NSTX

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

High Harmonic Fast Wave Heating Studies for L and H Mode NSTX Plasmas

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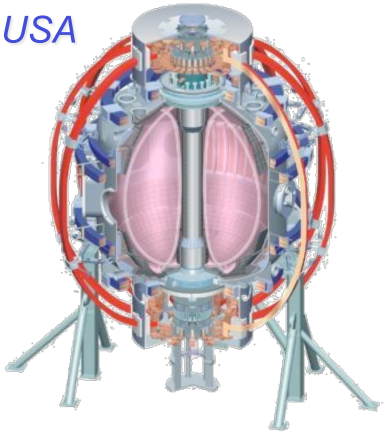

APS-DPP Meeting
Atlanta, Georgia, November 2-6, 2009

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ABSTRACT

Fast wave research on NSTX is directed toward understanding the coupling of some RF power to edge loss processes. These losses are driven in the vicinity of the antenna as opposed to resulting from multi-pass edge damping. PDI edge losses through ion-electron collisions and direct energetic ion losses appear to be significant, the latter possibly causing clamping of the edge rotation. Deuterium H-mode heating studies reveal that core heating is degraded at lower k_ϕ (- 8 m^{-1} relative to 13 m^{-1}) as for the L-mode case at elevated edge density, consistent with edge wave damping depending on the location of the onset density ($n_{onset} \propto B^* k_{||}^2/\omega$) relative to the position of the antenna. Fast visible camera images clearly indicate that a major fast wave edge loss process is occurring from the plasma scrape off layer (SOL) in the vicinity of the antenna and along the magnetic field lines to the lower outer divertor plate. Large type I ELMs, which are observed at both k_f values, appear after antenna arcs caused by precursor blobs, low level ELMs, or possibly dust. For large ELMs without arcs, the source reflection coefficients rise on a 0.1 ms time scale, suggesting that this rise time might be used to discriminate between ELMs and arcs.

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

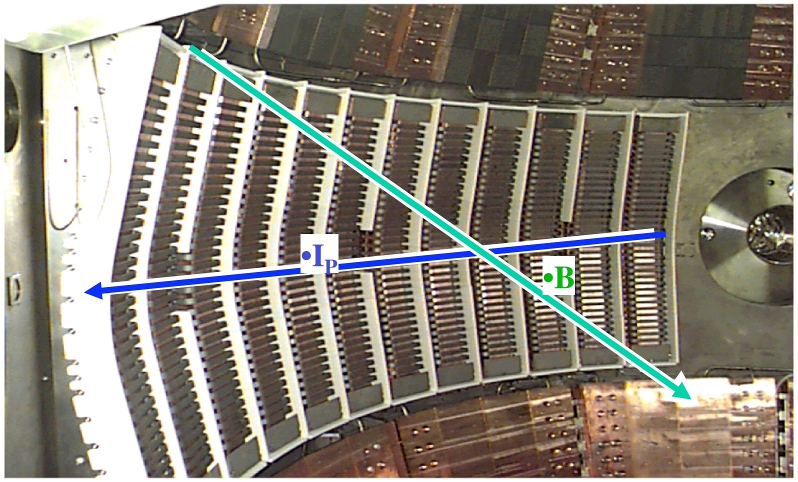
Need to maximize RF power coupling to core plasma and minimize power coupling to the edge plasma

Outline:

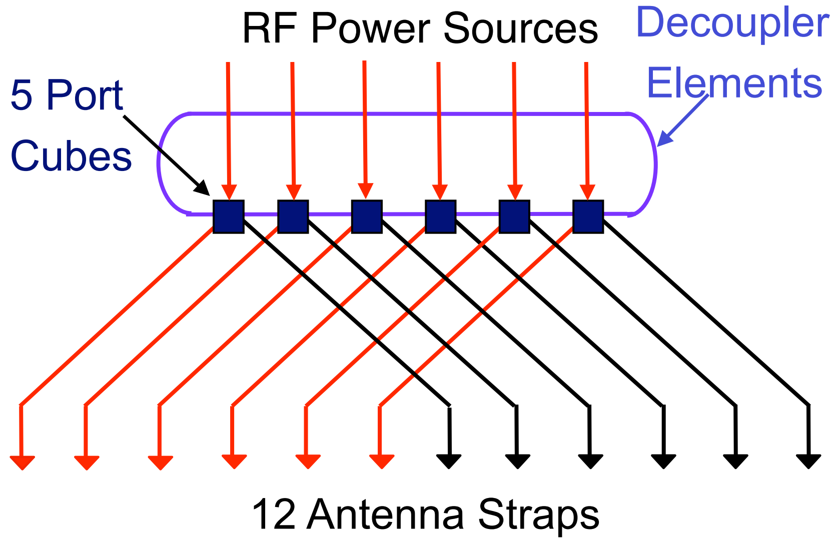
- L-mode coupling
  - Fast wave edge losses
  - PDI produced energetic ion losses

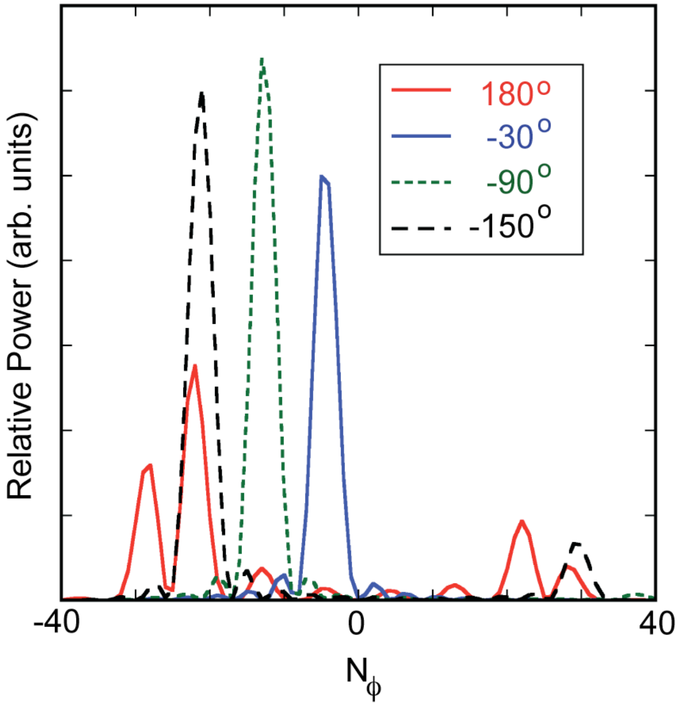
- H-mode coupling
  - Fast wave edge losses
  - Losses in scrapeoff region to the outer divertor scrape off zone – heated region dependence on magnetic field pitch and wavenumber
  - Coupling with type I ELMs
  - Arc detection in the presence of large ELMs using the derivatives of the reflection coefficients

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



HHFW antenna extends toroidally 90°



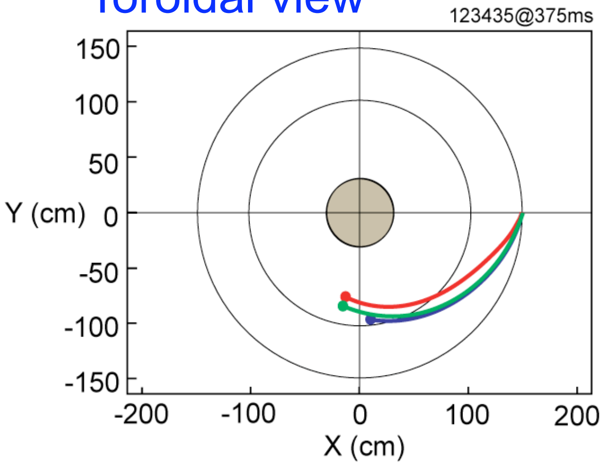


- Phase between adjacent straps easily adjusted between 0° to 180°
- Large B pitch affects wave spectrum in plasma core

Strong "single pass" absorption ideal for studying competition between core heating and edge power loss

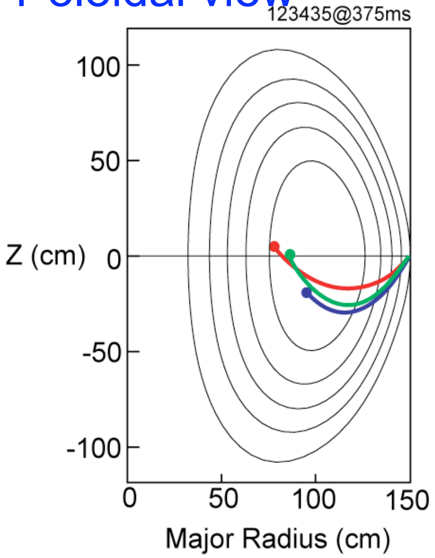
GENRAY:

Toroidal view



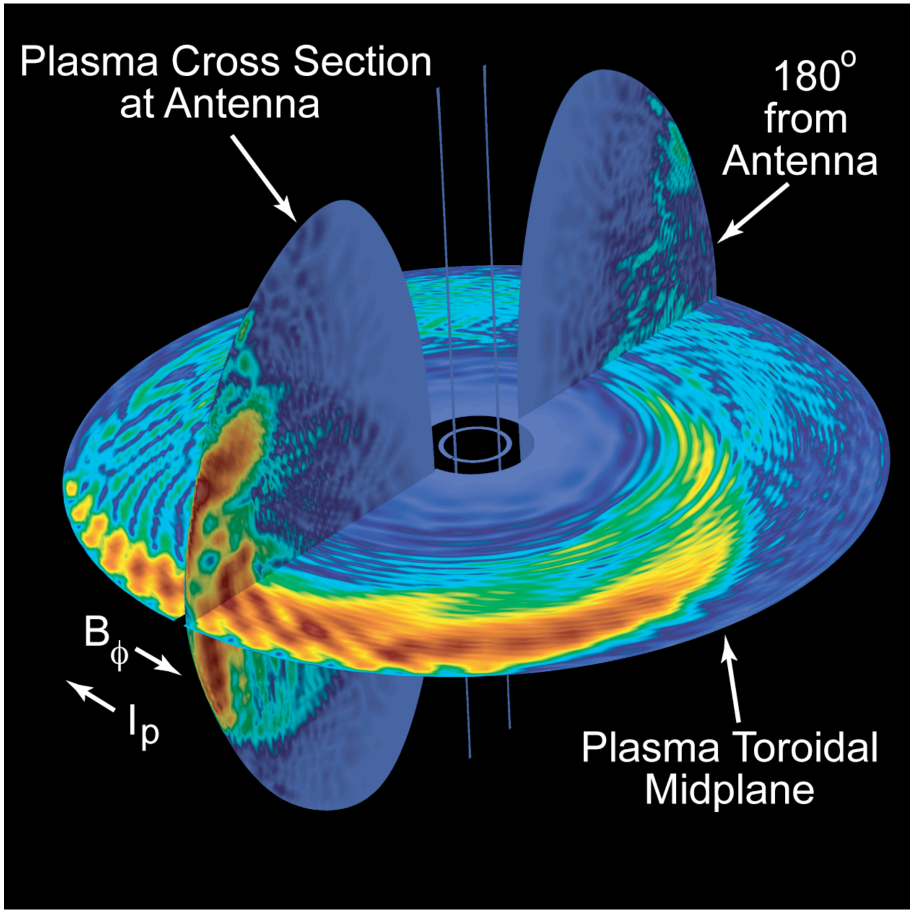
— -30°
— 180°
— -90°

Poloidal view



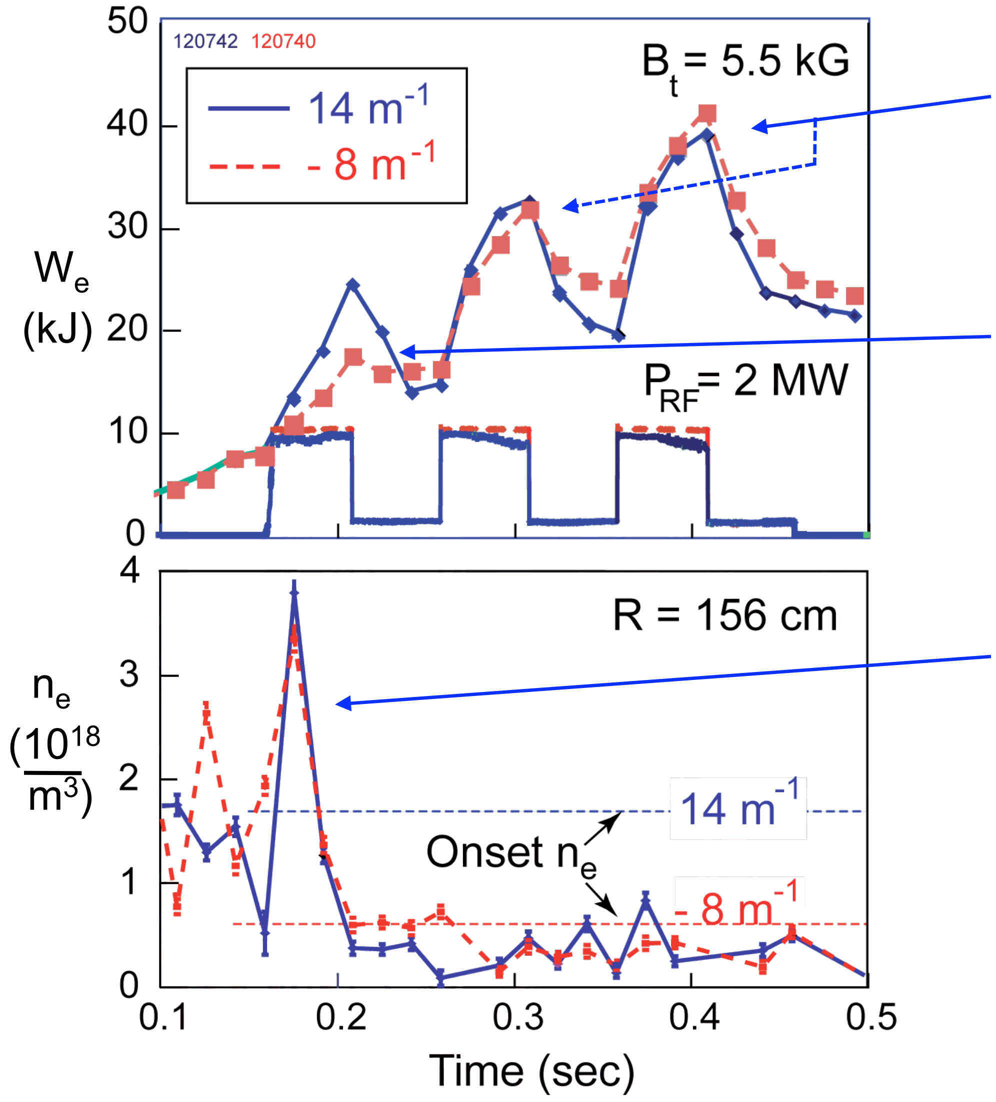
rays stopped at 80% deposition

AORSA: $|E_{RF}|$ field amplitude for -90° antenna phase case with 101 n_ϕ



- Edge power loss occurs in the vicinity of the antenna -- there is no multi-pass damping

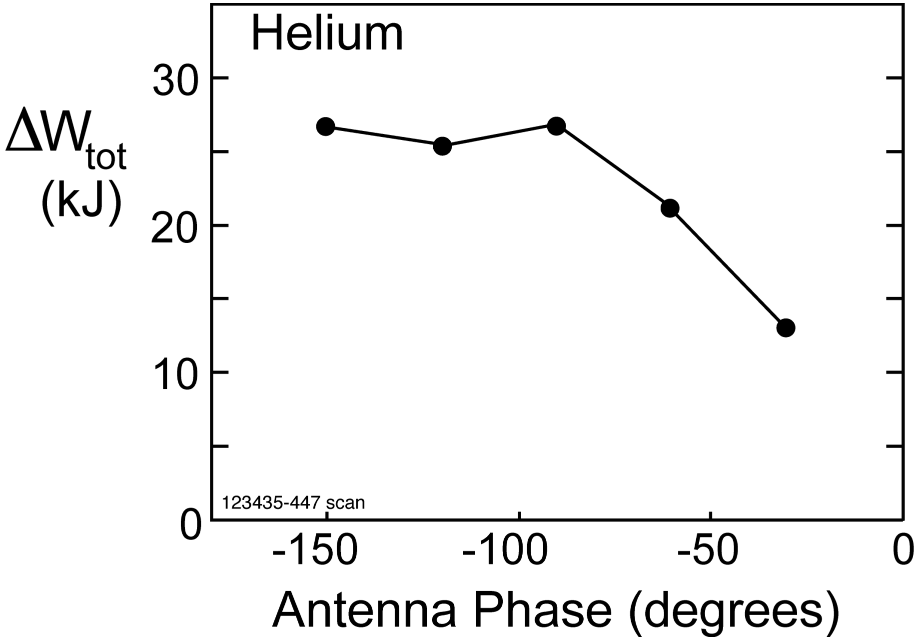
Edge power loss increases when perpendicular propagation onset density is near antenna/wall



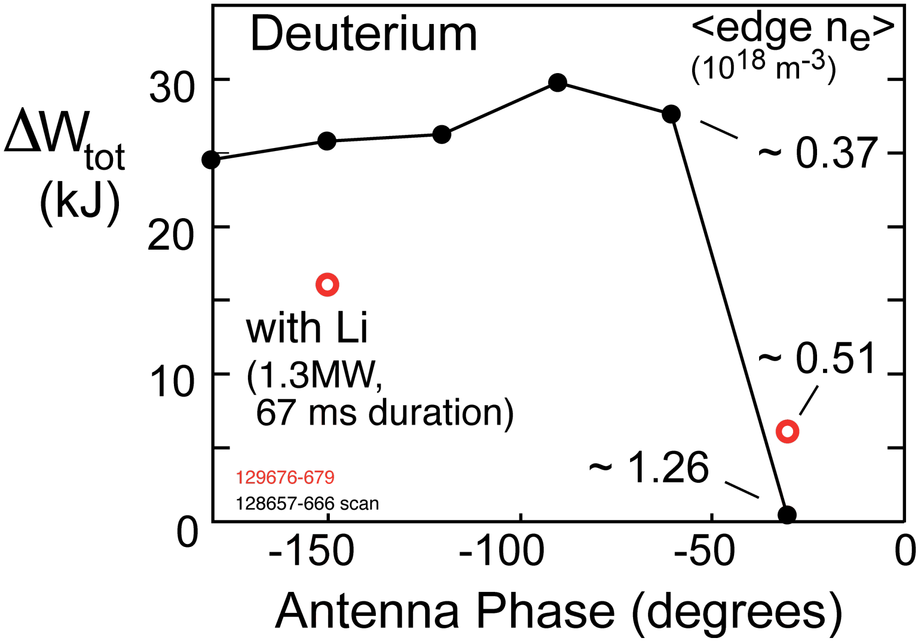
- ΔW_e at - 8 m^{-1} and 14 m^{-1} comparable for the last two RF pulses with low edge density
- ΔW_e at - 8 m^{-1} about half ΔW_e at 14 m^{-1} for the first pulse with large edge density
- Edge density affects heating when above onset density close to antenna, consistent with surface wave propagation near antenna/wall contributing to RF losses
  - $n_{onset} \propto B * k_{||}^2 / \omega$

RF-induced increase in stored energy maintained at low edge density in Helium and Deuterium plasmas

P_{rf} ~ 1.8 MW in He-4 plasmas
(~ 80 ms duration)

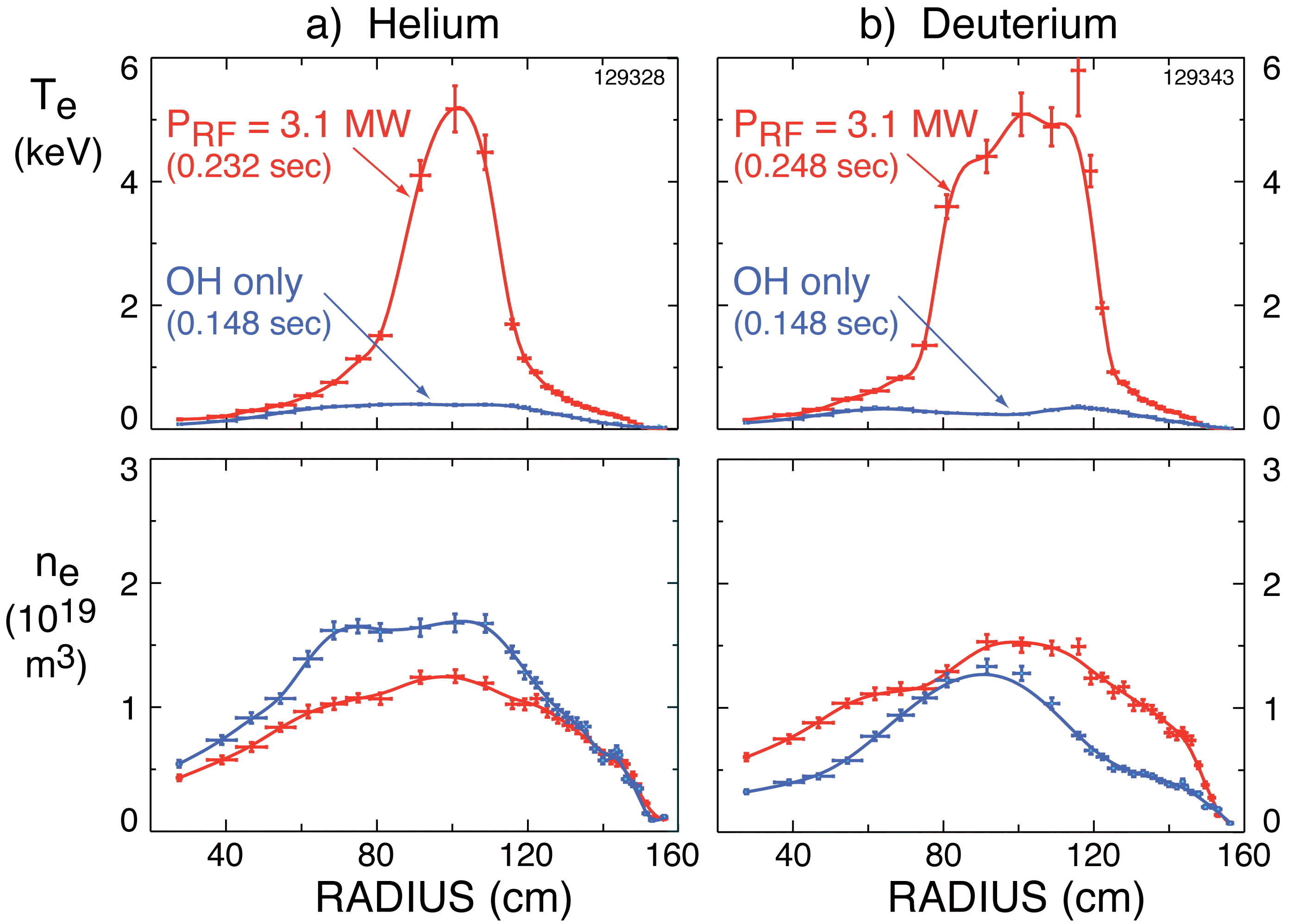


P_{rf} ~ 1.1 MW in D plasmas
(~230 ms duration)



- Fall off occurs when edge density exceeds onset density for perpendicular propagation of fast wave
- First measured increase in deuterium at -30° degrees (lithium injection)
- Very little heating at -30° in deuterium at elevated edge density

HHFW heating for -90° current drive phasing is greatly improved at low edge density

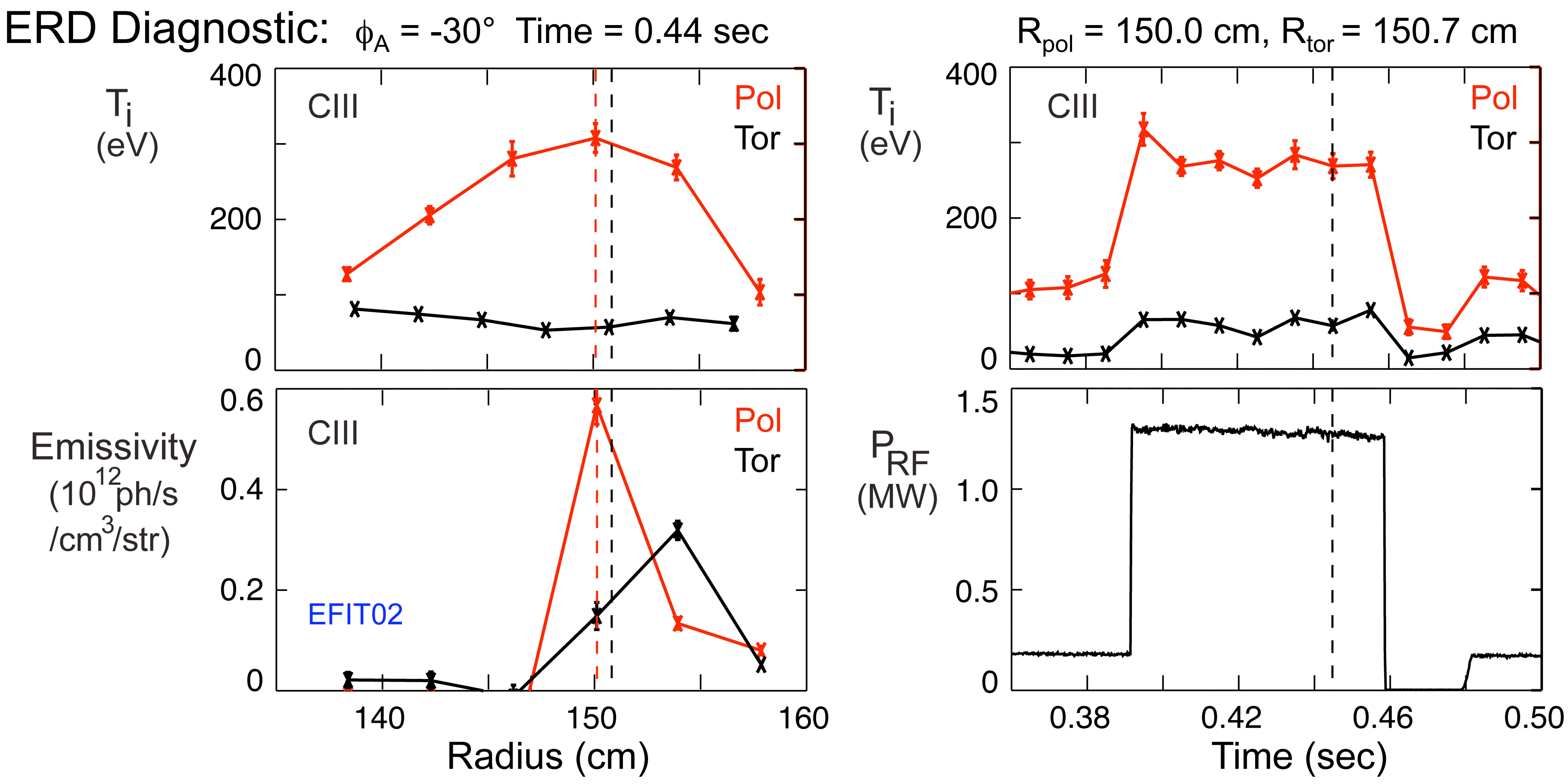


- $T_e(0)$ of ~ 5 keV produced to support high k scattering study of small scale turbulence (ETG mode?) in He and D_2 (see G. Taylor at this conference)

Edge loss mechanisms need to be identified experimentally and included in advanced RF codes

- Searching for edge RF power loss processes on NSTX:
  - Fast wave losses for propagating and reactive fields
    - associated sheath and collision effects
  - PDI effects
    - previously losses estimated at approximately 16% — 23% through collisional coupling of energetic ions to edge electrons
      [T. Biewer et al, Physics of Plasmas 12 (2005) 056108]
    - energetic ion losses
  - Non-toroidally symmetric, localized losses
  - There may be other important edge loss mechanisms

PDI heating in plasma edge may eject energetic ions



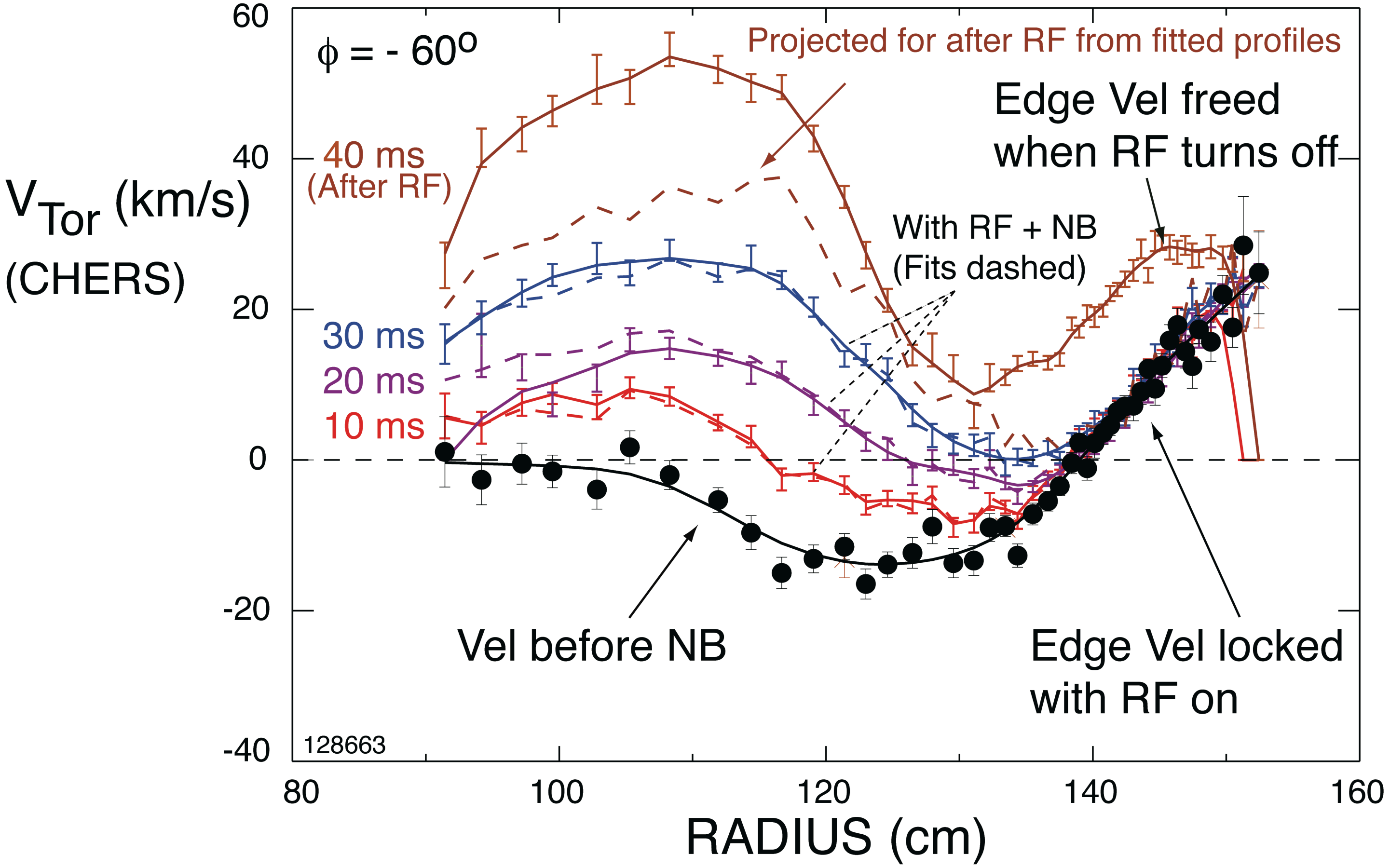
ERD Diagnostic: ϕ_A = -30° Time = 0.44 sec

R_{pol} = 150.0 cm, R_{tor} = 150.7 cm

- Edge ions are heated to hundreds of eV: CIII, CVI, LiII, and Helium
- Emission location for CIII and CVI is ~ 150 cm, just inside separatrix
- Edge ion heating may result in loss of energetic ions to SOL and the divertor region

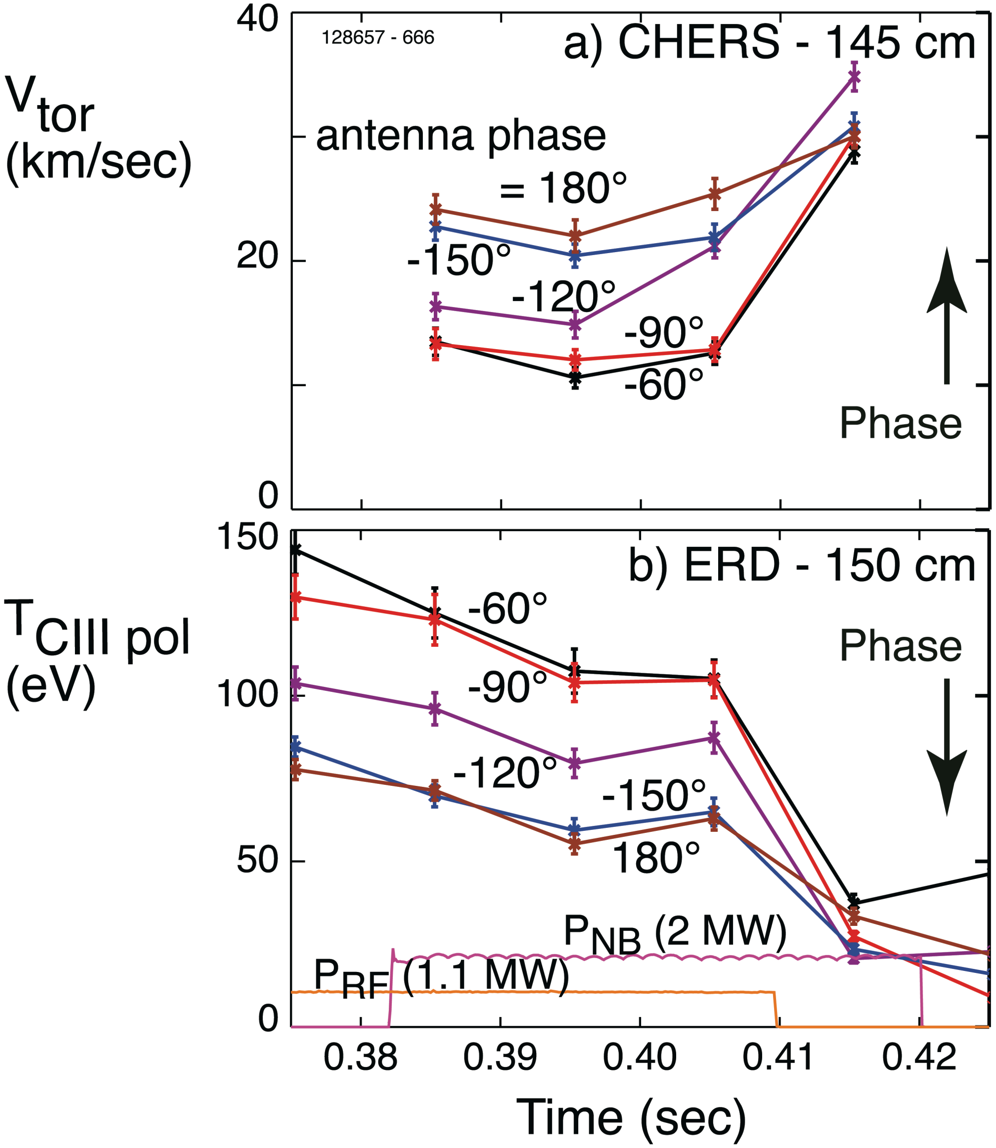
Edge toroidal velocity appears to be locked when the RF is on with the NB pulse

40 ms beam pulse – RF turned off at 30 ms during beam pulse



- Mechanism causing this edge effect not understood, but may point to edge ion loss
- RF apparently provides a drag on core plasma rotation as well

Edge toroidal velocity level decreases with phase as edge ion energy increases

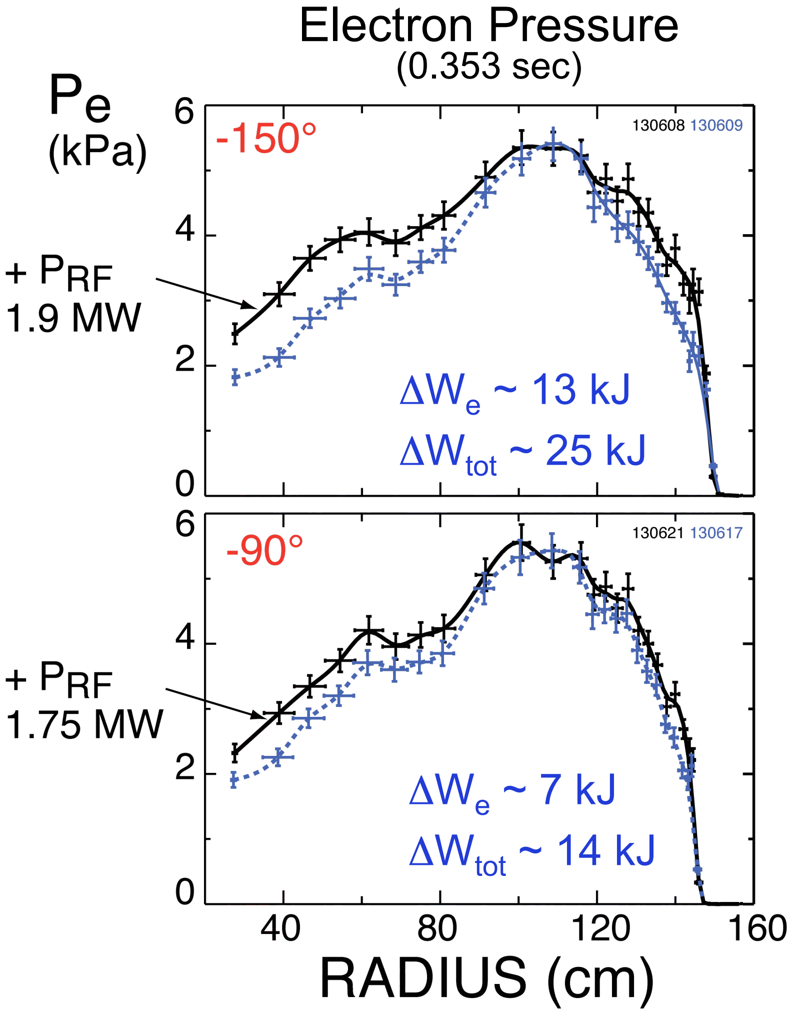


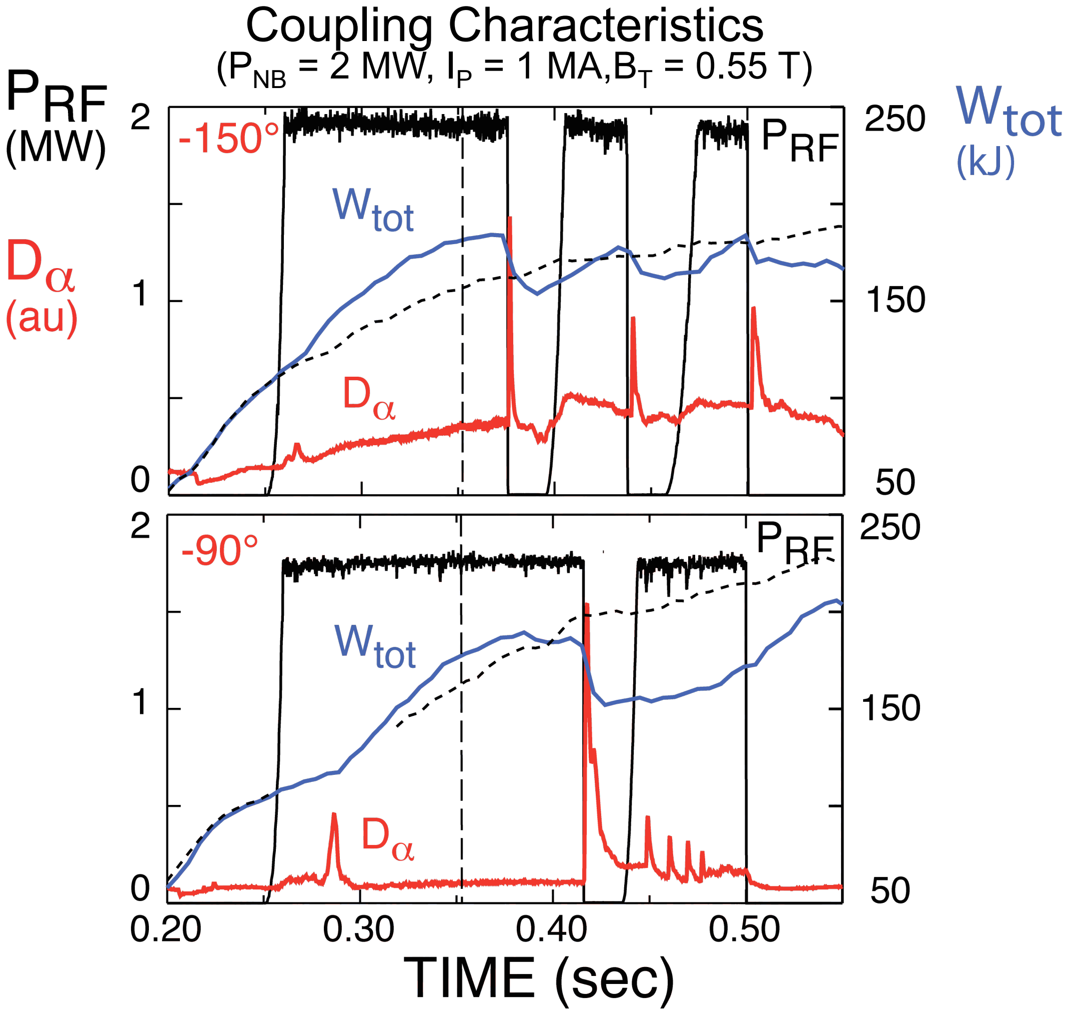
- This correlation between edge V_{tor} and $T_{C\ III\ pol}$ suggests ion loss or trapping is affecting rotation
- V_{tor} goes to approximately the same value after RF turn off
  - energetic edge ions decay in about 2 ms after end of RF

Initial H-mode experiments show heating dependence on k_ϕ similar to that for L-mode

- Degradation of heating at -90° (k_ϕ = -8 m^{-1}) relative to that at -150° (k_ϕ = -13 m^{-1})
- Major edge power loss channel observed
  - Losses from SOL in front of antenna to the outer divertor plate linked along the magnetic field lines
- Strong edge pressure gradient appears to lead to large type I ELMs at both antenna phases
  - Arcs occur prior to excursion of divertor D_{alpha} light in both cases
- Study of coupling to ELMing H-modes begun
  - Heated divertor zone location depends on magnetic field pitch and somewhat on phase
- 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

Heating of H-mode plasmas is less efficient at lower antenna phase/lower k_ϕ

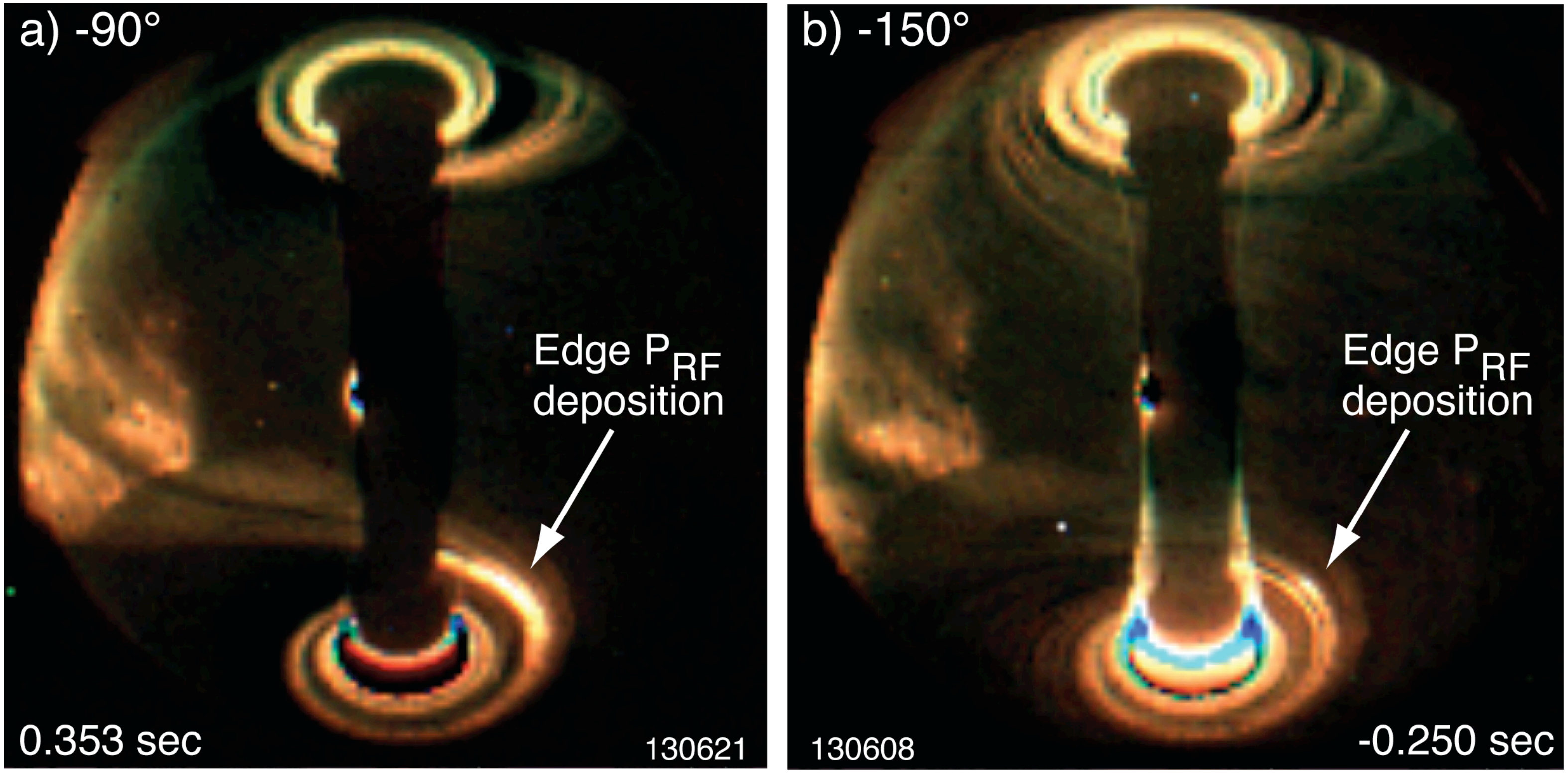

Electron Pressure
(0.353 sec)


Coupling Characteristics
(P_{NB} = 2 MW, I_P = 1 MA, B_T = 0.55 T)

- $\tau_{\Delta W tot}$ ~ 20 ms gives η_{eff} ~ 66%, 40% for -150°, -90° antenna phasings
- P_{RF} losses coupled to edge are ~ 0.7MW, 1.1 MW for -150°, -90°

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

P_{RF} ~ 1.8 MW, P_{NB} = 2 MW, I_P = 1 MA, B_T = 5.5 kG

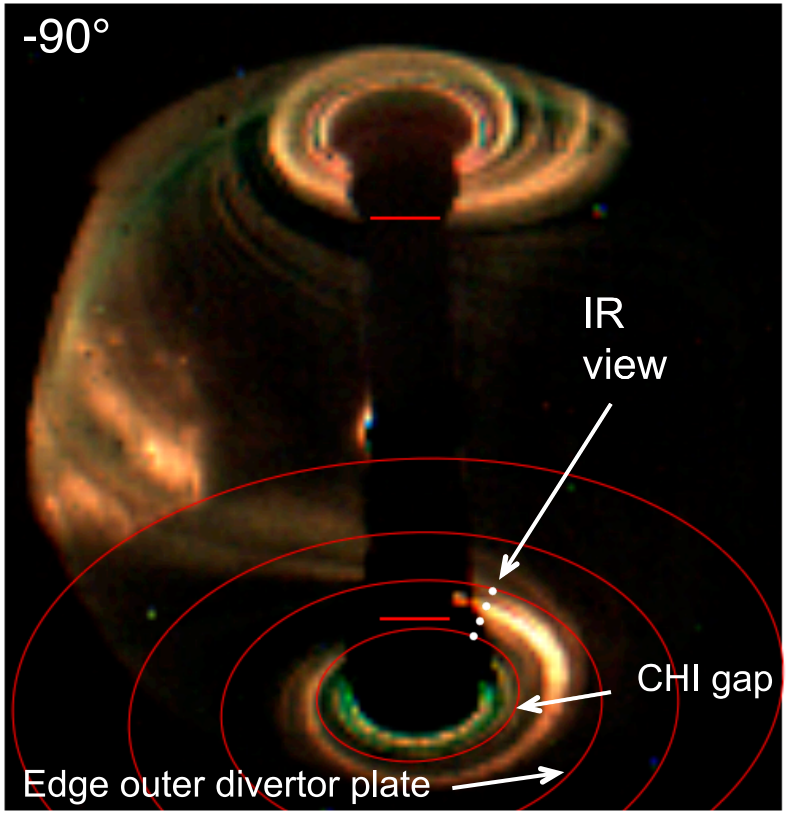


- "Hot region is much more pronounced at -90° than at -150°
  - Edge power loss is probably greater at -90°
  - Also, suggests fields move away from wall at -150° along with the onset density
- Time for "hot" spot to decay away is ~ 20 ms at -90° and ~ 8 ms at -150°

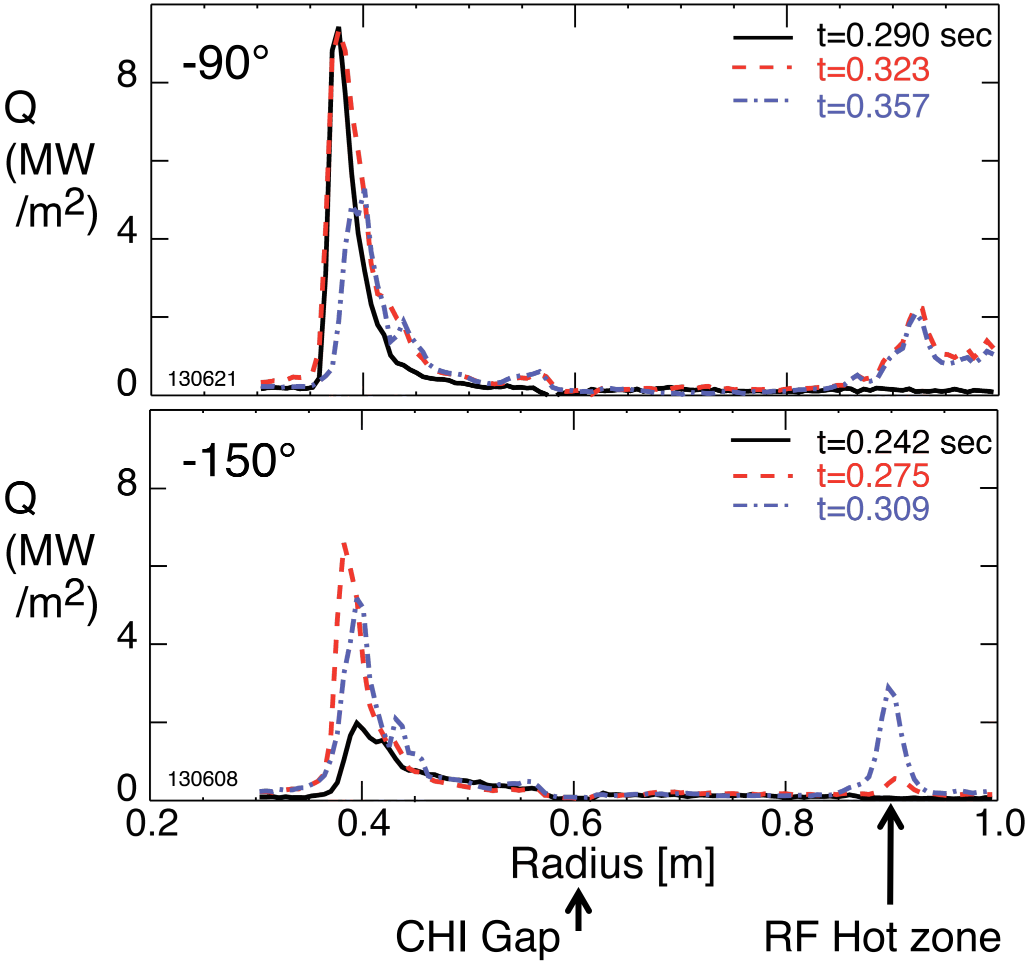
Infrared measurements show significant RF power deposition in the hot zones

Visible Camera with Subtraction

Shot 130621 (0.41562 s - 0.43762 s)



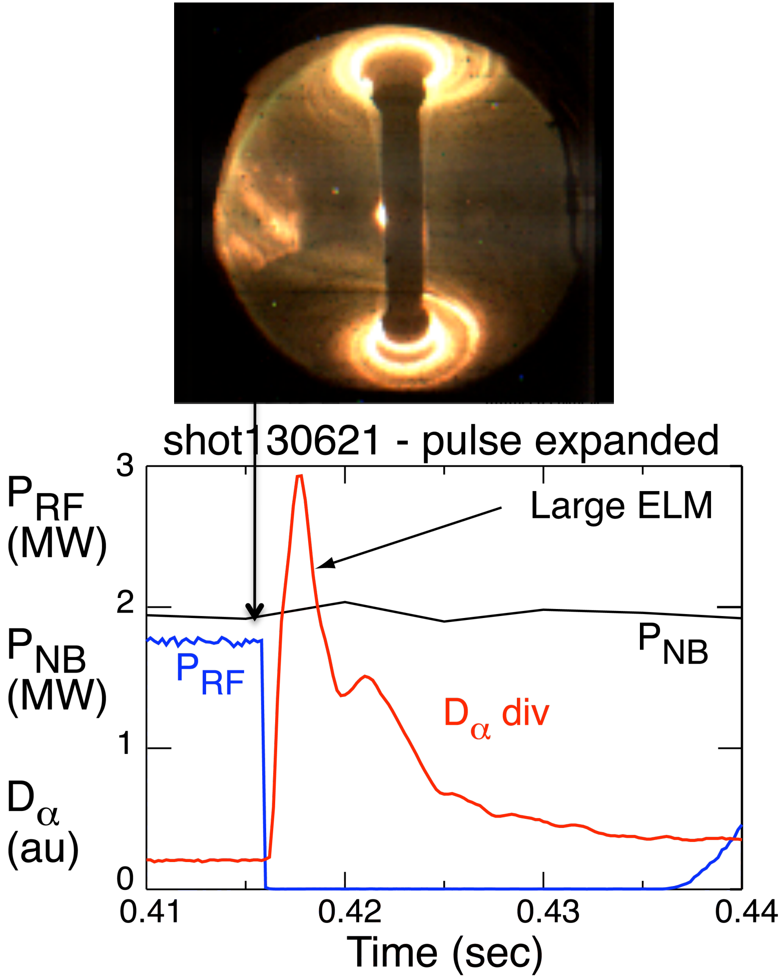
Infrared Measured Heat Flux



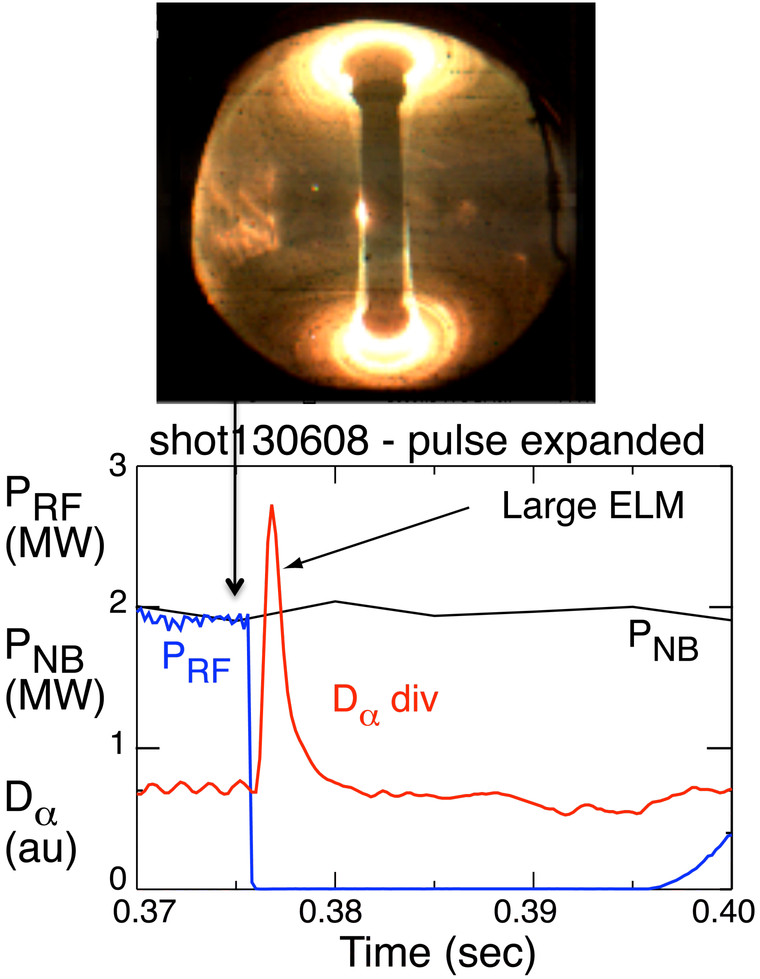
- IR results indicate several hundreds of kW deposited on outer divertor plate
- Deposition for -90° farther out along with onset density

RF arc occurs just prior to the type I ELM for both antenna phases

Phase = - 90° just prior to arc before ELM

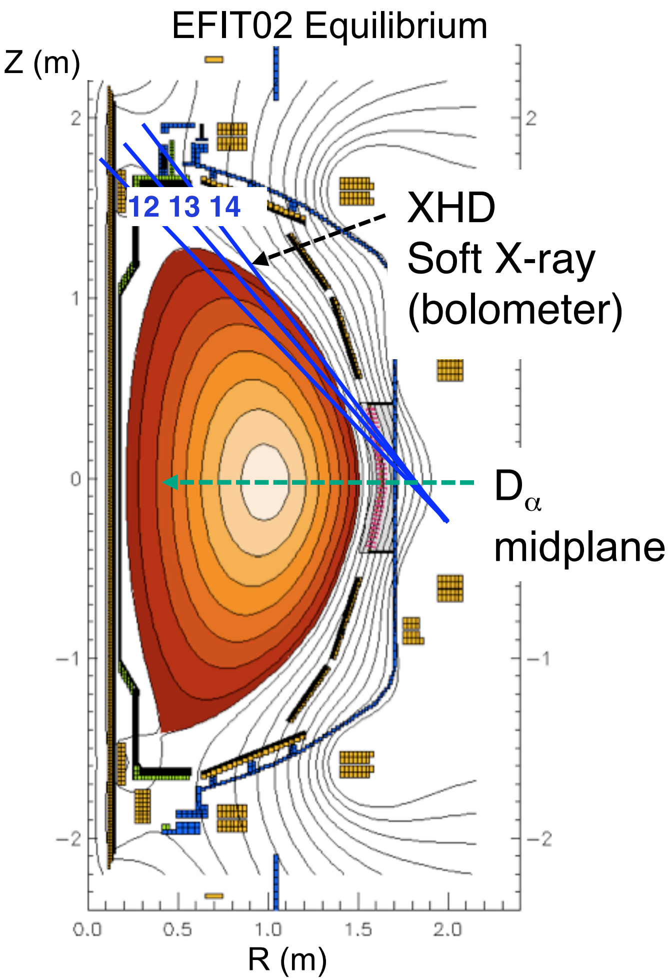


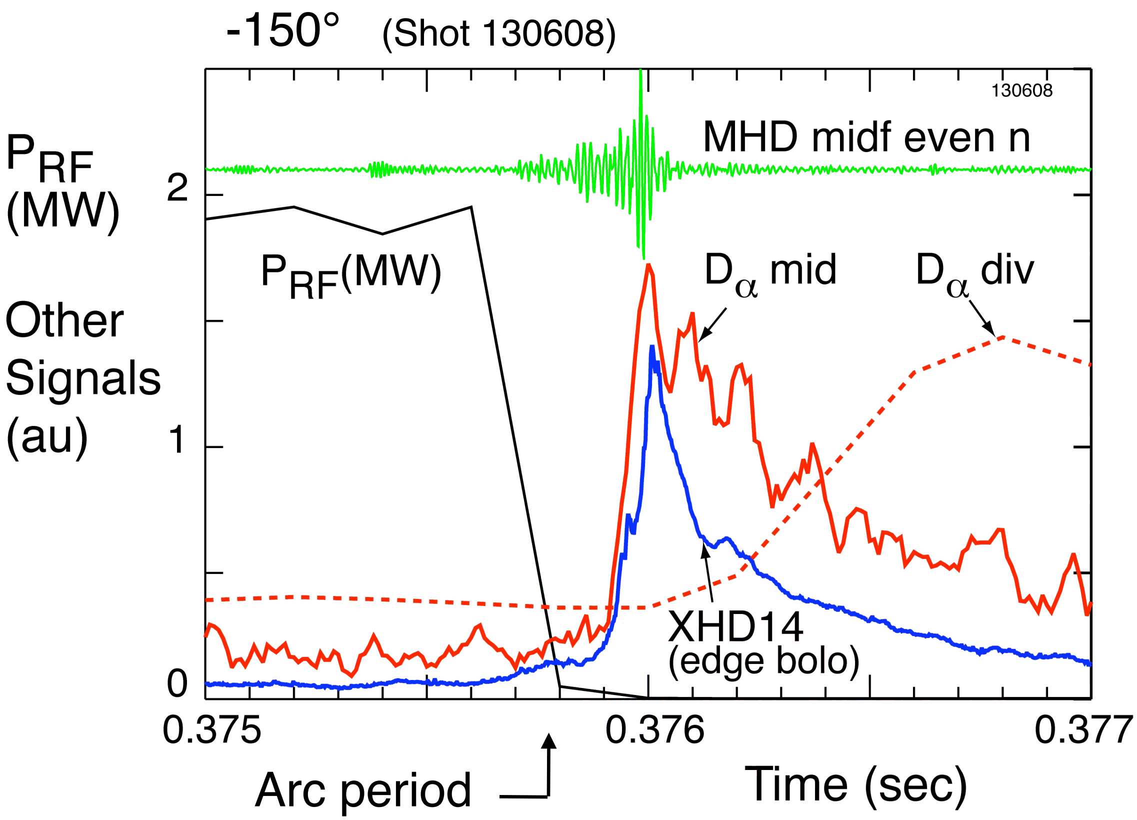
Phase = - 150° just prior to arc before ELM



- RF is off prior to rise in divertor D_α signal for ELM
- Need to look for precursors that cause arc in antenna

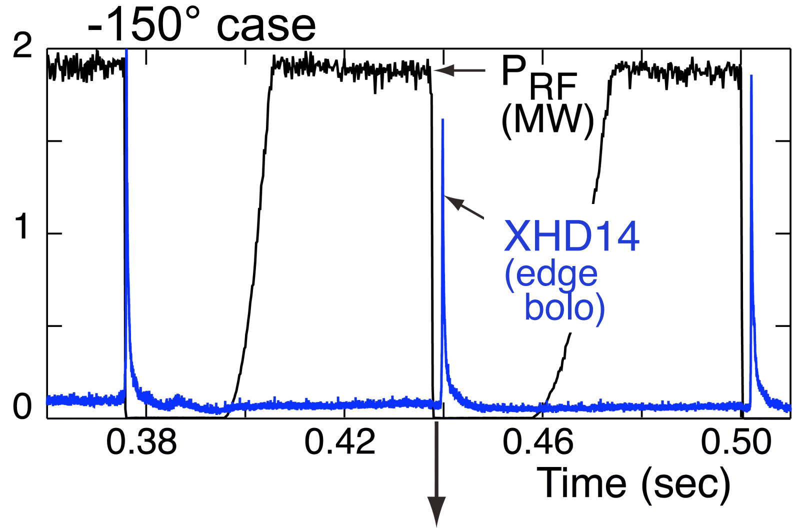
Soft X ray, D_a mid and MHD signals are best indicators of early ELM phase

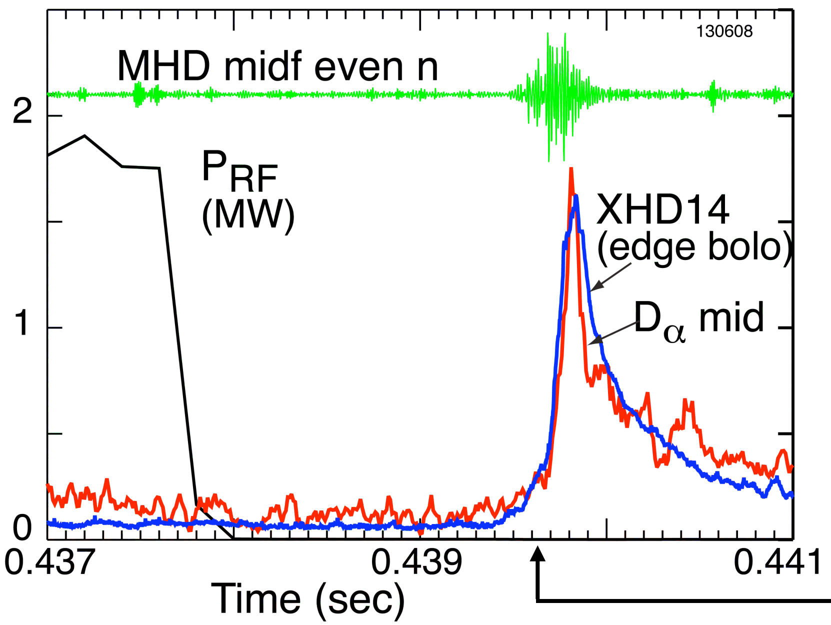




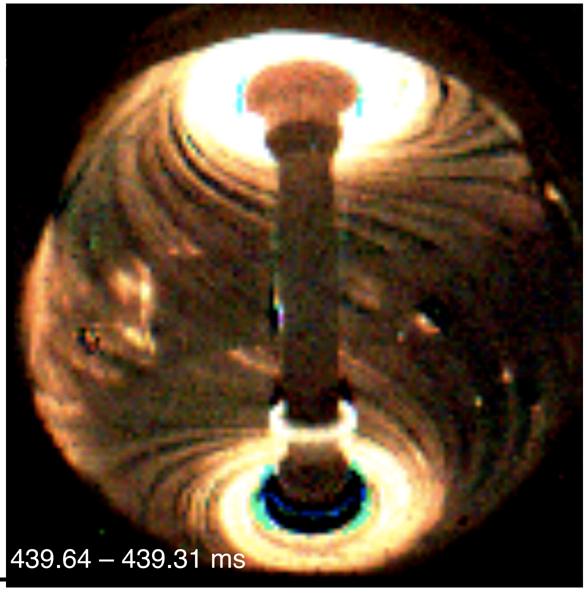
- Precursors are apparent on all three signals
- Possible causes of arc are plasma from pre-ELM or blob, and possibly dust (sputtered material) entering the antenna box

Type 1 ELMs can occur after removal of RF power (arc or cutoff)



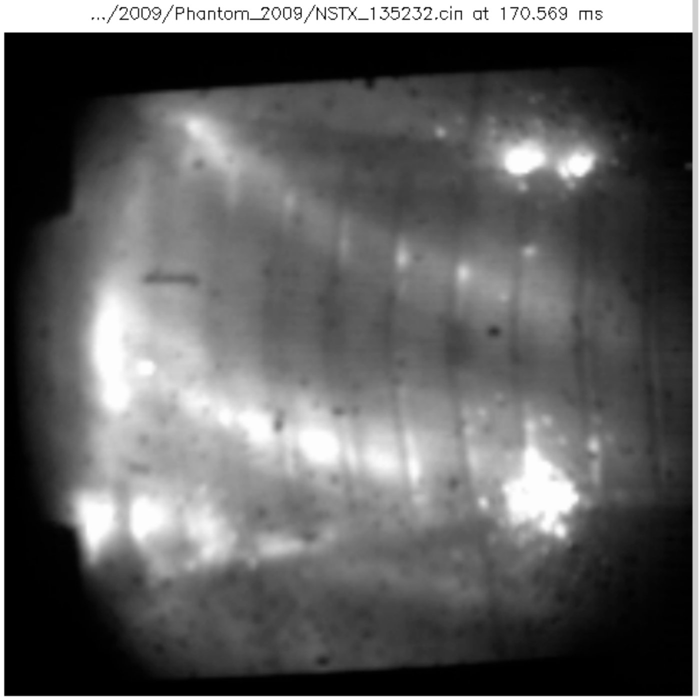


- Delay of ELM after removal of P_{RF} suggests RF supports higher edge pressure without ELM
- Some MHD activity near arc - - blobs?
- ELM helical structure begins early in ELM buildup

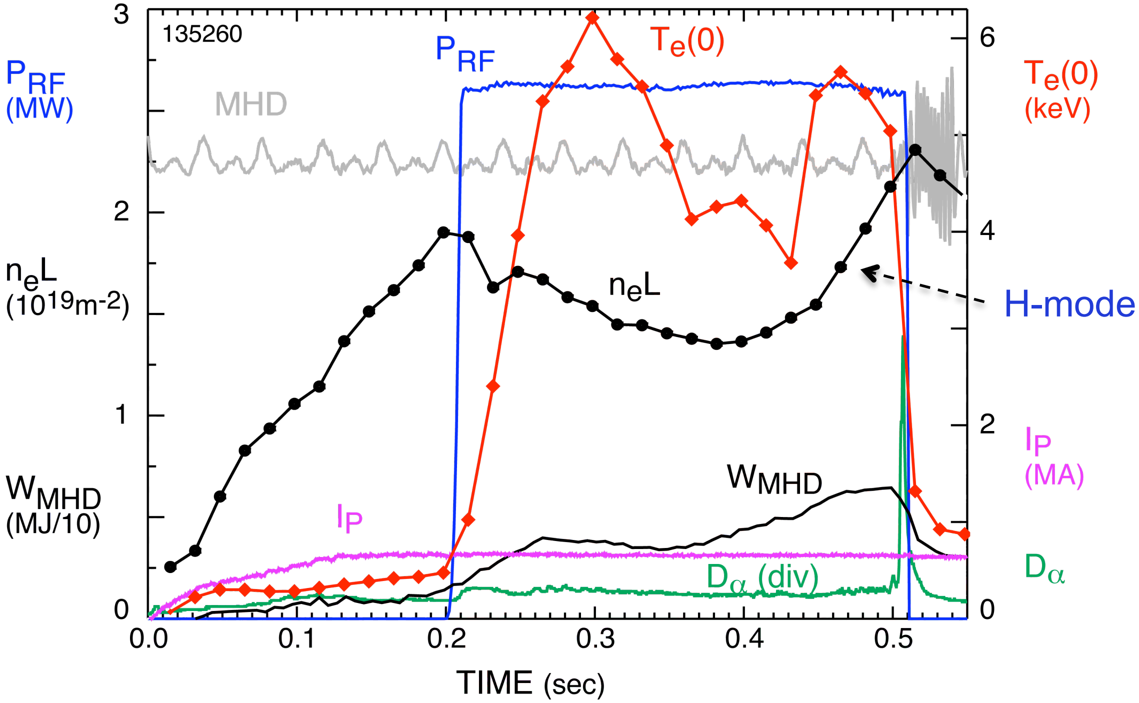


Ejection of material from antenna surfaces appears to be the cause of the arcs during RF plasma operation

Start of plasma conditioning at P_{RF} = 0.5 MW – no antenna arc



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



- Lithium sputtering from outside of antenna enclosures and BN limiters 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
- After plasma conditioning to high power, P_{RF} up to 3.7 MW has been sustained without arcs – example shown above for P_{RF} = 2.7 MW ⇒ $T_e(0)$ up to 6.2 keV

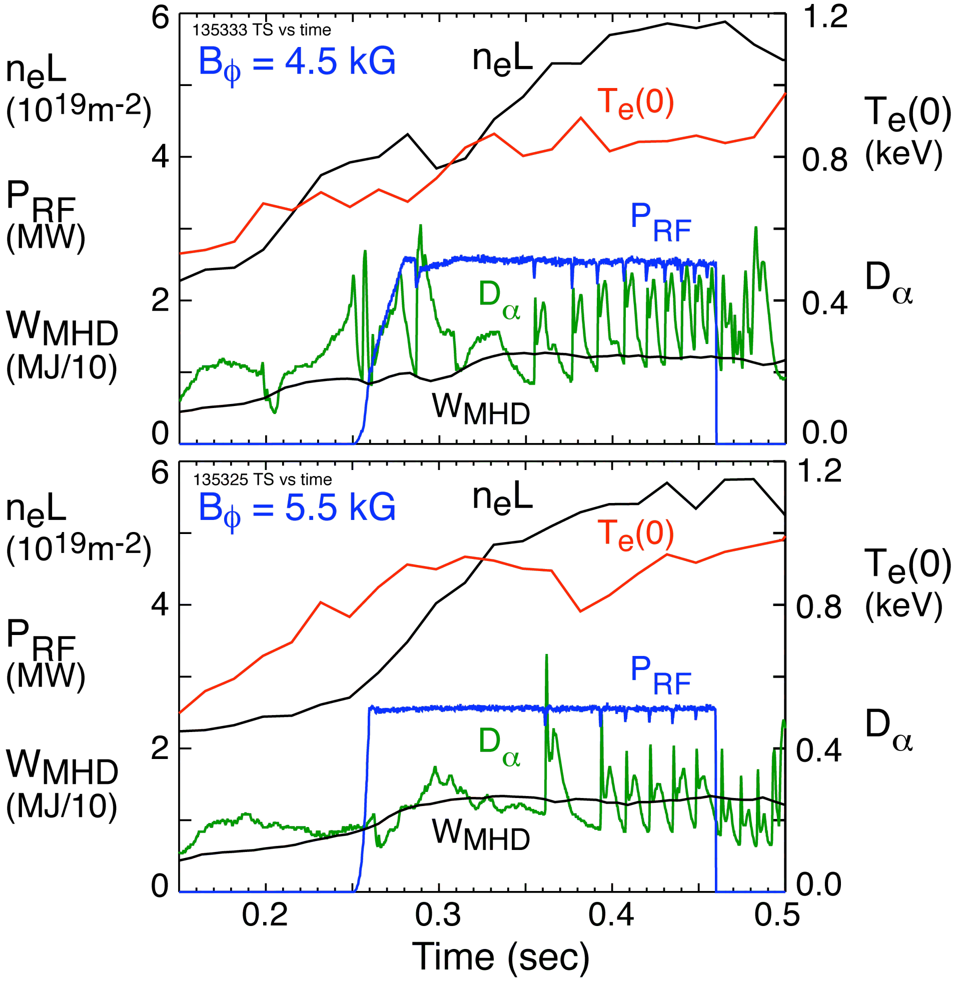
Study of RF heating of the outer divertor plates versus magnetic field pitch and antenna phase

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

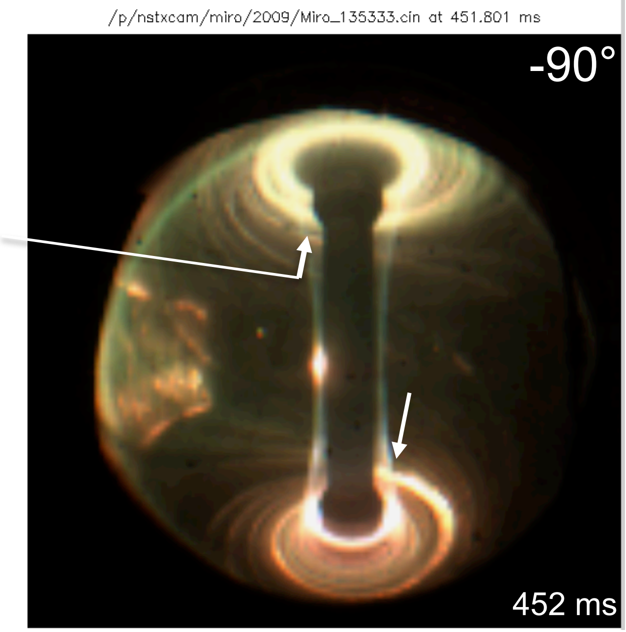
B_ϕ and	ϕ_A	Shot #
5.5 kG	-90°	135325
4.5 kG	-90°	135333
4.5 kG	-150°	135337
5.5 kG	-150°	135339

- Powered through ELMs without arcs for these cases
- Edge power loss is increased with higher density and ELMing activity

ϕ_A = -90° discharge parameters

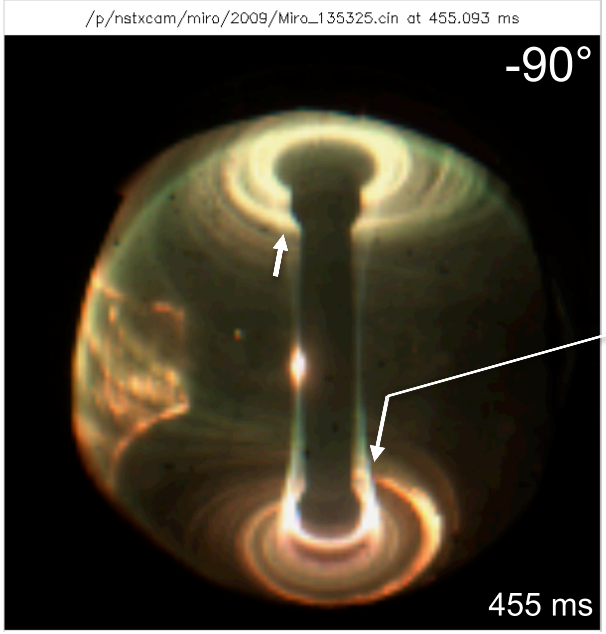


RF heated pattern on lower divertor plate follows the change in magnetic field pitch



Bay G

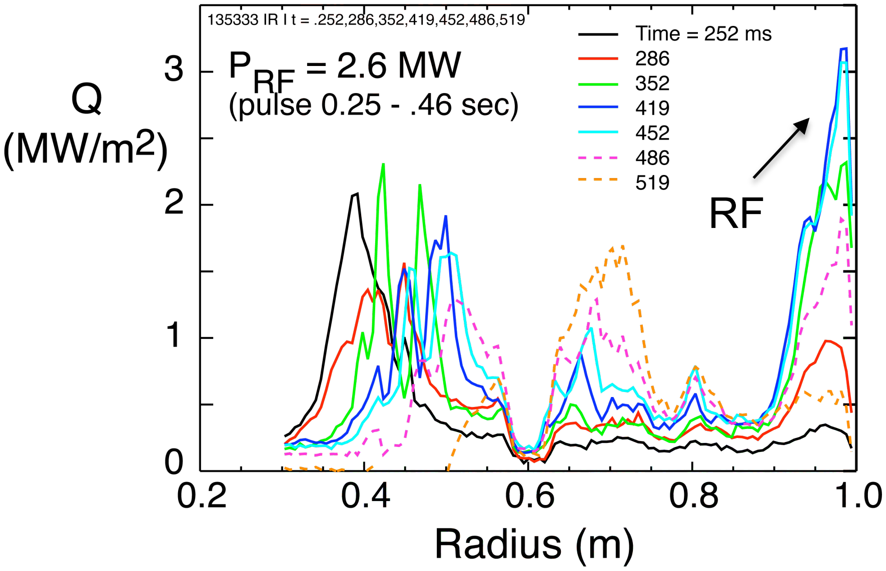
IR view



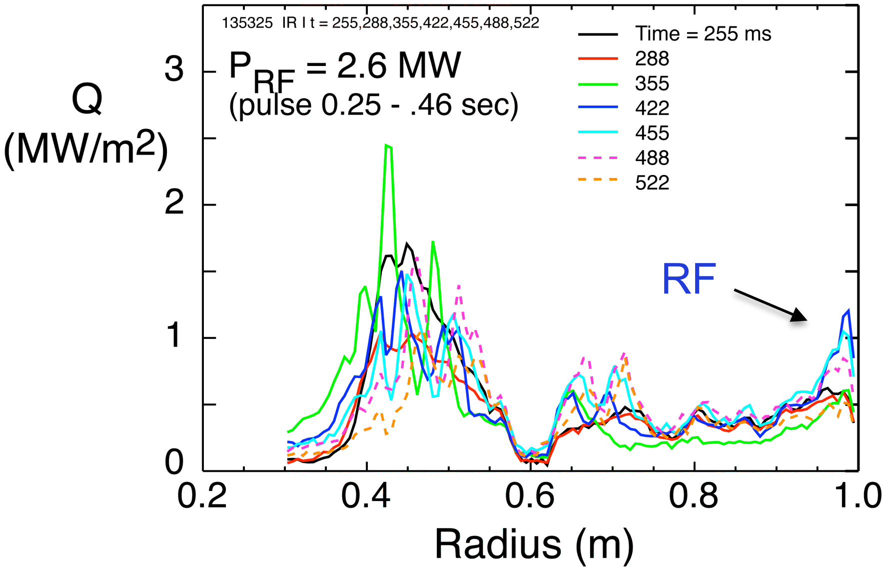
Bay I

IR view

B_ϕ = 4.5 kG, I_P = 0.8 MA

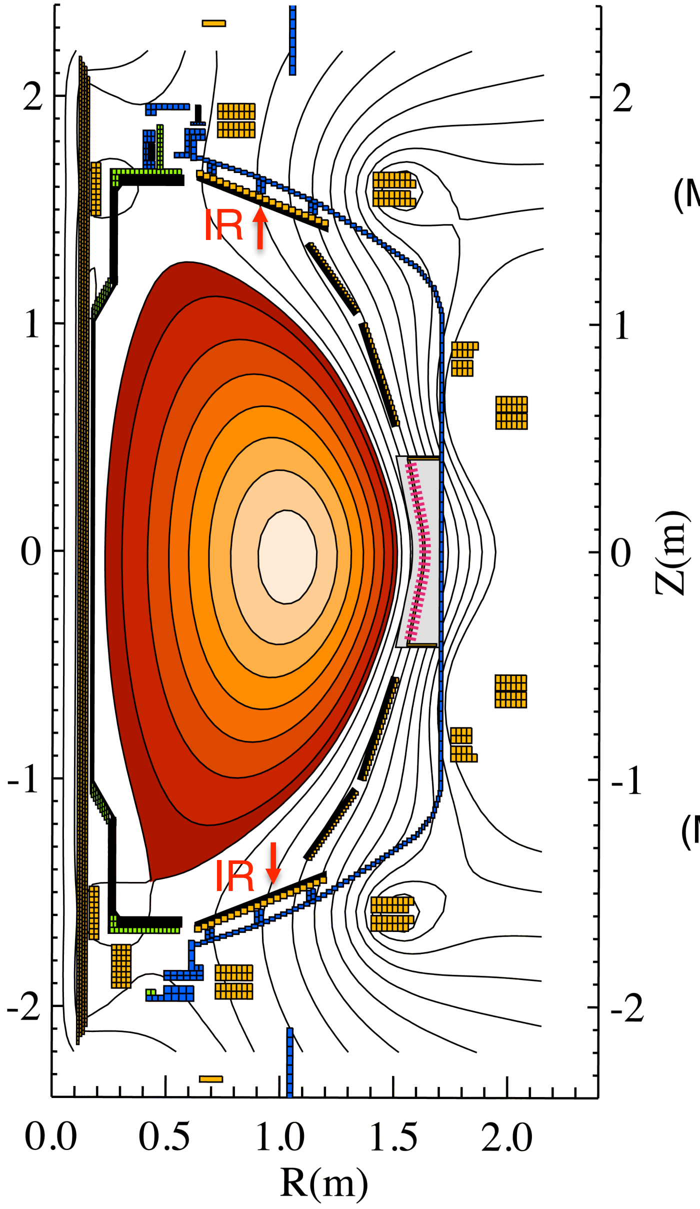


B_ϕ = 5.5 kG, I_P = 0.8 MA

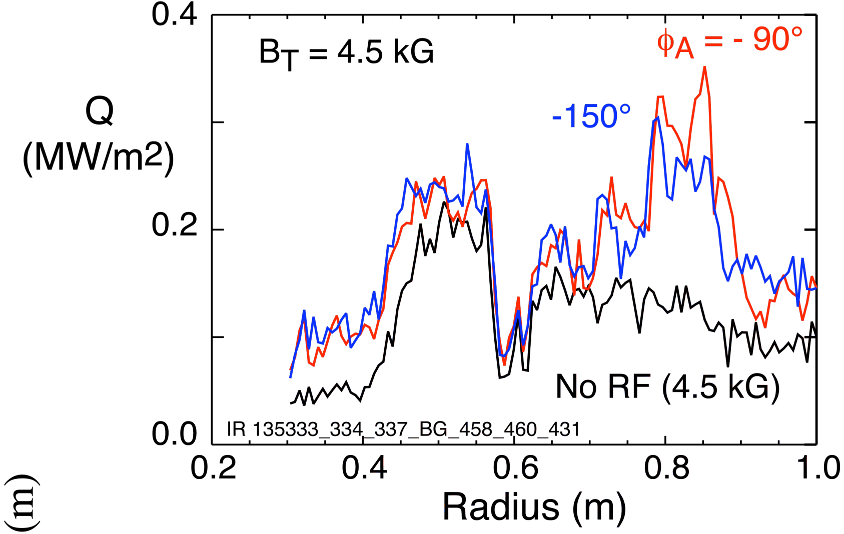


Location of heat flux has small dependence on phase at lower and upper divertor plates

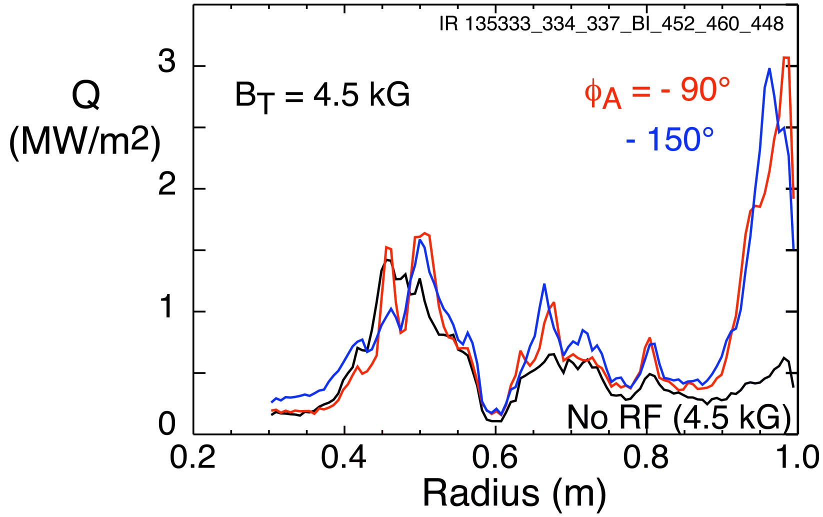
from \EFIT02, Shot 135333, time=445ms



Top IR heat flux at Bay G versus antenna phase (I_P = 0.8 MA)



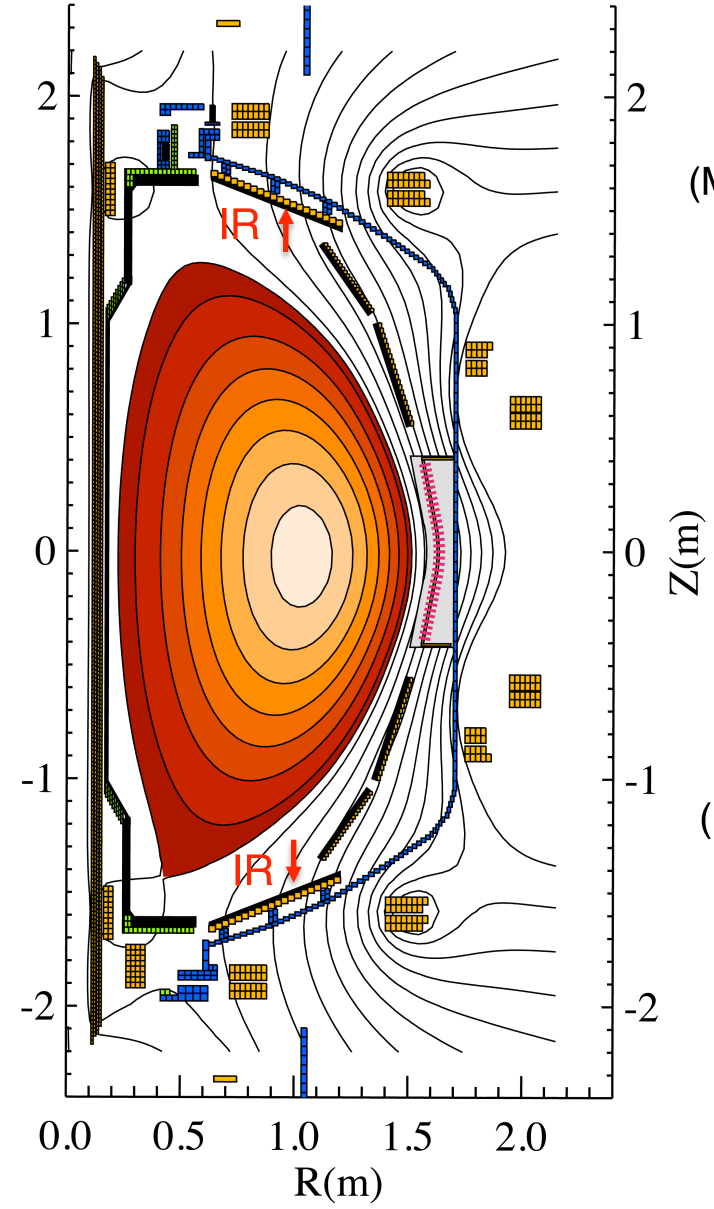
Bottom IR heat flux at Bay I versus antenna phase (I_P = 0.8 MA)



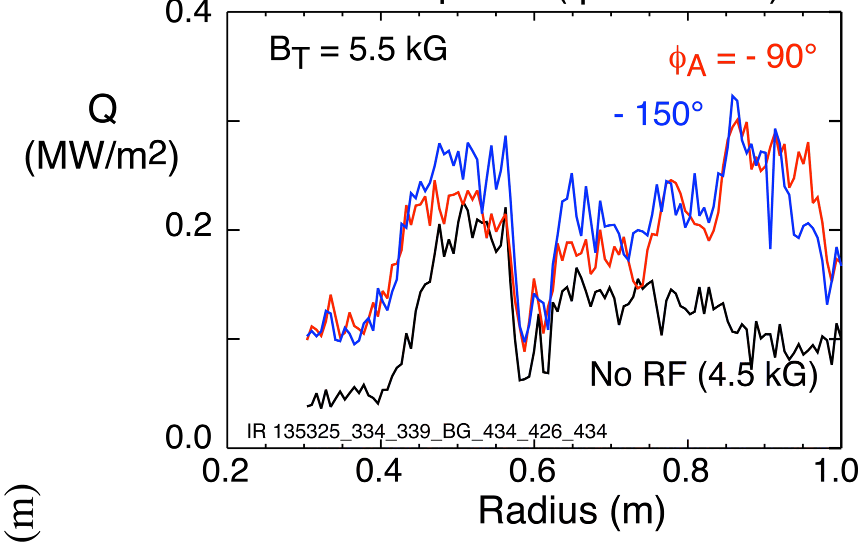
Heat flux moves inward by ~ 2 cm for shorter wavelength

Location of heat flux has a strong dependence on field pitch at lower and upper divertor plates

from \EFIT02, Shot 135325, time=445ms

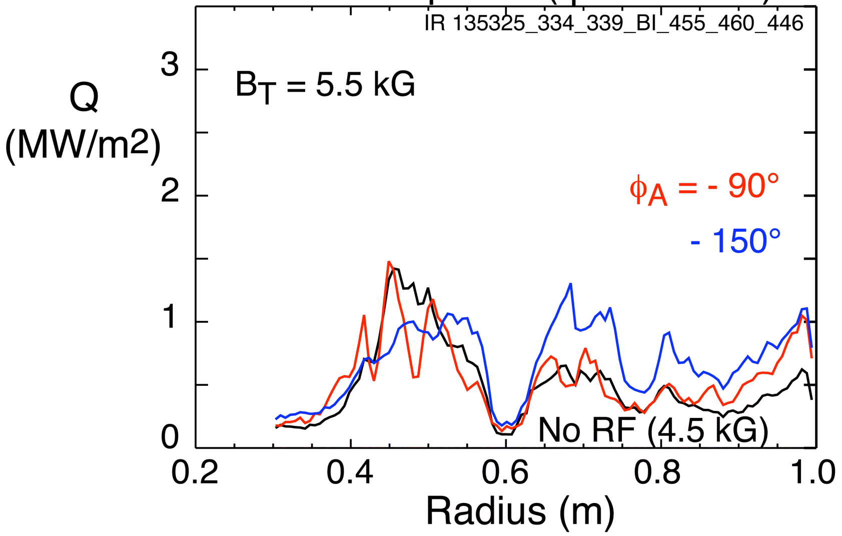


Top IR heat flux at Bay G versus antenna phase (I_P = 0.8 MA)



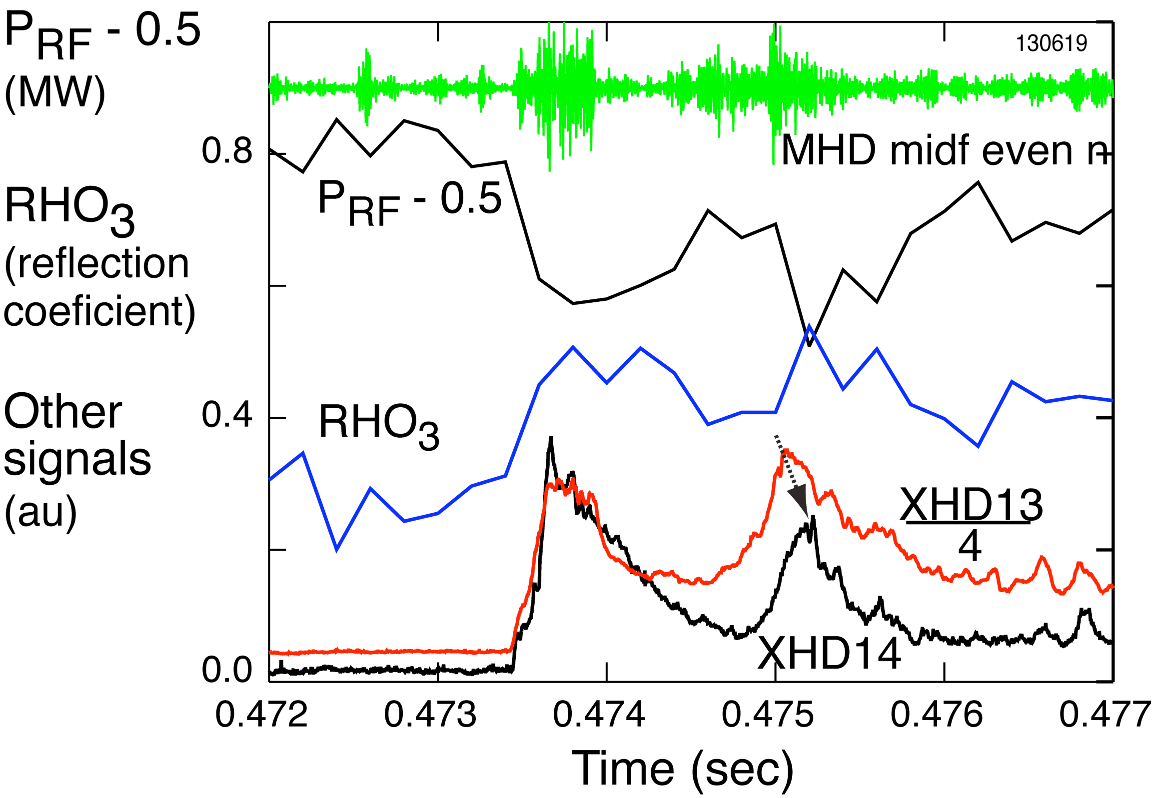
Heat flux moves outward by ~ 10 cm

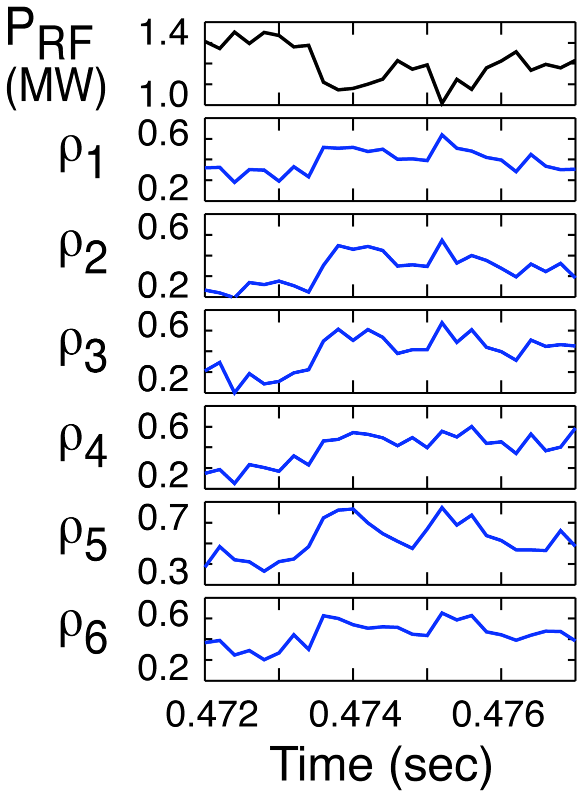
Bottom IR heat flux at Bay I versus antenna phase (I_P = 0.8 MA)



Heat flux moves outward and toroidally

Effect of large type I ELM on RF power coupled

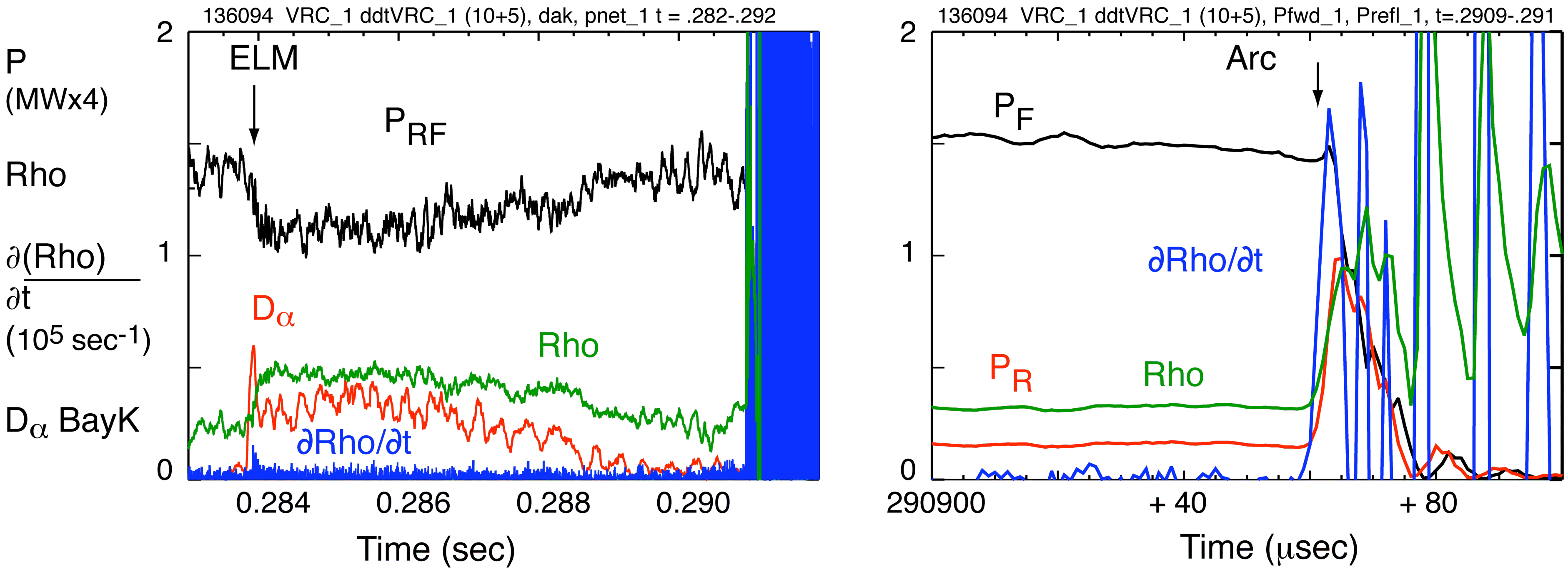




- P_{RF} = 1.3 MW not tripped off with trip RHO value set to 0.7
- Two RHO peaks due to two type I ELMs are coincident with increases in edge density (XHD14 $\propto n_e^2$)
- Rise time of RHO is slow relative to that for an arc – can be used to discriminate between arc and ELM

Discriminating between arcs and ELMs with the time derivative of the voltage reflection coefficient

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
- Ringing in ∂rho/∂t occurs during the fall off of the power in the transmission system after source turn off

Major fast wave power loss observed in edge may be important for ITER

- Good heating efficiency maintained at lower k_ϕ for lower edge density
  - ⇒ Suggests propagating fast wave edge loss ($n_{e\ onset} \propto B * k_{||}^2 / \omega$)
- Major fast wave power loss channel observed in edge
  - ⇒ Losses from SOL in front of antenna to outer divertor plate linked along magnetic field lines
- Effect could be important for ITER since wave number is relatively low for some heating/CD scenarios:
  - ⇒ $k_\phi \sim 4\ m^{-1}$ at 53 MHz for CD phasing in ITER ➞ $n_{e\ onset} \sim 1.4 \times 10^{18}\ m^{-3}$
  - ⇒ Divertor region sputtering has been observed at lower harmonics

    [J-M. Noterdaeme et al., FED **12** (1990) 127; S. Wukitch et al., RF Conf. (2007) 75]
  - ⇒ Careful tailoring of edge density profile may be important in ITER
- Advanced RF codes are needed to predict edge losses for all edge fast wave fields
  - ⇒ NSTX is ideal platform for benchmarking advanced models for edge loss processes