Experiments to Modify the Scrape-off Layer in NSTX

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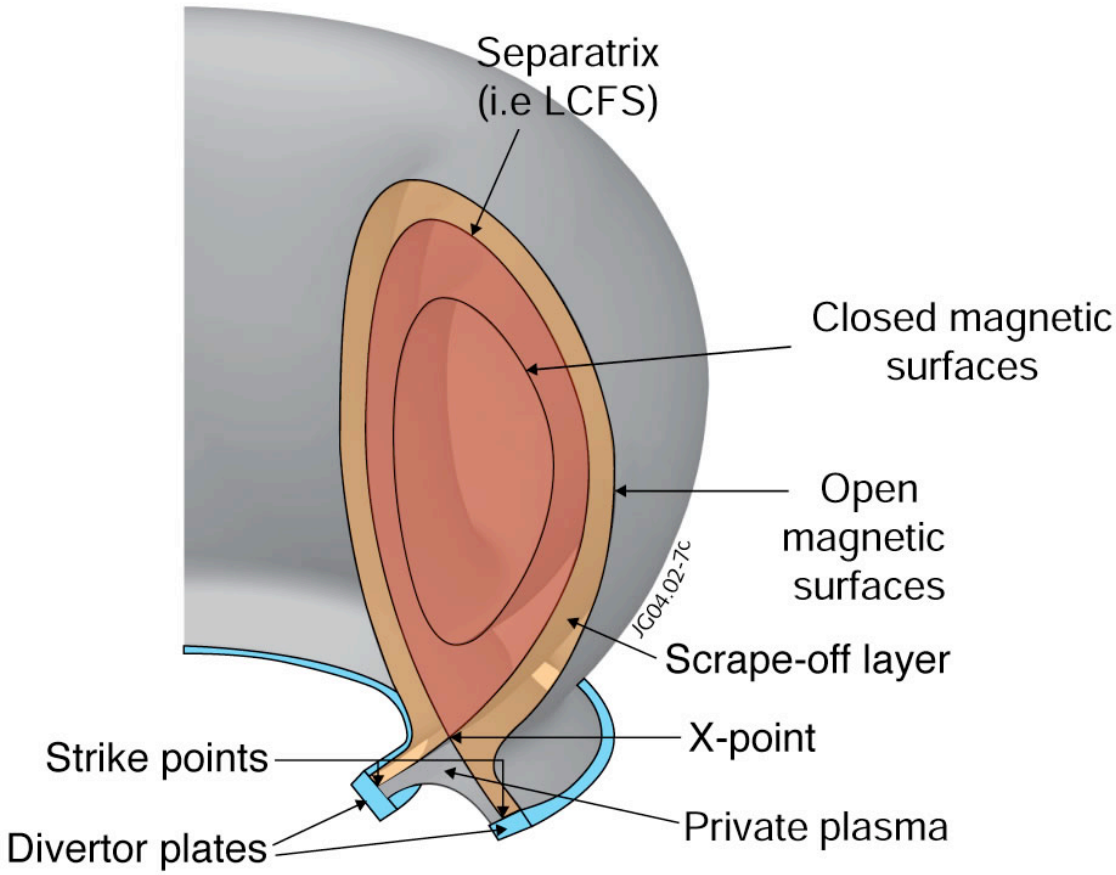
- Tokamak divertors and the divertor heat flux problem
- NSTX SOL biasing results and interpretations
- Plans for NSTX and future applications

Columbia University Dec. 5, 2008

Tokamak Divertor Design



- Shields impurities from main plasma
- Easier H-mode access (reasons unknown)
- May make helium ash pumping easier
- Allows divertor plates to be removed

http://www.jet.efda.org/pages/focus/plasma-edge/index.html

Divertor Plate Heat Flux for DEMO

- A 1000 MWE tokamak reactor will have $P_\alpha \sim 500$ MW of alpha heating power going to the vacuum vessel wall

- A significant fraction of this (~ 250 MW) is likely to flow in the "scrape-off layer" (SOL) just outside the separatrix to the divertor plates at the bottom of the vessel

- The area of the SOL strike zone at this plate $A \sim 2\pi R\, \Delta_{plate}$, where Δ_{plate} is the radial heat flux width at the plate

=> Δ_{plate} will determine time-average divertor heat flux (transient heat flux could be much higher)

Estimate of Heat Flux for DEMO

- Assume $\chi_{sol} \sim a^2/\tau_E \sim 1\ m^2/sec$ (from ~ global confinement)
- Assume $\tau_{||} \sim L_{||}/C_s \sim \pi qR/C_s \sim 3 \times 10^{-5}$ sec (T_e~1 keV, R~6 m)

  => Δ_{SOL} (near outer midplane) ~ 0.5 cm

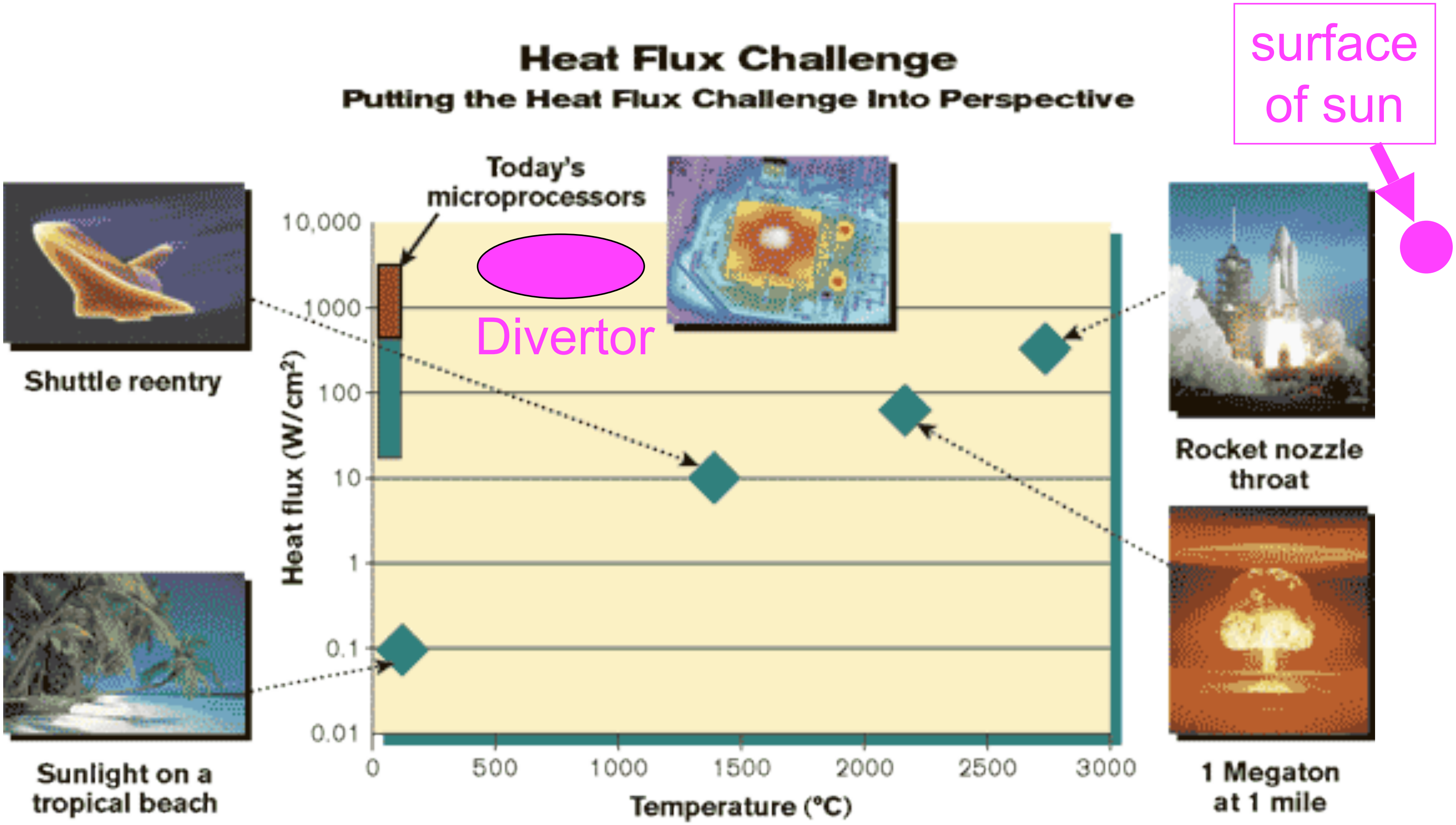
- Assume field line has grazing angle divertor plate of ~ 1-2º

  => Δ_{plate} (at divertor plate) ~ 20 cm

=> P_{plate} ~ 250 MW / [2π 6 m * 0.2 m] ~ **30 MW/m²**

(local 'high' spots could be much larger)

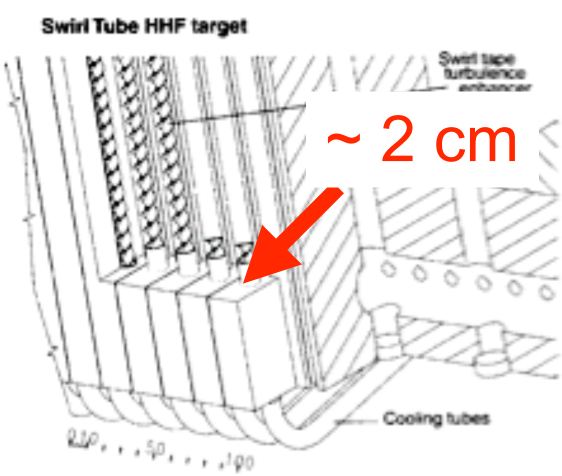
Heat Flux Comparisons



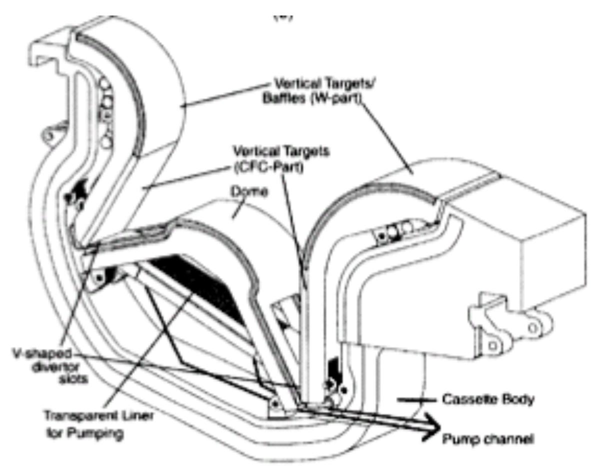
Andrew Delano and Devesh Mathur, Honeywell Electronic Materials, Semiconductor International, 10/1/2007 http://www.semiconductor.net/article/CA6482821.html

Divertor Plate Lifetime Issues

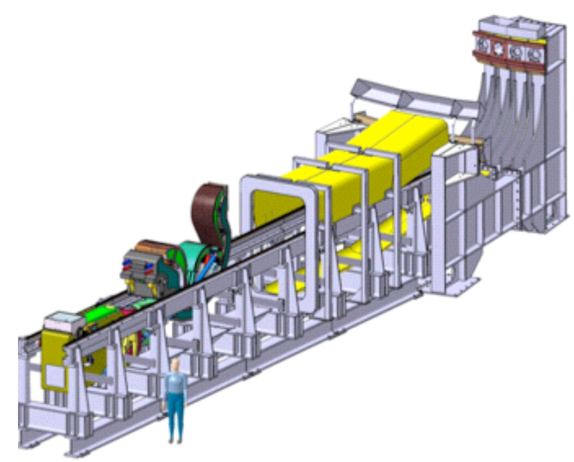
- Divertor plates cooling lines only ~ 2 cm below surface
- Expect tile surfaces to have erosion lifetime ~ 1 year (?)
- Catastrophic LOCA possible within ~ 1 sec of disruption



divertor plate



divertor cassette



divertor transporter

Possible Solutions

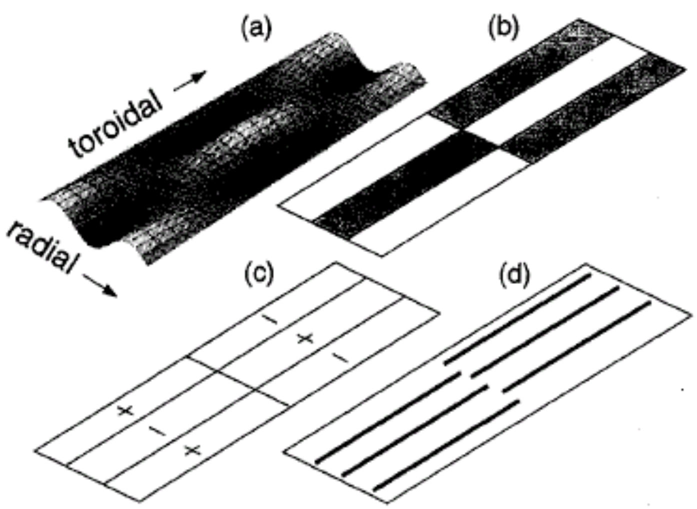
- Raise neutral density in SOL to make ‘detached’ divertor
- Add low-Z impurities to SOL to make ‘radiative’ divertor
- Expand magnetic footprint of divertor (e.g. Super-X)
- Ergodic magnetic limiter or divertor (e.g. Textor)

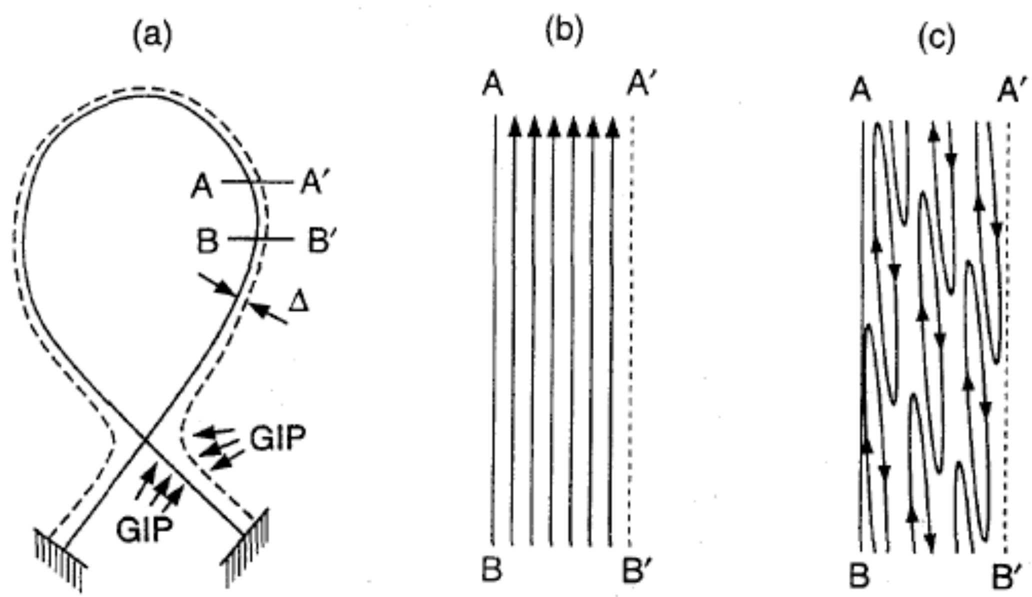
The first two are unlikely to work for a DEMO

The second two are difficult and expensive

Theory of Asymmetric Divertor Bias

- Asymmetric potential perturbations near divertor plate should create local *convective cells* which should modify SOL
  [R.H. Cohen NF (1997), Ryutov PPCF (2001), Cohen PPCF (2007)]
- Can make perturbations using ‘wavy’ plates, varying surfaces, gas puffing, or ICRF in SOL [Myra, D’Ippolito PoP (1993, 1996)]

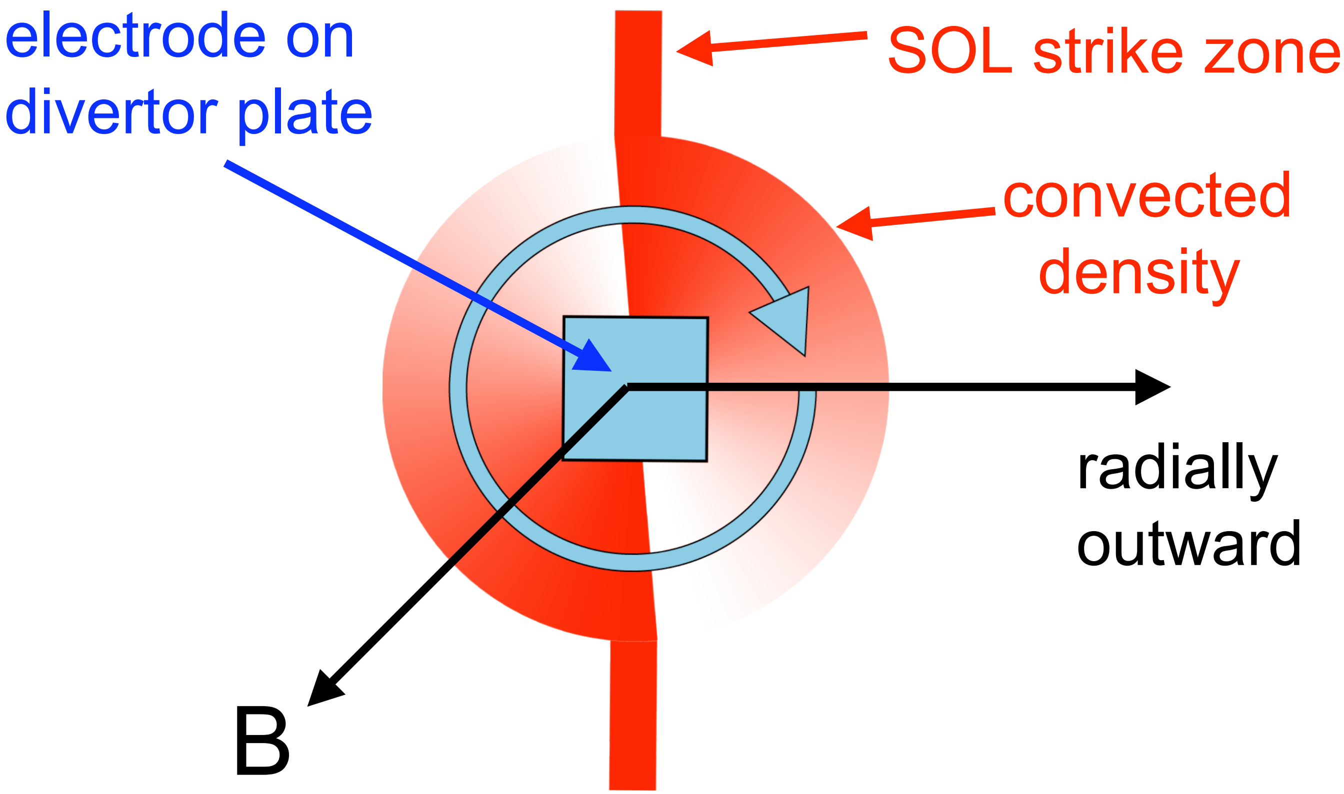




R.H. Cohen NF (1997)

Picture of Convective Cell Generation

- Goal is to broaden heat / particle SOL width at divertor plate by creating local convective cells



ExB Convection in the SOL

- Create DC *poloidal* electric field to make radial ExB flow
- To significantly modify SOL, radial ExB movement $\geq \Delta_{SOL}$

$$\Delta_{ExB} \sim v_{ExB}\, \tau_{II} > 1 \text{ cm}$$

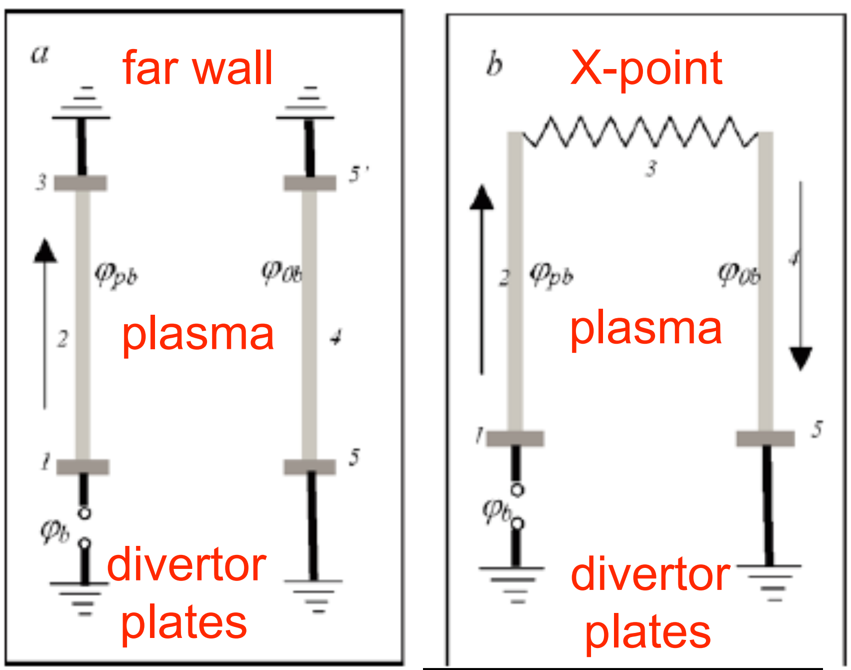
where $v_{ExB} = 10^8\, E_{pol}(\text{V/cm})/B_{tor}(\text{Gauss})$

- Assuming $\tau_{II} \sim L_{II}/C_s \sim 3\text{x}10^{-5}$ sec and B = 5 T

=> $E_{pol} \sim 10$ Volts/cm (*seems easy)*

Simplified Models of Plasma Potential

- Plasma potential φ_p modeled using $\sigma_{||}$ and divertor sheath
- Bias currents close either at far wall, or $\sigma_{\perp}$ near X-point



Results for φ_p "upstream":

$\varphi_p(+) / \varphi_p(-) \;\; >> 1$ (far wall)

$\varphi_p(+) / \varphi_p(-) \;\; \sim \;\; 1$ (X-point)

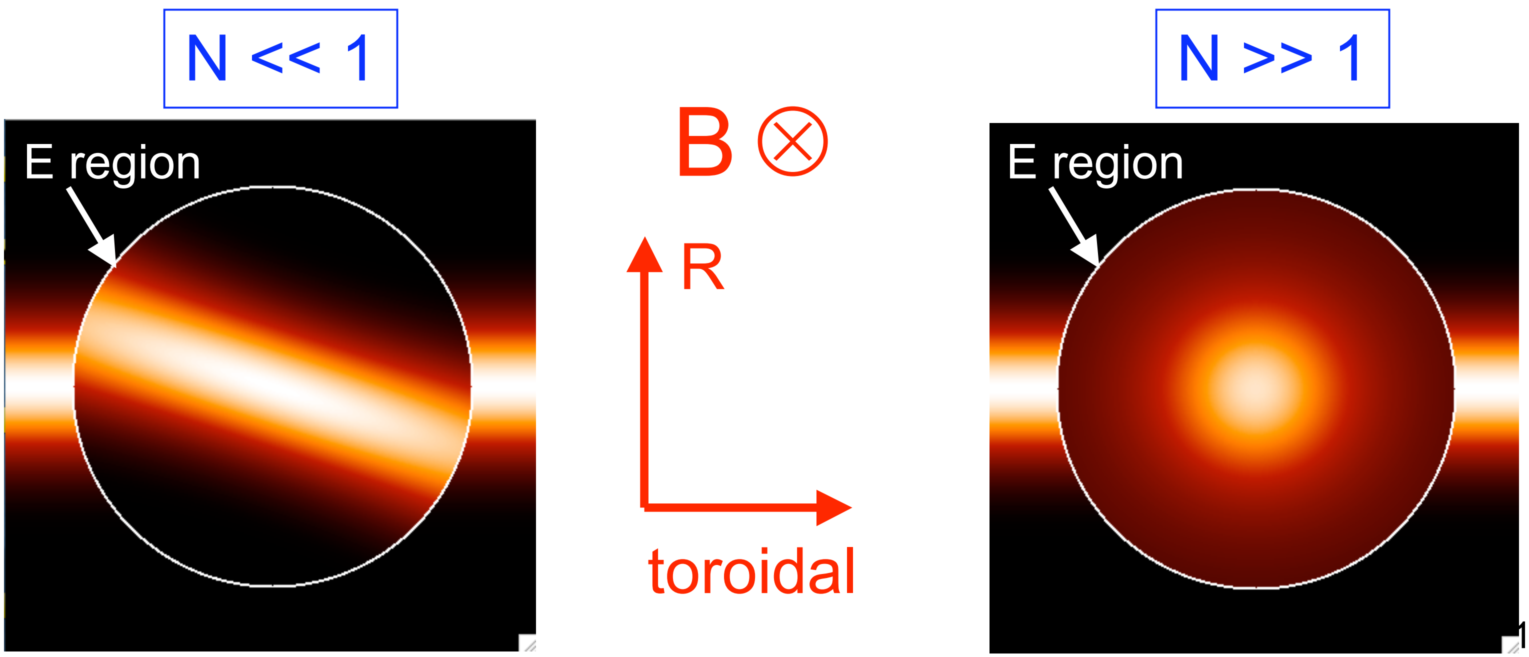
Effect of $\sigma_{\perp}$ on φ_p:

$\varphi_p(+) \sim \; \varphi_{bias} - T_e/e$ (low $\sigma_{\perp}$)

$\varphi_p(+) \Rightarrow T_e/e$ (high $\sigma_{\perp}$)

Convective Cell Rotation

- Number of rotations around B: $N \sim \tau_{||} v_{ExB} / 2\pi d_{\perp} \sim E_{\perp}(L_{||}/d_{\perp})$
- Looking along B into electrode on divertor plate, strike zone can broaden if N >> 1 and there is dispersion in rotation



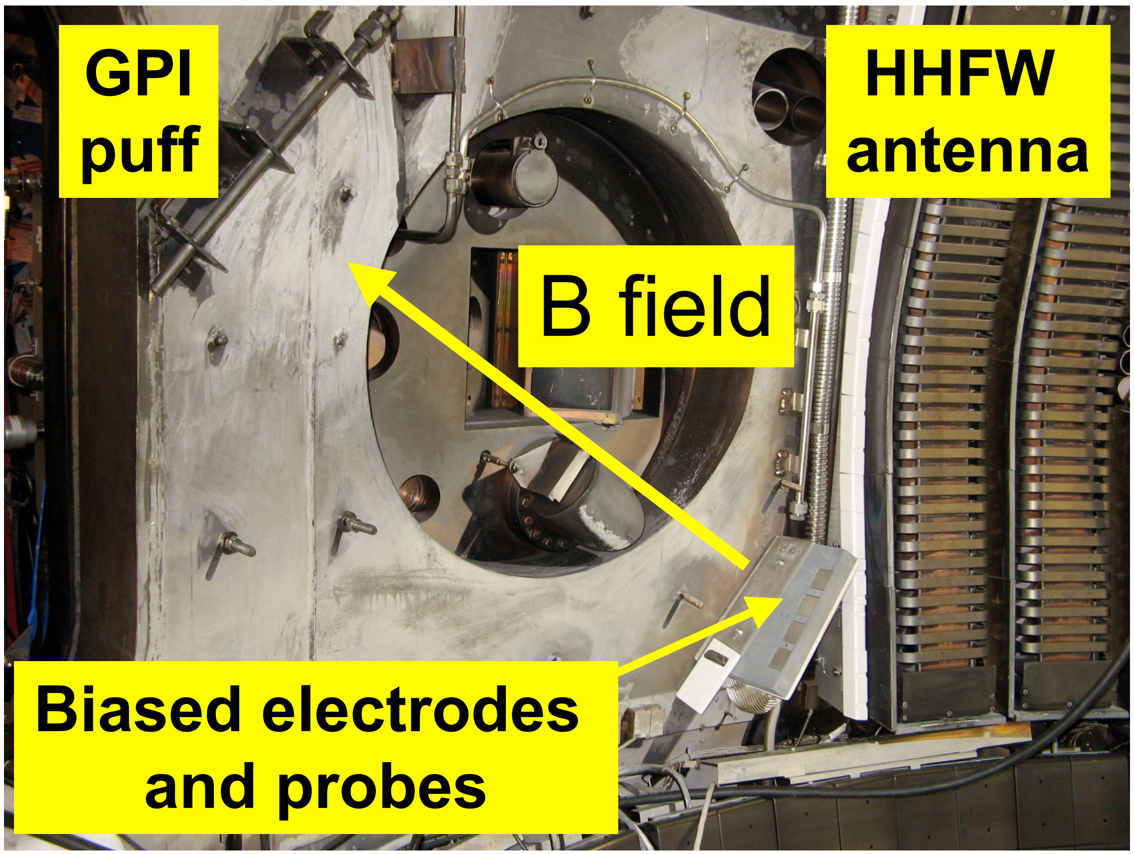
Open Physics Issues

- Effect of any ‘anomalous’ $\sigma_\perp$ (including neutral collisions) on the parallel penetration of poloidal electric field (high $\sigma_\perp$ could ‘short out’ any poloidal electric field)
- Extent of cross-field penetration of potential (would affect radial extent of SOL displacement or broadening)
- Effect of biasing on SOL turbulence (either generating it via Kelvin-Helmholtz instability, or ‘suppressing’ it)

=> *Predictions for change in SOL heat flux very uncertain*

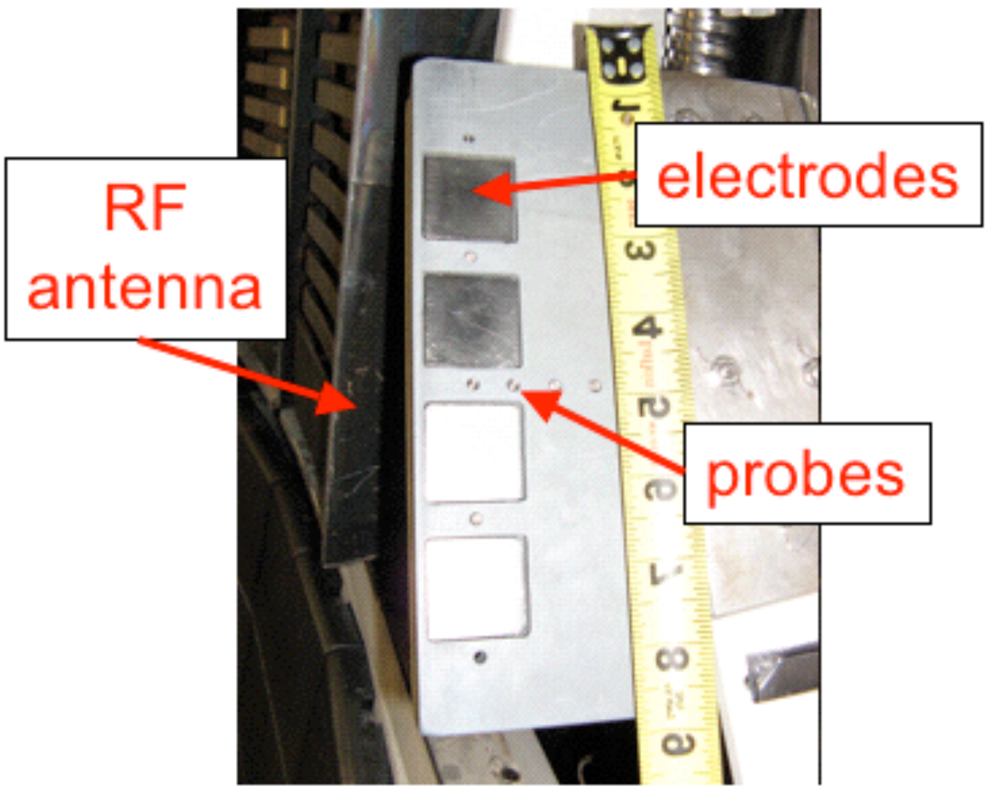
NSTX SOL Biasing Experiment

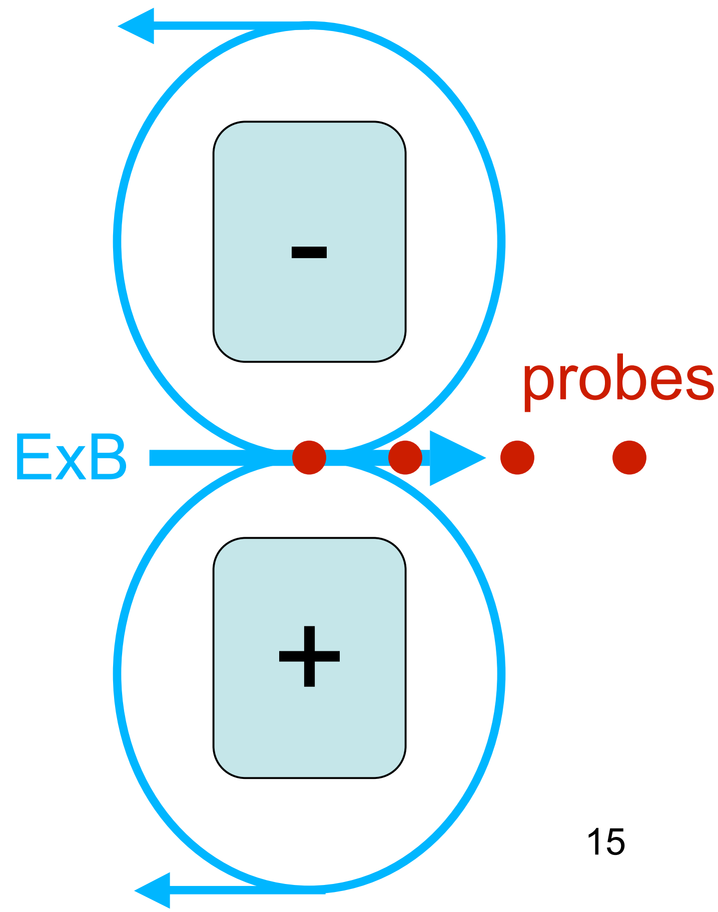
- Initial experiment located just below outer midplane
- Planning divertor electrode experiment for 2009 run



Biased Electrodes and Probes

- Electrodes biased ≤ ±100 V *with respect to vessel ground*
- Nearby Langmuir probes biased DC or swept ± 50 volts





Previous Experiments

- Some experiments have created a local E_{pol} in the SOL

  JFT-2M [Hara et al, J. Nucl. Mat. 241-243, 338 (1997)]
  C-Mod [Winslow and LaBombard, JNM '99, CPP (2001)]
  MAST [Counsell et al, J. Nucl. Mat. 313-316, 804 (2003)]
  CASTOR [Stockel et al, PPCF 47, 635 (2005)]

- MAST experiment was done to test ideas of Cohen/Ryutov, resulting in partial confirmation of theory, e.g. movement and broadening of D_α at biased divertor "ribs", but with large SOL heat input due to biasing itself (~ 250 kW)

- Other experiments have seen potential propagate along B

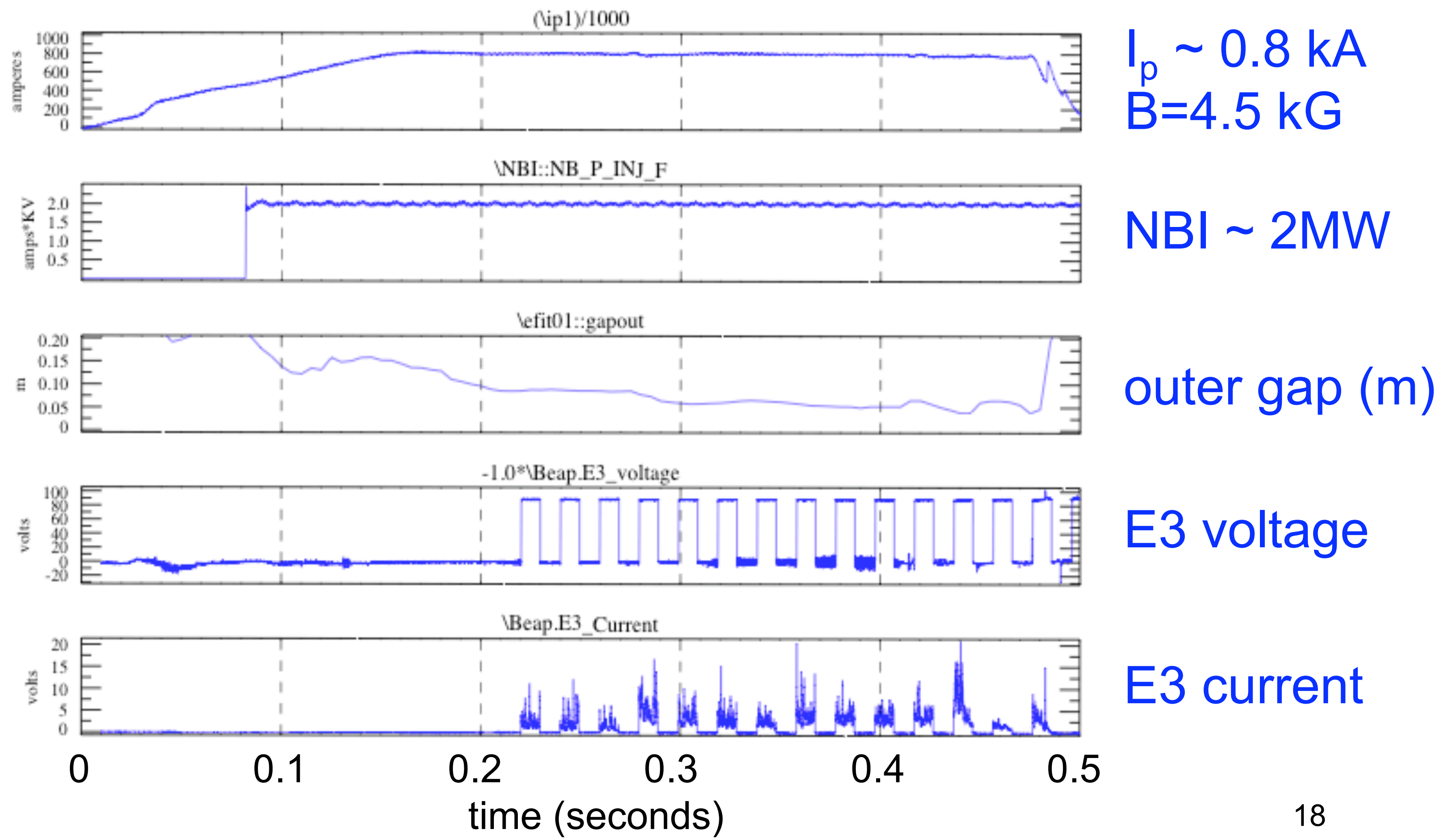
  DITE [Pitts and Stangeby, Plasma Phys. Cont. Fusion 32, 1237 (1990)]
  TEXT [Winslow et al, Phys. Plasmas 5, 752 (1998)]
  W7-AS [Thomsen et al, Plasma Phys. Cont. Fusion 47, 1401 (2005)]

Goals of this Experiment

- Measure the effect of electrode biasing on local density and potential using the local Langmuir probes
- Measure the effect of electrode bias on D_α light emission ~ 1 m along B using the gas puff imaging diagnostic
- Understand the physics behind these results in order to help design divertor plate electrodes (e.g. for NSTX)

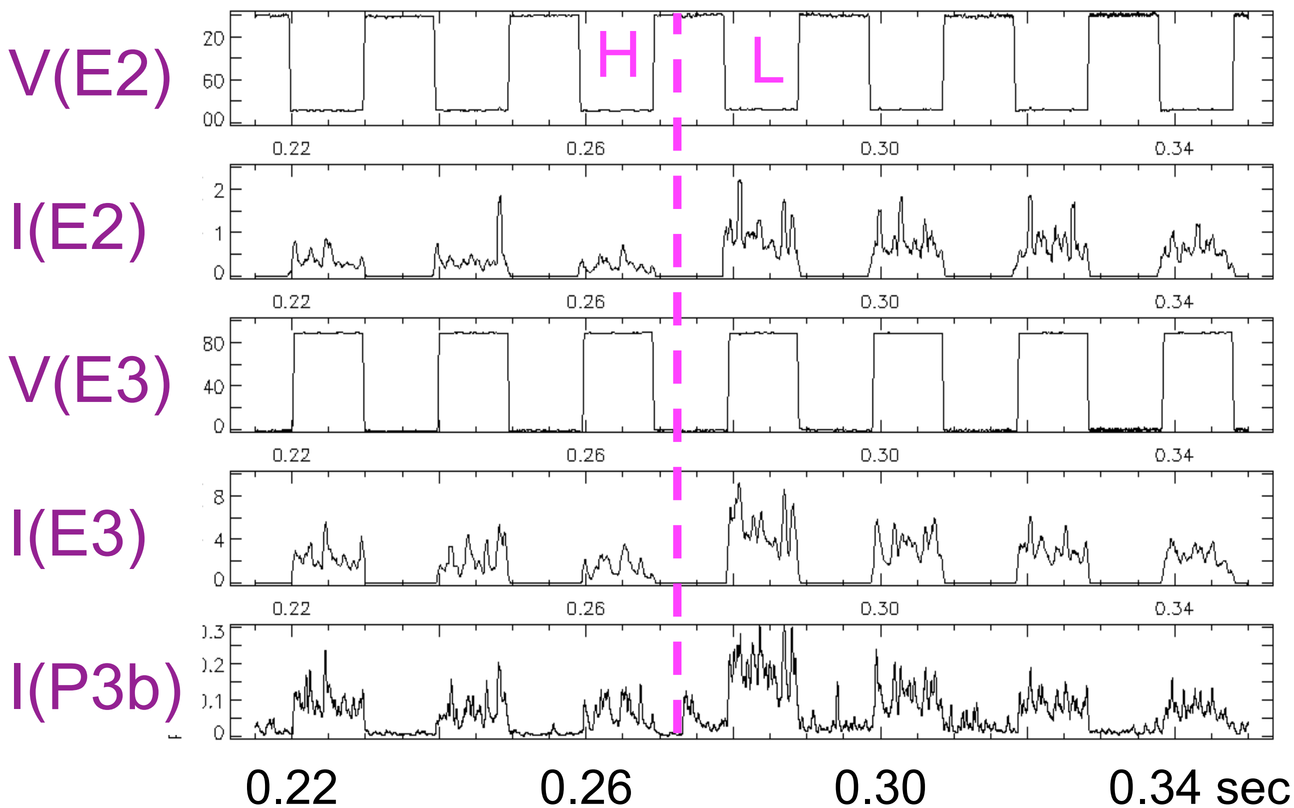
=> Did *not* expect any global plasma changes (and none were observed)

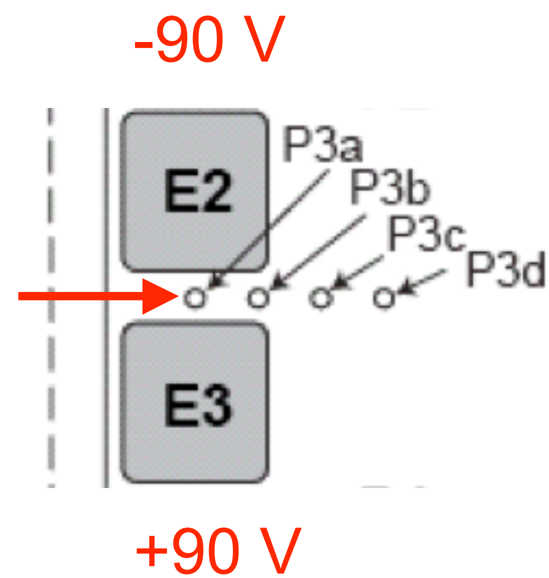
Typical NSTX Shot with Biasing



Electrode and Probe (I,V) Signals

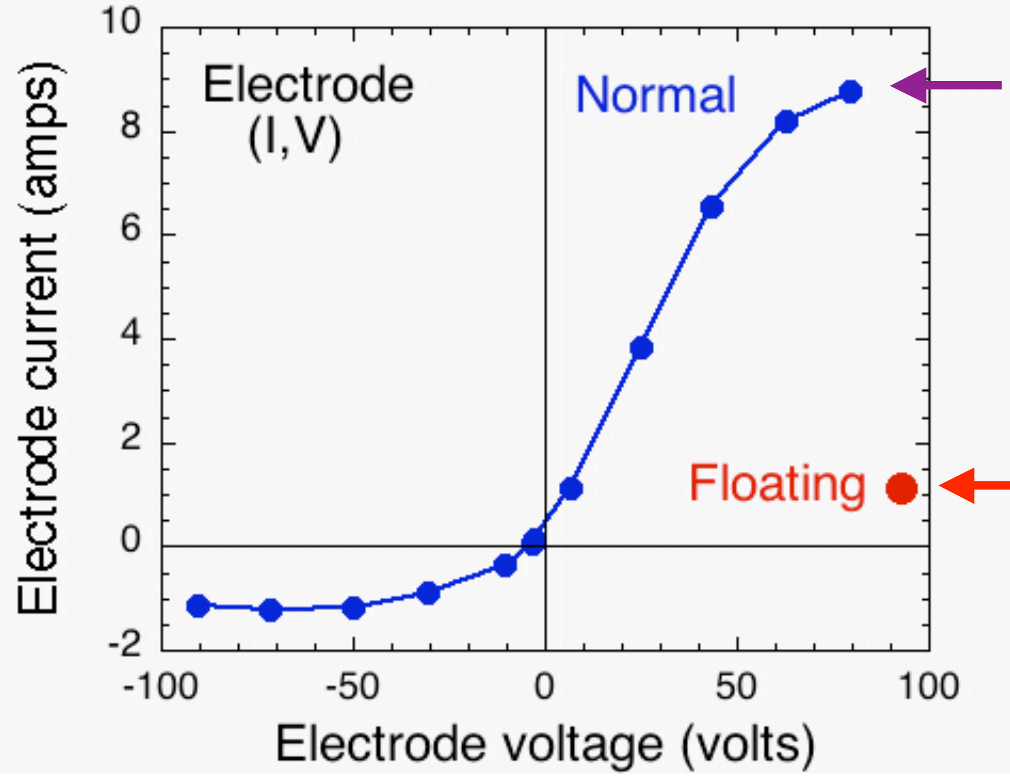
- Here E2 @ - 90 volts, E3 at + 90 volts, P3b @ +45 volts
- Large increase in probe current ~ density at each bias





Electrode (I,V) Characteristics

- Positive bias (electron) current >> negative bias (ion) current
- Implies significant ‘anomalous’ $\sigma_{\perp}$ (~ like a Langmuir probe)



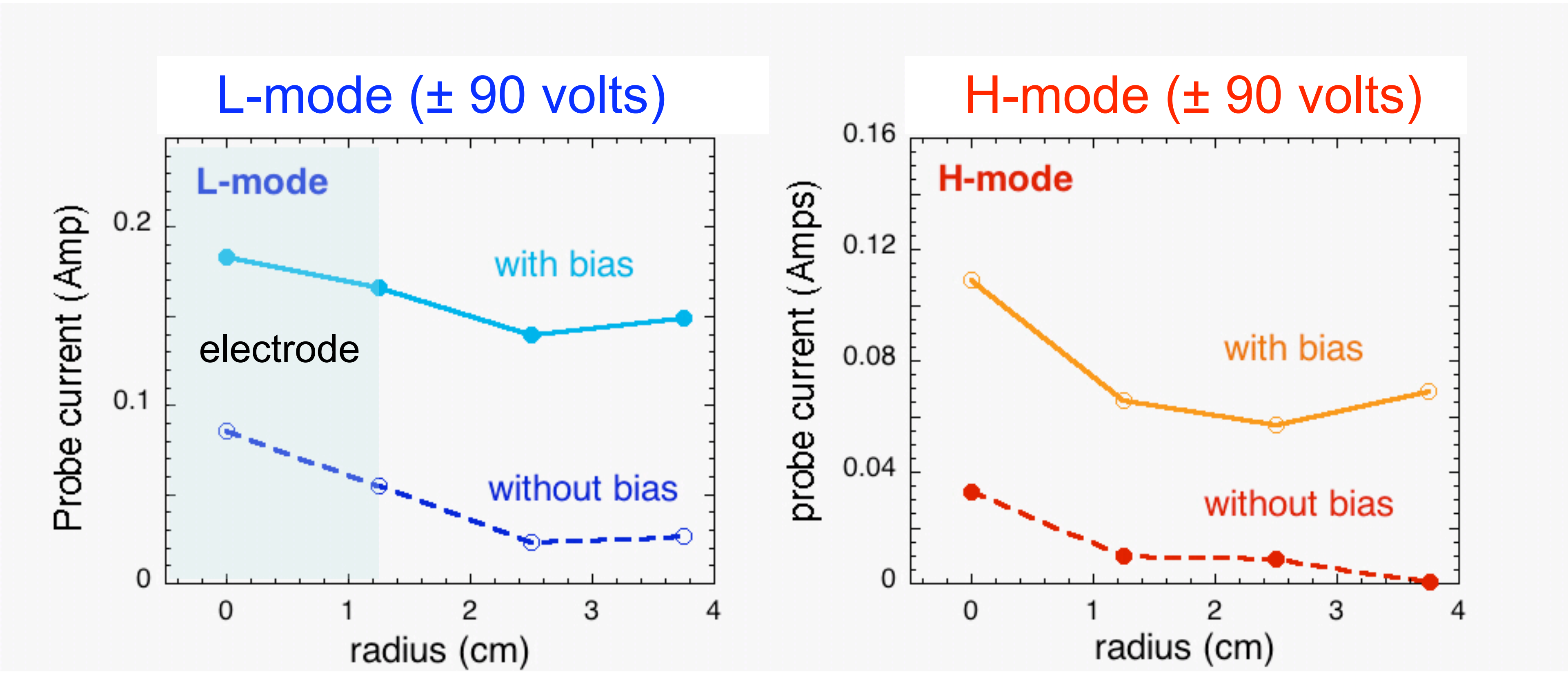
Power = IV ~ 1 MW/m^2

would be a problem for divertor heat reduction !

For “floating” electrodes current lower but effects on SOL also much less

Density Profile Effects

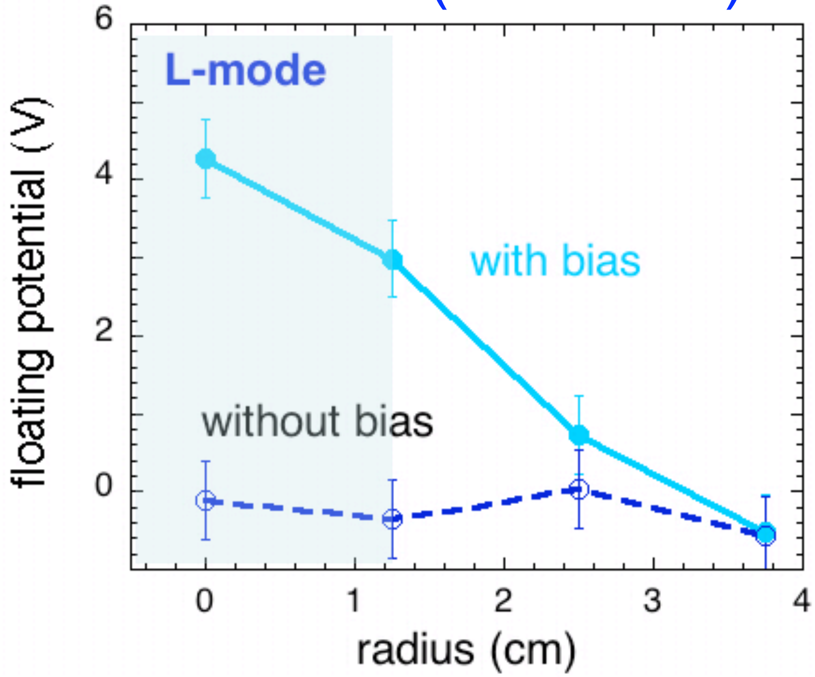
- Radial profiles of I_e ($\propto n_e$) averaged over ~ 10-30 cycles
- Typically n ~ 10^{11} cm^{-3} and T_e ~ 5-10 eV (probe at r=0 cm)



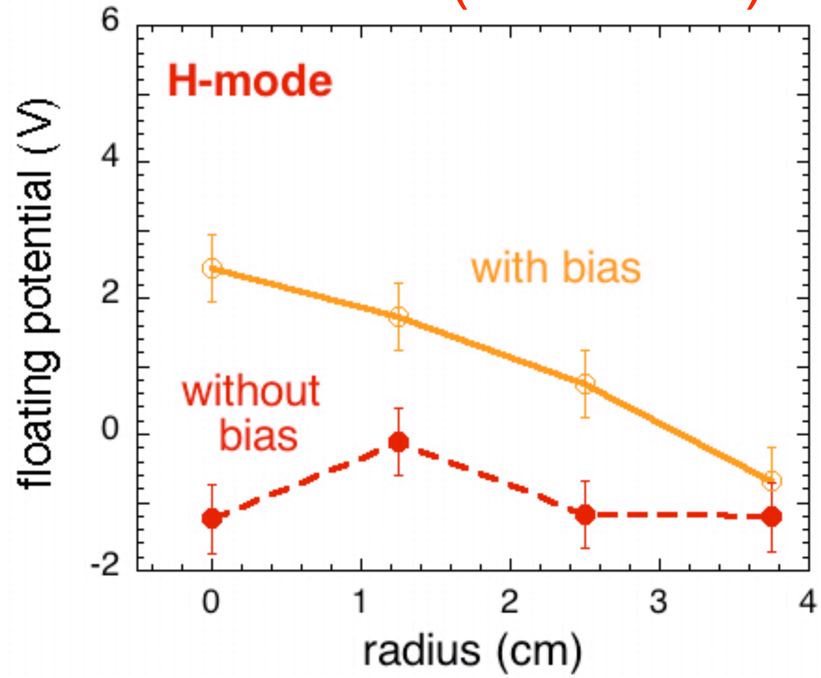
Potential Profile Effects

- Floating potential increases by ≤ 5-20% biasing voltage
- Increase in φ_f falls off ~ 2 cm away from electrodes

L-mode (± 90 volts)

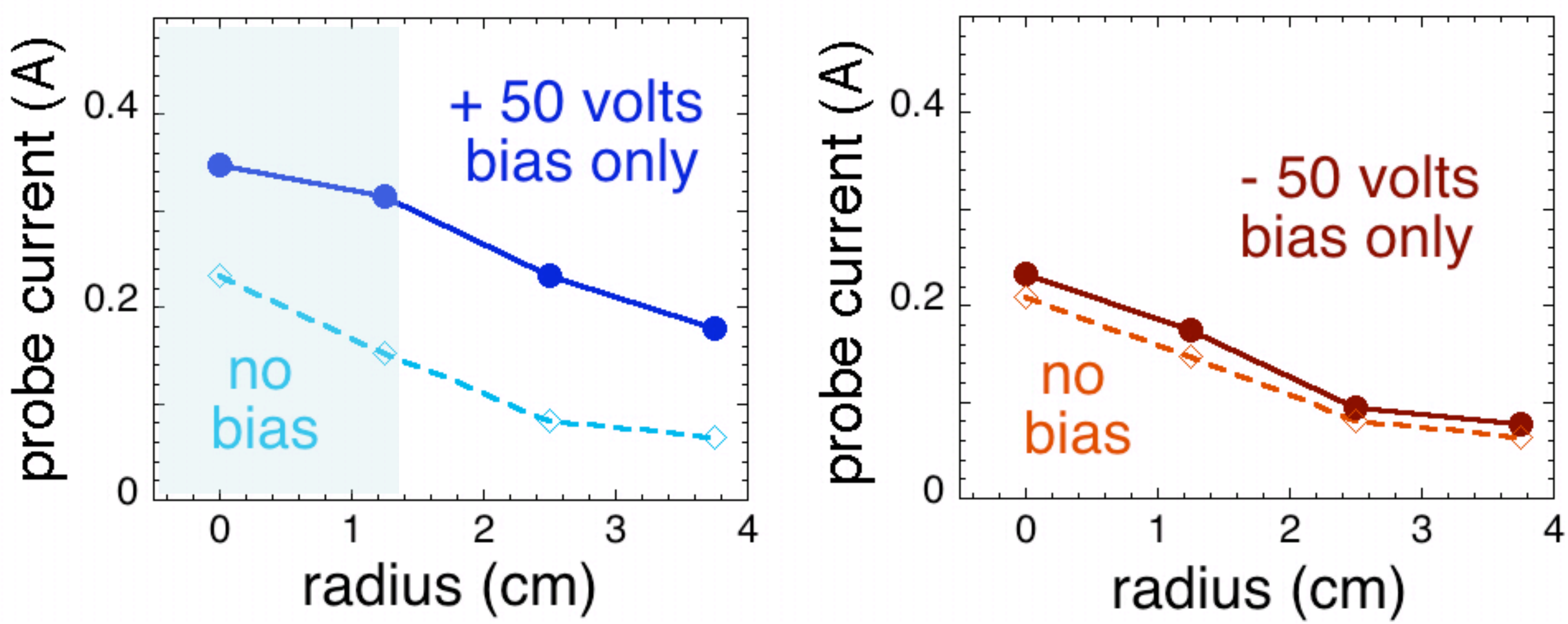


H-mode (± 90 volts)



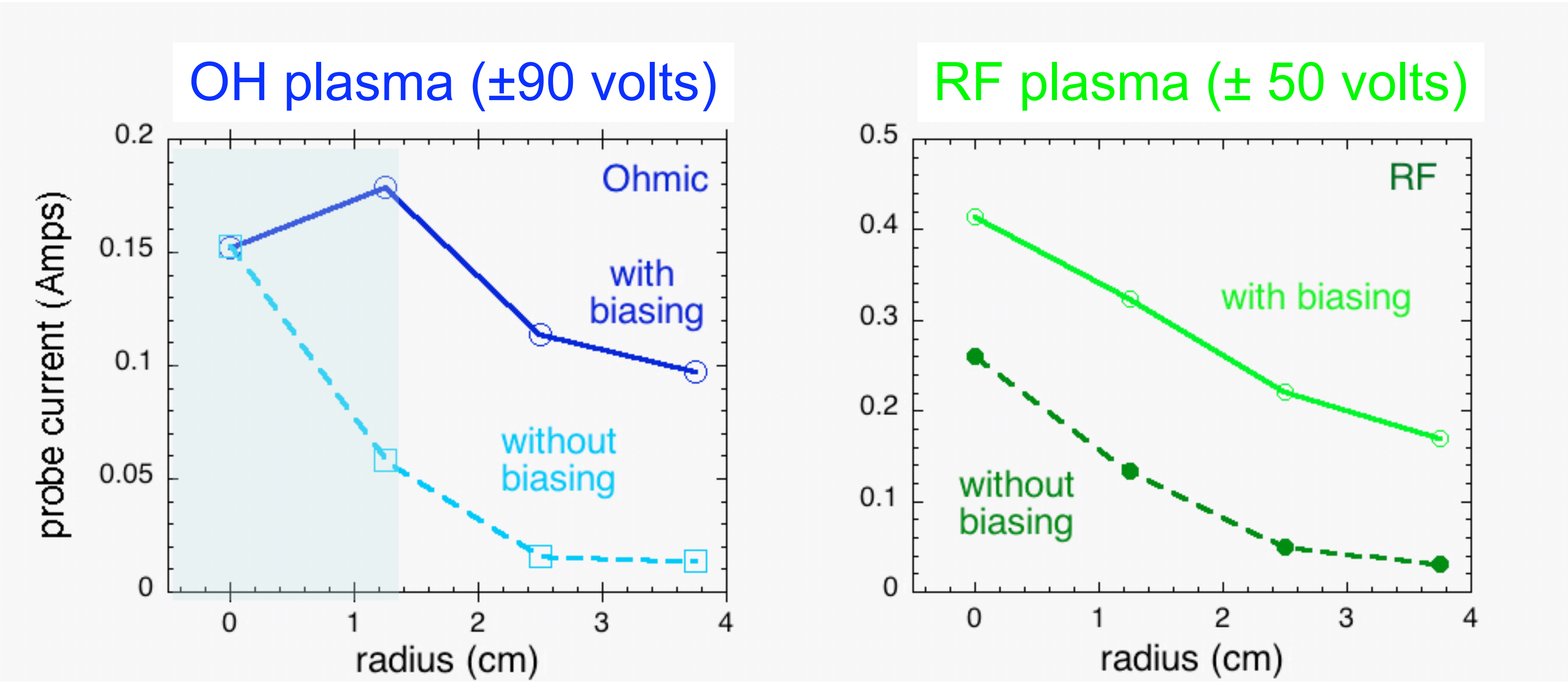
Single Electrode Response

- Density responds more to positive than negative electrode, ~ as predicted by Ruytov/Cohen from sheath theory
- But positive biasing requires a large power ~ 0.5 MW/m^2



Ohmic and RF Heated Plasmas

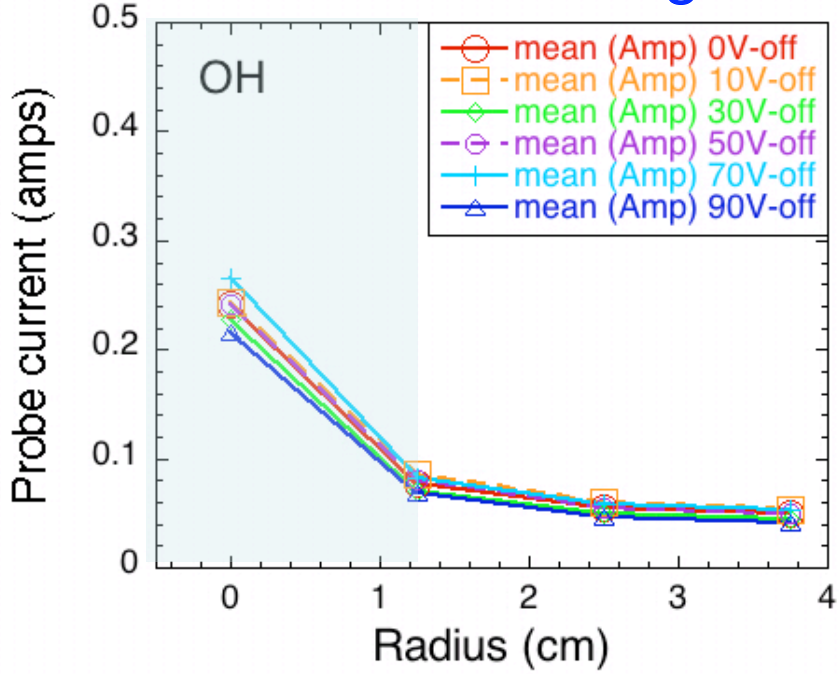
- Similar density profile changes seen in OH and RF plasmas



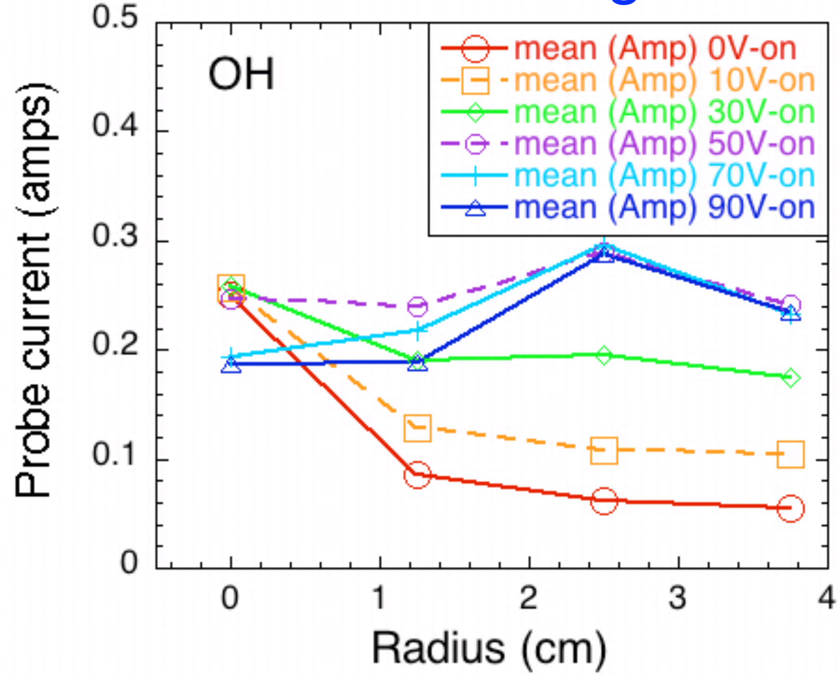
Electrode Bias Voltage Scan

- Effects on density profile vary with biasing voltage
- Need only V ~ 30 volts for most of effect to occur

without biasing

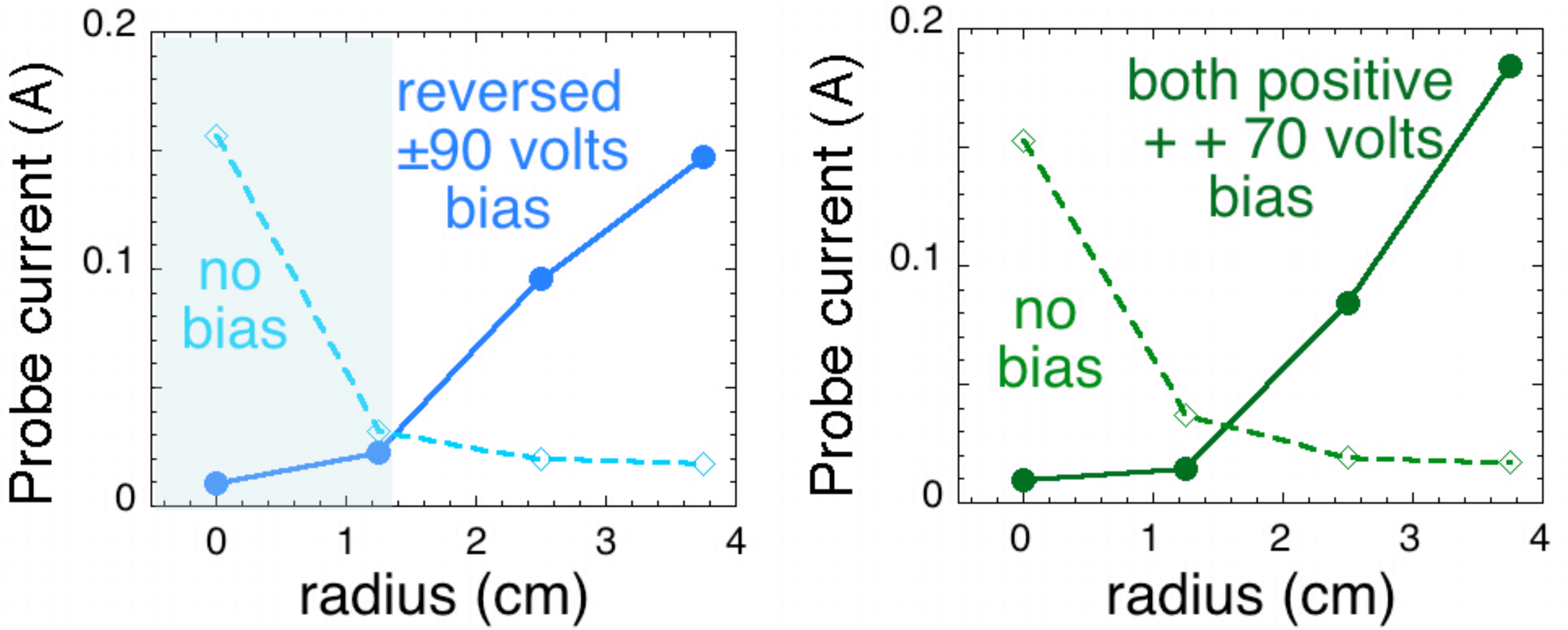


with biasing



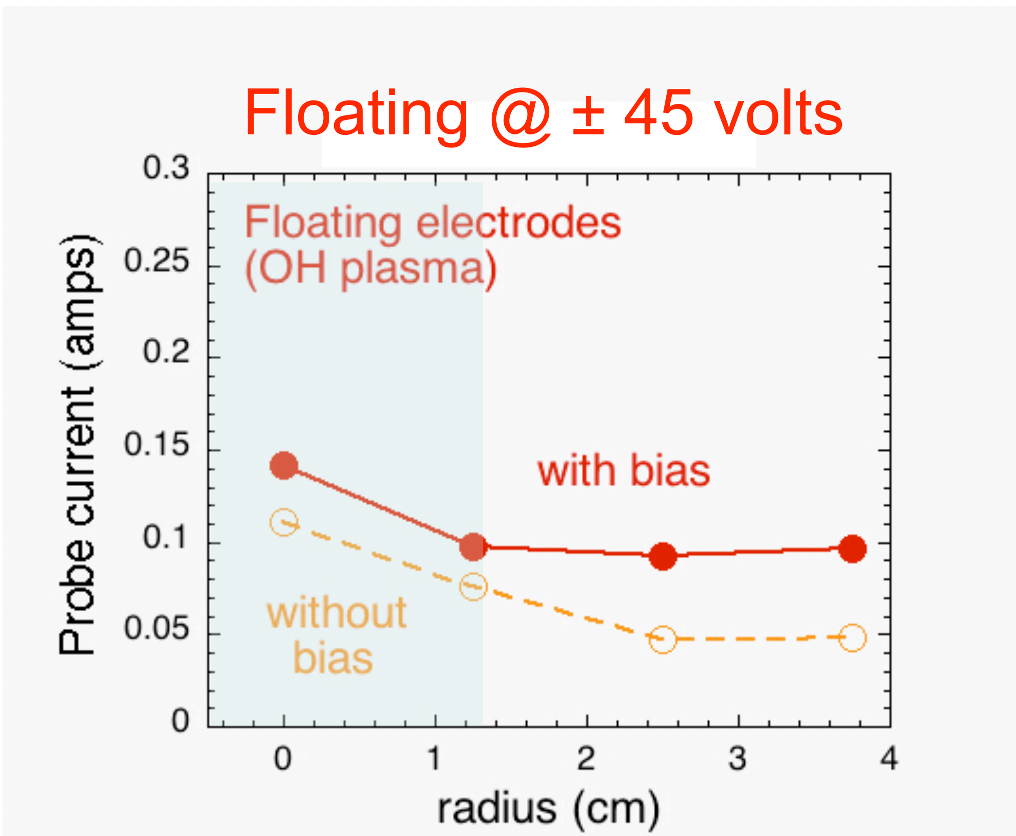
Reversed Polarity Electrodes

- Density profile reversed with opposite E polarity
- Similar effect when both electrodes are positive



Floating Electrode Response

- ‘Floating double probe electrode’ has less effect than electrodes biased with respect to the vessel wall

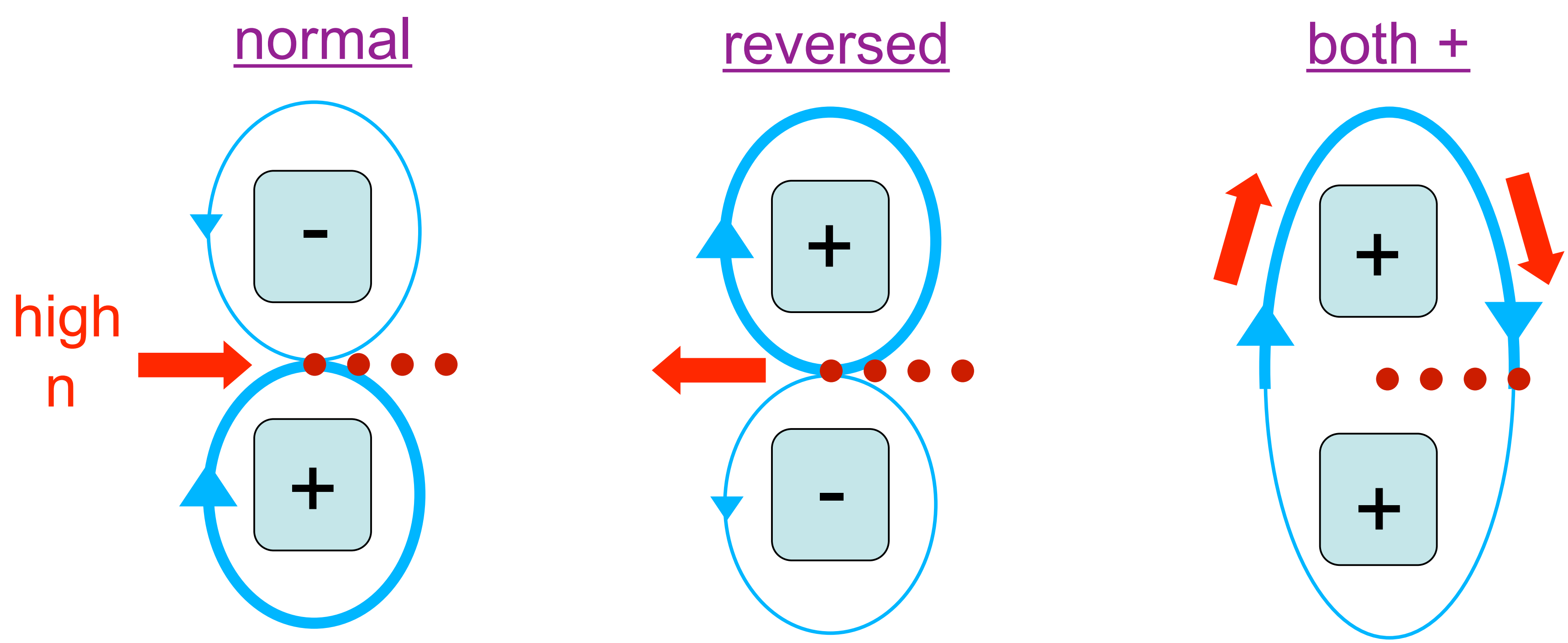


Floating ~ 1 Amp
Positive ~ 9 Amps
Negative ~ 1 Amp

floating electrodes draw ion saturation current, as expected

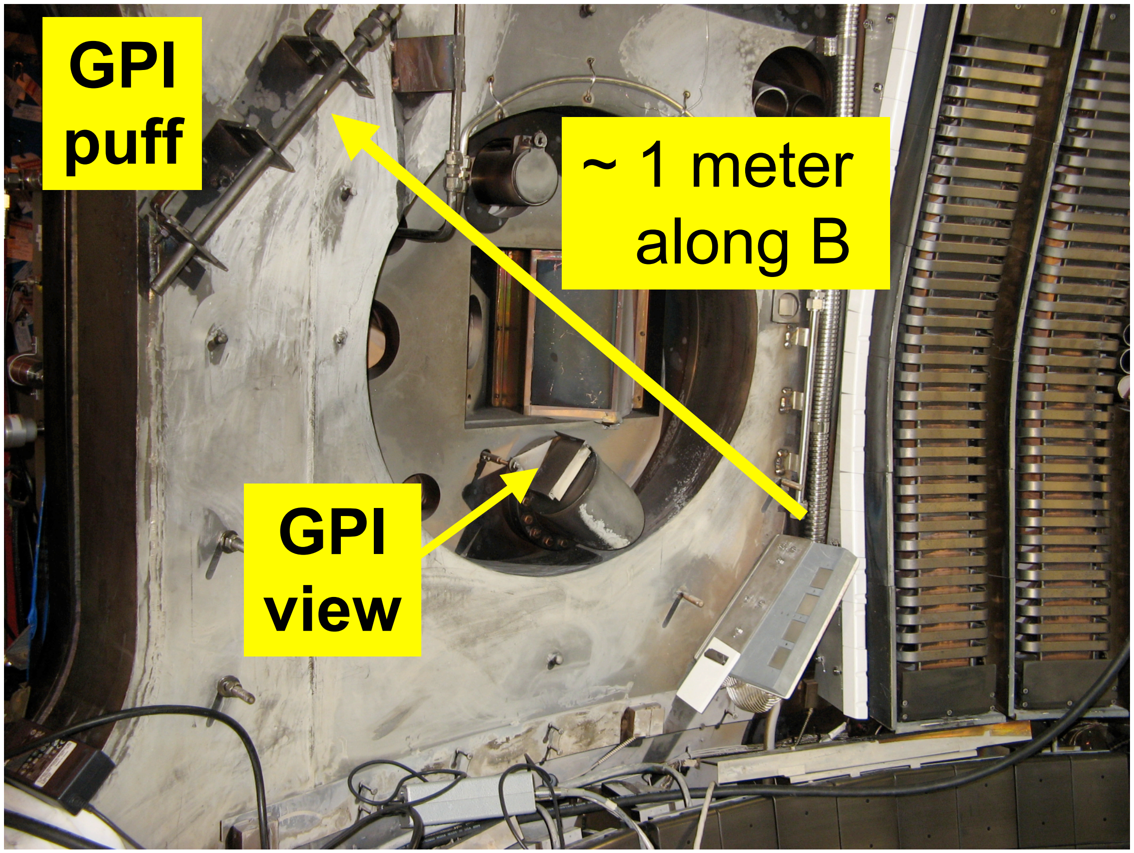
Qualitative Interpretation

- If E_{pol} ~ 50 V/cm => v_{EXB} ~ 2×10^6 cm/sec > 10 x v_{blob} !
- Density changes seem ~ consistent with expected flows

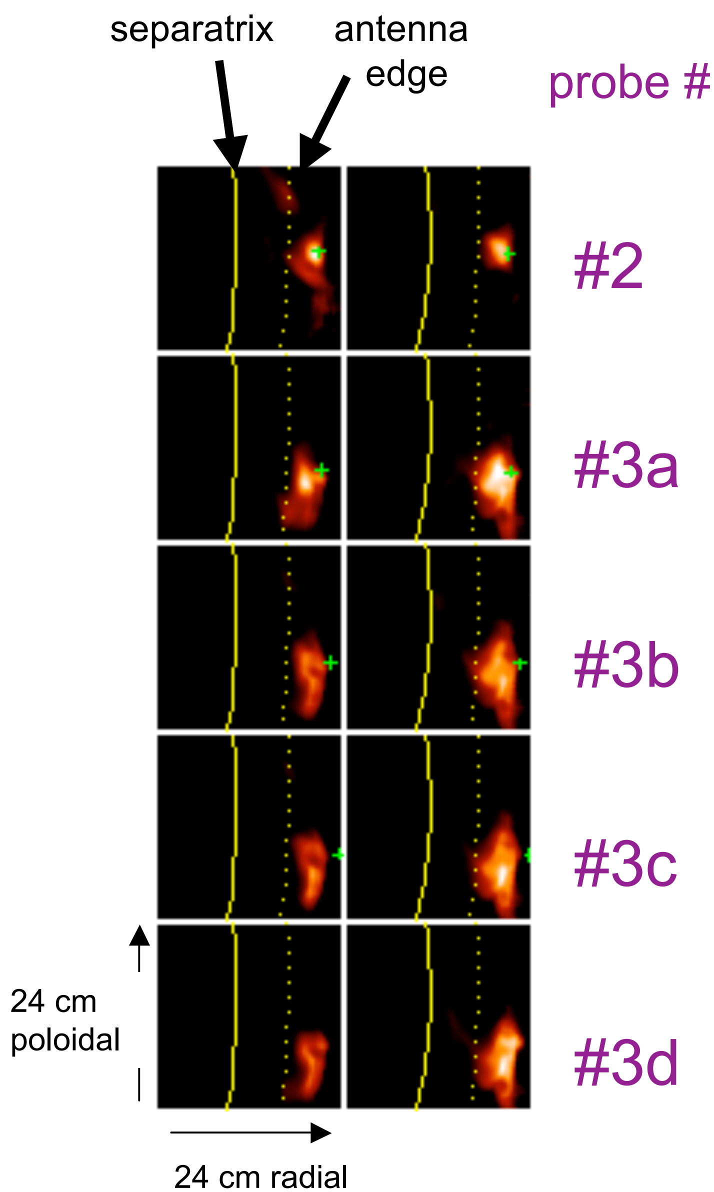


Effects of Biasing ~ 1 m Along B

- Gas puff imaging (GPI) diagnostic measures D_α in SOL



Correlation of Probes with GPI



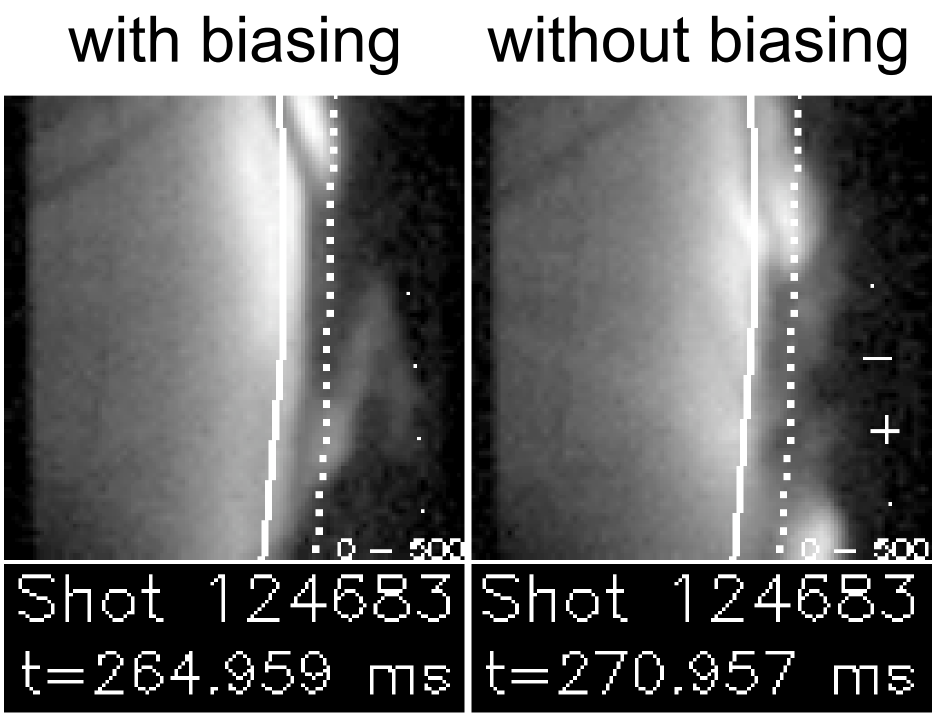
- High correlation of GPI fluctuations with probe fluctuations along B

  colors = correlation (80%=white)
  green = EFIT projection of B

=> can be used to locate electrodes in GPI field of view to look for effects of biasing there

GPI Movies With & Without Biasing

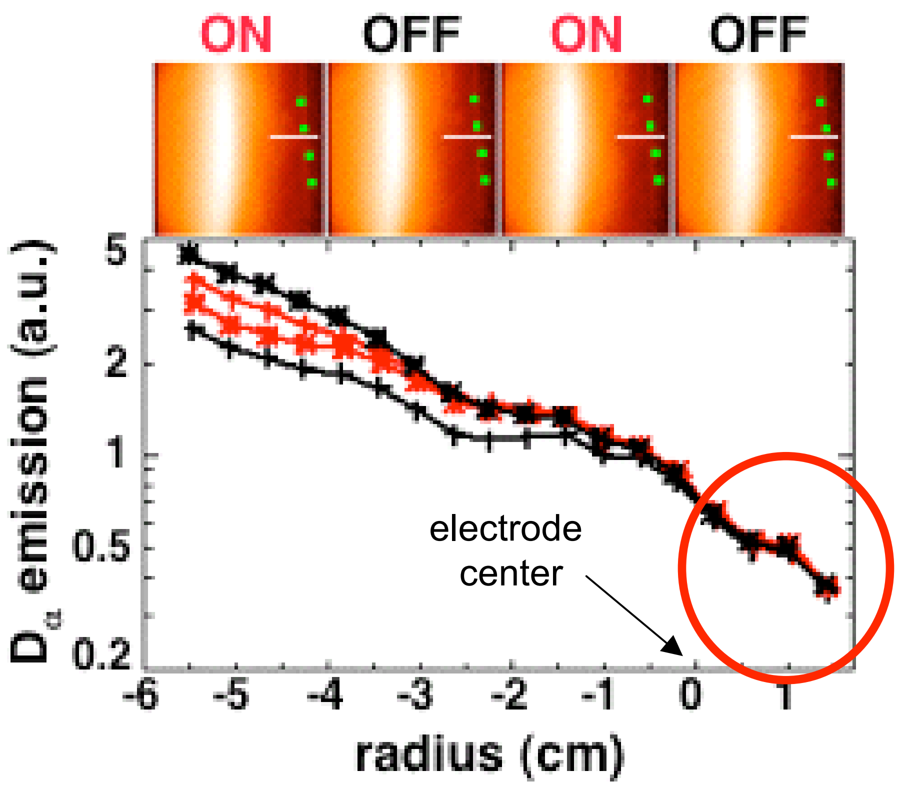
- Only marginally visible effect of bias on GPI turbulence



E2 = -95 volts
E3 = +40 volts

Radial Profile of D_α Emission

- No significant change in D_α profile at GPI during biasing



green dots = electrode centers

white line = range of this plot

red circle = radii of probes

Tentative Interpretation

- Parallel penetration of E_{pol} seems to be ≤ 1 m along B
- Anomalous $\sigma_\perp$ possibly from neutrals or turbulence
- Assuming $L_{||}$ ~ 30 cm, T_e ~ 8 eV, $d_\perp$ ~ 2 cm, $E_\perp$ ~ 50 V/cm

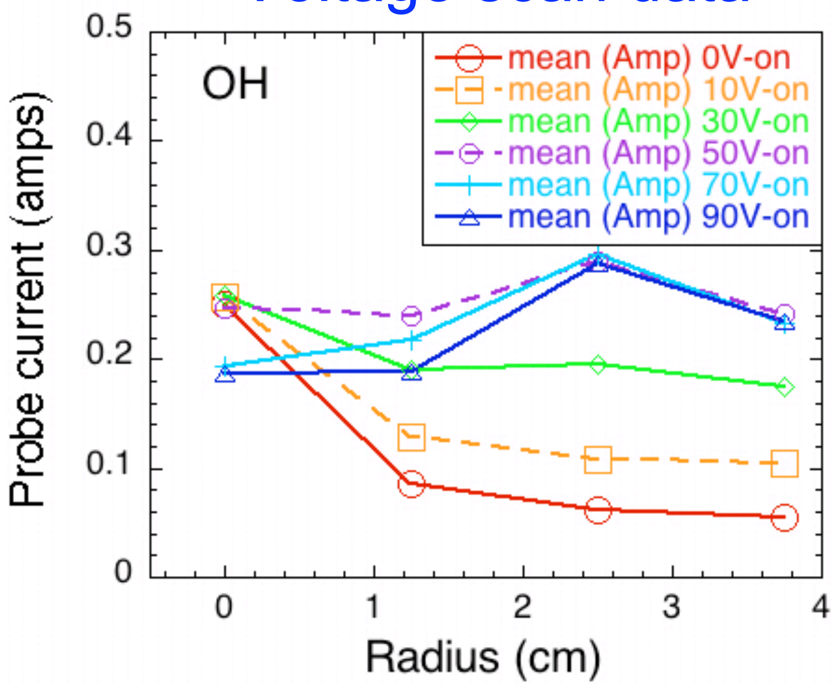
=> $N \sim \tau_{||} v_{ExB} / 2\pi d_\perp \sim 3$ (order-of-magnitude)

could be in regime of significant SOL modification

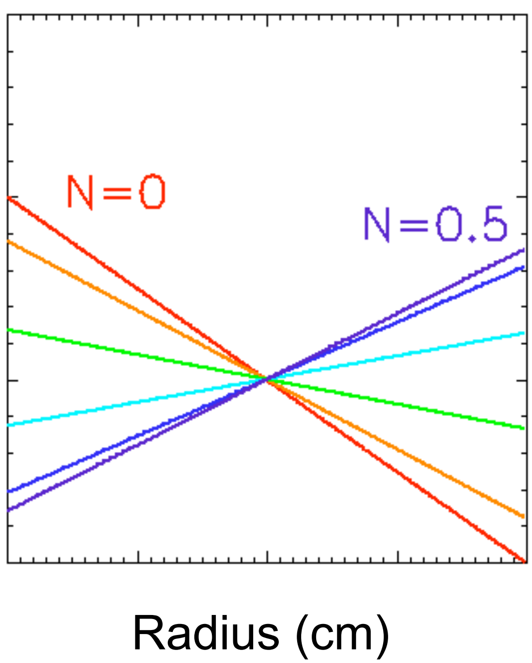
Simple Model for SOL Modification

- Assume constant ExB rotation with rotational spreading
- Best fit give N ~ 0.5 at ±90 volts, but not a very good fit

Voltage scan data



Simple Model



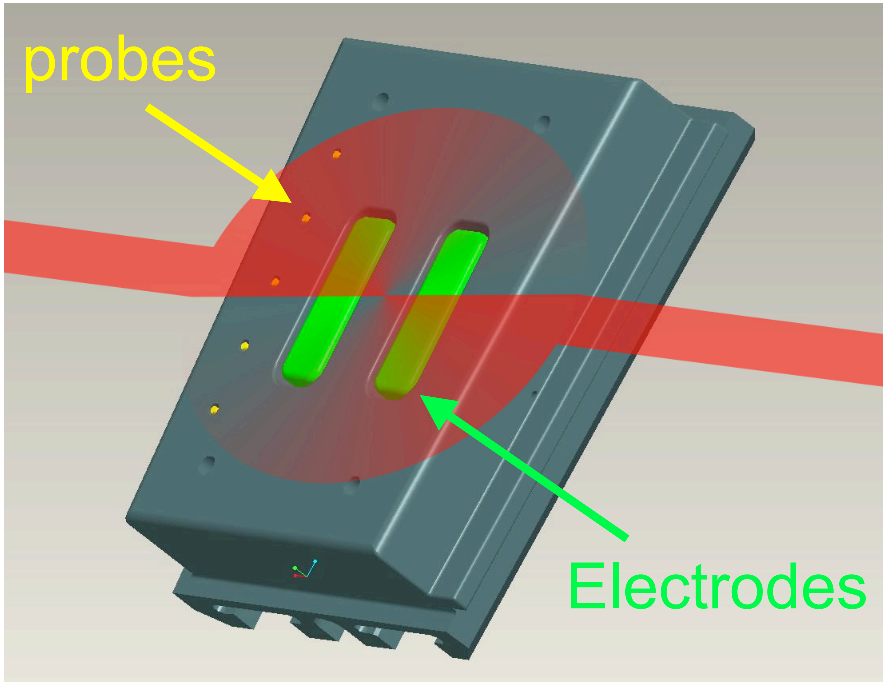
Better Model of Convective Flow

- Need to input pre-biasing density profiles both II and ⊥ to B
- Need to know φ_p effects due to biasing both II and ⊥ to B
- Need to know if biasing affects turbulent radial transport
- For divertor application, need to include effects of small angle of B to plate, X-point magnetic shear, maybe finite ρ_i and $f(v_e)$

=> could be done with SOL codes under development

NSTX Divertor Electrodes

- Electrodes in tiles between liquid lithium divertor segments
  - measure effects II and ⊥ B with camera + probes
  - learn to minimize power needed for SOL control



R. Ellis

Future Applications ?

- Power required for biasing divertor plates at $V \sim T_e$ and $I = I_{sat}$ would be acceptable if SOL effect was large
- Possible issue of electrode insulator damage in high neutron flux environment
- Could look for other methods to create convective cells
  - asymmetric neutral gas puffing at divertor plate
  - RF generation (ICRH, LH, ECRH at midplane)
  - biasing perturbed magnetic field lines at plate

Summary and Outlook

- Divertor heat flux is a serious problem for tokamak reactors
- One potential solution is convective cell generation in SOL
- Local E_{pol} *does* modify local density profiles in NSTX SOL
- Results qualitatively consistent with convective cell model

⇒ Additional experiments are needed on divertor plate biasing to understand the physics and to improve the efficiency