RF power deposition explorations in tokamaks using cameras and Langmuir probes

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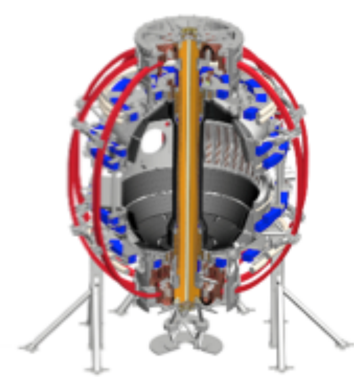
APS DPP Conference
November 16, 2015



RF power SOL deposition explorations in tokamaks

Outline:

- RF power deposition in the SOL on NSTX in HHFW regime
  - "Hot" RF spirals on the divertors
  - RF power flow along magnetic field in the SOL
  - Camera frame (png) subtraction views for detecting spirals
- RF power deposition in the SOL on KSTAR in the minority heating regime
  - Some deposition structure detected in and outside the divertor trench
  - Care must be taken to avoid ELM deposition for the camera frame subtraction (with RF minus without RF) at power level of ~ 600 kW
  - ECE and Langmuir probes are used to set camera frame times
  - More power needed to better discriminate RF power deposition from ELMs
- RF power deposition in the SOL on EAST in the minority heating regime
  - Some deposition structure detected in and outside the divertor trench, and on the antenna/poloidal limiter at Prf coupled ~ 500 kW
  - Deposition detected on divertor probes – especially near the outer vessel strikepoints
  - Apparently, ~ ¾ th of RF power is lost ohmically in the antenna/transmission system – more coupled power needed for SOL deposition detection
- Summary

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

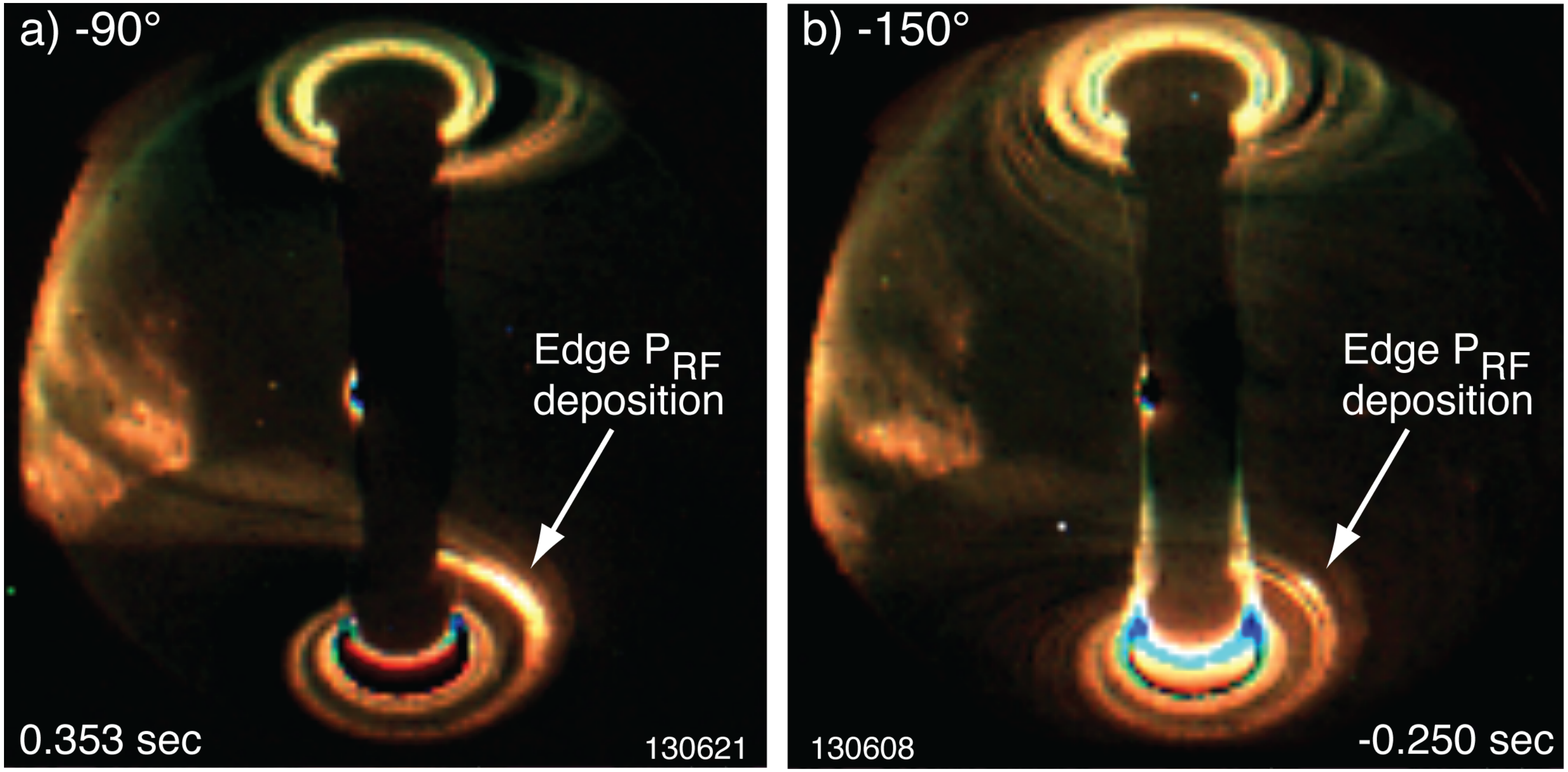
Density in SOL:

- Conventional wisdom for minority ion ICRF heating as on TFTR, JET, KSTAR, EAST, 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

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

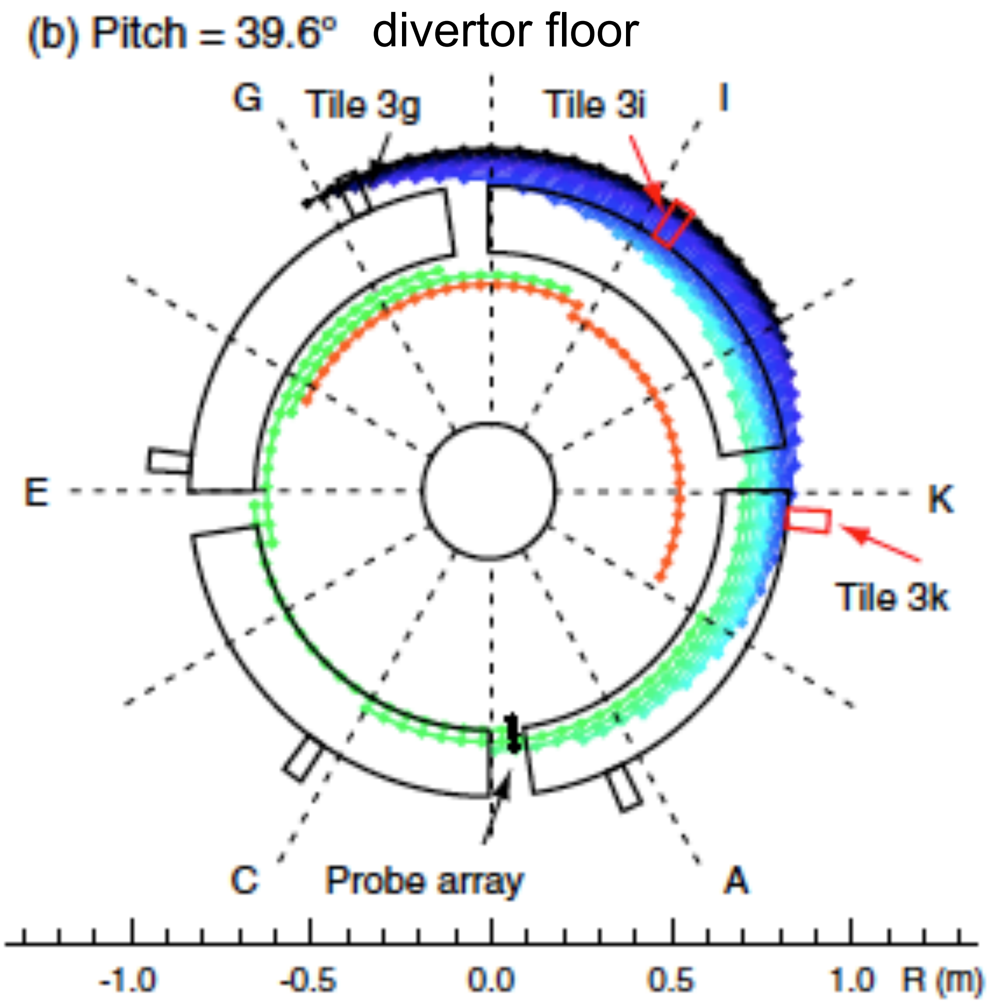
P_{RF} ~ 1.8 MW, P_{NB} = 2 MW, I_P = 1 MA, B_T = 5.5 kG



- 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)

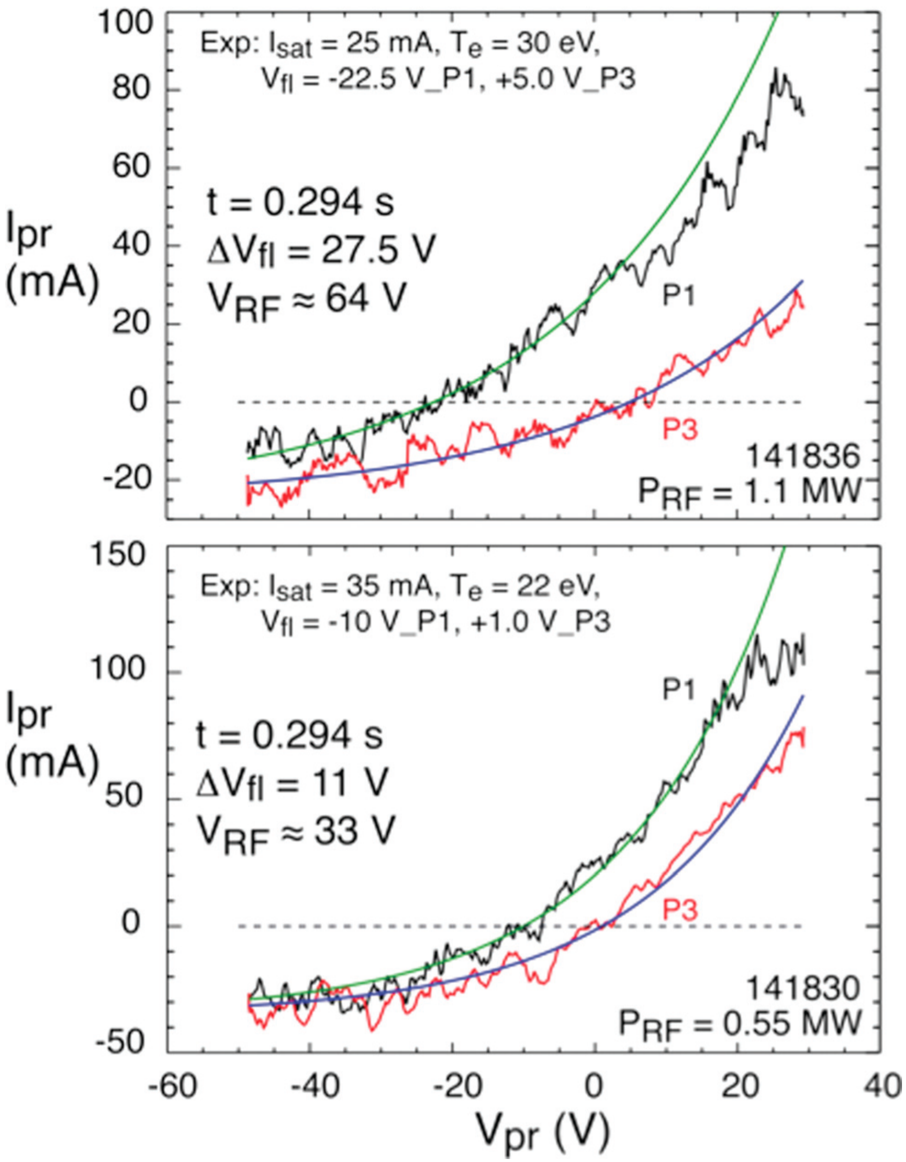


- Power flow is from antenna to divertor floor along field lines in SOL
- Only tiles and probes under the spiral collect RF produced electron current at zero voltage

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

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

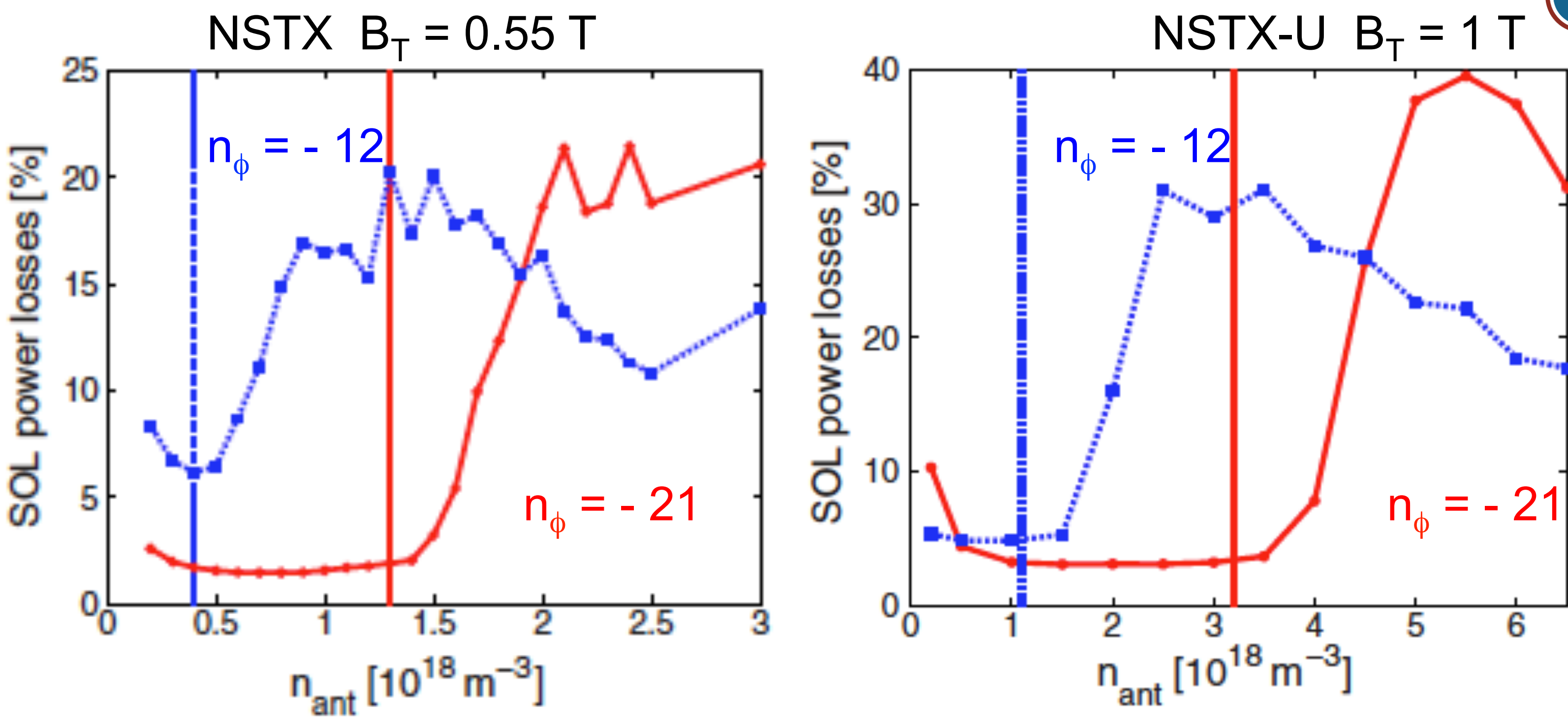
NSTX-U



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 $n > n_{cutoff}$

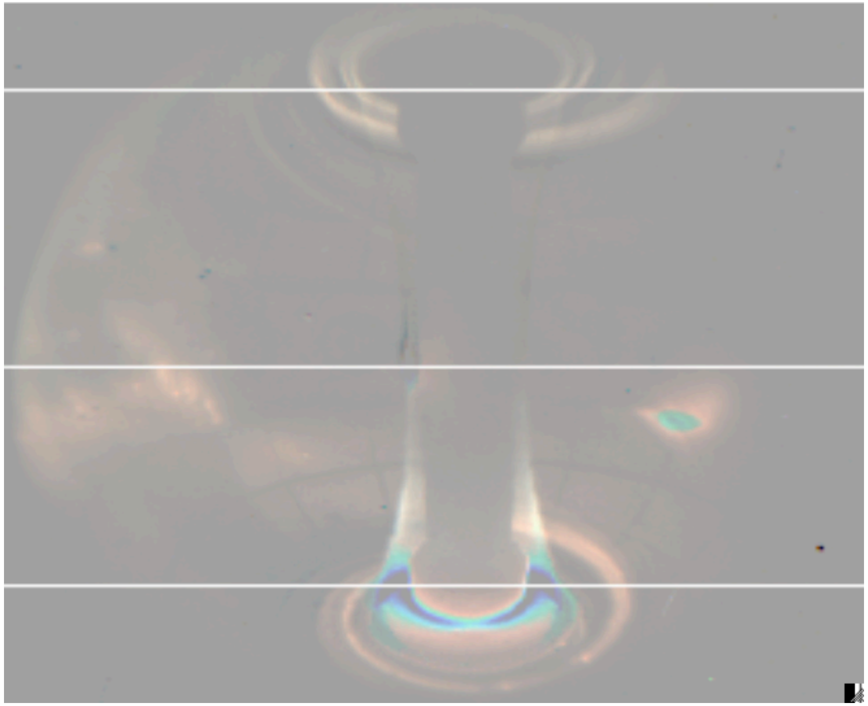


- The vertical lines represent the values of density for which the FW cutoff starts to be "open" in front of the antenna
- The RF power loss to the SOL increases substantially above n_{cutoff} (using a collision parameter in the SOL)
- These results match the experimental SOL loss trends

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

Subtraction of a camera png frame without RF from a png frame with RF highlights power deposition areas

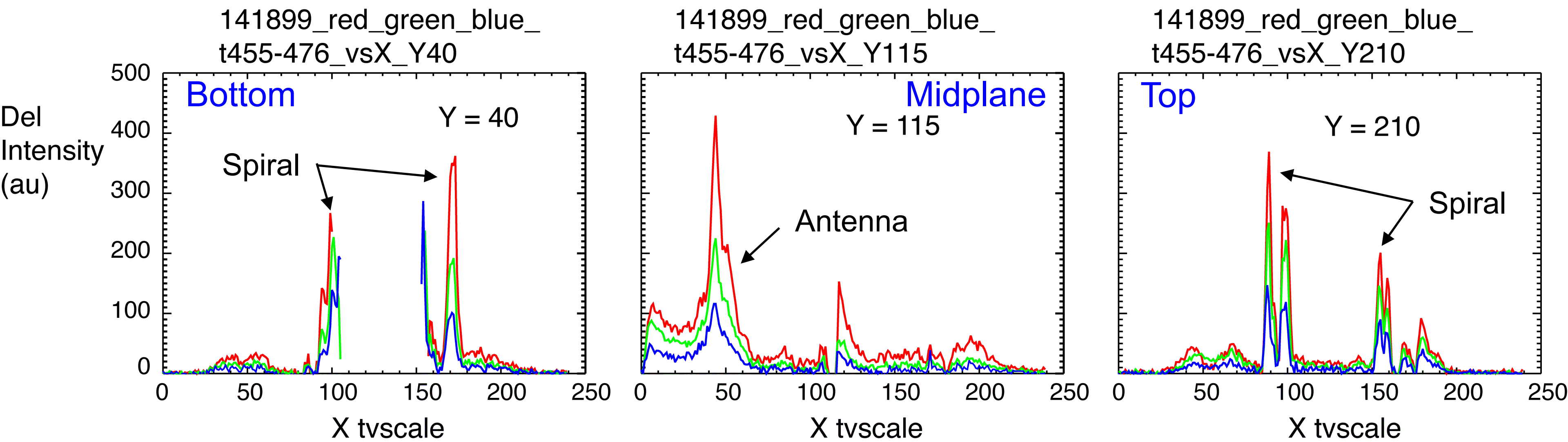
- Frames in png format are used for NSTX



NSTX shot 141899:
455s (wRF) - 476s (woRF)
P_{RF} = 1.3 MW, P_{NB} = 2 MW
B_T = 4.5 kG, I_P = 1 MA

- RF heat deposition is observed in top bottom spirals and on the antenna as before
- Intensities of light can be plotted along horizontal and vertical lines in red, green, and or blue

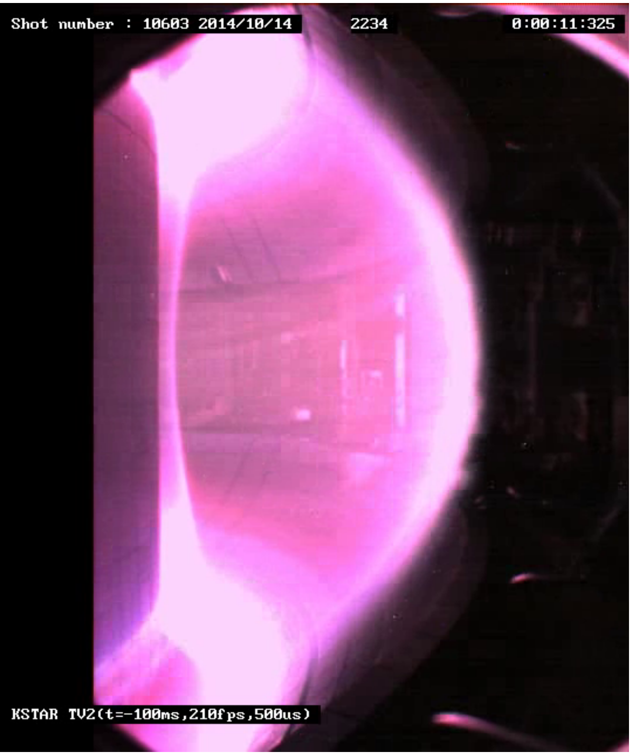
The Δ intensity camera signals at the bottom, midplane and top clearly indicate RF heat deposition areas



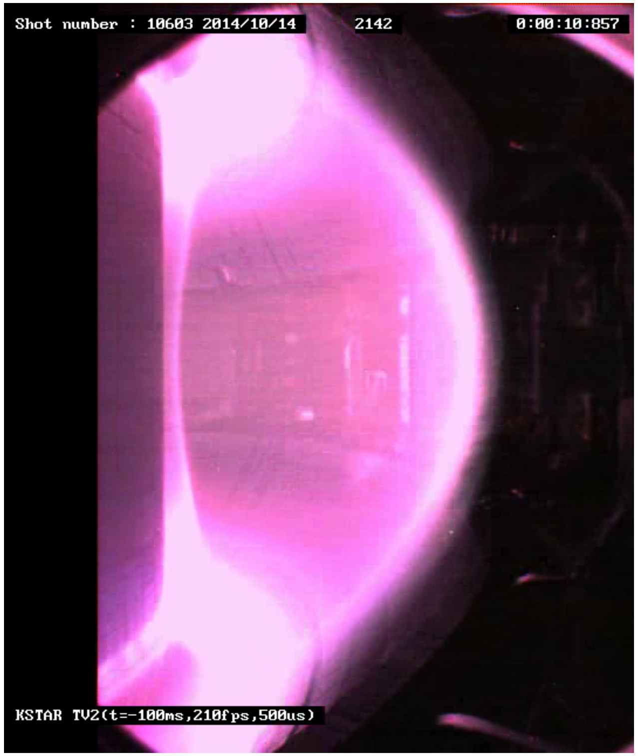
- The spiral deposition patterns are pronounced and deposition is observed on the antenna and inner wall as well (saturated color regions are not included in ΔI plots)
- Blue and green color plots can extend into the regions of saturation for red and serve as a proxy for the deposition profile

Subtraction of a camera png frames highlights power deposition areas in KSTAR

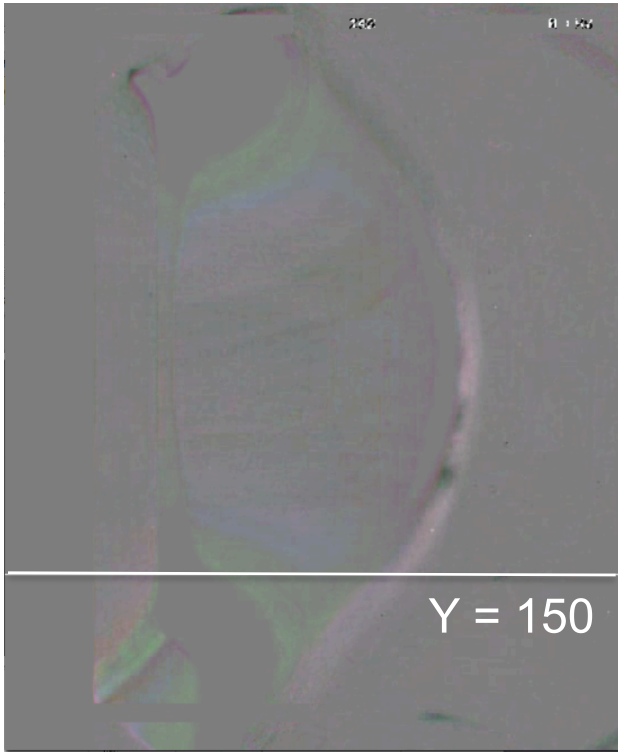
With RF 10.857s
Frame 2142



Without RF 11.325s
Frame 2234



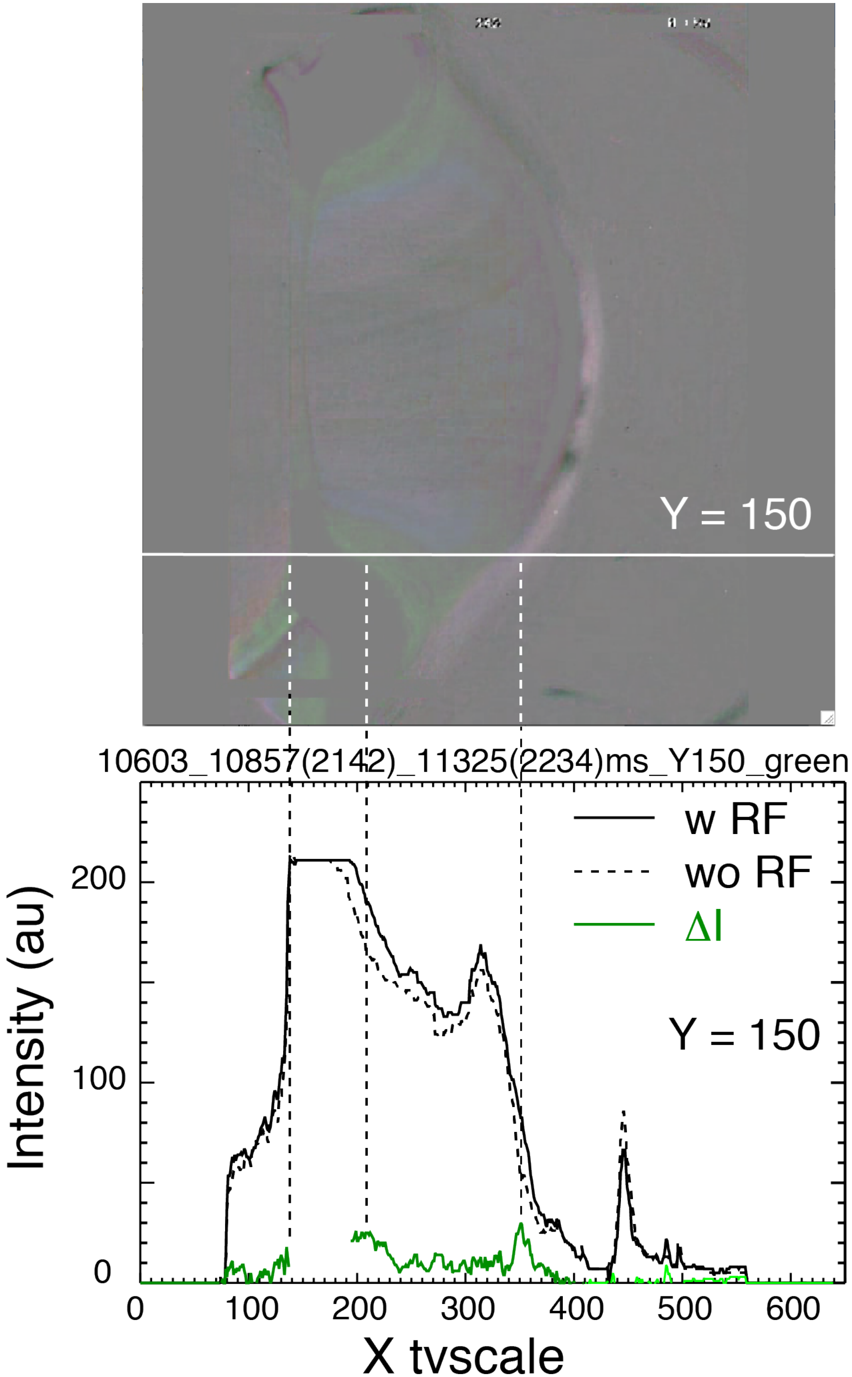
RF – Without RF



Shot 10603: P_{RF}= 600 kW, P_{NB} = 1.5 MW, I_P = 600 kA, B_T = 2T

- Contrast of deposition areas is weak ⇒ fraction of coupled power (~ 400 kW) deposited in the SOL is not large
- Deposition information is gained by plotting along a horizontal line

Subtraction of camera frames: with RF minus without RF

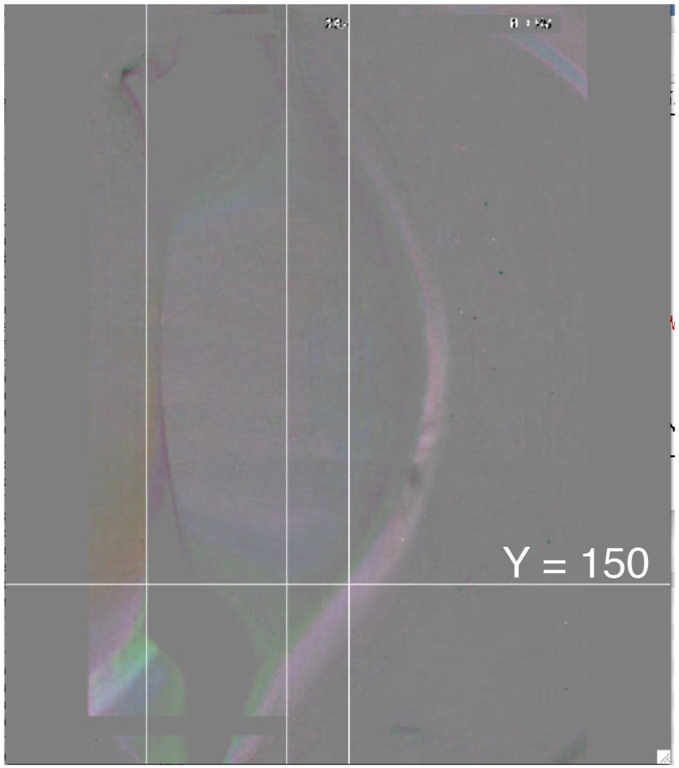


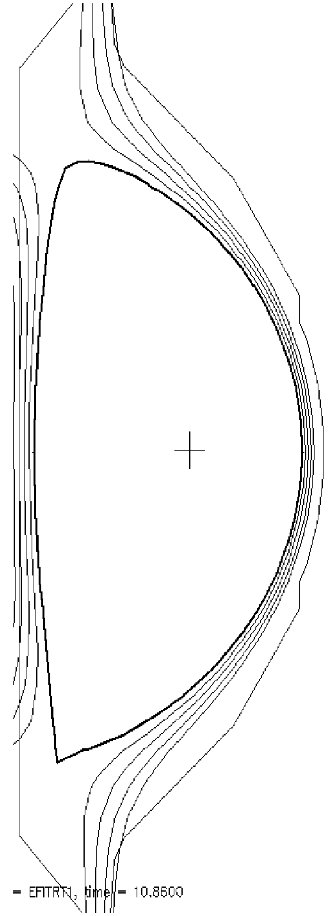
- 10857 ms – 11325ms
- Minimum brightness frames chosen at both times - care taken to avoid ELMs
- Black where all colors are saturated w and wo RF
- Weak difference at relatively low power coupled: ~ 400 kW

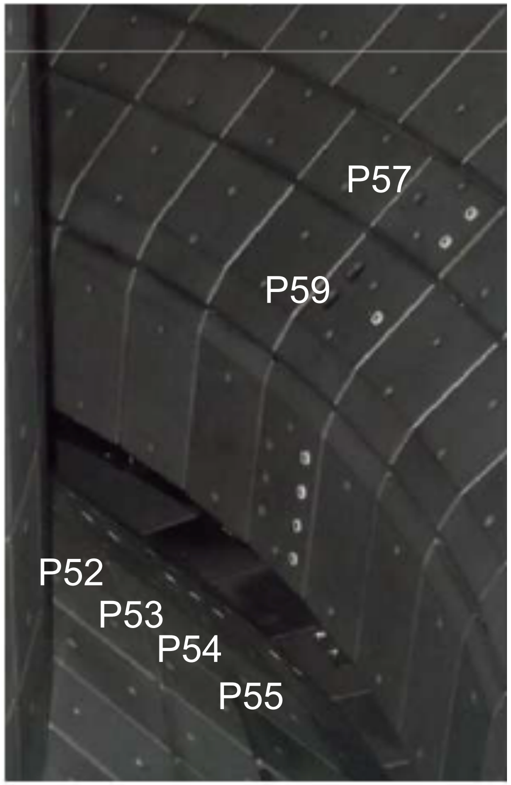
Plots along X at Y = 150 for green color

- ΔI is shown where green signals are not saturated
- There appears to be a green stripe pattern just outboard of the divertor trench where the RF SOL power loss is expected, and at the separatrix

The Isat signal of probe P59 is used to detect changes on the lower divertor shelf close to the divertor trench

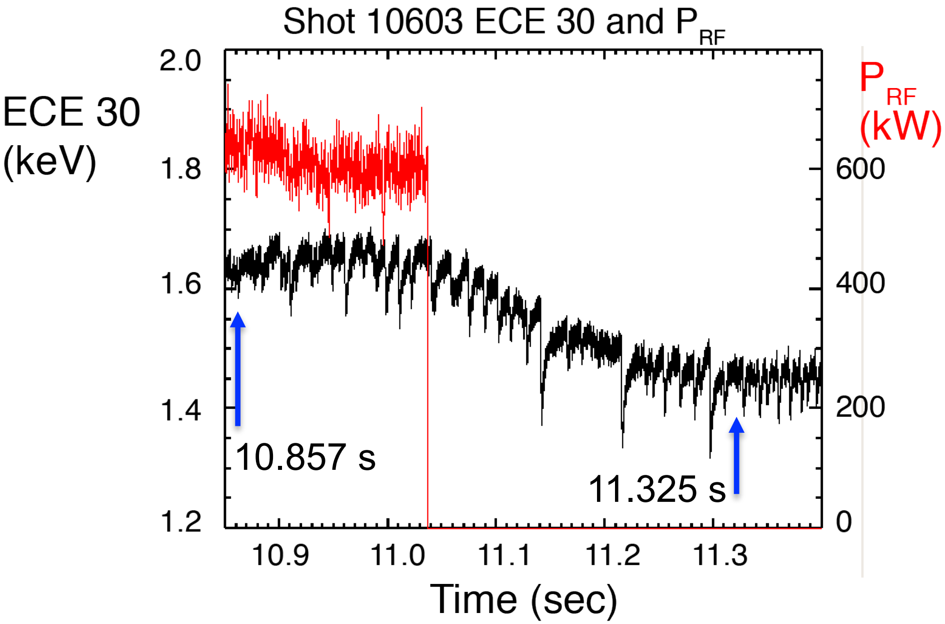




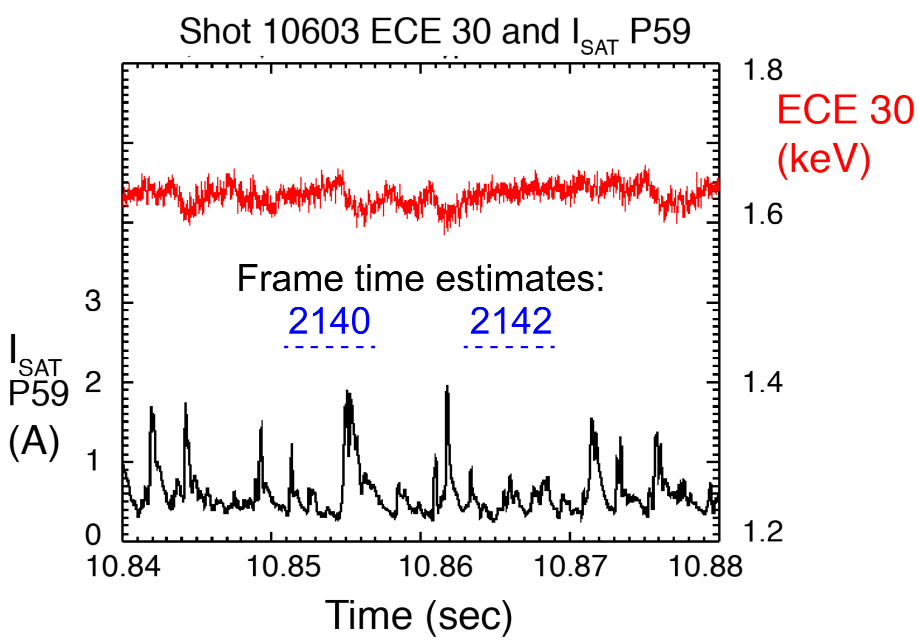


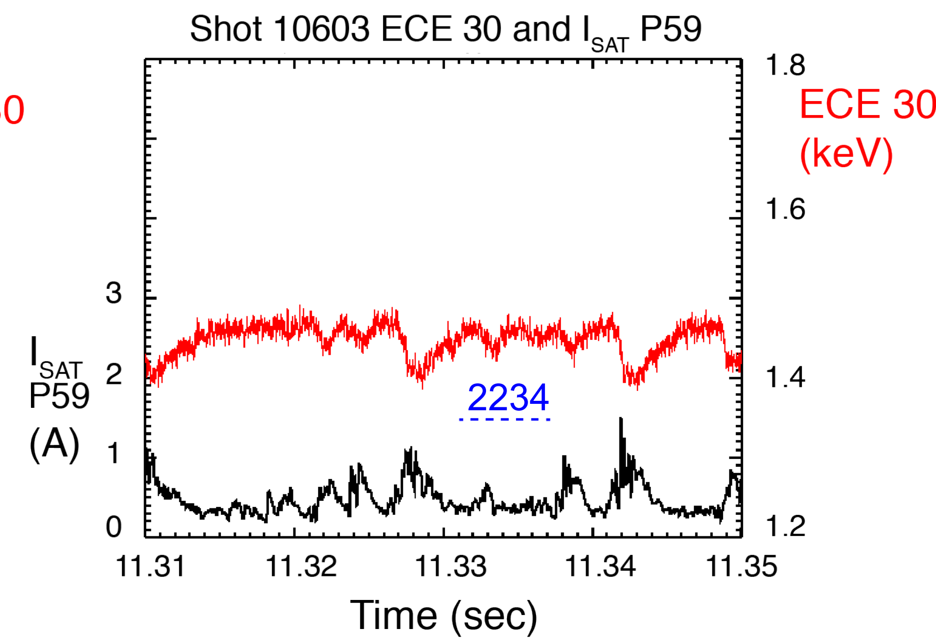
- The Isat signal should indicate strong deposition by ELMs, if any, in the green stripe zone at Y = 150
- Goal is to avoid ELM contributions to the plot of ΔI

Frames are selected for minimum brightness between ELMs



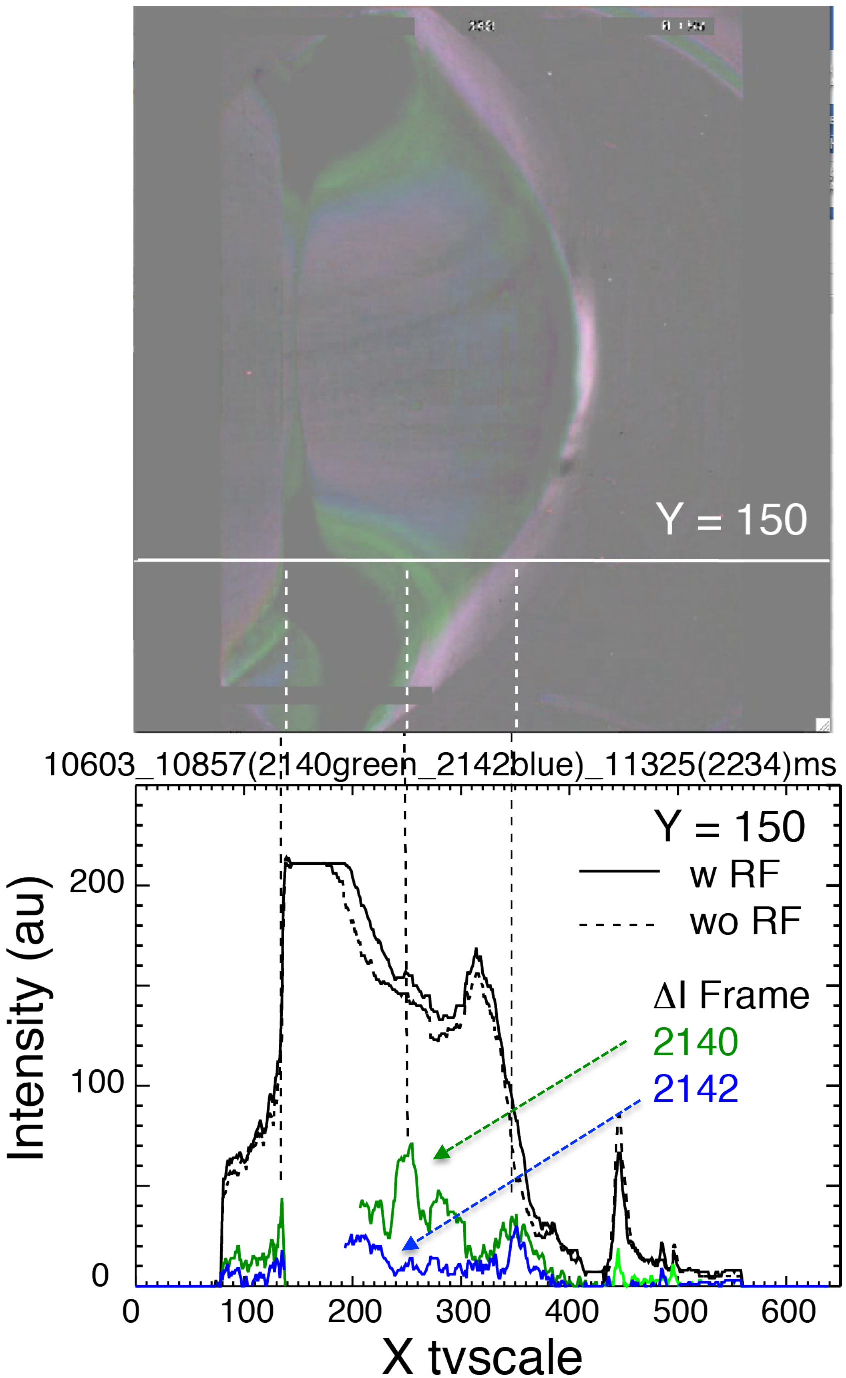
- I_{sat} values for probe 59 are shown for times at the arrows





- It is noted that even a small ELM increases the probe signal substantially

ELM contribution is evident for two frames before minimum brightness for 10857 ms

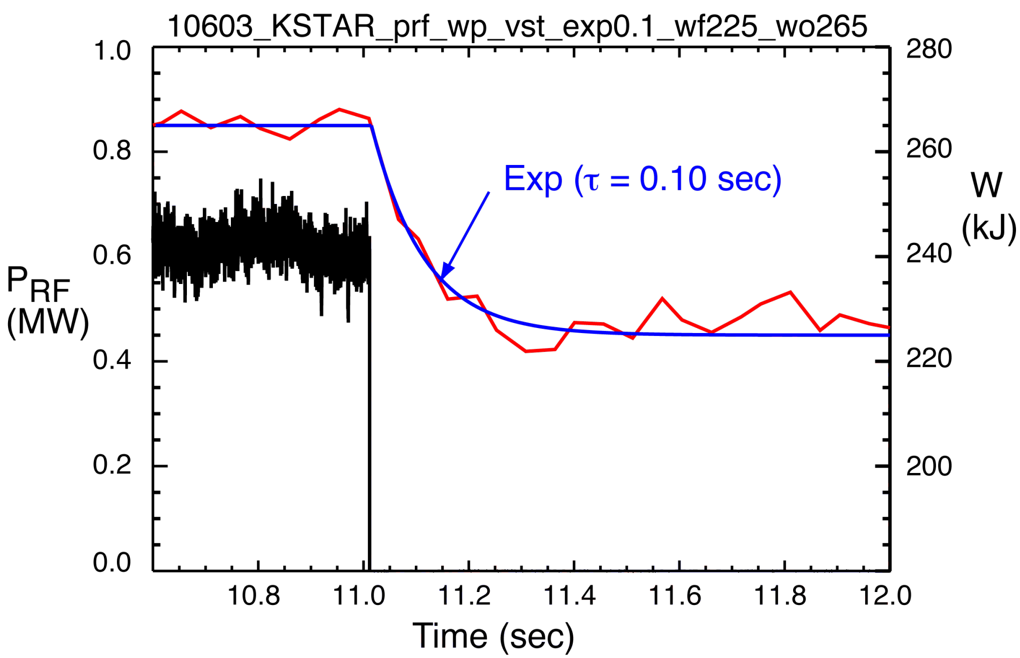


- Considerable enhancement of ΔI occurs at peak of probe 59 signal
- Bands for ELM are clearly visible away from divertor trench
- Some broadening of ΔI at the separatrix
- Higher RF power is needed to definitively distinguish SOL RF power deposition from ELM deposition

RF power increase is needed for study of SOL losses on KSTAR

KSTAR

ICRF heating on KSTAR with P_{RF} ~ 600 kW. Exponential decay of stored energy increment gives RF deposition in plasma of ~ 400 kW.



$P_{dep} = \Delta W/\tau$

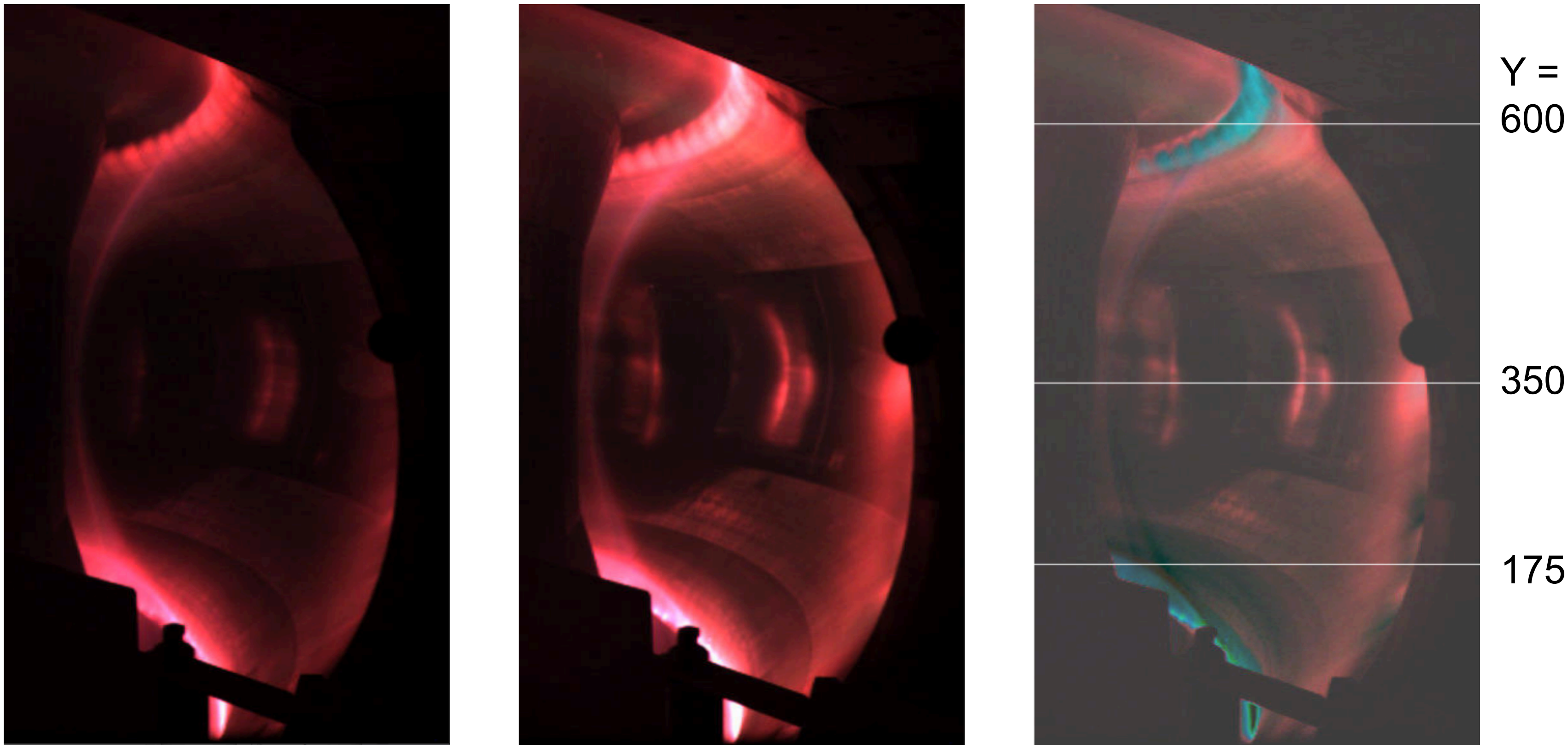
$= 40$ kJ/0.10s = 0.40 MW

- 2/3 of P_{RF} is coupled to core plasma
- Balance of power mostly due to ohmic losses in antenna system (~ 200 kW)
  - Ohmic losses minimized by copper plating of the antenna elements
- Power limited to ~ 600 kW by imposed standoff voltage limit of 25 kV during experiment
- Power increase is needed to facilitate looking for power losses in the SOL

Subtraction of a camera jpeg frames highlights power deposition areas in EAST

EAST

Without RF 3.697 s | with RF 4.204 s | RF – without RF

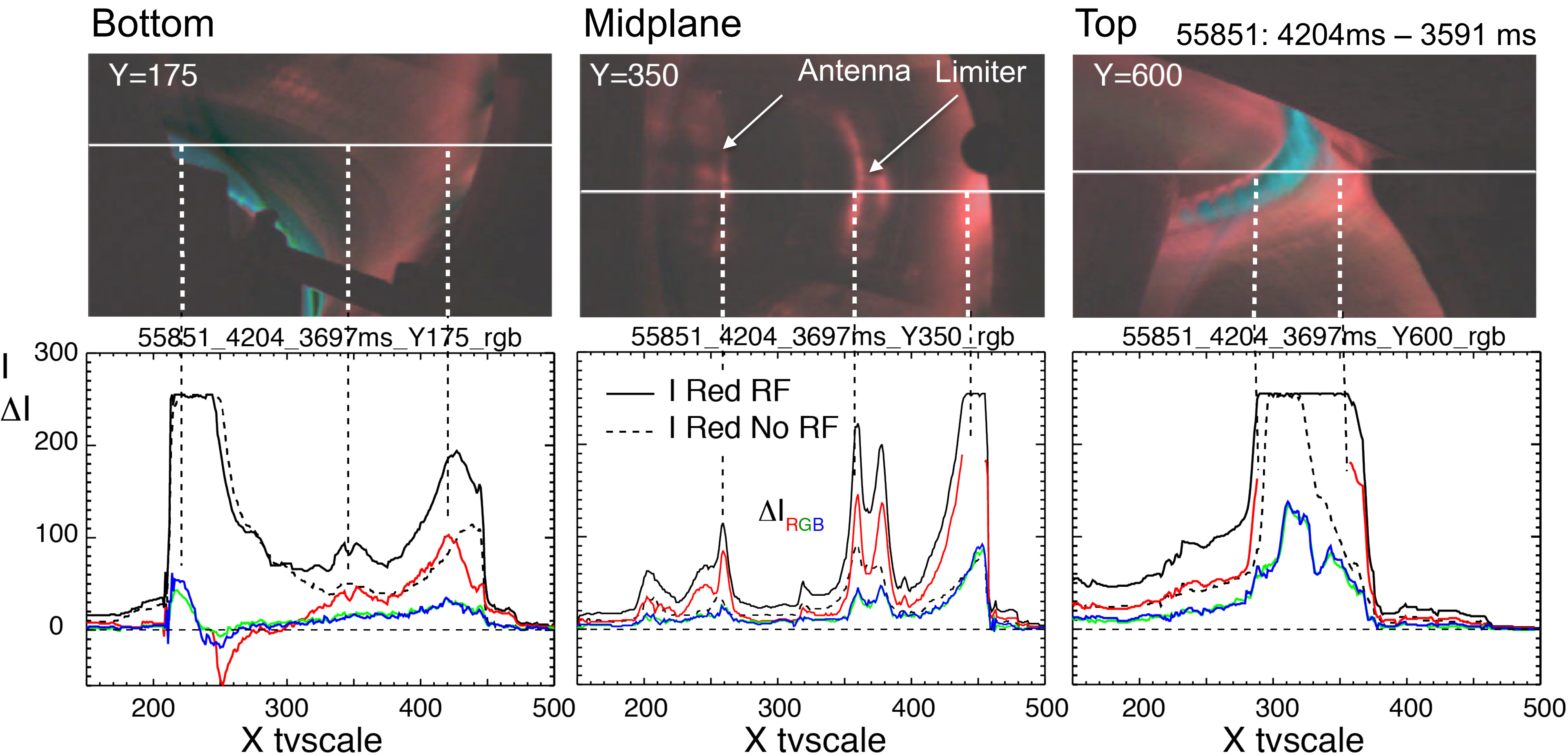


Shot 55851: P_{RF}= 2MW, I_P = 400kA, B_T =2.45 T at R =1.7 m

- Contrast of many deposition areas is good ⇒ fraction of coupled power (~ 500 kW) deposited in the SOL is not large
- Deposition information is gained by plotting along the horizontal lines

RF power deposition areas evident at present power level on EAST

EAST

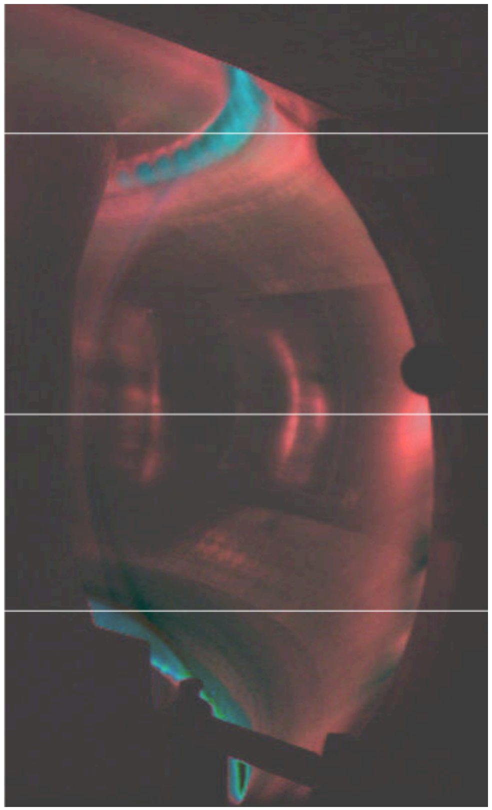


- Note that considerable heating occurs outside divertor regions bottom and top
- For midplane (Y=350) RF heating of the antenna and limiter is clearly indicated (as in the case of NSTX)
- Detail of RF deposition should be much clearer at higher RF power

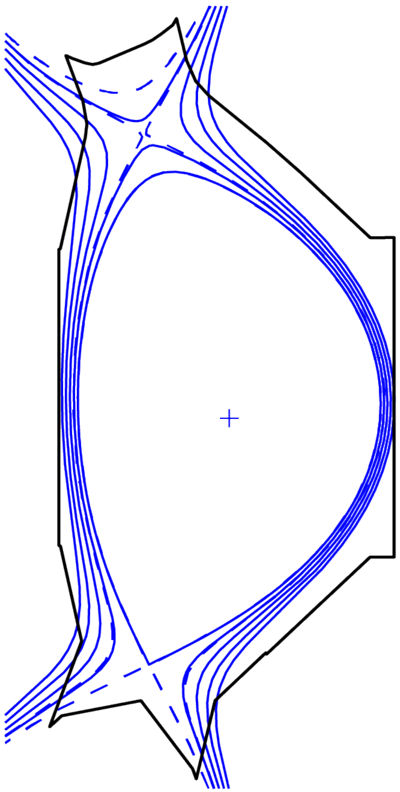
Field lines intercept divertor probes out from separatrix to ~ 3 cm at midplane

EAST

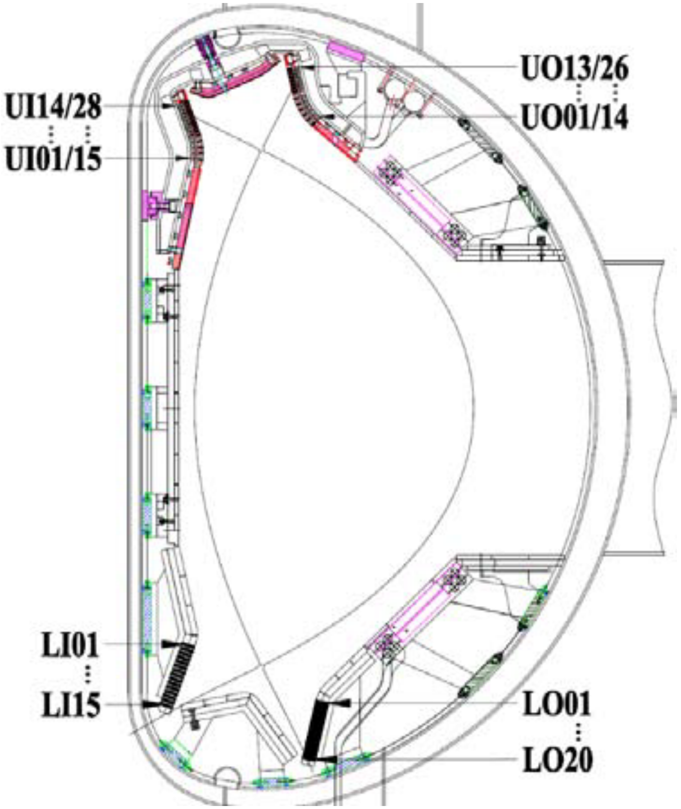
Deposition pattern



EFIT SOL to 4 cm



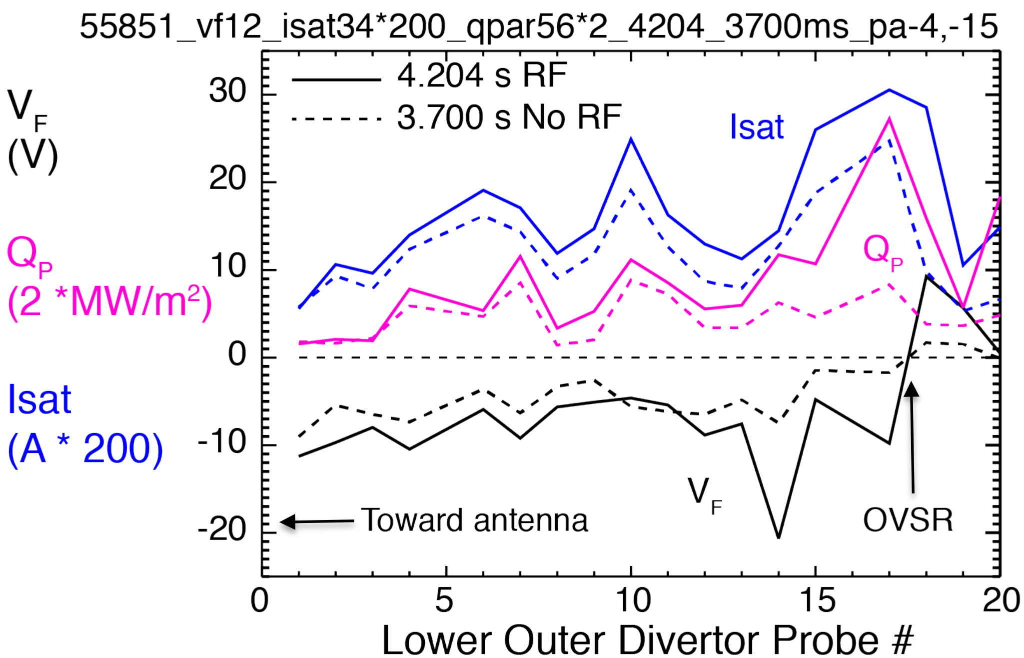
Probe locations

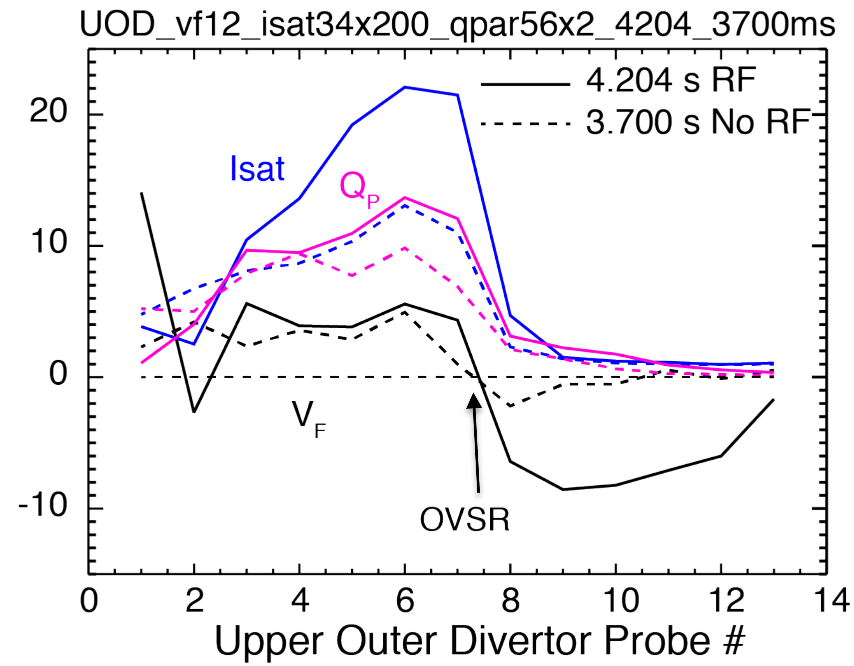


- Probes intercept field lines in front of antenna from separatrix/outer vessel strike radius to ~ 3 cm/edge of divertor shelf

Probe measurements show RF heat deposition peaks near the outer vessel strike radii

EAST



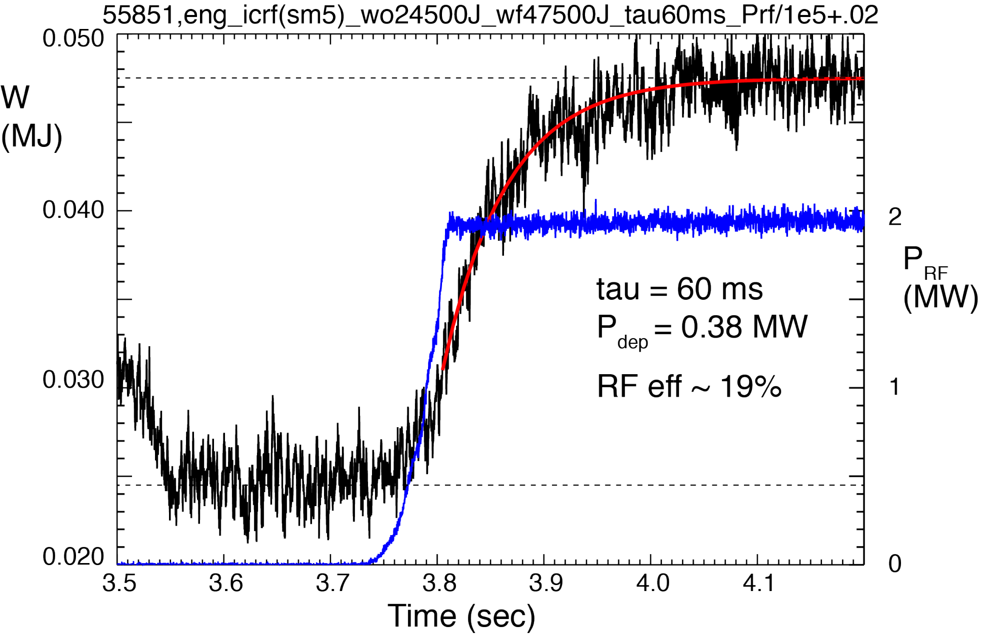


- For LOD: I_{sat} and Q_{par} increase toward the OVSR
  ΔV_F is generally negative toward antenna and peaks negatively near the OVSR
- For UOD: I_{sat} and Q_{par} peak near the OVSR
  ΔV_F is mostly unchanged toward antenna and peaks negatively past the OVSR
- Need probes on shelf to see probe effects for RF SOL deposition near the antenna

Enhancement of power coupled to plasma is needed for determining SOL losses in EAST

EAST

ICRF core heating efficiency is low in EAST



- $P_{dep} = \Delta W/\tau$
  $= 23$ kJ/0.060s = 0.38 MW
- Applied P_{RF} ~ 2 MW net from source
- ΔP_{rad} ~ 0.150 MW as a rapid loss
- ~ ¾ of P_{RF} is lost in system

- The antennas on EAST and transmission components are not copper plated
  - The ohmic losses in the antenna system are likely quite high
- Considerable gain in coupled power percentage should be obtained by plating the antenna.
  - Plating alone would provide that more of the launched power reaches the plasma but the total power would still be voltage limited
- Plating plus slotting should allow considerably more total ICRF power to be applied to the launchers and coupled to the plasma.

Summary

- Camera frame subtraction gives indications of SOL power deposition on NSTX (HHFW regime), KSTAR (minority regime) and EAST (minority regime)
- The nature of the RF deposition appears to be different on EAST and KSTAR relative to that for NSTX – no spiral evident at the RF powers used
  - Deposition at the midplane (antenna/limiter) appears to be strong on EAST similar to NSTX
- SOL RF deposition may be present in KSTAR outboard of the divertor trench in line with the strikepoints of magnetic field lines passing in front of the antenna
  - ELM effects are minimzed but may still be present
- Visible SOL RF deposition in EAST appears to be well outboard of the divertor trenches
  - Probes possibly show SOL RF deposition effects, especially on the lower outer divertor V_f
  - Need probes on the outer divertor shelf to map SOL RF deposition to the near antenna magnetic field strike points
- At present power levels coupled on KSTAR and EAST the SOL RF deposition appears to be small – a clear determination of the losses should be possible at higher coupled power