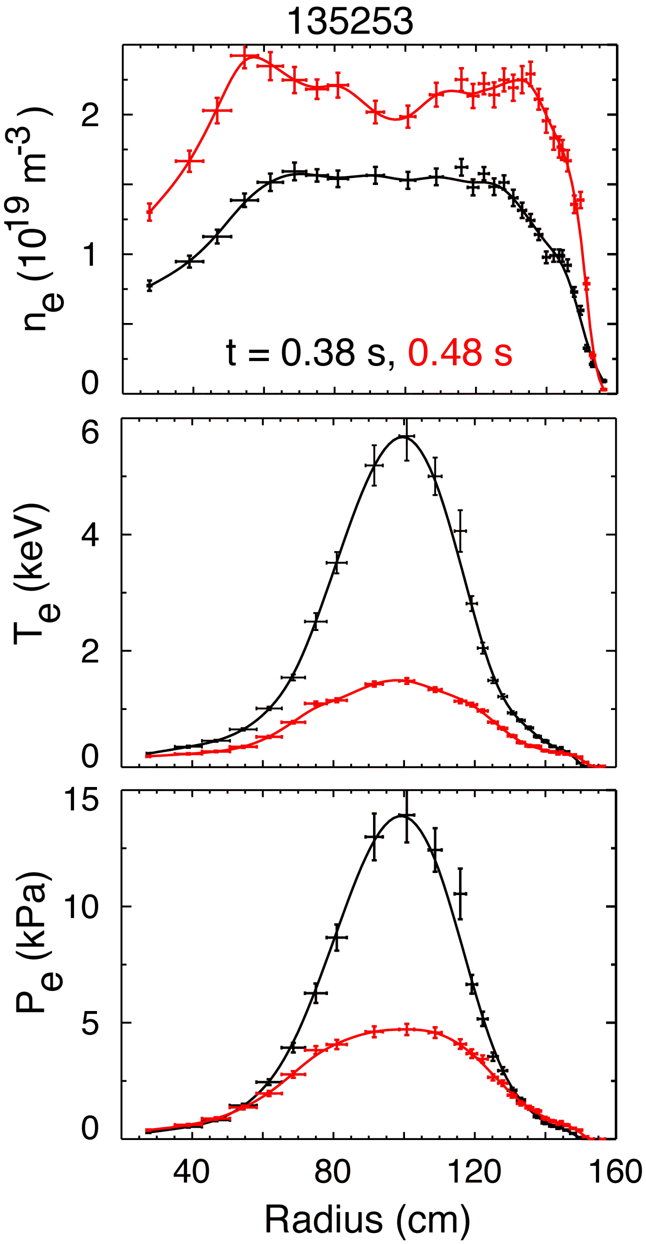
HHFW antenna extends toroidally 90°

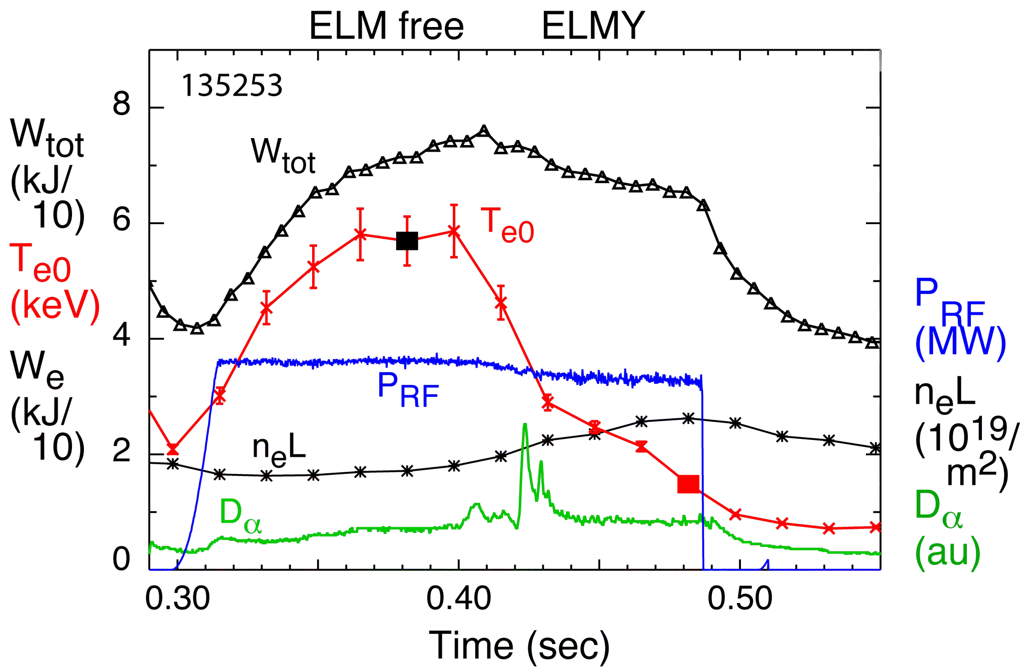




- Phase between adjacent straps easily adjusted between 0° to 180°
- $\phi_{Antenna}$ = - 90° for this presentation ($k_{||}$ = -8 m^{-1} in B direction)

RF-only H-mode Thomson scattering characteristics





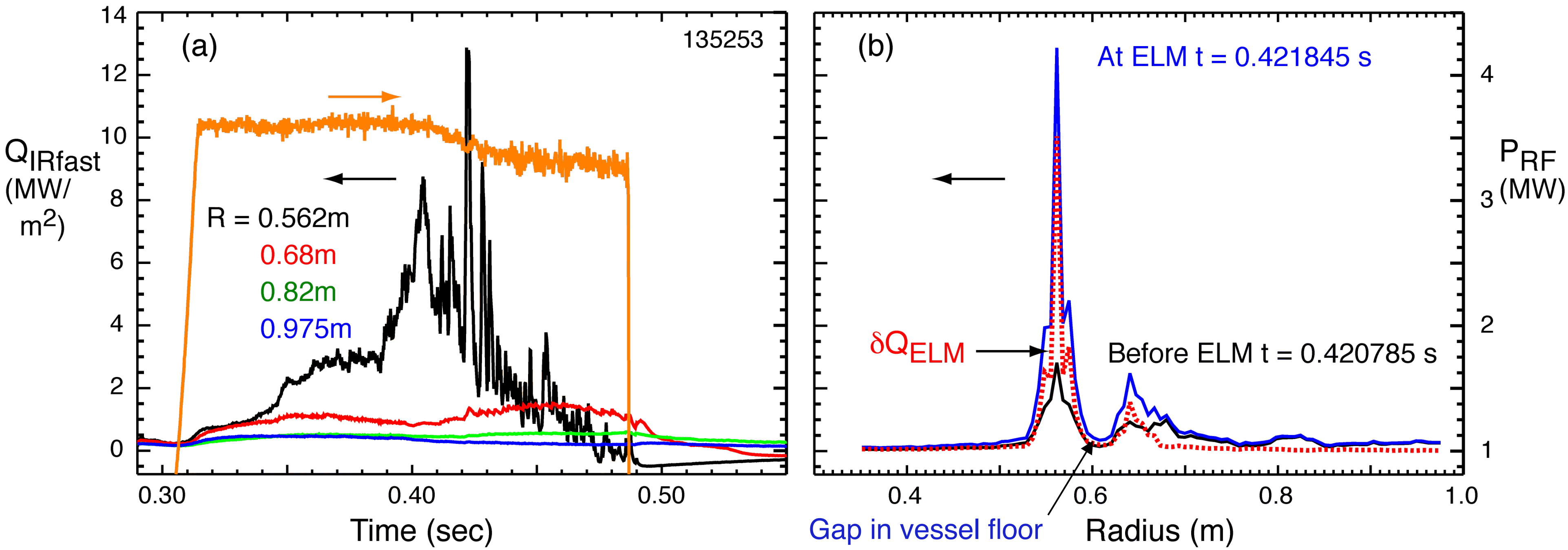
P_{RF} ~3.7 MW, I_P = 0.65 MA, B_T = 5.5 kG, Helium
ϕ_{Ant} = - 90°, k_ϕ = -8 m^{-1}

- Transition to ELMy H-mode is accompanied by:
  - Steepening of edge density gradient
  - D_α indication of large ELMs
  - Drop off of $T_e(0)$, W_{tot}, electron pressure

ELM Properties

ELM heat deposition peaks strongly at the outer strike radius as measured with the fast IR camera at Bay H

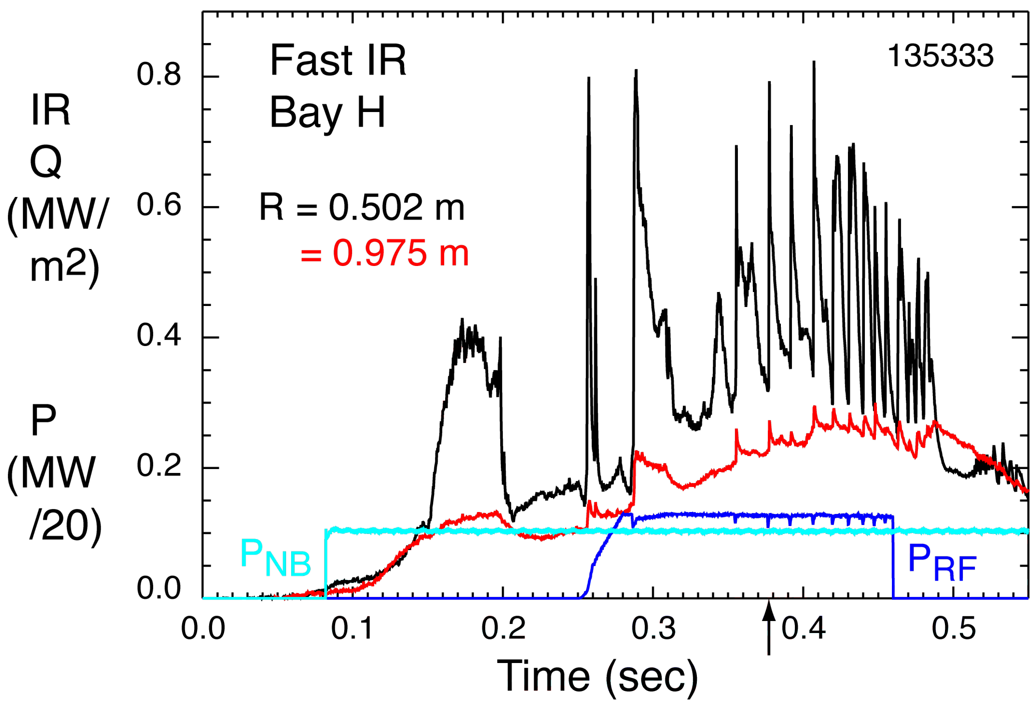
P_{RF} ~ 3.7 MW, I_P = 0.65 MA, B_T = 5.5 kG, Helium

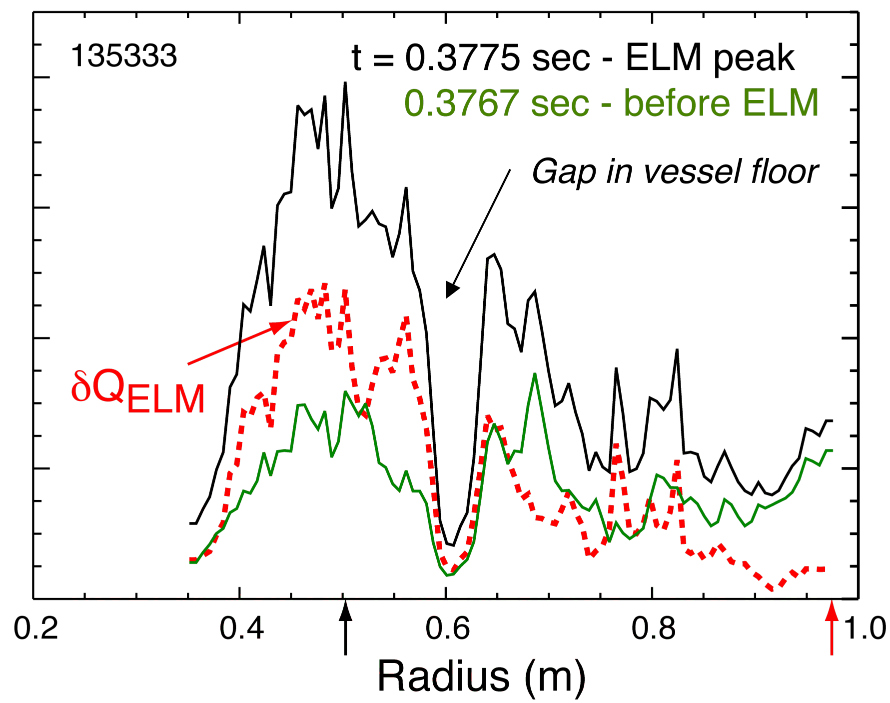


- The fast IR heat deposition measurement clearly shows the strong ELM heat deposition on the lower divertor plate at R = 0.562 m (divertor strike radius)
- Elm heat deposition peaks at ~ 10 MW/m^2 with a half width of ~ 1 cm
  - Falls off by ~ 2 orders of magnitude at R ~ 1 m
- Small effect of largest ELM is barely evident on the net RF power
  - ELMs are located away from the antenna

ELM power deposition is not as strongly peaked about the strike radius for HHFW + NBI H-modes

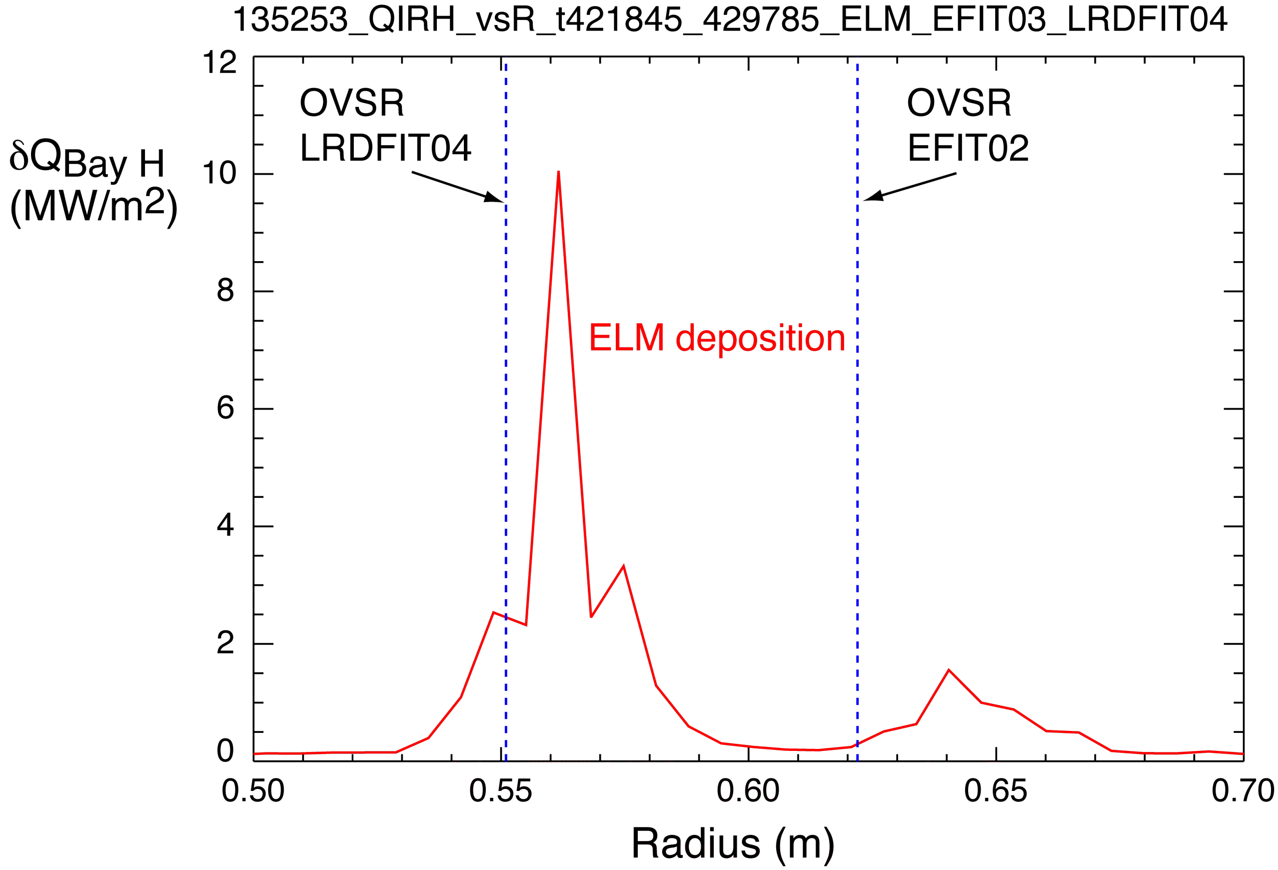
P_{RF} ~ 2.6 MW, P_{NB} = 2 MW, I_P = 0.8 MA, B_T = 4.5 kG, D_2, ϕ_{Ant} = -90°





- Fast IR camera shows ELM heat deposition peaked at outer strike radius – falls off by ~ 1 order of magnitude at the start of the RF hot zone (R ~ 0.94 m)
- Broader ELM heat deposition with NBI may be due to the presence of energetic beam ions

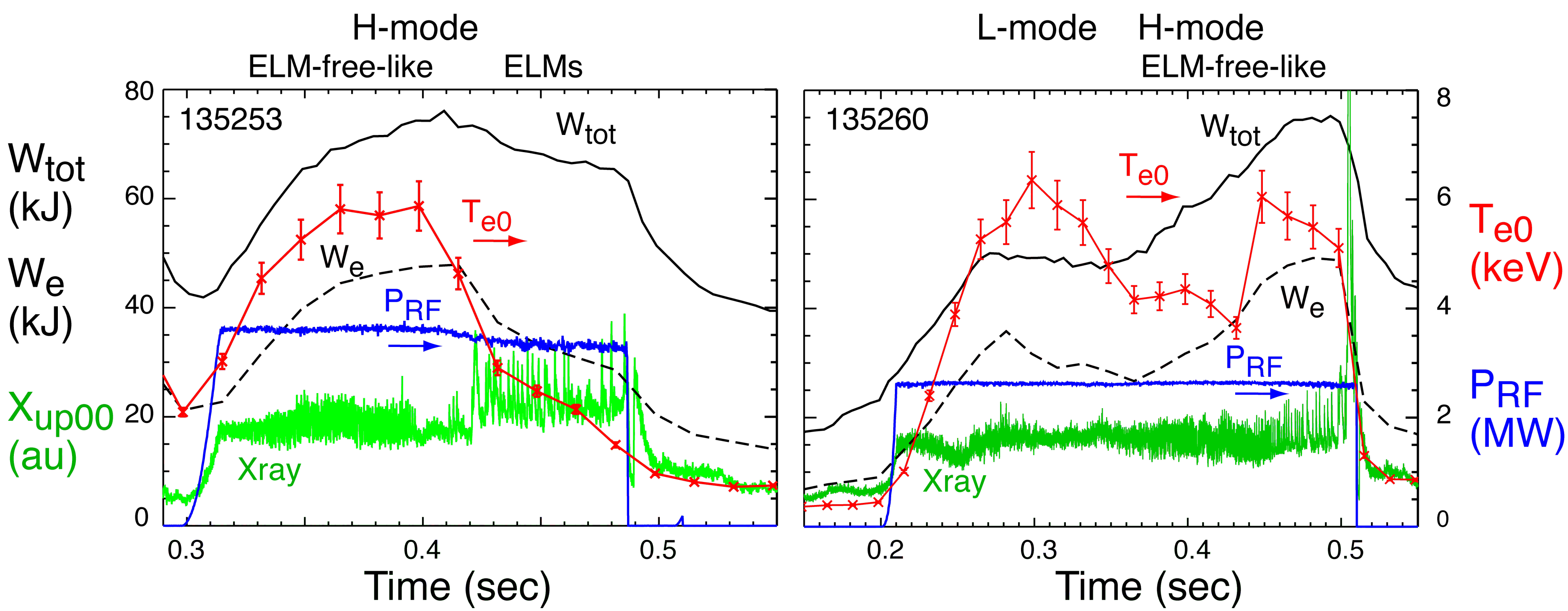
Outer vessel strike radius (OVSR) for LRDFIT04 gives better fit to HHFW ELM deposition



- Fast IR camera shows ELM heat deposition peaked just outside outer vessel strike radius for LRDFIT04 equilibrium
- Comparison with LRDFIT04 and EFIT02 equilibria shows importance of using appropriate equilibrium magnetic surfaces for Spiral mapping of magnetic field strike points in predictions of “hot” RF deposition patterns later

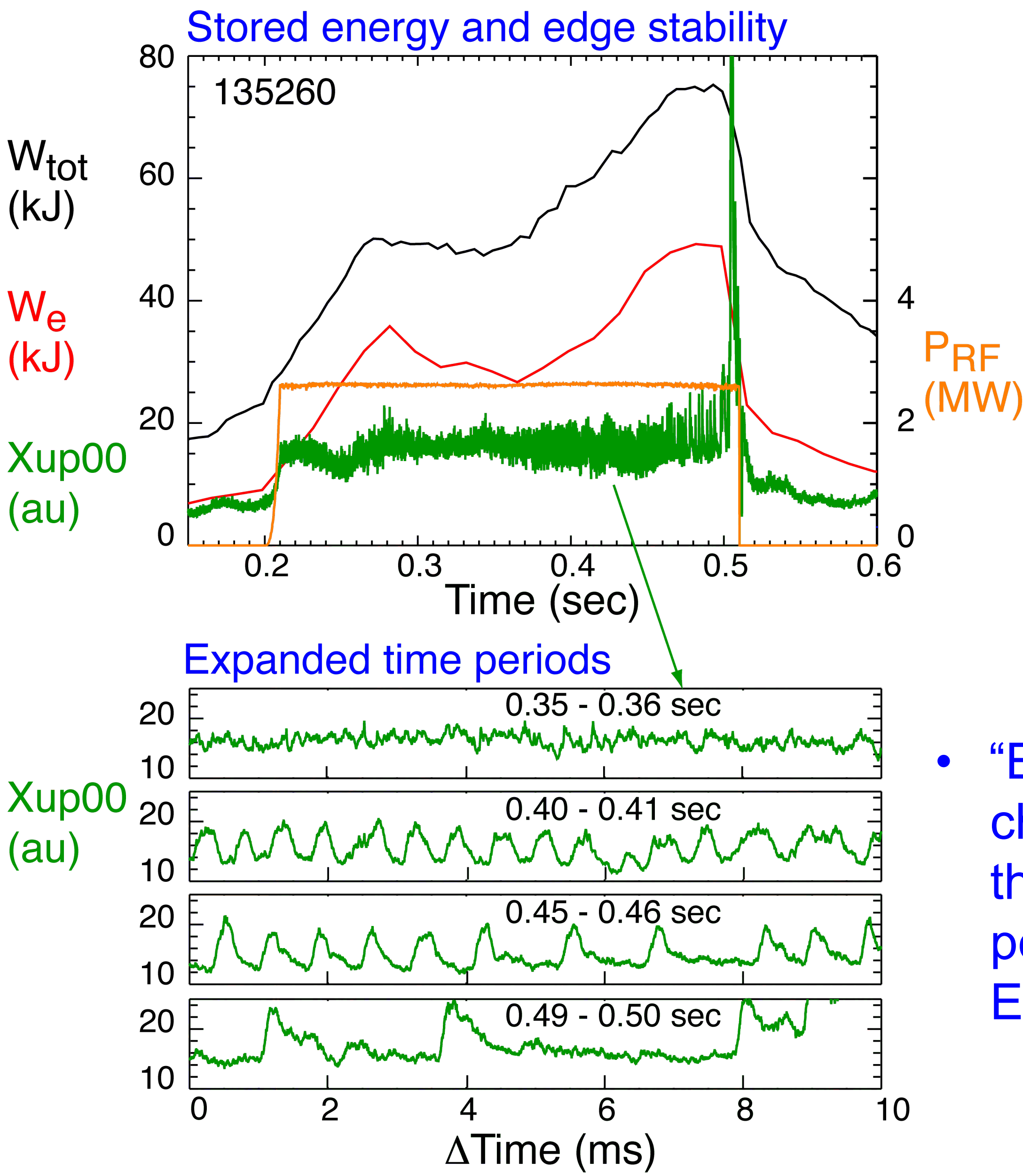
ELMs reduce heating efficiency for the RF H-mode as for the NB H-mode case

I_P = 0.65 MA, B_T = 5.5 kG, Helium



- At P_{RF} = 3.7 MW ELM-free-like transition to ELMy H-mode results in 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

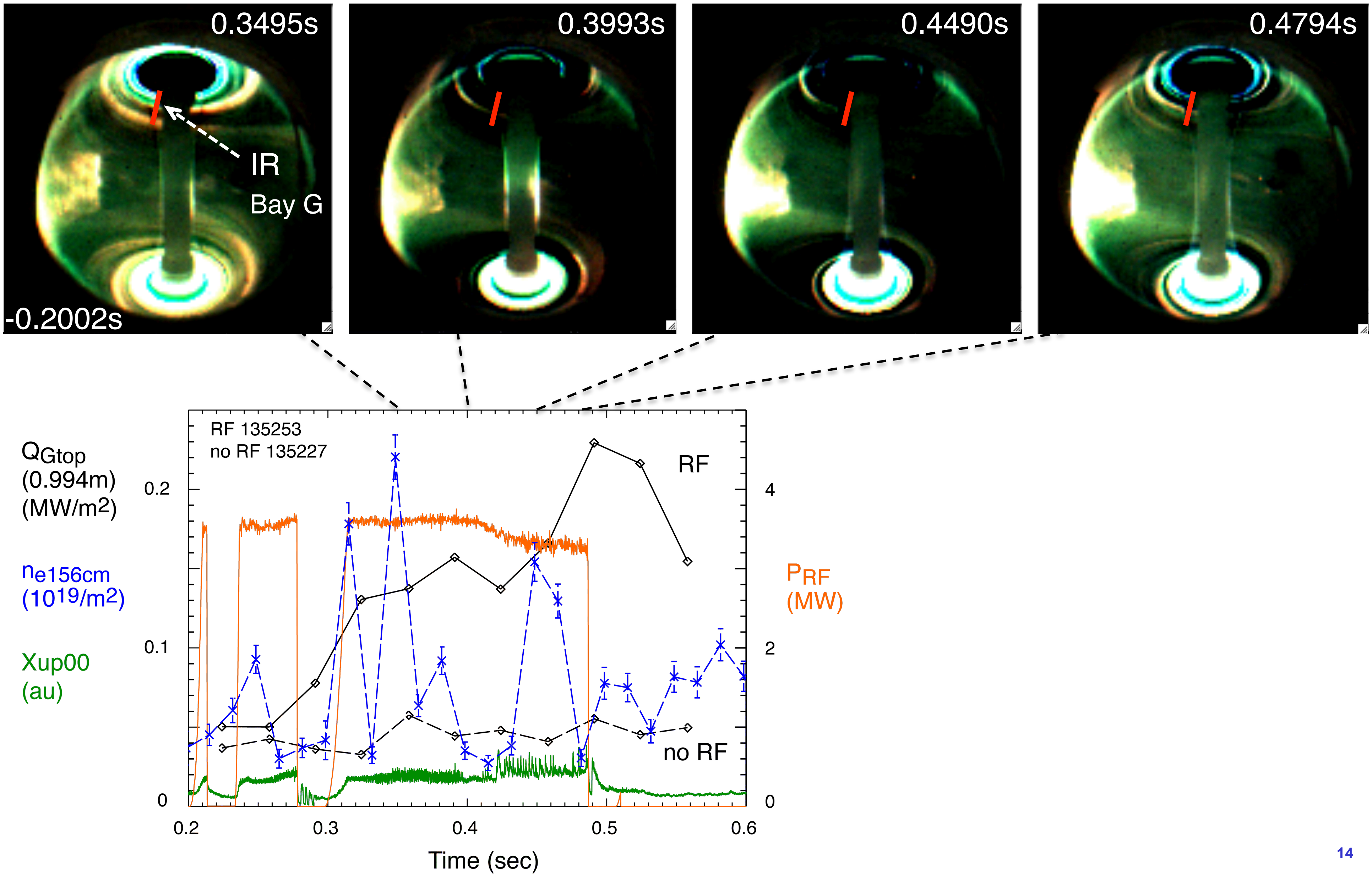
Stored energy increase period is accompanied by edge oscillations and small ELMs

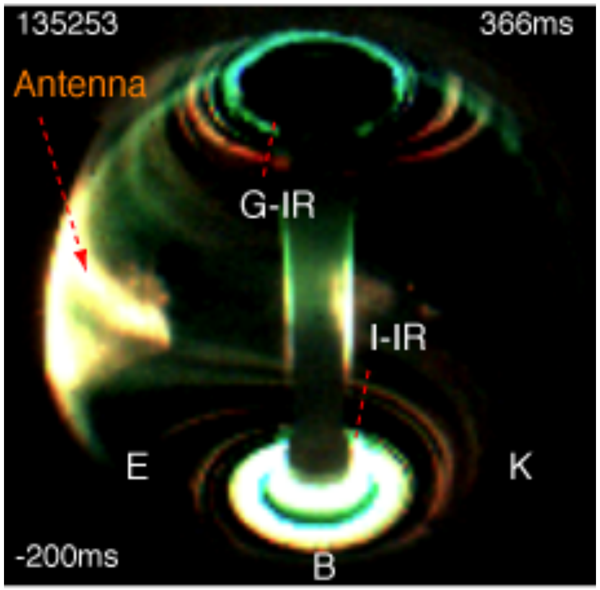


- "ELM-free-like" period is characterized by edge oscillations that peak on top of density pedestal and are followed by small ELMs

RF Heat Deposition on Divertors

Camera views and IR at Bay G-top indicate heating at divertor plate – heat flux increases during ELMy phase

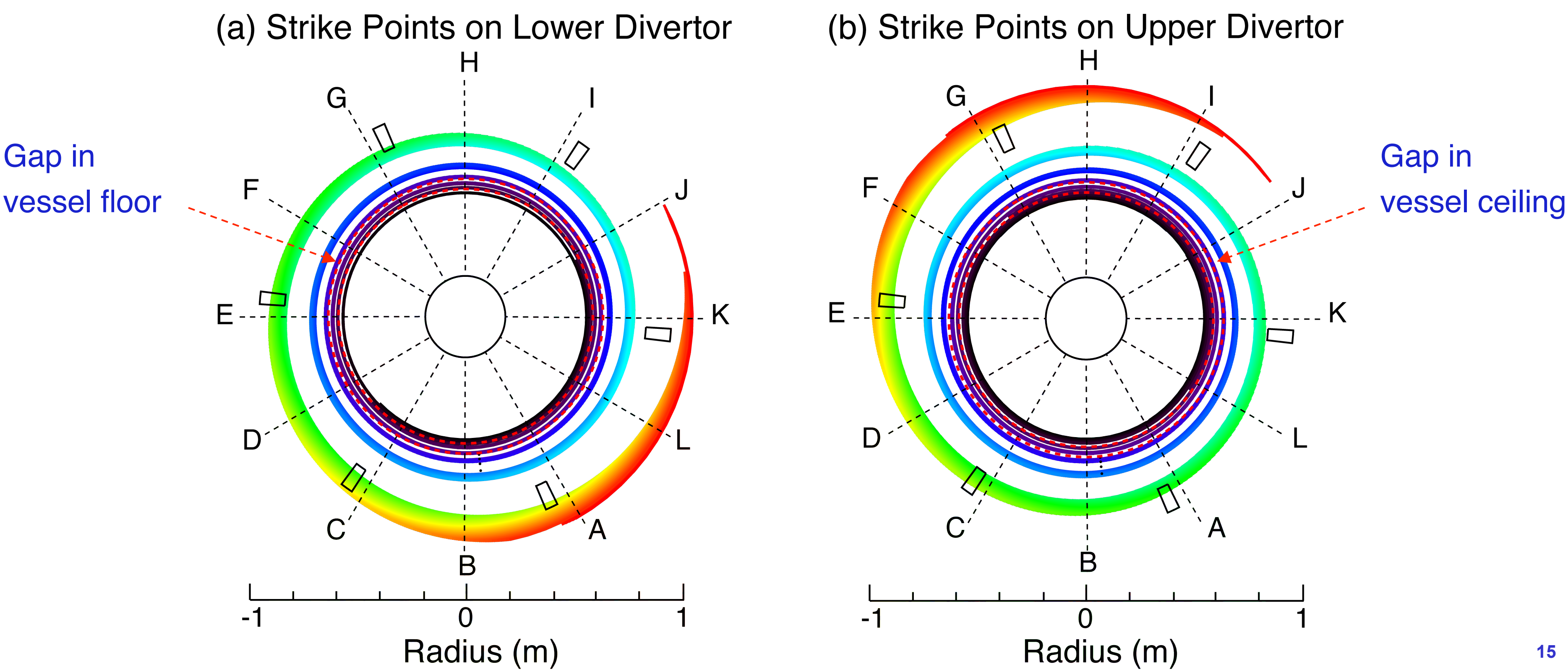




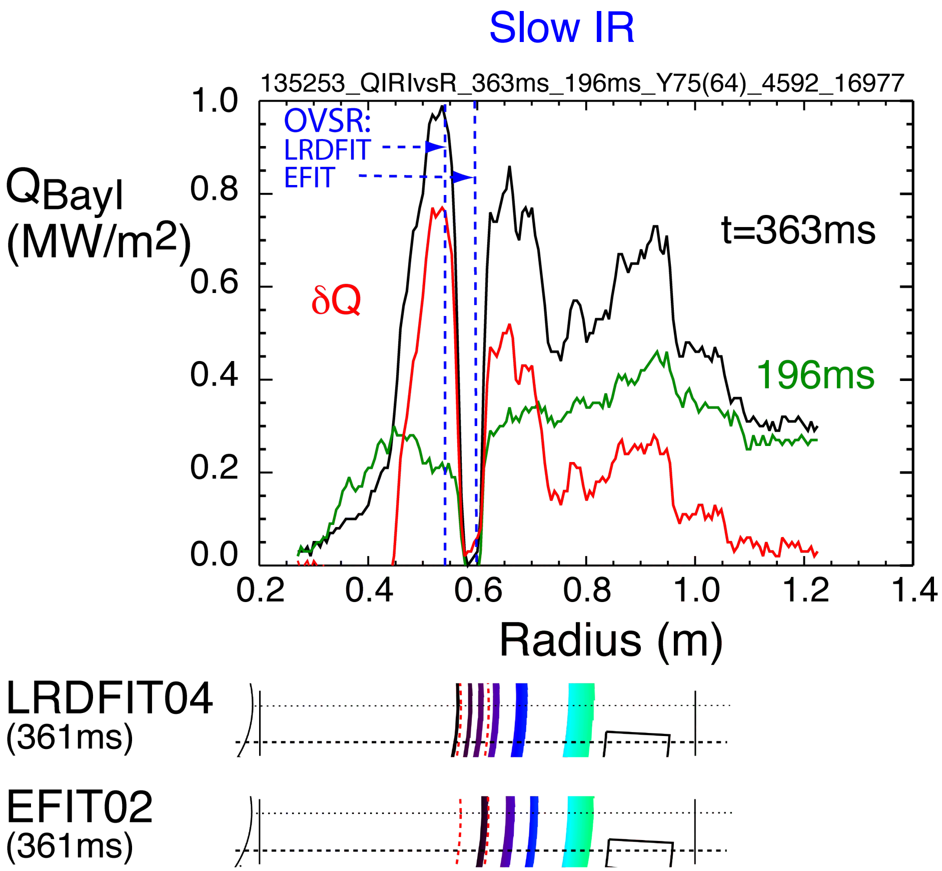
Spiral magnetic field line strike points are similar to RF heat deposition patterns

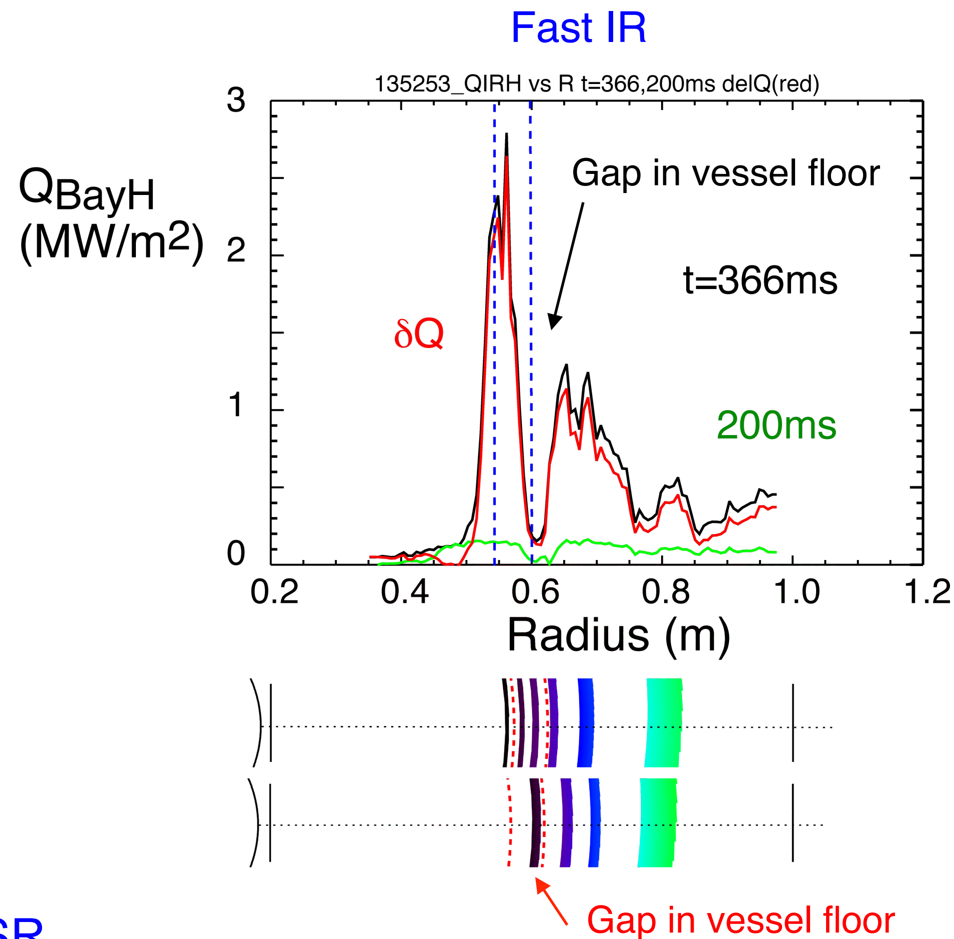
- Spiral mapping of field line strike points show similar pattern to RF heat deposition on divertor floor and ceiling (here using LRDFIT04 equilibrium for 361 ms)

R. Perkins et al., PRL **109**, 045001 (2012).



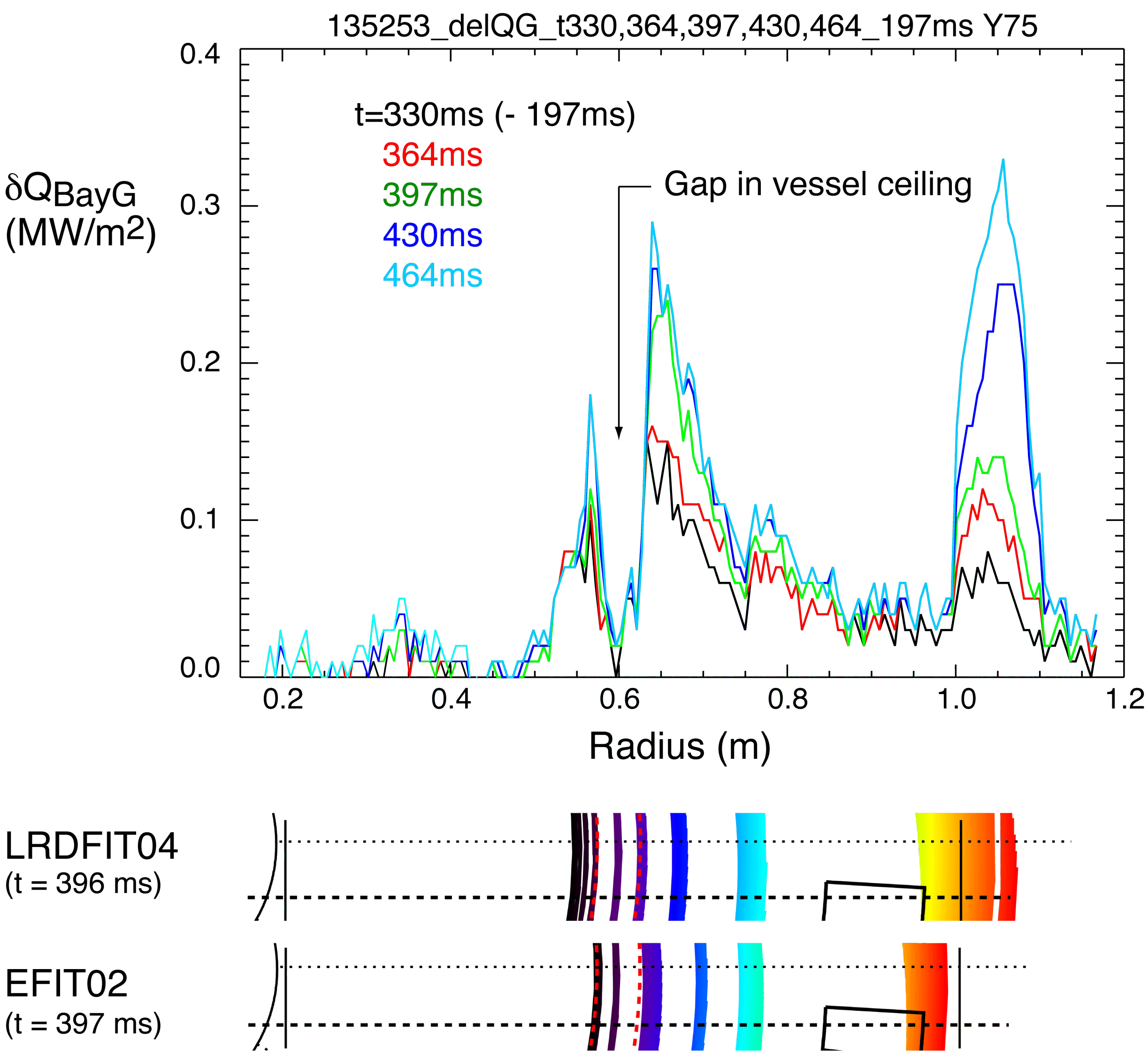
Comparison of Bays I and H bottom RF heat deposition to field-line strike spirals





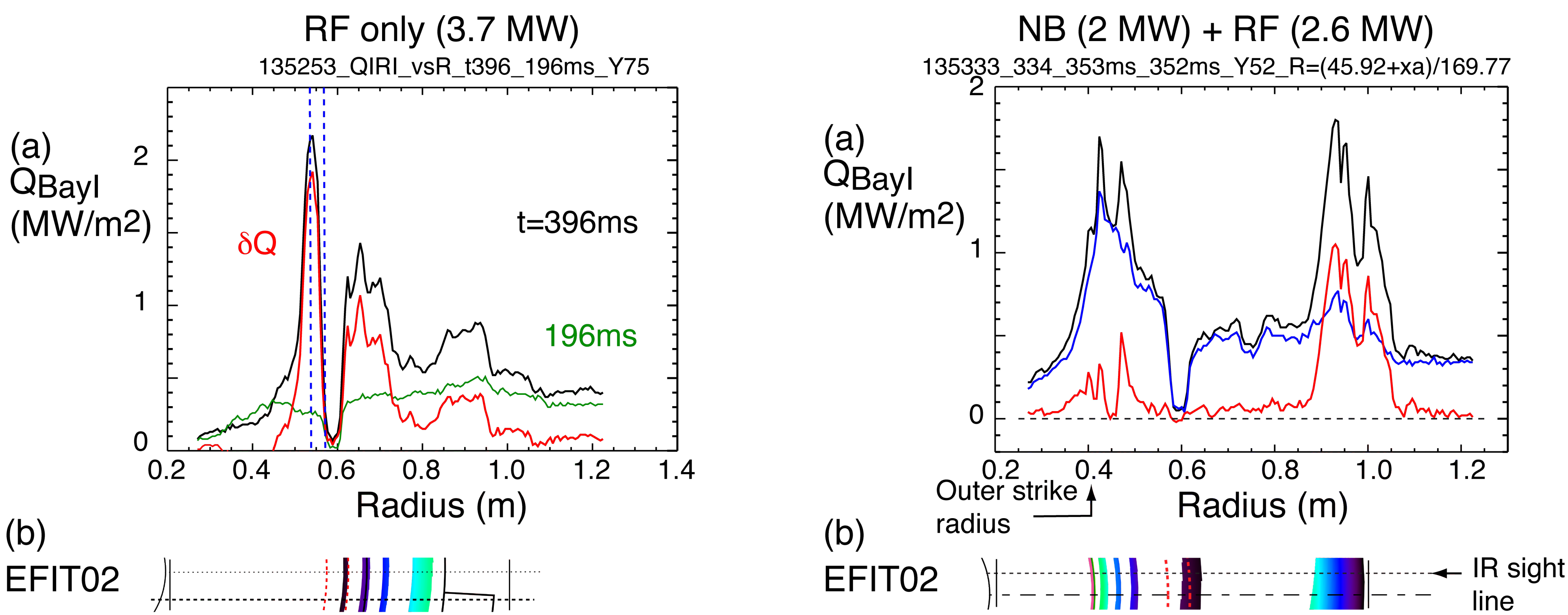
- Match with LRDFIT is better near the OVSR.
- Both spiral fits indicate RF loss peaks outboard of the vessel gap
- Fast Q_{IRH} suggests an RF heat loss peak inboard of gap near OVSR
- Enhanced background heating for R > 0.65 is thought to be caused by turbulence particle loss from plasma (along with possible emissivity variations)

RF heat deposition at BayG top relative to field-line strike spiral



- LRDFIT04 gives better Spiral fit to location of upper divertor RF heat deposition
- RF heat deposition at BayG top is clearly resolved

RF heat deposition at Bayl bottom for P_{RF} ~ 3.7 MW is much less than for NB + HHFW case with P_{tot} ~ 4.6 MW

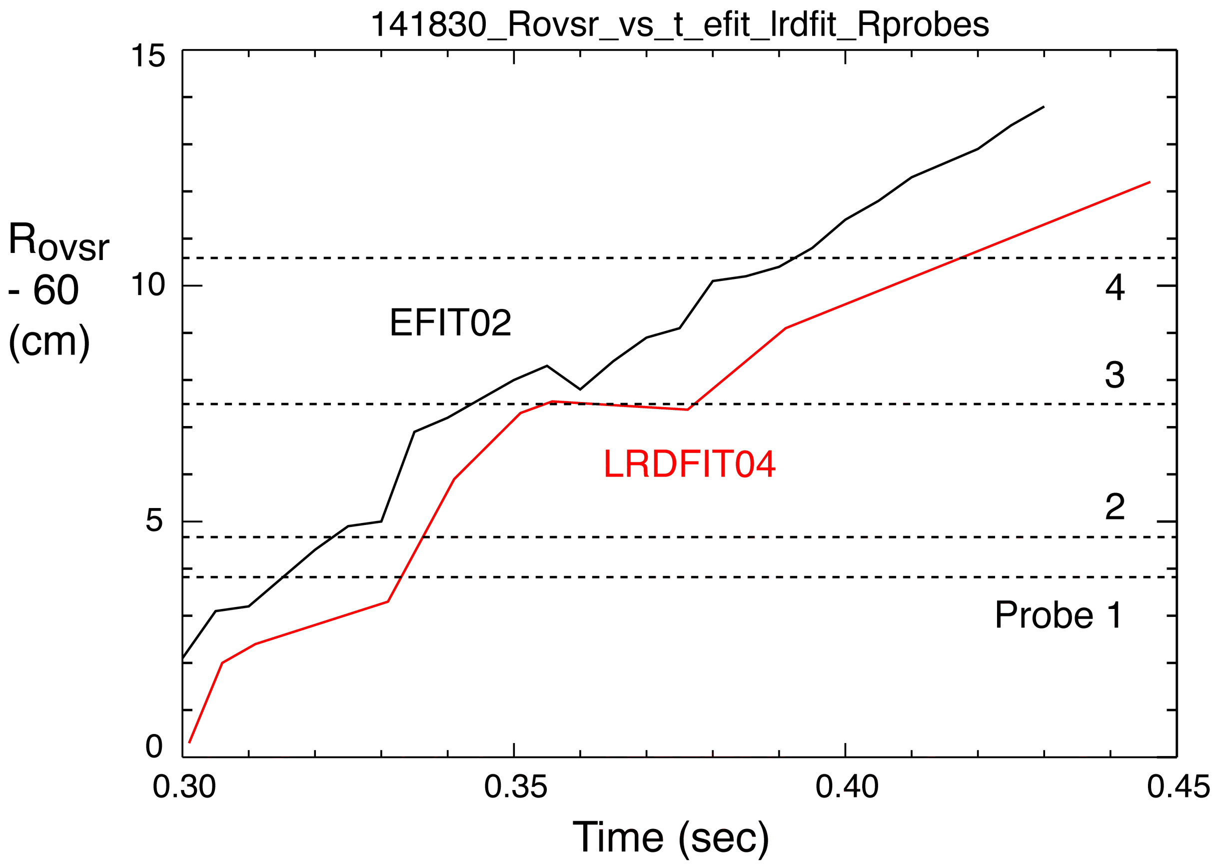


(See R. Perkins et al., Oral GO6.012)

- Heat loss is reduced by lower density in plasma edge.
- Intense part of spiral is moved toroidally away from Bayl.
- The heat deposition bump at larger radius > 0.8 m for RF only case does not correspond to Spiral location

Sweeping outer vessel strike radius past Langmuir probes allows determination of the better equilibrium fit

Shot 141830: ϕ_{ANT} = -90° (k_ϕ = 8m^{-1}), B_T = 5.5 kG, I_P = 0.65 MA, helium, P_{RF} ~ 0.55 MW

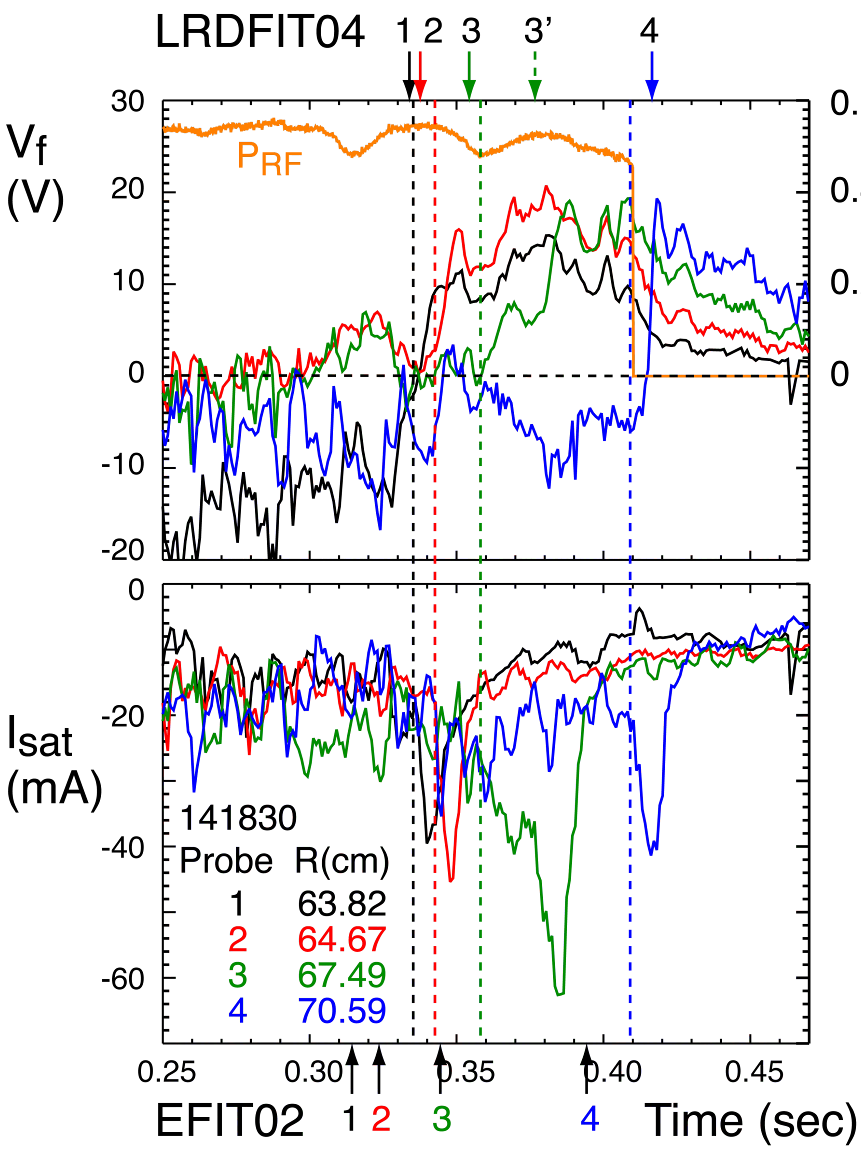


- Outer vessel strike radius for LRDFIT04 is at a smaller radius than that for EFIT02 at any given time – typically by 1 – 2 cm
- Also, the LRDFIT04 passes the probe radius at a later time

J. Kallman, et al., RSI **81**, 10E117 (2010).

Sweeping OVSR past Langmuir probes indicates that LRDFIT04 best matches the outer vessel strike radius

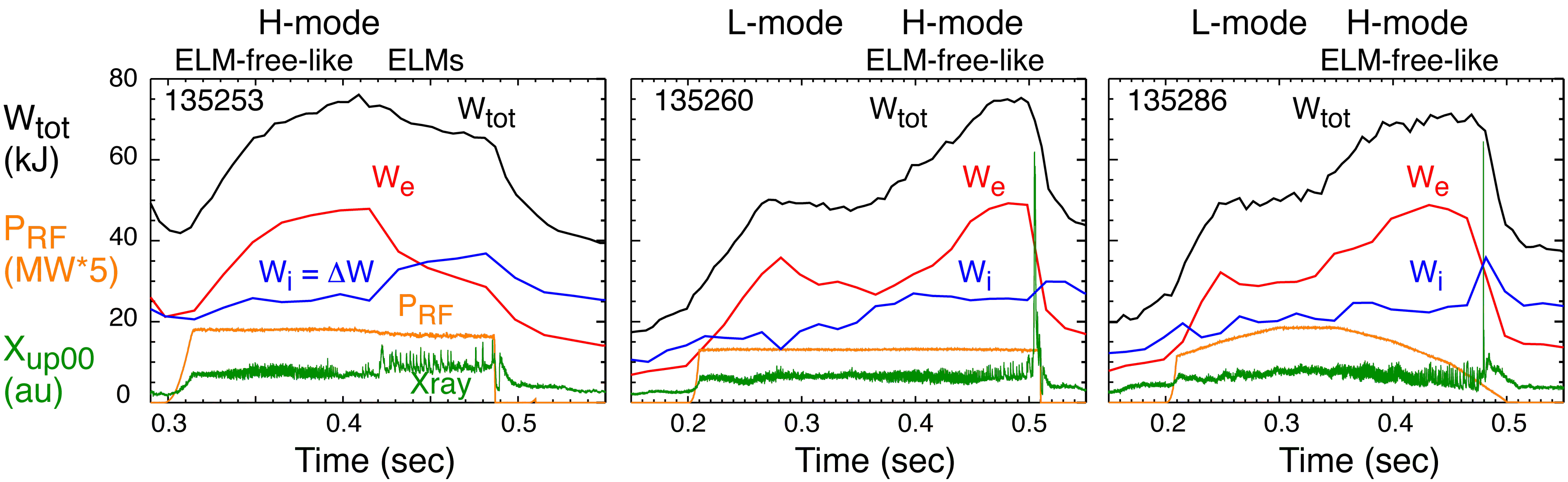
Shot 141830: ϕ_{ANT} = -90° (k_ϕ = 8m^{-1}), B_T = 5.5 kG, I_P = 0.65 MA, helium



- OVSR appears to occur where the floating potential is near zero and begins to move strongly positive – and where the saturation current begins to decrease strongly
- The peak in the saturation current occurs in the private flux region.
- LRDFIT04 is within ~ 2 ms of OVSR crossing times for probes 1 – 3, ~ 8 ms for probe 4
- EFIT02 is ~ 20 ms before the crossing times

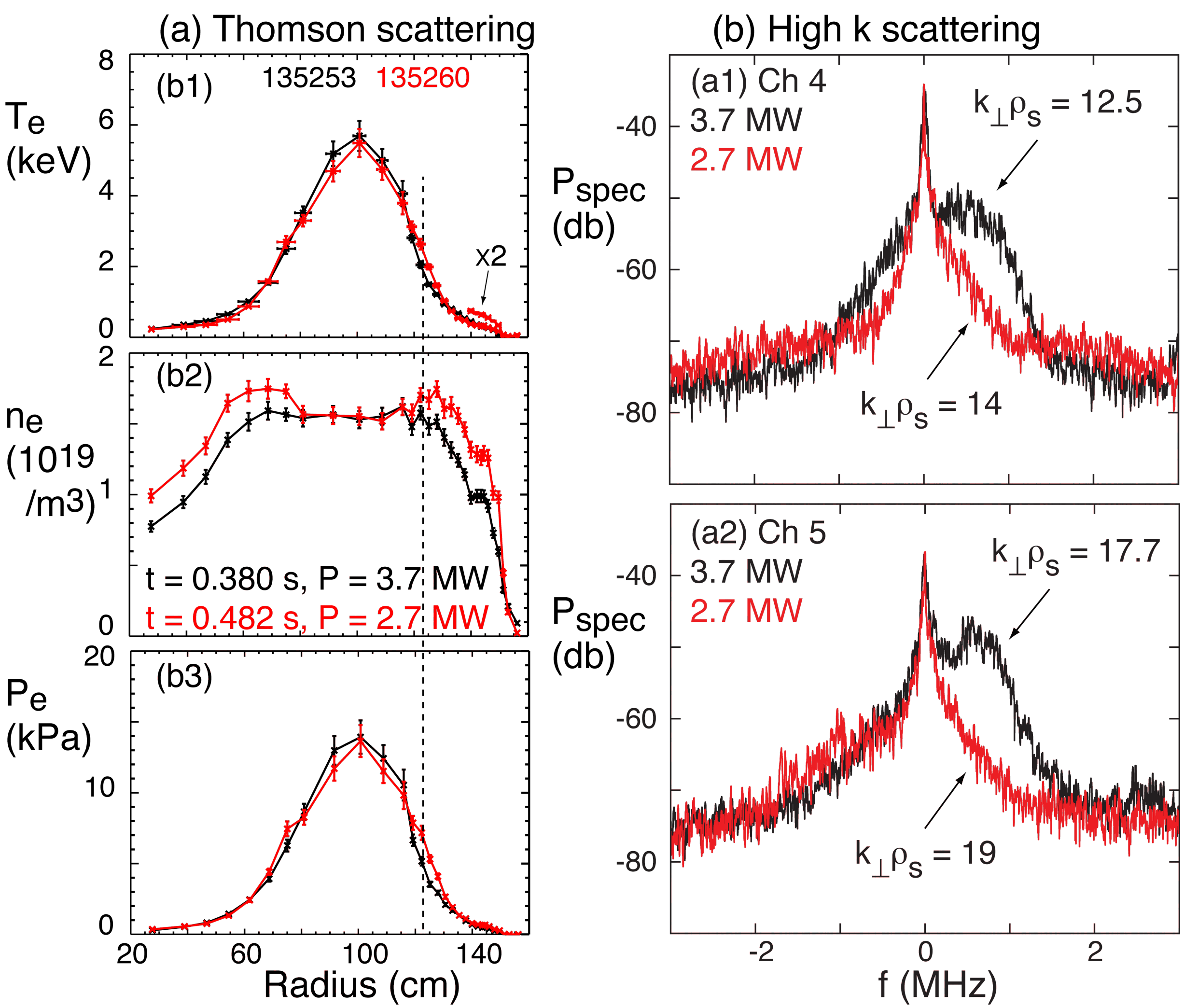
Saturation of Stored Energy

Stored energies saturate near same value in the ELM-free-like H-mode period



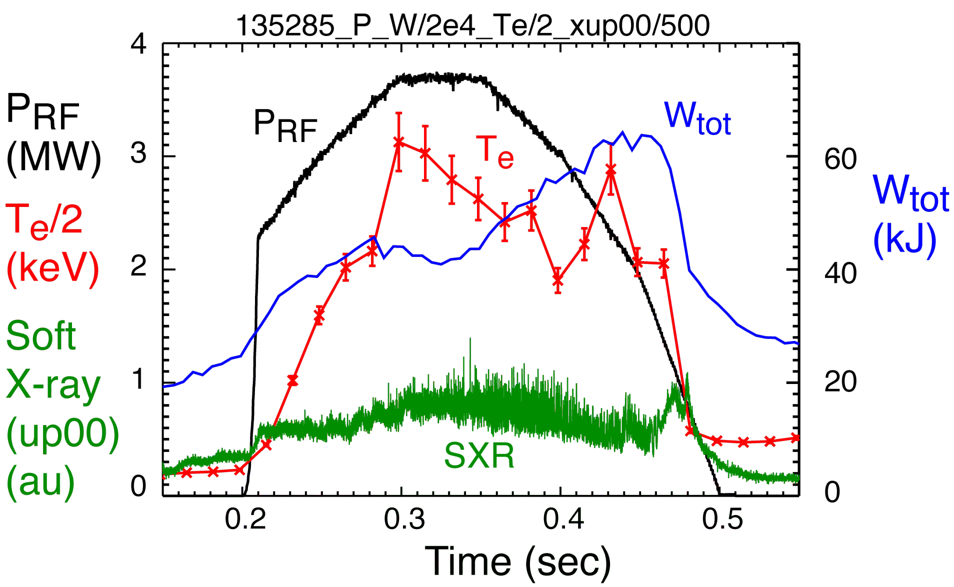
- Suggests that turbulence is causing the electron pressure profiles to become stiff (electron-ion coupling is relatively small for the conditions studied here)
- ETG turbulence is suspected in this HHFW electron heating regime

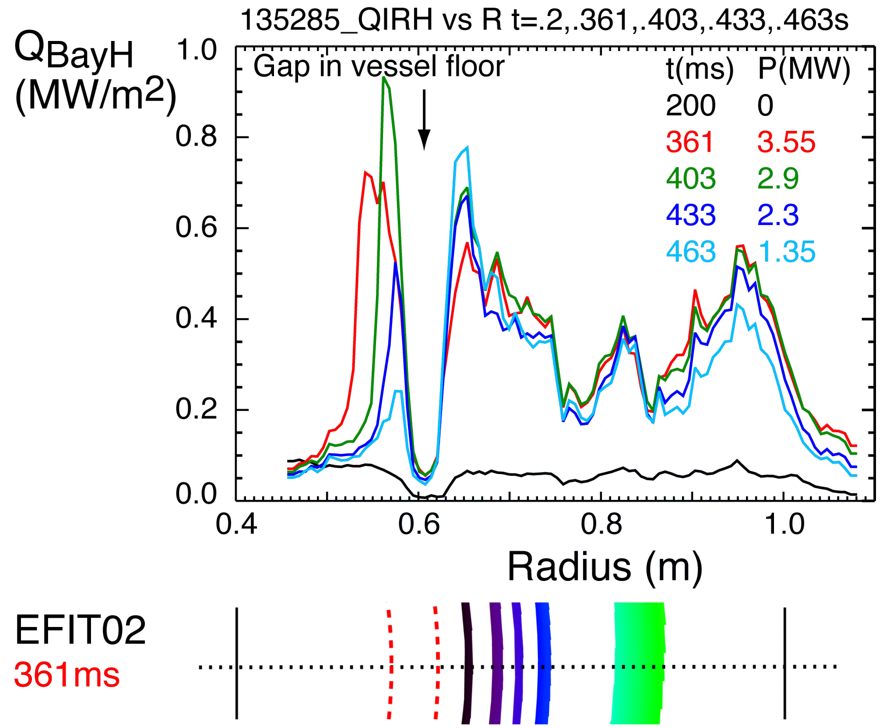
High-k scattering measurements indicate that ETG turbulence increases with RF power



- Thomson scattering profiles are well matched at saturated stored energy times for P_{RF} = 3.7 MW and 2.7 MW
- High k turbulence increases by an order of magnitude at the higher power
  - ETG turbulence may cause the saturation of stored energy with increasing/decreasing RF power
- Difficult to measure difference in divertor heat due to turbulence with limited data set – still under study

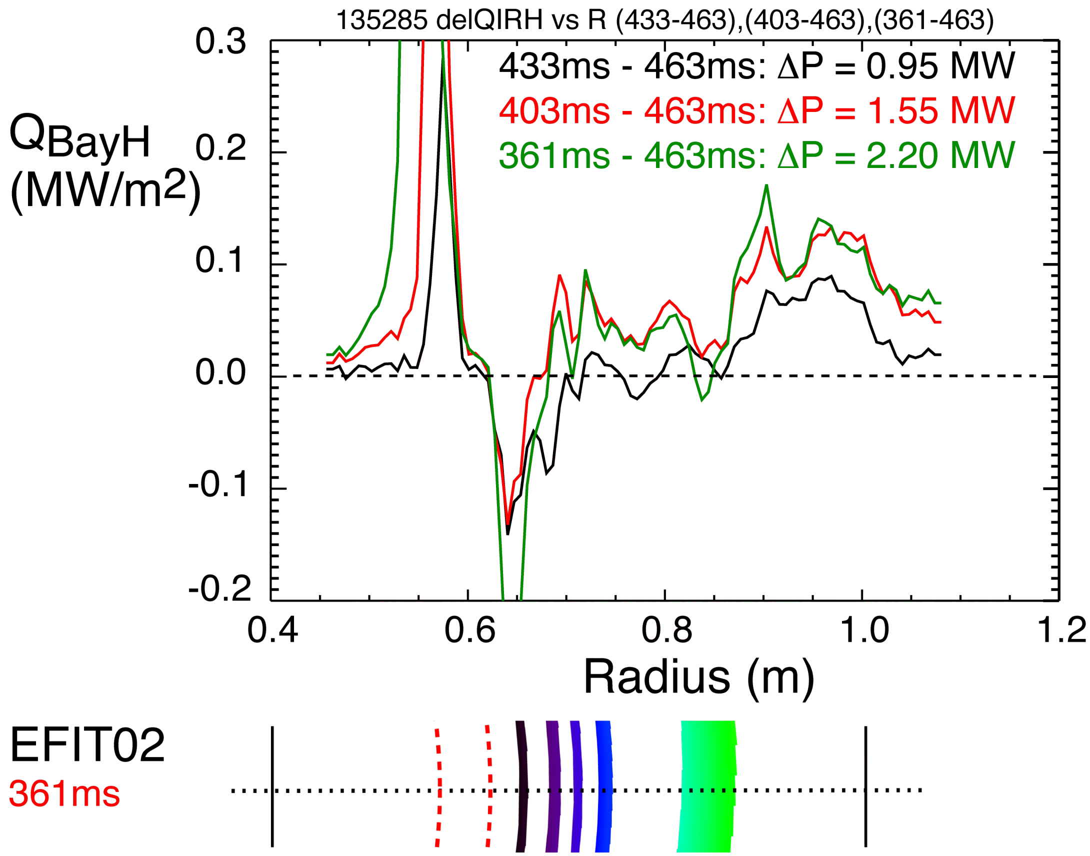
W_{tot} increases and heat deposition on outer divertor plate is mostly maintained as RF power is decreased





- The stored energy saturates in the ELM-free-like RF H-mode even with P_{RF} falling
- OVSR crosses vessel gap during P_{RF} fall-off, but Q_{IR} near gap suggests that heat deposited there follows W_{tot}
- The lack of decay in Q_{IR} across the outer divertor region with decreasing P_{RF} suggests the heat deposition comes mostly from the plasma - perhaps due to turbulence in the SOL
- Difficult to extract direct RF power flow to the divertor for this low RF loss case

Decay of W_{tot} from 361ms to 463ms suggests that some direct RF deposition on divertor plate occurs but it is small



- Q_{IR} falls around 0.1 MW/m^2 while P_{RF} falls by 2.2 MW from 3.55 MW to 1.35 MW
- Again, the lack of decay in Q_{IR} across the outer divertor region suggests the heat deposition comes mostly from the plasma, perhaps due to turbulence in the SOL

Conclusions

- HHFW generated ELMs deposit their heat flux in a narrow region about the divertor outer strike radius
  - The heat flux is observed to peak to ~ 10 MW/m^2 with a half flux width of only ~ 1 cm
    - Much more strongly peaked than for comparable NBI+HHFW conditions
  - The outer strike radius location is most accurately predicted with LRDFIT04

- SOL RF heat deposition away from the OVSR is observed on the lower and upper outer divertor plates during the ELM-free-like H-mode phase
  - Direct RF power loss appears to be small except in the vicinity of the OVSR for this low density regime
  - Spiral code matches the upper divertor deposition location using LRDFIT04, but both LRDFIT04 and EFIT02 projections fall inboard of the apparent lower divertor RF heat deposition spiral – perhaps the RF heat deposition is small relative to emissivity variations

- Stored energy saturates during the ELM-free-like H-mode phase suggesting turbulence is leading to fixed electron temperature profile gradients
  - High k turbulence measurements show a strong turbulence increase with power which may account for the saturation (electron temperature profile resilience)
  - Divertor heating due to this turbulence is under study but appears to be linked more to W_{tot} than to P_{RF} during the fall-off of P_{RF}