U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

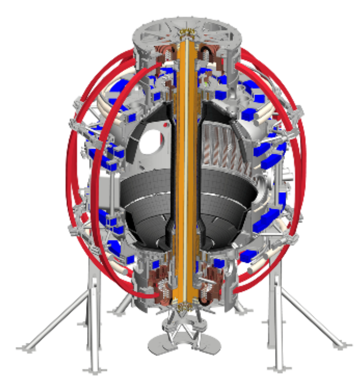
Field-Aligned SOL Losses of HHFW Power and RF Rectification in the Divertor of NSTX

R. J. Perkins[1], J. C. Hosea[1], M. A. Jaworski[1], J.-W. Ahn[2], A Diallo[1], R. E. Bell[1], N. Bertelli[1], S. Gerhardt[1], T. K. Gray[2], G. J. Kramer[1], B. P. LeBlanc[1], A. McLean[3], C. K. Phillips[1], M. Podestà[1], L. Roquemore[1], S. Sabbagh[4], G. Taylor[1] and J. R. Wilson[1]

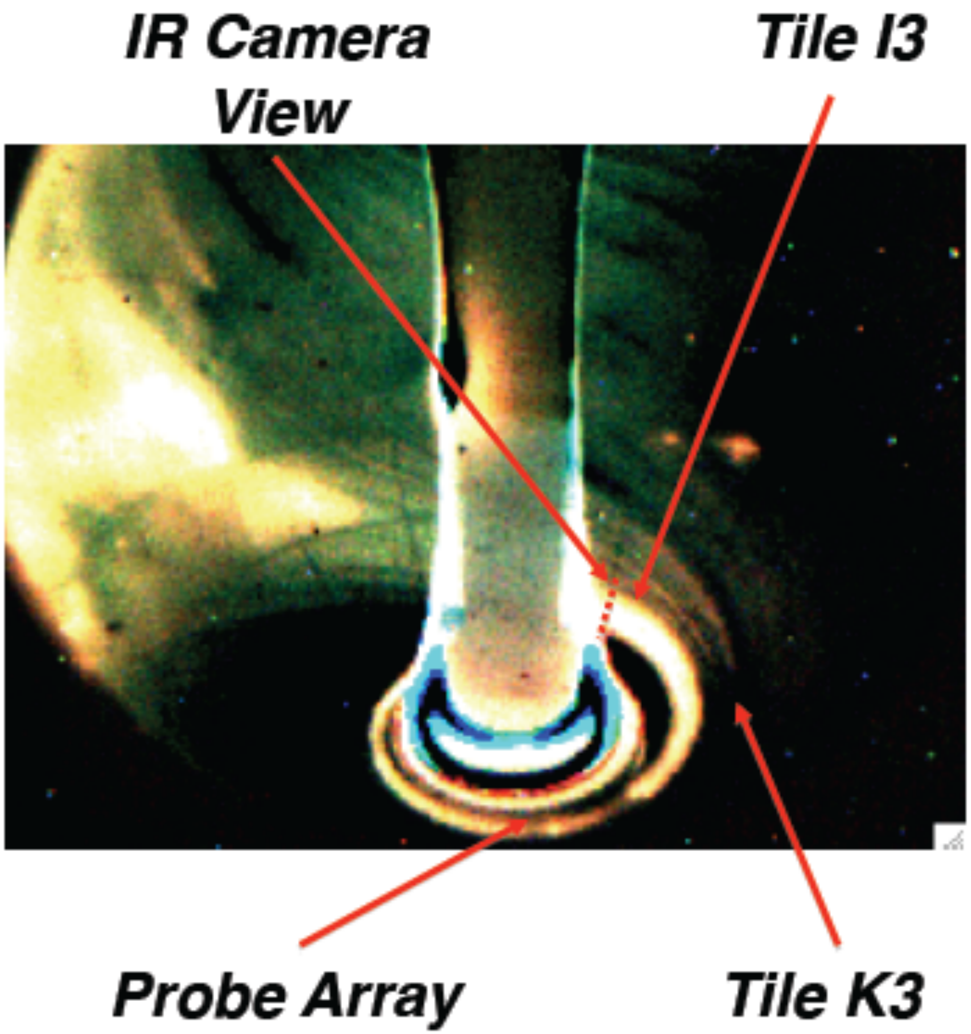
1 Princeton Plasma Physics Laboratory
2 Oak Ridge National Laboratory
3 Lawrence Livermore National Laboratory
4 Columbia University

November 5, 2015

PPPL



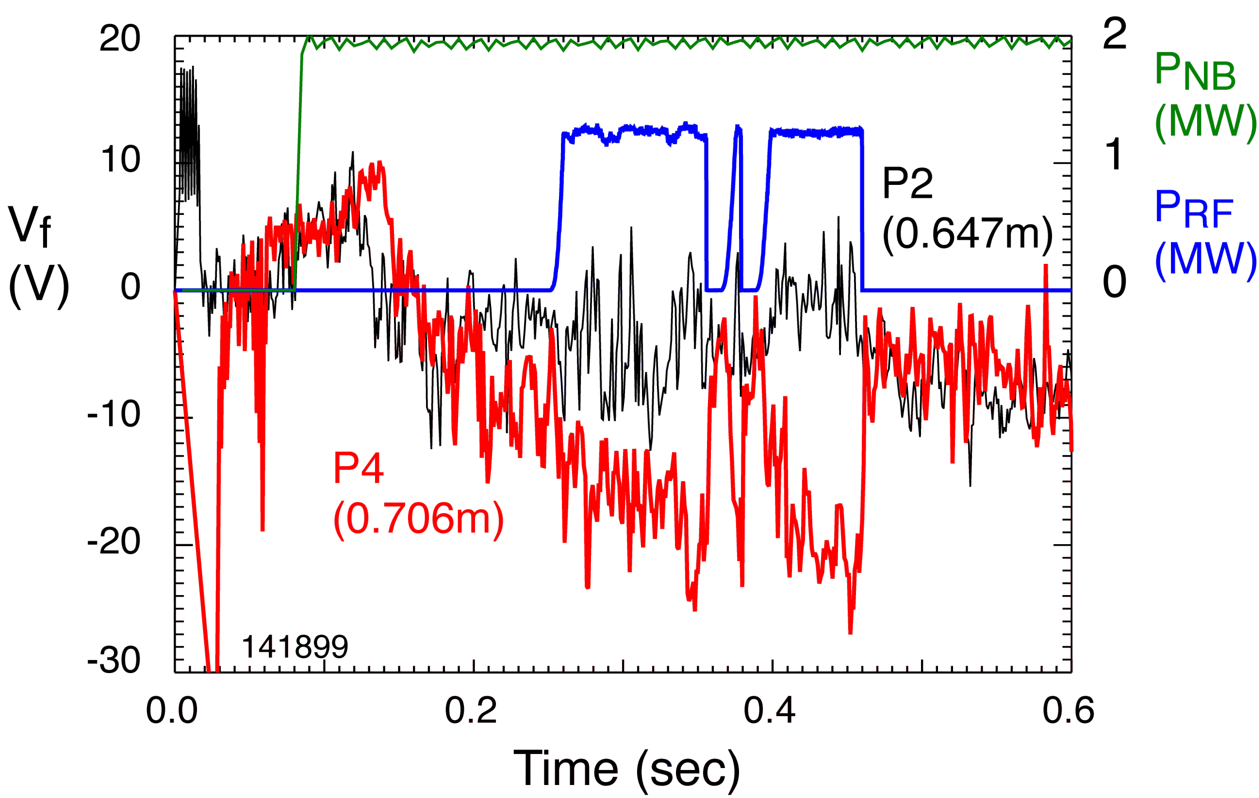
Significant loss of HHFW power to the divertor along SOL field lines; possibly due to RF rectification



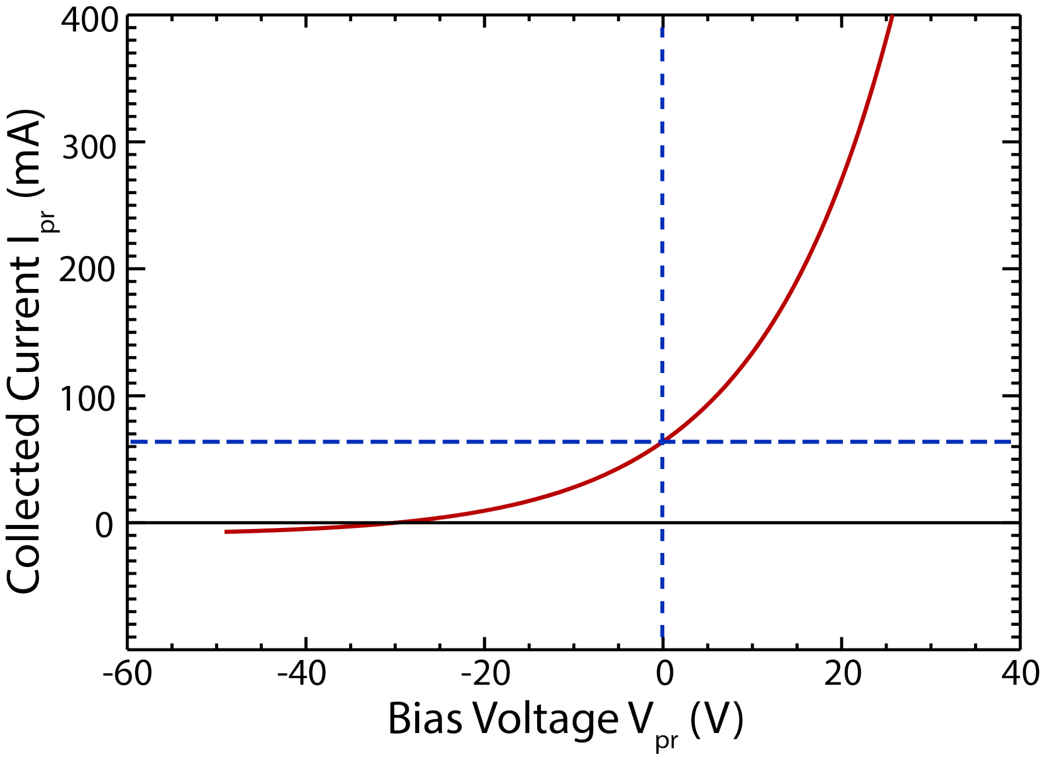
- Up to 60% of coupled power is not reaching the core
- Hot spirals form on upper & lower divertor during RF
  - Heat flux up to 2 MW/m^2 (for 1.8 MW coupled P_{RF})
- RF rectification could be converting HHFW power to heat flux
  - Requires RF fields in divertor region
  - Could be general to ICRF systems
- Divertor diagnostics respond strongly to RF when under spiral

HHFW strongly affects floating potential when probe is under spiral

- Probe P4 floating potential (red plot) responds strongly to RF
- Probe P2 has much weaker response (black plot)
- RF-induced effects are localized to spiral
- Similarly, tile currents increase under spiral

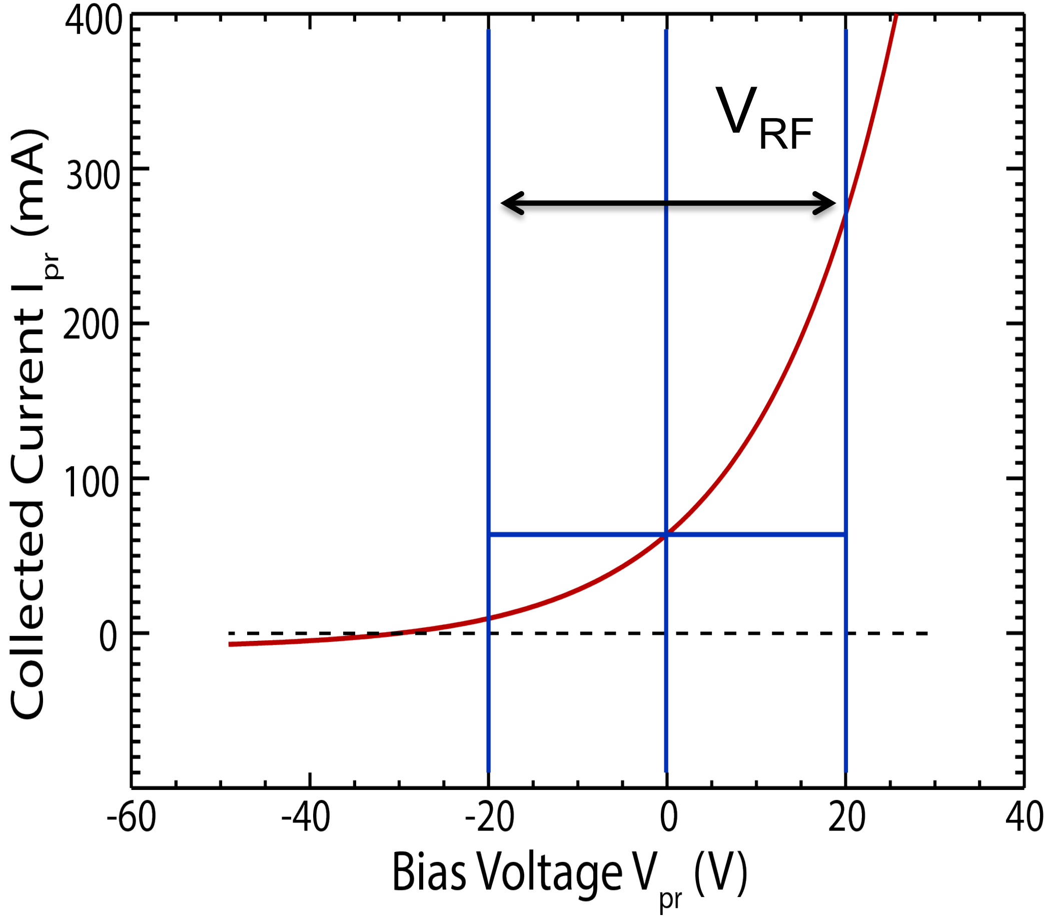


RF rectification is an phenomena due to non-linear IV characteristic of probe/surface



- IV characteristic of probe (or divertor tile) is nonlinear
  - Exponential for Maxwellian distribution

RF rectification is an phenomena due to non-linear IV characteristic of probe/surface



- IV characteristic of probe (or divertor tile) is nonlinear
  - Exponential for Maxwellian distribution
- Adding an oscillating potential produces non-zero average of collected current

RF increases electron current New floating potential depressed

Equation for current collected at bias V

$$J(V) \quad = \quad J^{sat}\left[-1 + \exp\left(\frac{V - V_{fl}}{T_e}\right)\right]$$

RF increases electron current
New floating potential depressed

$$V_{RF} \sin \omega t$$

Equation for current collected at bias V

$$J(V) = J^{sat}\left[-1 + \exp\left(\frac{V - V_{fl}}{T_e}\right)\right]$$

Add RF potential and average over an RF cycle

$$J_{RF}(V) = J^{sat}\left[-1 + I_0\left(\frac{V_{RF}}{T_e}\right)\exp\left(\frac{V - V_{fl}}{T_e}\right)\right]$$

RF increases electron current
New floating potential depressed

$V_{RF} \sin \omega t$

Equation for current collected at bias V

$$J(V) = J^{sat}\left[-1 + \exp\left(\frac{V - V_{fl}}{T_e}\right)\right]$$

Add RF potential and average over an RF cycle

$$J_{RF}(V) = J^{sat}\left[-1 + I_0\left(\frac{V_{RF}}{T_e}\right)\exp\left(\frac{V - V_{fl}}{T_e}\right)\right]$$

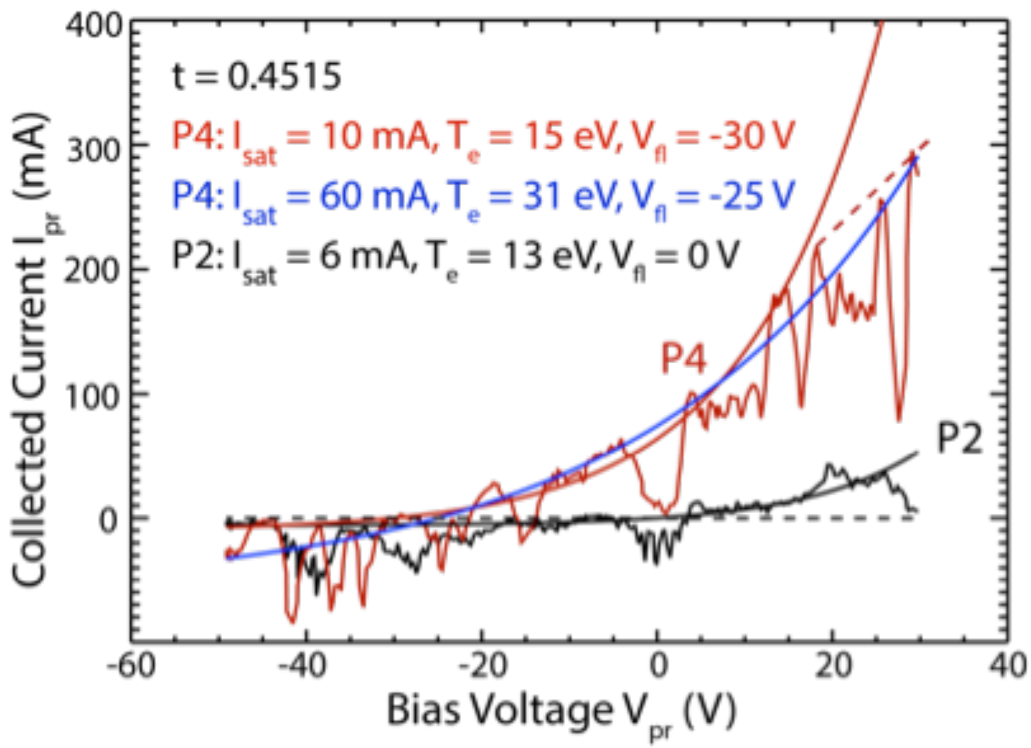
New floating potential V_{flRF}

$$\exp\left(\frac{V_{fl} - V_{flRF}}{T_e}\right) = I_0\left(\frac{V_{RF}}{T_e}\right)$$

A. Boschi and F. Magistrelli, *Nuovo Cimento* **29** 487 (1963)

Langmuir probe IV characteristics altered by RF spiral

- Probe 4 (under spiral, red curve) characteristic altered by HHFW
- Could be a ~ 30 V shift in floating potential due to RF rectification
  - However, could be ~ 16 eV of plasma heating
- Divertor turbulence prevents accurate determination



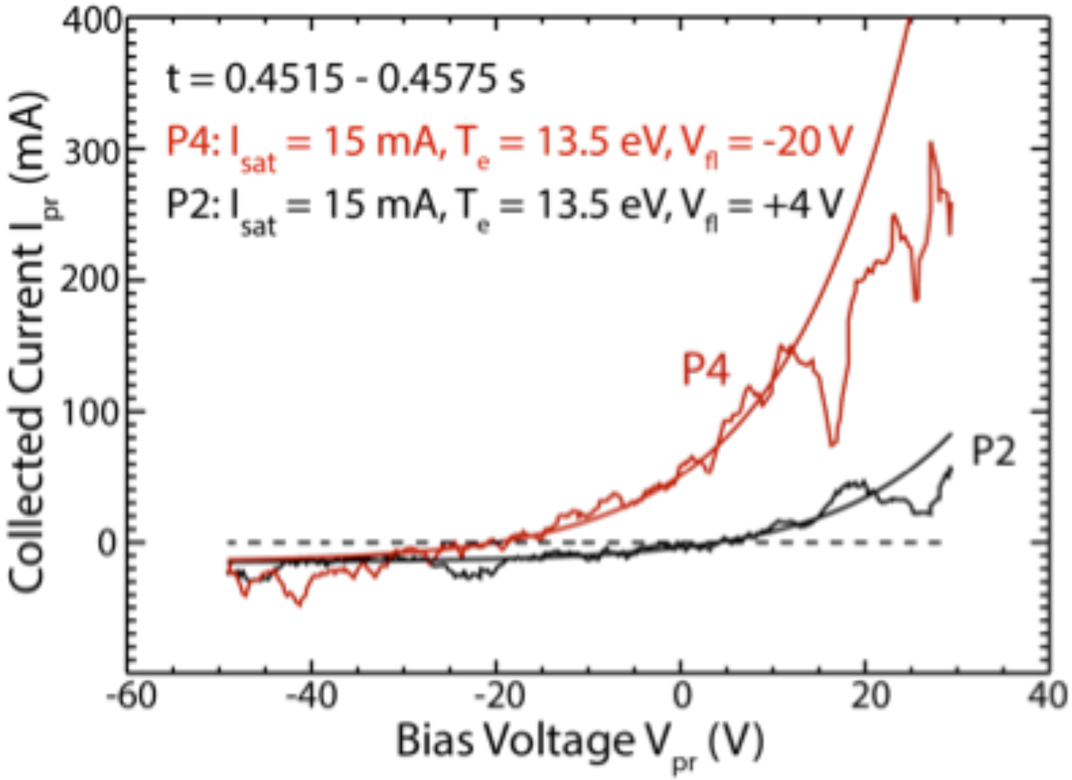
Averaging sweeps smooths turbulence, allows better fitting

- Assume RF rectification
  - Fit both characteristics with exponentials with same T_e and n_e

- Departure from exponential at higher bias expected for oblique magnetic fields

- Change in floating potential: 24 V

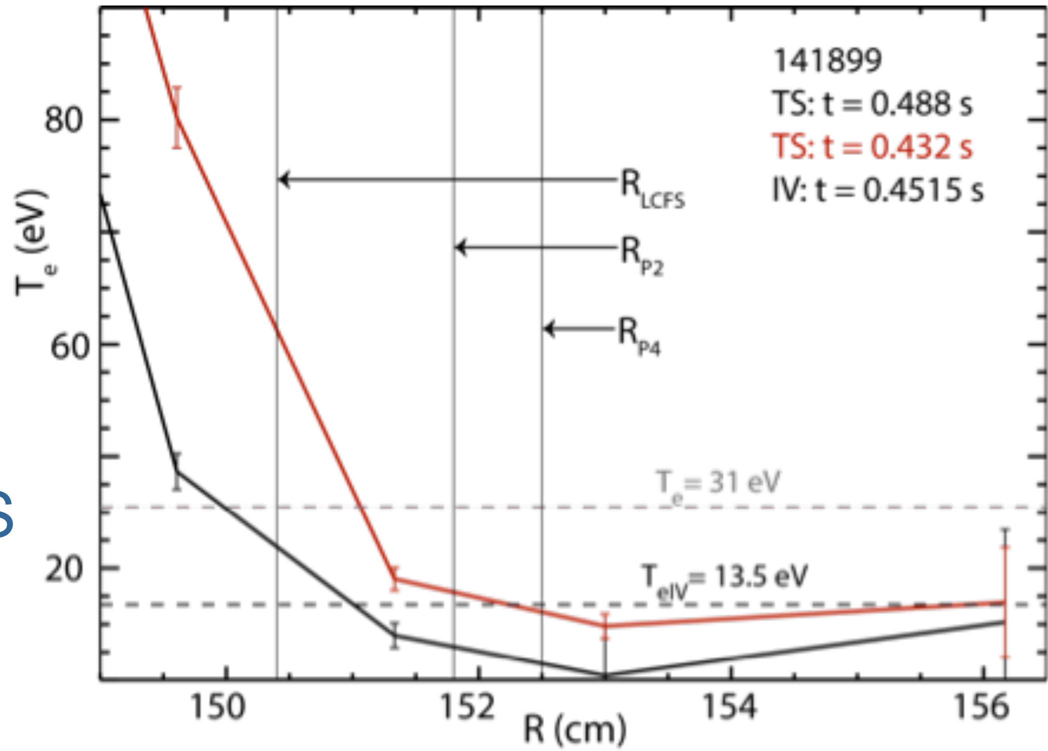
- Estimated V_{RF}: 44 V



$$\exp\left(\frac{V_{fl} - V_{flRF}}{T_e}\right) = I_0\left(\frac{V_{RF}}{T_e}\right)$$

Midplane T_e measurements support RF rectification hypothesis

- Thomson Scattering provides T_e profile at midplane
- Assuming RF rectification: T_e = 13.5 eV,
  - Decent agreement with TS
- Assuming plasma heating: T_e = 31 eV
  - Much larger than TS measurements



R. J. Perkins *et al.*, *Phys. Plasma* **22**, 042506 (2015)

Heat flux to surface consists of ion and electron contributions

$$Q(V) \quad = \quad -J^{sat}V + 2.5T_iJ^{sat} + 2T_eJ^{sat}\exp\left[\frac{V - V_{fl}}{T_e}\right]$$

Ion energy flux from sheath voltage drop

Ion thermal flux

Electron thermal flux

P. Stangeby "The plasma boundary of magnetic fusion devices," Ch. 2

Adding RF increases heat flux (at same bias) due to increased electron current

$$Q(V) = -J^{sat}V + 2.5T_i J^{sat} + 2T_e J^{sat} \exp\left[\frac{V - V_{fl}}{T_e}\right]$$

Ion energy flux from sheath voltage drop

Ion thermal flux

Electron thermal flux

Add RF potential and average over an RF cycle

$$Q_{RF}(V) = -J^{sat}V + 2.5T_i J^{sat} + 2T_e J^{sat} I_0\left(\frac{V_{RF}}{T_e}\right) e^{(V - V_{fl})/T_e}$$

Adding RF increases heat flux (at same bias) due to increased electron current

$$Q(V) = -J^{sat}V + 2.5T_iJ^{sat} + 2T_e J^{sat} \exp\left[\frac{V - V_{fl}}{T_e}\right]$$

Electron current without RF

Electron current with RF

$$Q_{RF}(V) = -J^{sat}V + 2.5T_iJ^{sat} + 2T_e J^{sat} I_0\left(\frac{V_{RF}}{T_e}\right) e^{(V-V_{fl})/T_e}$$

Adding RF increases heat flux (at same bias) due to increased electron current

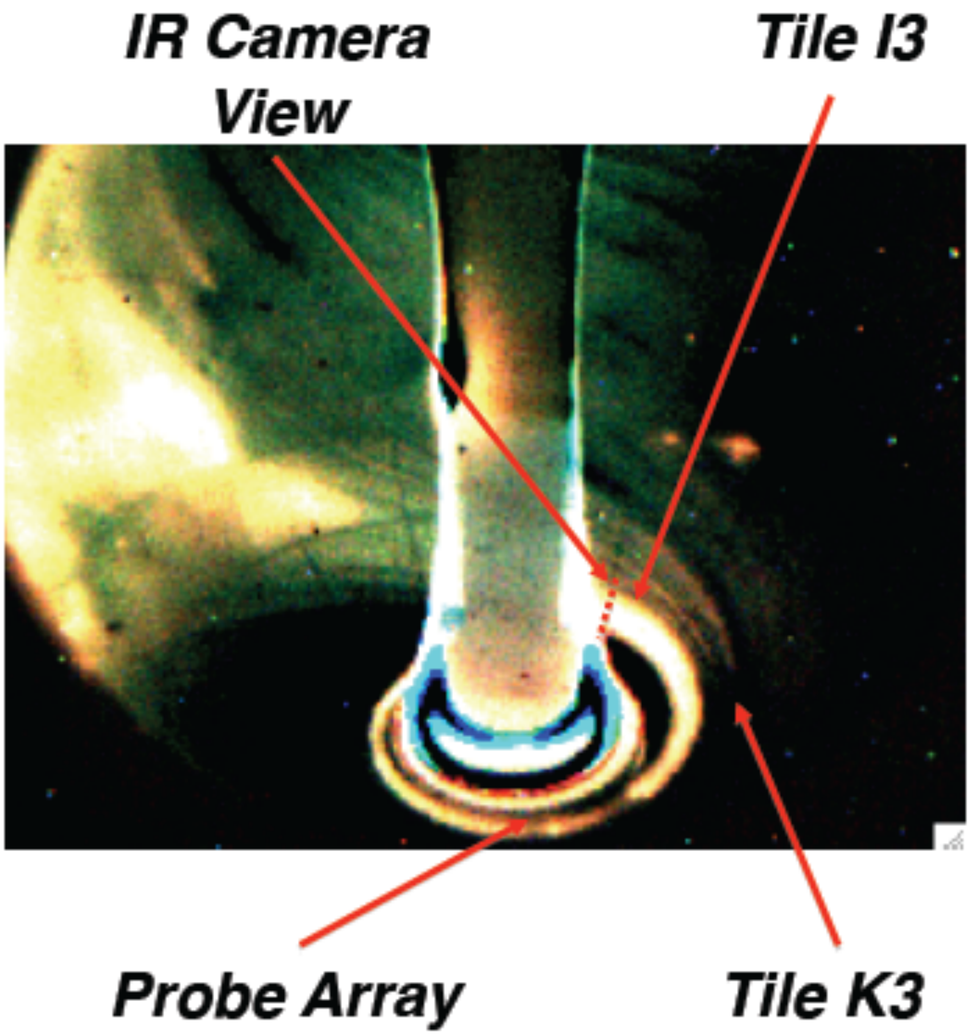
$$Q(V) = -J^{sat}V + 2.5T_iJ^{sat} + 2T_eJ^{sat}\exp\left[\frac{V - V_{fl}}{T_e}\right]$$

Add RF potential and average over an RF cycle

$$Q_{RF}(V) = -J^{sat}V + 2.5T_iJ^{sat} + 2T_eJ^{sat}I_0\left(\frac{V_{RF}}{T_e}\right)e^{(V-V_{fl})/T_e}$$

V_{RF} ~ 44 V → ΔQ_{RF} = 0.1 MW/m^2

Comparison of Q_{RF} prediction by RF rectification to heat flux measured by IR camera is currently difficult

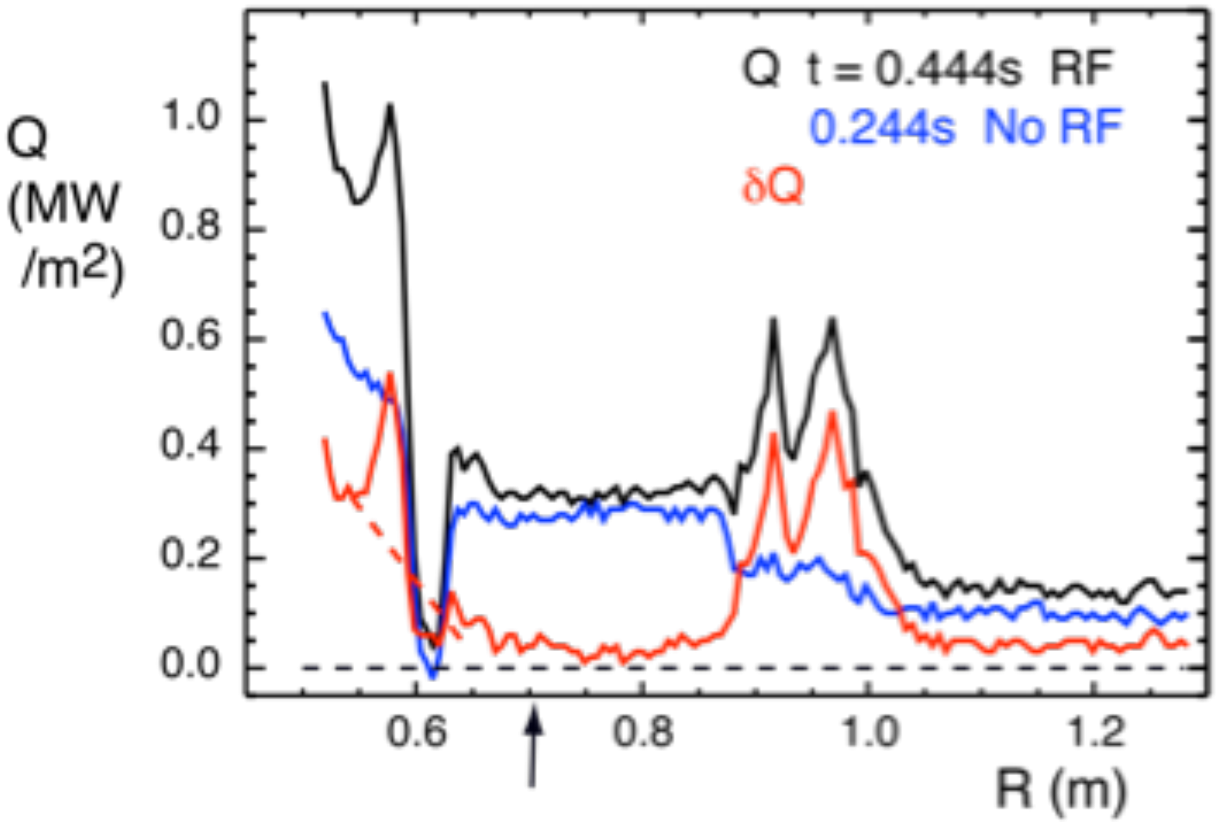


- Heat flux profiles obtained at Bay I
- Langmuir probes located at Bay B
  - 150^{o} of toroidal separation
- Strong toroidal variations in spiral intensity

Rough extrapolations suggest RF-rectification prediction is plausible, but better data is needed

- $\delta Q = Q_{RF} - Q_{noRF}$ reveals different spiral passes across Bay I
- Probe radius closest to second spiral pass
- Subtract off estimate of plasma exhaust from second peak
  - Estimate 0.3 MW/m^2 from heat flux profile
  - Larger than prediction from V_{RF} but does not account for spiral variation

Heat Flux Profile at Bay I



Probe Radius

R. J. Perkins *et al.*, *Phys. Plasma* **22**, 042506 (2015)

Improved diagnostics on NSTX-U will allow for definitive comparisons

- New radial array of divertor Langmuir probes
  - Located at Bay I where most intense part of spiral is anticipated to fall
  - Probe electronics will detect RF (30 MHz) component of signal
    - Direct measurement of V_{RF}
- ORNL is providing a wide-angle IR view of divertor
  - Obtain heat flux measurement at probe location
- Will perform a dedicated power scan
  - Determine scaling of measured heat flux and V_{RF}
  - Determine if RF-rectification predictions of heat flux are accurate

Conclusions

- SOL losses of HHFW power are significant for NSTX
  - Possibly a fast-wave propagation effect that is more apparent in ST geometry
- RF rectification is a likely explanation for changes to floating potential and currents
- RF rectification can potentially explain the spiral heat flux
  - Potentially the long sought mechanism converting HHFW power to heat flux to outer divertor
  - Current predictions are in the right range, but better data is needed
- Experiments and diagnostics upgrades on NSTX-U will allow for more a definitive comparison