HHFW Operations on NSTX-U

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Physics Operations Course
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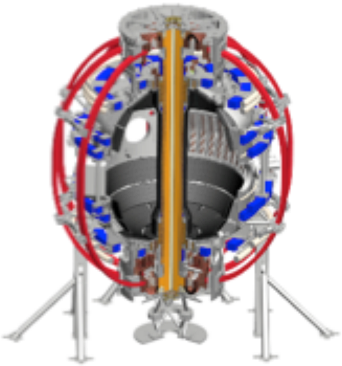


HHFW Operations on NSTX-U

Operational goal is to couple as much HHFW power as possible to the core plasma

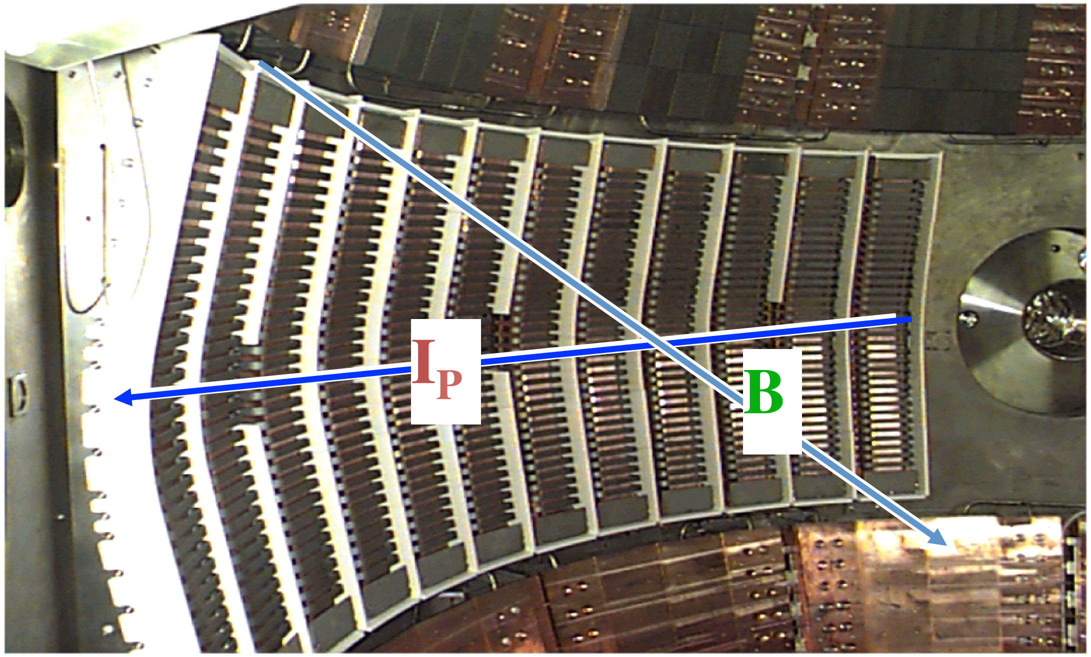
  - With the desired phase for heating and/or current drive

Outline:

- HHFW system
  - Matching and decoupling
- Coupling to plasma
  - Function of
    - Gap between antenna and separatrix
    - Density in SOL
      - In contrast to the minority heating case, for HHFW coupling a relatively large fraction of RF power can deposit in the SOL at elevated SOL density
    - Phasing between antenna straps
    - Antenna conditioning
- Coupling to H-modes
  - XP 1510 by R. Perkins et al. is for NSTX-U study of HHFW heating RF only and RF + NBI H-modes
    - ELM deposition on the divertor regions – RF and RF + NBI
    - Effect of density excursions during ELMs on coupling
    - Matching with ELMs – RF and RF + NBI
    - Methods need to be introduced in the HHFW system to permit optimized RF coupling to ELMy NBI plasmas on NSTX-U
- Coupling to startup plasmas

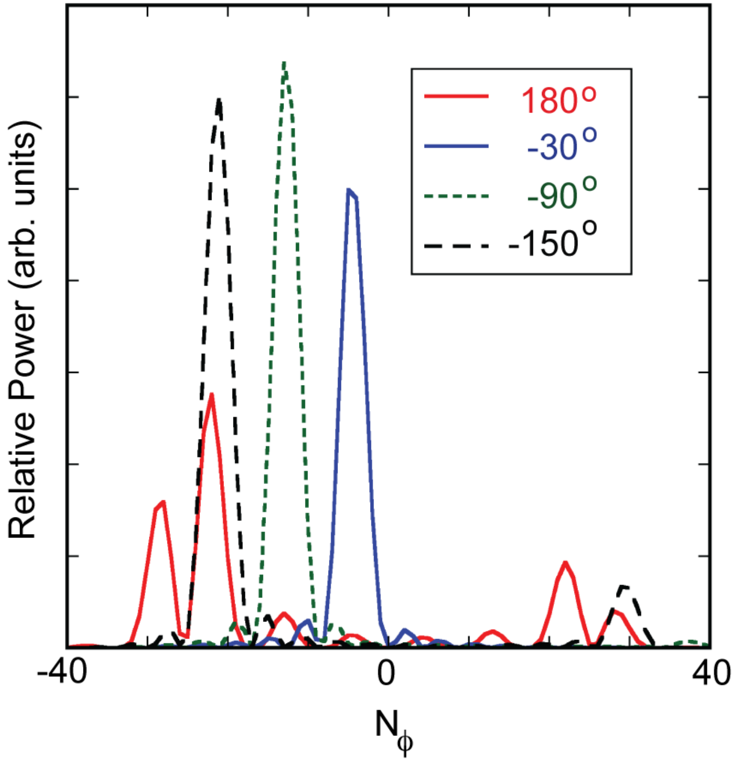
NSTX HHFW antenna has well defined spectrum, ideal for studying dependence of heating on antenna phase

HHFW Antenna



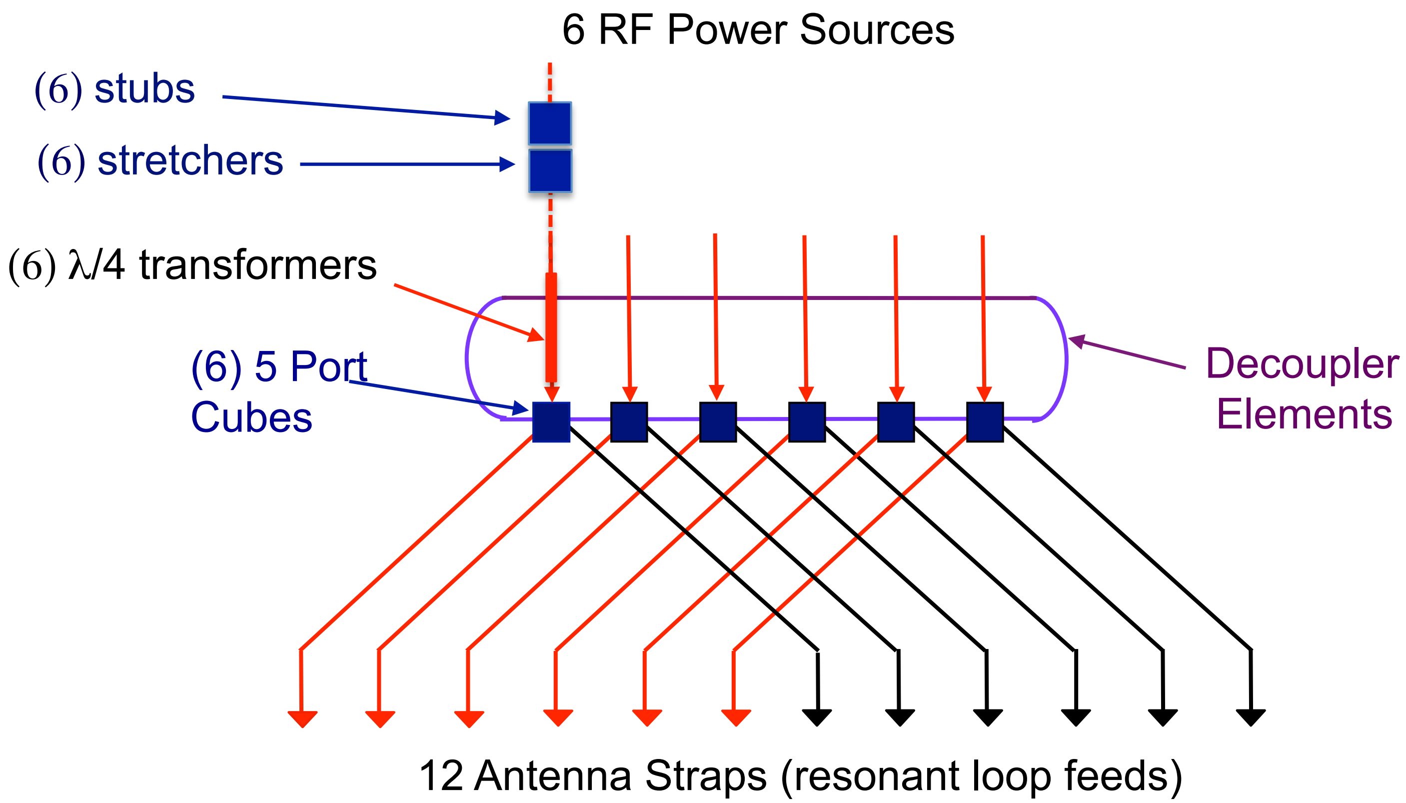
12 strap HHFW antenna extends toroidally 90°

Spectra for several phasings between straps



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

System for applying power to the HHFW antenna must both match to the plasma loading and decouple between sources to allow phasing



- Decoupling is important for phasing between straps to select launched spectrum
  - Adjacent straps are decoupled by directing power from the adjacent cube junctions to offset mutual coupling between the adjacent straps

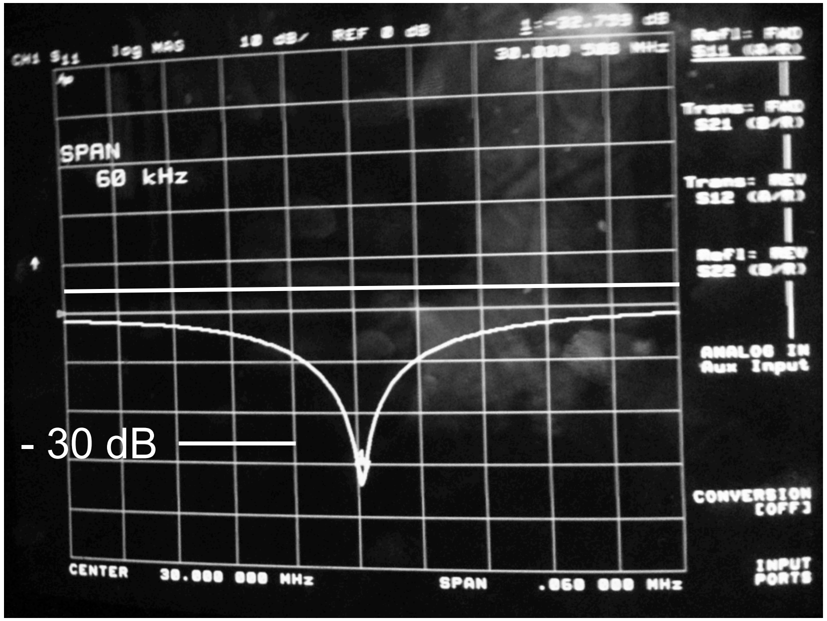
Resonant loop feeds on NSTX-U

Resonant loops connect ends of current straps through top and bottom feedtroughs for each of 12 straps

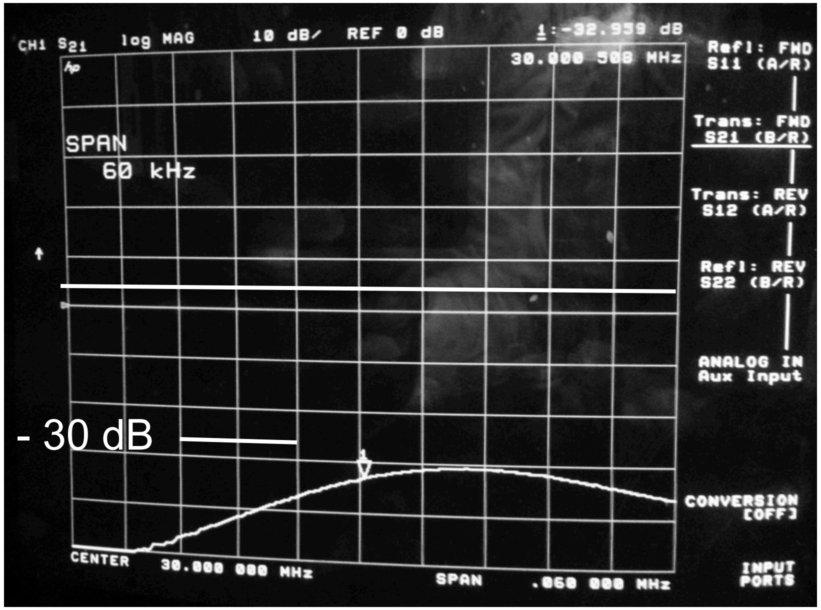
Decoupling is set for vacuum matching

S_{11} and S_{21} values for sources #1 and #2 matched and decoupled

S_{11} single peak with decoupler



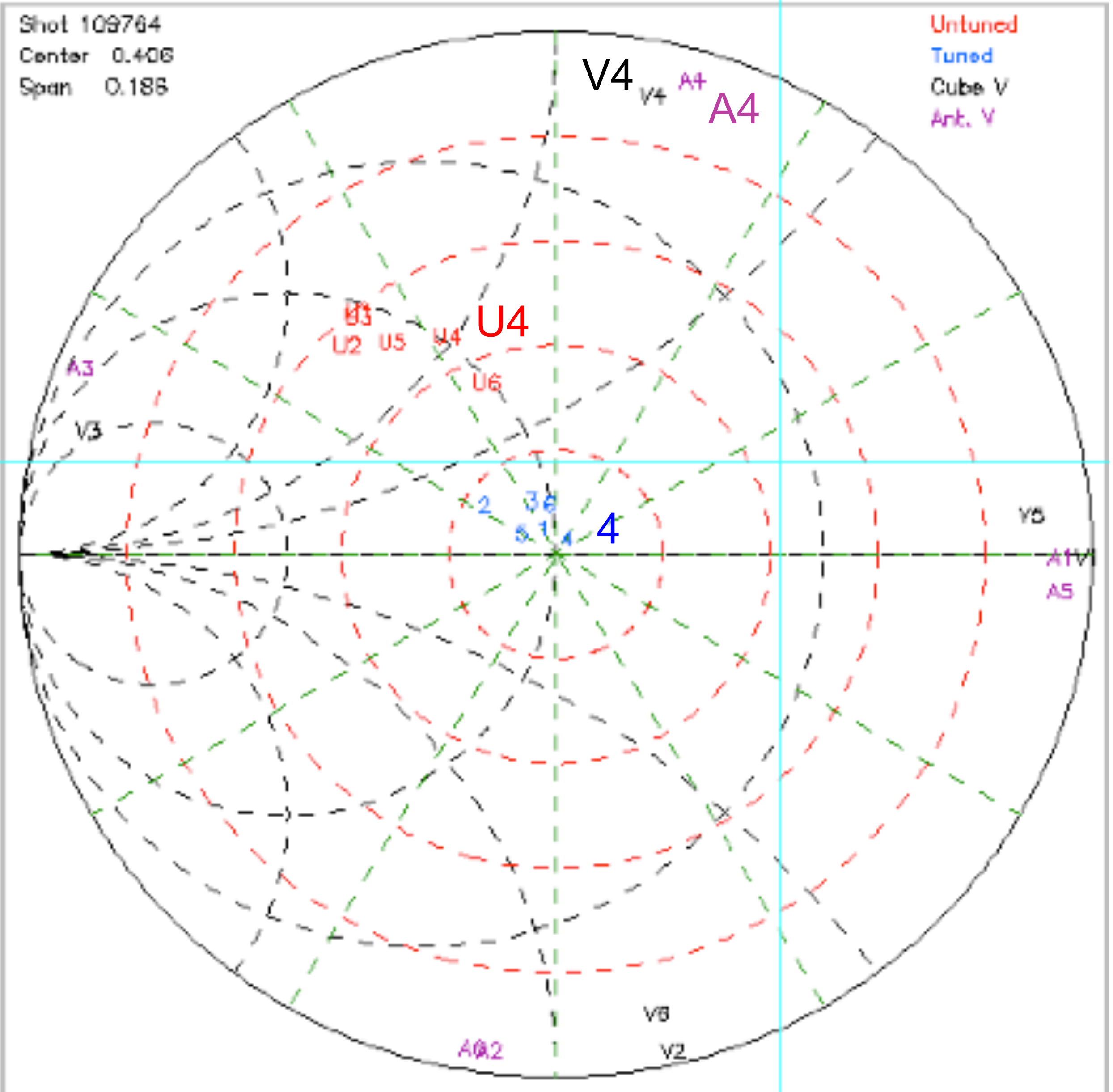
S_{21} coupling of #2 to #1 is < - 30 dB



- Without decoupling the match is double peaked and at center frequency power from one source is fed into the other source
- With decoupling the match is single peaked and the coupled power to the other source is down by ~ - 30 dB

6 antenna sets are matched together for chosen phasing

Smith chart for voltage reflection coefficient ρ



Smith Chart shows antenna matching to 6 sources:

90° phasing

Ant. Voltage: A1 - A6

Cube Voltage: V1 - V6

Untuned ρ: U1 - U6

Tuned ρ: 1 – 6

RF operator adjusts stubs/ stretchers between shots for matching 6 sources simultaneously

Coupling change or arc during shot moves tuned ρ values toward periphery of chart

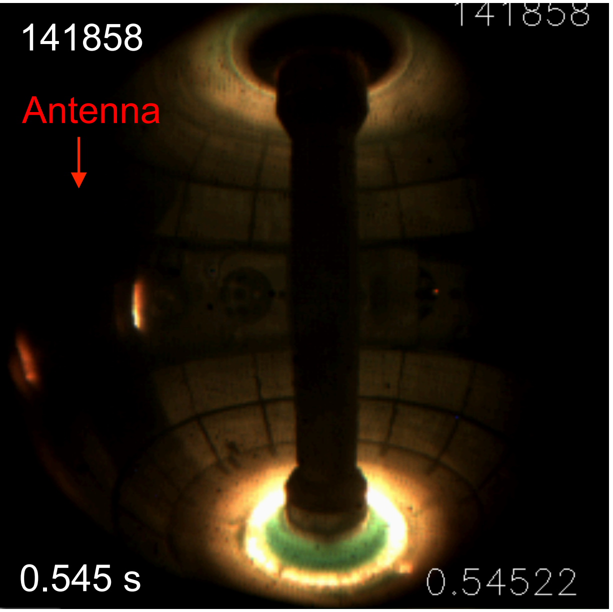
- RF pulse is cutoff for ρ > 0.7

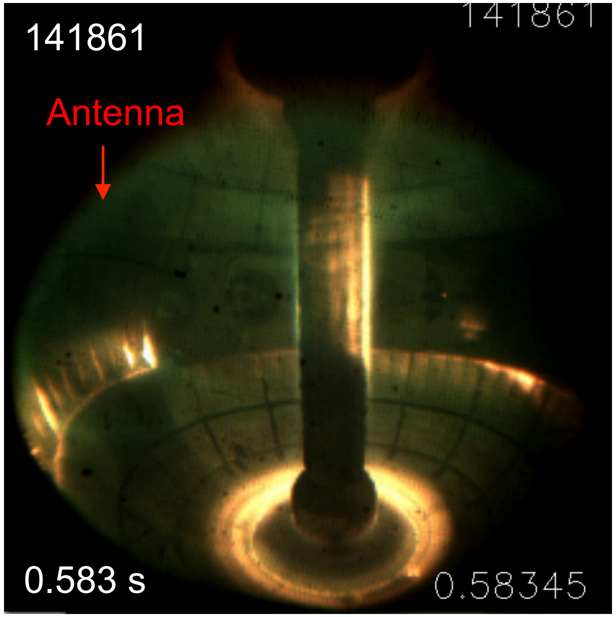
Coupling depends on gap from separatrix to antenna

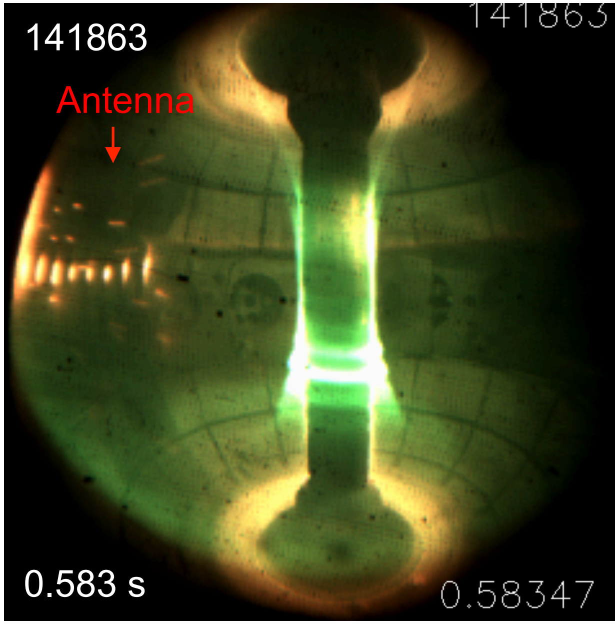
- Conventional wisdom is that the gap should be as small as practicable to optimize loading resistance to plasma
- However, avoiding energetic NB ion bombardment sets minimum gap

Gap must be large enough to avoid NB ion bombardment - RF antenna serves as poloidal limiter

Scan of Z position of plasma with P_{NB} = 2 MW, P_{RF} ~ 1 MW, I_P ~ 0.65 MA





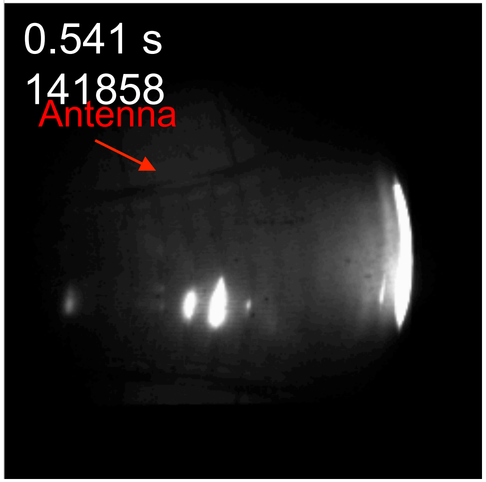


Midplane gap	~ 6 cm	~ 6 cm	~ 5 cm
Gap at interaction zone	~ 6 cm	~ 4 cm	~ 4 cm
Z_C position	~ -3.5 cm	~ - 20 cm	~ + 16 cm

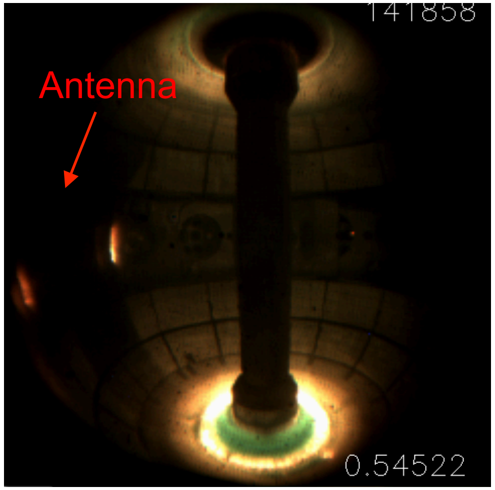
- Physics operator needs to monitor interaction with antenna for all operations and maintain adequate gap

Gap with neutral beam must be larger than with RF only to limit energetic ion deposition on antenna

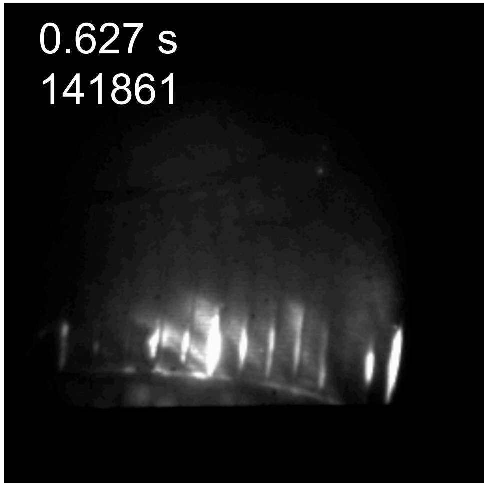
Centered Z_C = -3.5 cm



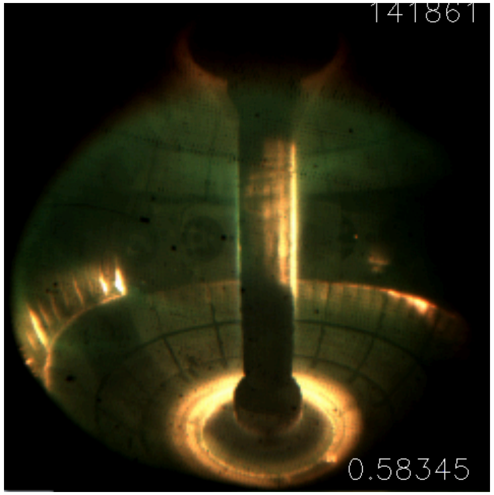
Gap = 6.5 cm



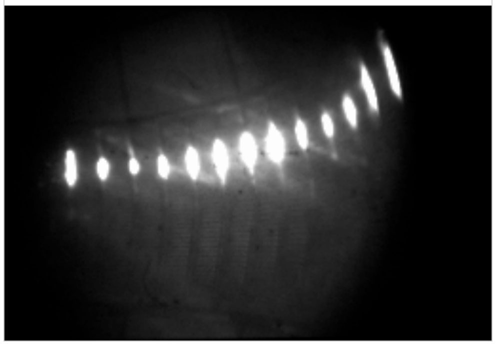
Down Z_C = -20.2 cm



Gap = 6.6 cm

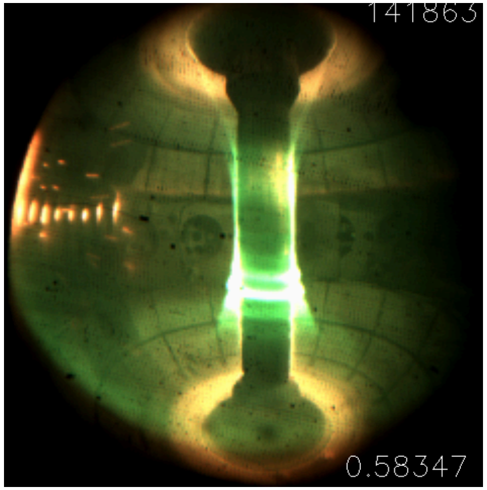


Up Z_C = +16.0 cm



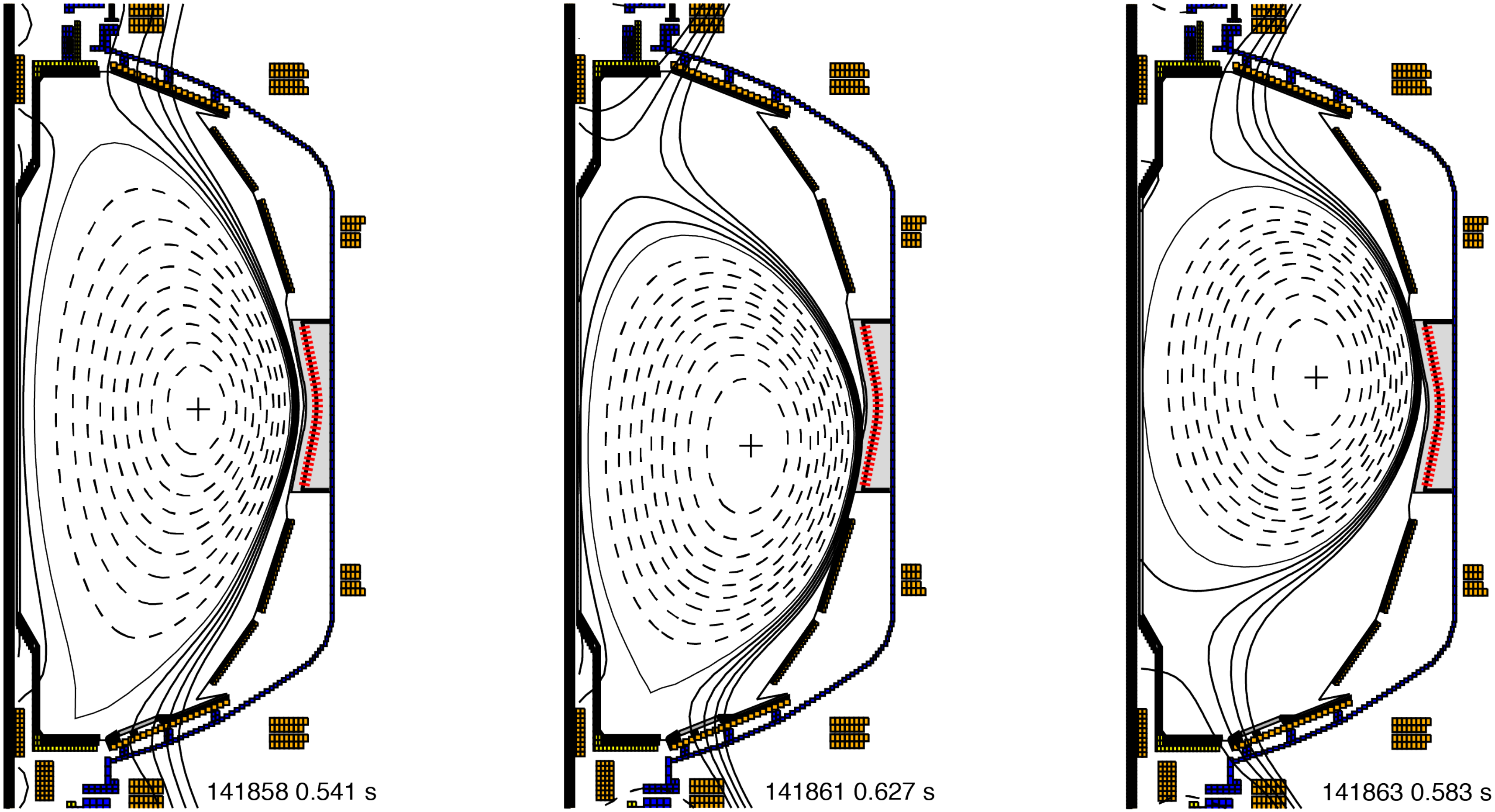
0.583 s
141863

Gap = 7.7 cm



Gap of ~ 6.5 cm insufficient for some conditions (P_{NB} ~ 2 MW, P_{RF} ~ 1.1 MW, I_P ~ 0.67 MA)

EFIT equilibria for the Z scan showing gaps



Z_C position ~ -3.5 cm ~ - 20 cm ~ + 16 cm

- Smallest gap between separatrix and antenna sets interaction zone

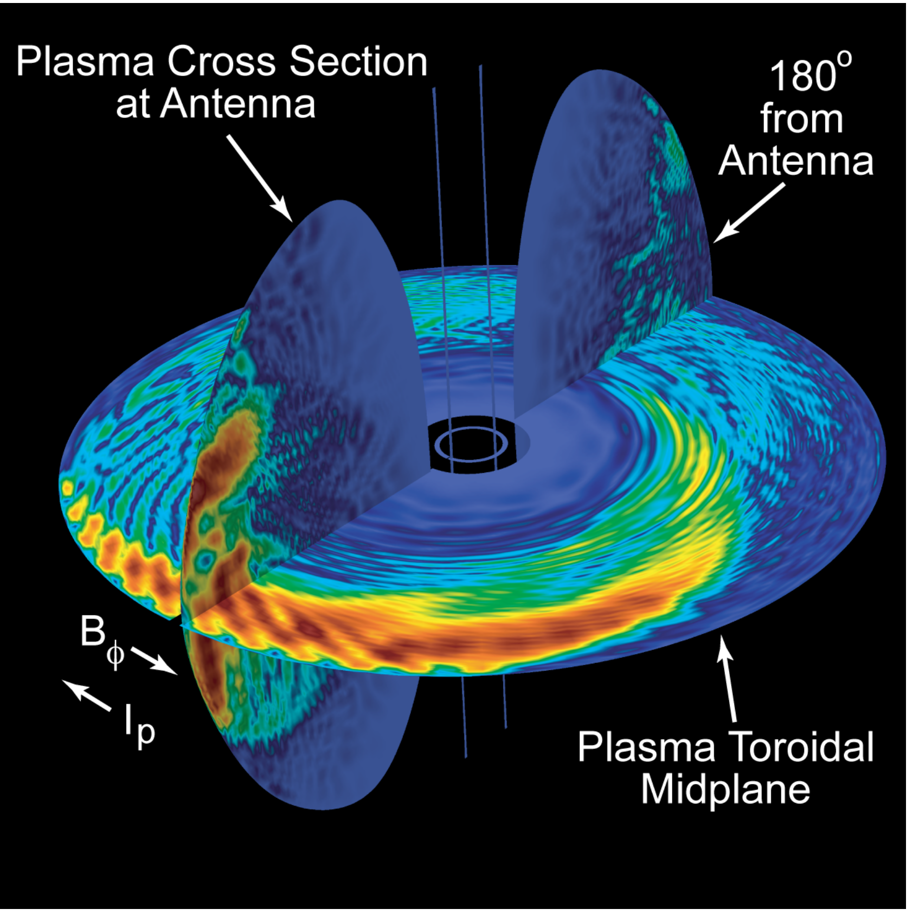
Coupling to plasma inside the separatrix is affected by density in the SOL

Density in SOL:

- Conventional wisdom for minority ion ICRF heating as on TFTR, JET, ITER, etc., is that the edge density should be set as high as possible
    - Gas puffing is being studied on several tokamaks as a means to enhance ICRF coupling on ITER
- Not the case for HHFW
    - A large fraction of the HHFW power goes to the SOL when the density at the antenna exceeds the fast wave cutoff density ($n_{cutoff} \sim B\, k_{\phi}^{2} / \omega$)
    - Need to keep density relatively low near the antenna

Strong "single pass" absorption into center of plasma core predicted with no density in the SOL

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

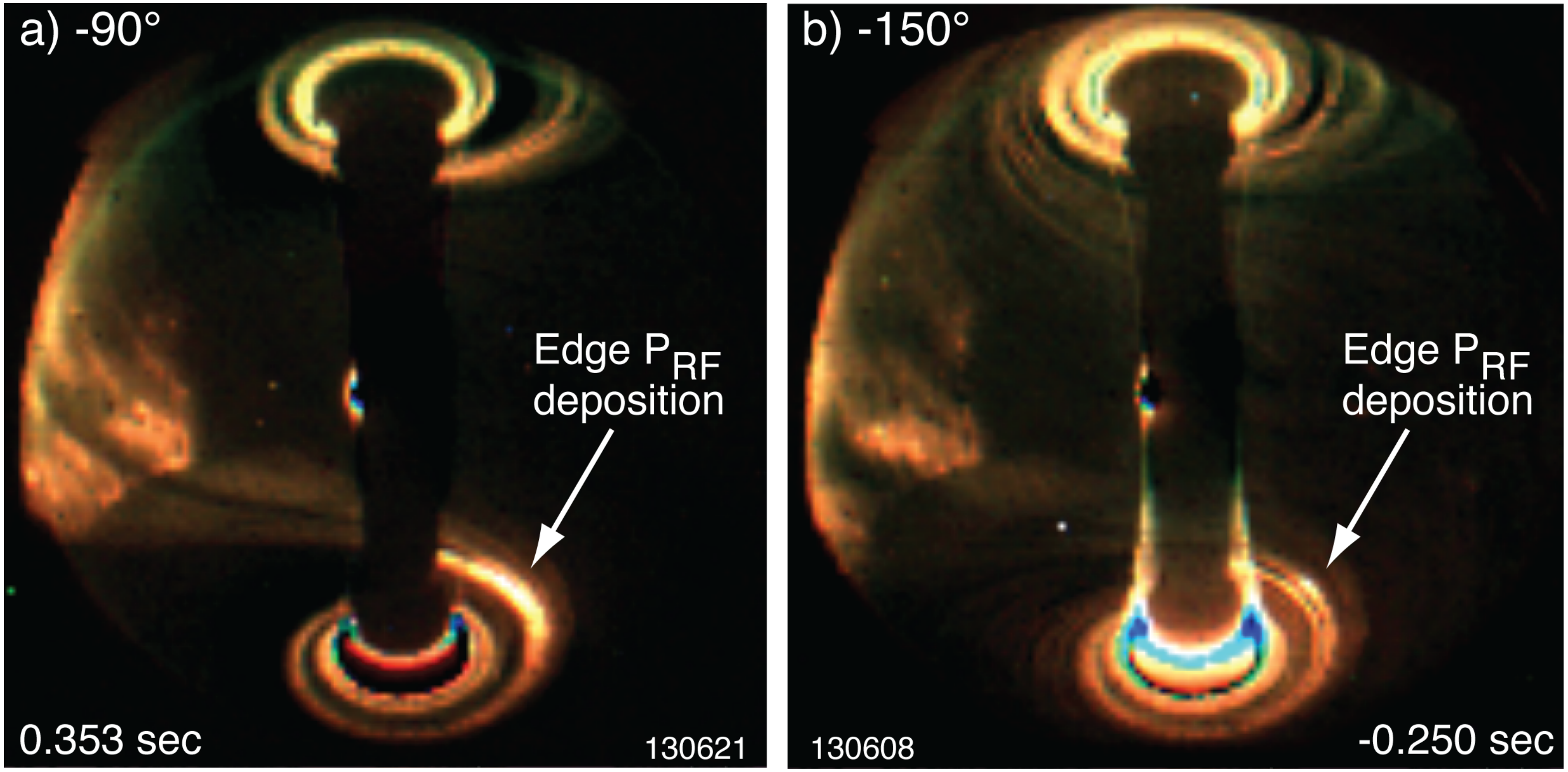


- If waves are started at the separatrix there is very good HHFW efficiency predicted
- However, propagation across the SOL can lead to substantial loss of RF power
- NSTX/NSTX-U parameters are ideal for studying competition between core heating and edge power loss since there is no multi-pass damping

- Note that Helicon operation on DIII-D will be at substantially higher harmonics than for HHFW on NSTX/NSTX-U: similar power loss in the SOL is expected

HHFW RF power deposition in the SOL heats the tiles on the outer divertor plates in a spiral pattern

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

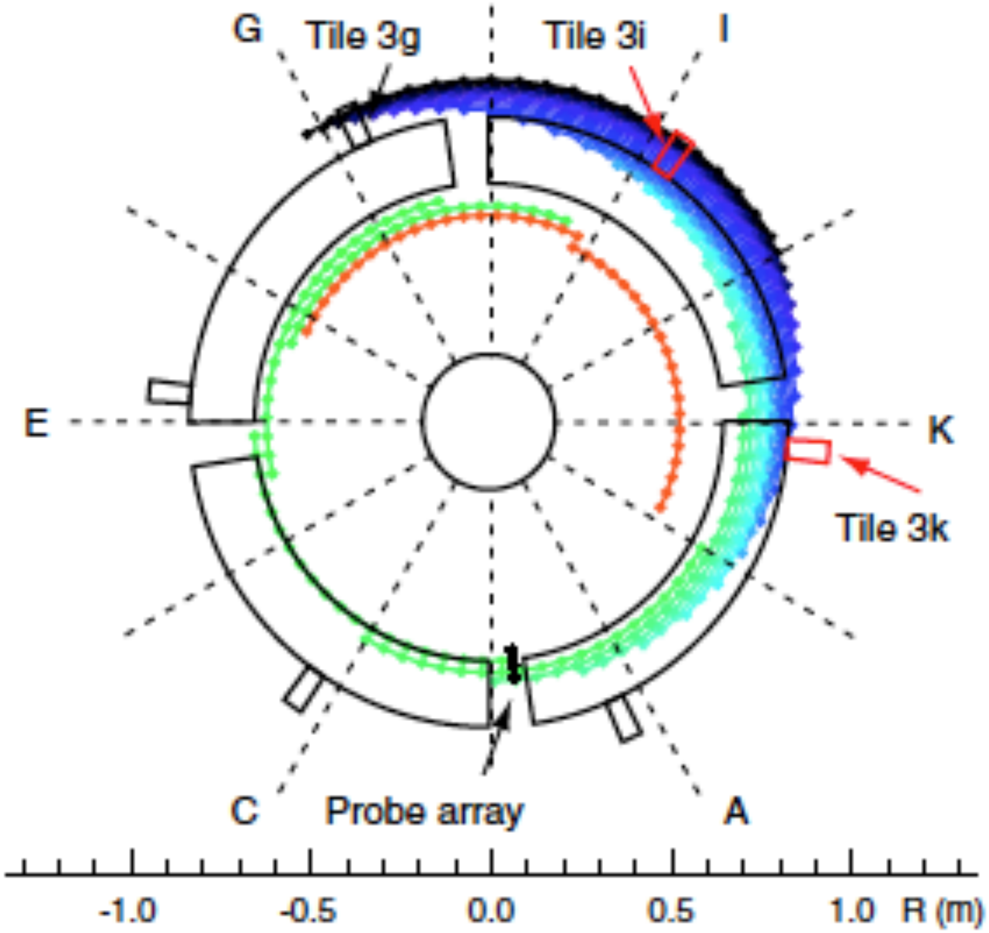


- Spiral thought to be due to fast waves propagating along magnetic field lines from in front of the antenna to the divertor floor/ceiling
- "Hot" region is much more pronounced at -90° than at -150° due to the lower value of n_{cutoff}

Field-line strike point spiral matches RF heating spiral

Field line strike points calculated with the SPIRAL code for shot 141899 for field lines started in front of the antenna from midplane SOL radii between 157.5 cm (antenna R) and 152 cm (LCFS R)

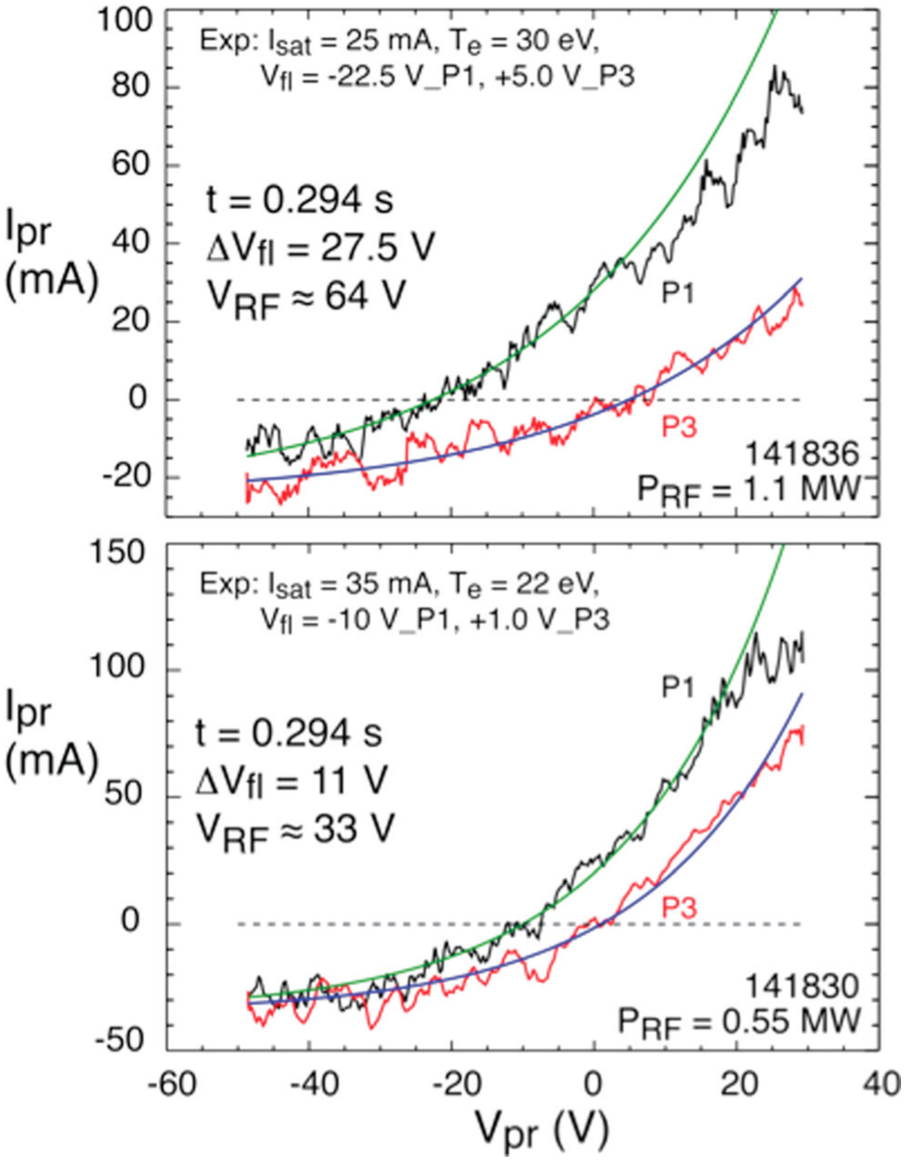
(b) Pitch = 39.6° divertor floor



- Power flow is from antenna to divertor floor along field lines in SOL
- Only tiles and probes under the spiral collect RF produced electron current at zero voltage

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

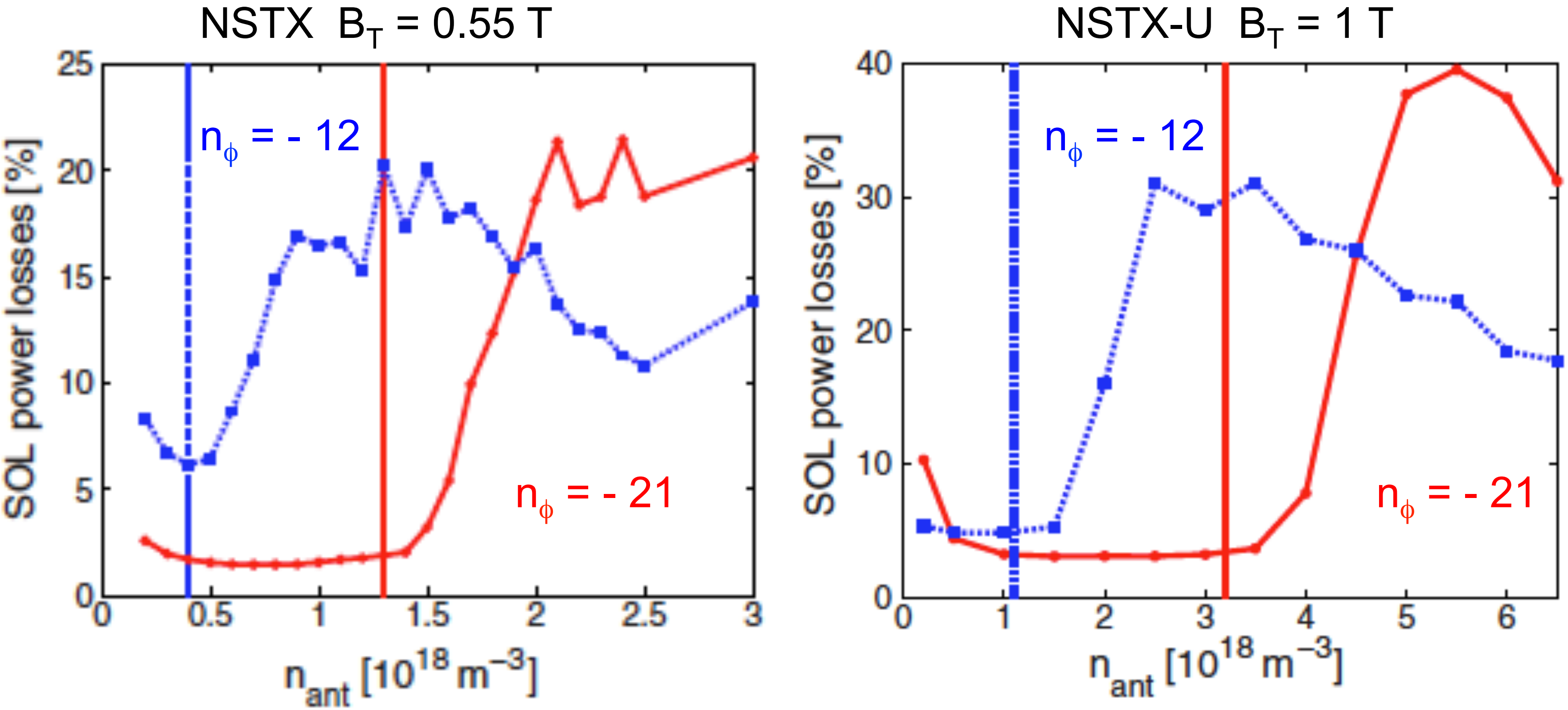
Probe measurements indicate that RF field rectification at the divertor/wall is causing the RF heating spiral



Perkins et al., PoP **22** (2015) 042506

- P1 (under spiral) IV characteristic shifts in – V_{pr} direction relative to P3 (outside spiral) at same T_e
- V_{RF} deduced from shift is substantial and depends on P_{RF}:
  - V_{RF} is ~ 64 V at 1.1 MW and ~ 33V at 0.55 MW for shots shown
- The calculated δQ values deposited from RF rectification compares well with the IR camera measurements

AORSA modeling including the SOL plasma shows a strong increase in RF E field in the SOL for n > n_{cutoff}



NSTX B_T = 0.55 T

NSTX-U B_T = 1 T

- The vertical lines represent the values of density for which the FW cutoff starts to be “open” in front of the antenna
- The RF power loss to the SOL increases substantially above n_{cutoff} (using a collision parameter in the SOL)
- These results match the experimental SOL loss trends

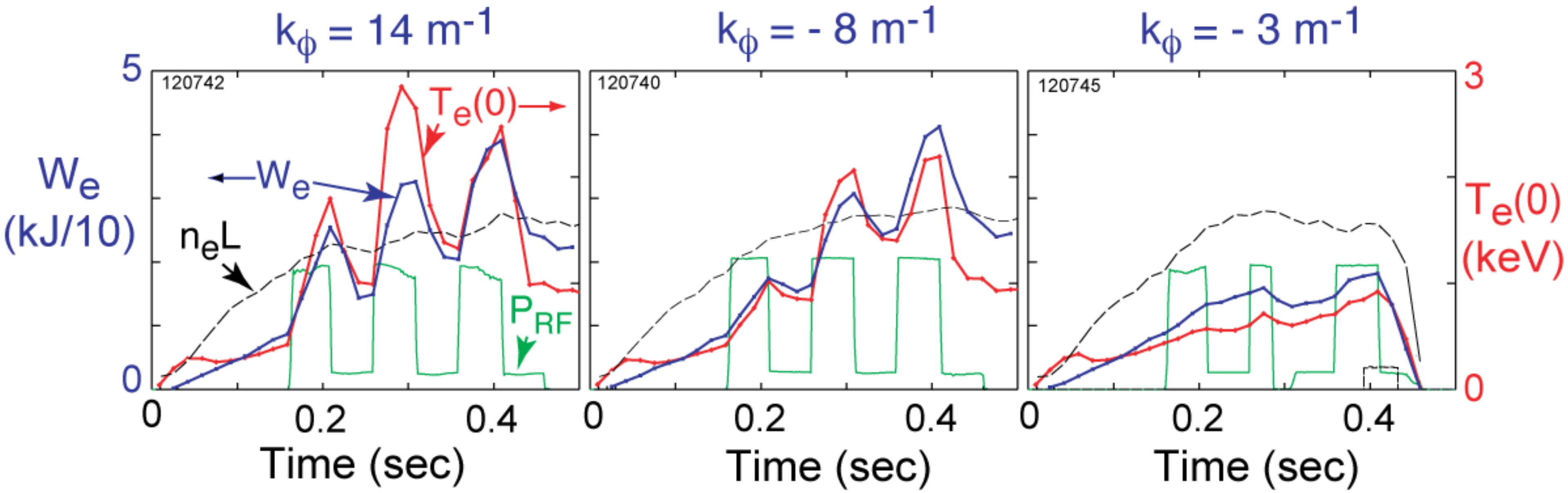
Bertelli et al., Nuclear Fusion **54** (2014) 083004

Phasing effect on coupling

- Antenna loading increases with decreasing phase between current straps
  - Any phase can be selected for heating
  - Lower phase is needed for current drive
  - Minimum phase is set by efficiency of coupling to core plasma

HHFW electron heating drops at lower k_ϕ

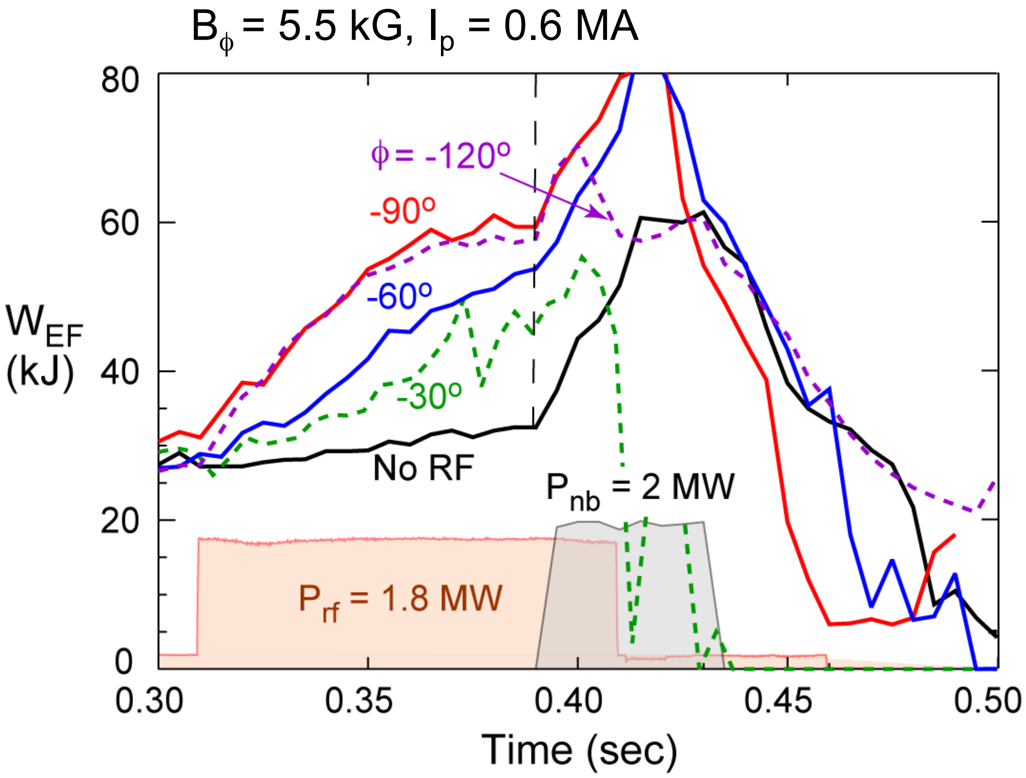
Electron heating for B_T = 5.5 kG, I_P = 720 kA, P_{RF} = 2 MW

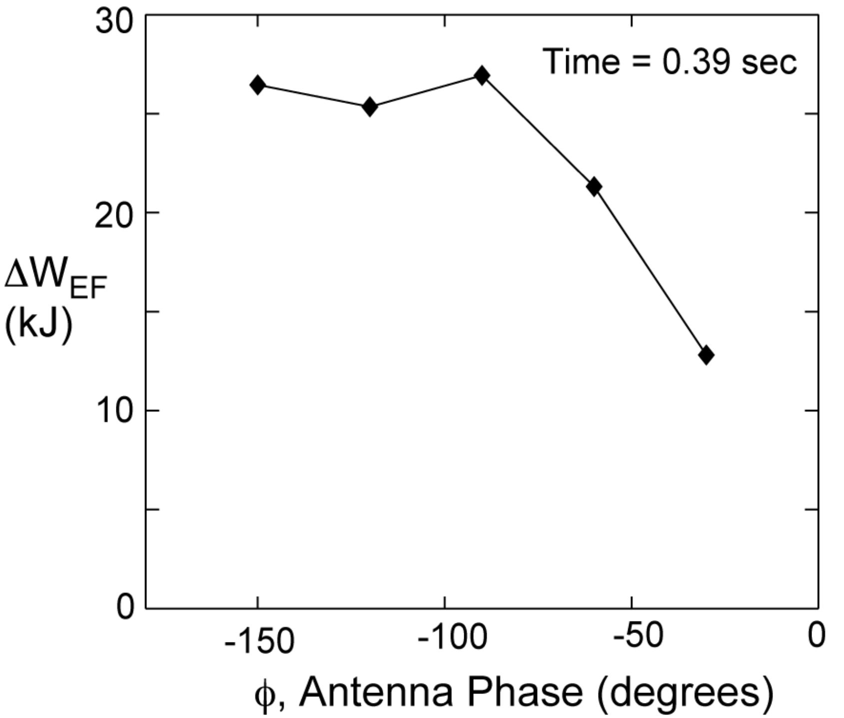


- Heating at k_ϕ = - 8 m^{-1} greatly improved by increasing B_T to 5.5 kG from 4.5 kG
- Clear strong dependence on k_ϕ – almost no heating at k_ϕ = - 3 m^{-1}
- Drop off relates back to density near antenna being above the cutoff density

Heating efficiency at B_T = 5.5 kG decreases for $\phi < -90^o$ ($k_\phi < -8\ m^{-1}$)

- Heating efficiency at strap-to-strap antenna phase $\phi = -30^o$ is approximately half the efficiency at $\phi = -90^o$





- Lower phase efficiency should be improved on NSTX-U at B_T = 1 T and I_P = 2 MA

Current drive difficult at low B_T

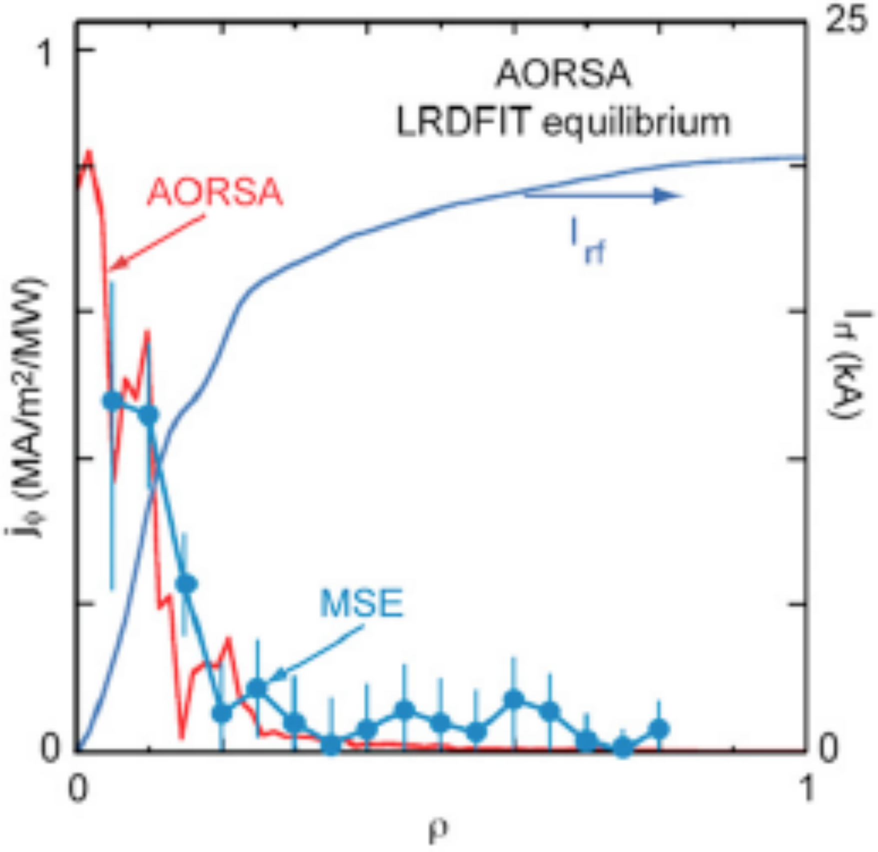


Figure 7. Comparison of MSE data with AORSA full spectrum simulation using MSE-constrained equilibrium obtained with LRDFIT.

- Current drive is limited by poor coupling to core at low phase and by electron trapping at large magnetic field pitch
- Should be better on NSTX-U with larger B_T and relatively small I_P

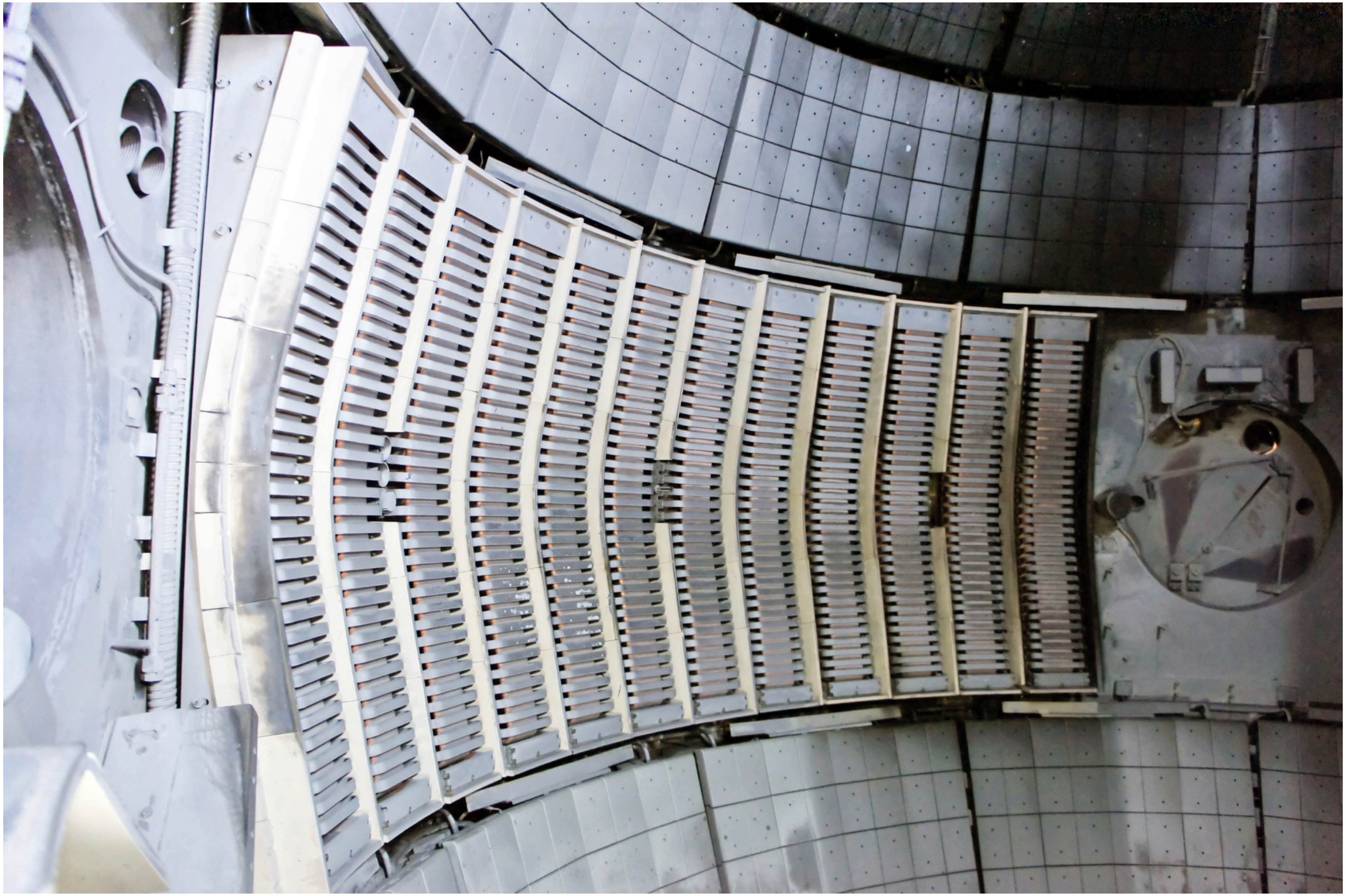
Phillips et al., Nucl. Fusion (2009) 075015

Antenna conditioning is required to enhance RF standoff voltage and thereby coupled power

- Vacuum conditioning is used for spot knocking and out gassing
- Plasma conditioning under XMP026 is used to clean off tokamakium

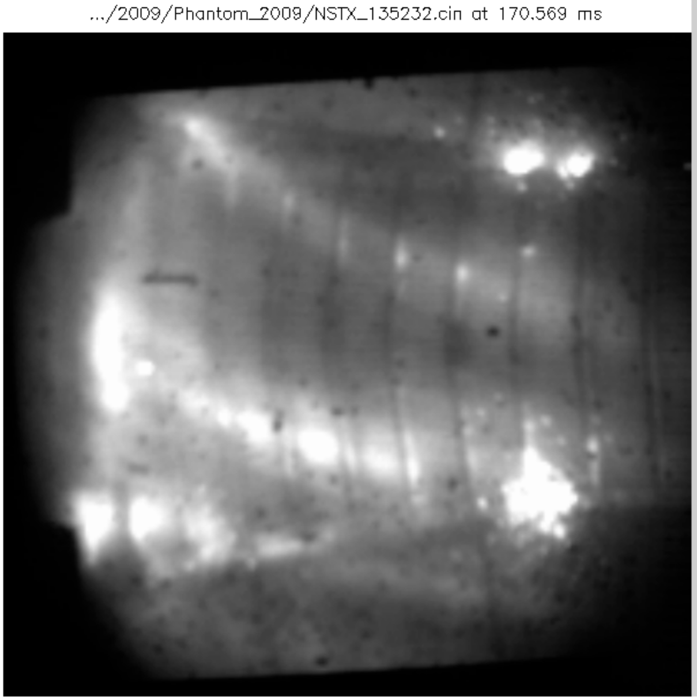
Antenna gets covered by lithium evaporation

Photo at the end of the 2010 experimental campaign

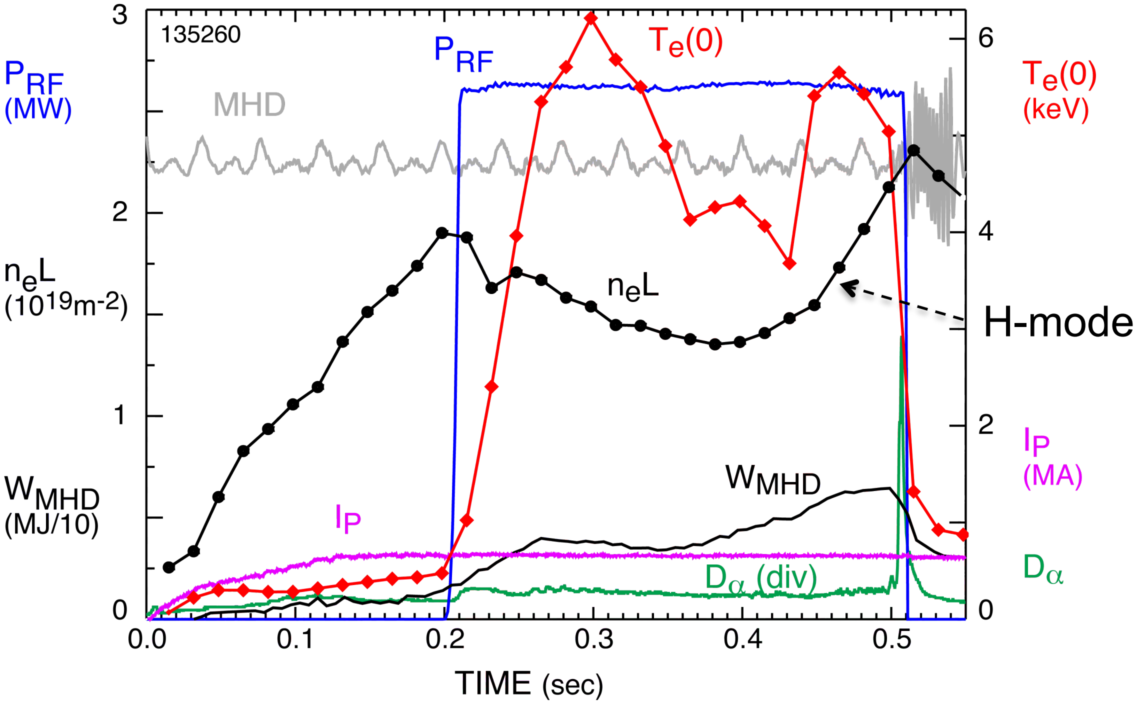


Plasma conditioning to eject lithium from antenna surfaces permits access to H-mode with HHFW alone

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



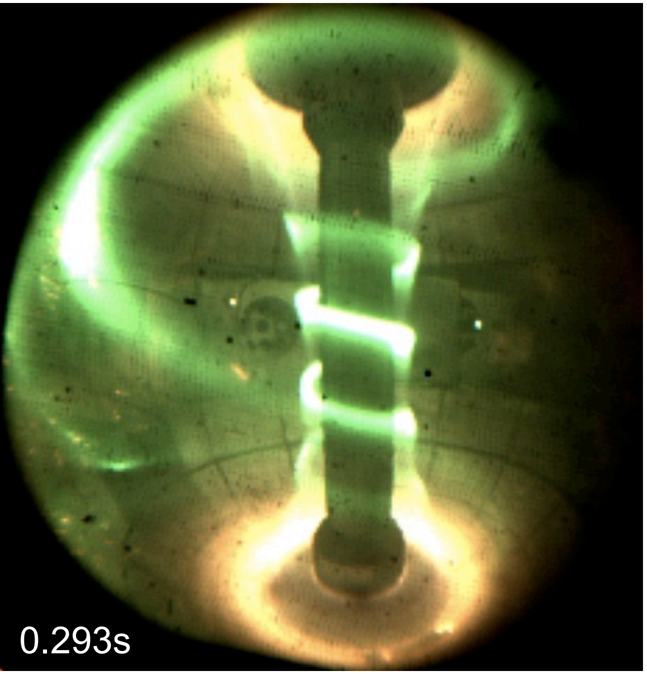
Heating after plasma conditioning with P_{RF} = 2.7 MW (He, B_ϕ = 0.55T)



- Lithium sputtering from outside of antenna enclosures and BN limiters can cause arcs if material (dust) enters faraday shield enclosure
- 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
- Better to optimize lithium use and not evaporate directly on the antenna

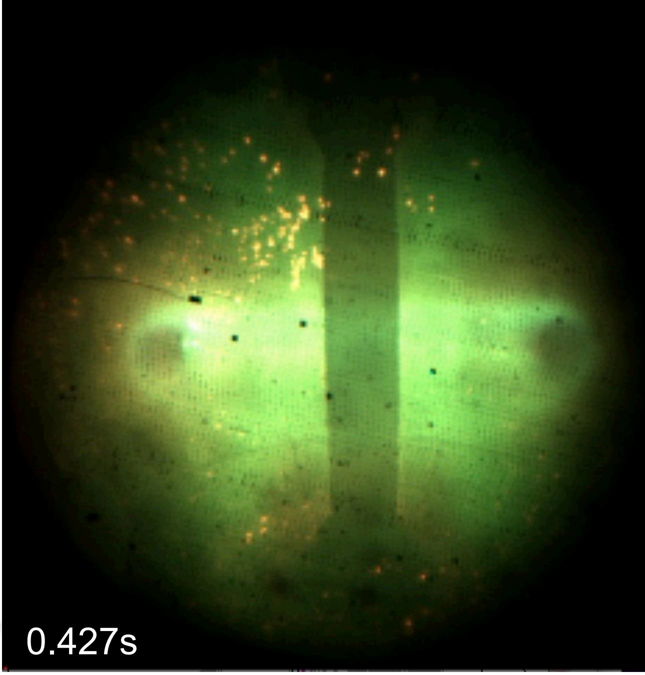
Lithium deposition affects HHFW antenna with coatings and dust projectiles (don't vent machine to air)

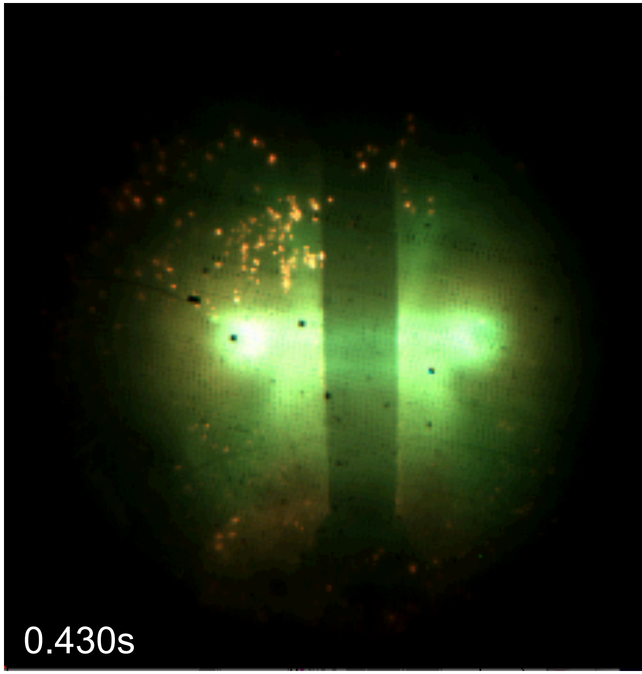
Shot 141988 B_T = 4.5 kG, I_P = 0.9 MA,
Helium, P_{RF} = 1.9 MW



- Lithium from top of antenna moving along magnetic field line

- Lithium projectiles at end of shot
  - Moving outward toward antenna
  - Vent of machine created lithium compounds



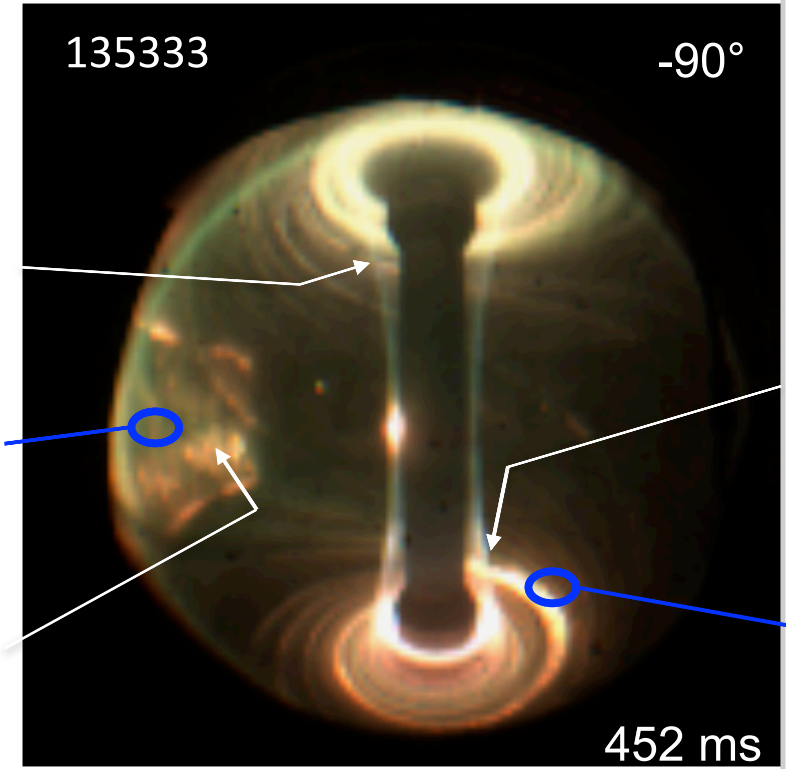


Coupling to H-modes

- XP 1510 is for the study of HHFW heating of RF only H-modes and RF + NBI H-modes on NSTX-U

- Diagnostic set is improved to support the study of SOL RF losses on NSTX-U
- RF coupling to RF only H-mode is not sensitive to ELMs
  - ELMs cause a very small density perturbation in front of antenna even for small gaps
- RF coupling to H-modes with NBI is difficult since ELMs cause large density excursions in front of the antenna
  - Cause relatively large power reflection from the antenna
  - Can cause the antenna arc protection circuit to trip

IR camera and probe upgrade: critical for documenting RF edge heating



Bay G
IR view

Antenna
probes,
reflectometer

Antenna
IR view
& visible view

Bay I
Wide angle
IR view

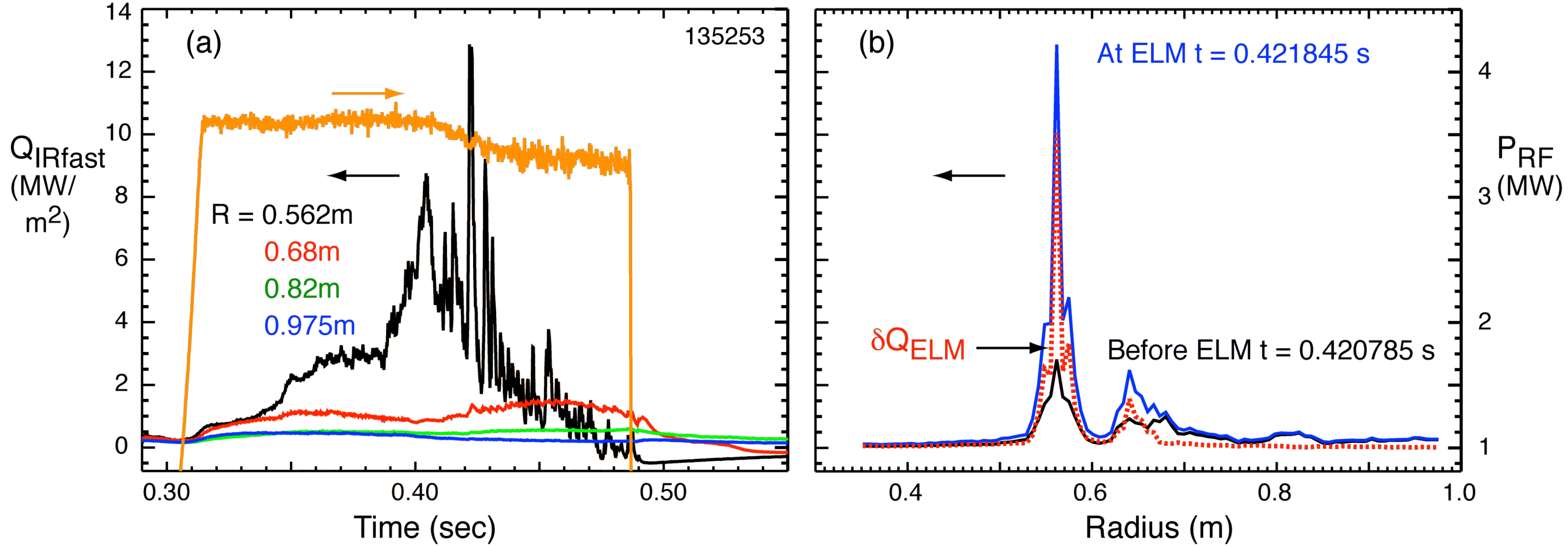
Bay J probes (Langmuir and RF)
- 6 poloidal Langmuir probe array for radial coverage top and bottom
- Extend RF probe to plasma edge

B_T = 4.5 kG, I_P = 0.8 MA

- Diagnostics configured: to “see” hot HHFW streak over wide range of field pitch
- IR views: at bottom, top and antenna
- Probes for measuring IV characteristics and RF fields: Coaxial Langmuir and RF probe

ELM deposition is very close to the OVSR with RF only

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

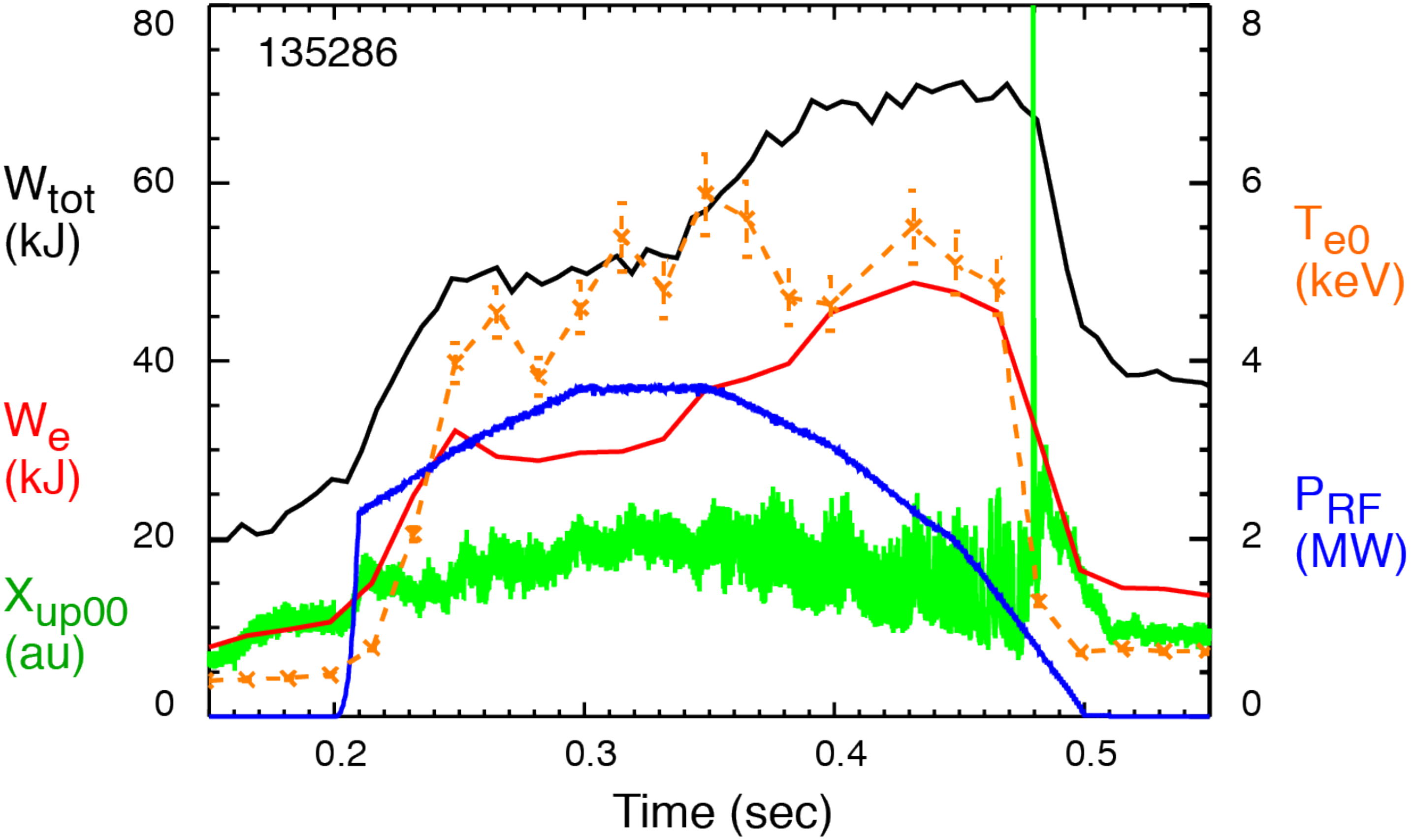


Fast IR measurements of heat flux at Bay H versus (a) time for 4 major radii at the divertor tiles and (b) major radius at the time of the largest ELM and at the minimum preceding it.

- 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) with a half width in R of ~ 1 cm
- Small effect of largest ELM is barely evident on the net RF power
  - ELMs are located away from the antenna

Relatively ELM-free H-mode held for some time even during a drop in P_{RF}

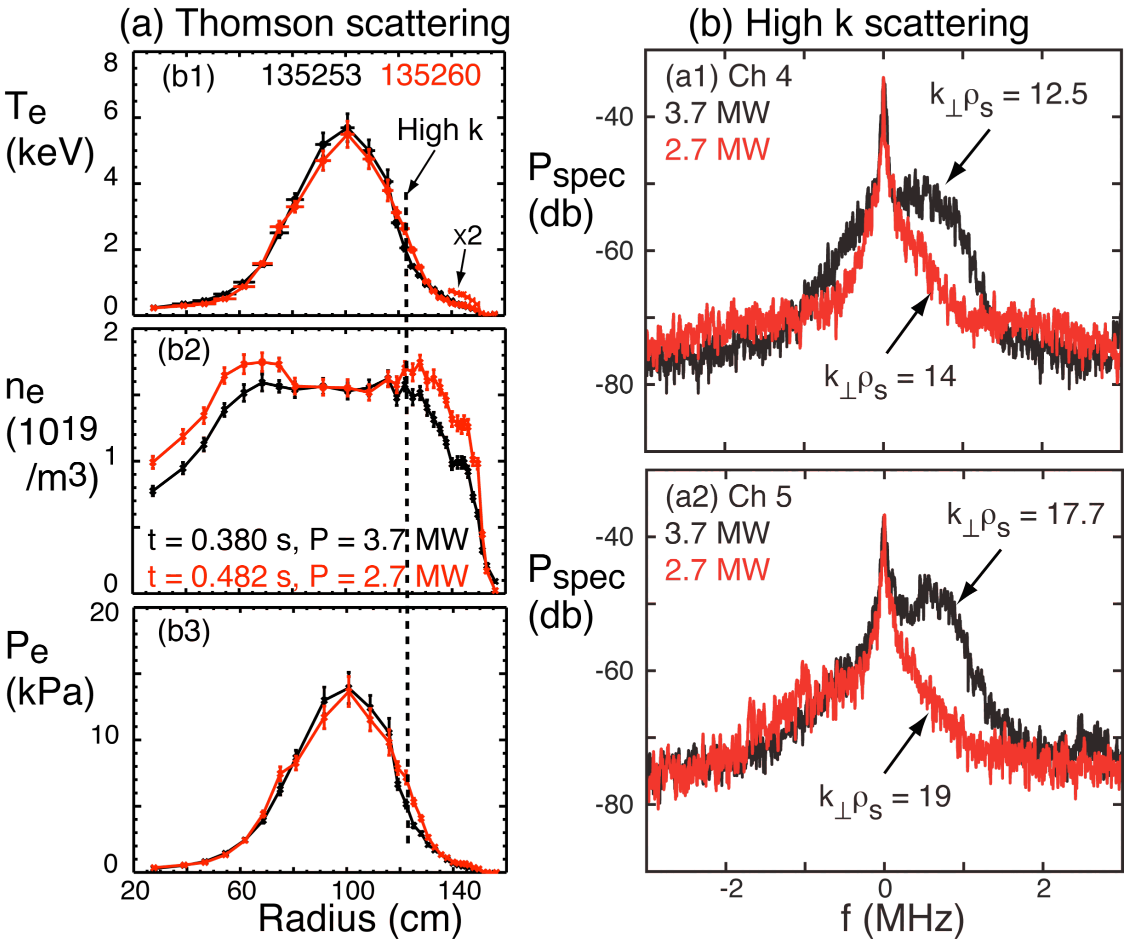
Stored energy during the ELM-free-phase for a programmed P_{RF} which falls from P_{RF} ~ 3.7 MW to zero in ~ 150 msec. (B_T = 0.55 T, I_P = 0.65 MA, helium, $k_{||}$ = $-8m^{-1}/\phi_{Ant}$ = -90°)



- The fluctuations observed in the edge X-ray signal are located in the pedestal

Efficiency is relatively low for RF only ELM-free plasma at higher power - ETG mode excitation possible cause

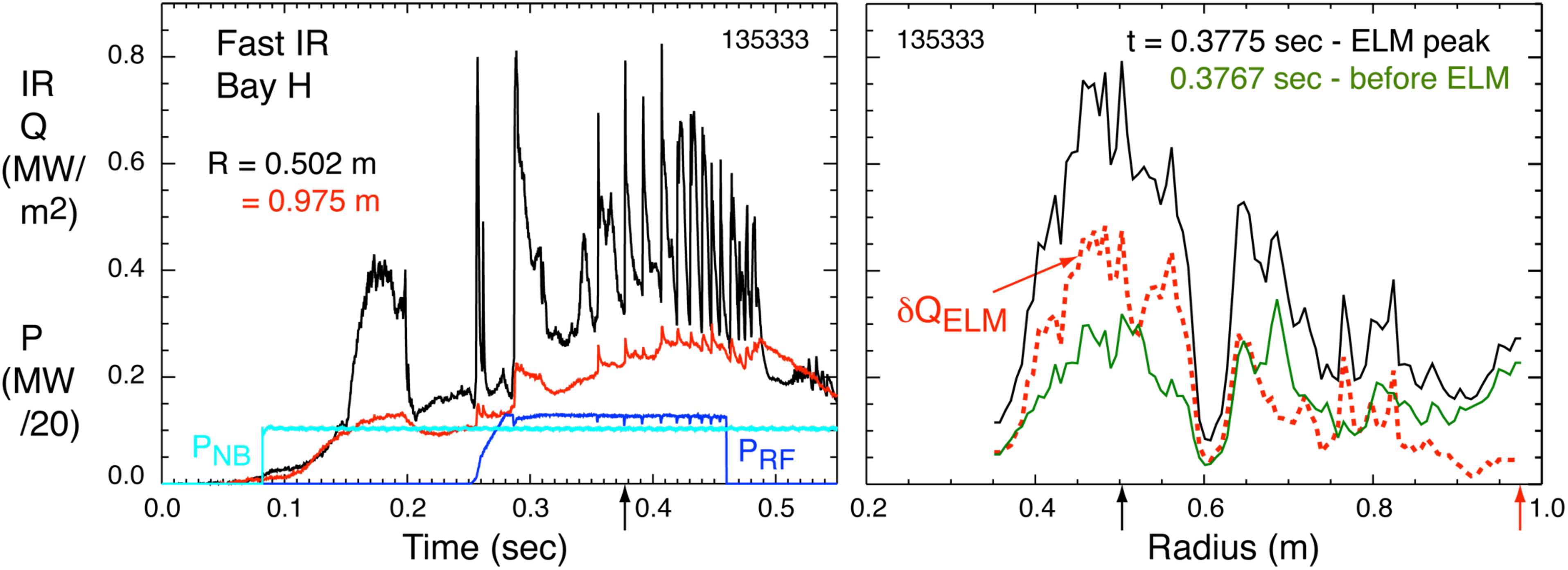
(a) Thomson scattering profiles and (b) high-k scattering spectra for 3.7 MW (135253 at 0.380 sec) and 2.7 MW (135260 at 0.482 sec)



- Need to understand the effect of ETG etc. modes on RF core loss in NSTX-U

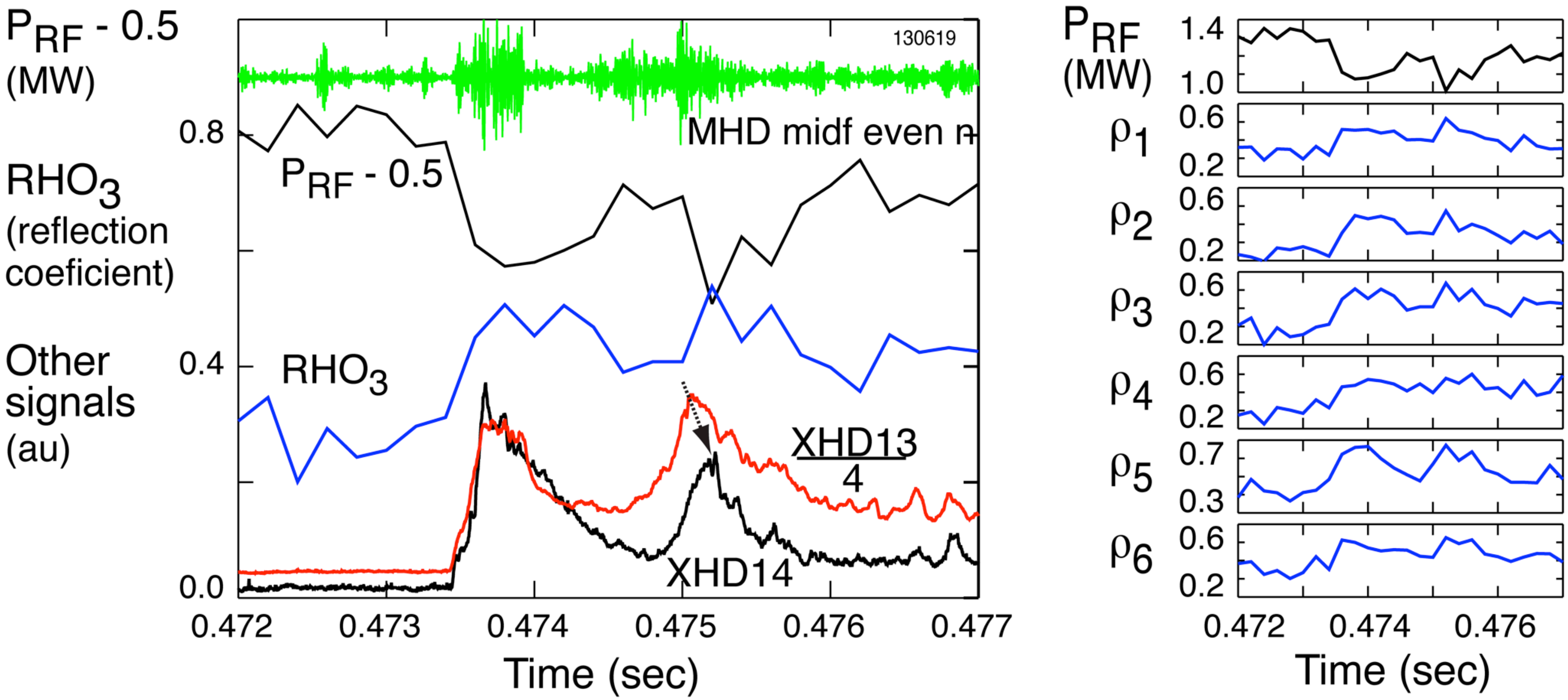
For RF + NBI H-mode the ELM power deposition extends well out in major radius towards the antenna

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



- 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)
- Density excursion in the SOL has clear effect on P_{RF}

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

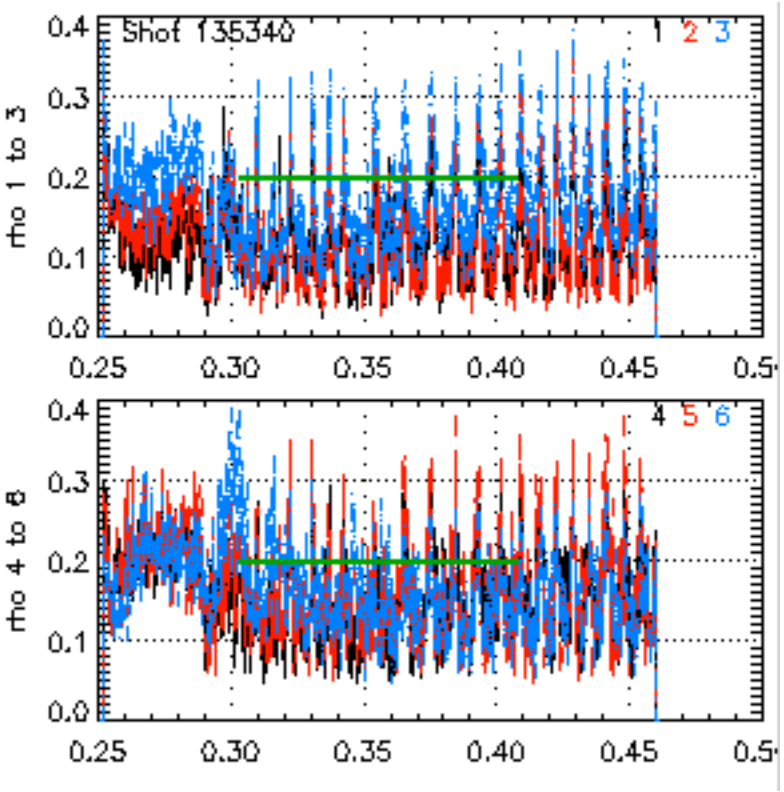
Two RHO peaks due to two type I ELMs are coincident with increases in edge density (XHD14 $\propto n_e^2$)

Rise time of RHO is slow relative to that for an arc – can be used to discriminate between arc and ELM

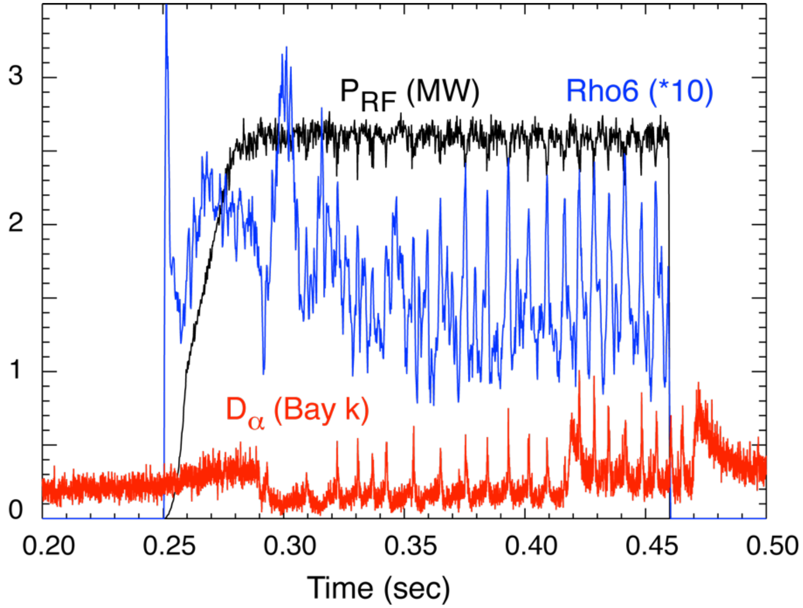
Coupling through ELMs made possible by setting average matching level and a high ρ reflection trip value (0.7 here)

RF source response to ELMs for Shot 135340

Source voltage reflection coefficients



ELM behavior

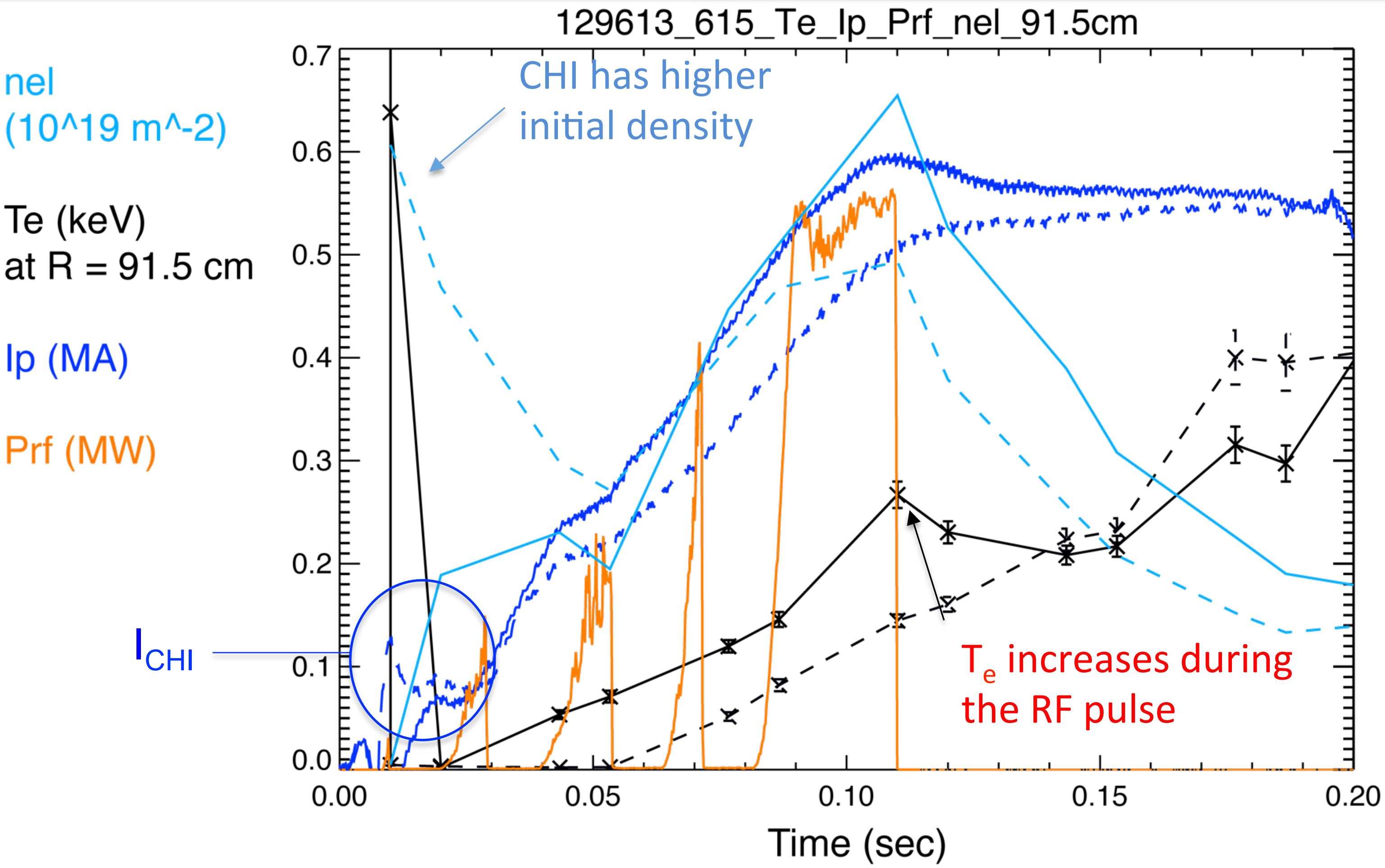


- For optimized coupling to ELMy NBI plasmas, we need to introduce power splitter/hybrids to direct the reflected power to dummy loads and away from the sources

Coupling to startup plasmas for ramp up

- Some success on CHI and ohmic startup plasmas
- Difficulty in matching to startup plasma is that the density changes in time
  - RF pulse drops out from mismatches when ρ exceeds 0.7
- Two settings of the RF matching with three sources each are planned for NSTX-U to extend the time of RF power application
- In the future, it is desired to instrument the matching stubs to move during the RF pulse to maintain the match
  - Sliding joints for this purpose have been developed for ITER

Comparison of shot with RF/no CHI (129613) and shot with CHI/no RF (129615)



CHI has higher initial density

T_e increases during the RF pulse

- T_e versus time for R = 91.5 cm (black) clearly shows core RF heating during the RF pulse
- CHI produces an initially higher density and an enhancement of I_p for the first ~ 20 ms

Conclusion

- For successful RF heating and current drive on NSTX-U, a close collaboration between the RF operator and the physics operator is required to match to the several plasma regimes

- Also, a close collaboration between the RF group and the NSTX-U team is required to obtain the data and perform the analysis for understanding and optimizing the RF performance