NSTX HHFW Conditioning and Operation with the Upgraded Dual Feed Antenna

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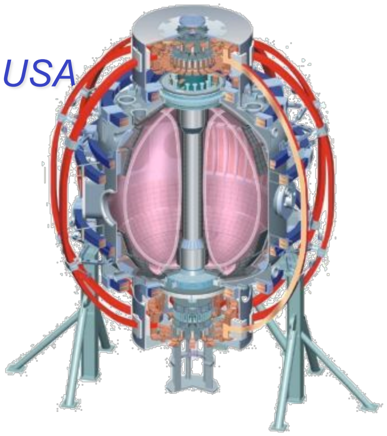

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NSTX HHFW conditioning and operation with the upgraded dual feed antenna

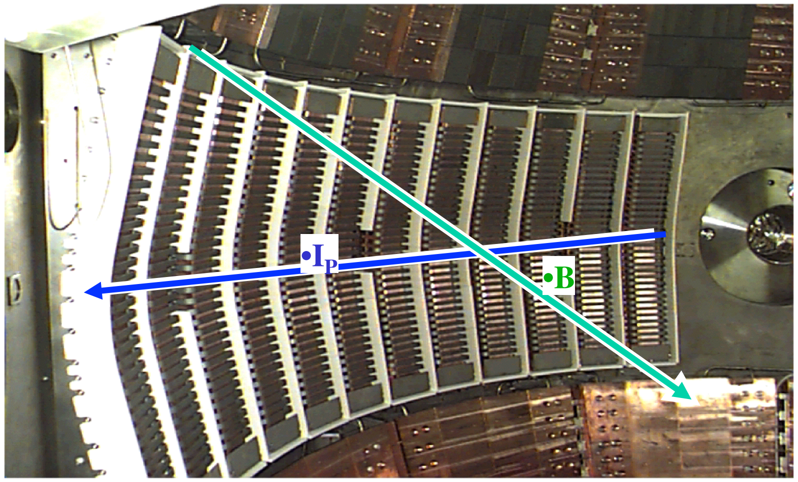
Outline:

- Antenna upgrade
- Conditioning for optimum antenna power capability
- Operation at higher power and with ELMs with upgraded antenna
- Optimization of coupling in the presence of ELMs
  - Reliable detection of arcs in the presence of ELMs

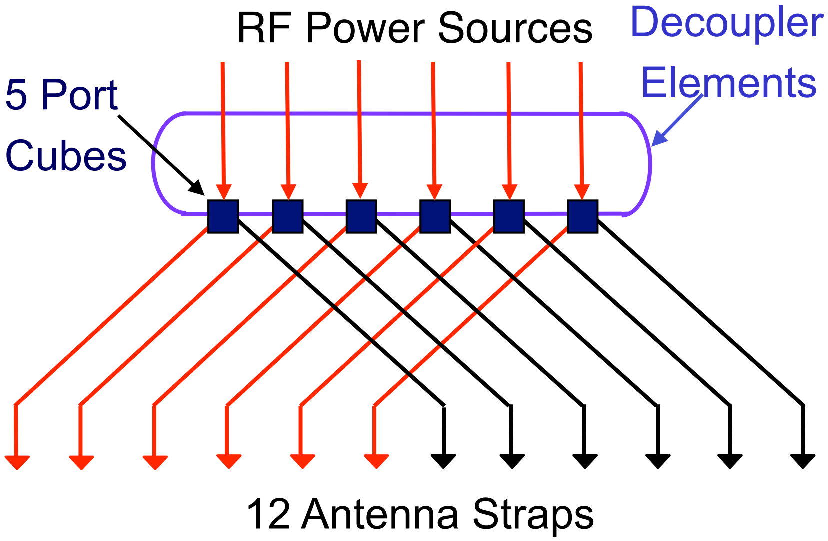
Antenna Upgrade

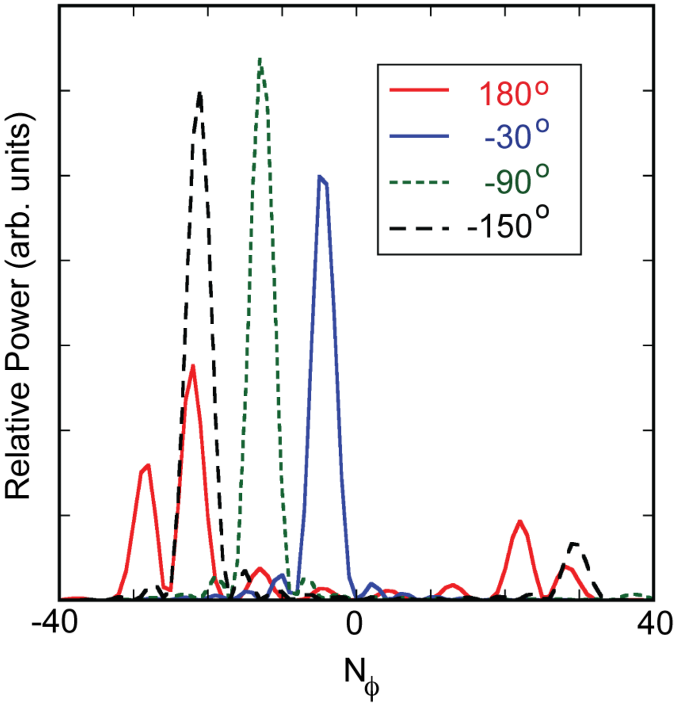
- Double end feed of antenna straps
- Maintaining parallel wave-number selectivity with proper decoupling adjustments

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



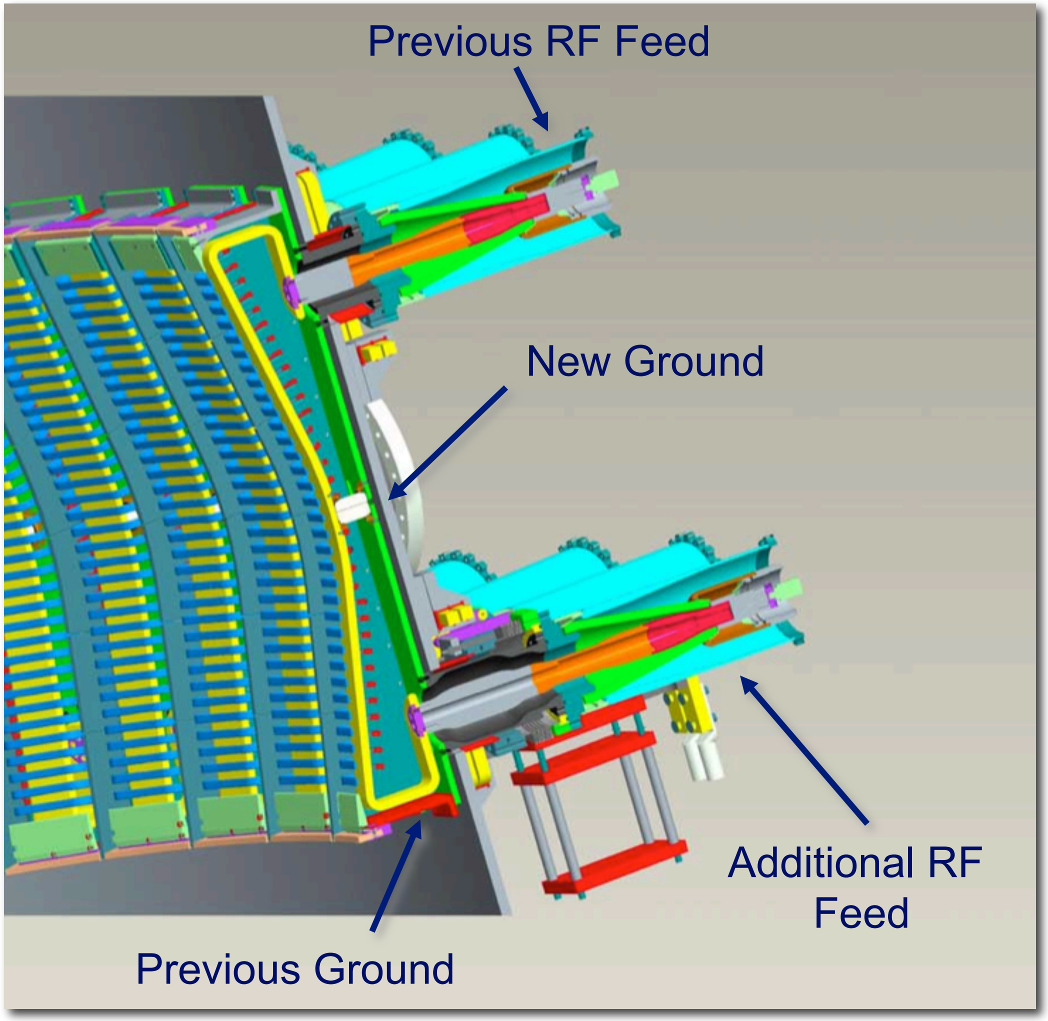
HHFW antenna extends toroidally 90°





- Phase between adjacent straps easily adjusted between 0° to 180°
- Large B pitch affects wave spectrum in plasma core

Antenna upgraded to have feeds at both ends of current straps in order to increase operating voltage

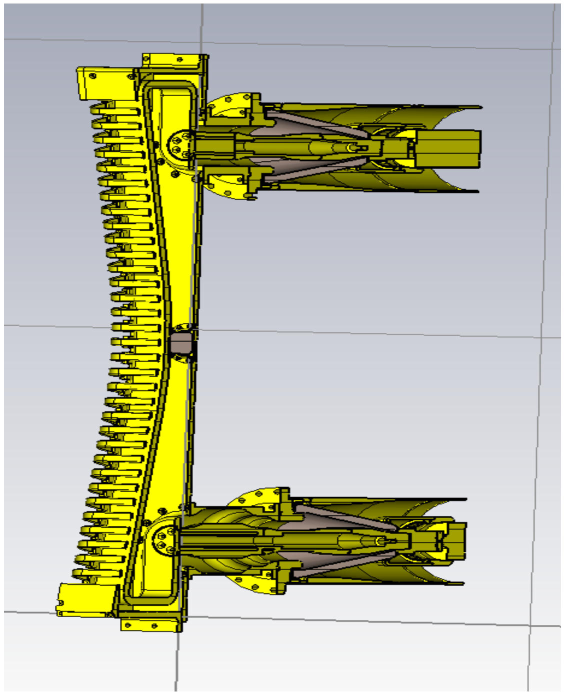


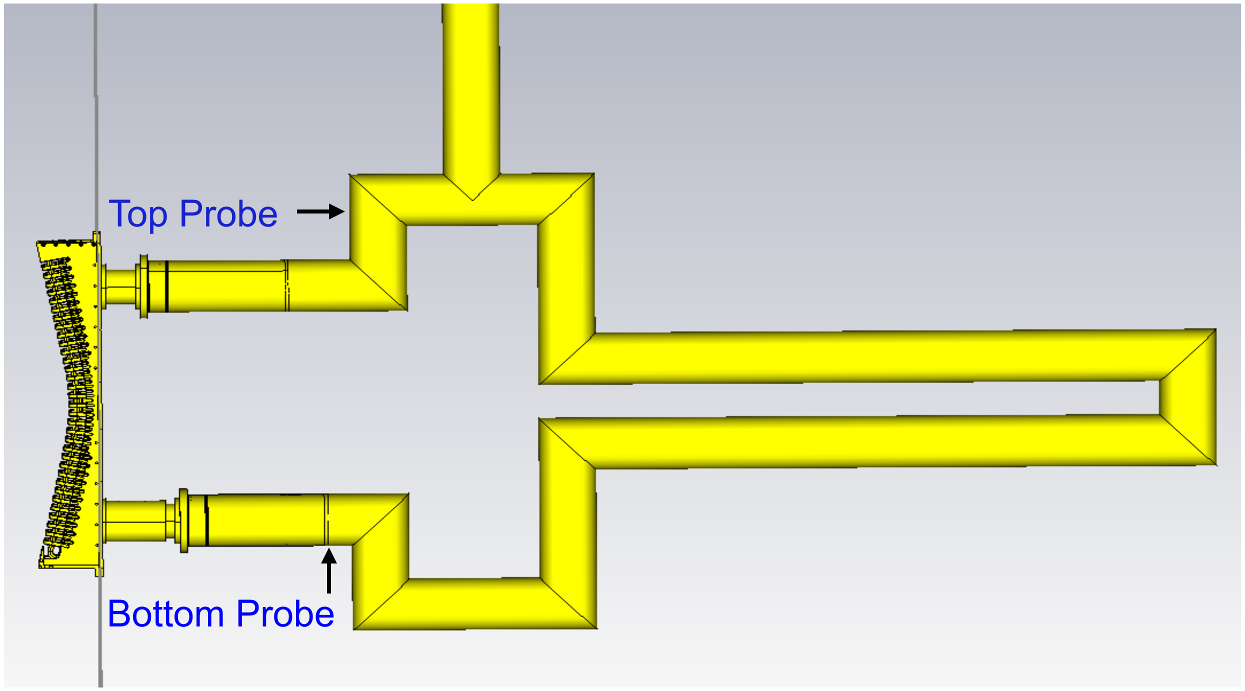
- 2009 Double-feed upgrade shifts ground from end to strap center.
- Lower strap voltage for a given strap current:
  - Approximately double power per strap for the same plasma load.
  - Permits larger plasma-antenna gap (lower load)

Electrical lengths set for resonance at 30 MHz – Antenna loop and cube loop between two antennas

Microwave Studio
used to predict lengths

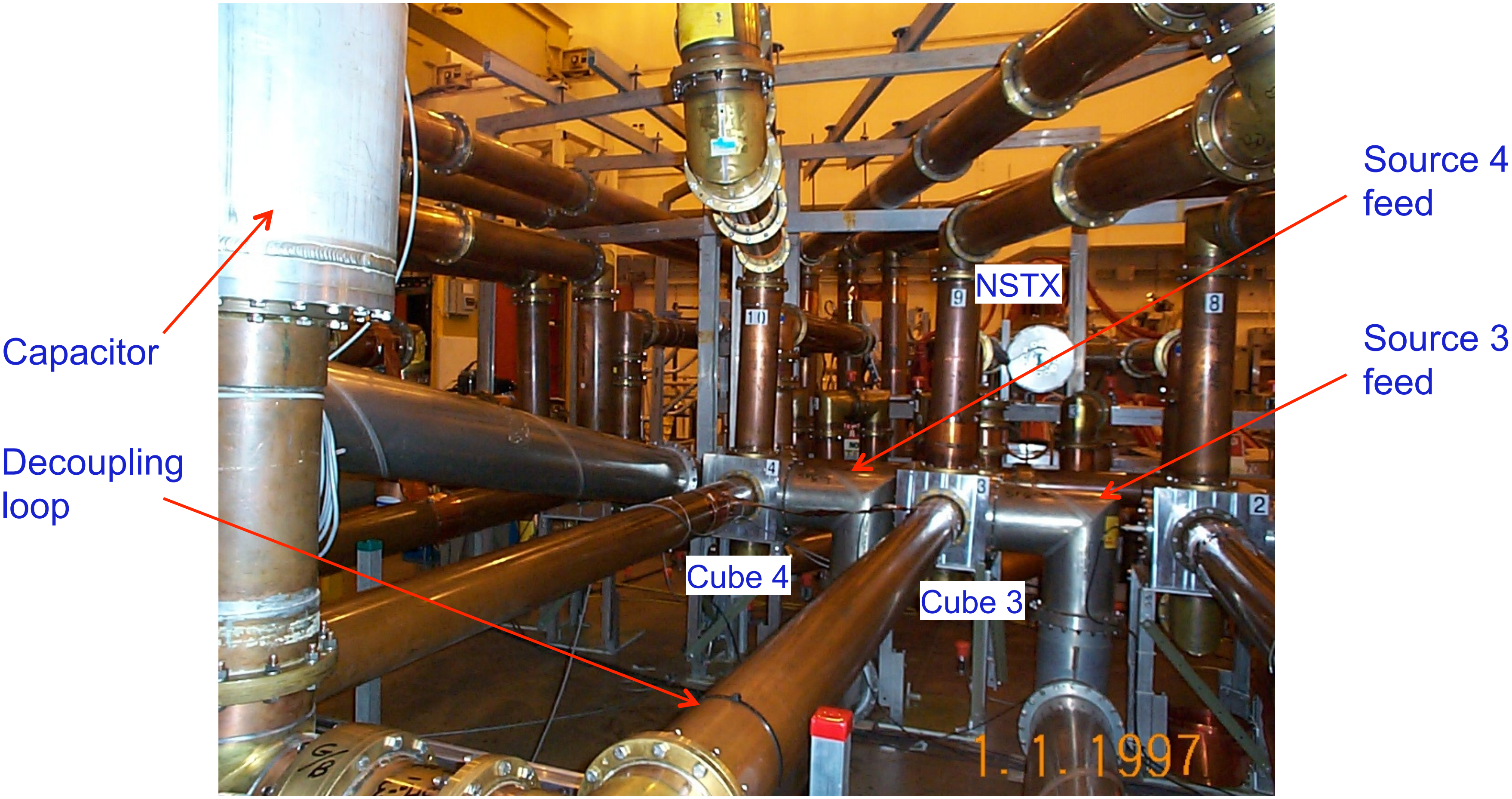
Loops made resonant to within ~ 5 kHz to
permit good decoupling between sources at cubes





- Antenna loop is one wavelength long to provide continuous current along antenna strap
- Similar configuration to that used on TFTR

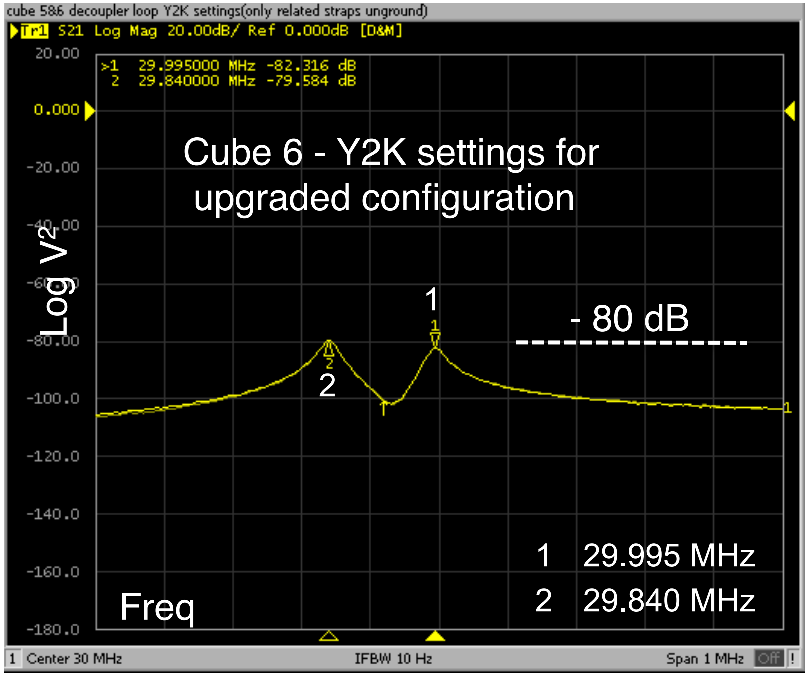
5 decouplers between adjacent source cubes are adjusted with commercial capacitors



- View of cube feed system looking toward NSTX
- Note that the 12 line antenna system takes considerable space even with mostly 6” lines
- ITER IC matching and decoupling system for 8 line antenna system using 12” lines will fill most of the port cell

Decoupler capacitor set to minimize coupling between sources 5 and 6 at cubes

- All antenna feed loops grounded except for those connected to cubes 5 and 6
- Feeding 6 gives two peaks prior to changing capacitor
- One 6 peak with correct capacitor setting to counter mutual coupling to 5
    - – signal at 5 is 33 dB down



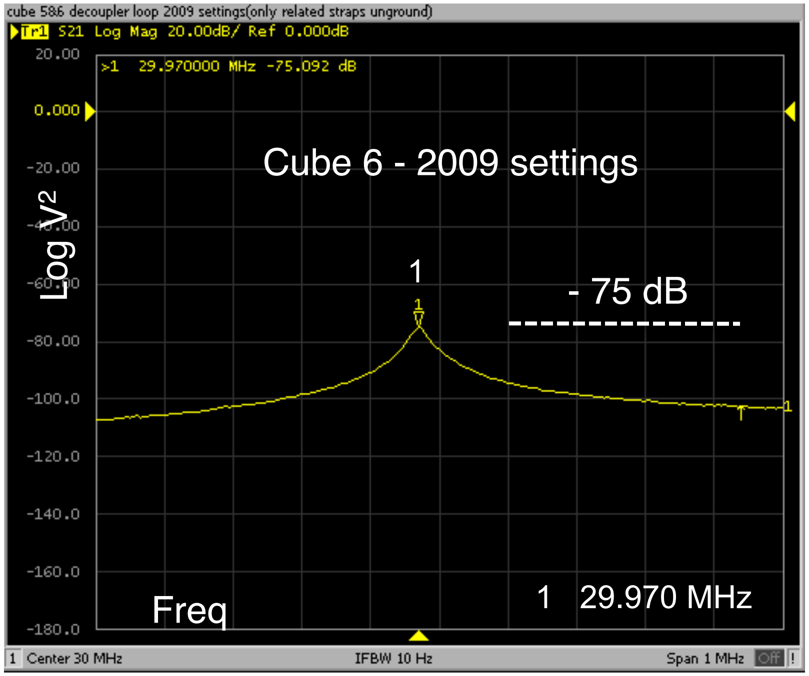
```
cube 5&6 decoupler loop Y2K settings(only related straps unground)
Tr1 S21 Log Mag 20.00dB/ Ref 0.000dB [D&M]
>1  29.995000 MHz -82.316 dB
 2  29.840000 MHz -79.584 dB
1 Center 30 MHz                 IFBW 10 Hz                 Span 1 MHz  Off
```

Cube 6 - Y2K settings for upgraded configuration

- 80 dB

1 29.995 MHz

2 29.840 MHz

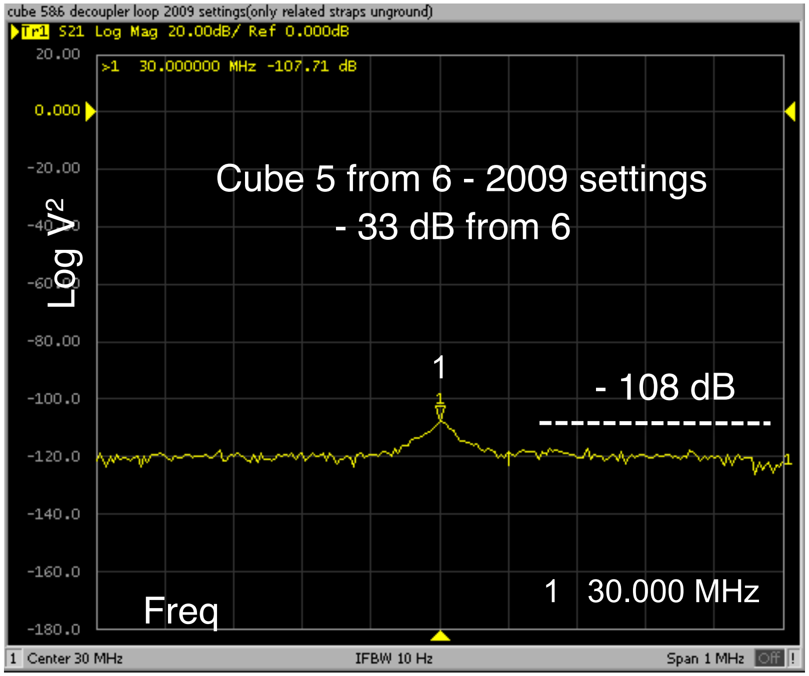


```
cube 5&6 decoupler loop 2009 settings(only related straps unground)
Tr1 S21 Log Mag 20.00dB/ Ref 0.000dB
>1  29.970000 MHz -75.092 dB
1 Center 30 MHz                 IFBW 10 Hz                 Span 1 MHz  Off
```

Cube 6 - 2009 settings

- 75 dB

1 29.970 MHz



```
cube 5&6 decoupler loop 2009 settings(only related straps unground)
Tr1 S21 Log Mag 20.00dB/ Ref 0.000dB
>1  30.000000 MHz -107.71 dB
1 Center 30 MHz                 IFBW 10 Hz                 Span 1 MHz  Off
```

Cube 5 from 6 - 2009 settings
- 33 dB from 6

- 108 dB

1 30.000 MHz

Conditioning for optimum antenna power capability

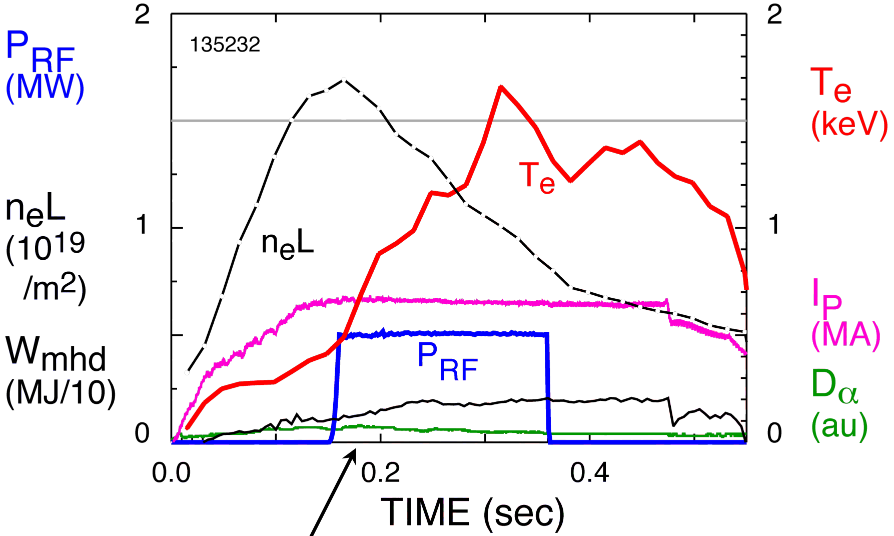
- Effect of lithium on conditioning

- Expulsion of lithium from antenna surfaces appears to cause arcing ⇒ RF magnetic field limit instead of voltage limit

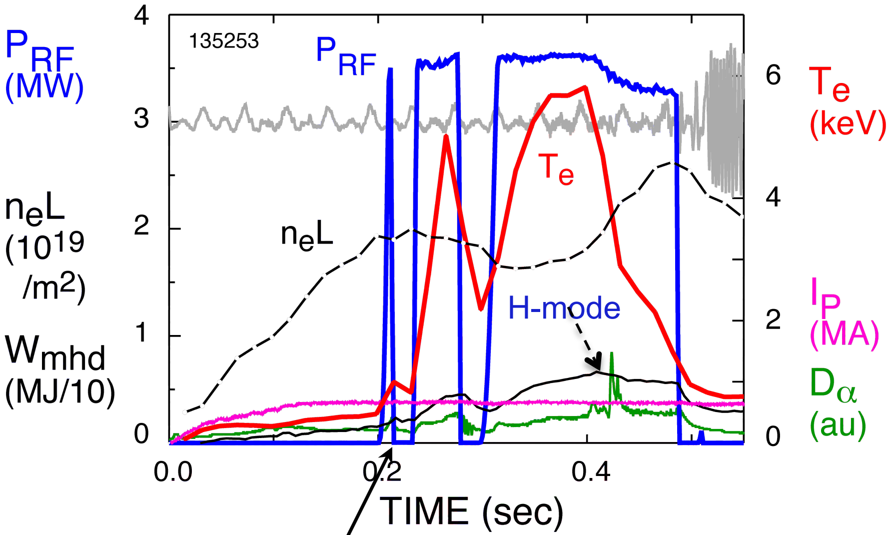
- Predicted voltage enhancement with upgrade not realized but operation more robust after conditioning – sustained H-mode with RF only

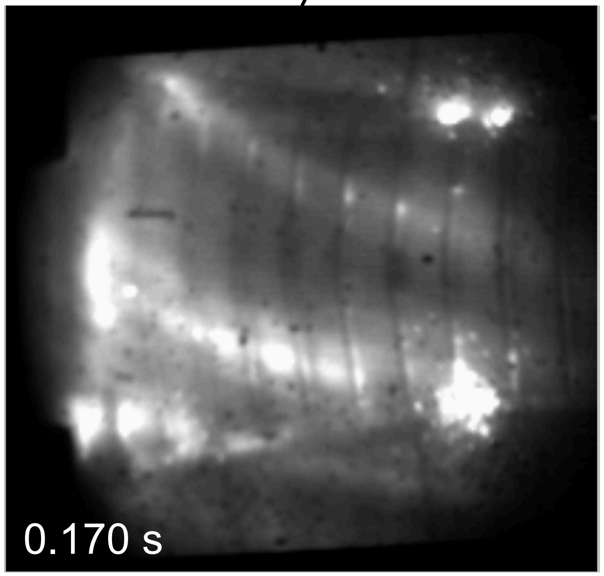
Ejection of material from antenna surfaces appears to be the cause of the arcs during RF plasma operation

Plasma Conditioning: 0.5 MW – no arc



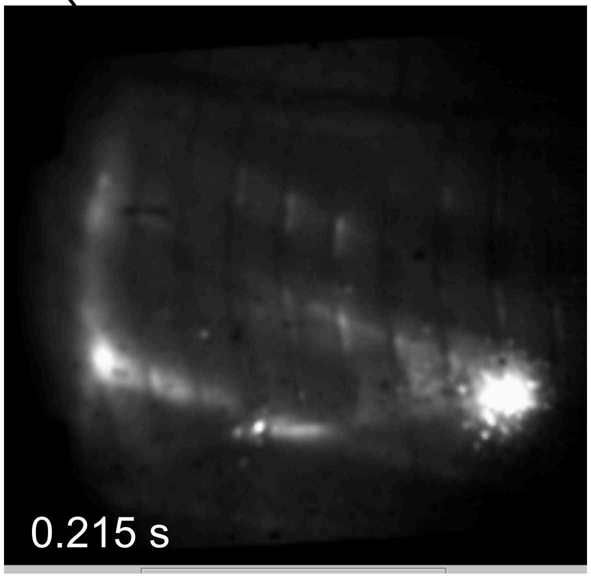
3.7 MW – 2 arcs





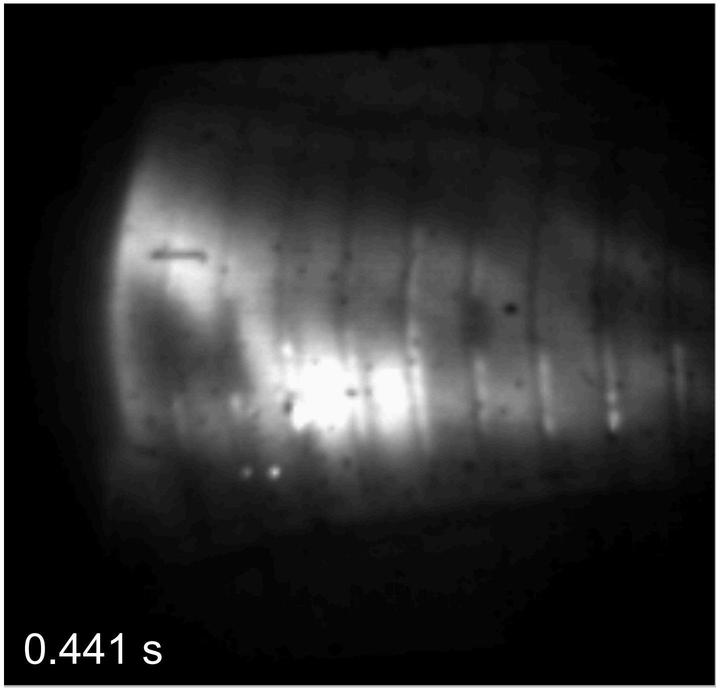
- Lithium sputtering from outside of antenna can cause arcs if material (dust) enters faraday shield enclosure

- 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

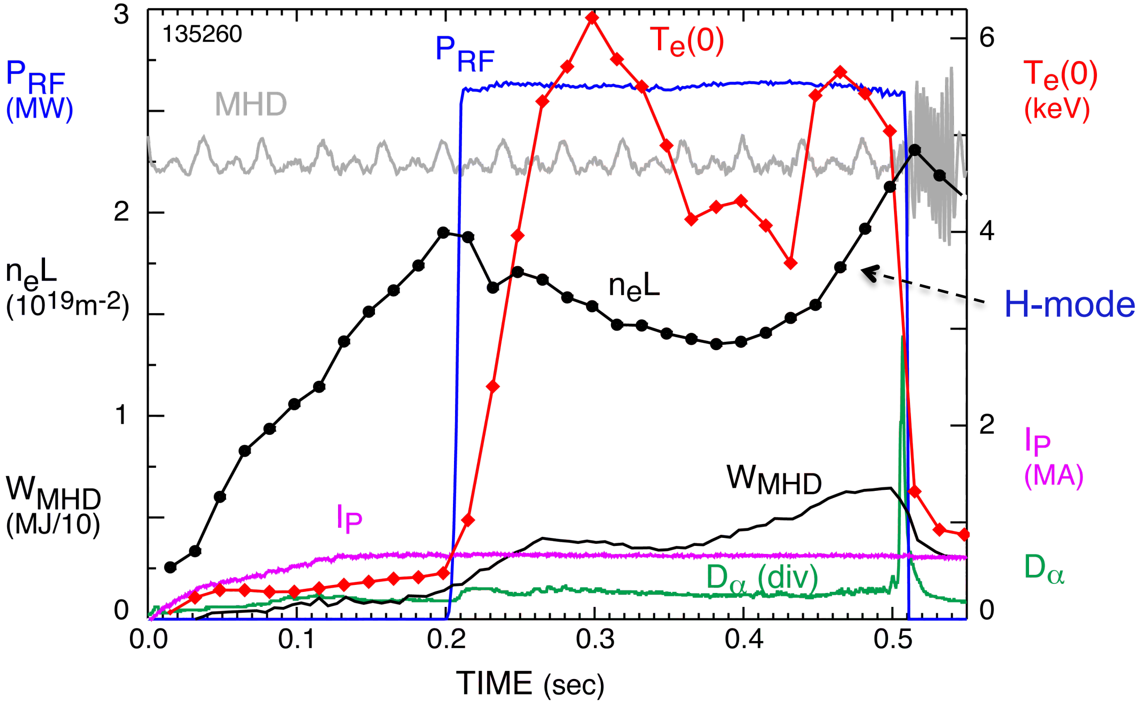


P_{RF} up to 3.7 MW sustained after plasma conditioning to high power

P_{RF} = 2.7 MW case
– no antenna arc



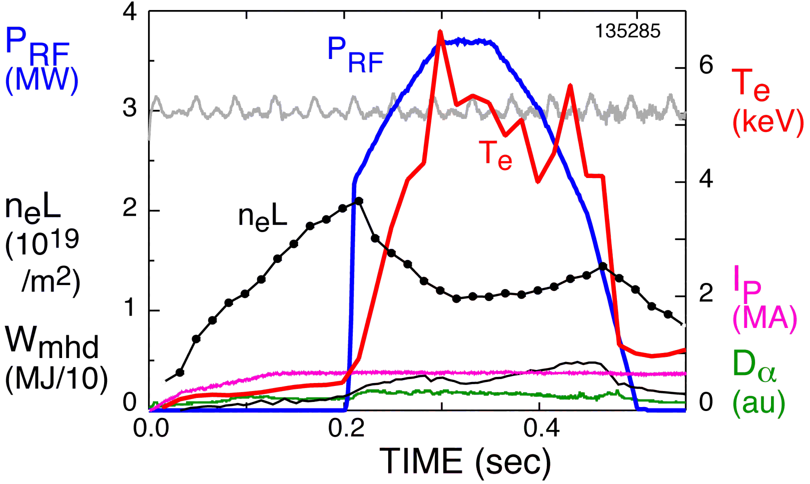
Heating after plasma conditioning with
P_{RF} = 2.7 MW (He, B_ϕ = 0.55T)



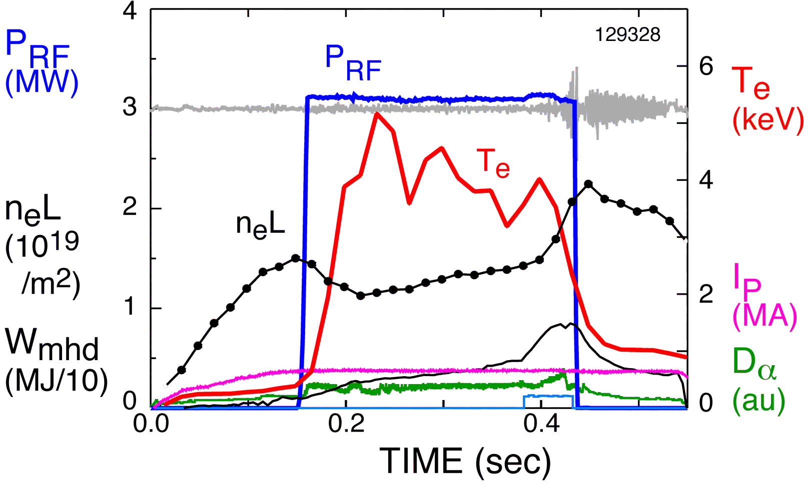
- Example shown above for P_{RF} = 2.7 MW ⇒ $T_e(0)$ up to 6.2 keV
- RF only H-mode produced near end of RF pulse
- Further conditioning indicated to eliminate the sputtering that persists

Power and operating voltage increased somewhat with upgraded antenna after conditioning

After Upgrade - 2009

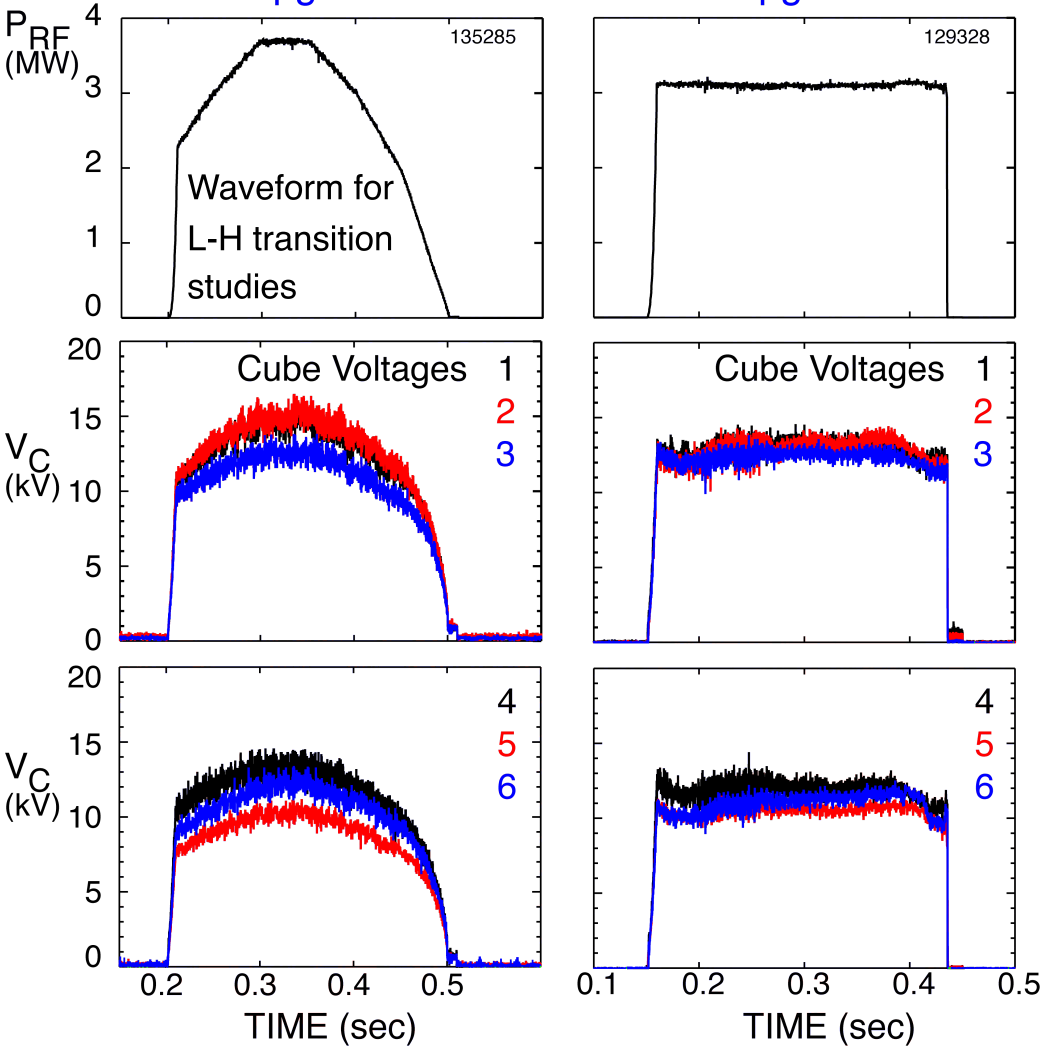


Before Upgrade - 2008



After Upgrade - 2009

Before Upgrade - 2008



- Comparable conditions after conditioning – B_T = 5.5 kG, I_p = 0.65 MA, Helium
- Increase in voltage capability should be greater

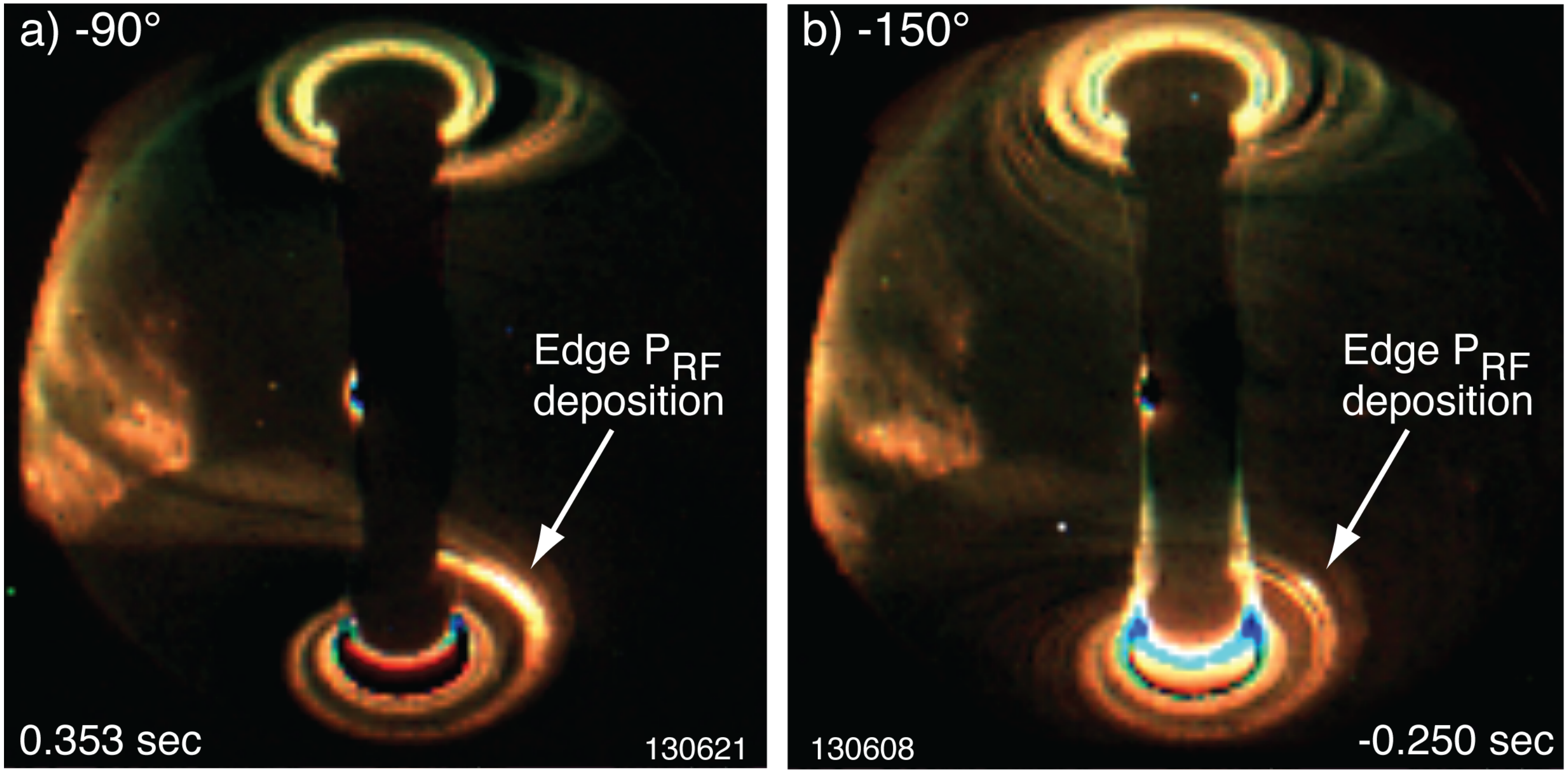
Operation with type 1 ELMs with upgraded antenna

Summary of results to be presented:

- Coupling with type I ELMs
- 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
  - Reliable arc discrimination should allow powering through ELMs

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



- “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

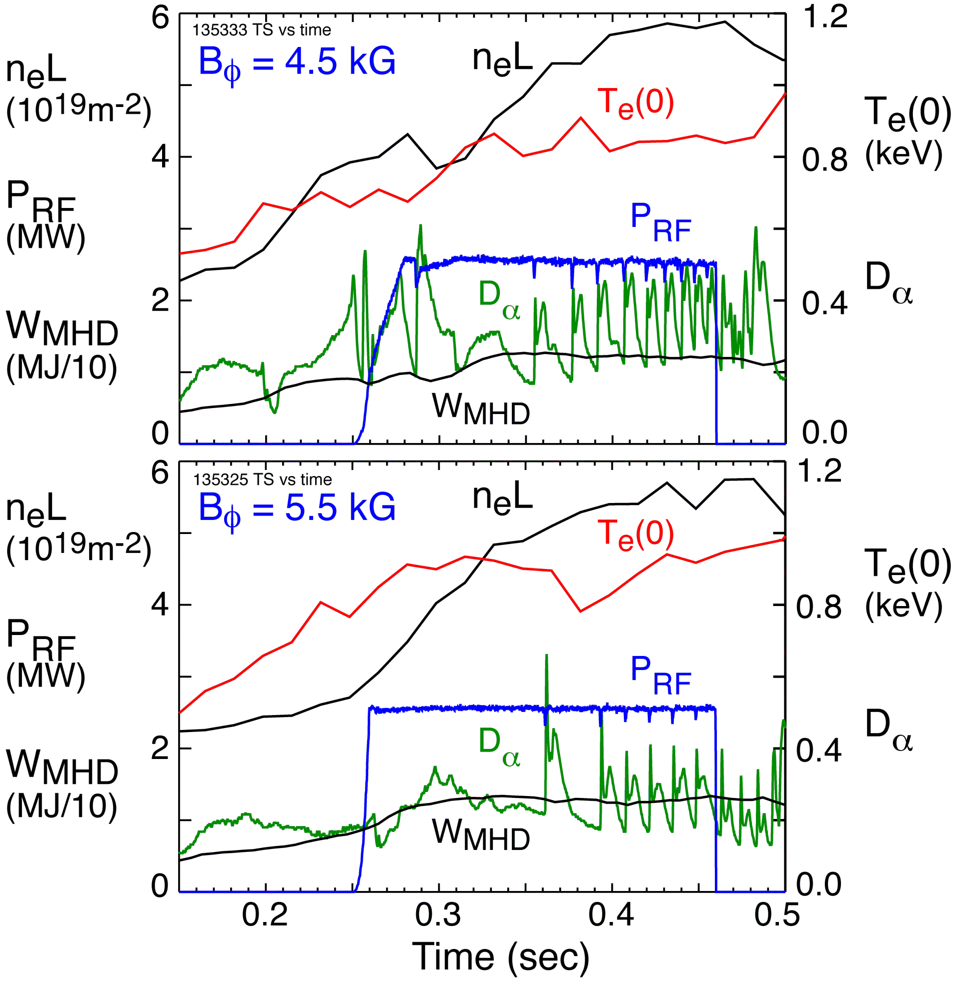
- ELMing discharges studied for I_P = 0.8 MA, P_{NB} = 2 MW versus:

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

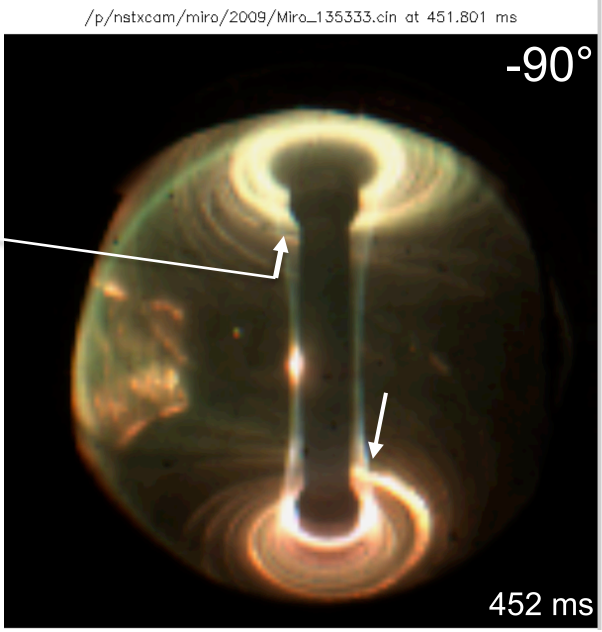
- Edge power loss is increased with higher density and ELMing activity

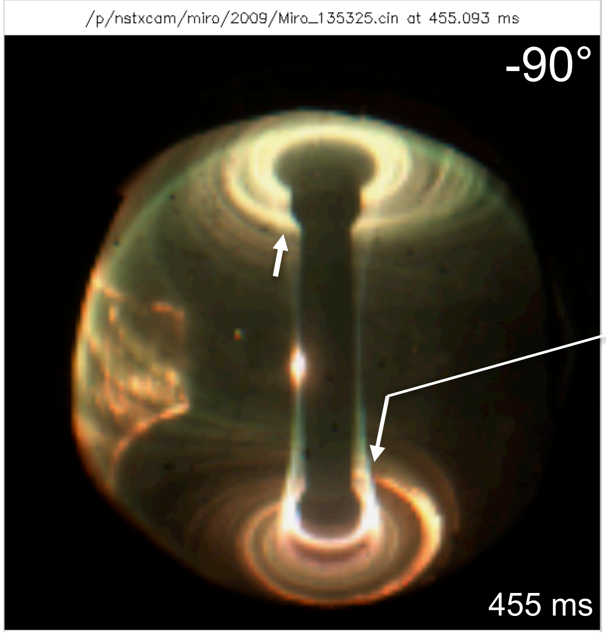
ϕ_A = -90° discharge parameters



RF heated pattern on lower divertor plate follows the magnetic pitch

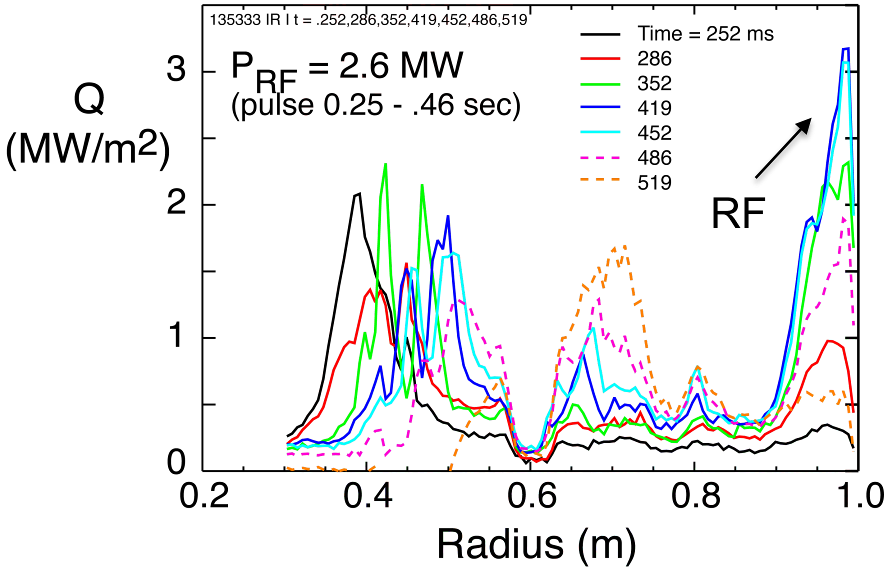
Bay G
IR view



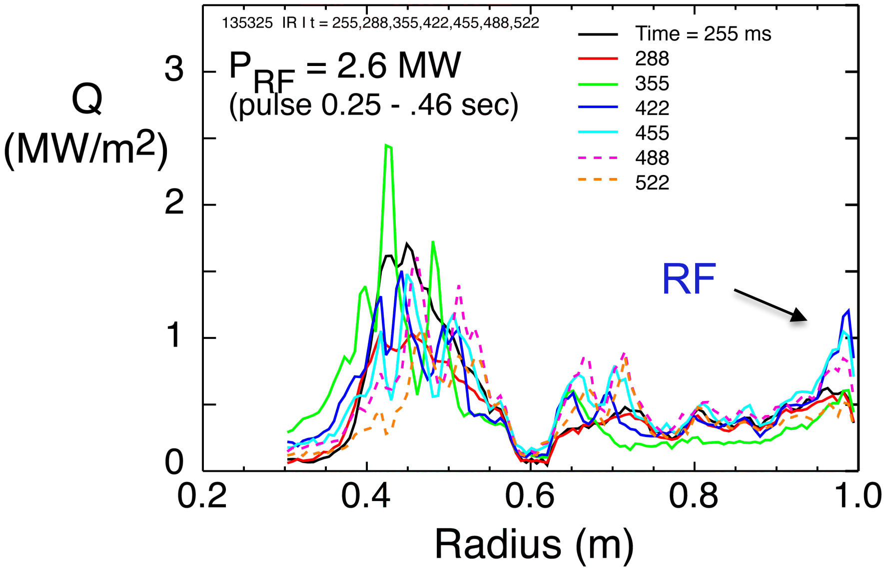


Bay I
IR view

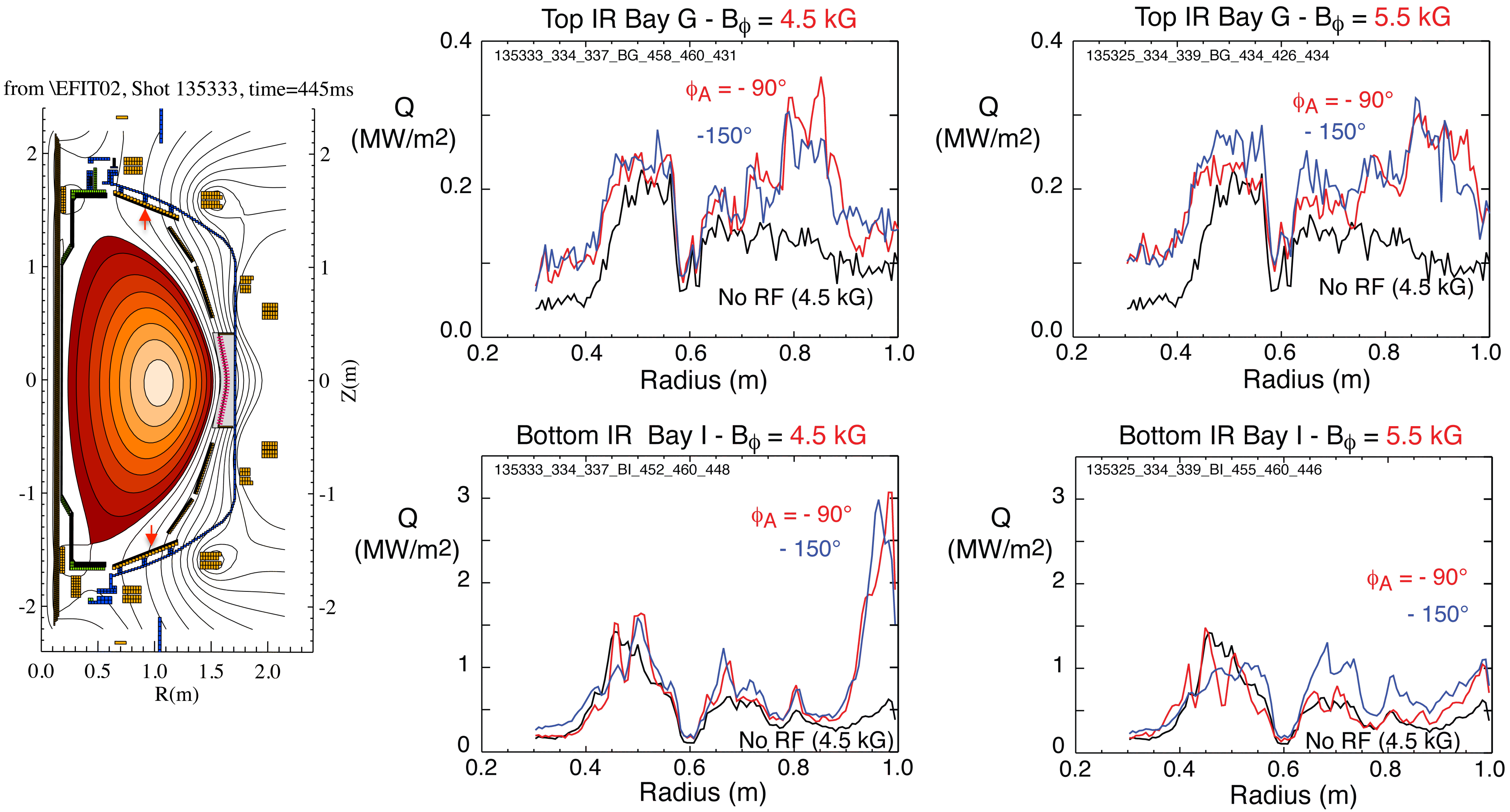
B_ϕ = 4.5 kG, I_P = 0.8 MA



B_ϕ = 5.5 kG, I_P = 0.8 MA



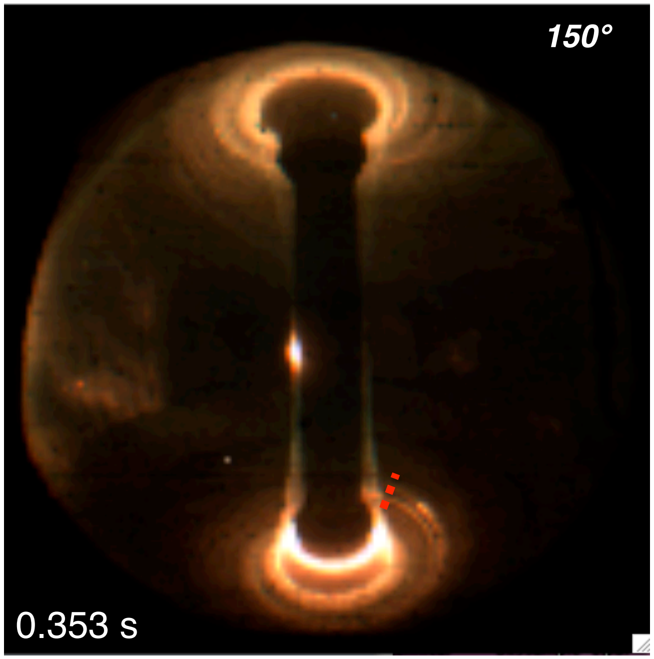
Location of heat zone has significant dependence on field pitch at lower and upper divertor plates


from \EFIT02, Shot 135333, time=445ms

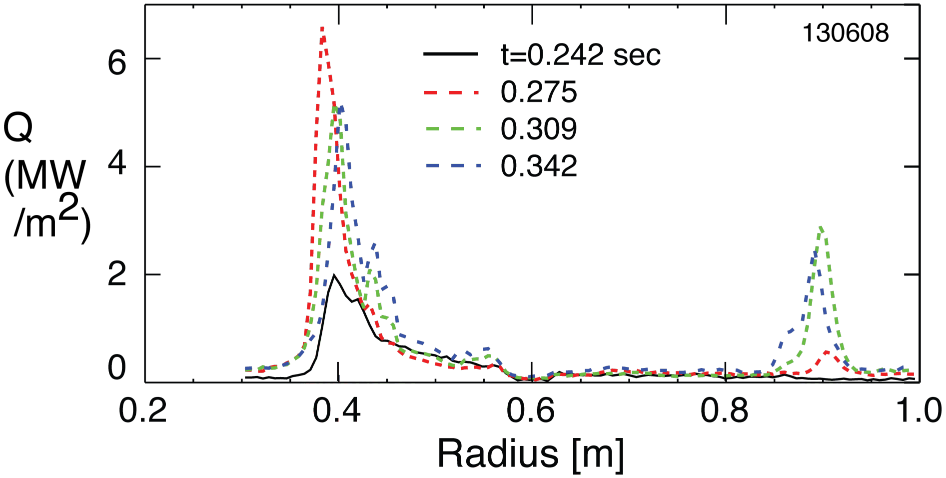
- ~ 8 cm shift outward with reduced field pitch
- Also, possibly a small shift with phase

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

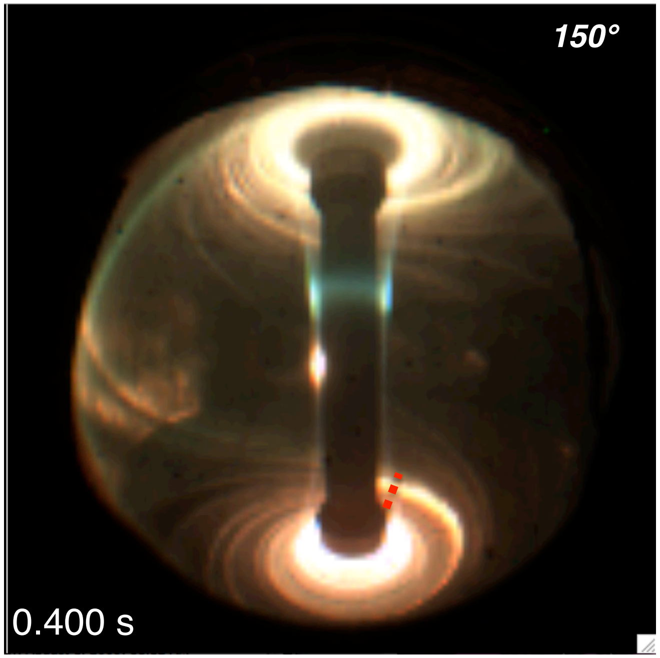
130608 ELM free – 5.5 kG, 1 MA



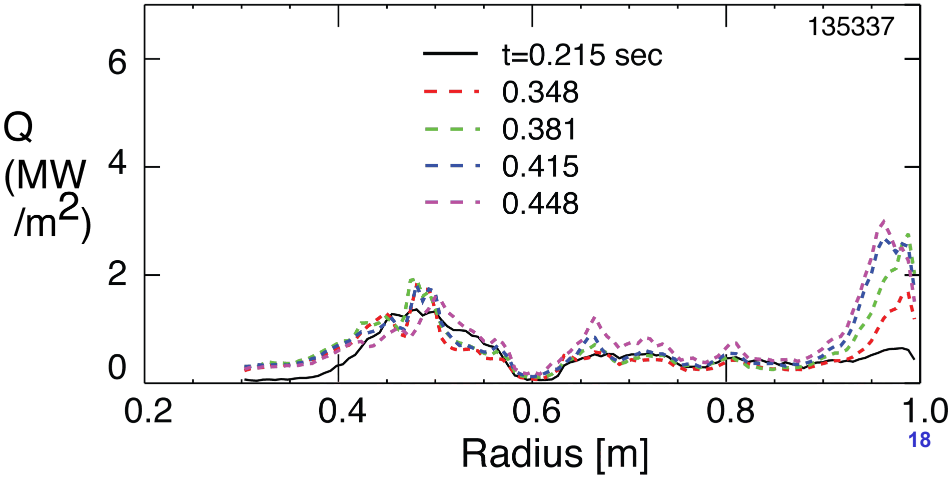
IR Bay I



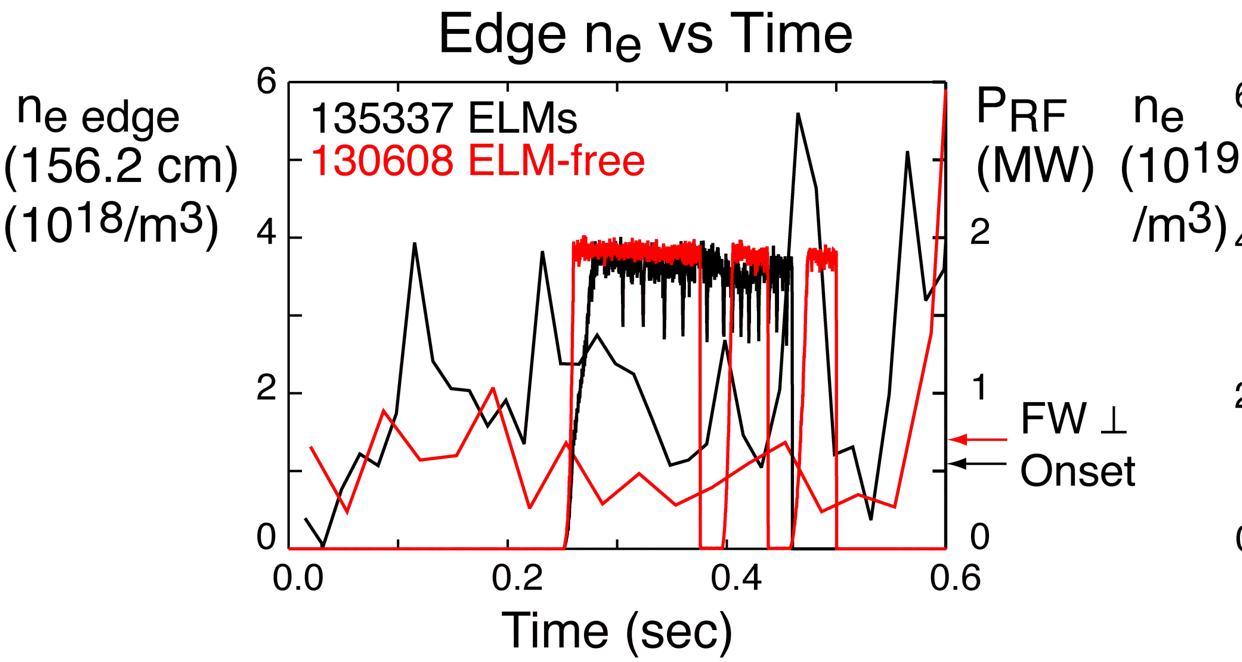
135337 with ELMs – 4.5 kG, 0.8 MA

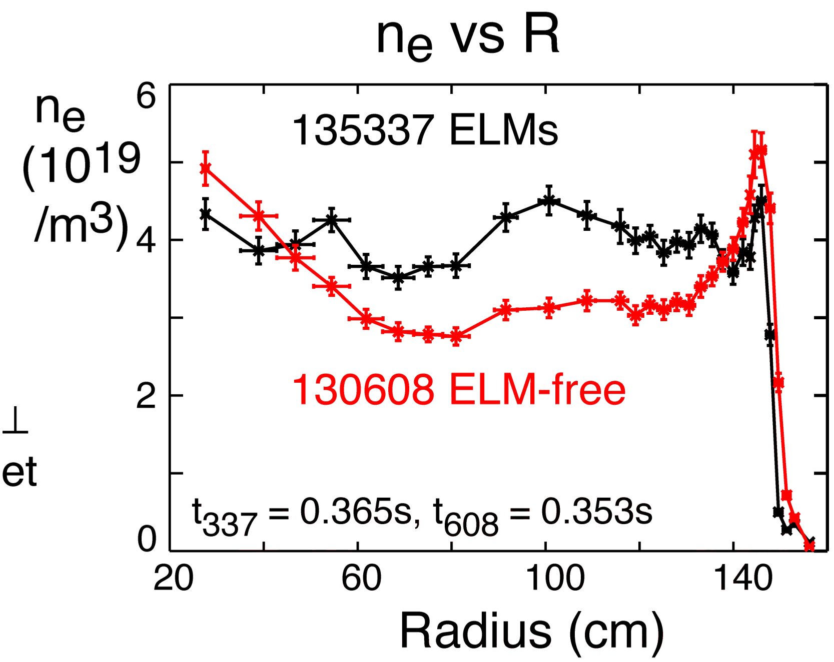


IR Bay I



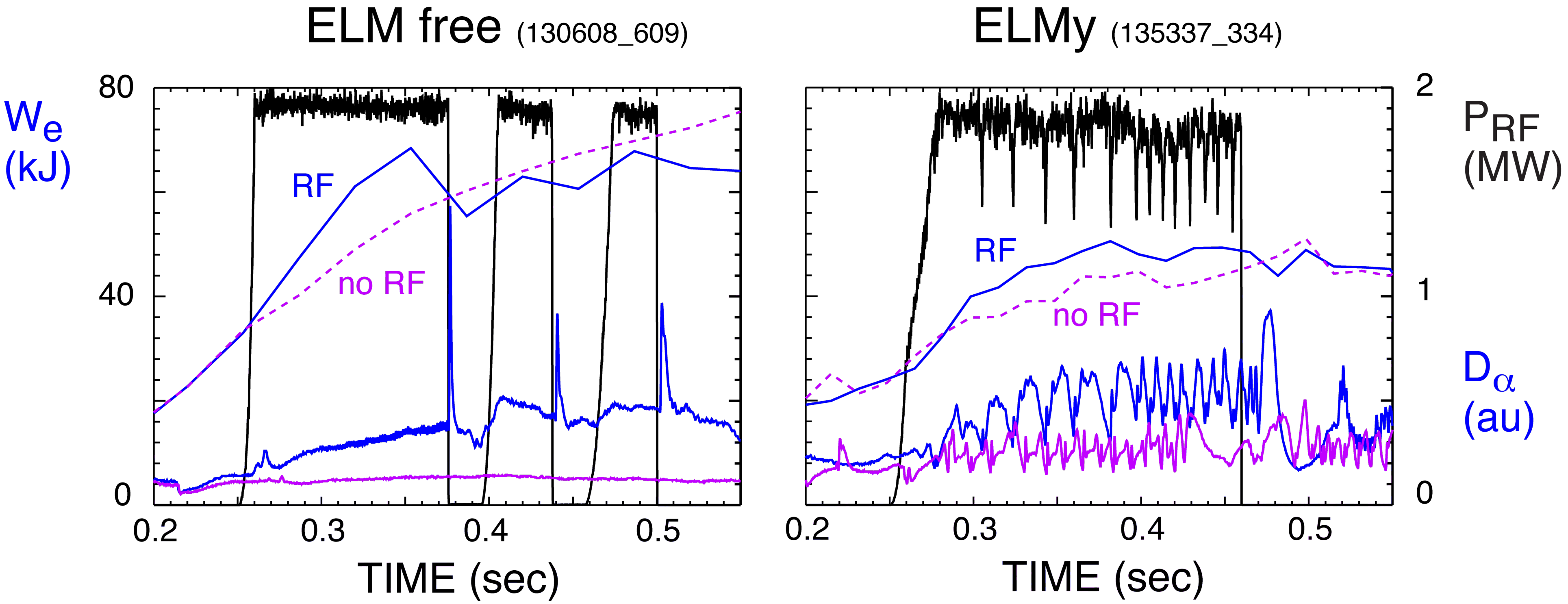
Higher edge loss with ELMs is consistent with higher edge density with ELMs





- 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

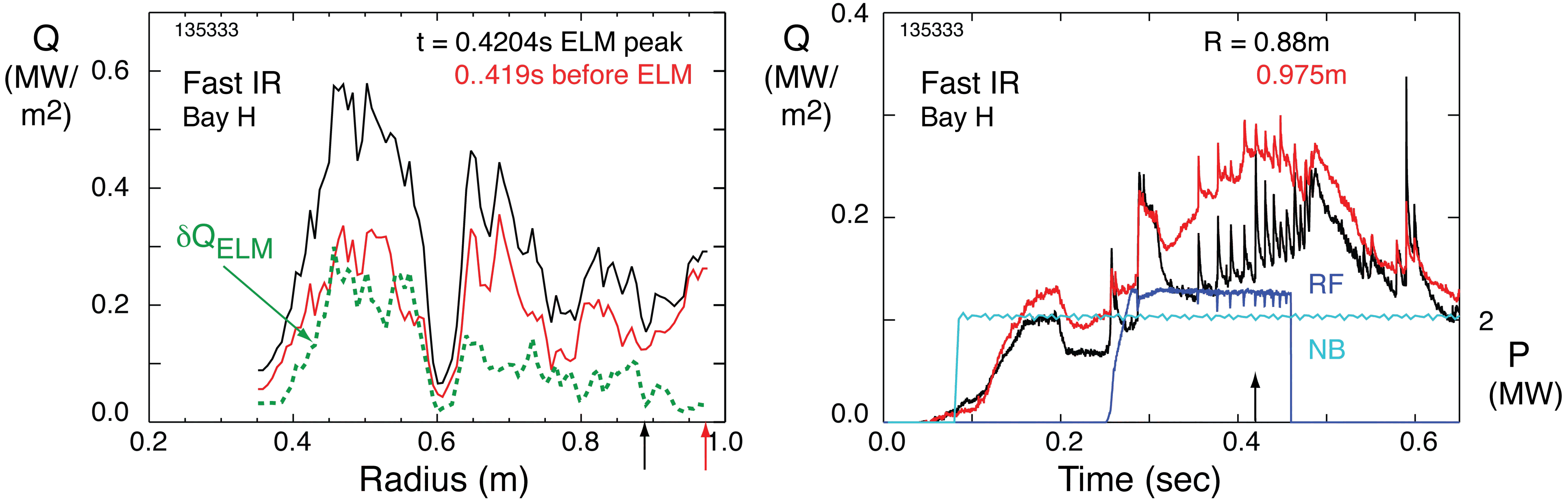
ELMs reduce plasma heating by ejecting energy (as for NB) as well as by producing higher edge density



- 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 loss to divertor directly

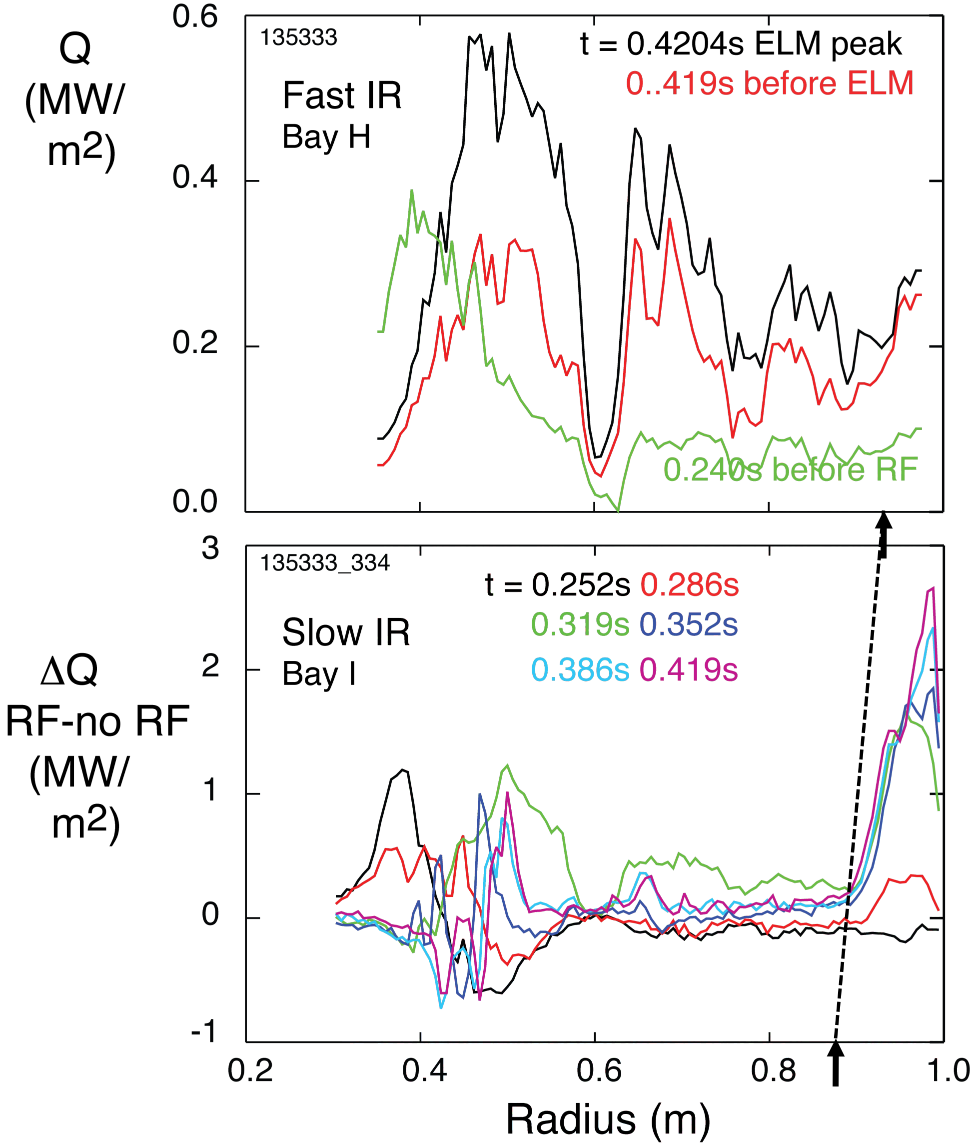
Fast IR at Bay H with Phase = -90°, B_T = 4.5 kG, I_P = 0.8 MA

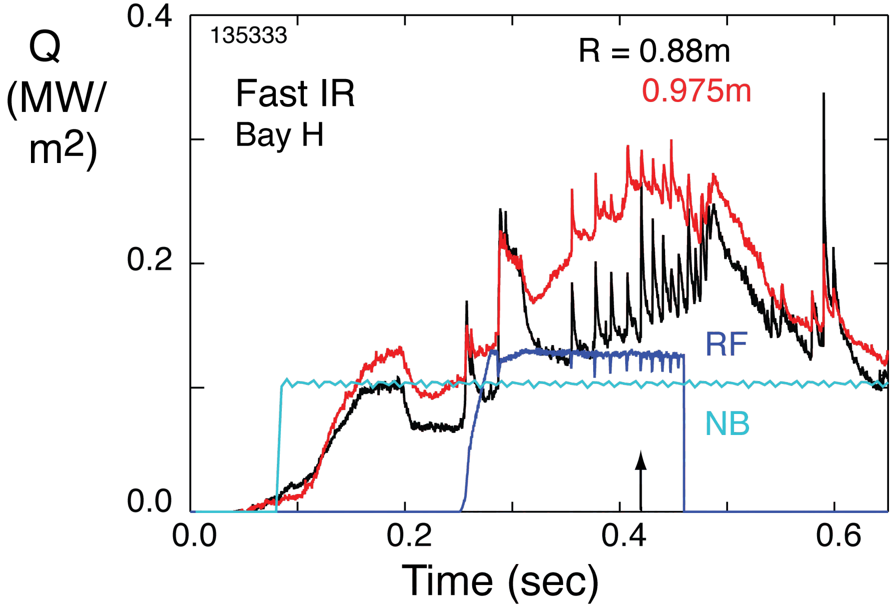


- Key question: does ELM contribute significant heat in the primary RF heated divertor zone?
  - *Probably not*
- Fast IR camera shows ELM heat deposition peaked at outer strike radius – falling to a low value towards the RF heated zone (R ~ 1.1 m)
- Future experiments are planned to determine the ELM effect on the primary RF edge heating zone at Bay H

RF "hot" zone should be in fast IR view at Bay H for I_P = 1 MA at B_T = 4.5 kG

B_T = 4.5 kG, I_P = 0.8 MA case





- Comparison with Bay I indicates shift of peak will suffice for viewing at Bay H
- Does ELM affect hot zone deposition directly?
  - *Again, not likely*

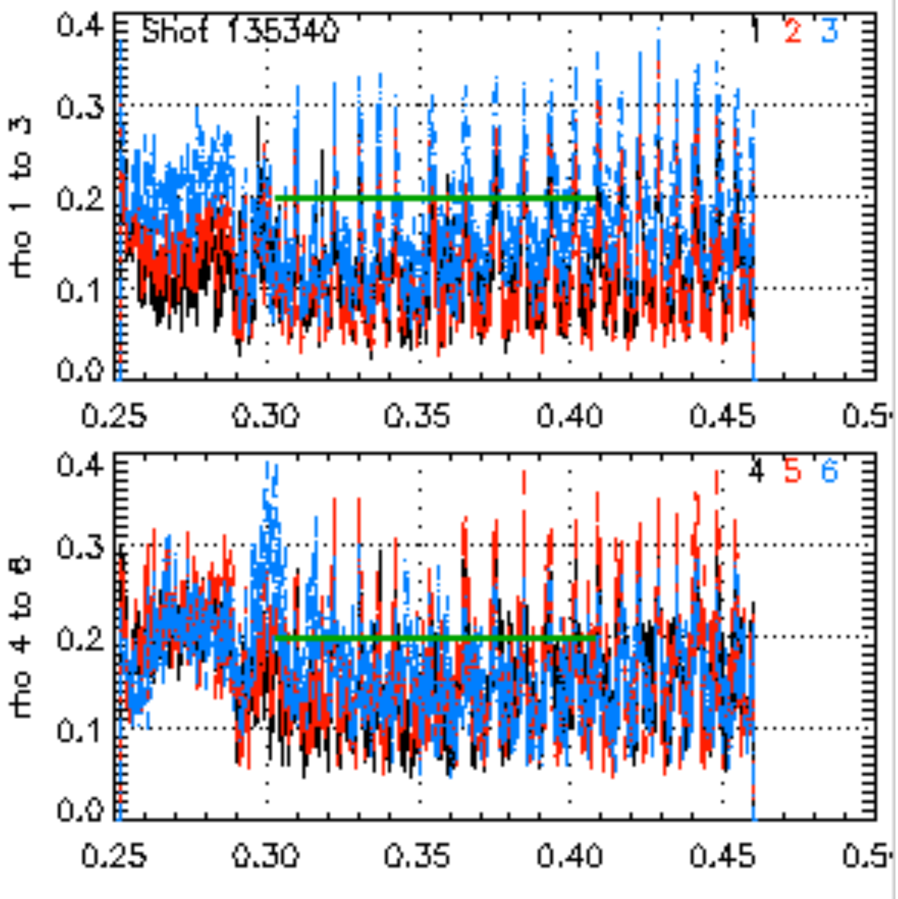
It is apparently not necessary to avoid or reduce coupling during ELMs

- ELM does not appear to interact directly with RF edge power loss
- Reliable arc detection in the presence of ELMs is needed for powering through ELMs
  - Arc detection using the derivatives of the voltage reflection coefficients may provide reliable arc discrimination relative to ELMs

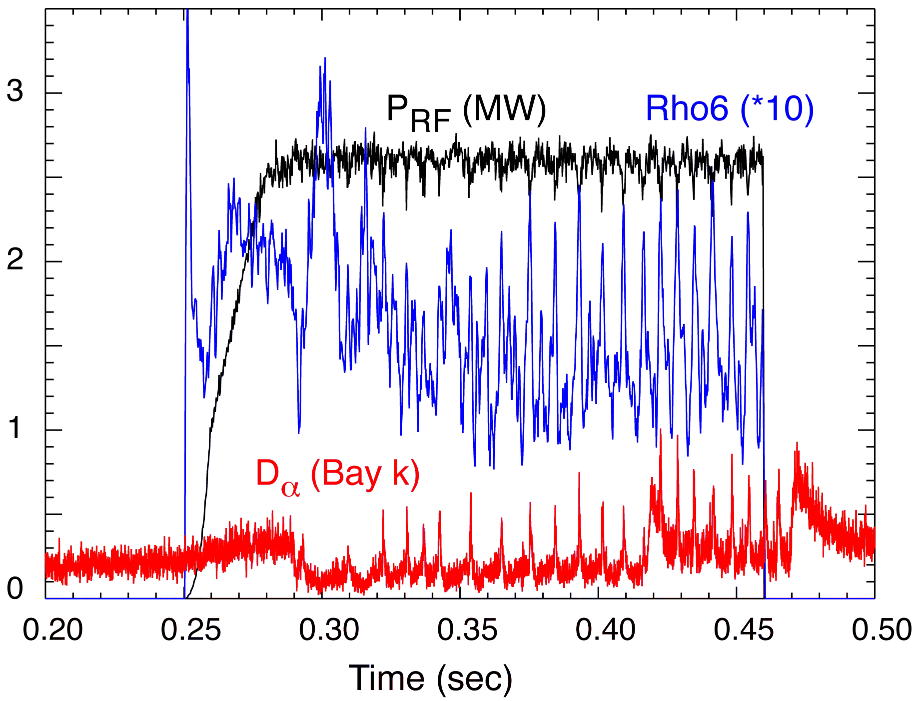
Coupling through ELMs made possible by setting matching level and a high rho trip value (0.7 here)

RF source response to ELMs for Shot 135340

Source voltage reflection coefficients



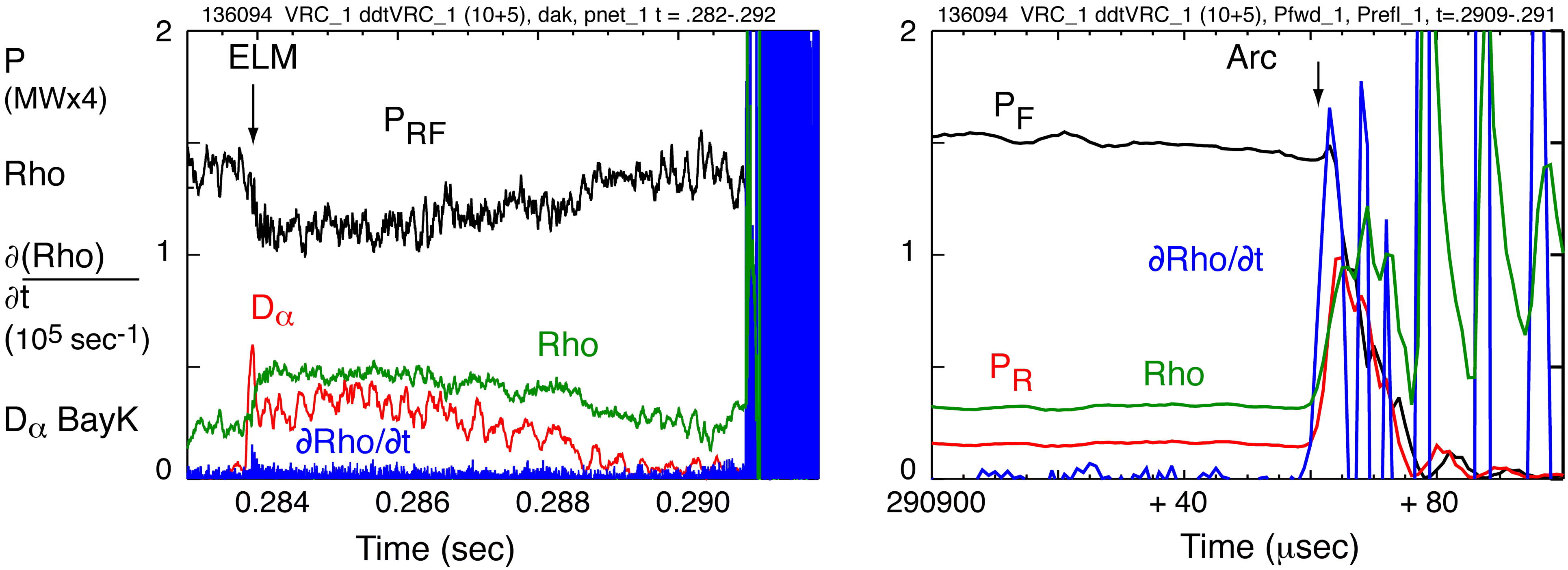
ELM behavior



- Safe coupling through ELMs requires a reliable arc detection scheme that can ignore ELM reflection coefficient

Detecting arcs with the time derivative of the voltage reflection coefficient allows powering through ELMs

Fast digitization parameters for source 2



- ∂rho/∂t gives a sharp peak at an arc which is about an order of magnitude larger than at the ELM
  - *rise time of arc ~ 3 μsec, of ELM ~ 50 μsec*
- Ringing occurs in the transmission system after source turn off
- Should be possible to frequency discriminate against arcs (e.g. high pass/low pass filter)

Summary

- Upgraded antenna commissioned
  - Good decoupling restored
- Lithium on antenna affects maximum power achieved
  - Plasma conditioning allowed higher power operation and more robust heating of H-mode plasmas with upgraded antenna
  - H-mode regimes established without and with NB injection
- RF edge power loss is increased with ELMs
  - Losses from SOL in front of antenna to the outer divertor plate linked along the magnetic field lines are greater than for ELM-free case
  - Increase appears to be linked to higher edge density with ELMs
  - ELM heat deposition is peaked at the outer strike radius and appears to have little direct interaction with the RF heated region – future experiments planned to be sure
- Arcs are not due to increase in reflection coefficient by ELM
  - Can power RF through an ELM in the absence of an arc
  - Time derivative of reflection coefficient can be used to discriminate between ELMs and arcs