Local effects of biased electrodes in the divertor of NSTX

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- Basic idea and related experiments
- NSTX electrodes and diagnostics
- Experimental results with biasing
- Modeling of convective cells in NSTX
- Possible future directions

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Providence RI, Abstract: PP8.00029

Abstract

One proposed solution to the problem of high scrape-off layer heat flux in tokamaks is to generate non-axisymmetric convective cells near the divertor plate to modify the local heating pattern [1]. To test this theory, four small rectangular electrodes were installed into the outer divertor plates of NSTX [2]. When the electrodes were located near the outer strike point and biased positively, there was an prompt increase in the nearby probe currents and probe potentials and an increase in the LiI light emission at the large major radius end of these electrodes. When an electrode located farther outward from the outer strike point was biased positively, there was sometimes a significant decrease in the LiI light emission at the small major radius end of this electrode, but there were no clear effects on the nearby probes. These changes are qualitatively consistent with the expected vertical motion due to a convective cell generated by the electrodes. Possible applications of this technique to future tokamaks will be discussed.

[1] R.H. Cohen et al, Plasma Phys. Cont. Fusion **49**, 1 (2007) and references therein
[2] S.J. Zweben et al, Plasma Phys. Cont. Fusion **54**, 105012 (2012)

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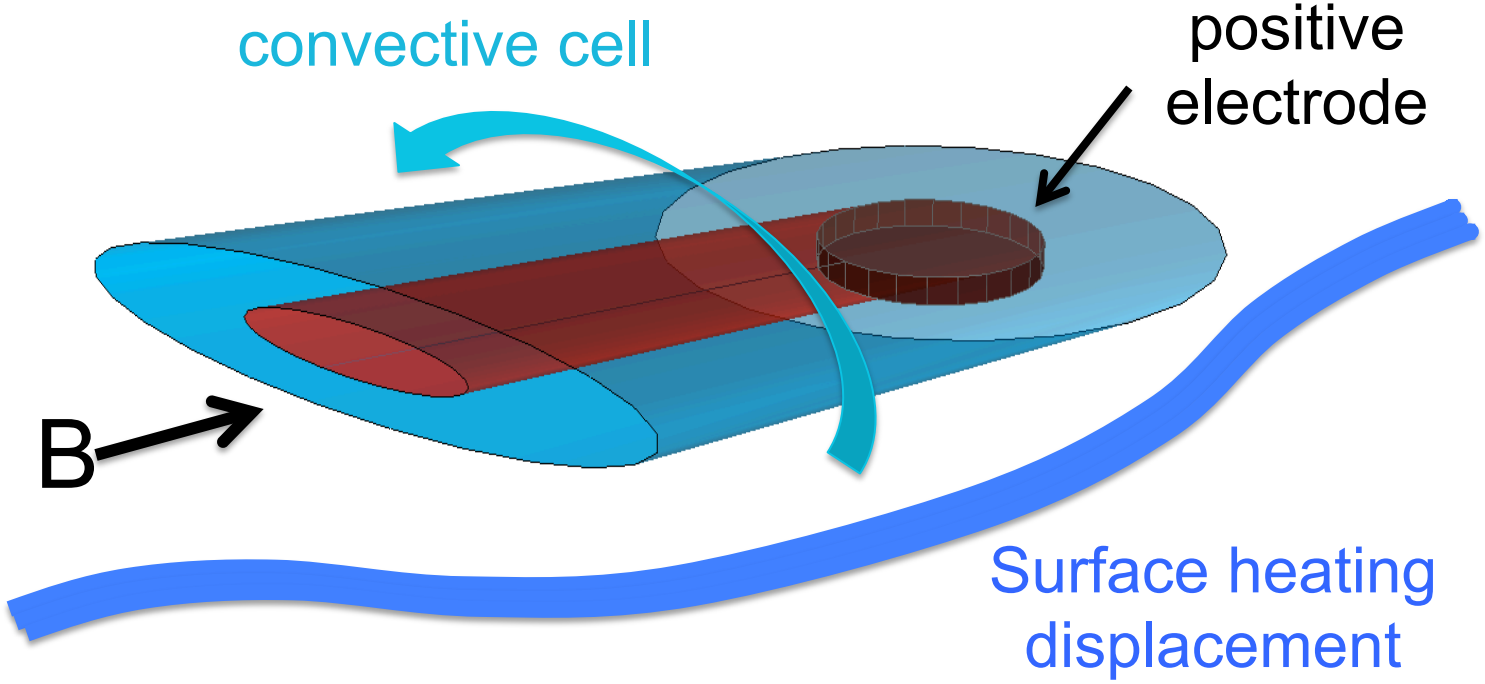
Basic Idea of Experiment

- Bias localized electrode on divertor plate surface
- Create convective cell extending along B field line
- Control radial location of local heat/particle flux

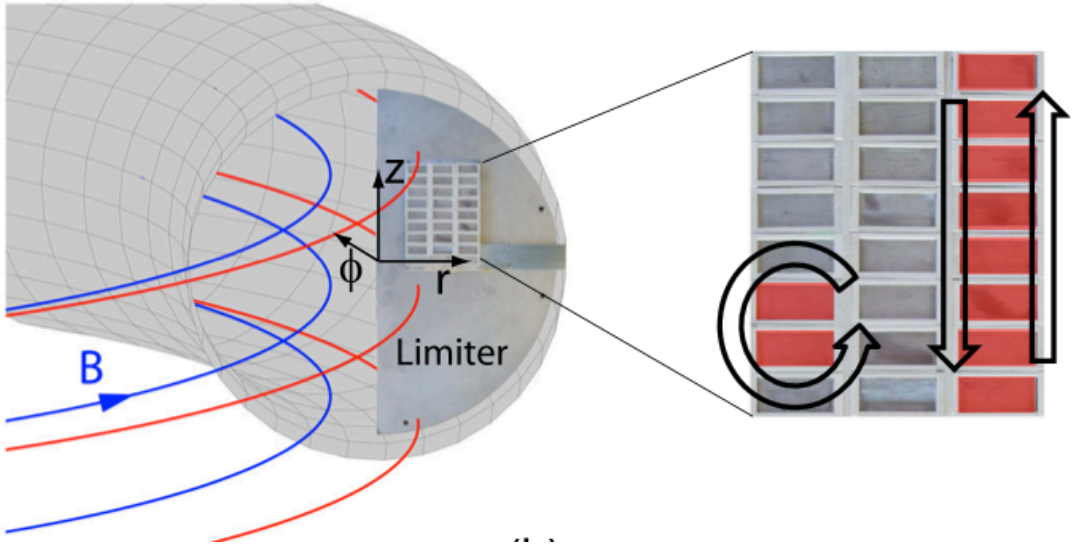


Related Work on Other Experiments

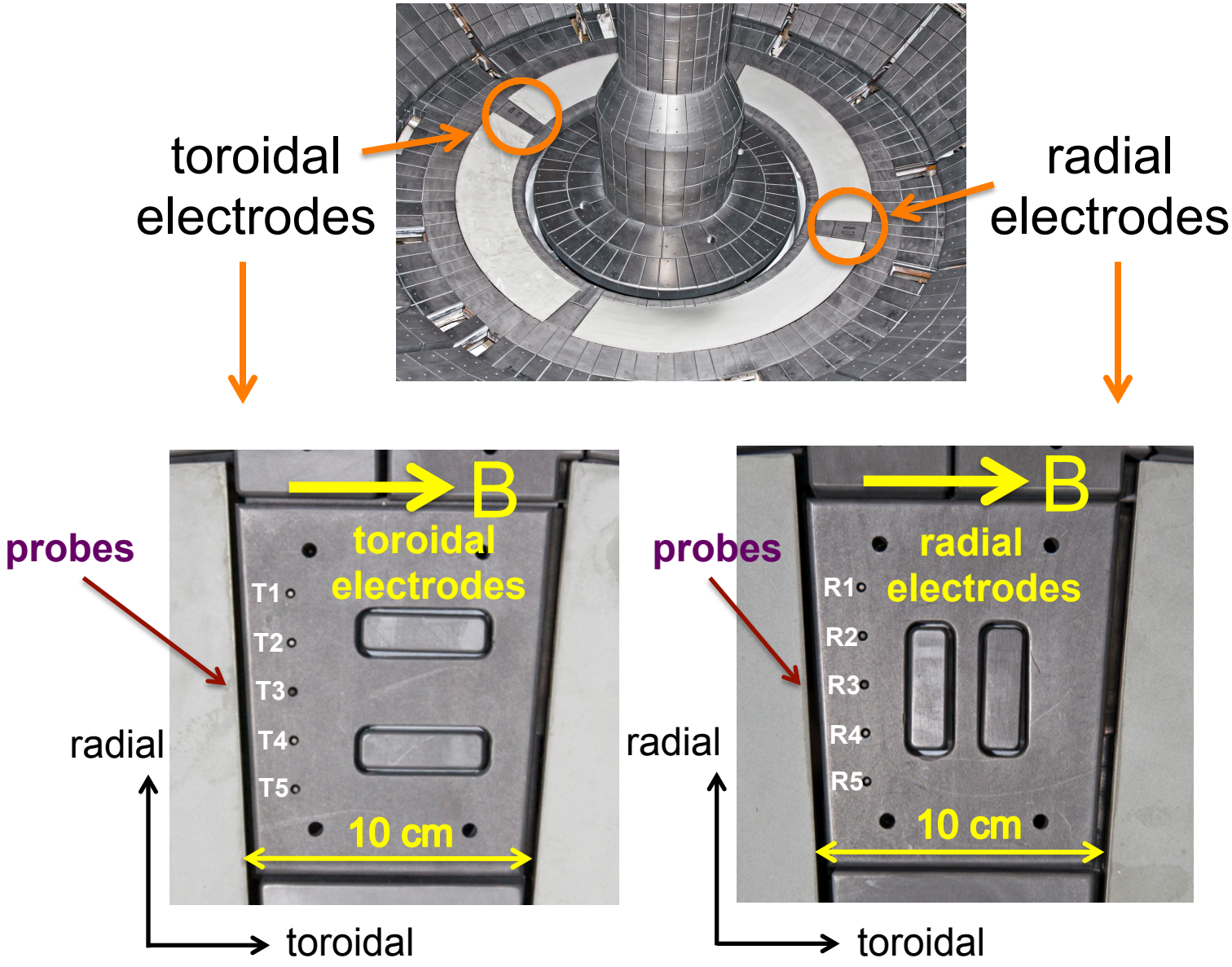
Some previous experiments on convective cell generation:

JFT-2M - Hara et al, J. Nucl. Mat. **241-243**, 338 (1997)
MAST - Counsell et al, J. Nucl. Mat. **313-316**, 804 (2003)
CASTOR - Stockel et al, PPCF **47**, 635 (2005)
NSTX - Zweben et al, PPCF 51. 105012 (2009)
TORPEX - Theiler et al, Phys. Plasmas 19, 082304 (2012)

2-D electrode biasing experiment in TORPEX



Electrodes and Probes in NSTX



Diagnostics for this Experiment

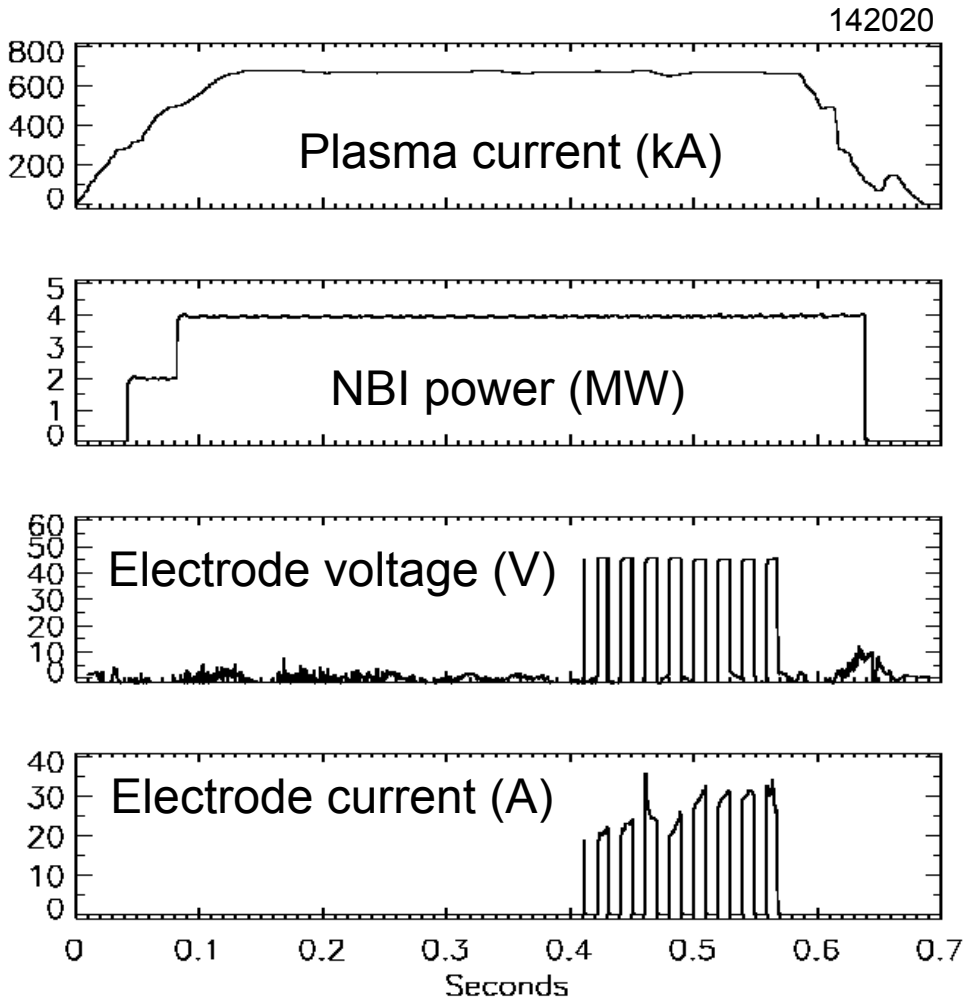
- Electrode current and voltage monitors at power supply

- Langmuir probe radial array next to each electrode pair
  - 5 probes 1/16” diameter with 1.5 cm radial spacing
  - tips approximately flush with surrounding grounded tile
  - ± 50 Volt biasing or sweeping, or floating
  - each probe insulated by 1 mm gap to tiles

- Optically filtered, high speed cameras viewing from above
  - Phantom 710 or 7.3, up to ~10,000 frames/sec
  - Li I (670.8 nm), Dα (656 nm) or IR (~900–1100 nm)

- Normal edge/SOL diagnostics on NSTX
  - *no non-local effects seen with divertor electrode biasing*

Electrode Bias in NSTX Discharges



Electrode bias Modulated at 50 Hz during steady-state of normal discharges

Voltage ≤ 90 Volts (normally positive)

Current ≤ 40 Amps per electrode

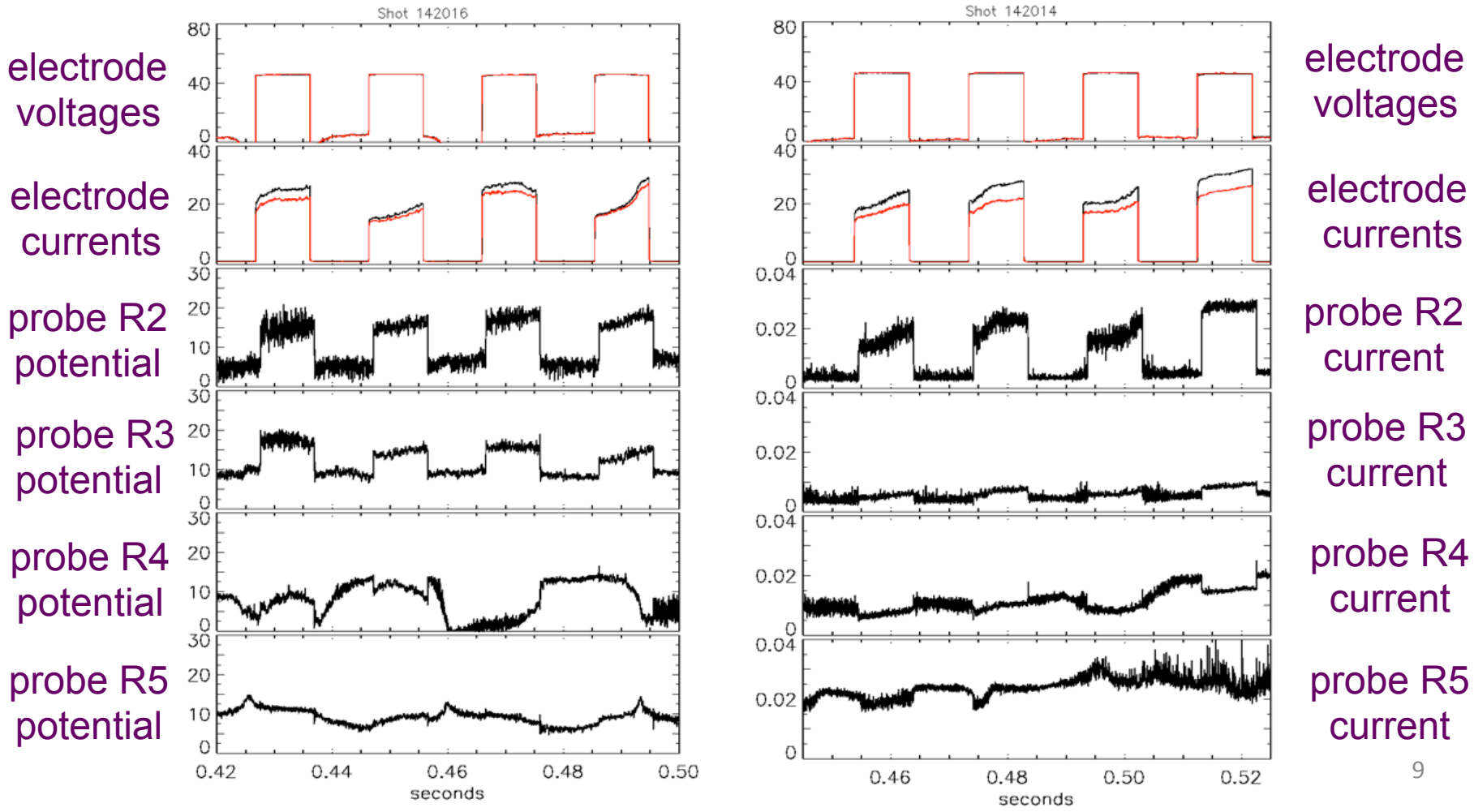
NSTX Runs with Electrode Biasing

- Either toroidal or radial electrodes biased in any one run
- Variable location of outer strike point (OSP) with respect to electrode major radius range of R=76-80 cm

Run	#1	#2	#3	#4	#5
type	**Radial**	**Toroidal**	**Toroidal**	**Radial**	**Toroidal**
shots	140333-347	140617-630	141839-899	142014-026	142490-507
I (kA)	300-650	900	640-1000	650-740	800-900
B(kG)	5.4-5.5	4.7	5.4	5.0-5.4	4.7
NBI(MW)	0-2	1.9-3.0	0-2	2-4	4
RF(MW)	0-1.5	0	0-1.3	0	0
OSP(cm)	40-70	62-75	40-79	76-80	72-75
shots	11	4	19	6	7
cycles	61	73	109	43	34
N + bias	1	1	2	2	2
V + bias(V)	90	90	90	50	50-90
I bias(A)	1.0	9.6	2.3	24.5	19
effect	**none**	**small**	**none**	**large**	**moderate**

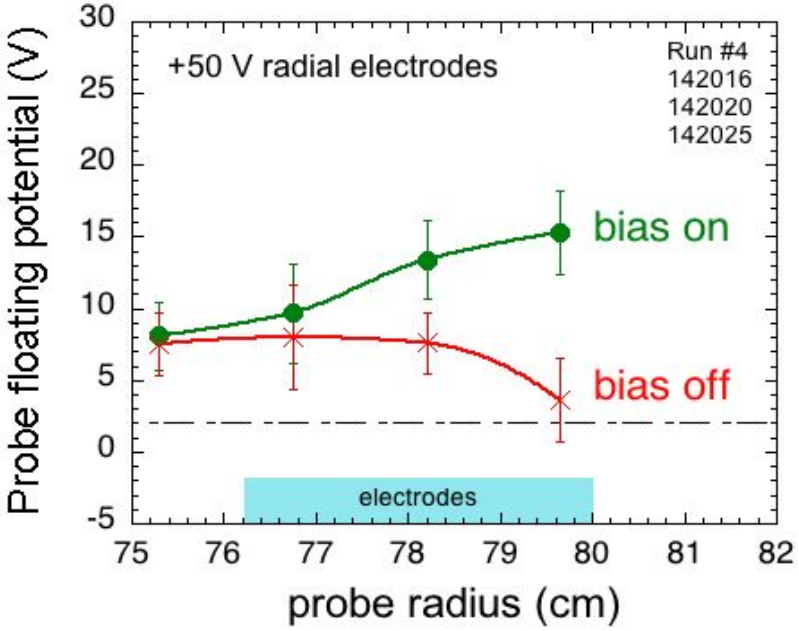
Probe Changes with Electrode Biasing

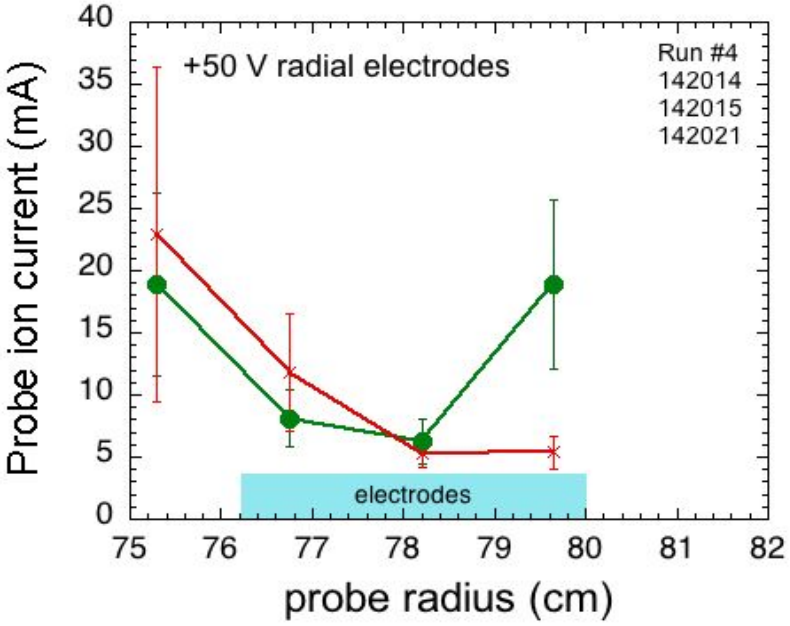
- This is for run with largest local effect on probes (Run #4), with OSP overlapping electrodes and/or small turbulence



Profile of Probe Changes (Run #4)

- This case for radial electrodes at + 50 Volts bias (Run #4)
- Floating potential and probe (electron) current increase at large-R end of electrodes by 10-15 Volts and x4





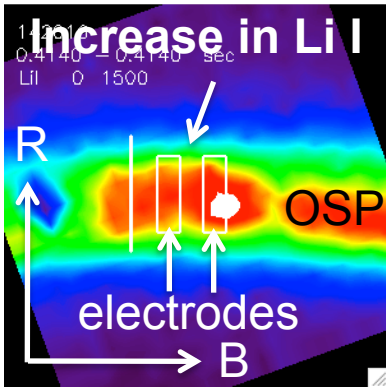
Camera View of Biasing Effects

- If OSP overlaps electrodes when biasing at +50 Volts (Run #4) see increase in Li I light at large-R end of electrodes

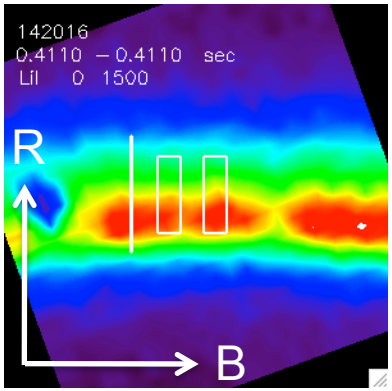
- If OSP is at smaller major R, no change in OSP strike location when the same electrodes are biased the same way

OSP overlaps electrodes

bias on

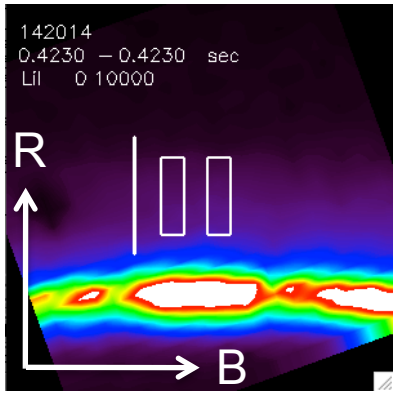


bias off

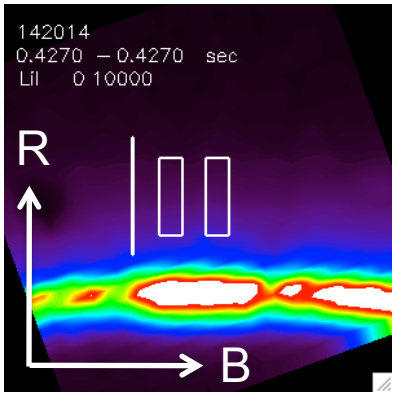


OSP at smaller major R

bias on



bias off

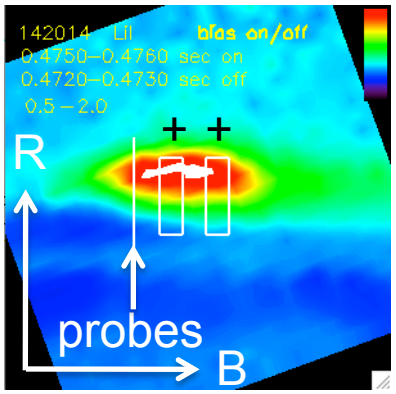


Normalized Camera Images "On/Off"

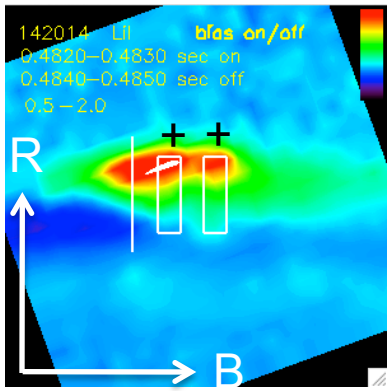
- Isolate effects by taking ratio of Li I light with biasing "on/off" for a shot with two electrodes at + 50 Volts (Run #4)

- See increase in light at large-R end of electrodes, extending a few cm upstream along B to probe array (vertical line), consistent with increase in probe currents at large-R end

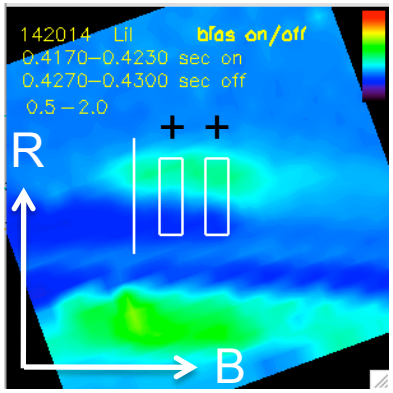
Bias turn-on time



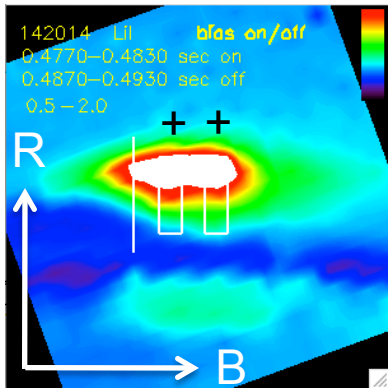
Bias turn-off time



Bias early in shot

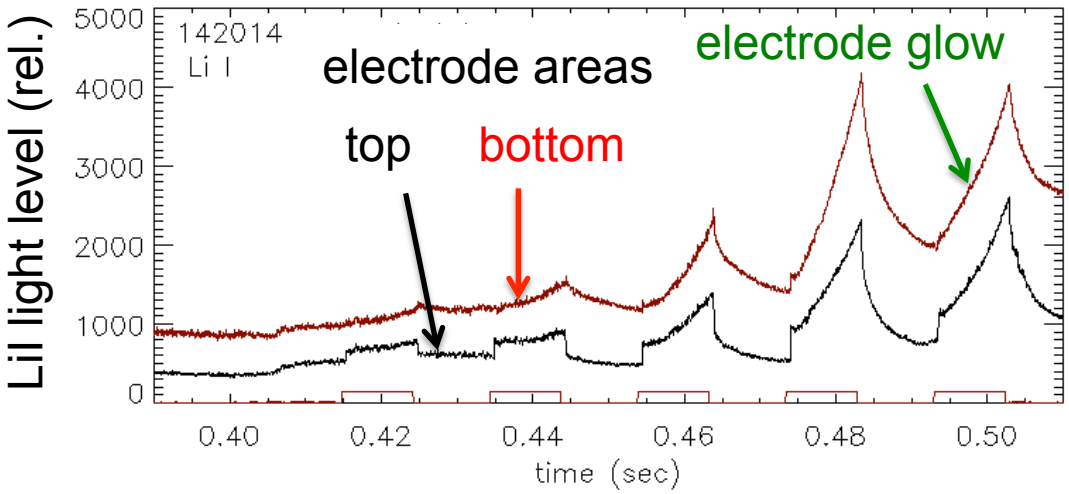


Bias late in shot

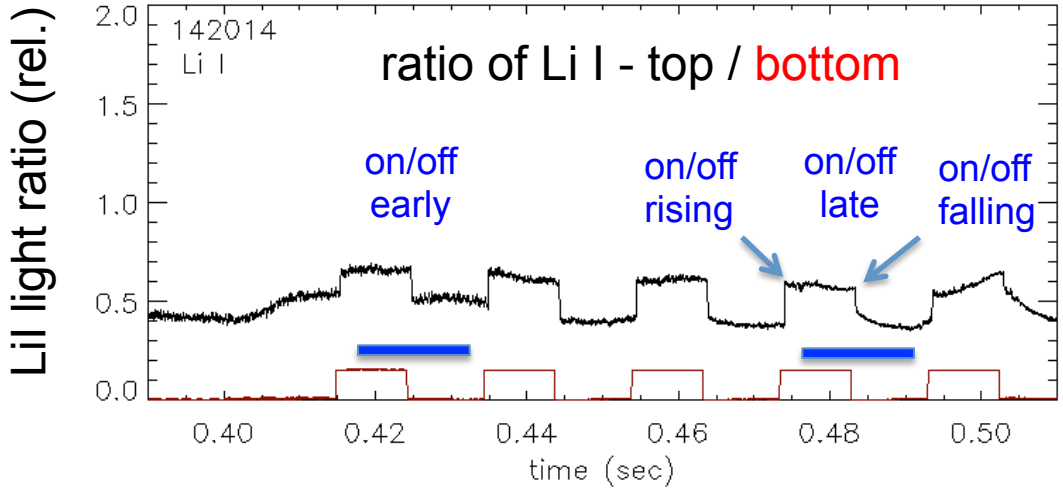


Time Dependence of Biasing Effects

- Consistent increases at top half of electrode with biasing



Li I light vs. time in top and bottom half of electrode region (electrode glow in both at late times)



Ratio of Li I light vs. time in top and bottom half of electrode region

Electrode Glow Effect at Late Times

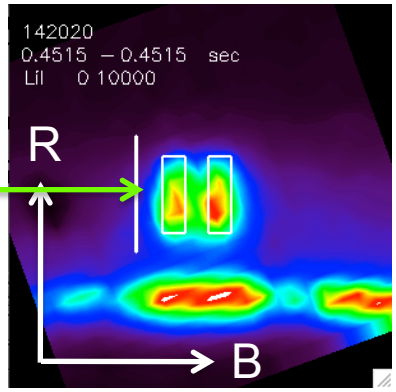
- After ~50-100 msec of + 50 Volt biasing, both electrodes begin to glow over their whole area, with or without bias

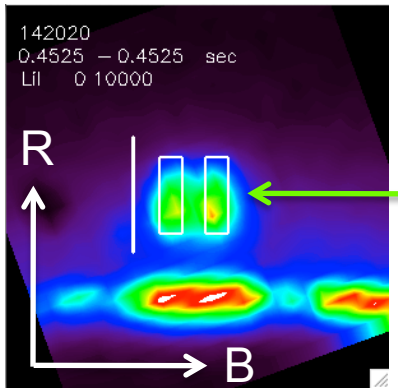
- Similar glow seen in IR filtered images, but not Dα, so glow apparently due to electrode heating and evaporation of Li from surface of electrodes due to previous bias cycles

bias on

bias off

Electrode glow

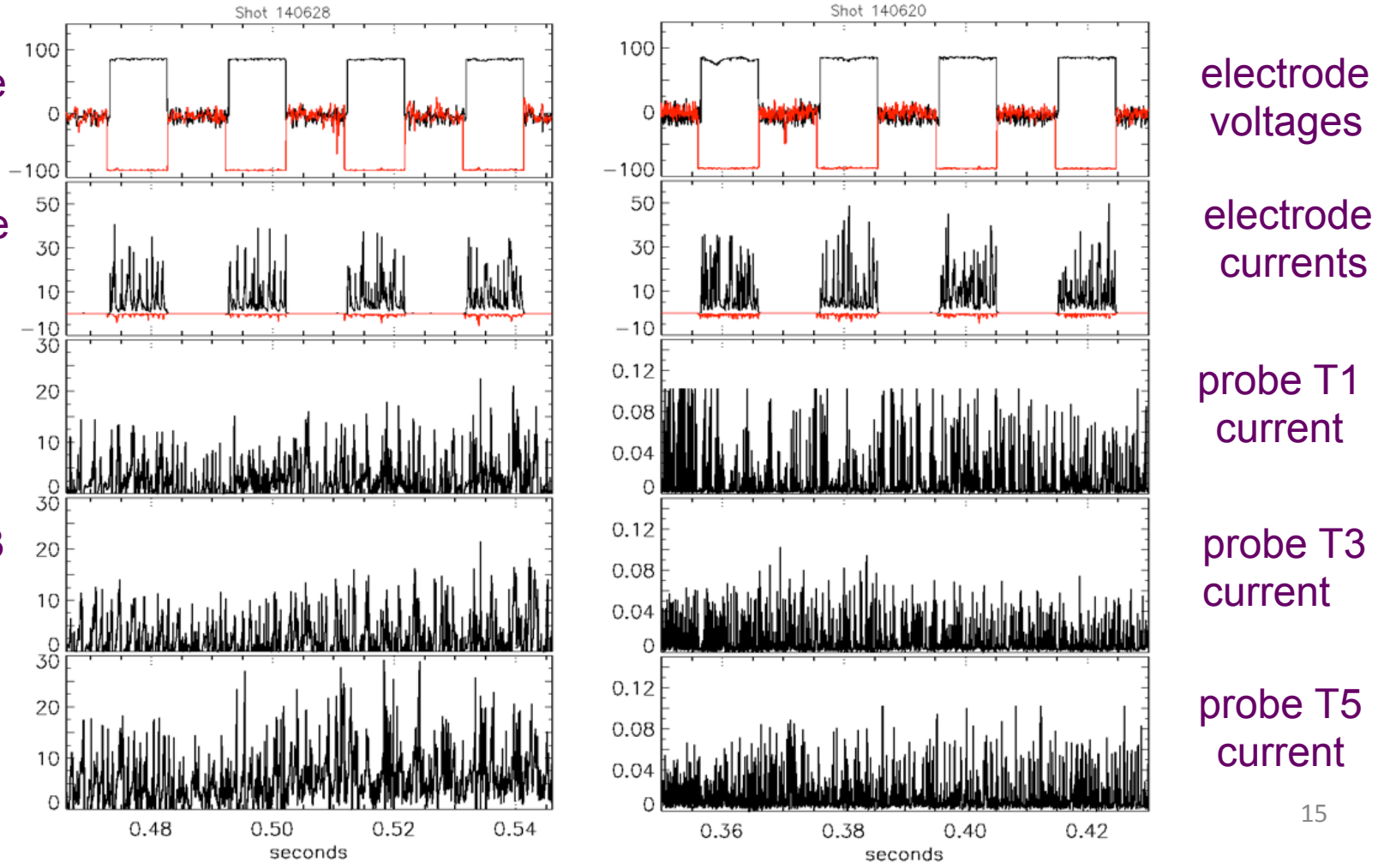




Electrode glow

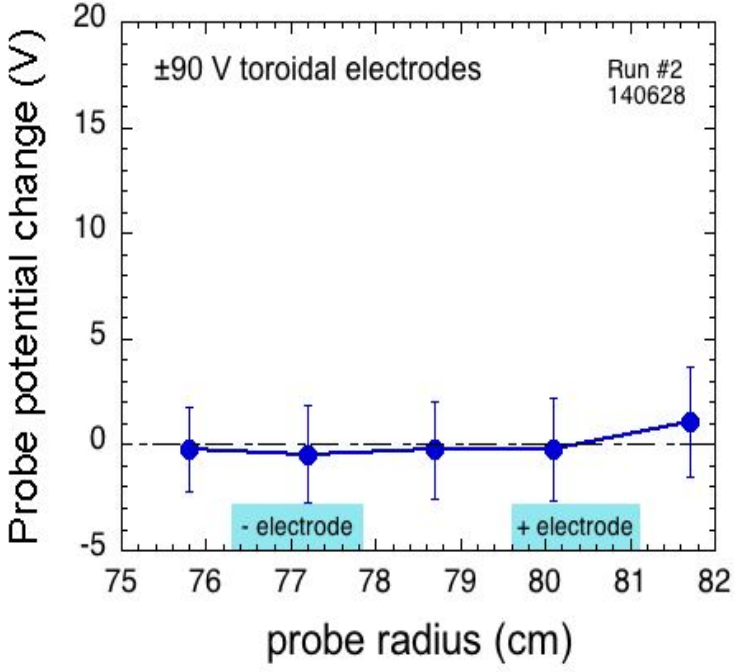
Probe Changes with Electrode Biasing

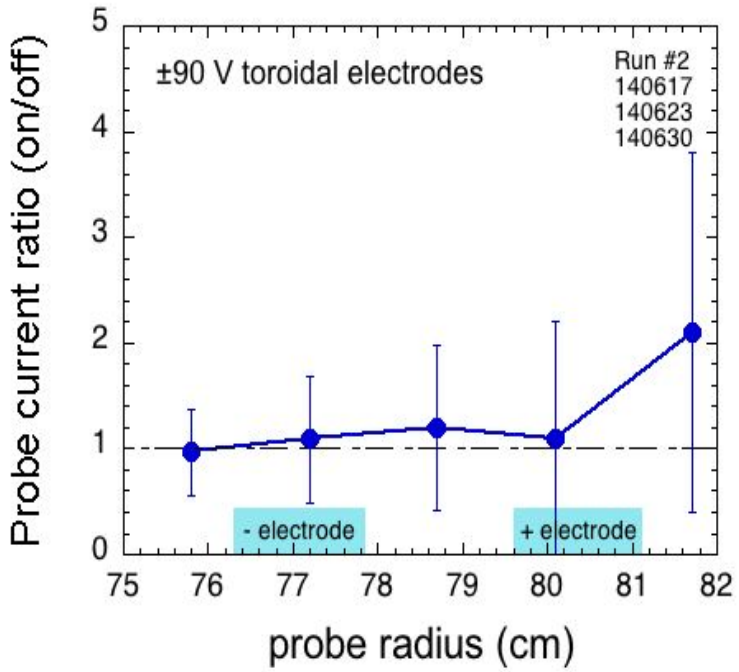
- No changes seen for Run #2 with electrodes far from OSP



Profile of Probe Changes (Run #2)

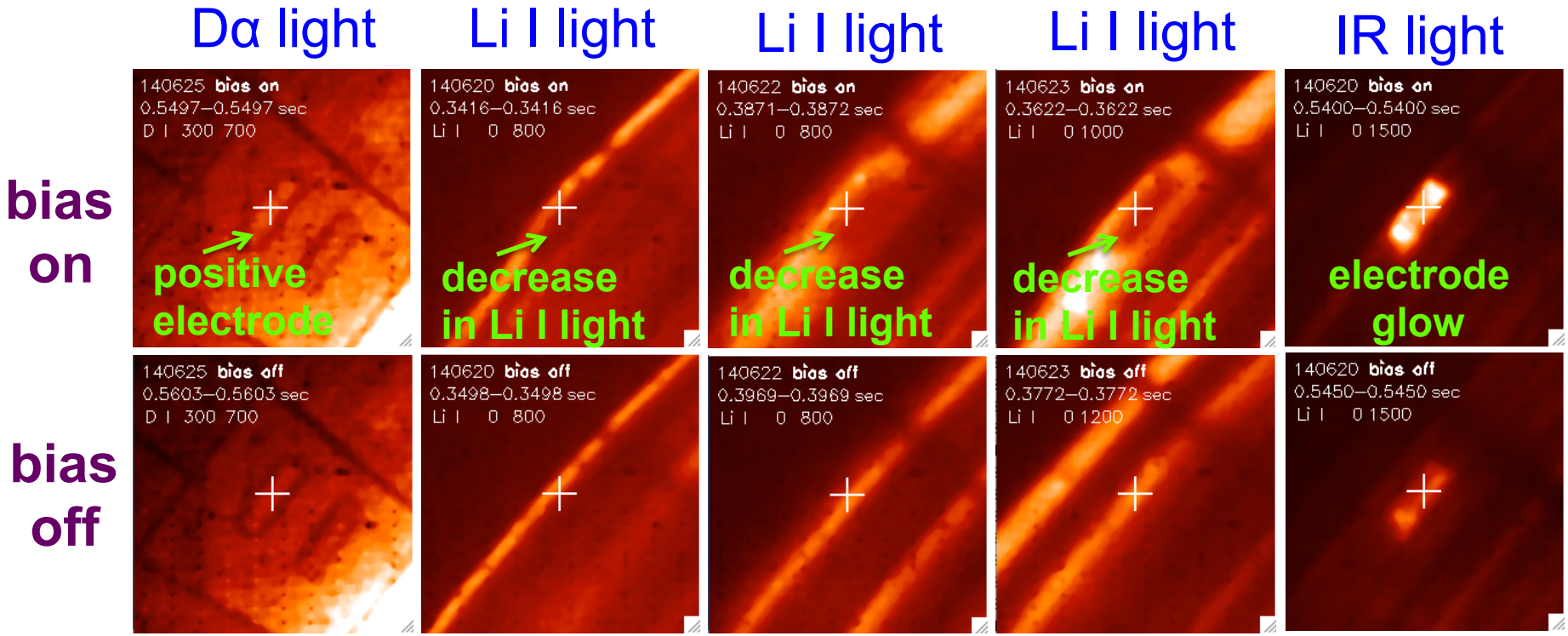
- This case for toroidal electrodes at + 90 Volts bias
- Floating potential and probe (ion) current *do not change* with this electrode biasing (OSP far from electrodes)





Camera View of Biasing Effects

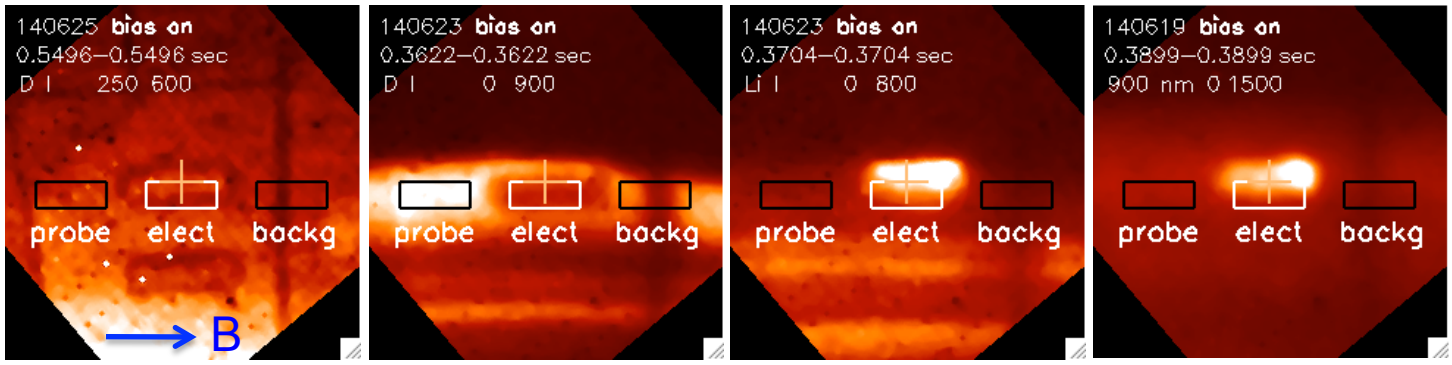
- For this Run #2, OSP far from toroidal electrodes, biasing of upper electrode at +90 Volts causes *decrease in Li I light* at small-R end of electrode (dark regions, top middle panels)



Evaluating Decrease in Camera Light

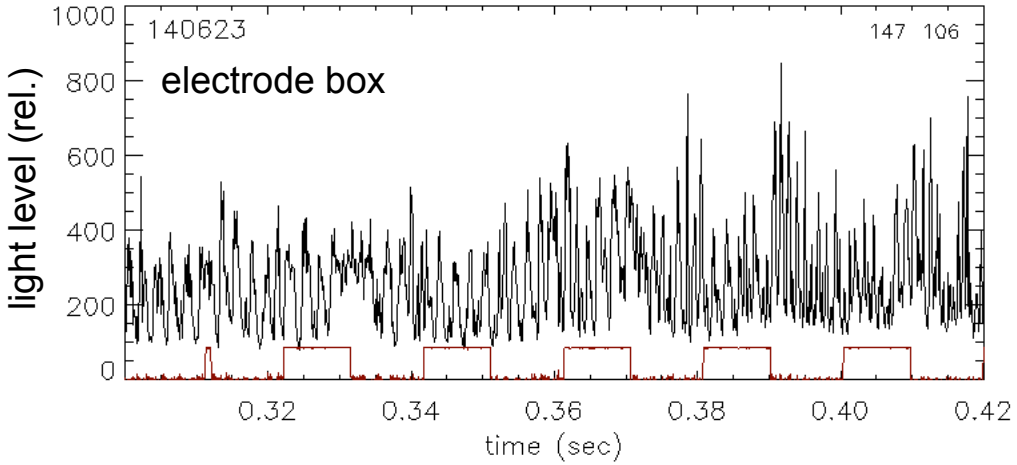
- For this run with OSP far from toroidal electrodes, use three boxes at same R to evaluate changes in Li I light at electrode (turbulence filaments are nearly constant along R direction)

- Ratio of light levels in these boxes measures local density changes during biasing, independent of turbulent filaments

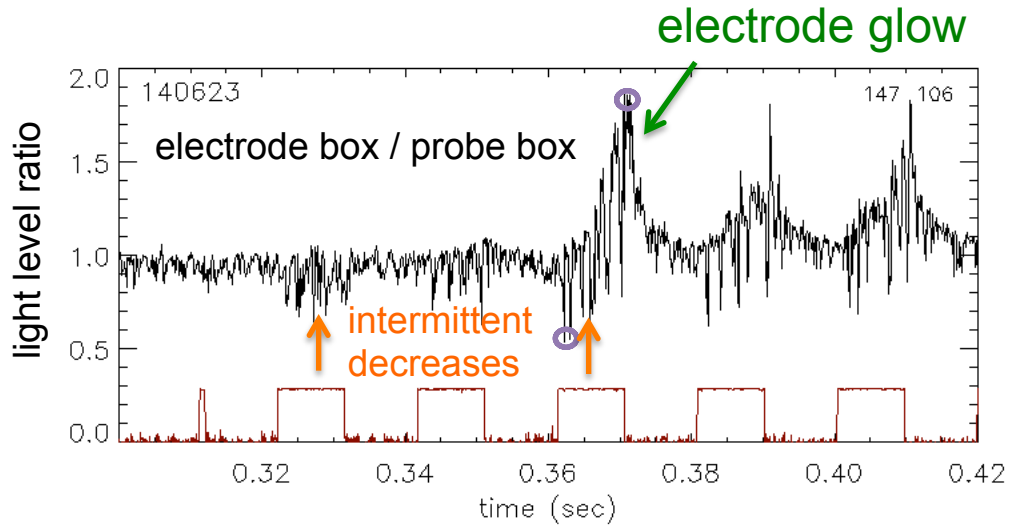


Time Dependence of Biasing Effects

- In Run #2, only small, intermittent decreases in small-R end of toroidal electrode with +90 Volts biasing



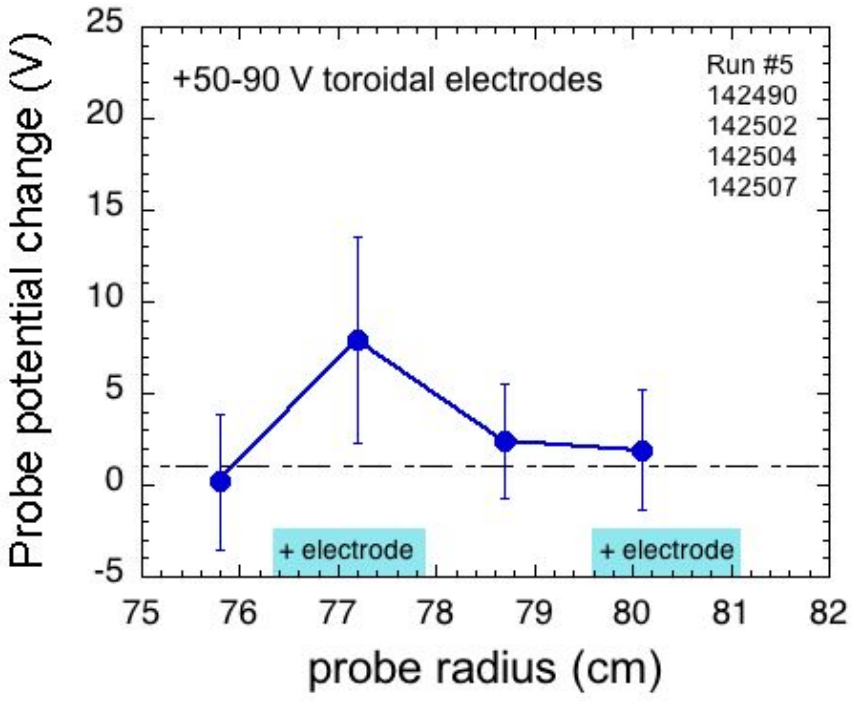
Li I light vs. time in electrode region (little effect of bias)

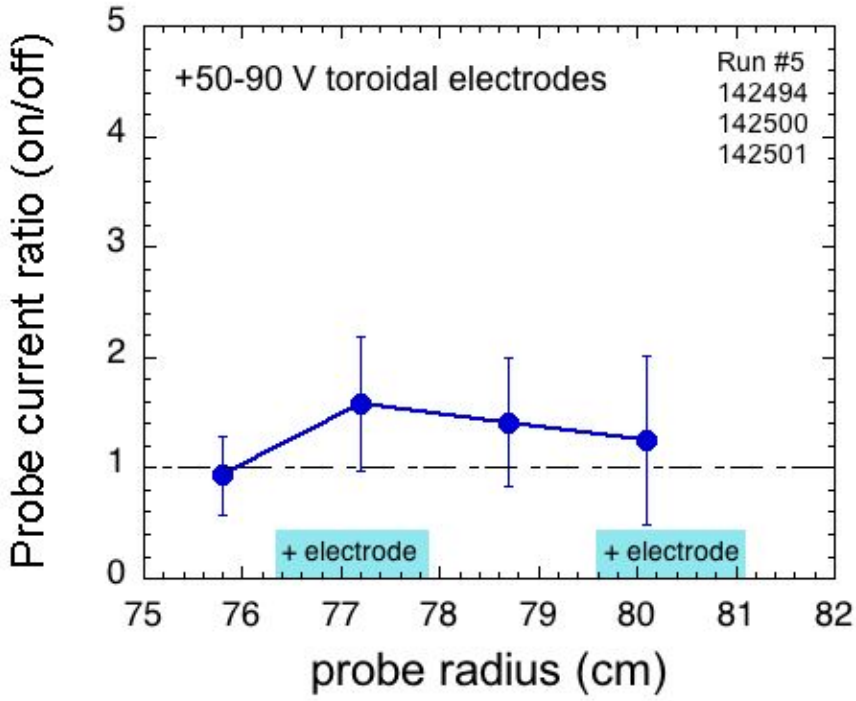


Ratio of Li I light vs. time in electrode box divided by probe box (electrode glow in both at late times)

Profile of Probe Changes (Run #5)

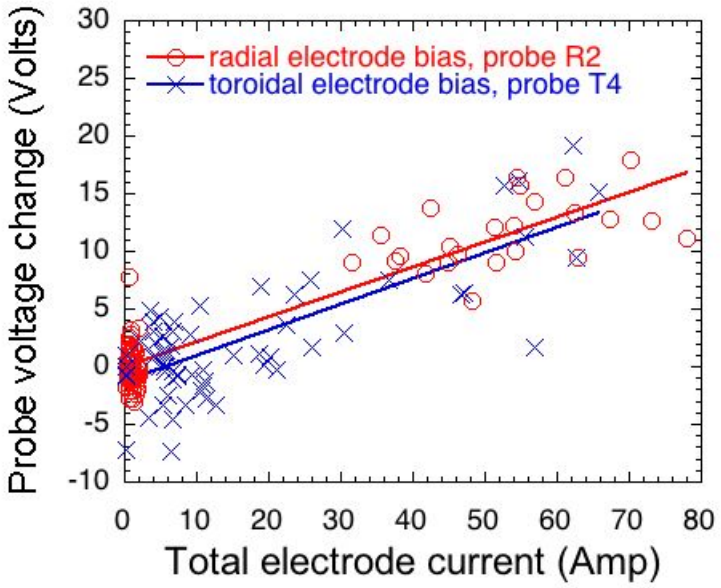
- Here both toroidal electrodes at +50-90 Volts bias (Run #5)
- Floating potential and probe (electron) current increase slightly at smaller R electrode (nearer OSP)

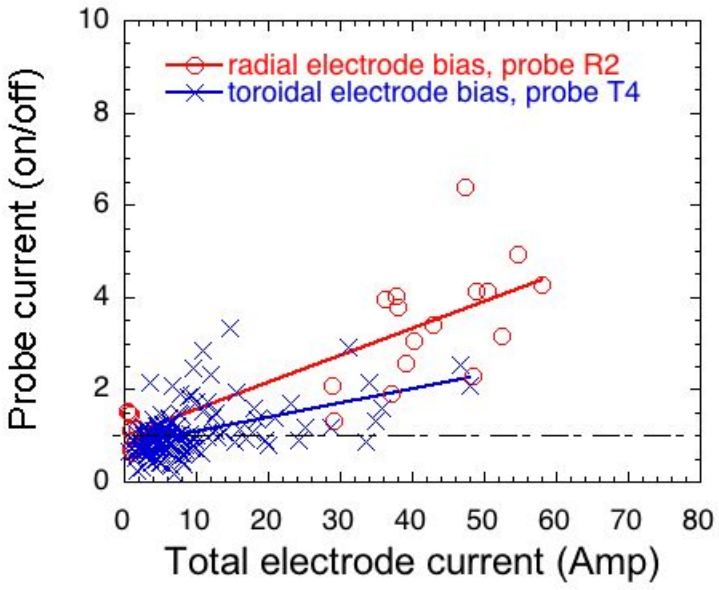




Database of Biasing Effects at Probes

- Plot probe response for all biasing cycles in Runs #1-5 vs. total current drawn by nearby electrodes I_{elect}
- Clearest effects at large-R probe for radial electrodes (R2), and probe near positively biased toroidal electrode (T4)
- Effects on probes increase significanty for $I_{elect} \geq 30$ Amp approximately same for toroidal and radial electrodes





Summary of Experimental Results

- With +50 Volts biasing of radial electrodes near OSP, see significant increase in probe currents, probe potentials, and local Li I light emission at large-R end of electrodes, suggesting an increase of plasma density at that location

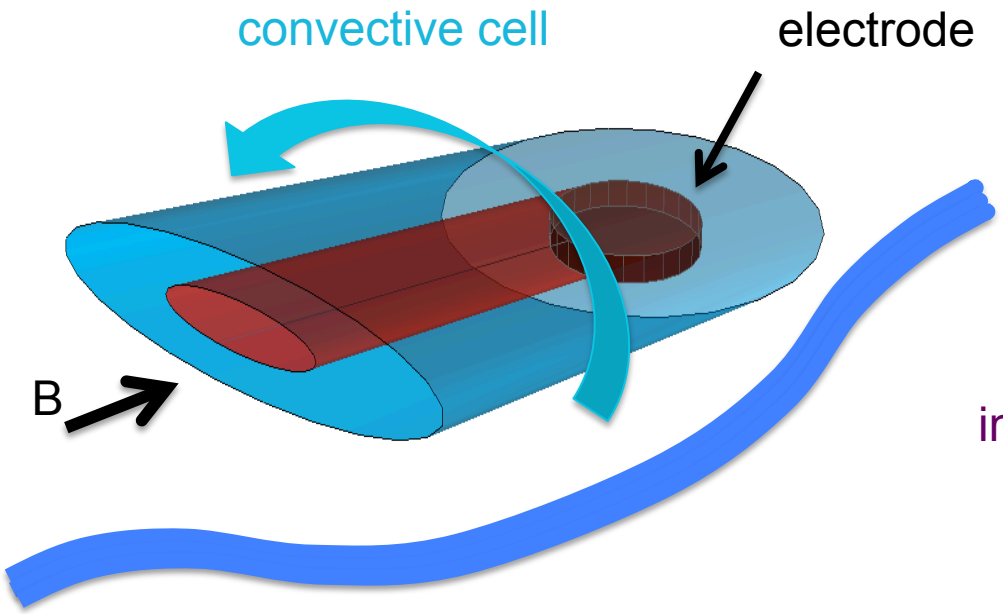
- With +90 Volt biasing of toroidal electrodes far from OSP, see small intermittent decreases in Li I light at small-R end of electrode, suggesting a decrease of density there

- In entire database, see local probe effects at ≥ 30 Amps with +50-90 Volts bias, and no effects for negative bias

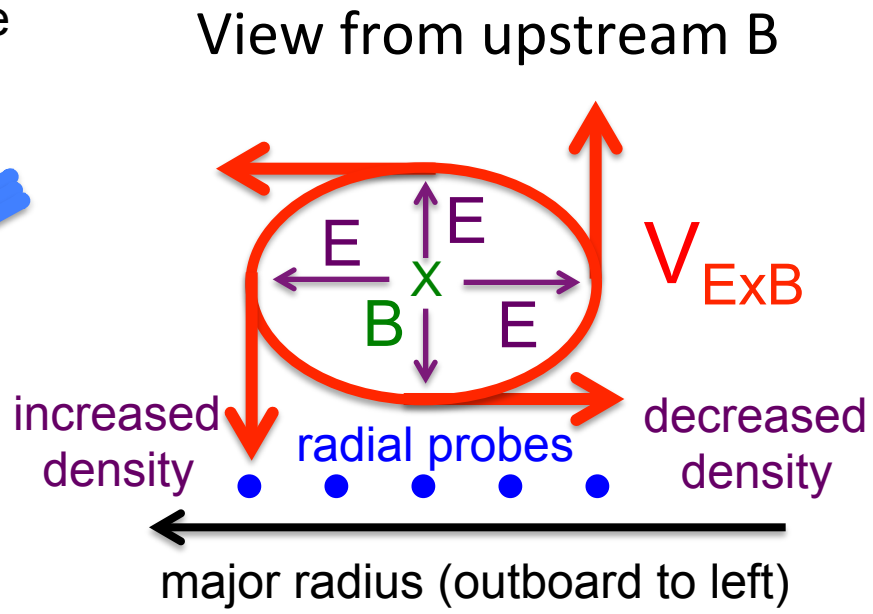
- No non-local effects due to electrode biasing seen on any other diagnostic (e.g. no effects on impurities or ELMs)

Qualitative Model of Convective Cells

- Convective cells were expected to displace high heat flux region to smaller major R due to radial ExB motion
- But maybe dominant effect was due to vertical ExB motion - increased density at large-R and decreased at small-R ?



Surface heating displacement ?



Quantitative Model of Convective Cells

- Make estimates of local plasma parameters and cross-field transport processes to understand experimental results

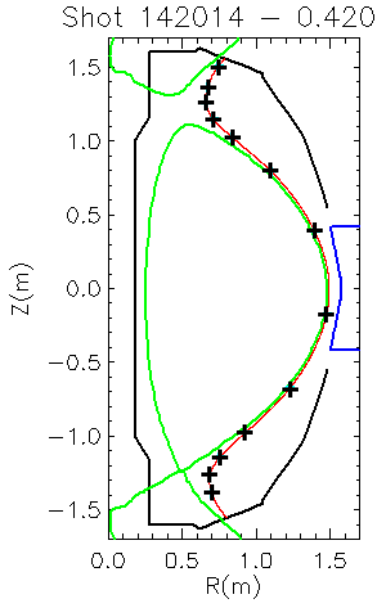
  electron density: $n \sim 5\text{-}10 \times 10^{12}$ cm^{-3}
  electron temperature: $T_e \sim 10\text{-}20$ eV
  neutral density: $n_o \sim 10^{10}\text{-}10^{11}$ cm^{-3}
  Debye length: $\lambda_D \sim 10^{-3}$ cm
  ion gyroradius (assuming $T_i = T_e$): $\rho \sim 0.1$ cm
  perpendicular scale length of cells: $L_\perp \sim 1$ cm
  parallel scale length of cells: $L_{II} \sim 2$ m
  potential inside convective cells: ≤ 50 Volts
  estimated V_{ExB} velocity of cell: $\sim 2 \times 10^5$ cm/sec
  poloidal turbulence velocity: $\sim 10^5$ cm/sec
  local poloidal flow velocity: $\sim 10^5$ cm/sec

- Estimated number of rotations of the plasma in cell over its length along B: $N = v_{ExB}\,(L_{II}/v_{II})/(2\pi L_\perp) \sim 3$, which should have a local effect on plasma hitting divertor surface

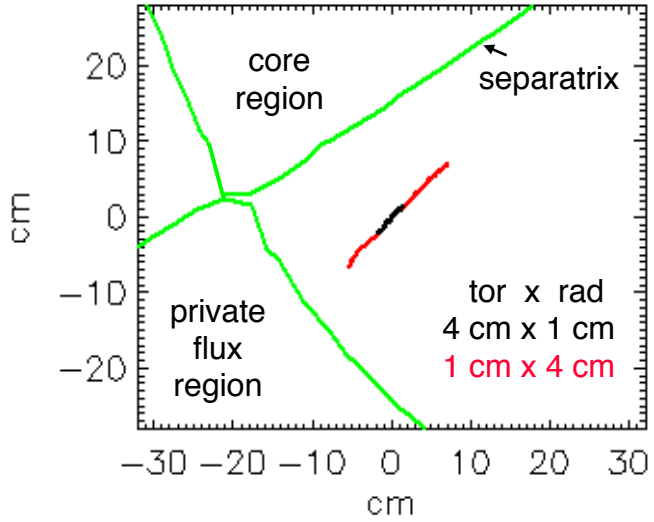
Upstream Effects of Biasing ?

- Magnetic flux tubes connected to electrodes in NSTX are very flattened as they approach X-region (≤ 3 mm at ~2 m upstream along B), due to large edge magnetic shear

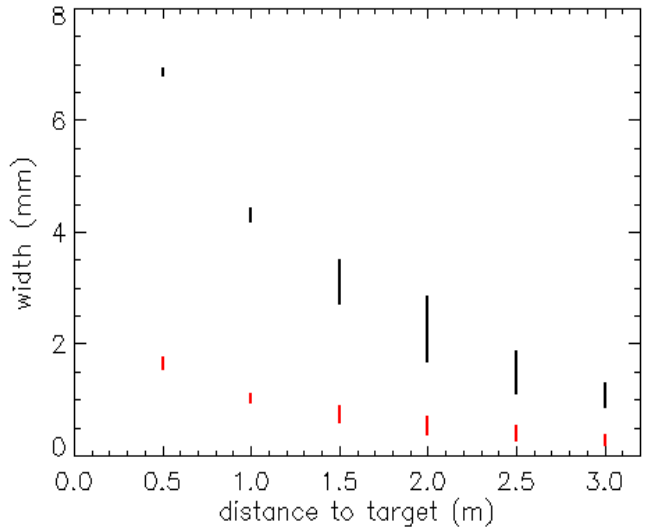
- This may have prevented effects of biasing upstream, which could be beneficial for use with future tokamak divertors



"+" at 1 meter intervals



electrode flux tube shapes



flux tube widths along B

Possible Experiments for NSTX

- Larger electrode to generate larger local effects on SOL, e.g. 10 cm x 10 cm tile with ~ 25 x 40 Amps ~ 1 kA

- 2-D array of such large tiles with externally programmable voltage controllers to rapidly optimize SOL heat flux

Desirable diagnostics:

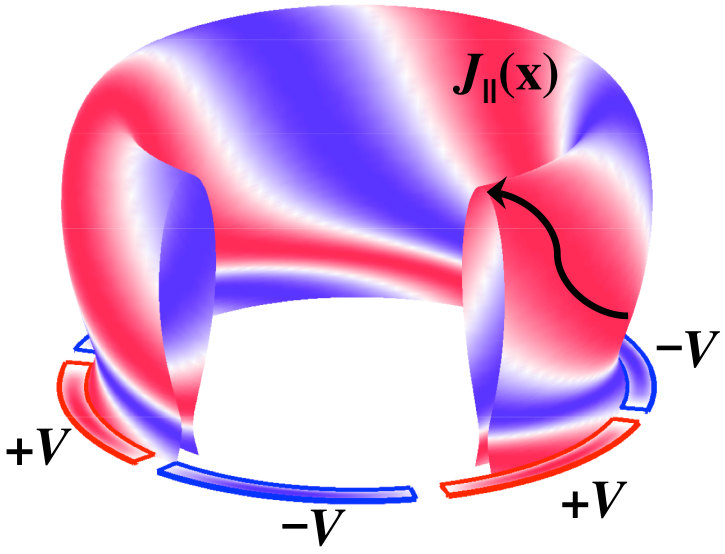
- IRTV for evaluation of local surface heat flux vs. biasing
- movable divertor probe to measure density and potential changes within flux tube connected to electrodes

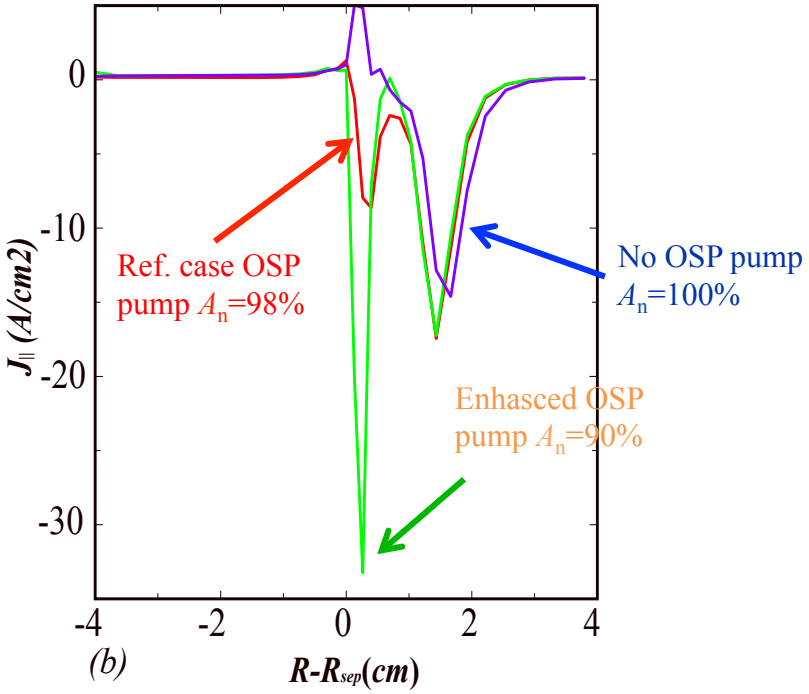
Potential design issues:

- Disruption forces need to be handled, e.g. in cables
- Power required for biasing needs to be minimized

Modeling for Future Experiments

- When optimized for achieving large amplitude, non-axisymmetric SOL perturbations are predicted to generate resonant magnetic perturbations & affect ELMs,* in addition to enhancing transport
- Modeling for ITER* shows that differential OSP pumping & puffing can drive substantial variations in SOL current profile





*I. Joseph et al, POP **19** 056124 (2012)

- These effects need to be evaluated in future experimentss

Conclusions

- Clear effects of positive biasing were seen within a few centimeters of the divertor plate electrodes in NSTX, especially when they were near the outer strike point
- Changes in the local probes and Li I light emission may be qualitatively consistent with expected convective cells
- Quantitative modeling was not possible due to complexity of physics and relatively limited diagnostic information
- Further experiments can be done on NSTX-Upgrade to better demonstrate SOL control and clarify physics