Electric fields and stationary drift flows in the island divertor SOL of Wendelstein 7-X

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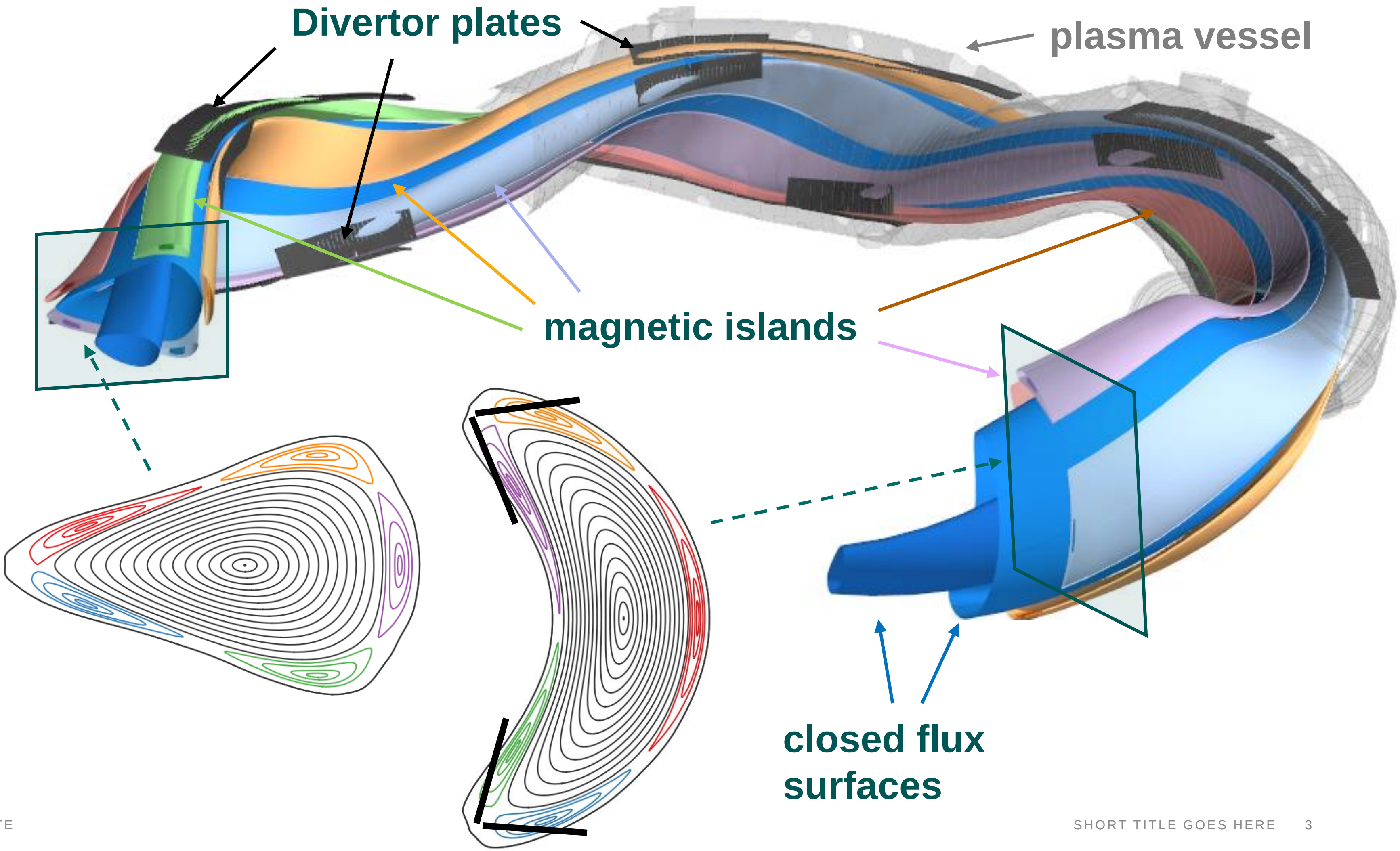
Summary / abstract

- **2D-resolved Langmuir probe measurements in the W7-X island divertor SOL uncover a complex spatial structure of T_e n_e, V_f.**
  - significant poloidal gradients and non-monotonic radial profiles are observed, sensitively depending on the magnetic structure (island size and position)
  - 2D distribution of plasma parameters is intricately related to the magnetic structure and hints at limitations of the current magnetic field reconstruction accuracy
- **resulting electric fields imply the presence of sheared stationary drift flows with poloidal velocities of a few km/s and typical structure sizes of down to 1 cm**
  - such flows are observed with a gas puff imaging diagnostic in qualitative agreement with the probe results
  - these flows imply a significant transport channel in the SOL → highly relevant for SOL transport modeling
- **physics behind the potential measurements not yet understood → implies that we are lacking a fundamental physics effect in the SOL**

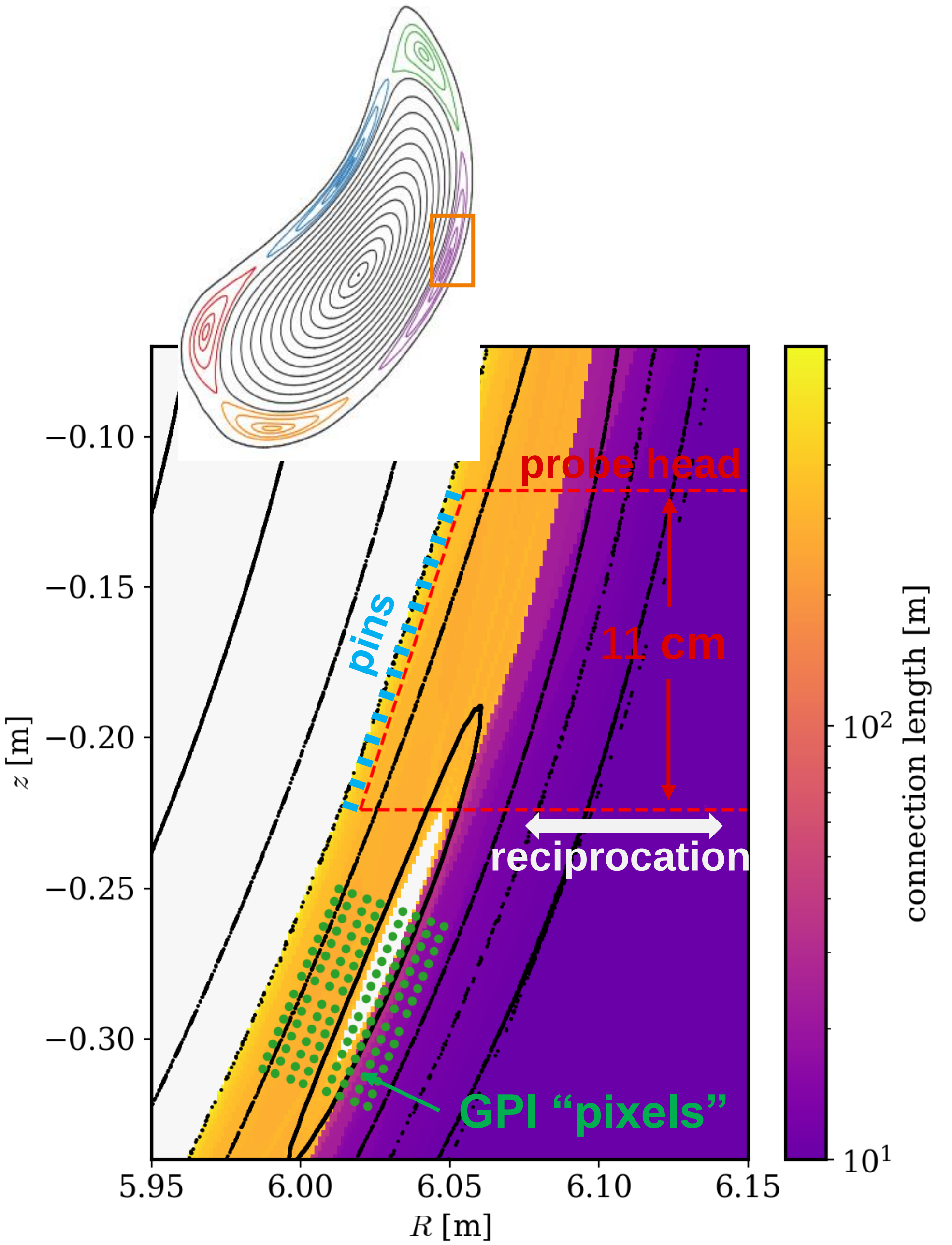
Introducing the island divertor scrape-off layer

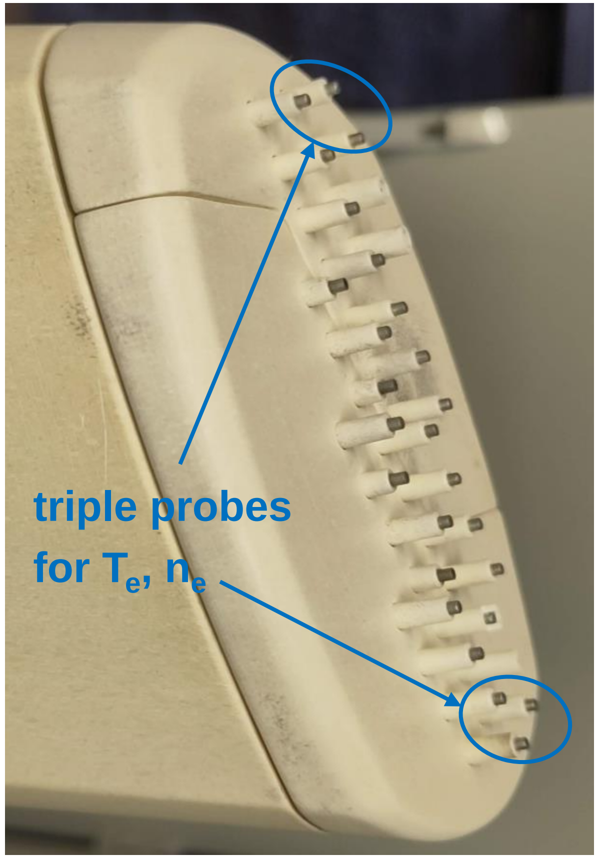
- chain of intrinsic resonant magnetic islands at the plasma boundary
- modular divertor units intersect magnetic islands
- compared to tokamaks:
    - longer connection length (smaller pitch angle)
    - additional regions beyond main SOL and PFR: target shadow region, closed field line region in island center



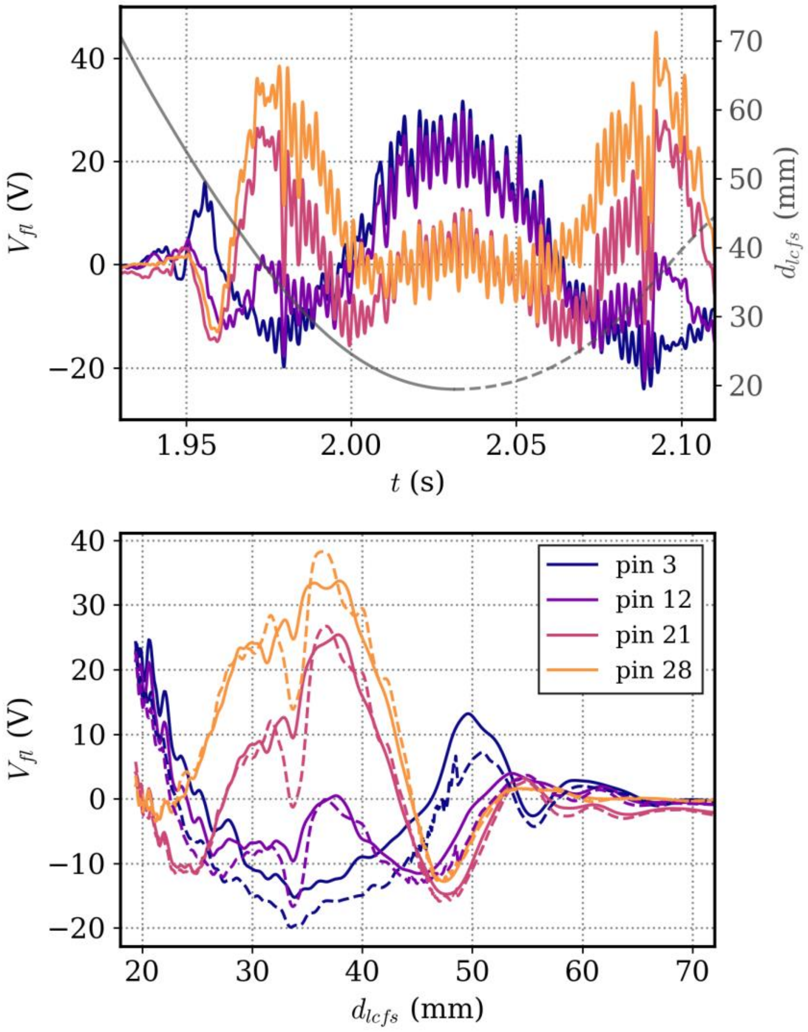
diagnostic setup

- MPM and GPI are located in stellarator-symmetric cross sections
- introducing MPM probe head “IPP-FLUC2”: poloidal-radial array of 29 pins, adjusted to flux surface geometry
- flexible operation modes (V_f, $I_{i,sat}$, triple probes, …)

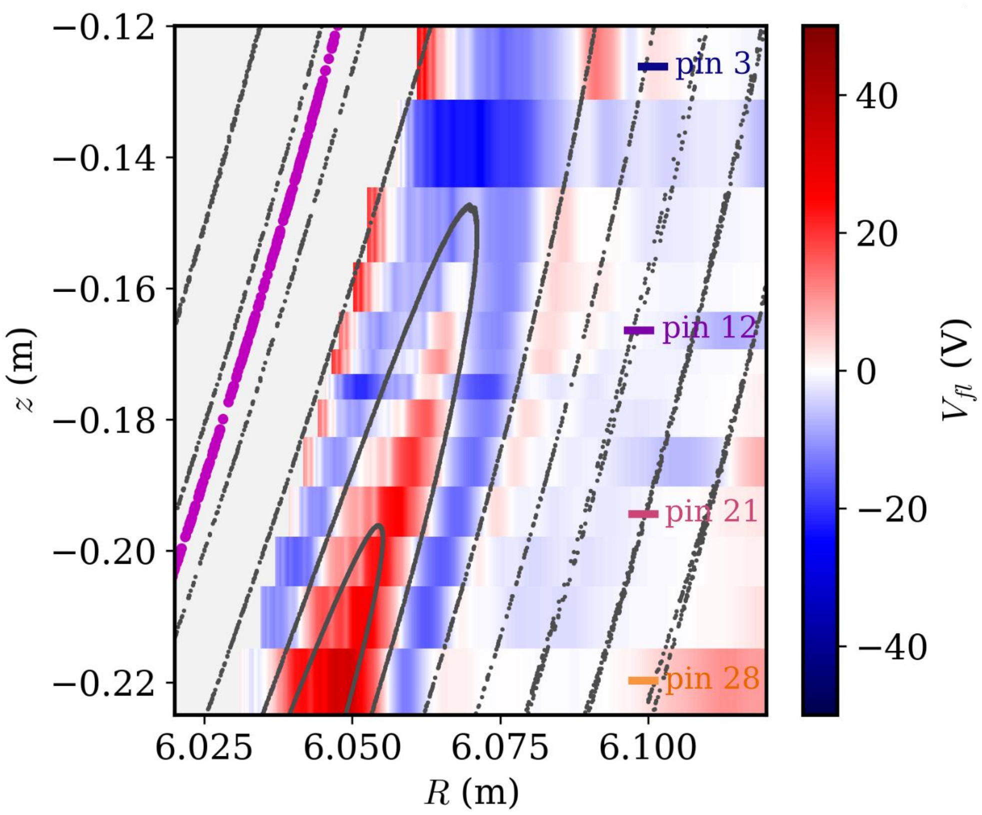




Constructing 2D maps of time-averaged quantities



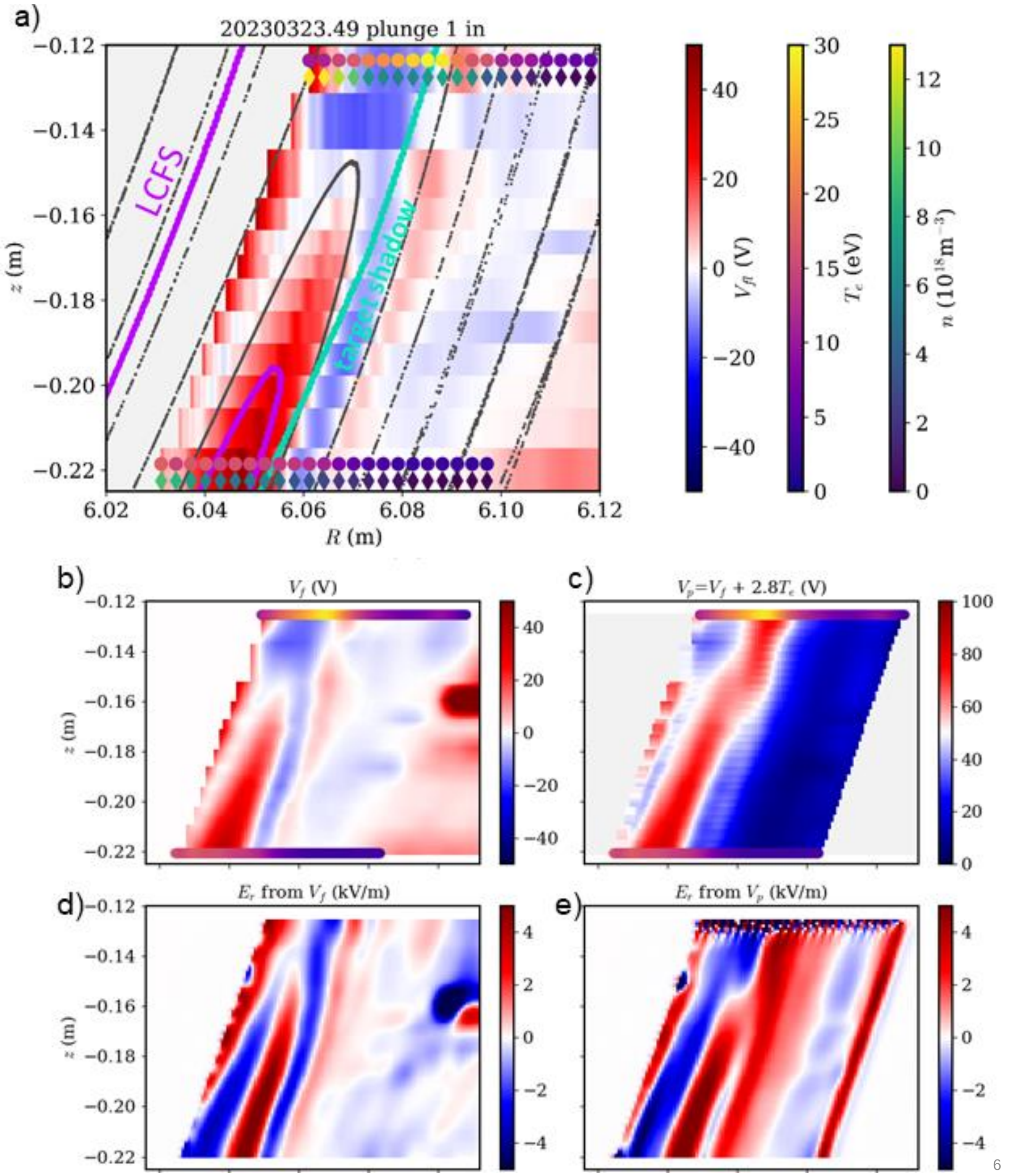
- **2D (*R*-*z*) map of V_f is obtained from radial scan of the poloidal probe array**
  (time averaged to time scales of the probe movement, ~ 10Hz)



2D structure of SOL plasma

- **V_f map is highly structured**
  - flux-surface aligned layers of positive → negative → positive V_f
- **T_e, n_e profiles modulated by connection length**
  - distinct T_e peak at target shadow boundary for upper profile
- **V_f map implies electric fields**
  - radial: ~kV/m → v_{pol} ~ km/s
  - poloidal: ~100V/m → v_{rad} ~ 100m/s
  - multiple E_r shear layers
- **these observations are roughly preserved when accounting for T_e contribution**

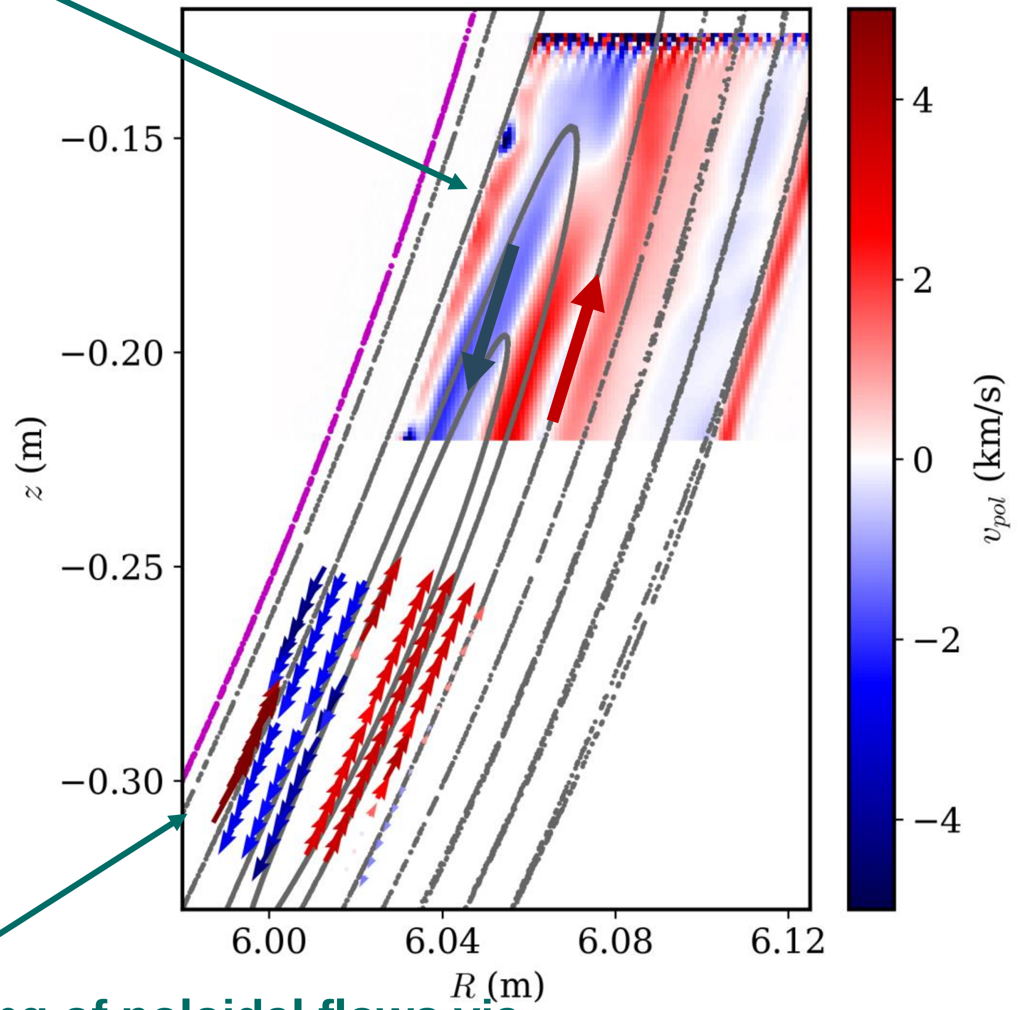
$$E_r = -\nabla_r V_p = -\nabla_r (V_f + 2.8T_e)$$



qualitative agreement on poloidal SOL flows between GPI and MPM

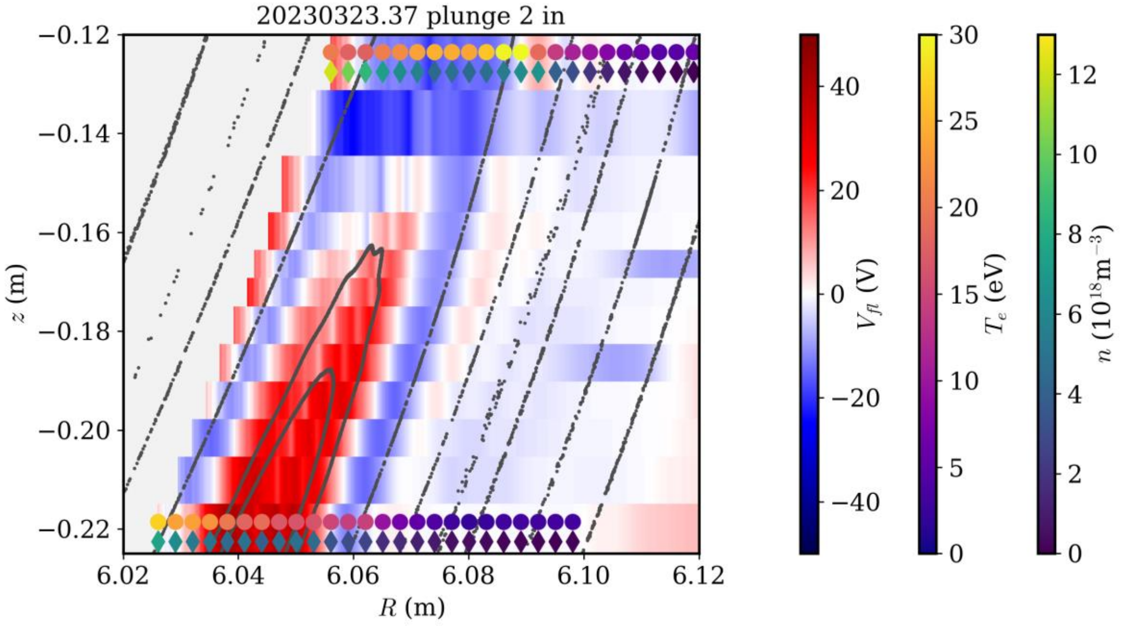
probes: $v_{pol} = E_r \times B = (-\nabla_r V_p) \times B$

- **both diagnostics observe sheared poloidal flows of km/s in the island SOL**
  - typically factor 1.5 – 2 higher velocities in GPI
  - poloidal variation across FoV for both diagnostics
  - radial offset between shear layer positions, but direct mapping not simply possible – different islands, and non-overlapping FoV w.r.t island
    → we don't know if flows "close" around each island
- **such flows have massive implications for SOL transport [Flom subm. to NF 2024]**
  - flows are "efficient" due to small pitch angle
    → effectively boosting poloidal transport by 10^3 compared to parallel transport
  - not included in current models (e.g. EMC3-EIRENE)



GPI: direct imaging of poloidal flows via spatio-temporal dynamics of fluctuations

Remainder of the paper

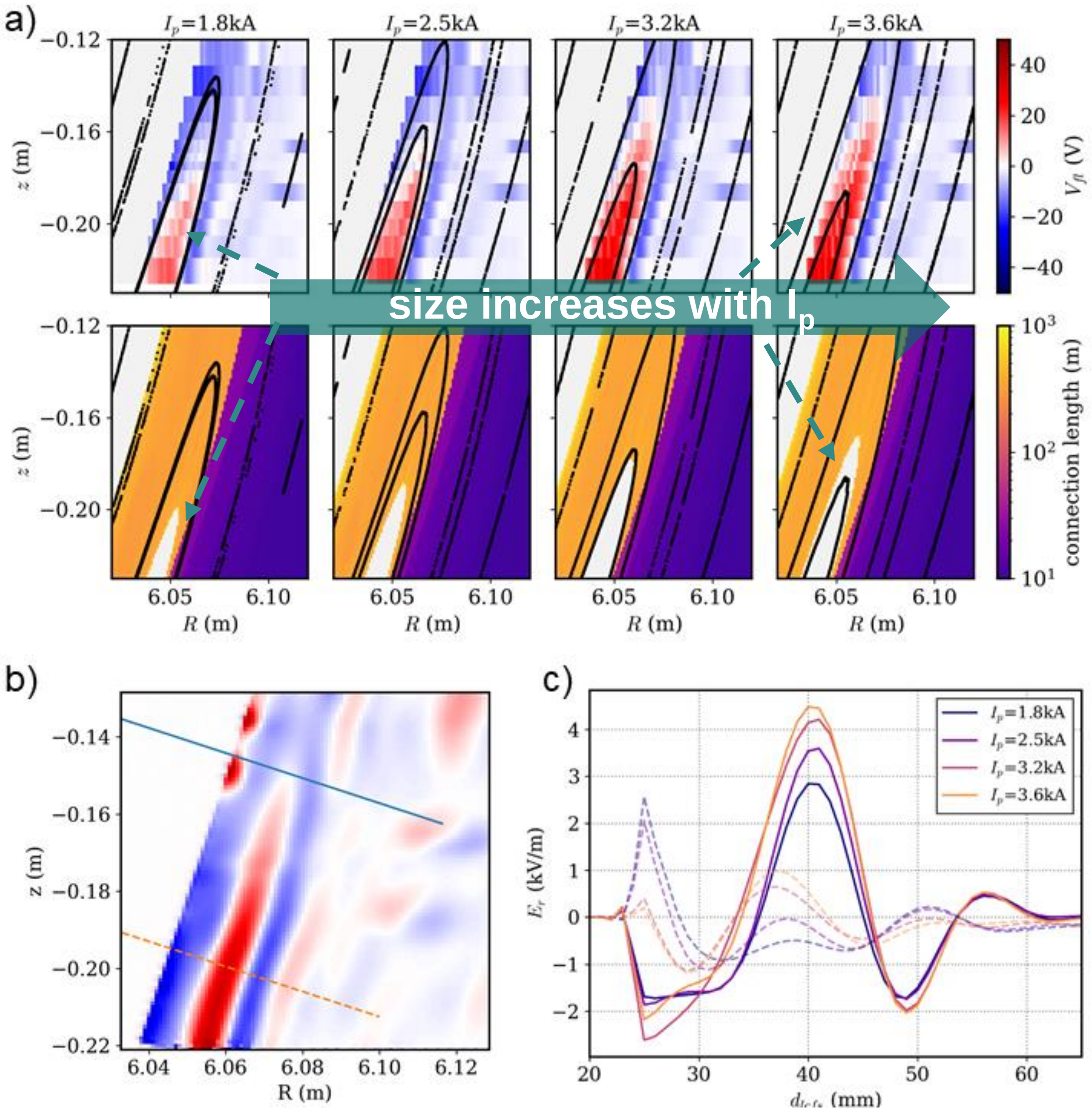


- **Half-time summary:**
  - non-monotonic T_e, n_e, V_f profiles across magnetic islands
  - sheared stationary poloidal flows

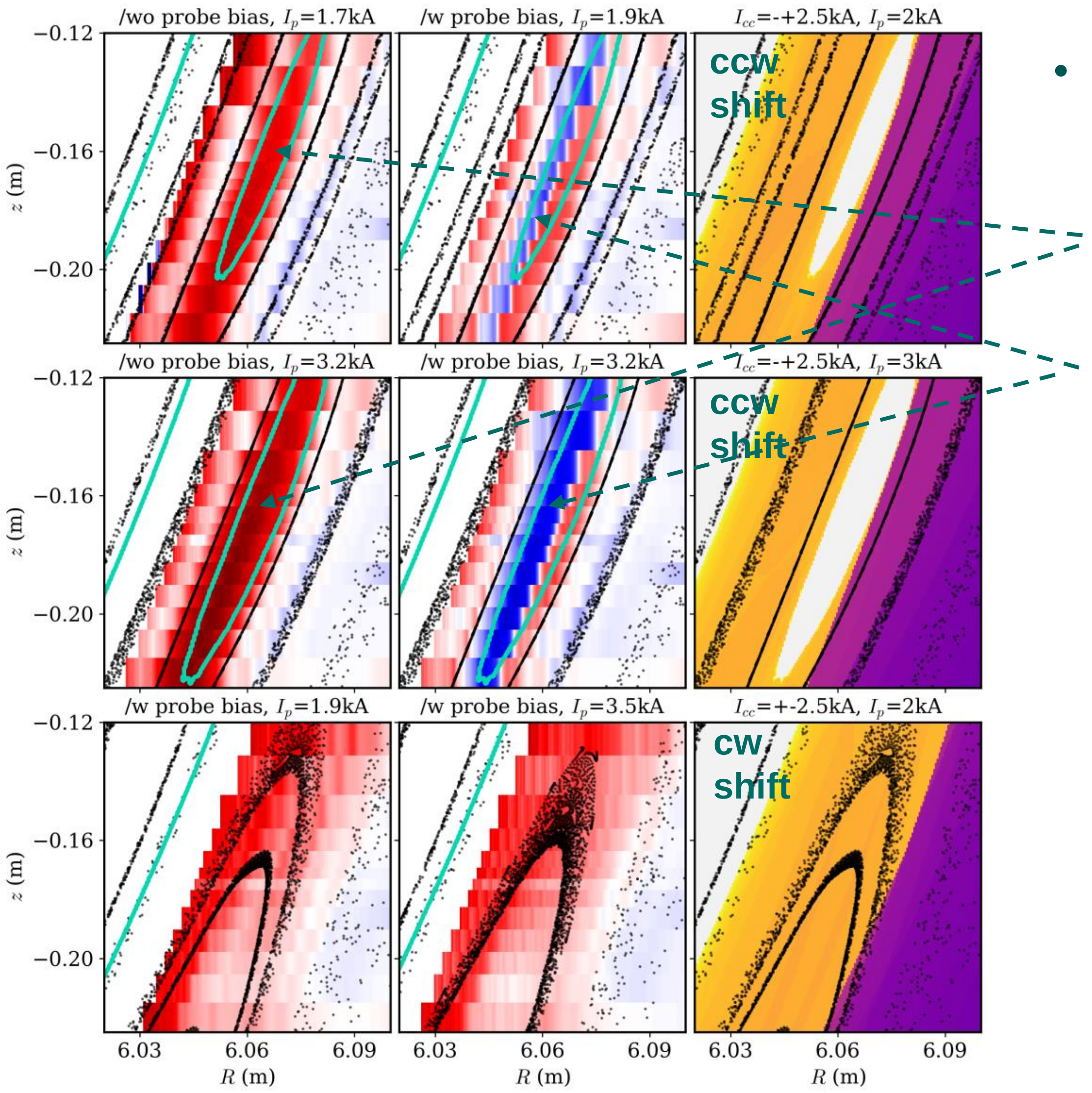
- **second half of the paper: survey across magnetic configuration space**
  - small radial shift of island position (plasma current)
  - poloidal shift of island position (control coils)
  - magnetic field direction
  - other 5/5 island configurations: low shear (MMG) , high mirror (KKM)
  - other island chains: low iota configuration (5/6 , diagnostics closer to X point)

radial shift of island position via plasma current

- **plasma current evolution (bootstrap current) changes iota and therefore island position**
  - positive V_f region is associated to island center
  - flat-top experiments with only I_p changing: both positive V_f and closed field line region grow (and radially move) with evolving current
  - E_r increases during I_p evolution → agreement with GPI [Ballinger 2024 , in preparation]



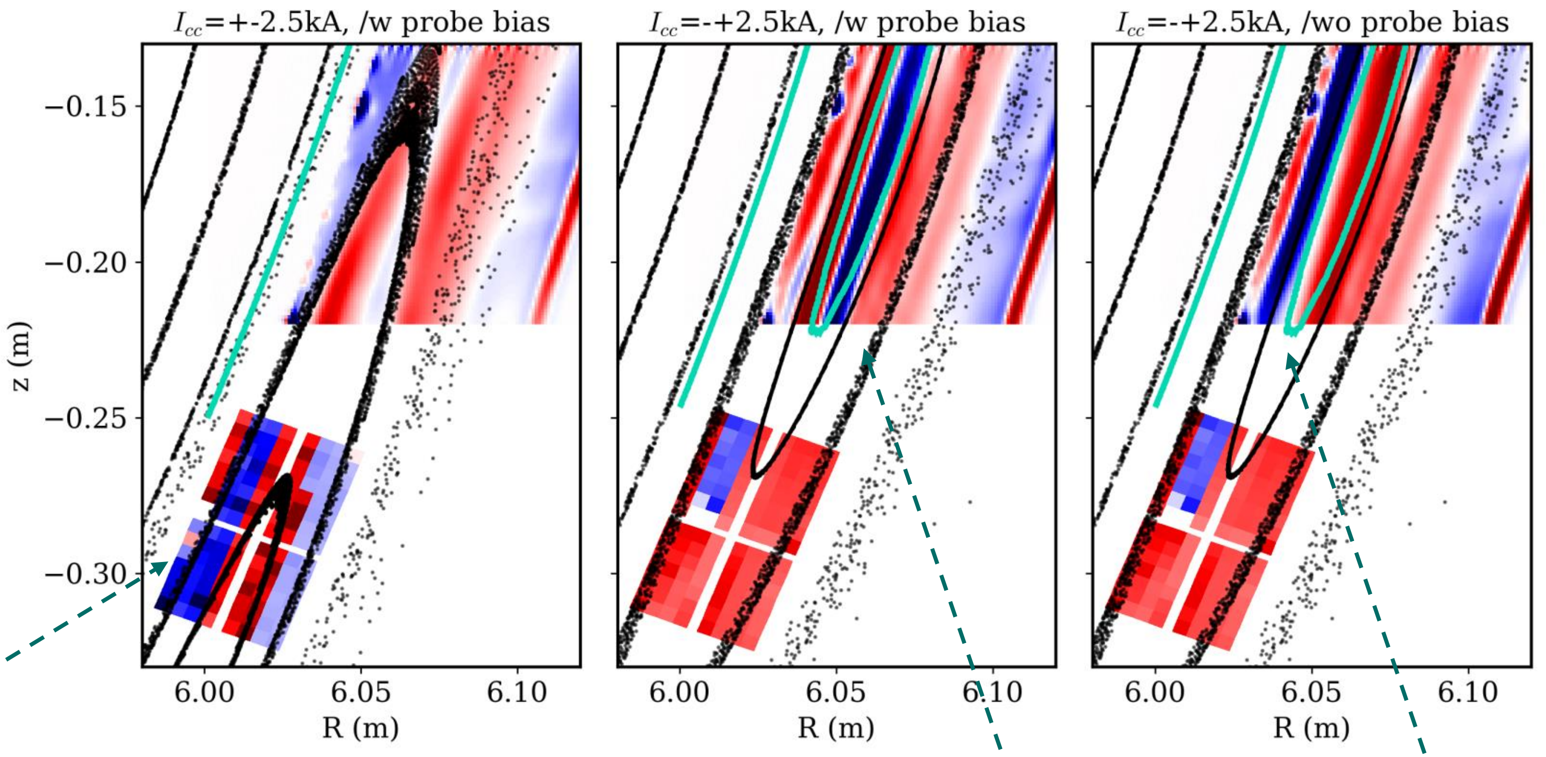
poloidal shift of island position via control coils



- **presence of negative bias voltage for $I_{i,sat}$ probes affects V_f measurements when probe enters O point**
  - positive V_f around O point (closed field lines) in case without bias voltage
  - negative V_f around O point region
  - size and position of negative V_f region scales in agreement with plasma current (→ island / O point position)
  - no effect of probe bias in cw shifted island case (entirely open field lines)
  - **generally, the presence of bias voltage (almost) never matters → this is not a technical malfunction, but a true physics effect related to magnetic geometry.**

poloidal flow velocities in island rotation case

- **complex, non-trivial flow patterns upon island rotation**
  - highly reproducible for each scenario and diagnostic across multiple experiments



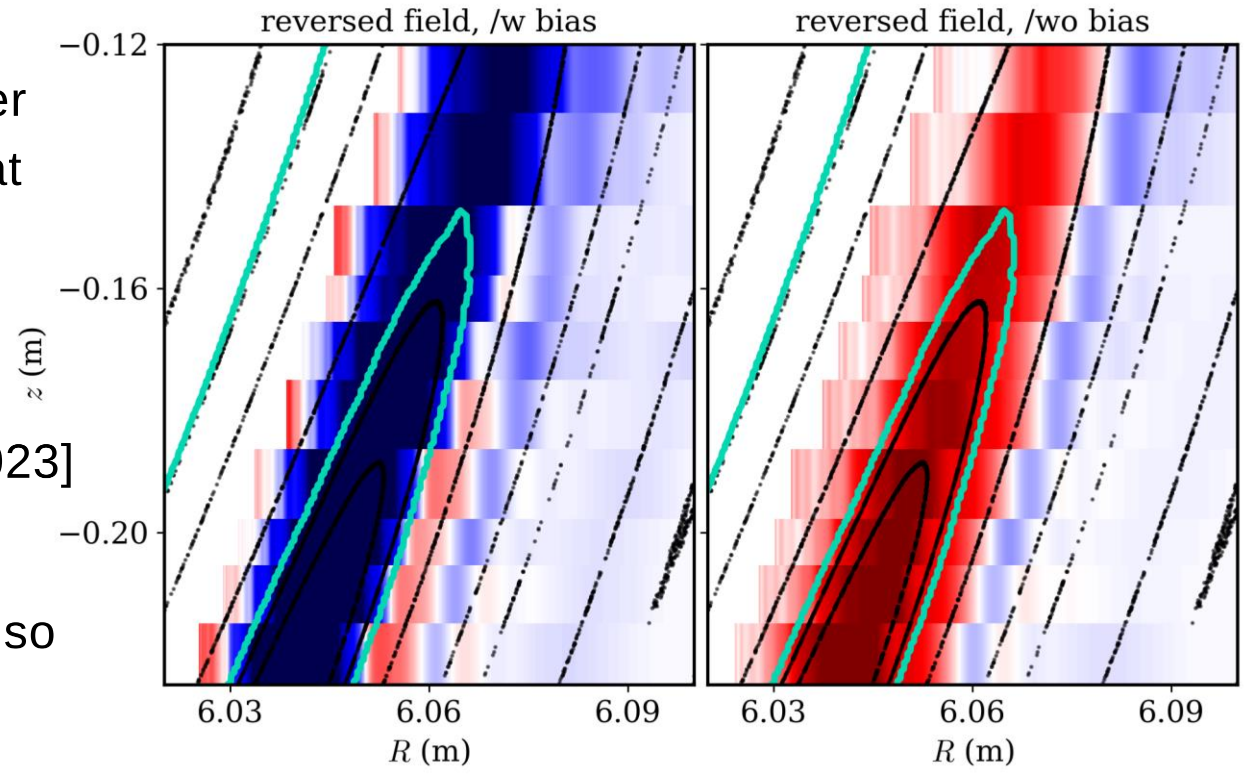
here, GPI views a position that is equivalent to the MPM FoV in the "unshifted" case. Three shear layers in the space of 5cm!

- for "MPM probes O point" case, effect of bias voltage flips the E_r map
- the "bias off" case agrees better with GPI

magnetic field direction

- **in reversed field experiments, the effect of negative bias from I_{sat} pins is much more pronounced**
  - reversed field experiments ran at slightly higher iota ($I_{pc,reversed}$=500A vs $I_{pc,forward}$=250A), but that doesn't explain the different behavior
  - we probably had a different (not well compensated) 1/1 (and 2/2) error field in reversed field experiments [Gao, Workshop 2023]
  - apparently random flips of v_{pol} directions are also seen by GPI in reversed field experiments

identical plasma scenarios

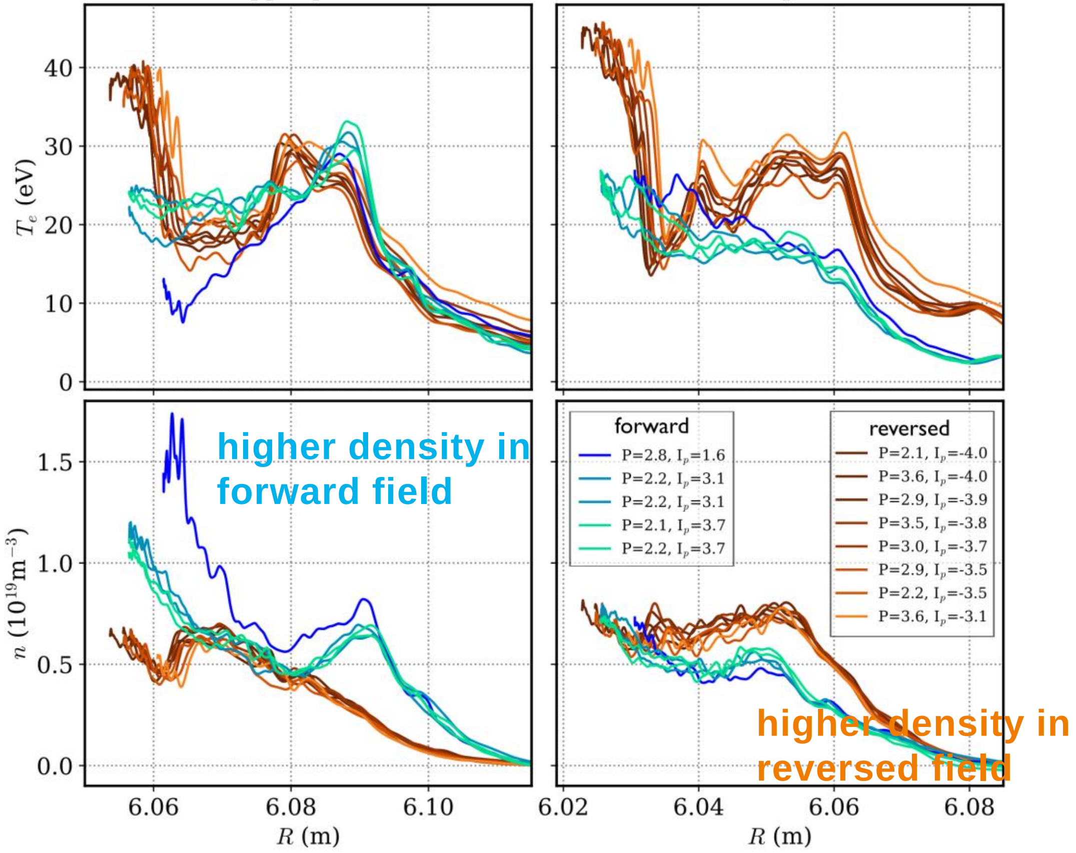


magnetic field direction – comparison of MPM profiles

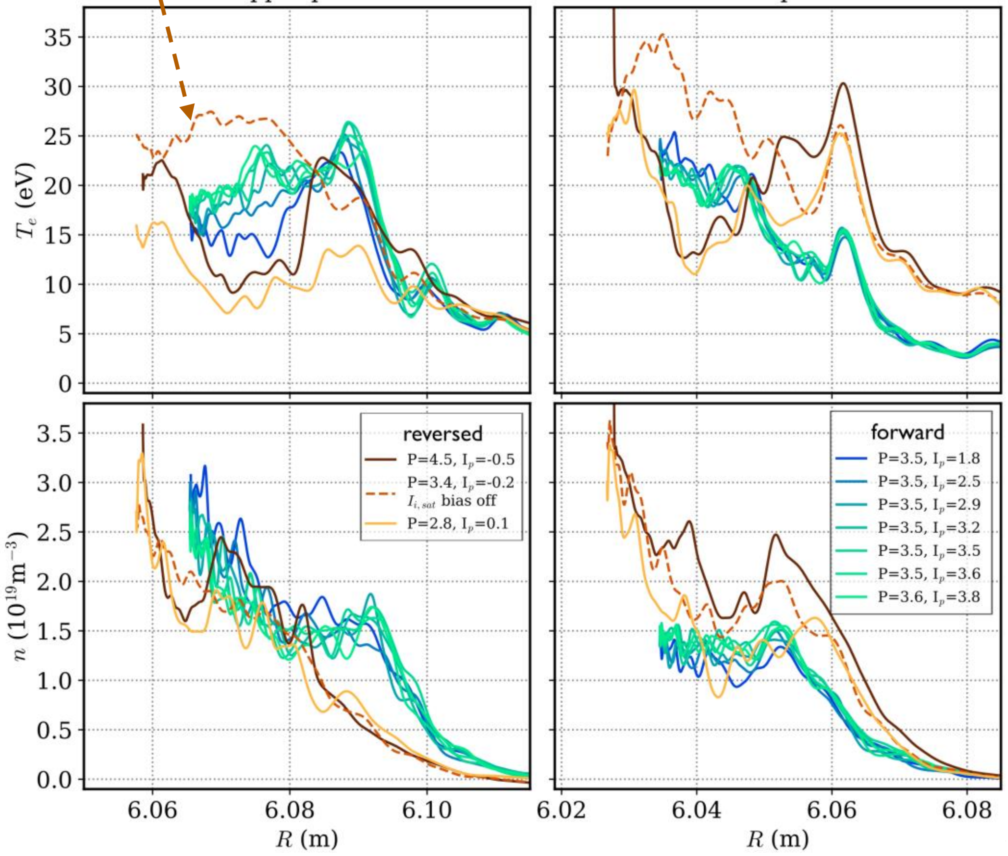
- position of T_e peaks depends on field direction (but TSR location doesn't)
- consistent profile shape for each field direction

- consistent profile shape for forward field
- effect of I_{sat} bias also affects T_e in reversed field experiments

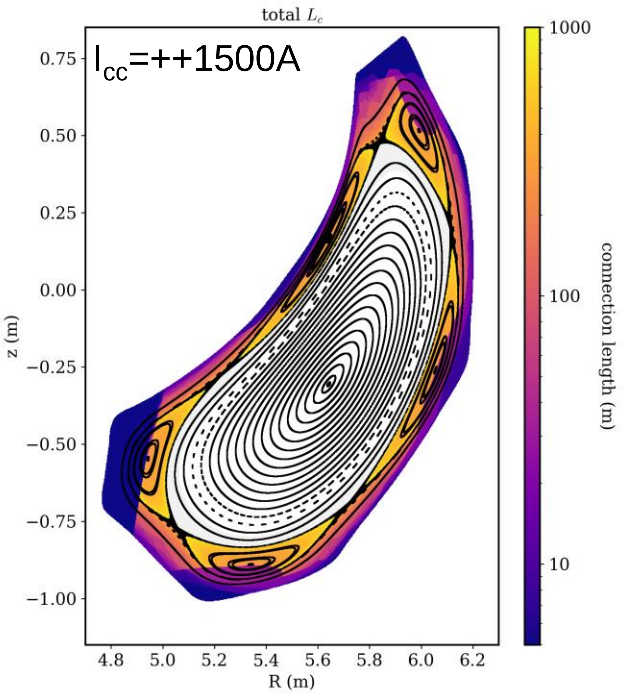
n_{dl}=4e19m^{-2}



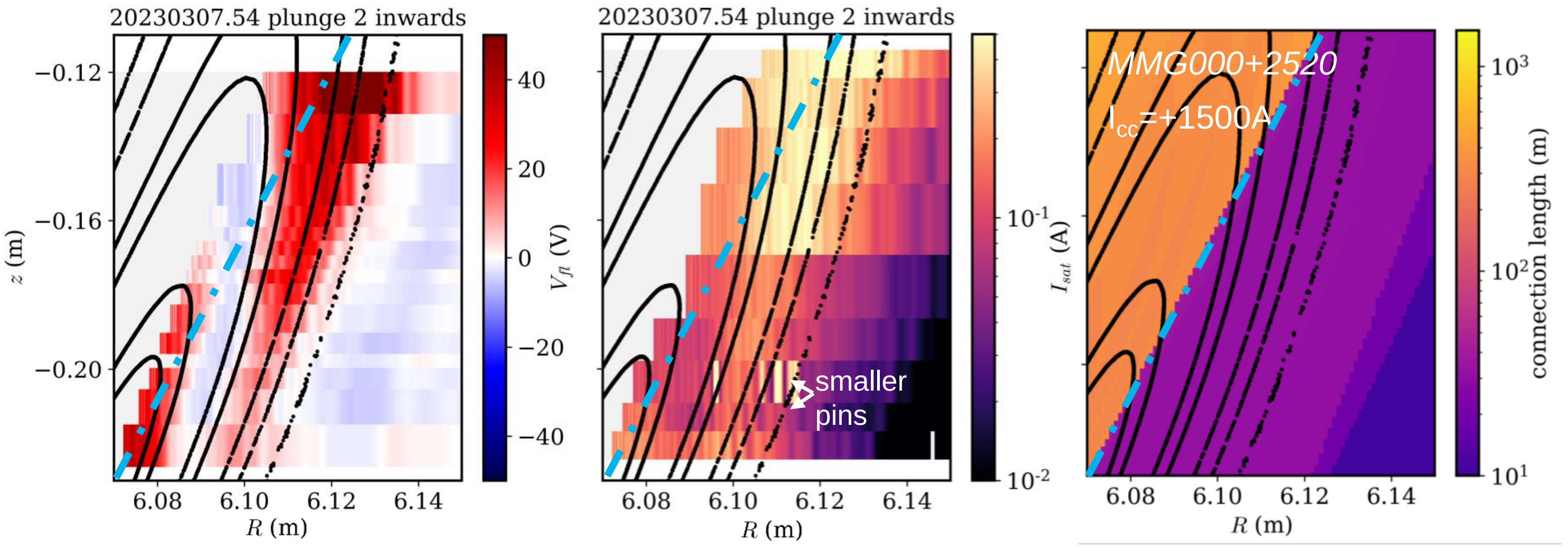
n_{dl}=8e19m^{-2}



Low shear , outward shifted configuration (MMG)

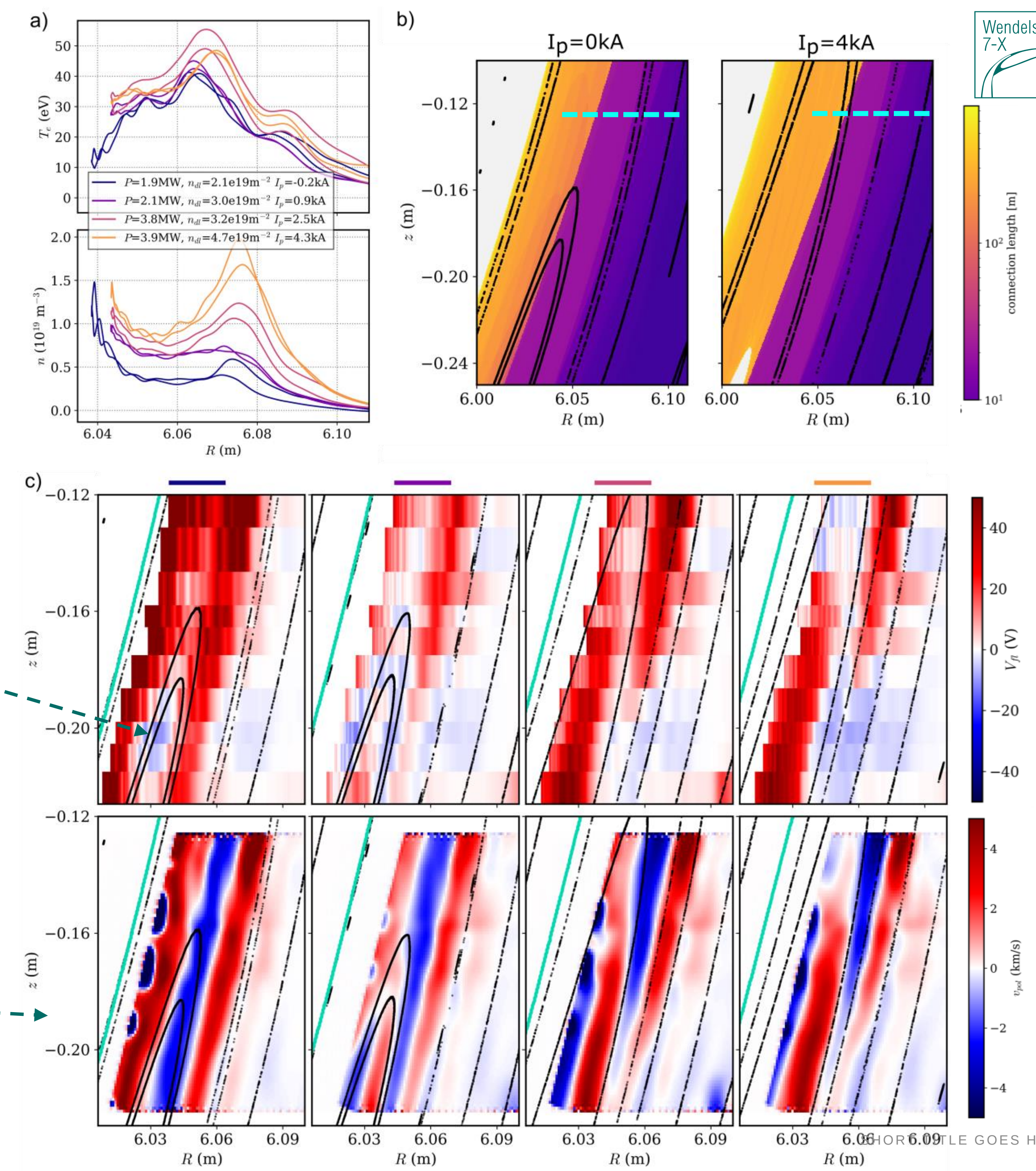


- **flux surface-aligned V_f map**
  - positive V_f around island center
  - strong poloidal gradient on outer island separatrix)
  - no relation to target shadow boundary → V_f is not dominantly set by sheath conditions
- **strong poloidal gradient of I_{sat}**
  - mostly due to T_e (~factor 5 higher at upper part of the FoV)
  - I_{sat} distribution rather follows flux surfaces than connection length, but still strong gradients on flux surfaces



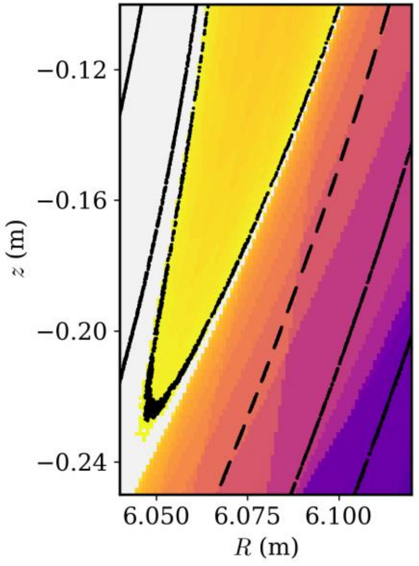
High Mirror configuration

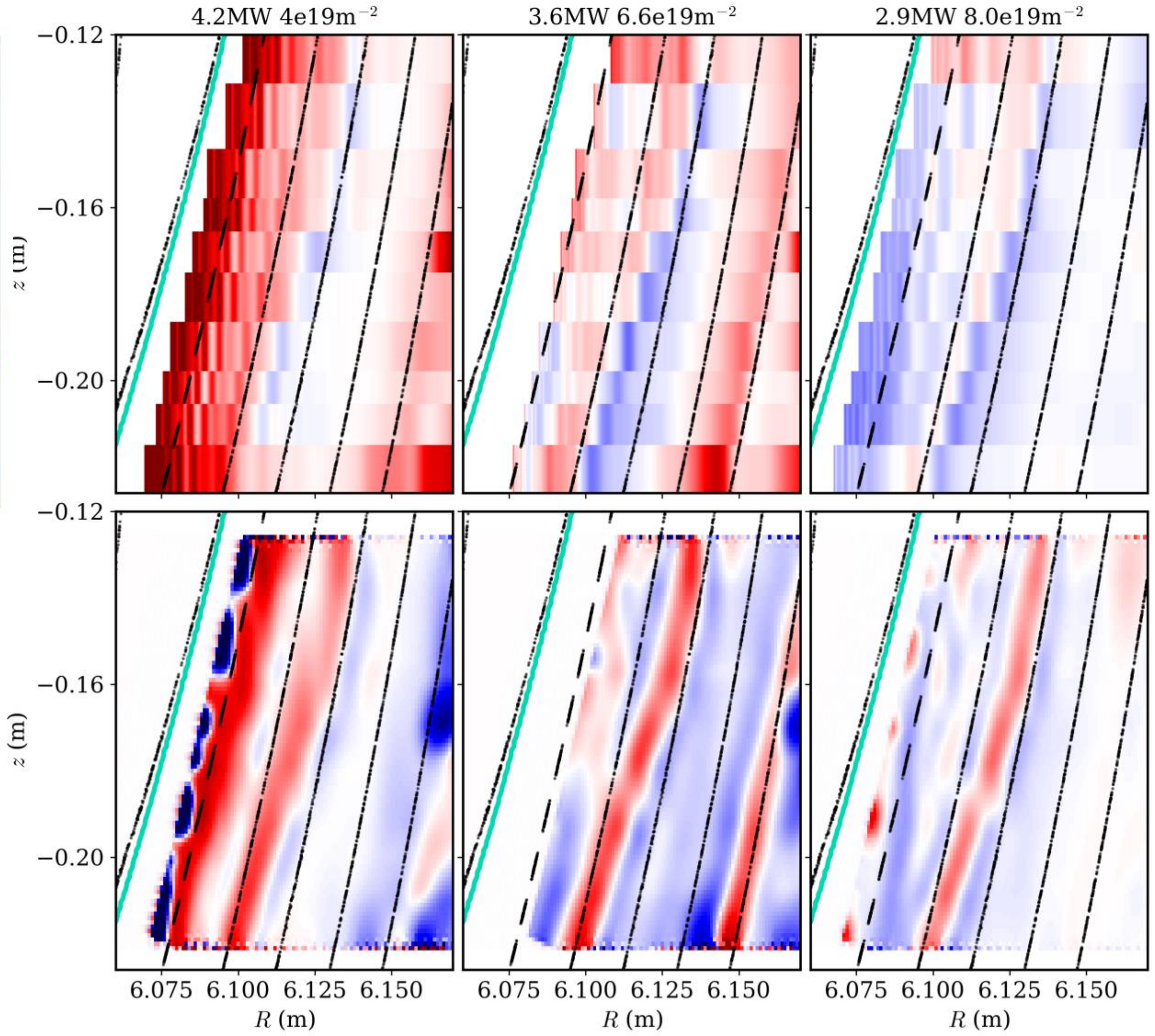
- **different island – divertor interaction geometry, compared to *standard***
  - rather similar T_e profiles with clear T_e peak around TSR for all experiments
  - SOL density and in particular SOL density peak at TSR depends on P, n_{dl}
- **Vf maps sensitive on P, n_{dl}**
  - low P, n: mostly positive V_f with a negative V_f hole (highly reproducible!)
  - for higher P, n: transition to two distinct positive Vf regions: 1) around the island center, 2) around the TSR border, but only in the upper part of the FoV
  - drift flows change accordingly



Low iota configuration

- **MPM FoV close to X point**
  - measurements entirely in private flux region (heat load limitations)
- **V_f maps depend on plasma scenario (P,n) , less on I_p**
  - rather uniform V_f distribution at higher SOL power density
  - towards lower SOL power densities, a single thin band of positive V_f remains (4cm deep into the PFR, outside of the island!)





possible explanations

- localized radiation effects, known from this configuration [Winters NF 2024, Zhang xxx]
- beta effects [Knieps NF 2022, Killer ISHW 2022]

Summary

- **complex 2D structure of steady state plasma parameters in the island divertor SOL**
  - intricately entangled with (fine details of the) magnetic geometry
  - typical scale length of cm → much smaller than island size
- **V_f and T_e gradients imply complex ExB flow patterns**
  - such drift flows are observed in qualitative agreement with GPI
  - these flows are a relevant SOL transport channel → edge modeling
- **fundamental questions raised by the 2D plasma parameter distribution**
  - (0. it is important to measure these in the first place. We need spatially resolving diagnostics)
  - V_f structure implies that we are missing physics. sheath effects? trapped particles and neoclassical physics might be relevant in the SOL?
  - V_f measurements can serve as a tool to diagnose magnetic field structure (biasing of the entire closed field line region, only happening in reversed standard and forward with shifted islands)
    → tool to assess asymmetries / error fields / iota reconstruction