NSTX-U EAST

U.S. DEPARTMENT OF ENERGY | Office of Science

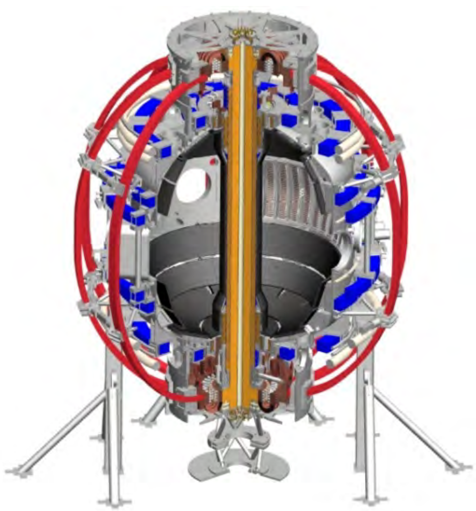
RF power deposition effects observed for the SOL in NSTX/NSTX-U and EAST and the accompanying RF effects on divertor Langmuir probes*

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC

J. C. Hosea, R. J. Perkins, M. A. Jaworski, N. Bertelli, C. Qin[a], G. Taylor, L. Wang[a], J. Yang[a], X.J. Zhang[a] and the NSTX-U and EAST Teams

PPPL, [a]ASIPP

APS-DPP Conference, San Jose, CA, November, 2016

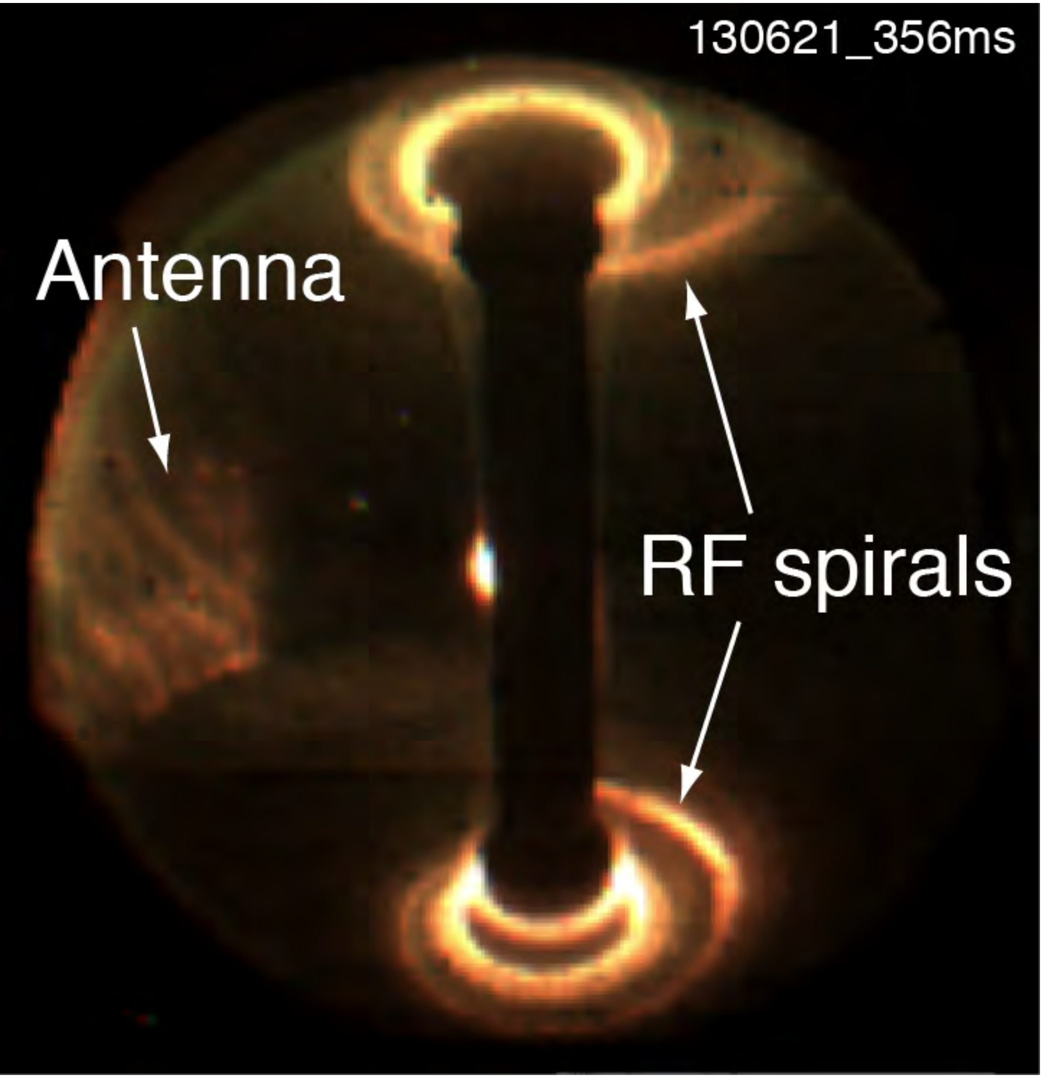


Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

* This work is supported by USDOE Contract No. DE-AC02-09CH11466

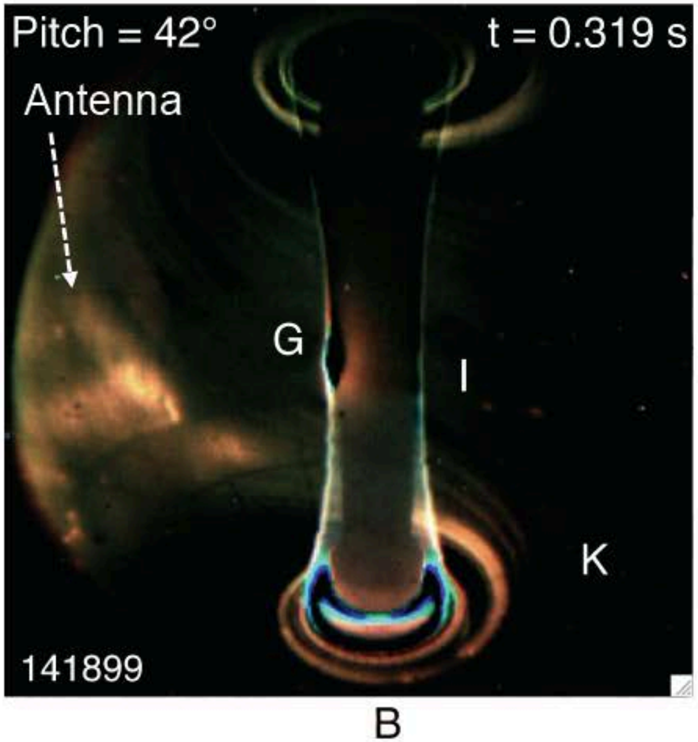
Edge RF deposition effects for HHFW heating on NSTX

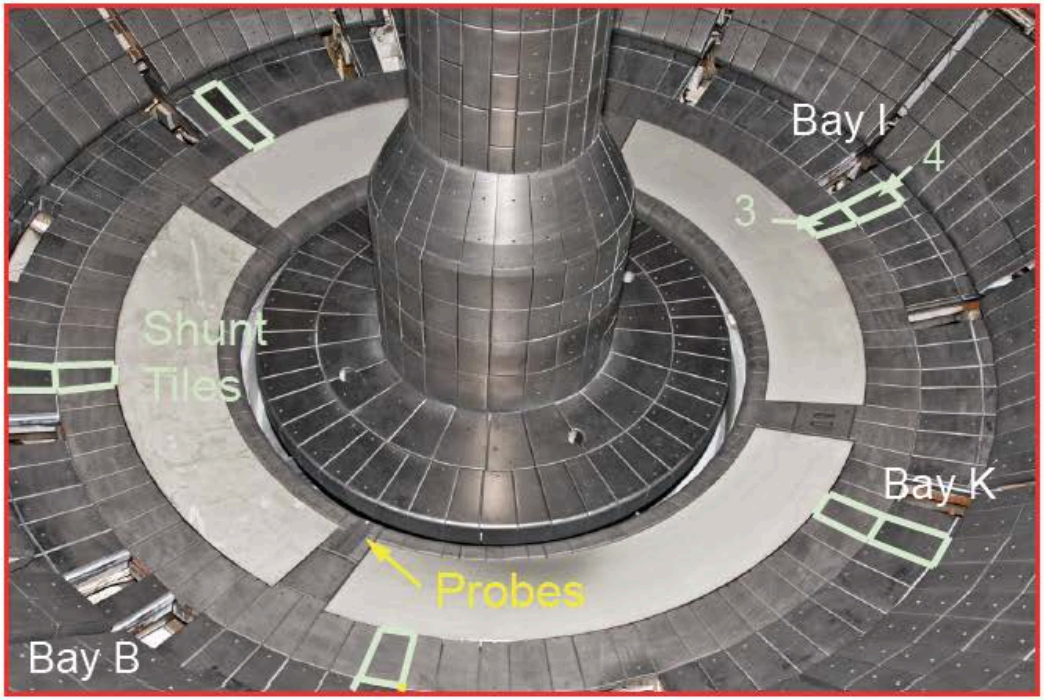
Significant HHFW power lost via the SOL to distinctive spirals on the divertor regions of NSTX



- RF power deposited in bright spirals on divertor
- Up to 60% of HHFW missing from core
- IR cameras show up to 2 MW/m^2 heat flux to divertor
- What is mechanism for RF deposition at the divertors?
- How does HHFW power propagate to the divertor?

"Hot" RF heat flux spiral on the divertor floor and instrumented tile/Langmuir probe locations on NSTX



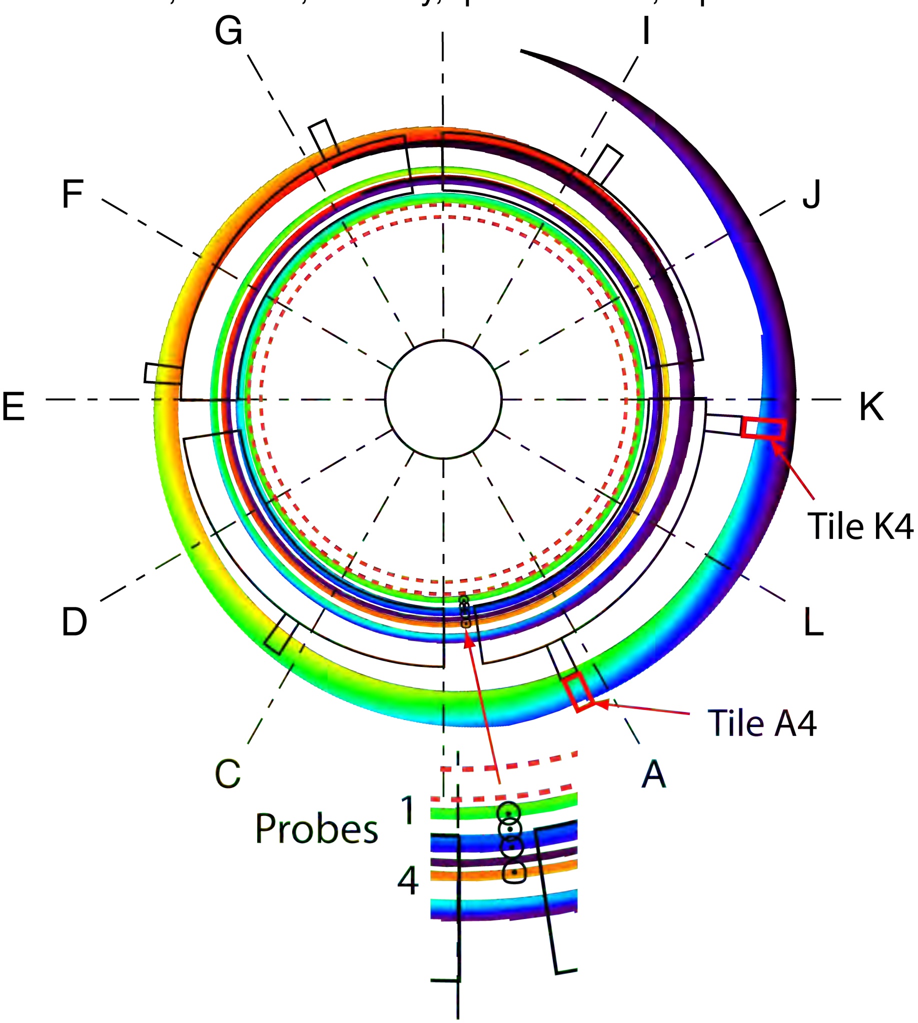


- Toroidal locations are indicated by Bay letters
- Langmuir probes at Bay B are used to determine RF effects on the divertor plate

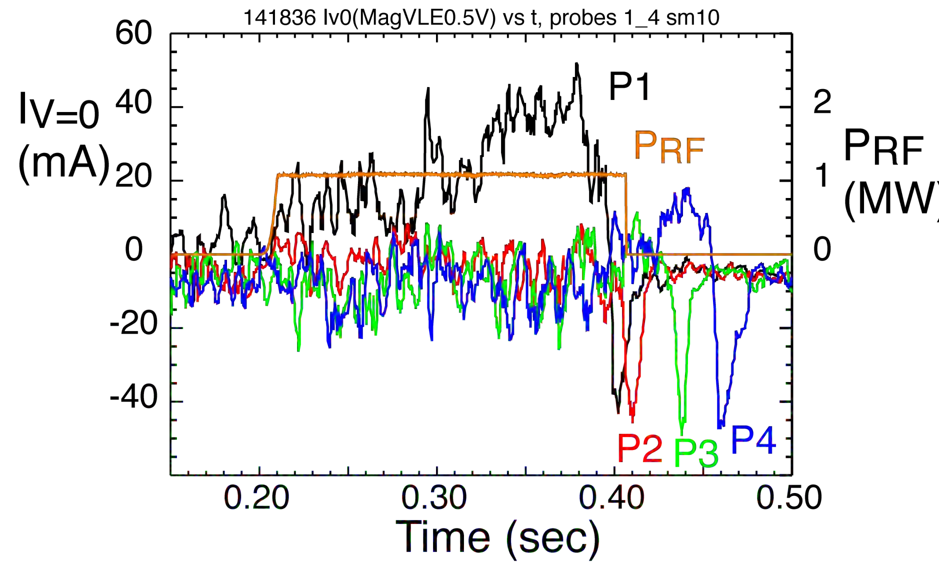
RF only discharge with probe 1 intercepting the RF heat flux spiral near the outer vessel strike radius

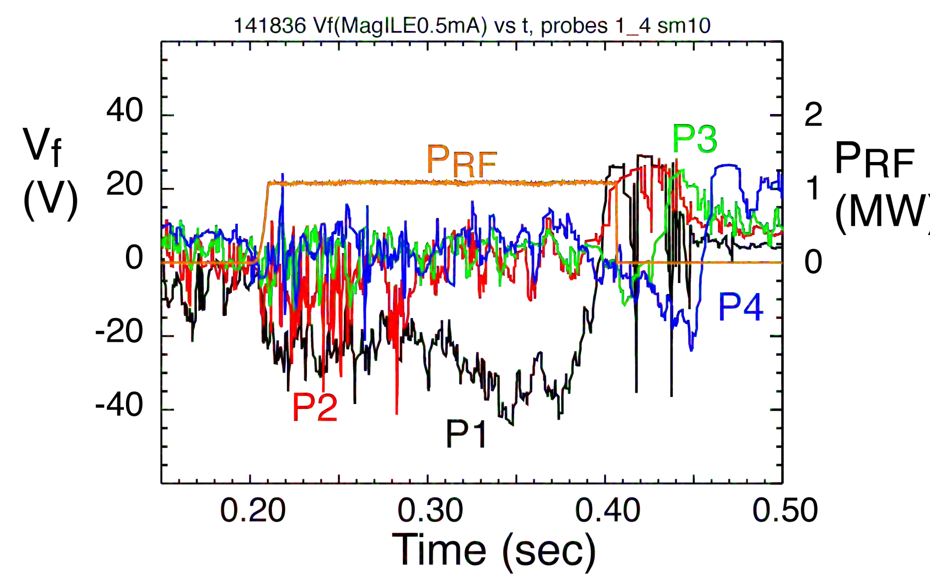
Strike points on the lower divertor

141836, 350 ms, RF only, I_P = 0.65 MA, B_T = 5.5 kG

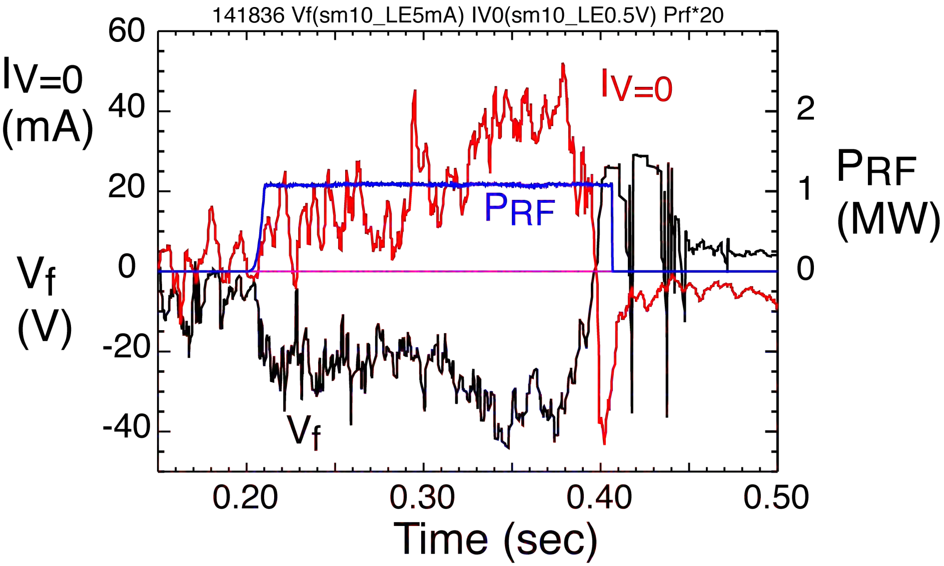


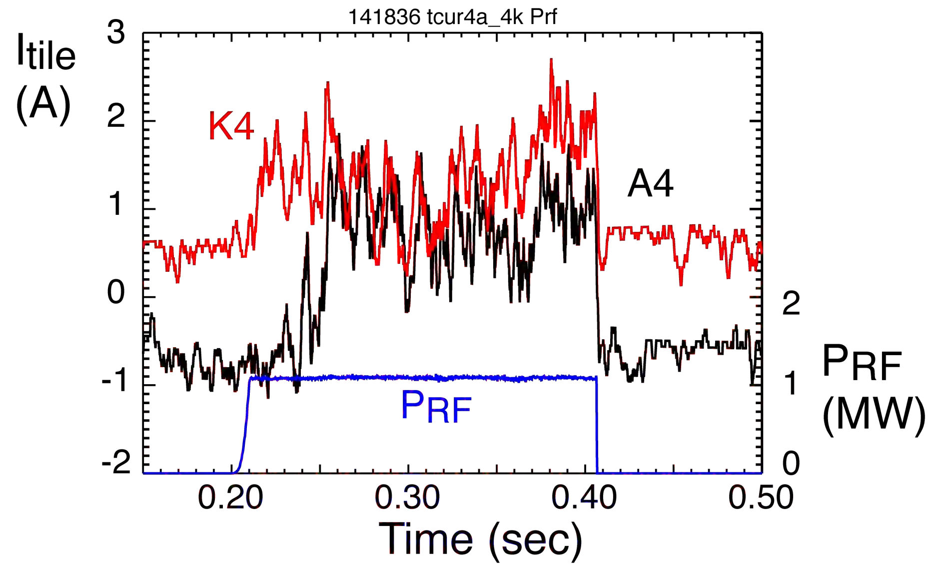
Probe characteristics





The RF heat flux spiral falls on tiles A4 and K4 for this RF only discharge

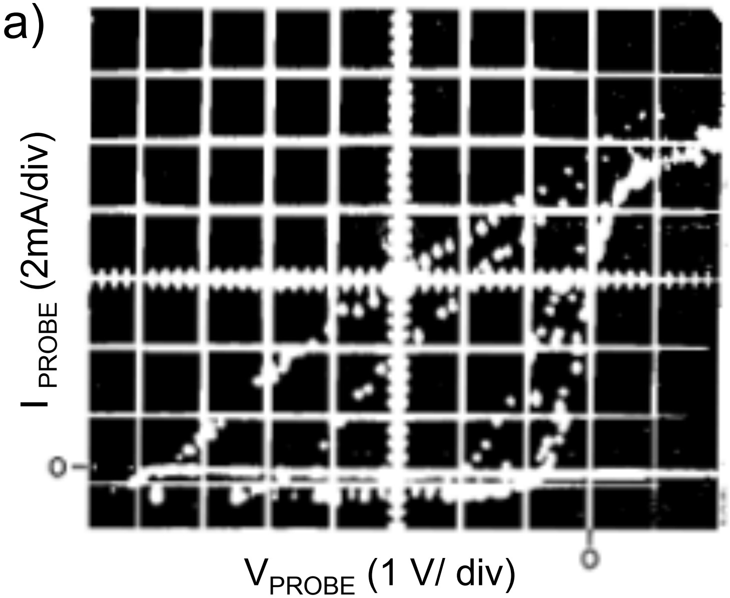




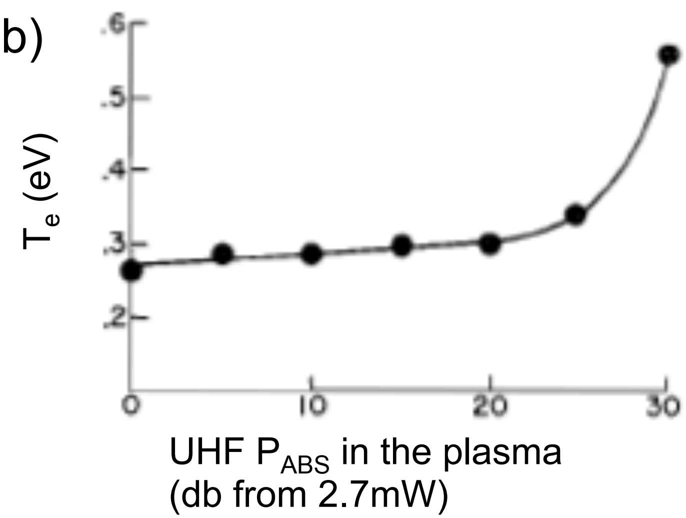
- ΔI_{tile} is up to 2.5 A on tile A4
- Current on tile A4 rises slowly after RF turn-on showing the movement of the plasma
- $I_{V=0}$ and V_f cross through 0 when the outer vessel strike radius passes over the probe

RF rectification causes a negative shift in the probe floating potential vs P_{RF}

a)



b)



a) Probe characteristics with RF rectification:

- V_{fl} moves to more negative V_{probe} as UHF cavity power is increased in 5 dB steps from 2.7 mW to 2.7 W

[J. Hosea, Stanford University Plas. Inst. Report #8 (1966).]

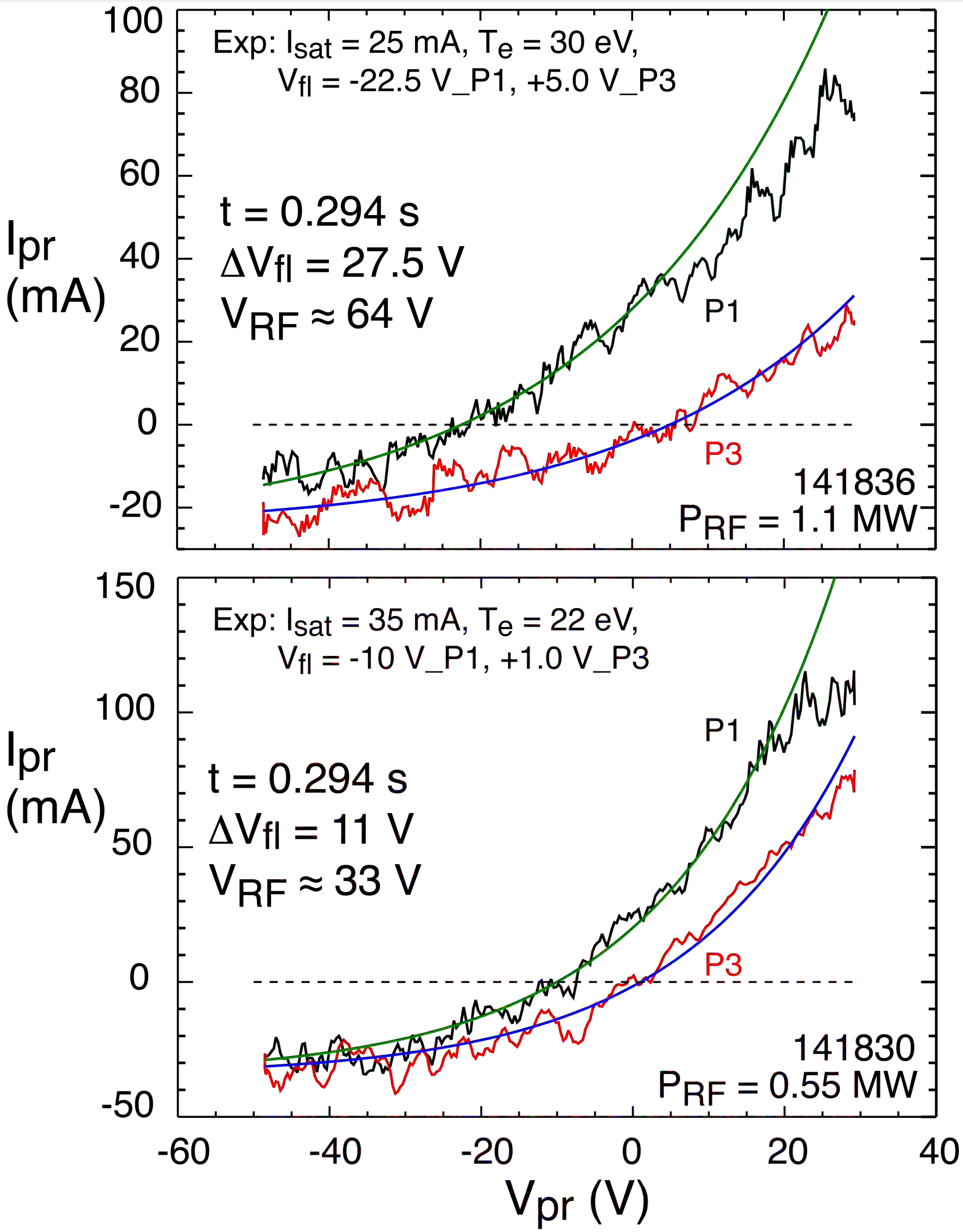
- For constant T_e, I_{sat}, and V_{plasma},

$$\exp(\Delta V_{fl}/T_e) = I_0(V_{RF}/T_e)$$

[A. Boschi and F. Magistrelli, *Il Nuo. Cimento* **29** (1963) 487.]

b) T_e, I_{sat} and V_{plasma} are approximately constant here except at highest power

Change in floating potential from P3 (no RF) to P1 (with RF under spiral) and V_{RF} vs P_{RF} (no NBI)



RF only – 141836, 141830
t = 0.294 s

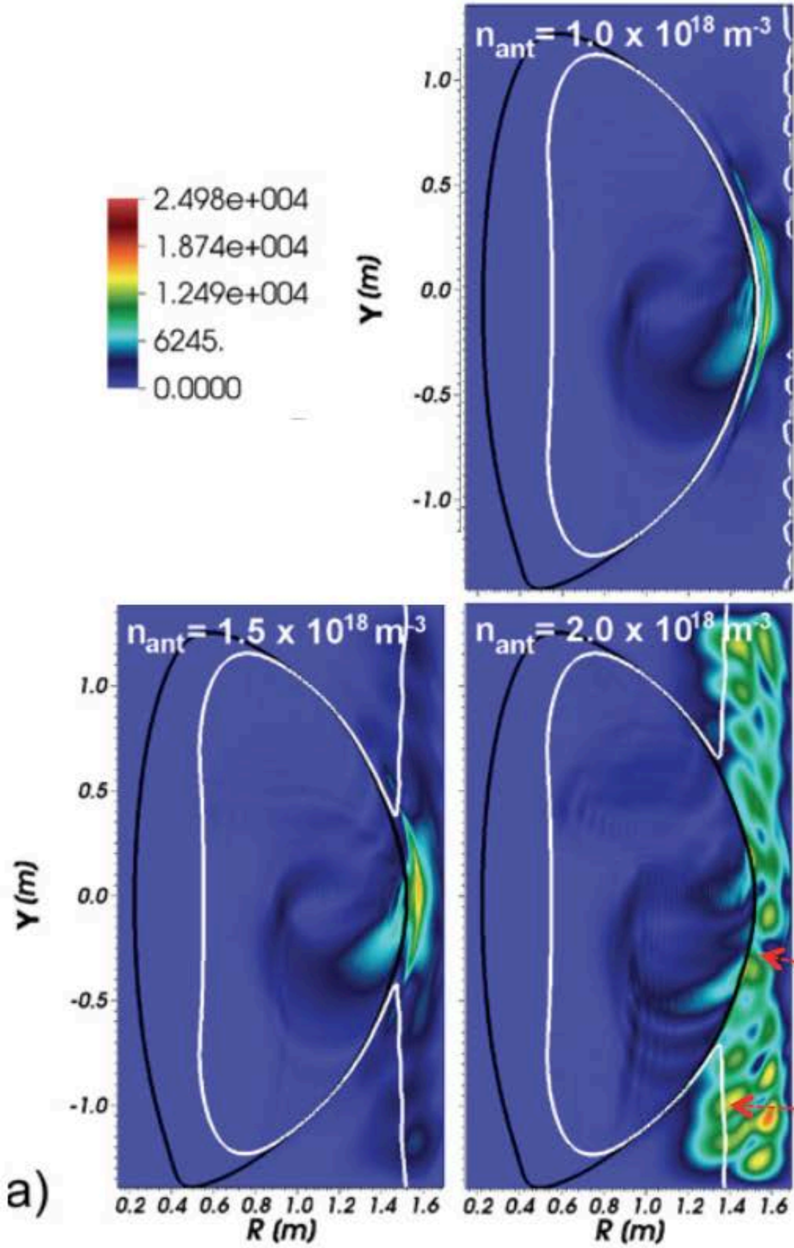
- Substantial decrease in V_{RF} with decrease in P_{RF}
  - P_{RF} 1.1 MW ⇒ 0.55 MW
  - V_{RF} ~ 64 V ⇒ ~ 33 V

    $[\exp(\Delta V_{fl}/T_e) = I_0(V_{RF}/T_e)]$

- Decrease is not 1/√ 2 but edge plasma conditions are different as well
  - note that I_{sat} decreases with P_{RF} and T_e increases with P_{RF} here

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

Far field fast wave rectification is likely cause of negative V_{fl} shift under spiral

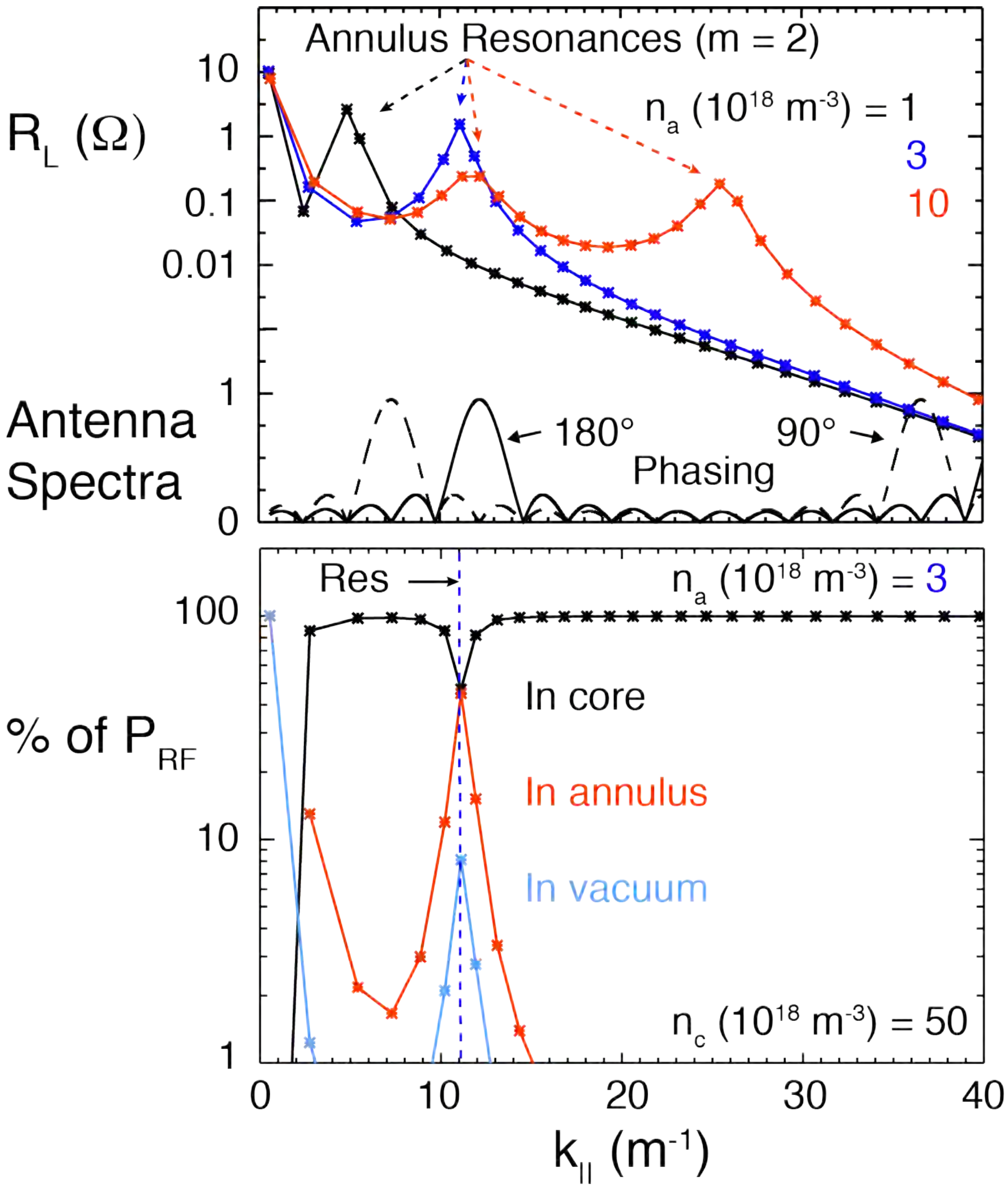


- Large RF electric fields in SOL are predicted by AORSA modeling
- Edge modes are evident in the SOL region when the density in front of the antenna n_{ant} exceeds the fast wave cutoff density

Electric field amplitude vs edge density

[N. Bertelli et al., NF **54** (2014) 083004]

SOL fast wave resonances are predicted in a two density step cold plasma cylindrical model



- Fast wave SOL resonances are supported by the annulus density
  - These are distinct from the coaxial mode which is confined to the vacuum region
- The $k_{||}$ for these resonances move across the antenna spectra with increasing density
- ~ 50% of RF power in the m = 2 resonant mode is lost in the annulus region
  - < 10% of RF power is in the vacuum

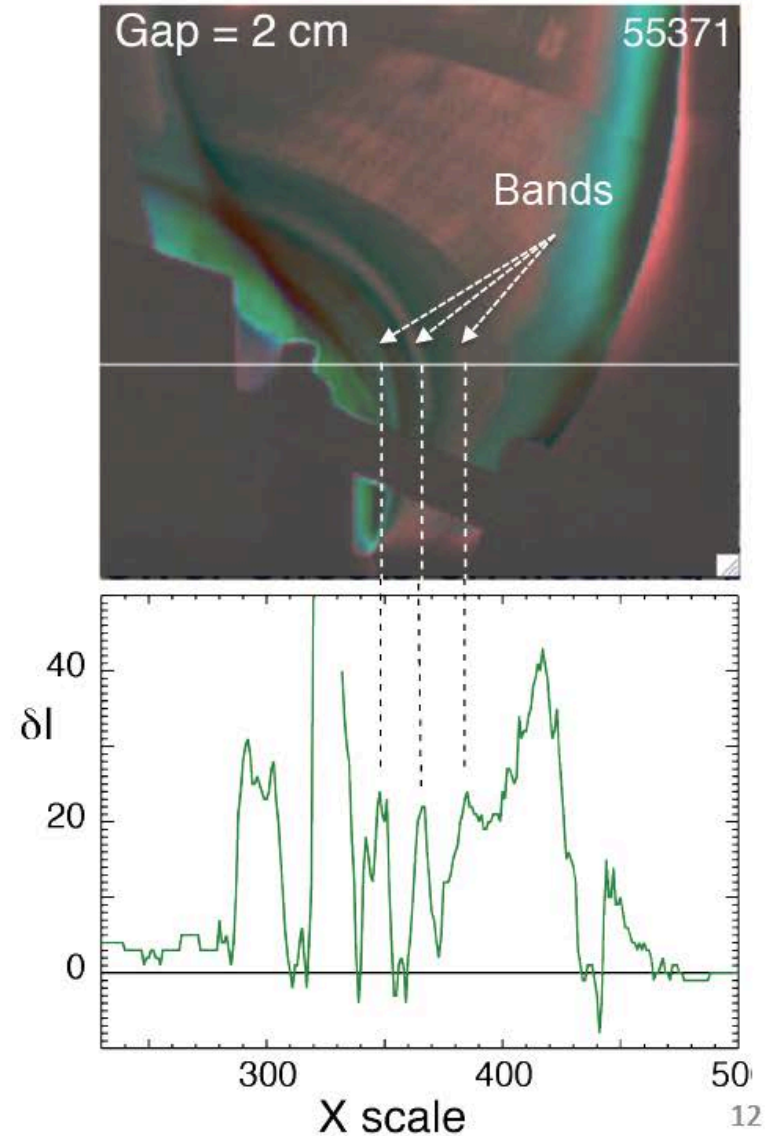
[R. Perkins et al., **EPS** (2015) P2.143]

Edge RF deposition effects for minority IC heating on EAST

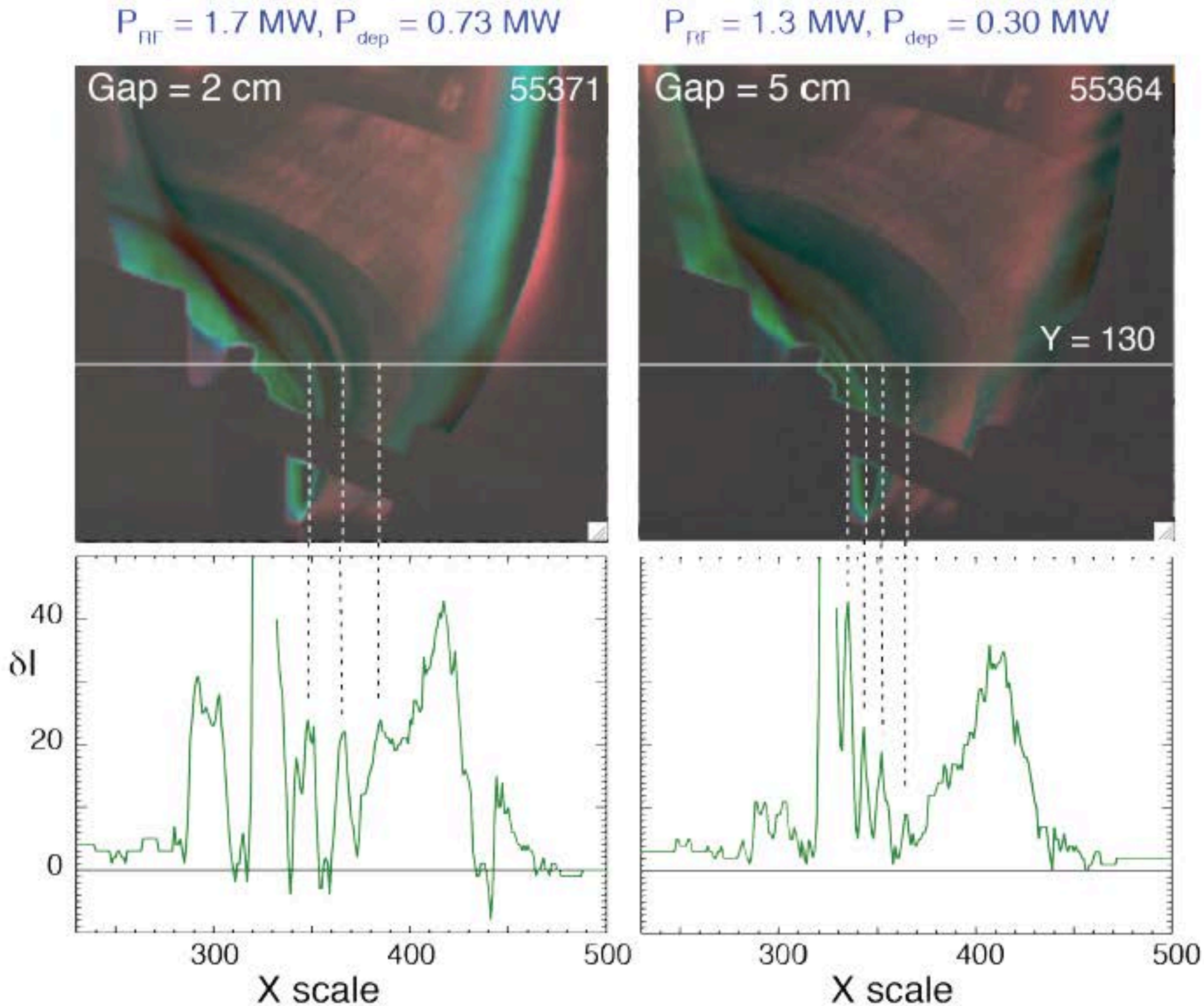
Subtraction of jpeg camera frames (with RF minus without RF) reveals RF deposition patterns on EAST

- Band RF deposition structure that depends on the antenna-separatrix gap is observed on the lower divertor
  - Possibly part of an RF deposition spiral (no ELMs in this discharge)
- Similar to spiral bands observed on NSTX
- Need more data at higher coupled power and more analysis to quantify the SOL RF deposition
  - An experiment is planned at higher RF power in the current experimental campaign

P_{RF} = 1.7 MW, P_{dep} = 0.73 MW

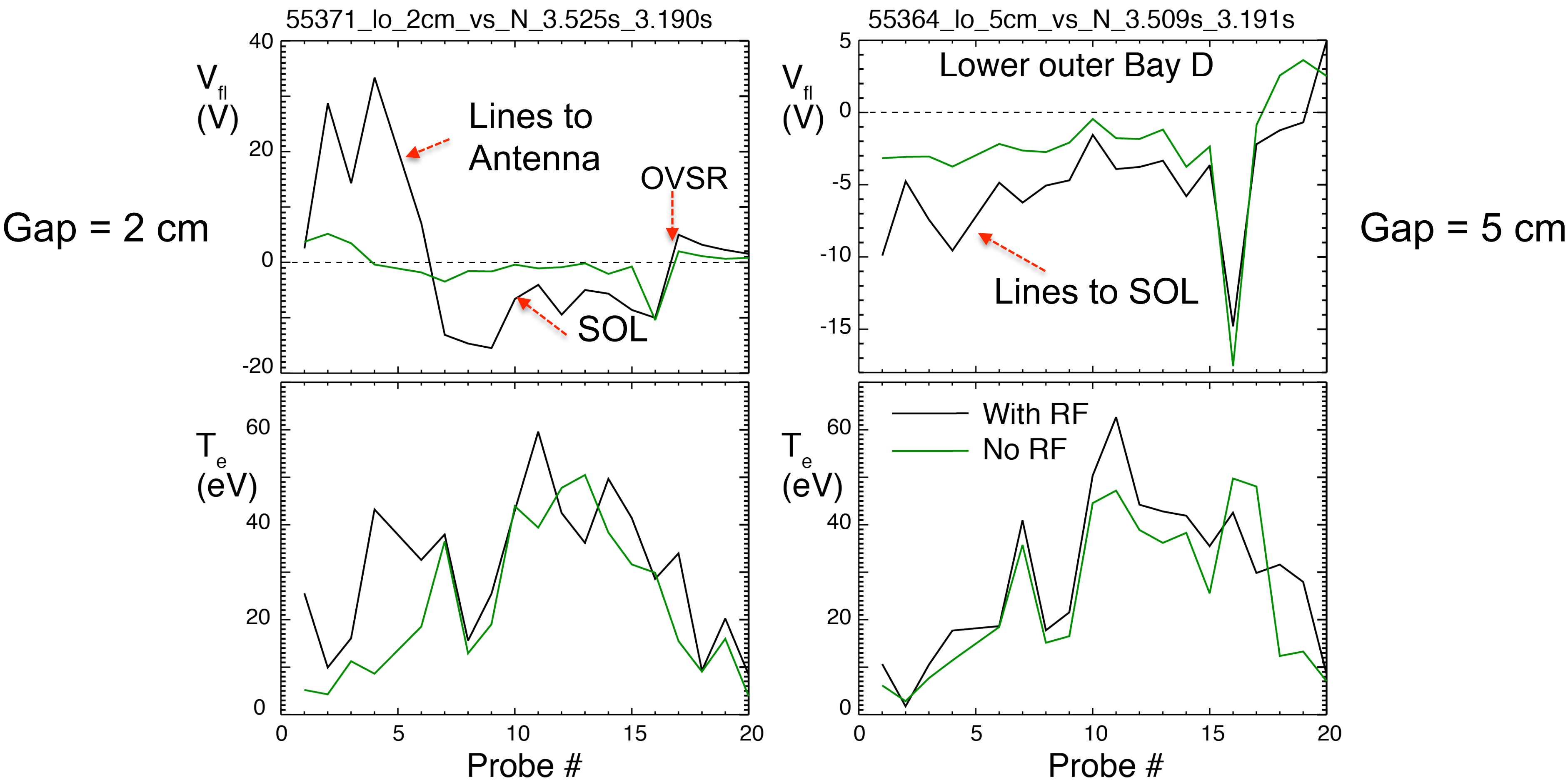


RF produced band structure depends on gap



- More and narrower bands are observed at 5 cm gap relative to 2 cm gap
- Broader bands at 2 cm may be due to higher coupled power

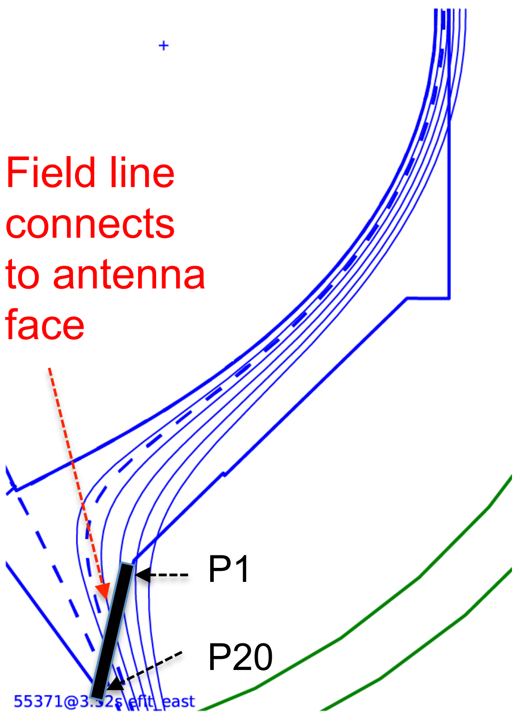
Lower outer divertor probe measurements show that RF effect on floating potential V_{fl} depends on gap



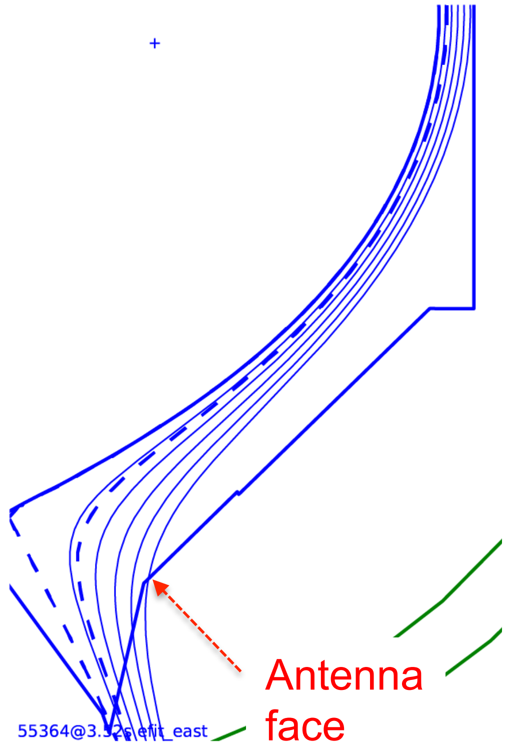
- For gap = 2 cm, positive δV_f is found for lower numbered probes and negative δV_f is found for higher numbered probes
- For gap = 5 cm, negative δV_f is found for all probes down to the OVSR

Intercepts of field lines in front of antenna on bottom divertor probes depends on the gap

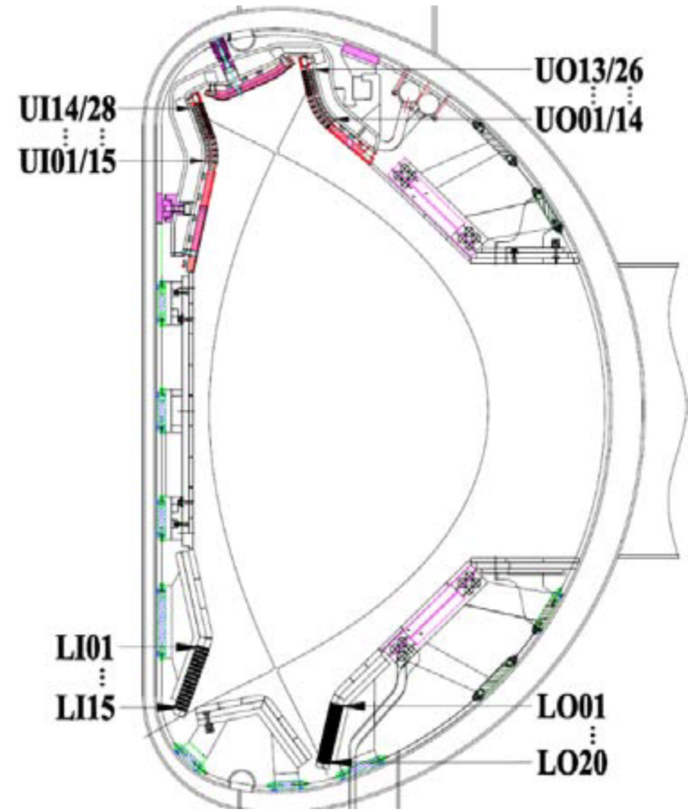
Gap = 2 cm



Gap = 5 cm

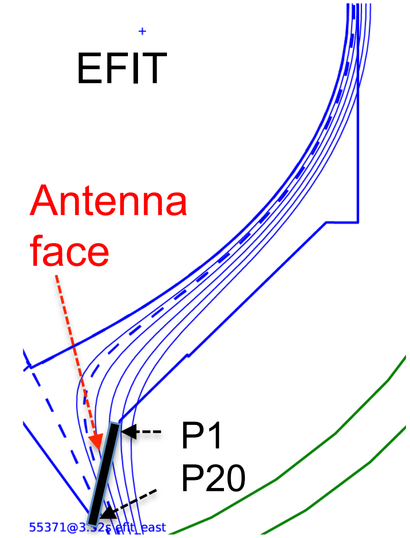


Probe locations

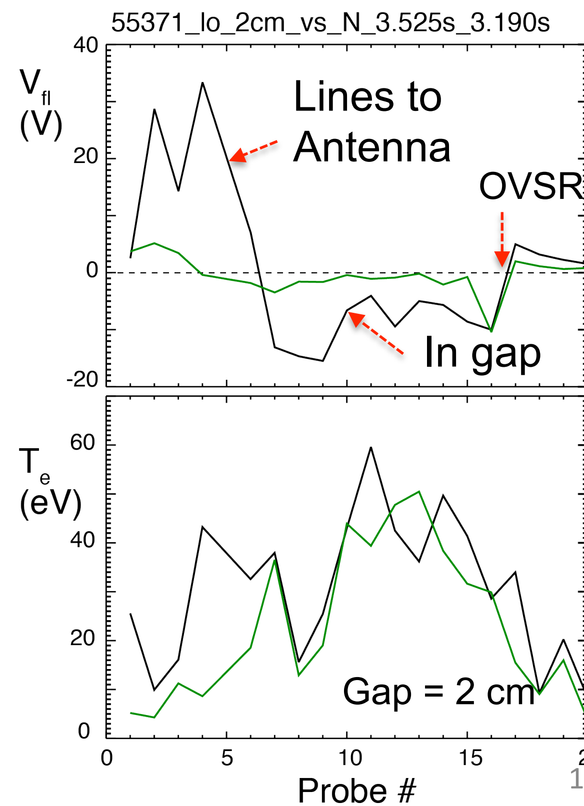


- Gap = 2 cm: probes intercept field lines in front of antenna from separatrix/ outer vessel strike radius to ~ 2 cm/middle of probe array
- Gap = 5 cm: probes intercept field lines in front of antenna from separatrix/ outer vessel strike radius to ~ 5 cm/above top of probe array

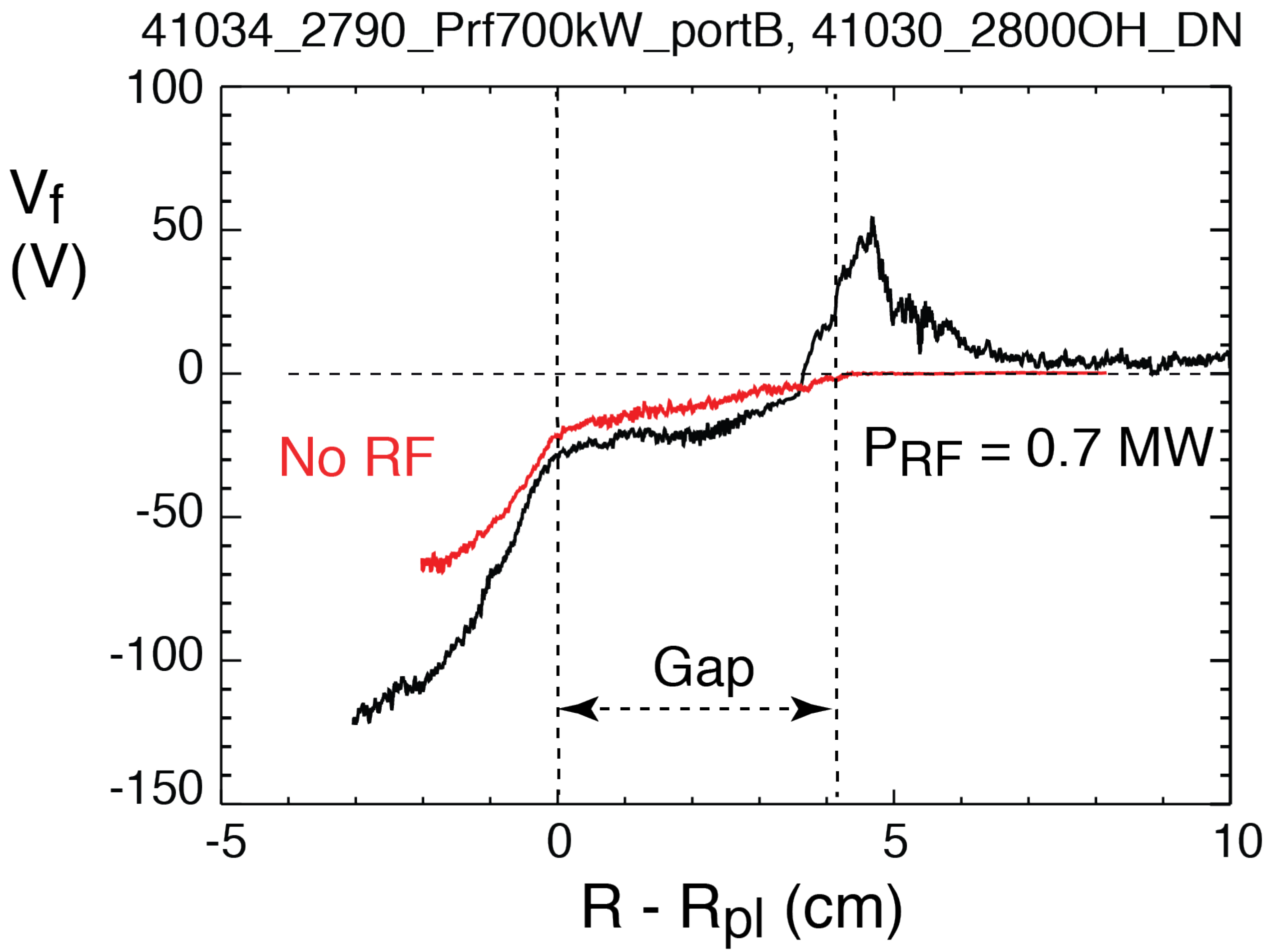
RF change of floating potential V_{fl} reverses polarity from the SOL to the vicinity of the antenna



- V_{fl} depends on magnetic field lines intercepting the antenna or passing in the antenna/separatrix gap
  - positive δV_f for field lines intercepting the antenna (as found on EAST, C-mod, Tore Supra and Asdex-U)
  - negative δV_f for field lines in the antenna/separatrix gap (as for NSTX)
- As for NSTX, fast wave rectification is likely cause for negative δV_{fl} in gap
  - RF voltage at divertor probe # 9 is $I_0(V_{RF}/T_e) = \exp(\Delta V_{fl}/T_e)$
  - $V_{RF\_P9} \sim 38$ V
- Cause of positive δV_{fl} requires further study
  - IV characteristic needs to be measured



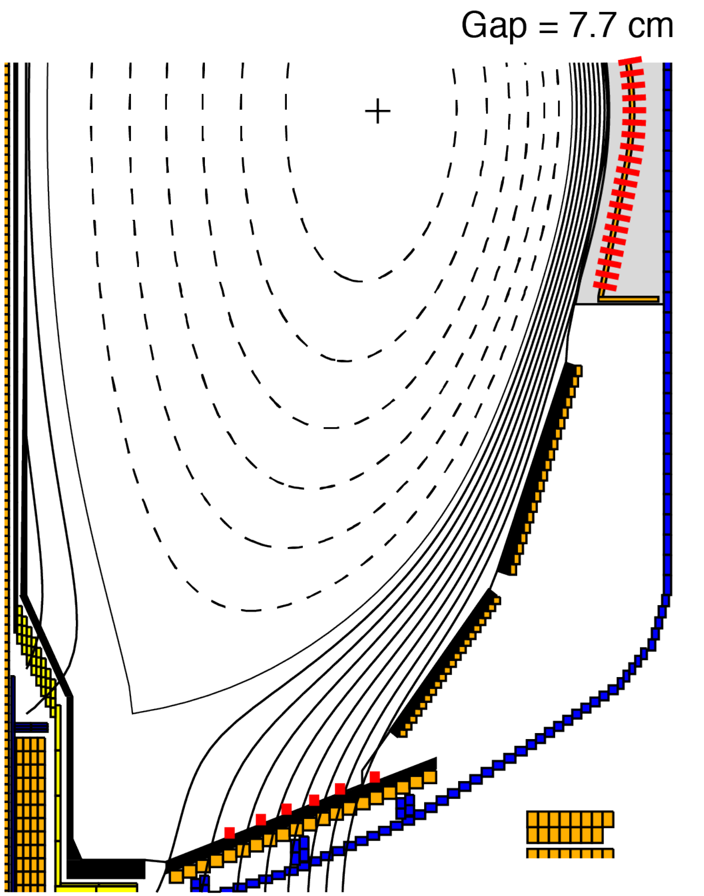
Reciprocating probe data shows similar dependence of δV_{fl} relative to field lines as for the divertor probes



- δV_{fl} is negative away from the antenna and is positive in the vicinity of the antenna
- The positive change in V_{fl} extends ~ 0.5 cm into the gap

Edge RF deposition effects for HHFW heating on NSTX-U

An expanded probe array will be used on NSTX-U to study the cause(s) for the change in δV_{fl} polarity

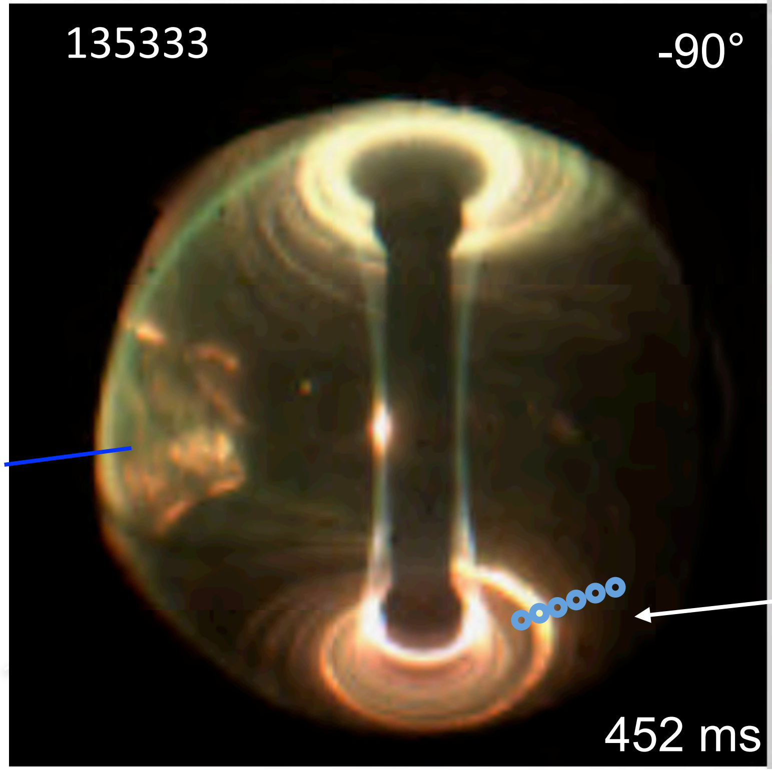


- This probe array can cover the entire separatrix/antenna SOL space
- These probes will be used to measure the I-V characteristics as well as the RF voltages across the probe sheaths.

RF sheath voltage will be measured directly on NSTX-U with coaxial probes and sheath rectification will be quantified

Antenna probes, reflectometer

Antenna IR view & visible view



B_T = 4.5 kG, I_P = 0.8 MA

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

- A wide angle IR camera will provide heat deposition measurements over much of the spiral
- Comparison of calculated RF rectification heat deposition to IR measurements will be used to quantify the heat contribution of the HHFW far field

Summary

- The floating potential of probes under the spiral on the lower divertor of NSTX shifts negatively relative to that for probes away from the spiral
  - This negative δV_{fl} is consistent with RF rectification of fast wave far fields
- AORSA and cold plasma cylindrical modeling predict enhanced SOL fast wave fields at SOL densities above the fast wave cutoff value near the antenna
- The floating potential of probes on the outer lower divertor of EAST shifts either negative or positive depending on the magnetic field lines striking a probe coming from the SOL away from the antenna or from the vicinity of the antenna
- Again, the negative δV_{fl} is consistent with RF rectification of fast wave far fields
- However, the cause of the positive δV_{fl}, also observed on other tokamaks, is not fully understood and needs further study
- We are extending our probe array on NSTX-U to intercept field lines across the entire SOL in front of the antenna to permit I-V characteristic measurements in the vicinity of the antenna
- The probes on NSTX-U are coaxial and will provide a direct measurement of the local RF field for comparison to rectification theory