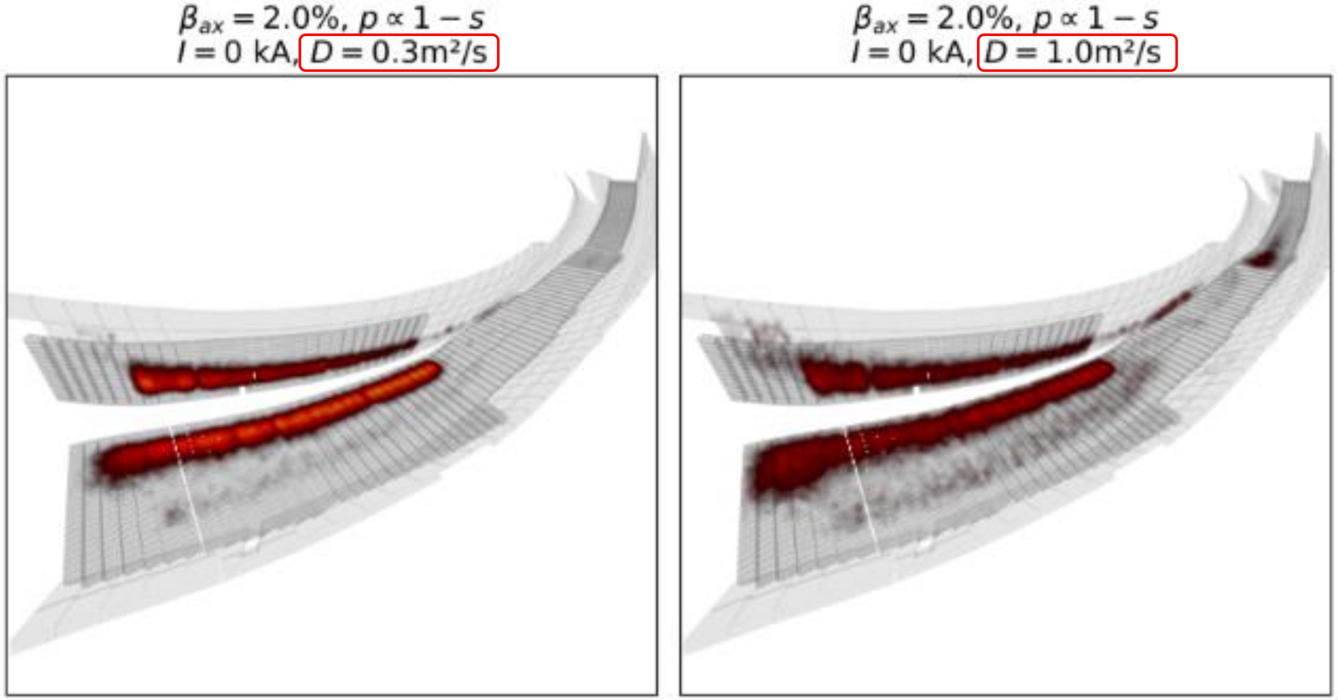
SOL Turbulence in W7-X

- **Status of understanding after OP1**
- **Open questions and outlook towards OP2**

compiled for TG Turbulence by C. Killer and S. Zoletnik on behalf of the W7-X Team

Motivation

- SOL turbulence can drive anomalous cross-field transport
  - can widen SOL profiles
    → spread heat loads on targets, reduce peak loads
  - but: heat fluxes need to stay within divertor region
- edge turbulence
  - can affect edge gradients
  - role for quality of confinement

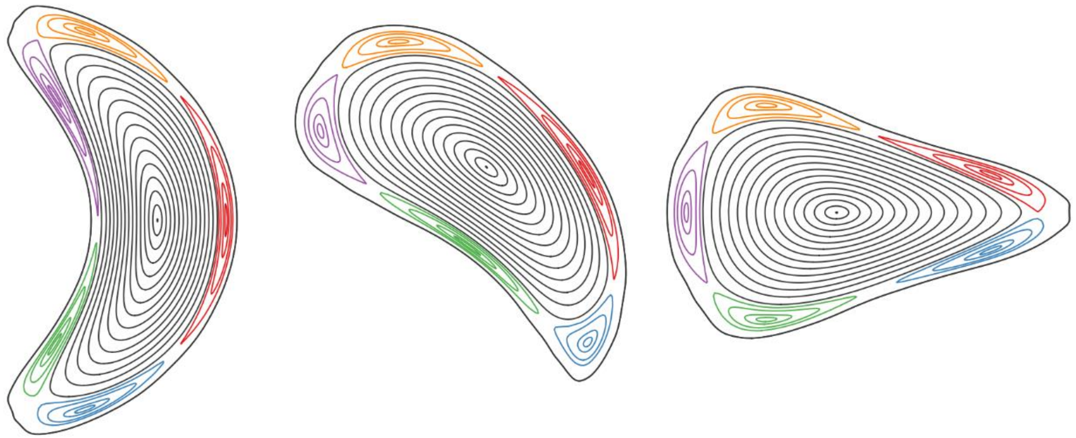


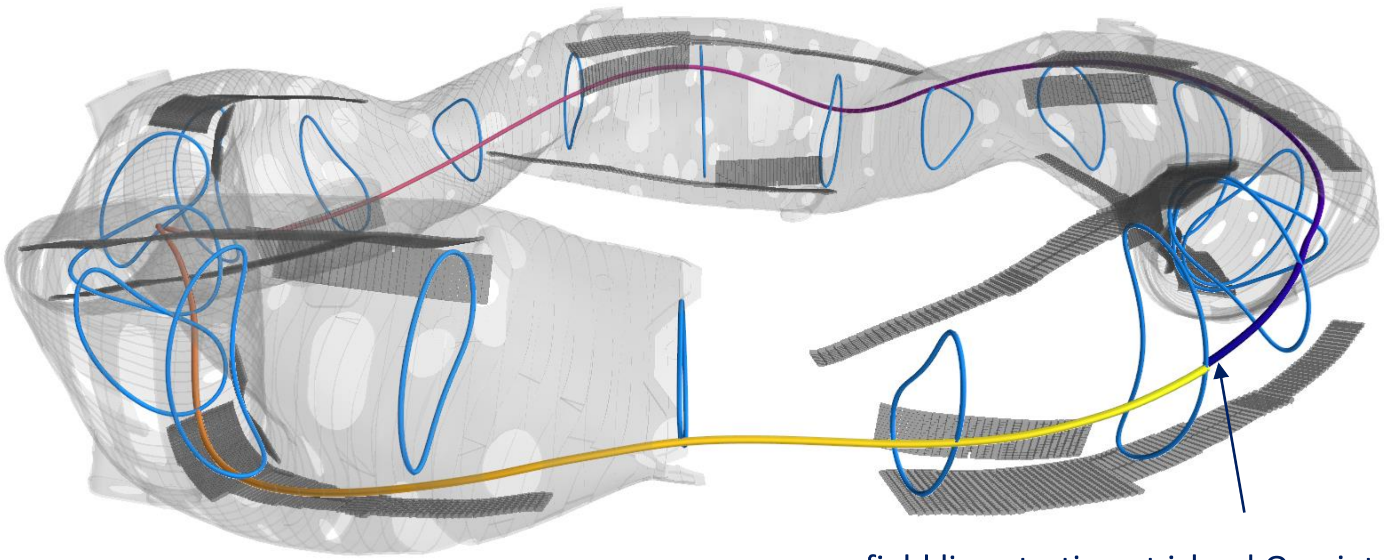
[A. Knieps, subm. to NF 2020]

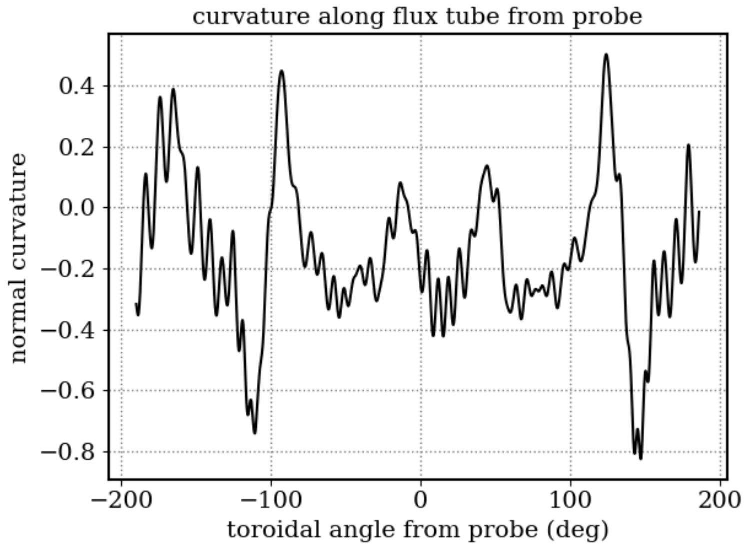
Introduction

Differences to the tokamak SOL

- 3D nature of W7-X SOL, 3D profiles
- magnetic islands → different topology
- non-uniform curvature drive
- edge iota ≈ 1 in standard configuration
  → field lines almost close upon themselves
- general theory still at infancy

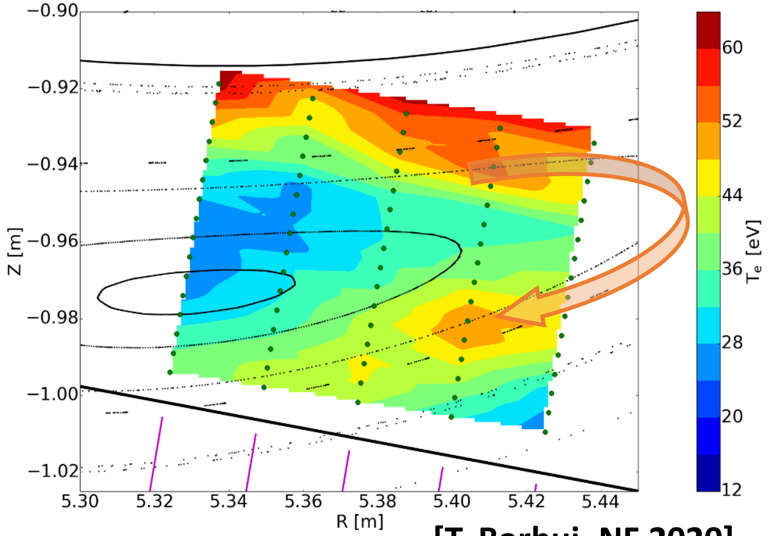




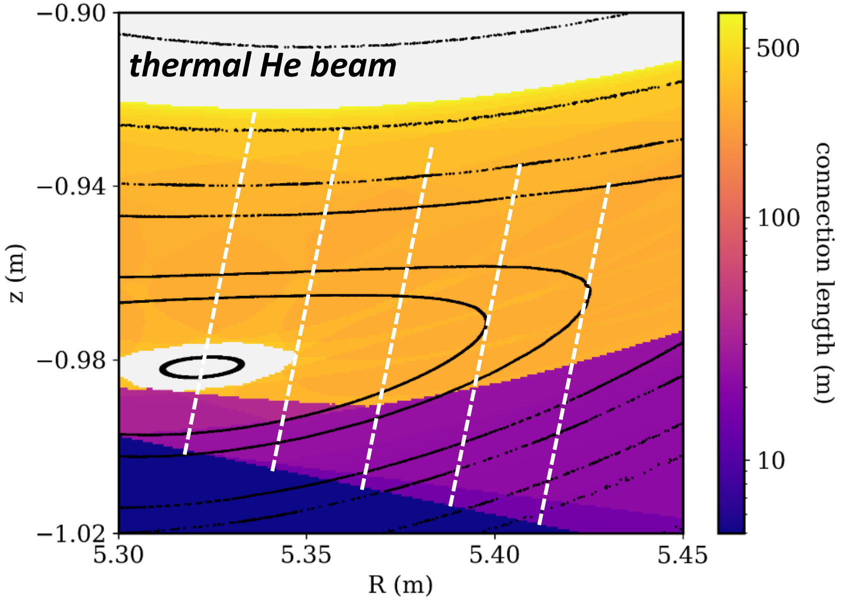


field line starting at island O point in outboard mid-plane

3D profiles in the W7-X island divertor SOL

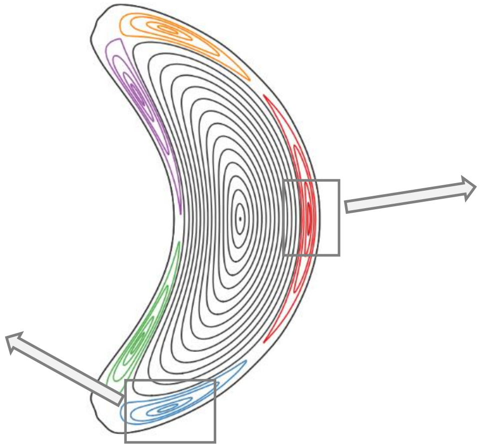


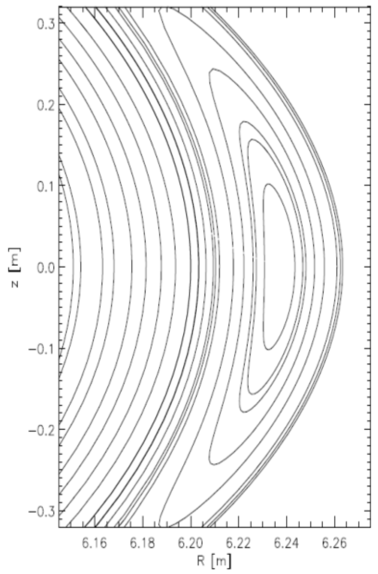
[T. Barbui, NF 2020]



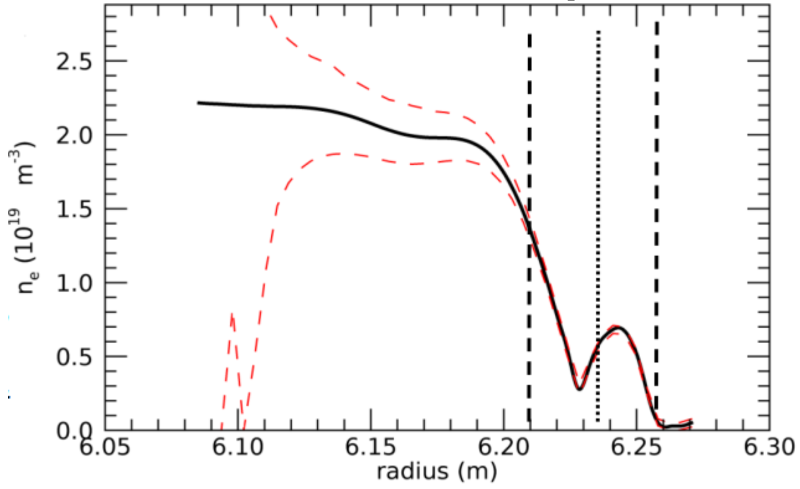
The instabilities that drive turbulence depend on gradients

- 3D profiles → 3D gradients
- island divertor has generally shallower SOL gradients than a tokamak SOL





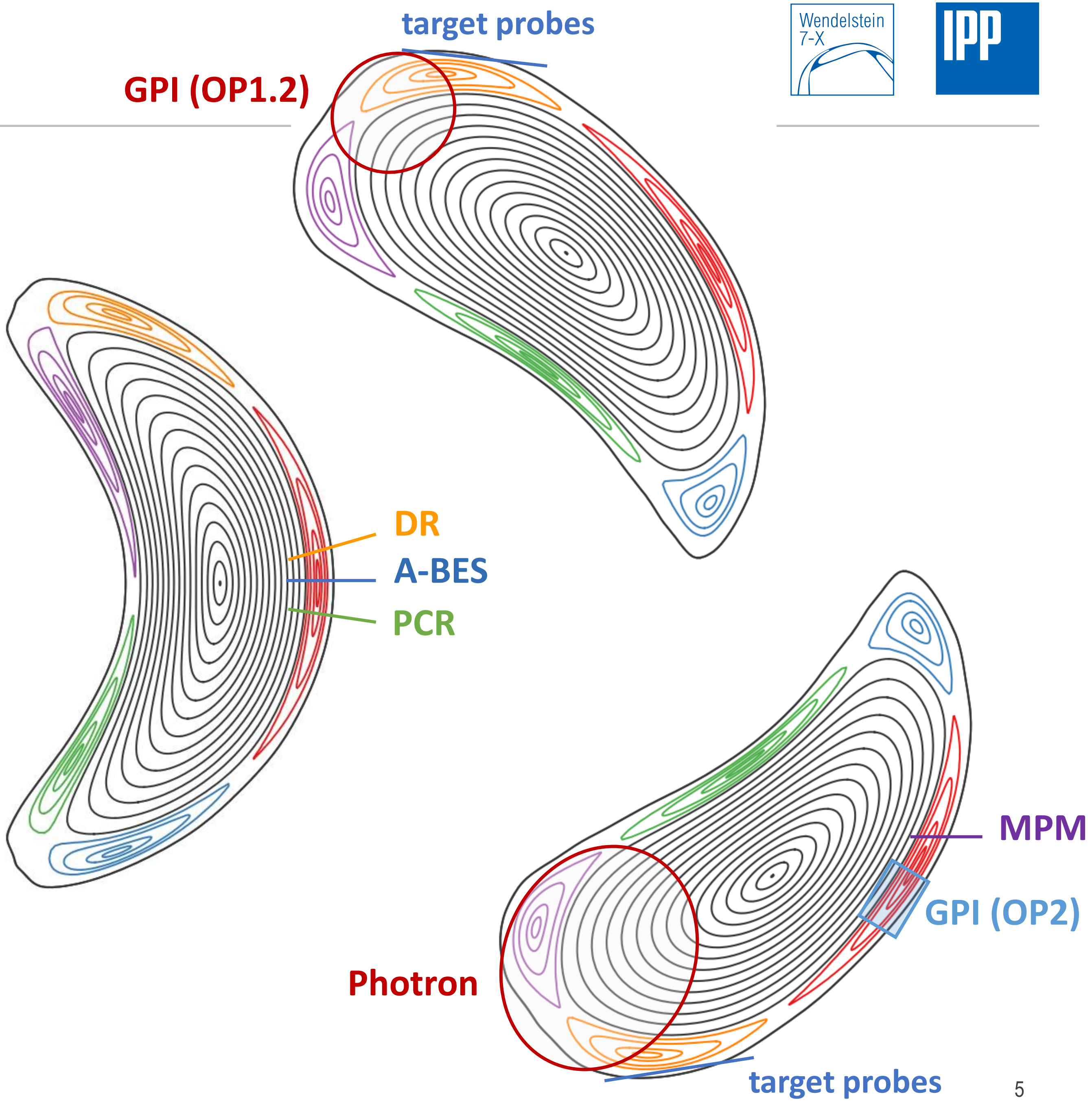
[S. Zoletnik PPCF2020]



SOL turbulence diagnostics

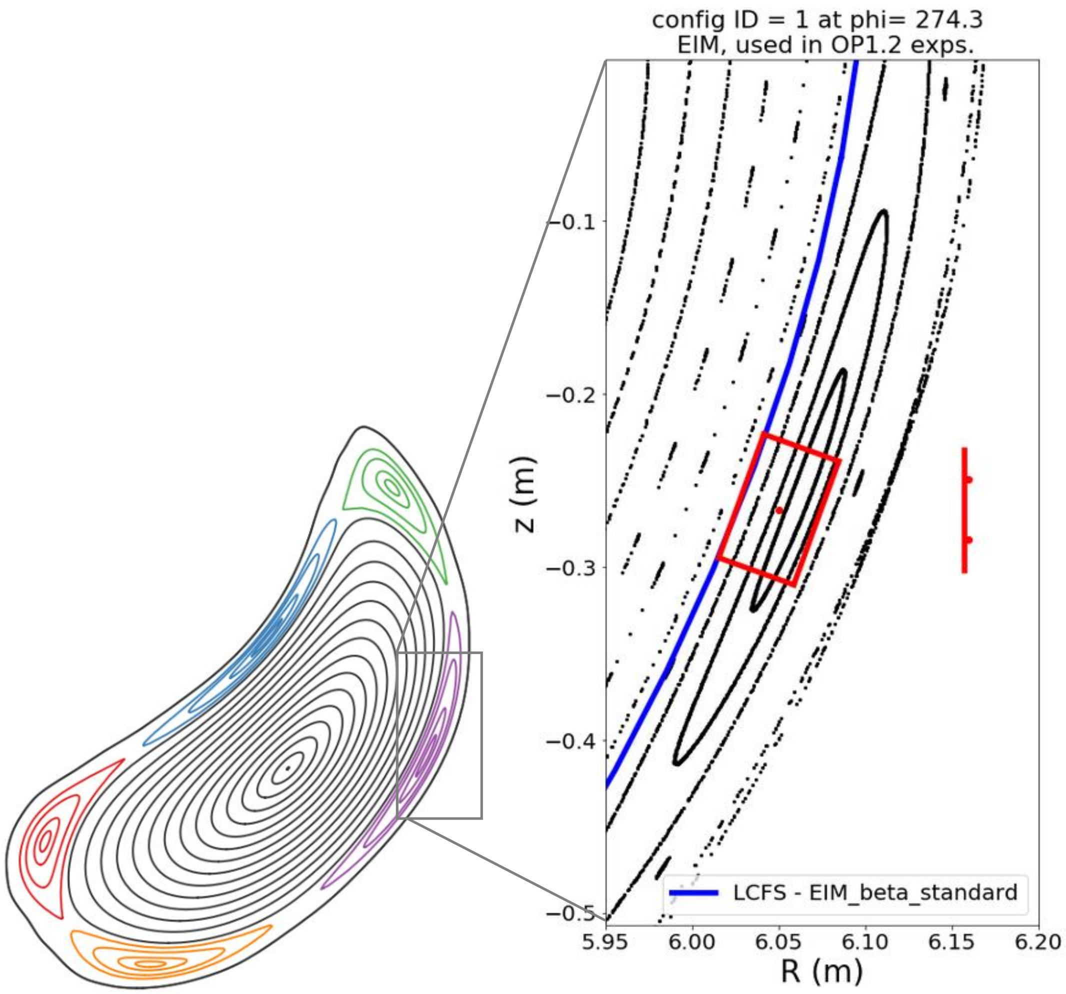
Challenges

- only few diagnostics for SOL turbulence in OP1.2
- diagnostics at different locations, with different spatial resolutions
- limited mapping capabilities
- limited run time of several important diagnostics so far (A-BES, reciprocating probes)



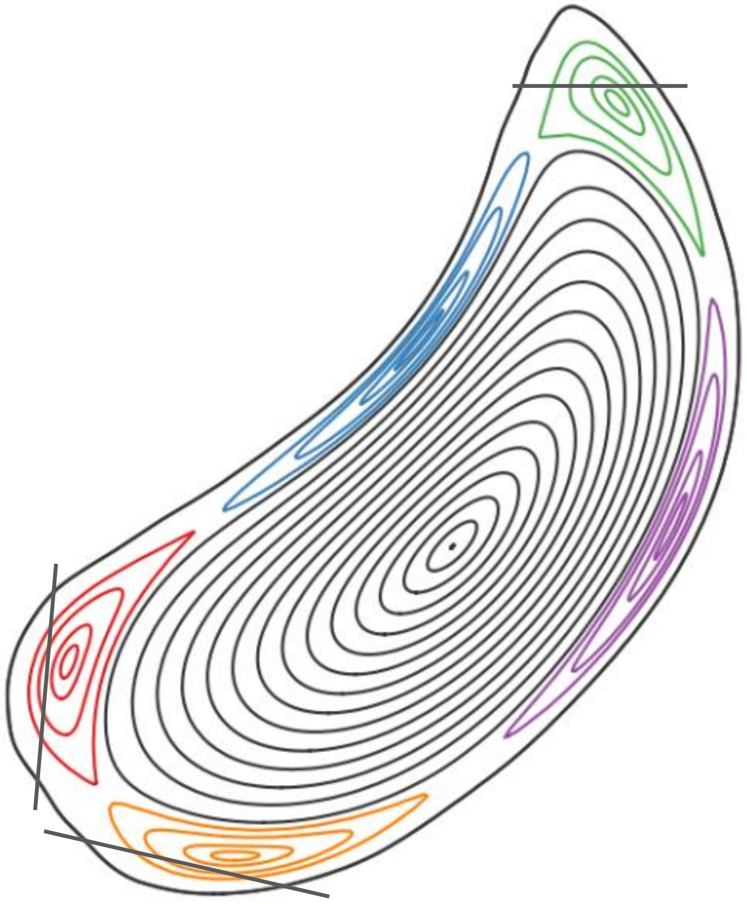
New Gas Puff Imaging Diagnostic for OP2 (MIT contribution)

- **GPI provides 2D images of fluctuating emission**
  - 8x16 pixels cover a 48x78 mm f-o-v
  - k_{max}~5.5 cm^{-1}
  - Δk^{pol}_{min} ~0.2 cm^{-1}
  - $\Delta\ k^{rad}_{min}$~0.32 cm^{-1}
  - f_{max} up to 1 MHz, but probably limited by photon flux to a few 100 kHz
- **GPI can address multiple topics**
  - Filaments: Dynamics through and around islands, generation, statistics
  - Turbulence in island structure
    - Relation of turbulence to island-associated mode activity
    - (k_{pol},f) spectrograms measured vs R
  - Edge coherent modes (F-o-v includes LCFS in some configurations)



Outline

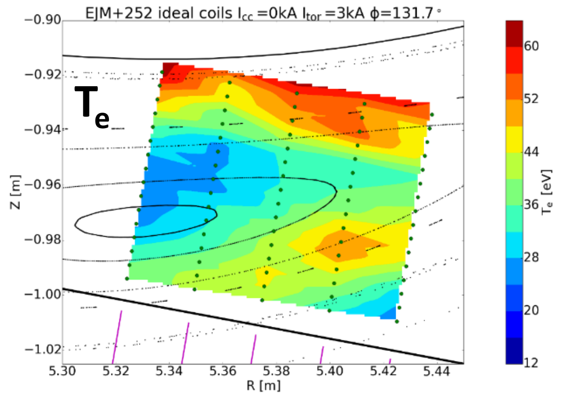
1. **Turbulent Filaments**
2. **Turbulence in the presence of magnetic islands**
3. **EM effects**
4. **SOL transport & divertor loads**

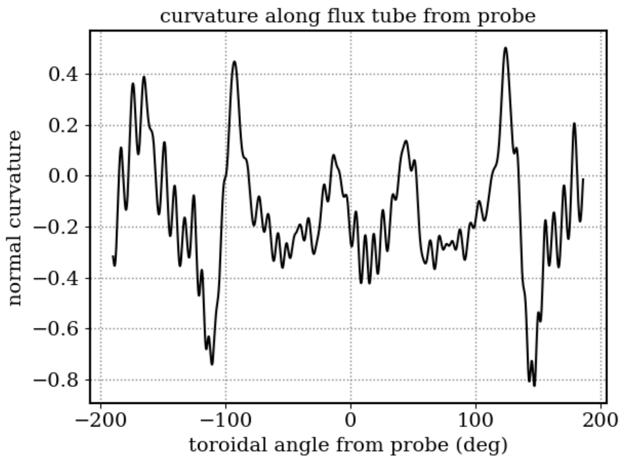


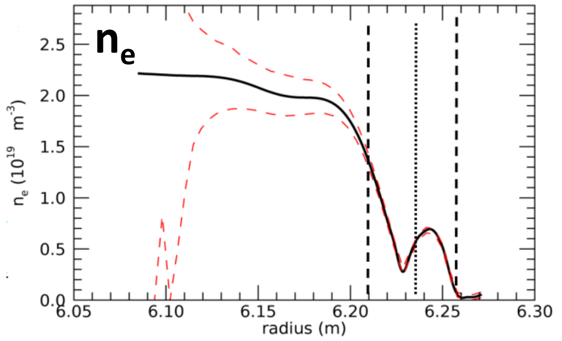
1. Turbulent Filaments

- **researchers:** Sandor Zoletnik, Gabor Kocis, Lilla Zsuga, Carsten Killer, Brendan Shanahan, Jim Terry, Sean Ballinger, Adrian von Stechow
- **general considerations:**
  - filaments occur in the toroidal plasmas in regions of bad curvature (pressure gradient || curvature)
  - in W7-X, curvature is non-uniform along a field line
  - in W7-X island divertor, pressure gradients can be complicated

  → it was initially unclear whether we can expect long filaments at all

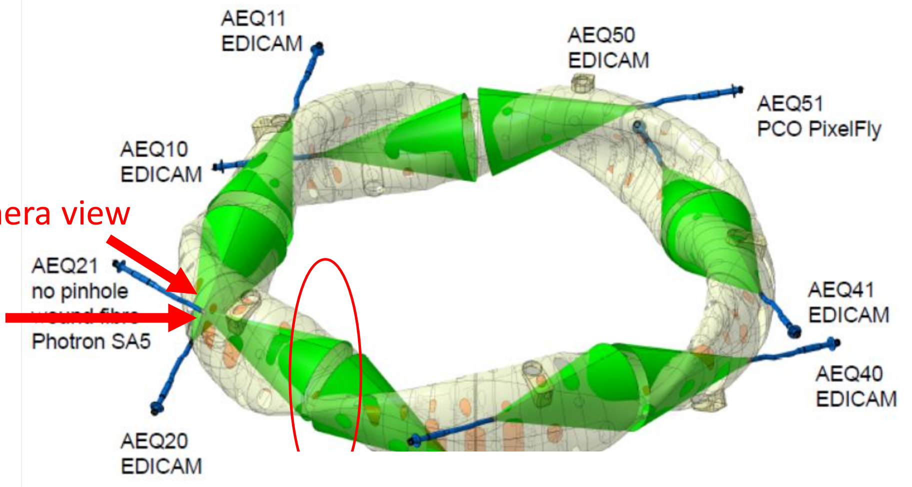


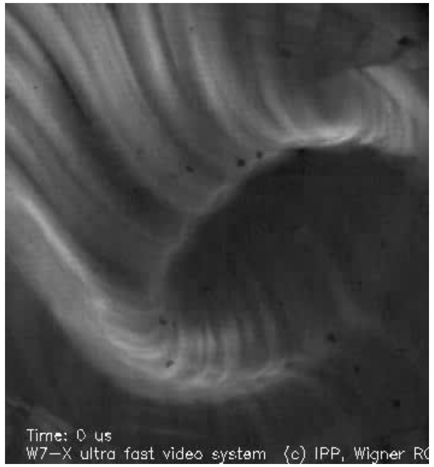




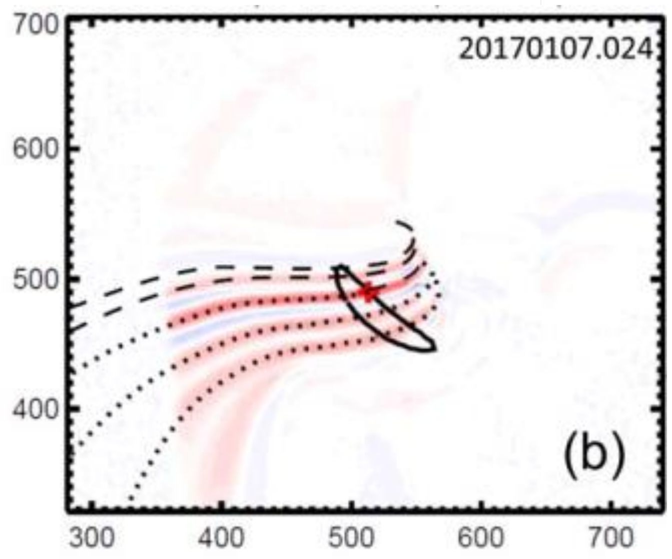
1. Turbulent Filaments

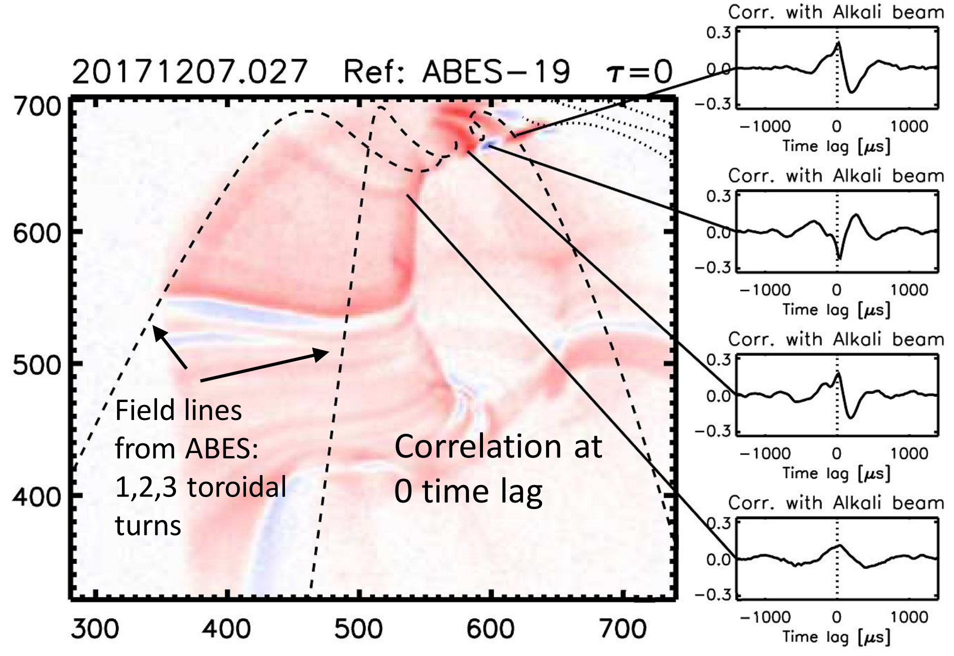
- **filaments observed by several diagnostics**
  - video cameras: already in OP1.1, throughout OP1.2
    Long parallel elongation (multiple toroidal turns)
    poloidal propagation
  - probes: parallel elongation of at least 10m seen by correlation of reciprocating and target probes





[G. Kocsis EPS2017]

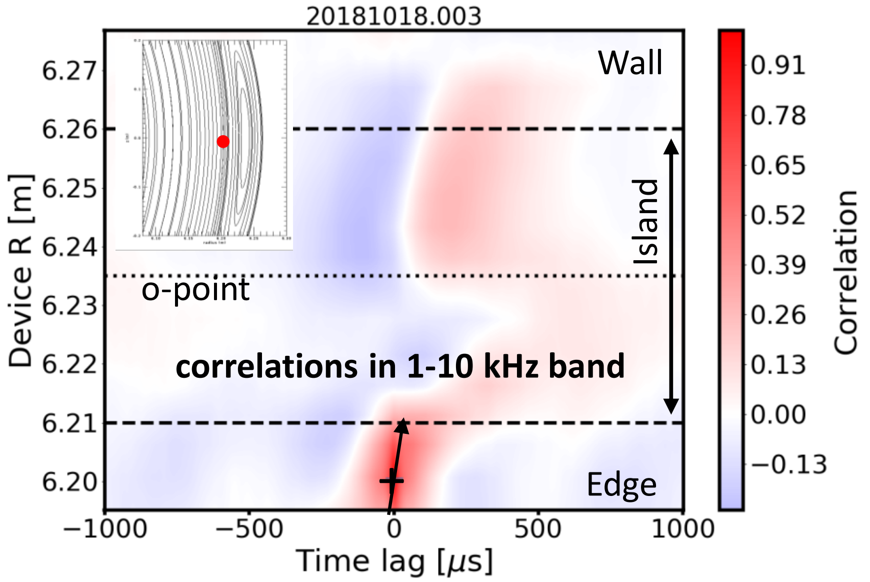




[S. Zoletnik]

1. Turbulent Filaments – in the island divertor

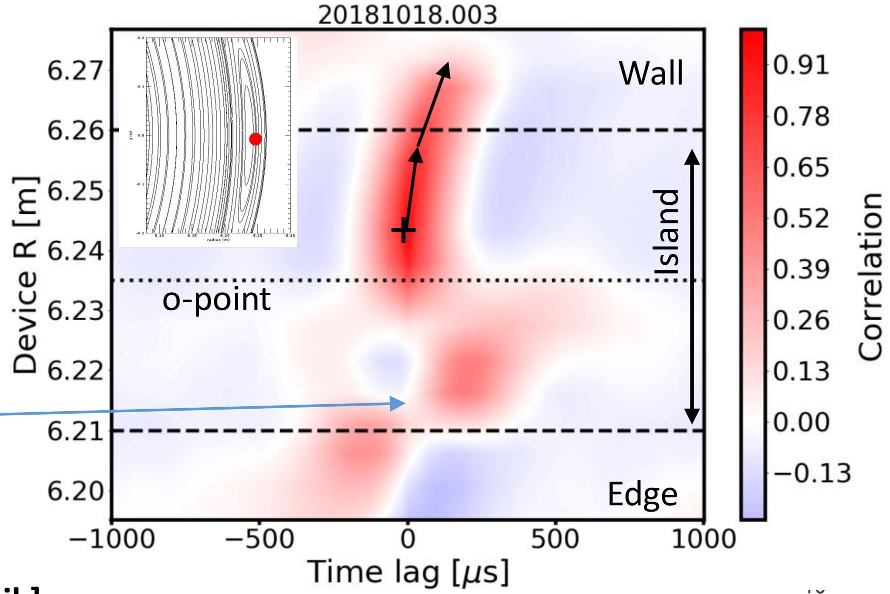
Perturbations orginate at edge plasma
- Radial velocity few 100 m/s
- Correlation disappears at separatrix
- Correlation on outboard side of island after ~200 µs



Structure propagate outward on outboard side of island
- Blob-like outward propagation, not diffusive
- Radial size is 2-3 cm
- Slowing down in SOL

  → might be indication of sheath limited regime (Entering short connection length zone.)

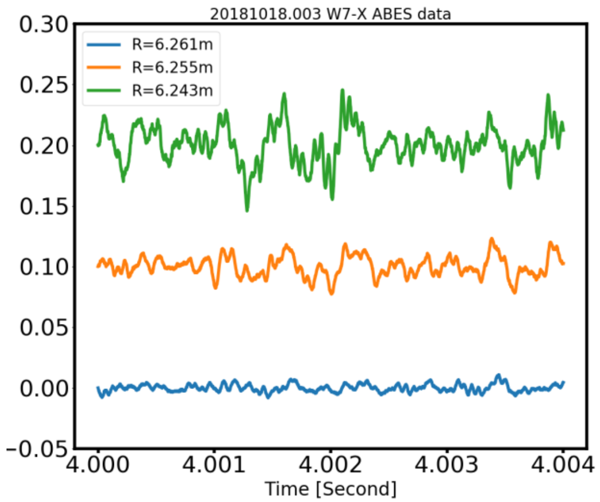
Complex picture in inboard side of island

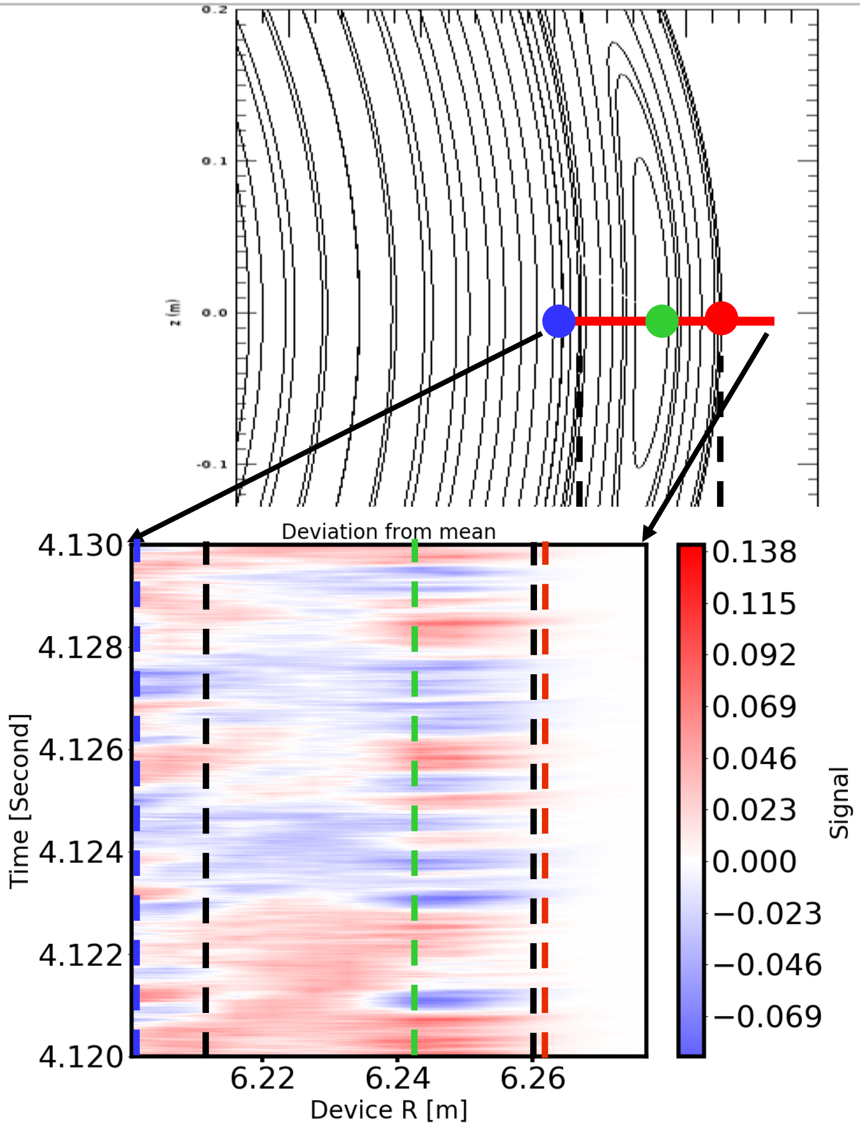


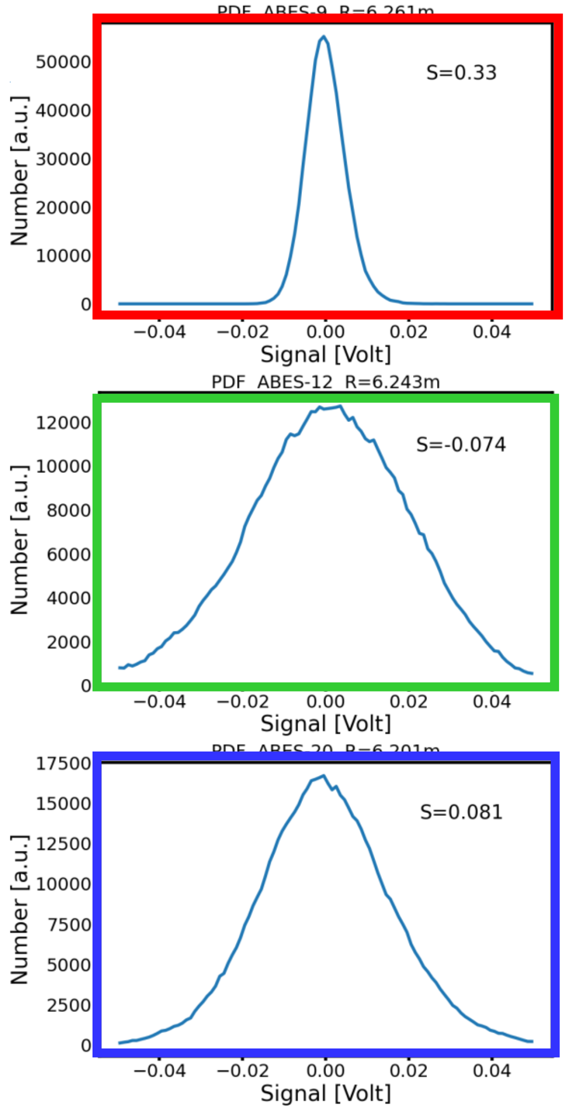
[S. Zoletnik]

1. Turbulent Filaments – in the island divertor: intermittency

Signals don’t look intermittent.





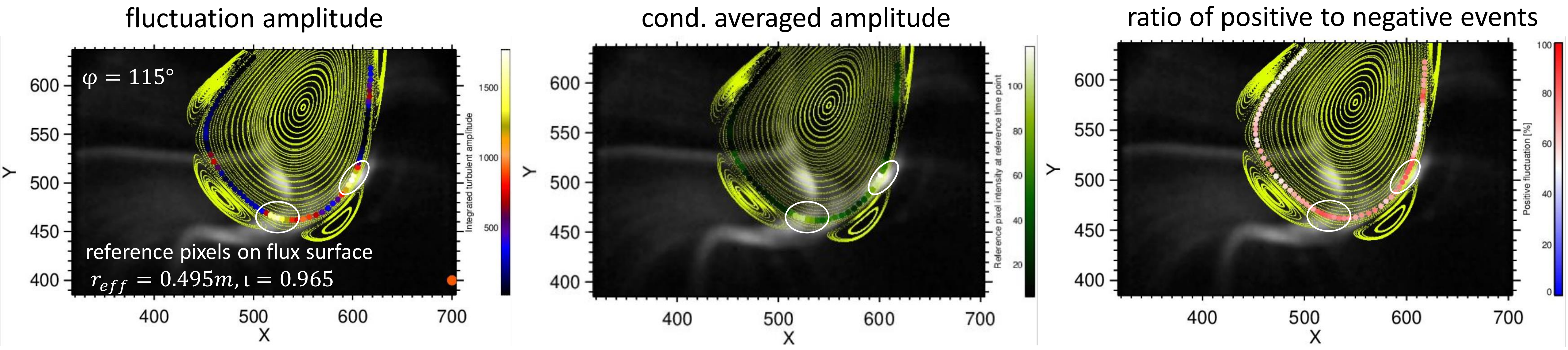


In time-R plots individual events can be identified: both positive and negative
→ larger event rate, overlapping events?

almost normal PDFs

[S. Zoletnik]

1. Turbulent Filaments – in the island divertor

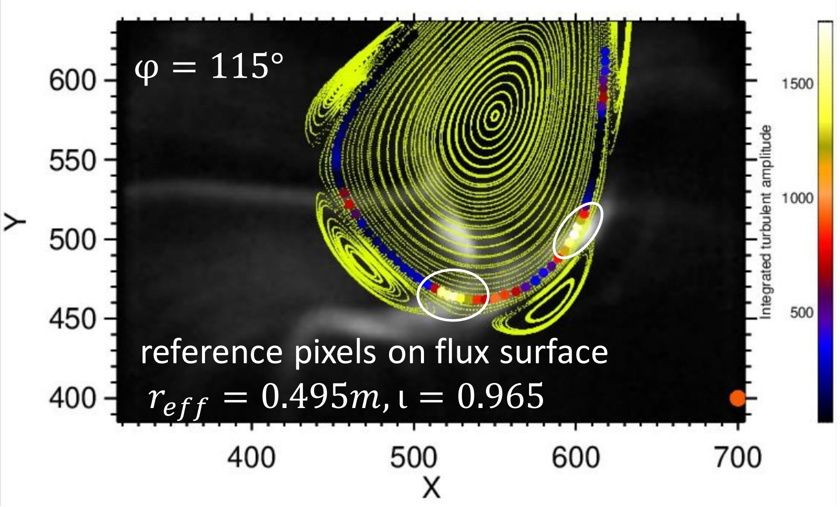


- **fluctuations are not constant on a flux surface**
- **appear to be enhanced close to X points (but inside LCFS)**

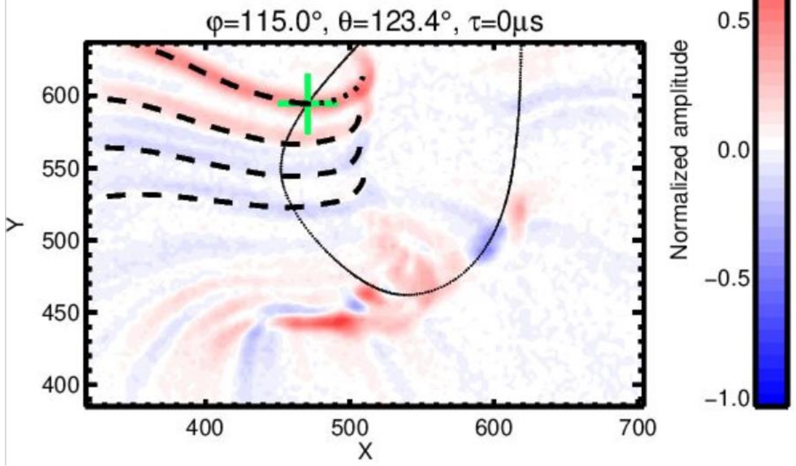
- #20181016.017: standard configuration detachment scenario (P_{ECRH}=5MW)
- Fast camera: 90kHz, tangent view, CIII line detection

[L. Zsuga]

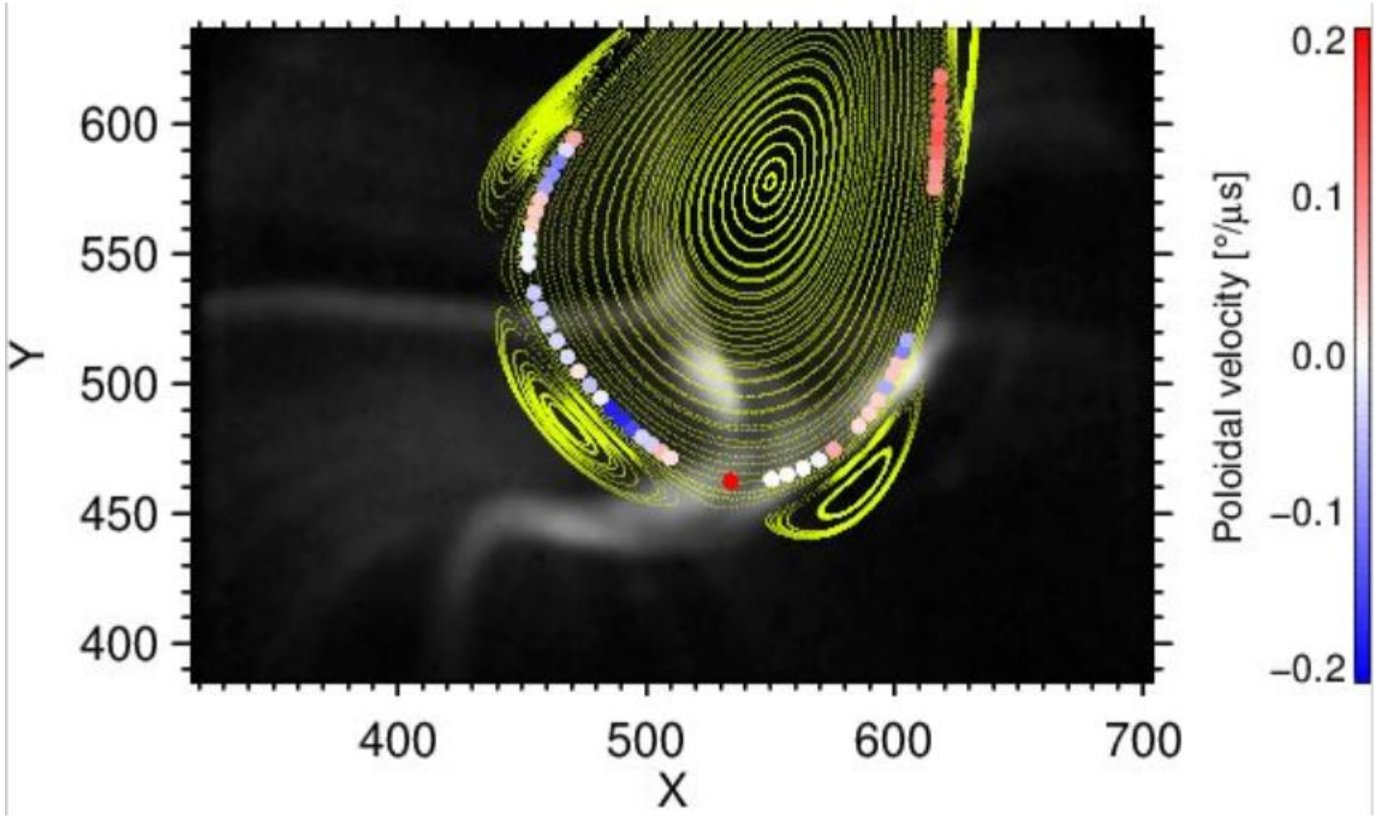
1. Turbulent Filaments – in the island divertor



conditional average for all pixels
→ shows filamentary character



poloidal velocity (~E_r) varies strongly on a flux surface

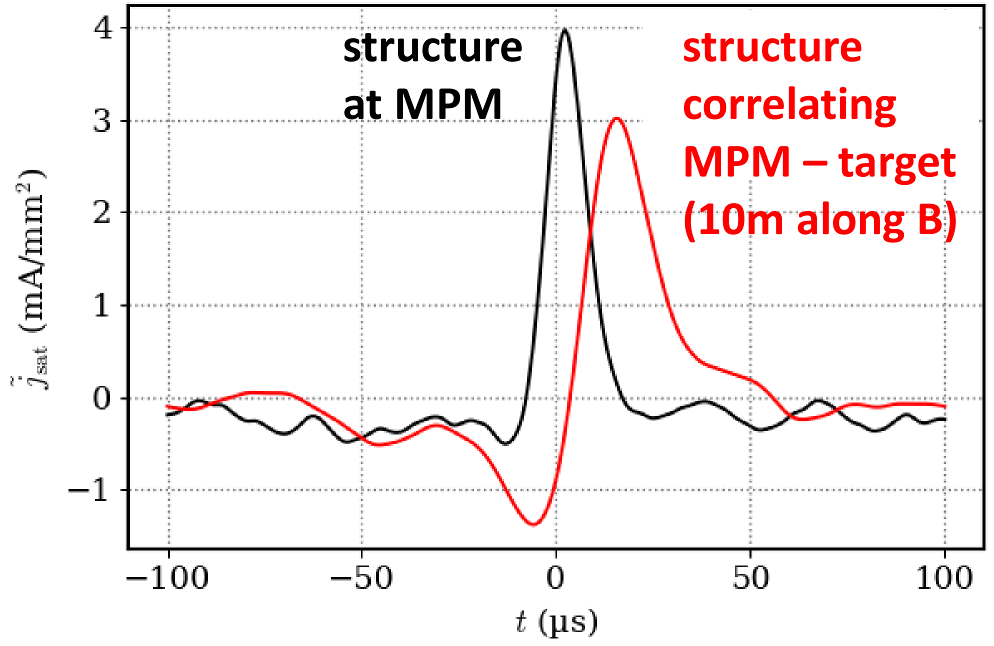


[L. Zsuga]

1. Turbulent Filaments – outside of islands

- **probe measurements outside of islands show interchange-type filaments**
- **extending to the target, fast parallel response**
- **statistics similar to A-BES: PDFs close to normal**

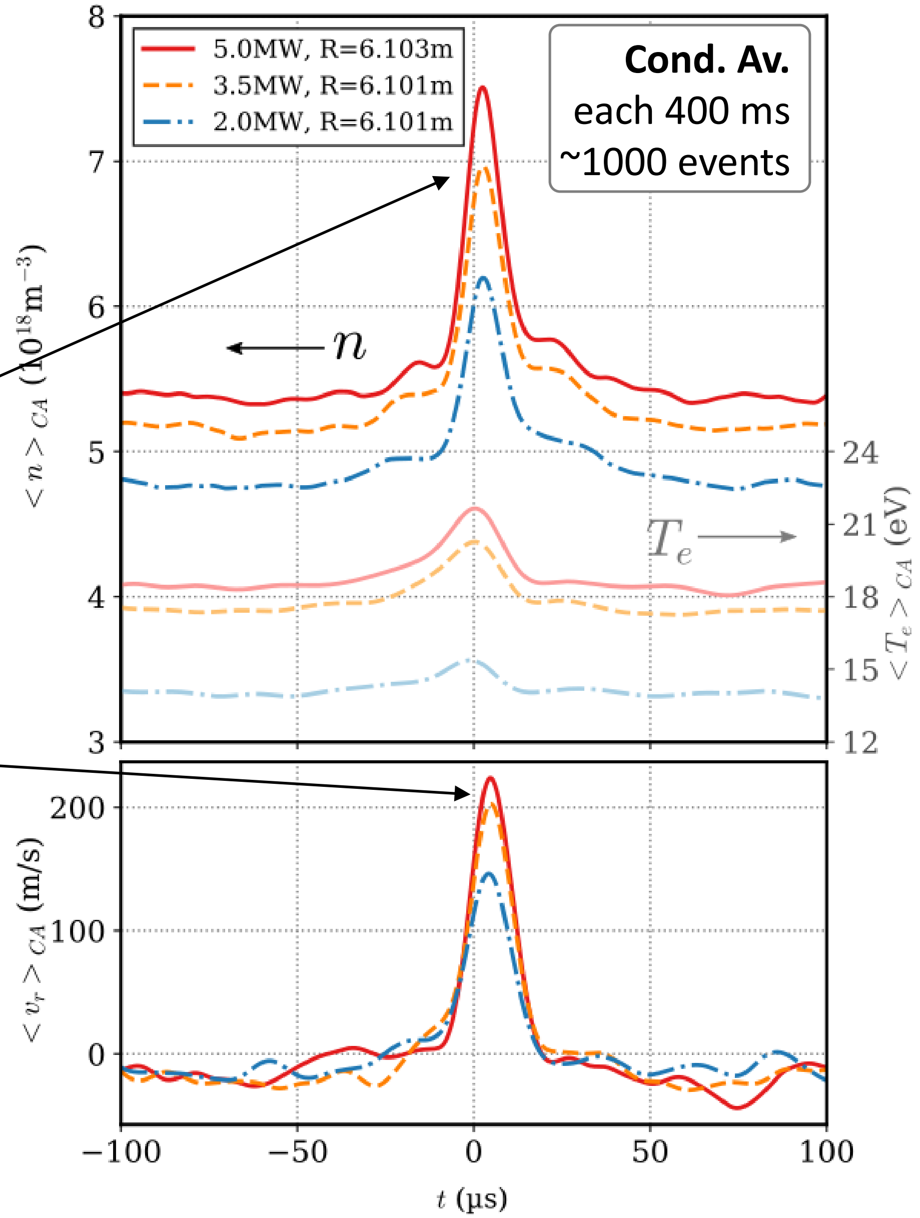
conditionally averaged density events



monopole density peak

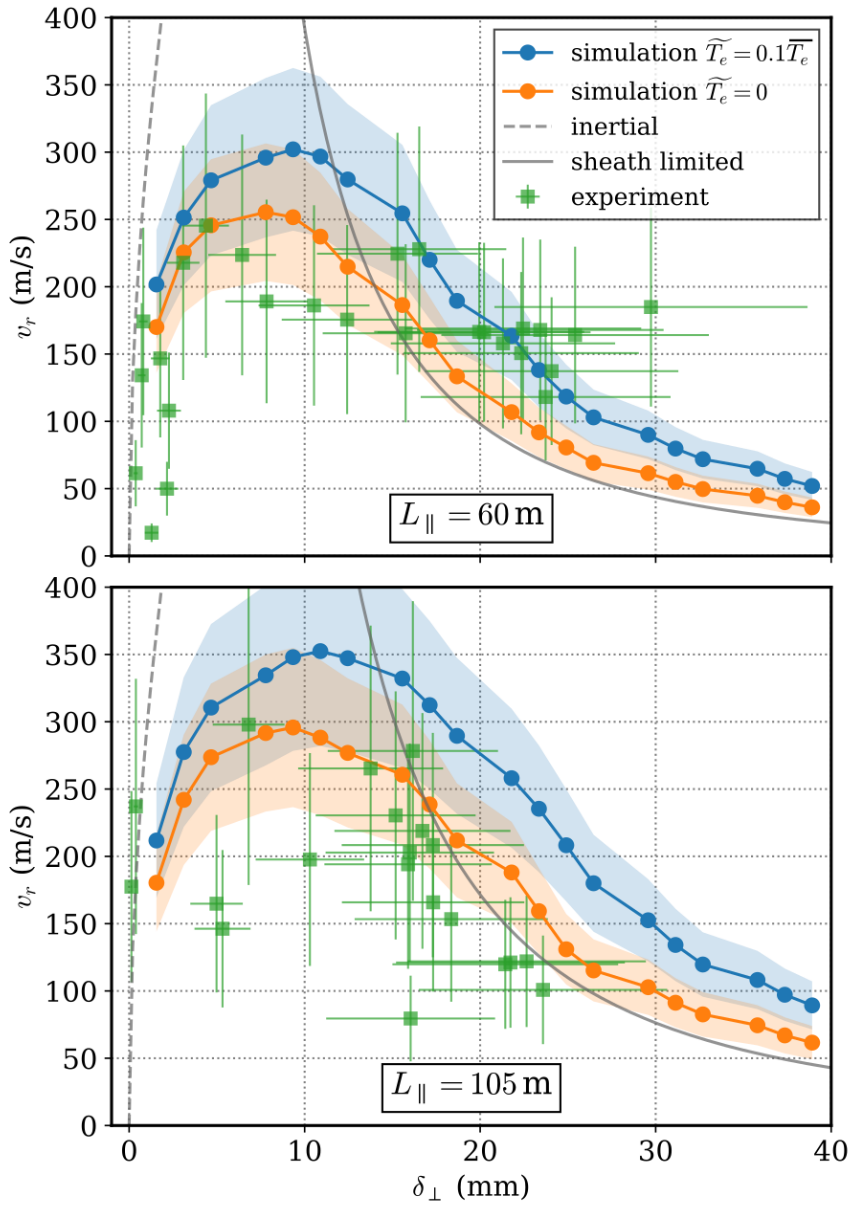
E_{pol} peak

→ v_r=ExB/B²



1. Turbulent Filaments – outside of islands

- **relatively slow radial filament propagation (compared to tokamaks)**
- **in agreement with simulations, this is due to smaller curvature in W7-X → less radial transport**



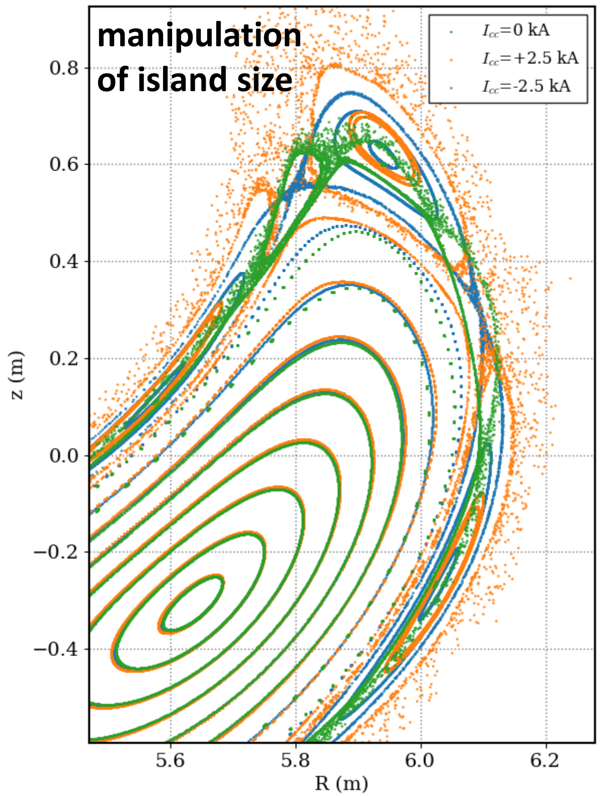
[B. Shanahan]

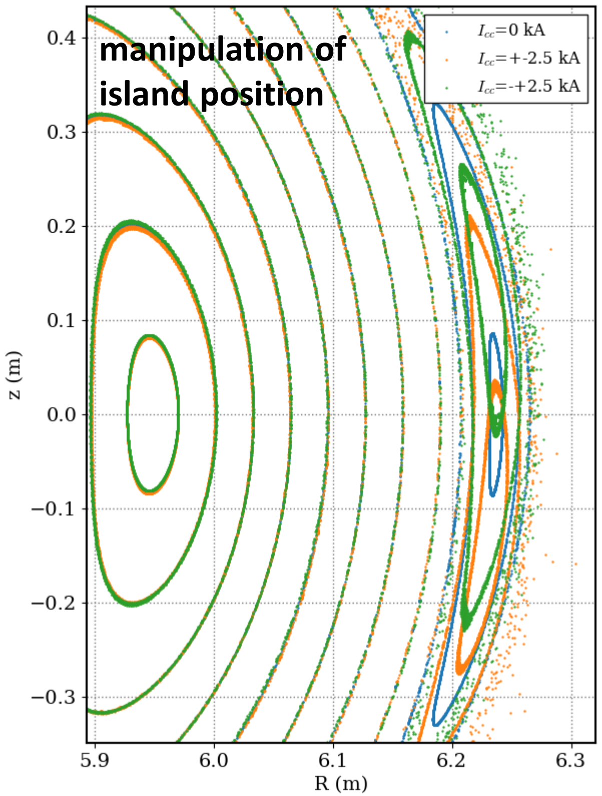
1. Turbulent Filaments – Open questions

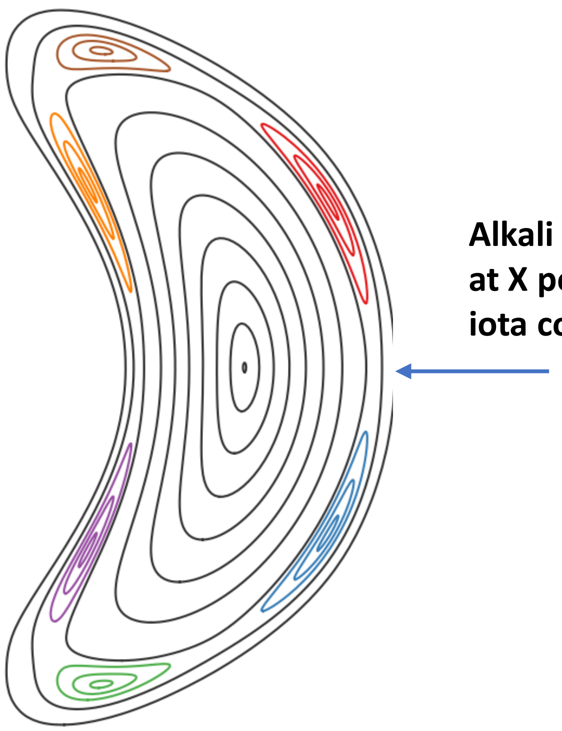
- **filament generation mechanism?**
  - probes data, indicating interchange type filament drive, implie only short radial propagation due to life time and v_r
  - A-BES data in island implies much longer radial propagation distances. role of modes seen by A-BES and others?
- **relation to magnetic topology**
  - 3D filament propagation in islands
  - role of magnetic shear at X points
- **Why is intermittency so low?**
  - local filament generation
  - multiple toroidal turn filaments
  - filament generation rate is higher than in tokamaks

1. Turbulent Filaments – Refining studies in OP2.1

- **Collect more data with improved diagnostic coverage under controlled conditions: more runtime of Alkali beam and probes, new diagnostic GPI**
- **role of magnetic topology**
  - Investigate role of islands by island manipulation with control coils
  - Investigate dynamics at X vs O points







Alkali beam directly at X point in Low iota configuration

1. Turbulent Filaments – Refining studies in OP2.1

- **Collect more data with improved diagnostic coverage under controlled conditions: more runtime of Alkali beam and probes, new diagnostic GPI**
- **role of magnetic topology**
  - Investigate role of islands by island manipulation with control coils
  - Investigate dynamics at X vs O points
- **role of plasma scenario**
  - Investigate filaments in detachment under controlled conditions
  - Investigate differences at low-high density (collisionality)

Unexplored areas

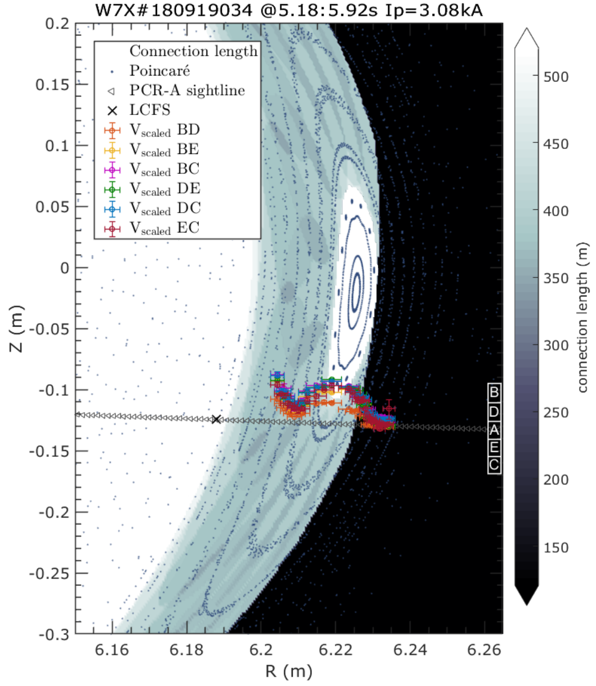
- relation of filaments to MHD modes
- relation of filaments to divertor / PFC heat loads

2. Turbulence in the presence of magnetic islands

- **researchers:** Andreas Krämer-Flecken, Xiang Han, Xiang Haoming, Sandor Zoletnik, Gabor Kocsis, Lilla Zsuga, Carsten Killer, Shaocheng Liu, Sean Ballinger, Jim Terry, Adrian von Stechow
- **topics**
  - modification of turbulence by magnetic islands
  - mode activity, plasma crashes

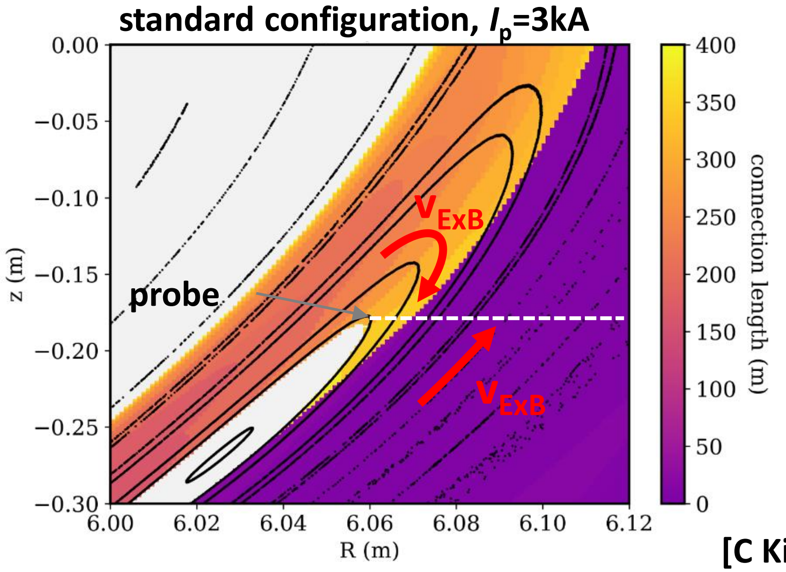
2. Turbulence in the presence of magnetic islands

- plasma profiles modified (often flatten) across islands
  → affects gradients, and therefore turbulence drive
- poloidal ExB flow around islands can occur
  → taking turbulent fluctuations with them ("*poloidal spreading*")
  → also, additional velocity shear layer which might affect turbulence

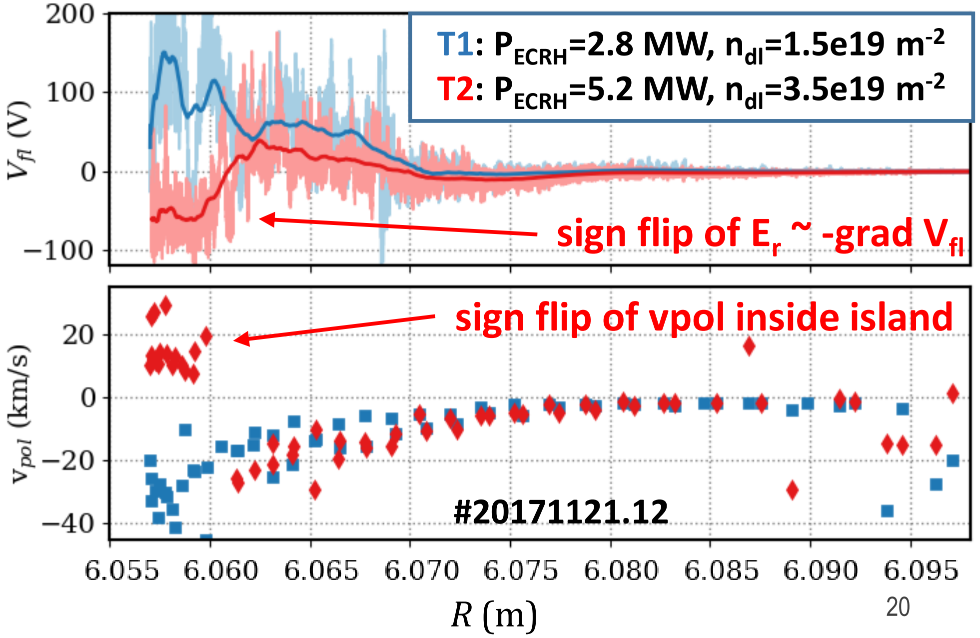


[X Han]

$v_\perp$ flows observed with PCR and MPM



[C Killer]



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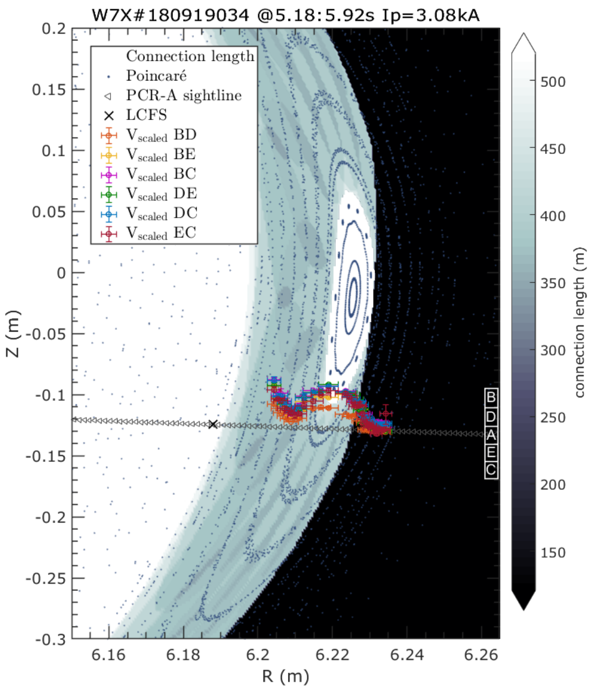
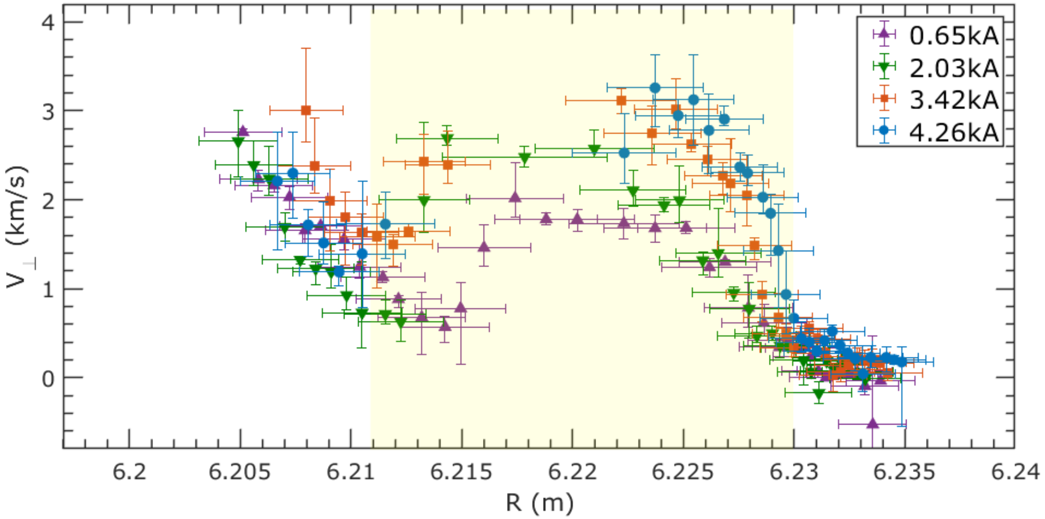


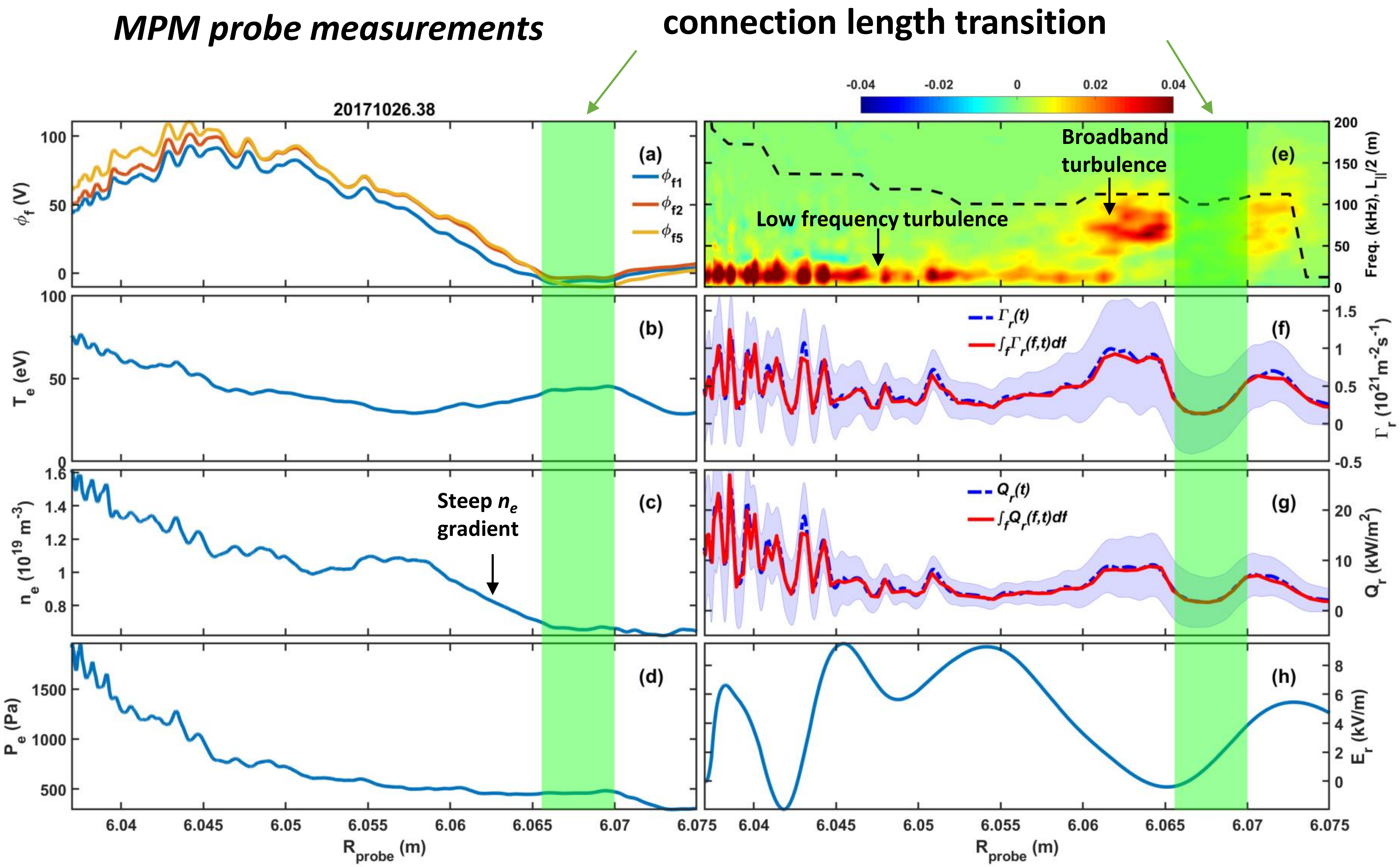


- $v_\perp$ flows depend on plasma conditions
- $v_\perp$ flows depend on iota (→island position)
  - studied in iota scan experiments
  - sensitive to even small iota changes by toroidal plasma currents
- turbulence suppression aligning with $v_\perp$ shear observed by PCR

[X Han]

2. Turbulence in the presence of magnetic islands

- turbulence activity is modified by magnetic island
- closely related to magnetic topology and plasma profiles

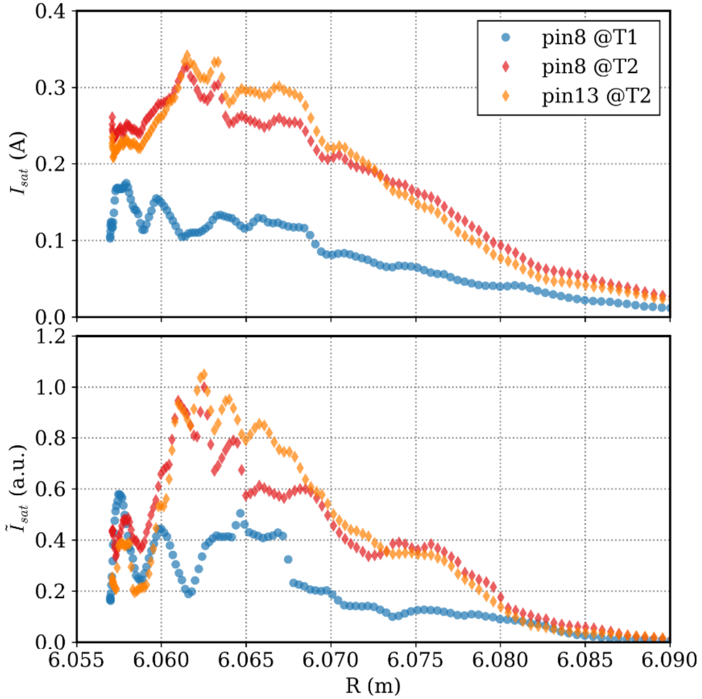


[S. Liu, NF2019]

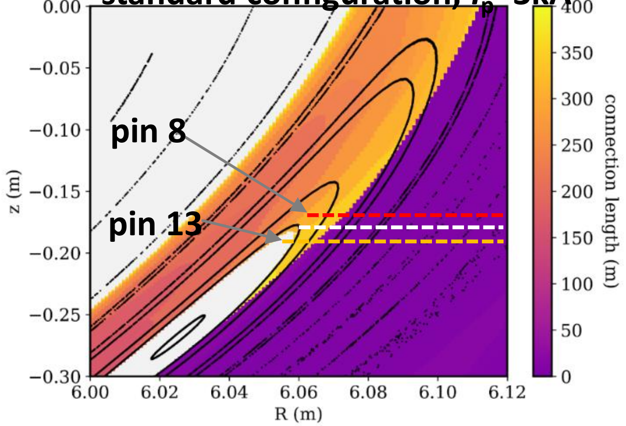
2. Turbulence in the presence of magnetic islands

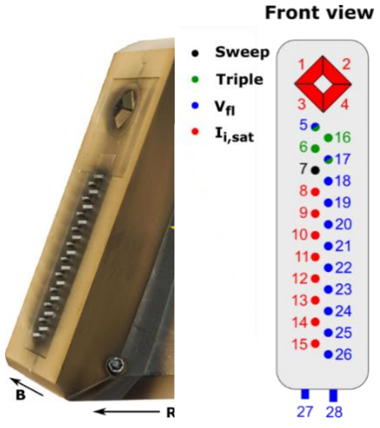
- **turbulence activity is modified by magnetic island**

MPM results



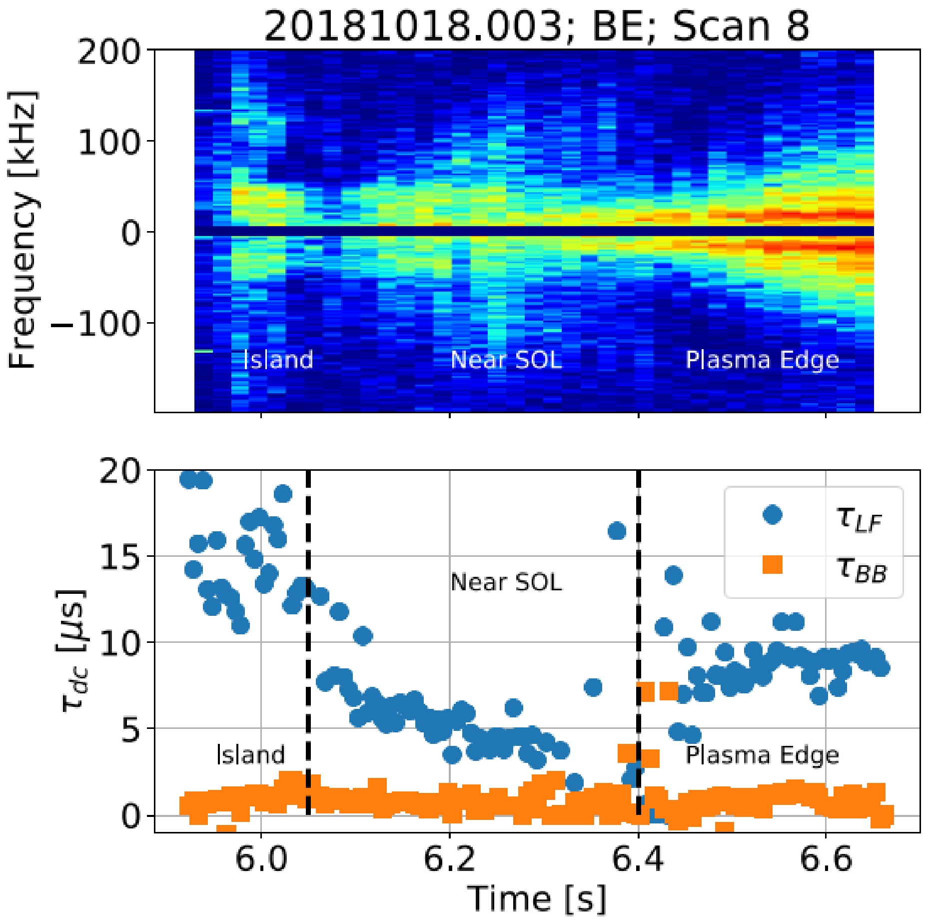
standard configuration, I_p=3kA





[C Killer]

PCR results – de-correlation time



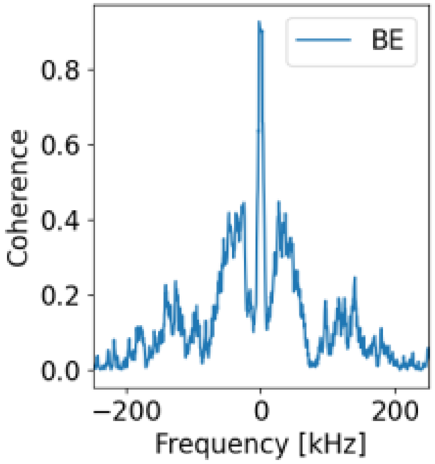
[A. Krämer-Flecken]

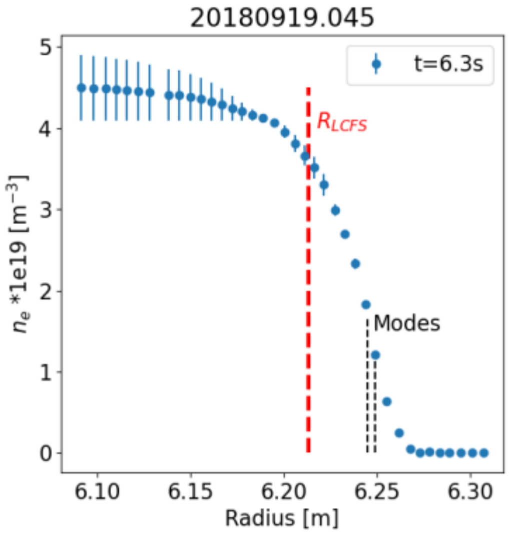
2. Turbulence in the presence of magnetic islands

- **rich mode activity observed**
  - ~1kHz: in islands, seen by many SOL diagnostics
  - ~10kHz: in edge (and outside islands in some cases), often quasi-coherent
  - ~100kHz: in SOL, might be related to Alfvenic activity seen by Mirnov probes

2. Turbulence in the presence of magnetic islands - *Modes*

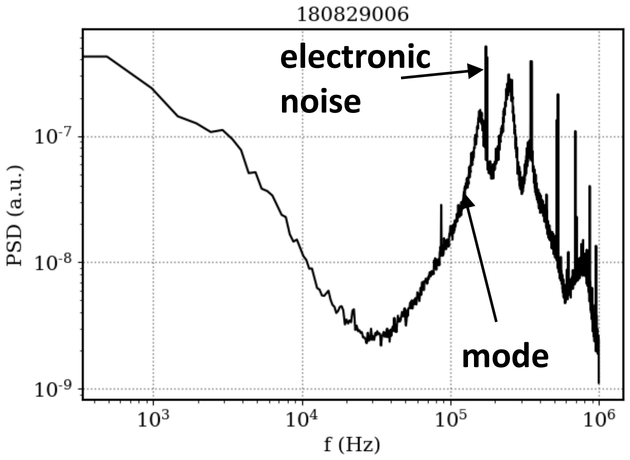
PCR: mode activity in island at ~20-40kHz and ~130kHz



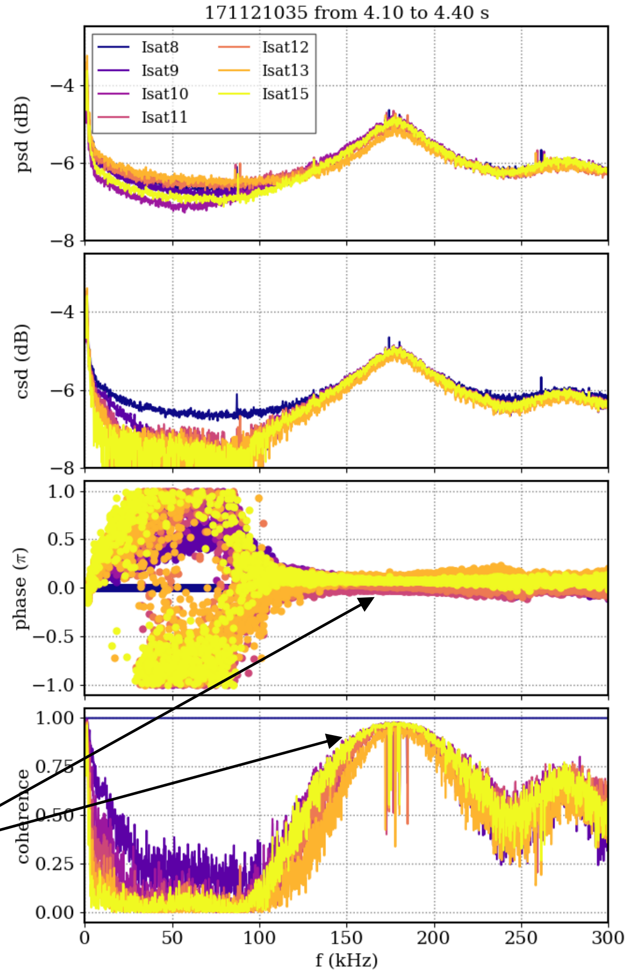


[A. Krämer-Flecken]

MPM Isat spectrum

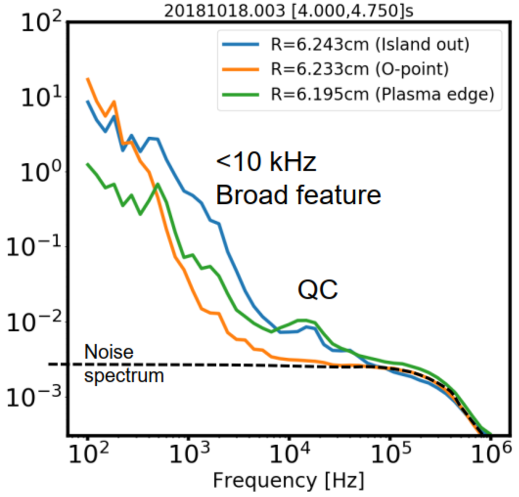


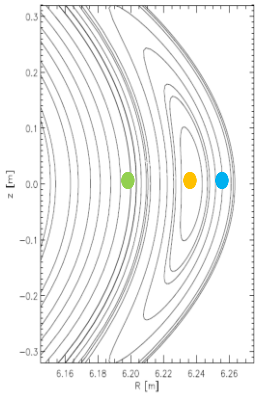
[C. Killer]



coherent mode
across multiple
Isat pins

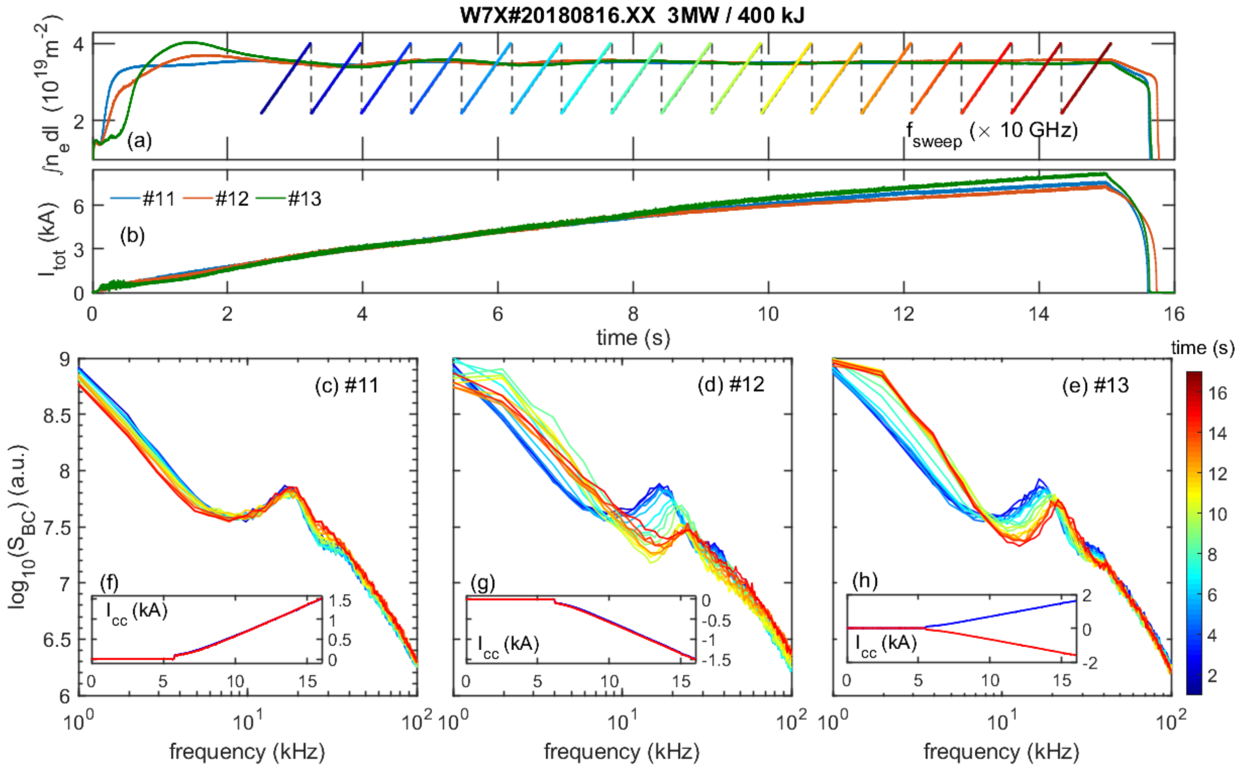
A-BES spectrum





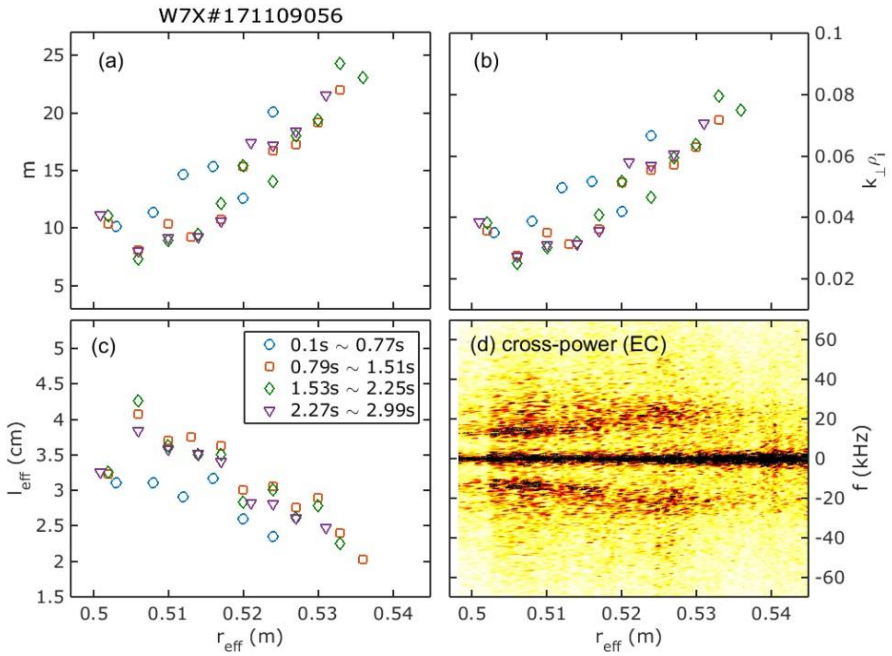
[S. Zoletnik]

2. Turbulence in the presence of magnetic islands – *Mode activity*



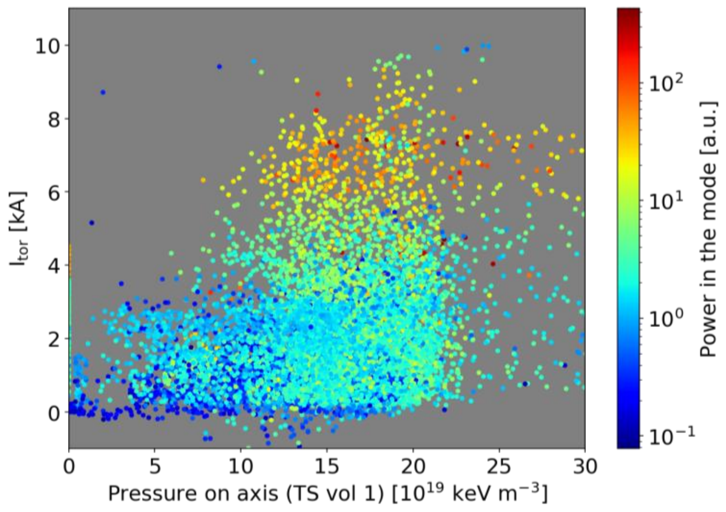
[X Han]

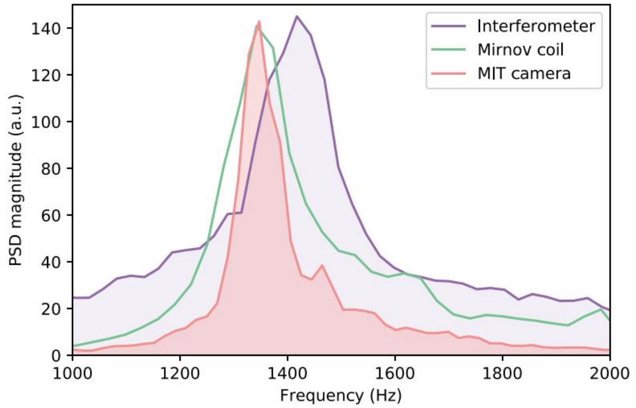
- QC mode in plasma edge
- typically 10-25kHz
- $8 \leq m \leq 25, k_{\perp}\rho_s \leq 0.1$
- visible in EJM and KKM (iota=5/5)
- QC mode is sensitive to iota changes (already ΔI_p~1kA makes a difference)



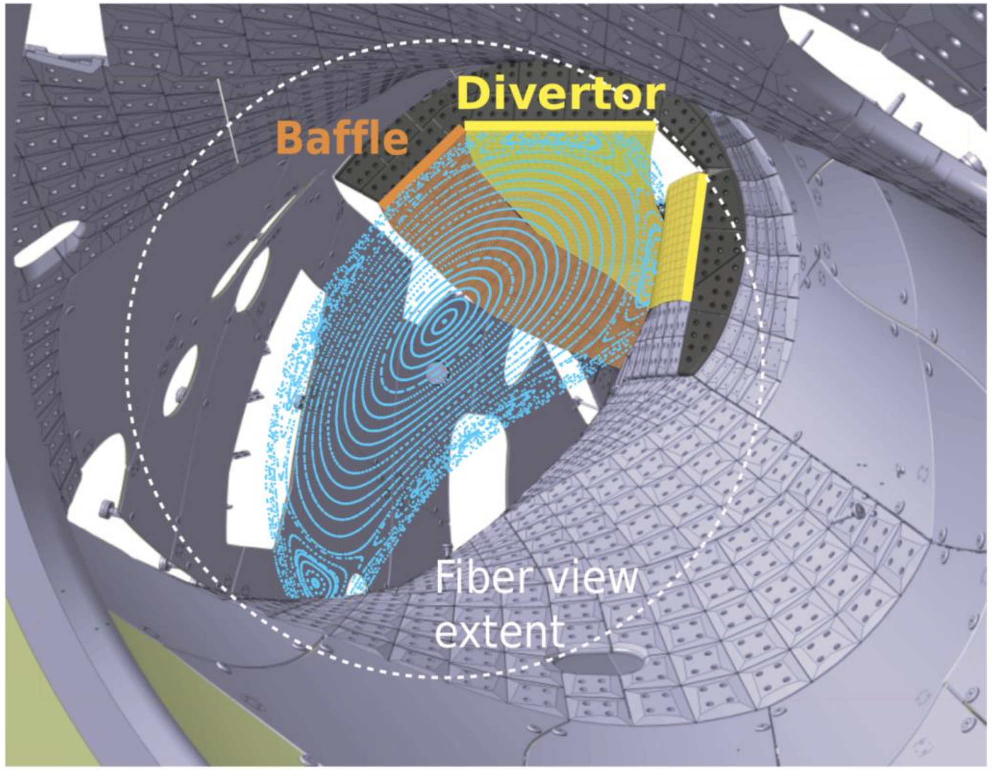
2. Turbulence in the presence of magnetic islands – *The 1-2kHz mode aka Low frequency mode*

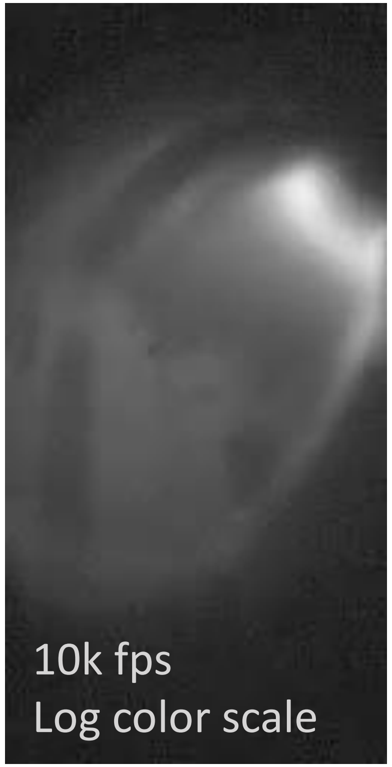
- **observed by many SOL diagnostics**
- **dedicated investigations focused on cameras / magnetic fluctuations (Ballinger) and PCR (Haoming)**





[Sean Ballinger]



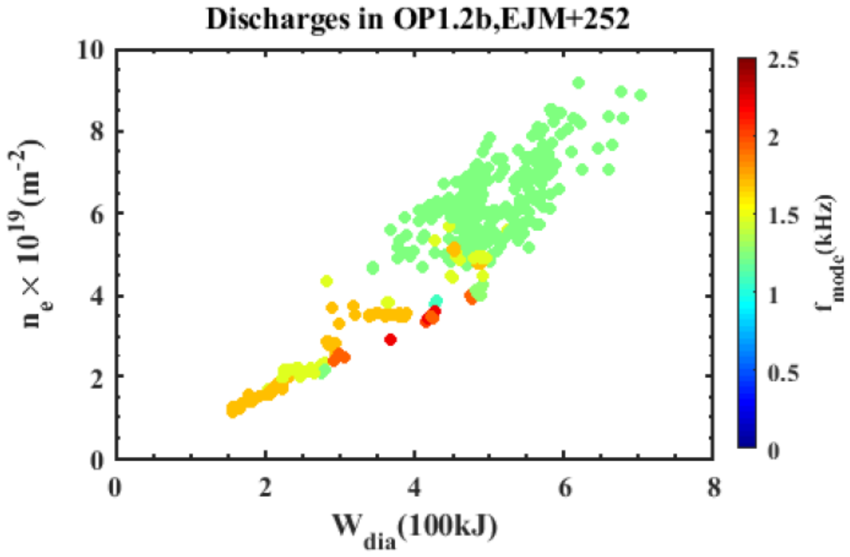


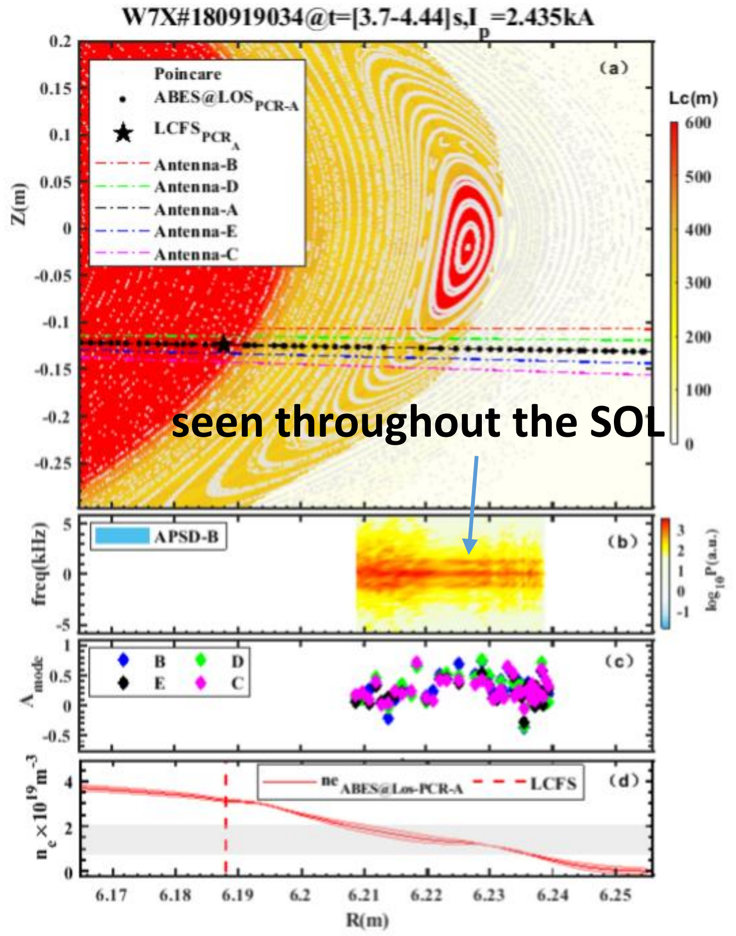
2. Turbulence in the presence of magnetic islands – *The 1-2kHz mode aka Low frequency mode*

- **observed by many SOL diagnostics**
- **dedicated investigations focused on cameras / magnetic fluctuations (Ballinger) and PCR (Haoming)**

questions

- is the LFM connected to filaments?
- what it its origin and what does it depend on?
- does it contribute to transport?

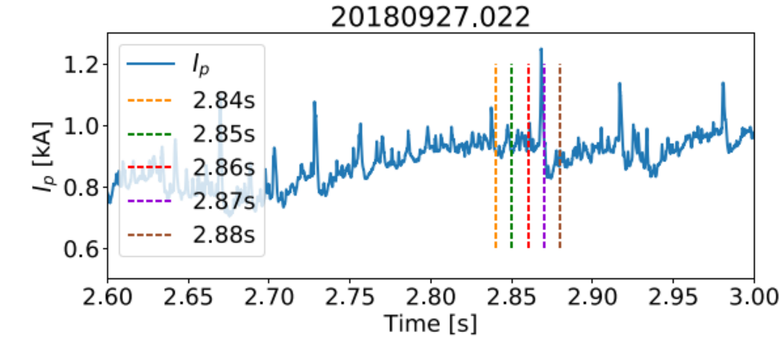


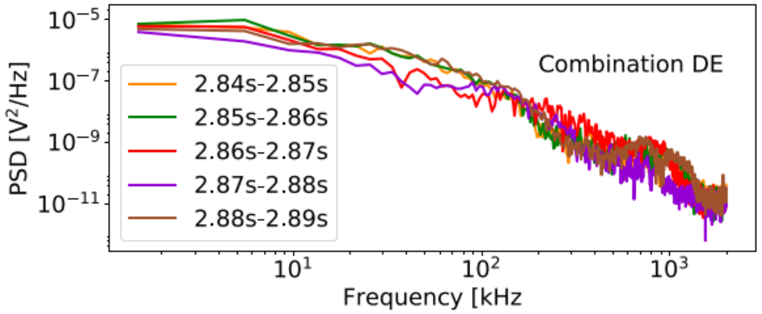


[X Haoming, paper in preparation]

2. Turbulence in the presence of magnetic islands – *Plasma crashes in FMM configuration*

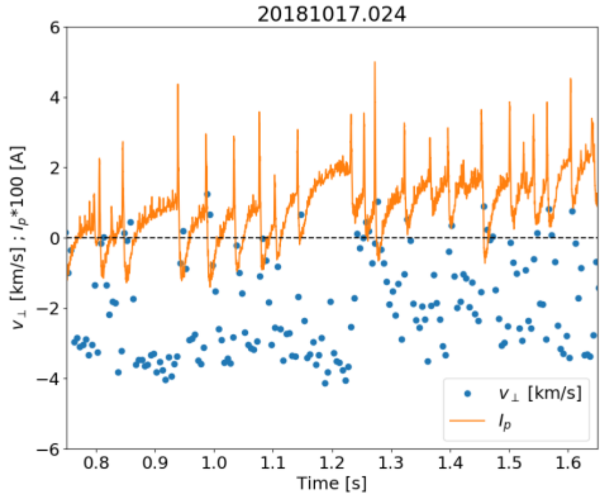
Mode activity interrupted by I_p-spikes





[A.Krämer-Flecken]

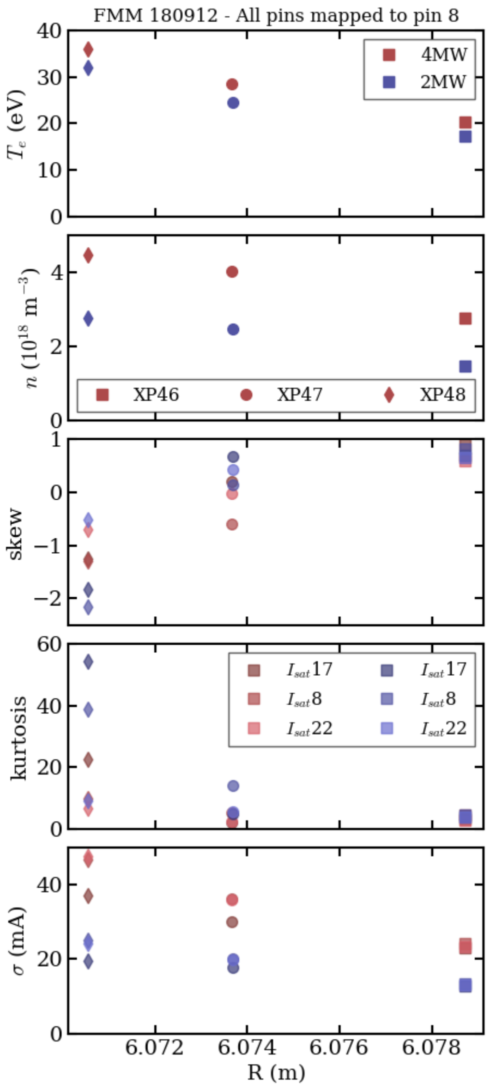
PCR outside 5/5-island - profile relaxation



$v_\perp$ jumps from plasma edge to SOL

[A.Krämer-Flecken]

MPM results: inversion position close to 11/10 island chain

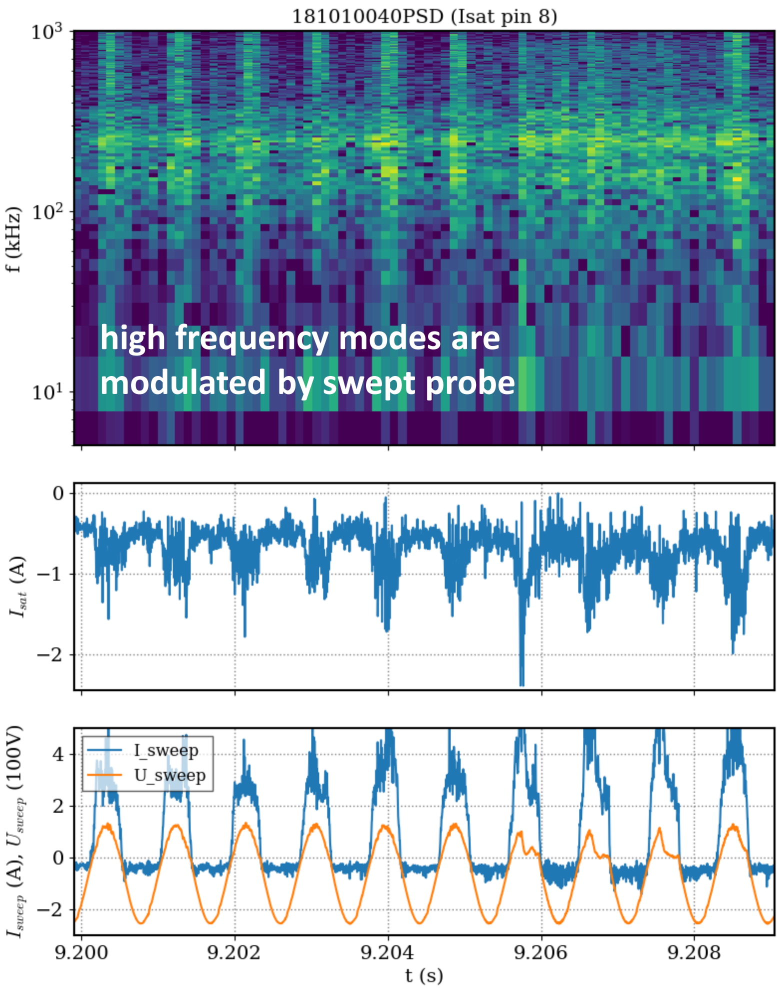


of $\tilde{I}_{sat}$

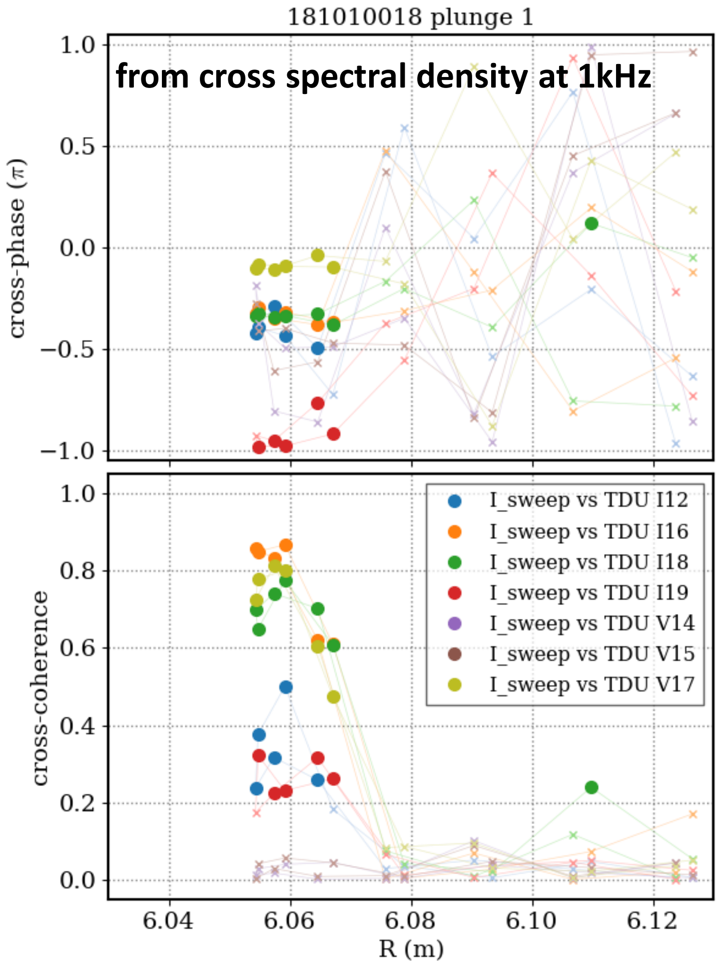
[C. Killer]

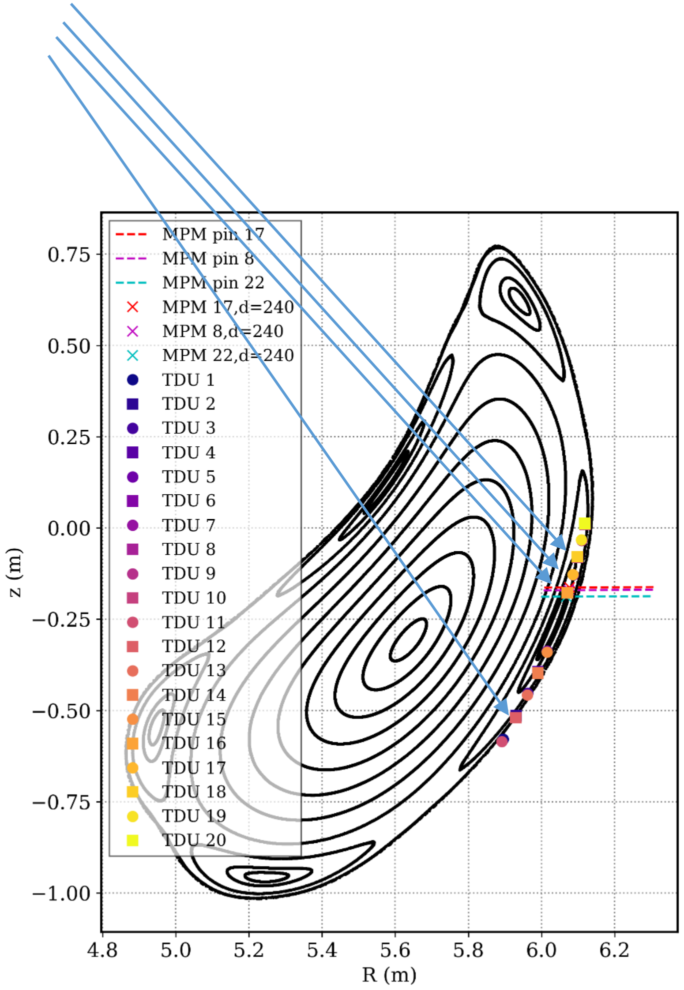
2. Turbulence in the presence of magnetic islands – *active perturbation experiments*

swept Langmuir probe on MPM (f~1kHz) perturbs plasma



1kHz perturbation is picked up by target probes





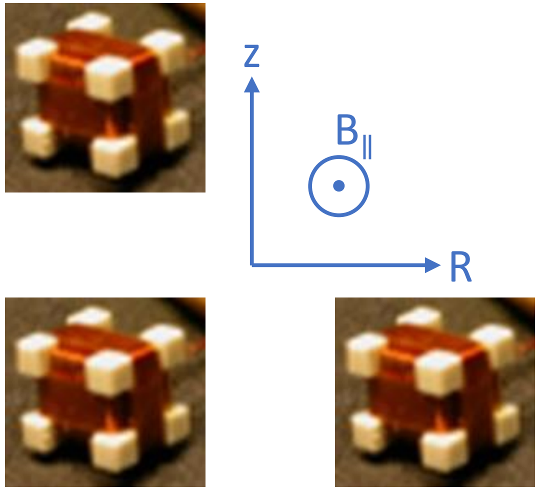
[C. Killer]

2. Turbulence in the presence of magnetic islands

- **summary**
  - islands modify turbulence, $v_\perp$
  - rich mode activity associated with islands
- **open questions**
  - is the turbulence activity related to local gradients?
  - what does the E_r shear in the islands depend on, and how does it affect turbulence
    → can we control the shearing rate?
  - what triggers the modes (gradients? currents? magnetic shear? flow shear?)
  - relation of modes to filaments
  - do modes contribute to transport?
- **approach for OP2.1:**
  - settle on a few experiment scenarios that are most important
  - ensure optimized diagnostic coverage

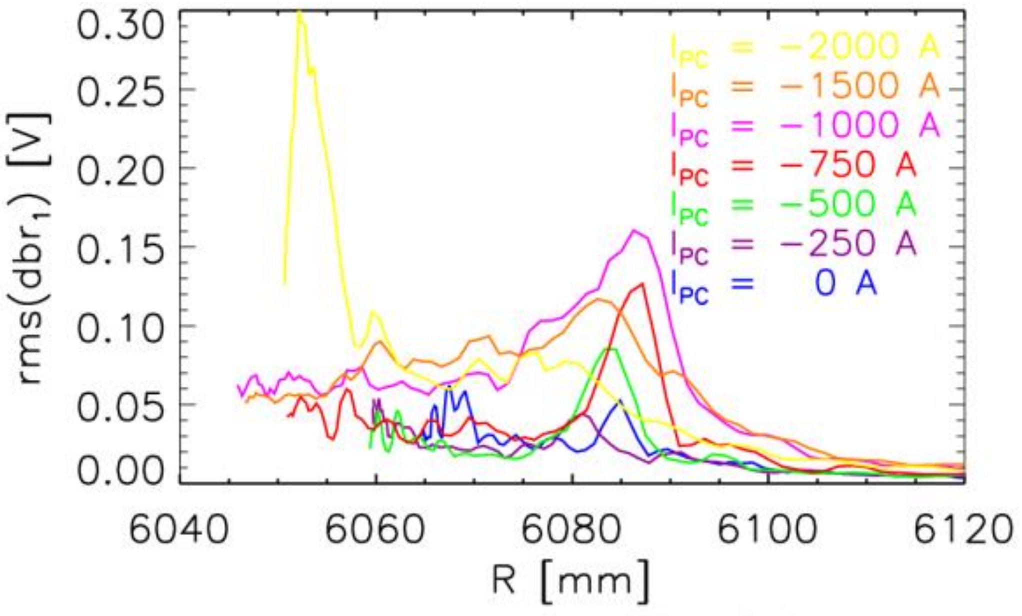
3. Electromagnetic effects

- **measurements of magnetic fluctuations with three 3D pick-up probes in OP1.2b**
- **magnetic fluctuations are modified across magnetic island**
- **researchers: Monica Spolaore, Zhuo Huang**



[M. Spolaore JINST 2019]

standard configuration - iota scan using planar coils



[M. Spolaore JINST 2019]

3. Electromagnetic effects

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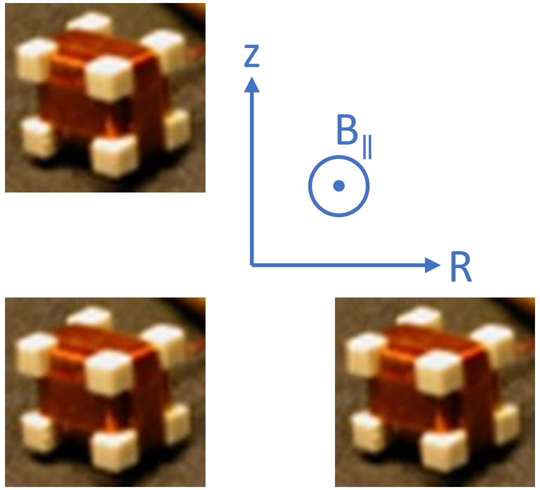
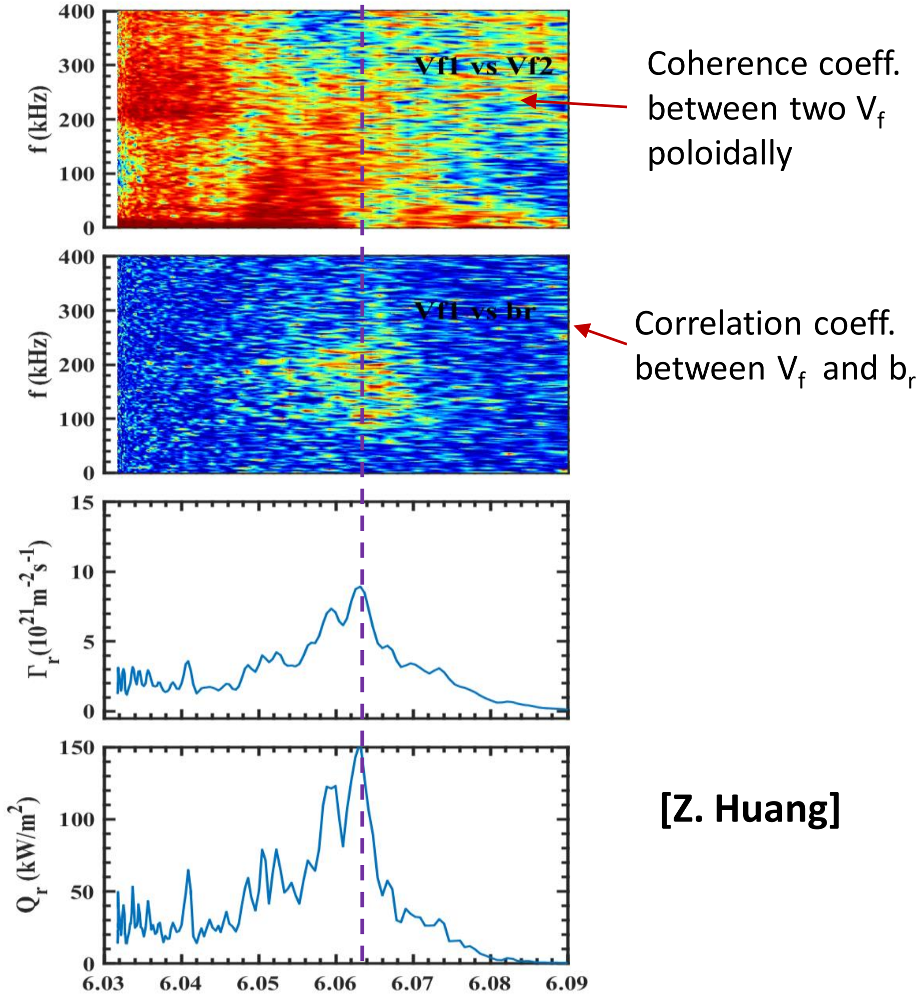


[M. Spolaore JINST 2019]

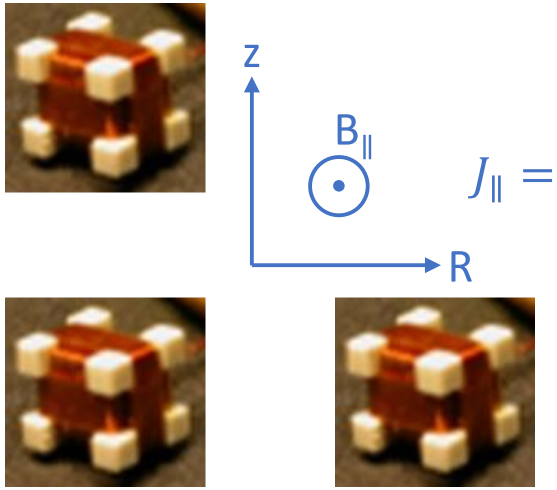
magnetic fluctuations from FZJ-COMB2



[Z. Huang]

3. Electromagnetic effects

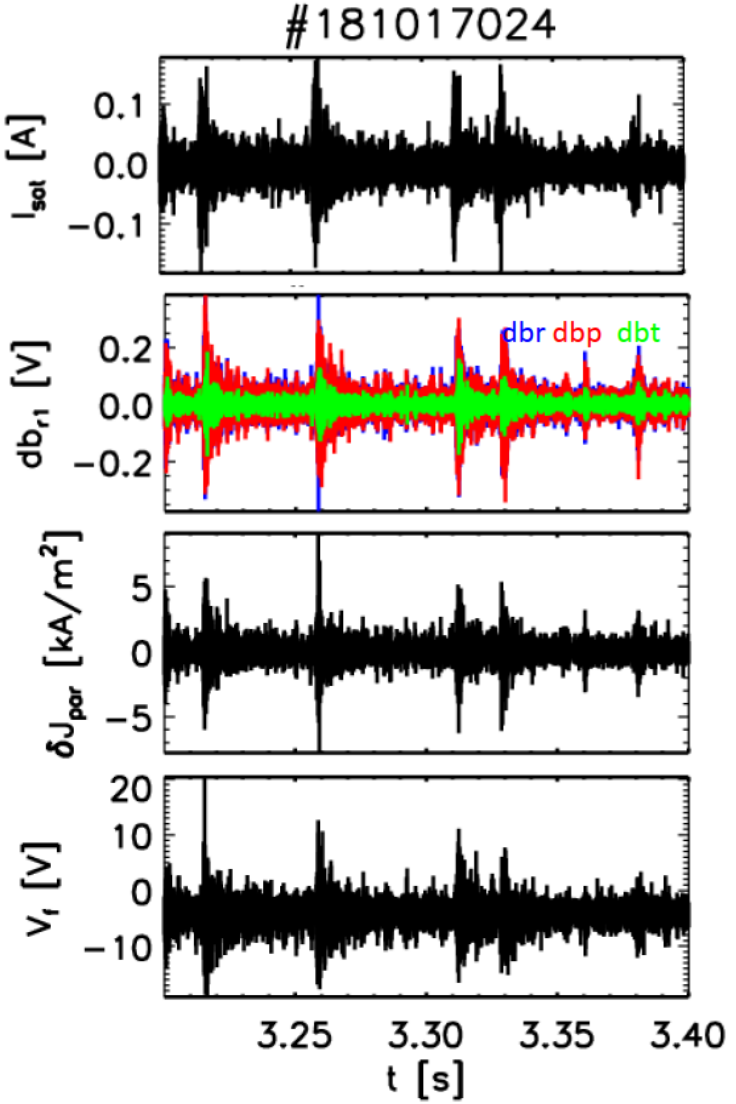
- **measurements of magnetic fluctuations with three 3D pick-up probes in OP1.2b**
- **reconstruction of parallel current density**
- **no sign of electromagnetic turbulence so far**
  (i.e. the turbulent events do not affect the magnetic field)



$$J_{\parallel} = \frac{(\nabla \times B)_{\parallel}}{\mu_0}$$

[M. Spolaore JINST 2019]

plasma *crashes* in limited configuration (*FMM*)



3. Electromagnetic effects

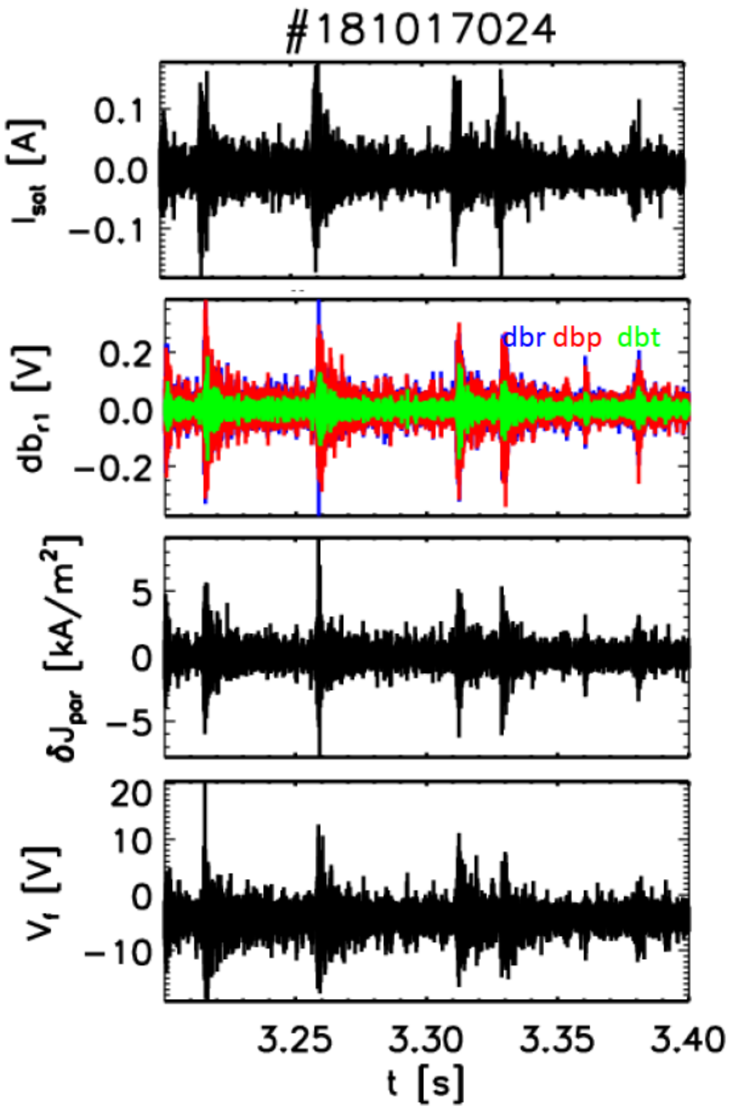
Summary of OP1

- magnetic fluctuations detected
  - perturbation strength so far ≤ 10^{-4}
  - proof of diagnostic concept for tri-axial probes → J_{par}
  - effect of islands on magnetic fluctuations observed
- only few data sets due to limited run time of probe and technical challenges

Outlook towards OP2

- obtain more data on magnetic + electric probe fluctuations
  - magnetic configuration, local island topology
  - density (detachment / attachment)
  - high beta scenarios
  - relation to turbulence strength, mode activity

plasma *crashes* in limited configuration (*FMM*)



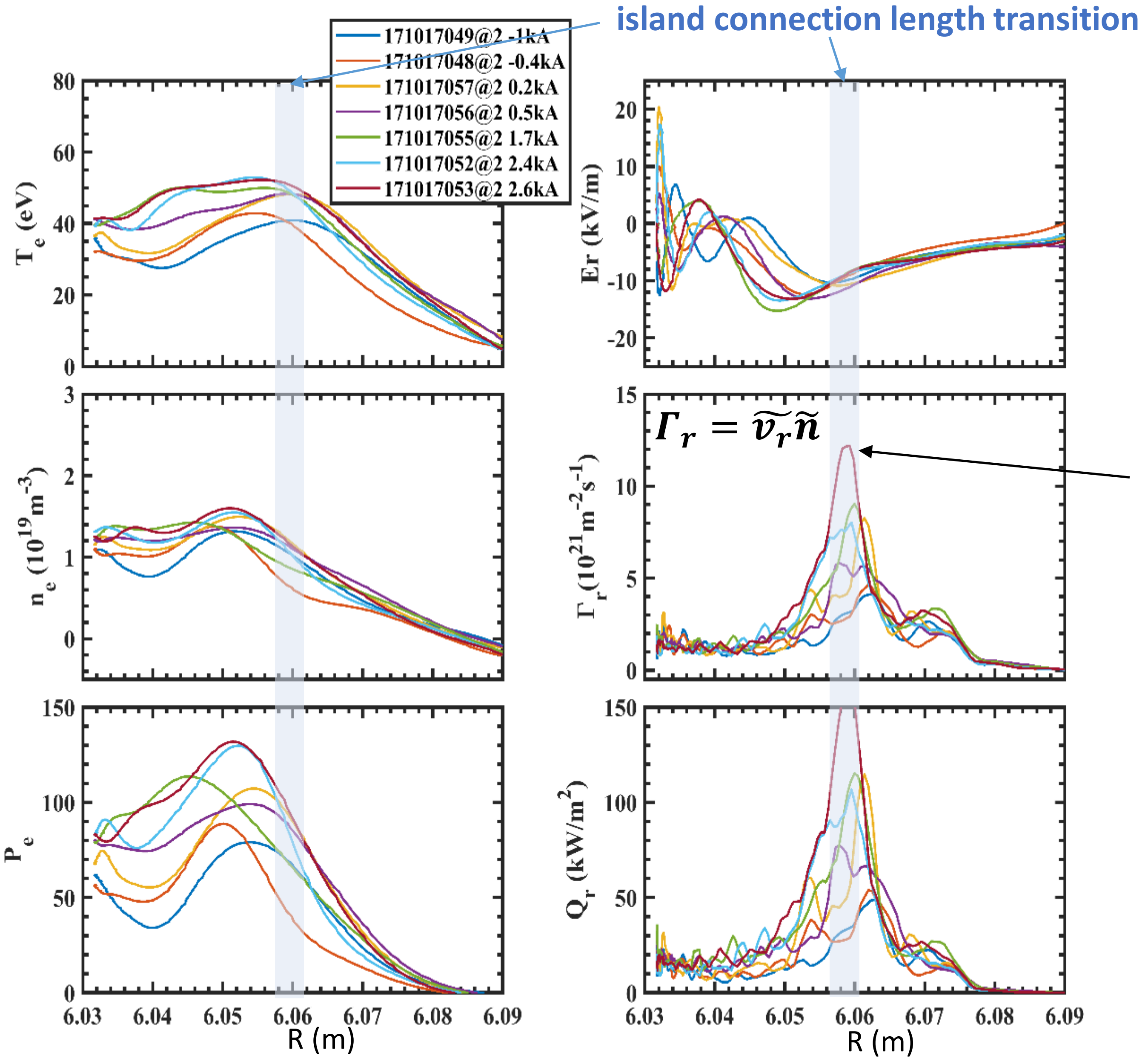
4. SOL transport & Divertor loads

- **researchers:**
  - DR (Daniel Carralero, Teresa Estrada, Emmanouil Maragkoudakis, Thomas Windisch)
  - MPM (Shaocheng Liu, Zhuo Huang, Carsten Killer, Yann Narbutt)
- **general considerations:**
  - modeling with EMC3-Eirene gives plausible results for $D_{perp} \sim 1 m^2/s$
    → approach this experimentally
  - in tokamaks: filaments can contribute significantly to SOL cross-field transport, high skewness and kurtosis of density fluctuations in SOL
  - E_r plays an important role for divertor loads
    - via drift effects (W7-X: Hammond PPCF 2019)
    - via turbulence control (suppression by E_r shear), impacting both edge confinement quality and SOL width

4. SOL transport & Divertor loads

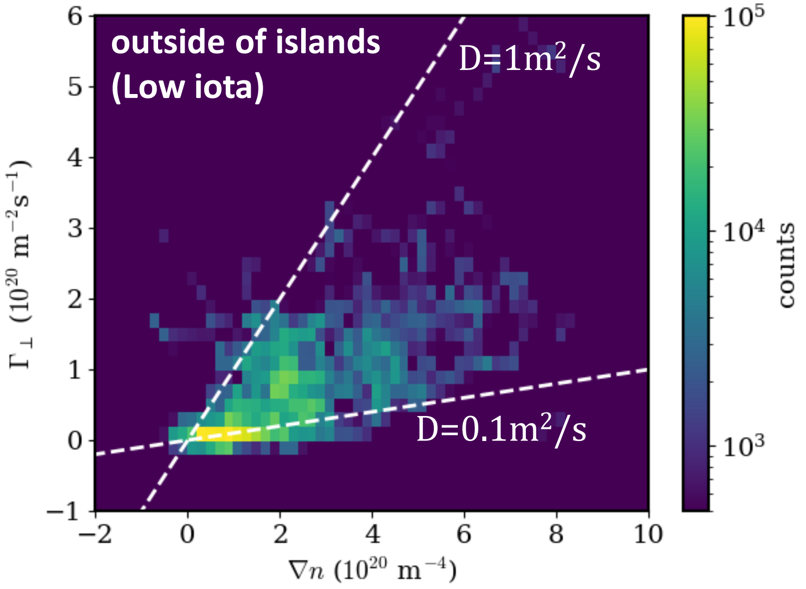
[Zhuo Huang]

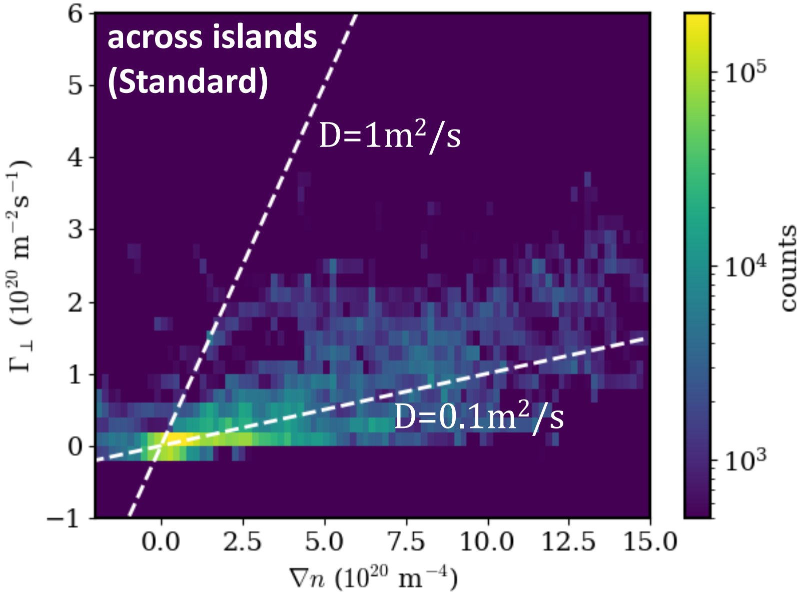
- **MPM probe measurements provide background plasma profiles and fluctuating transport**



radial transport peaks at L_c transition region

4. SOL transport & Divertor loads



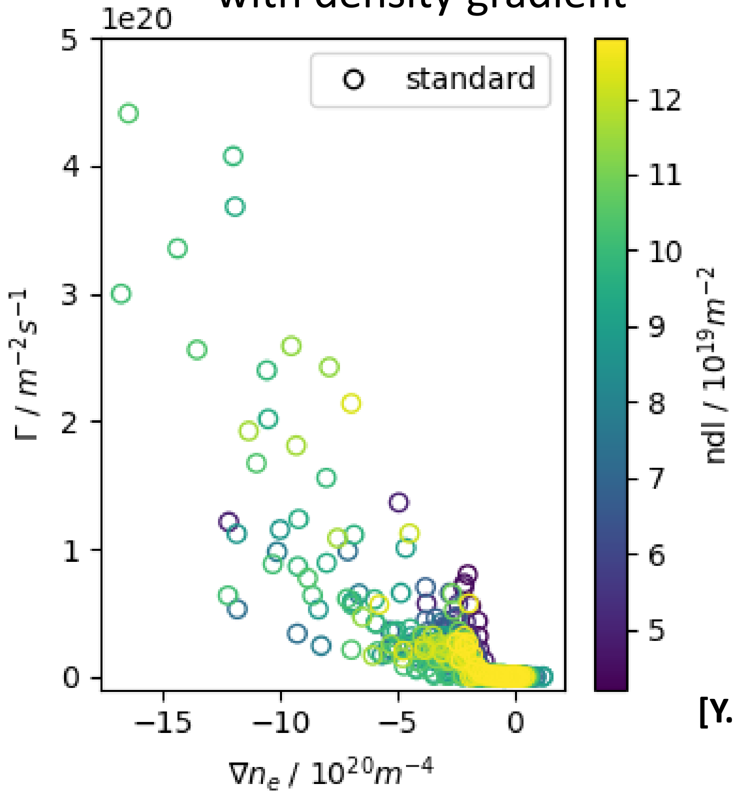


[C. Killer]

estimate $D_\perp$ from MPM profiles: $D_\perp = \frac{\Gamma_r}{\nabla n}$

→ $D_\perp$ appears smaller than expected in simulations *(preliminary result!)*

turbulent flux increases with density gradient



[Y. Narbutt]

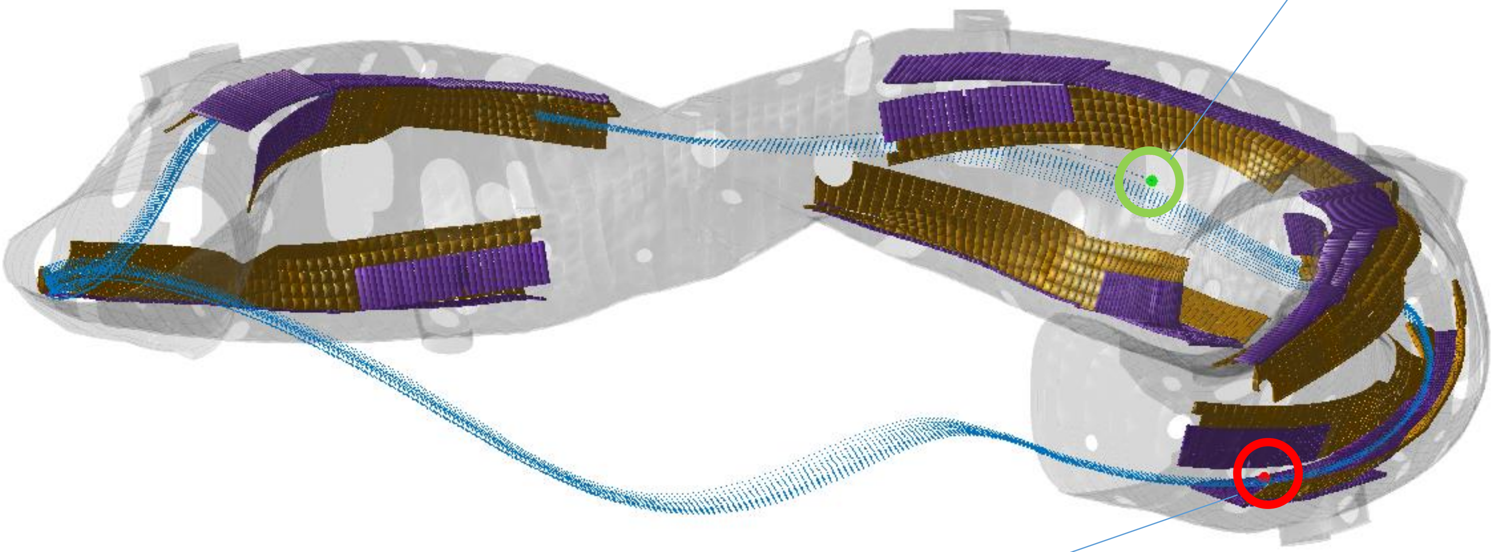
4. SOL transport & Divertor loads

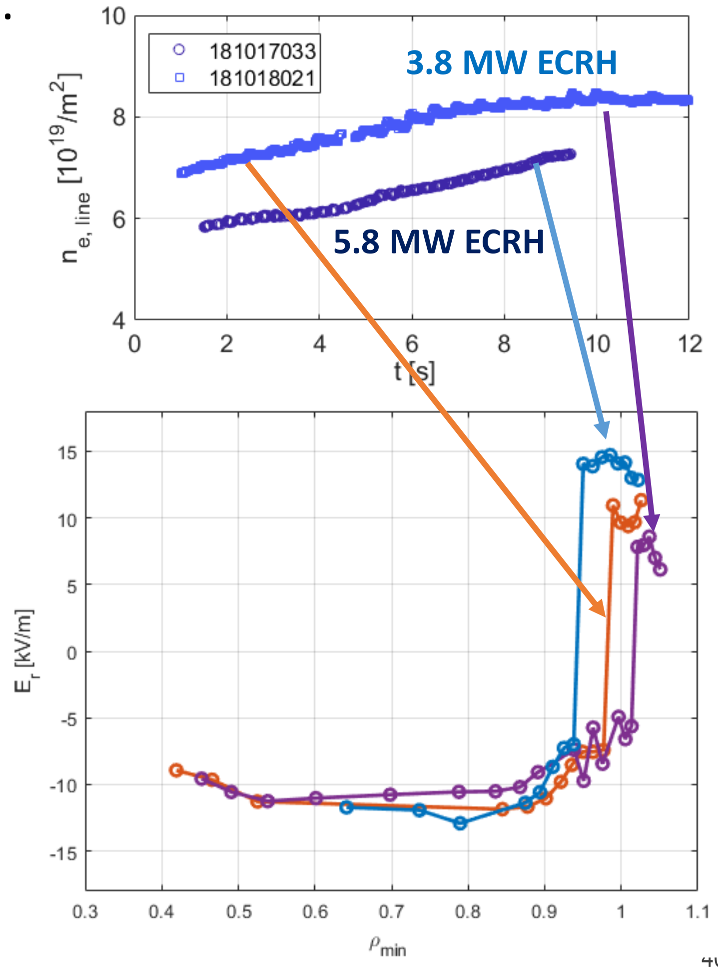
- **summary: role of filamentary transport**
  - seems (so far) to be no major contributor to SOL transport (relatively slow v_r, almost normal PDFs)
    - probes: short radial propagation outside of islands [Killer/Shanahan PPCF 2020]
    - A-BES: complicated filament behavior but also rather slow velocities inside islands [Zoletnik PPFC 2020]
  - preliminary probe analysis indicates that cross-field transport only accounts fro D~0.1-0.5m²/s
  - direct comparison of SOL (turbulent) transport and divertor loads not yet started

this can already be done on the basis of OP1.2b data
→ start soon, so that follow-up questions can be addressed for OP2.1

- **Role of Er shear for divertor loads**
  - compare SOL Er with divertor loads (IR, probes) on same flux tube
  - check for drift effects and dependence on density, heating power, …

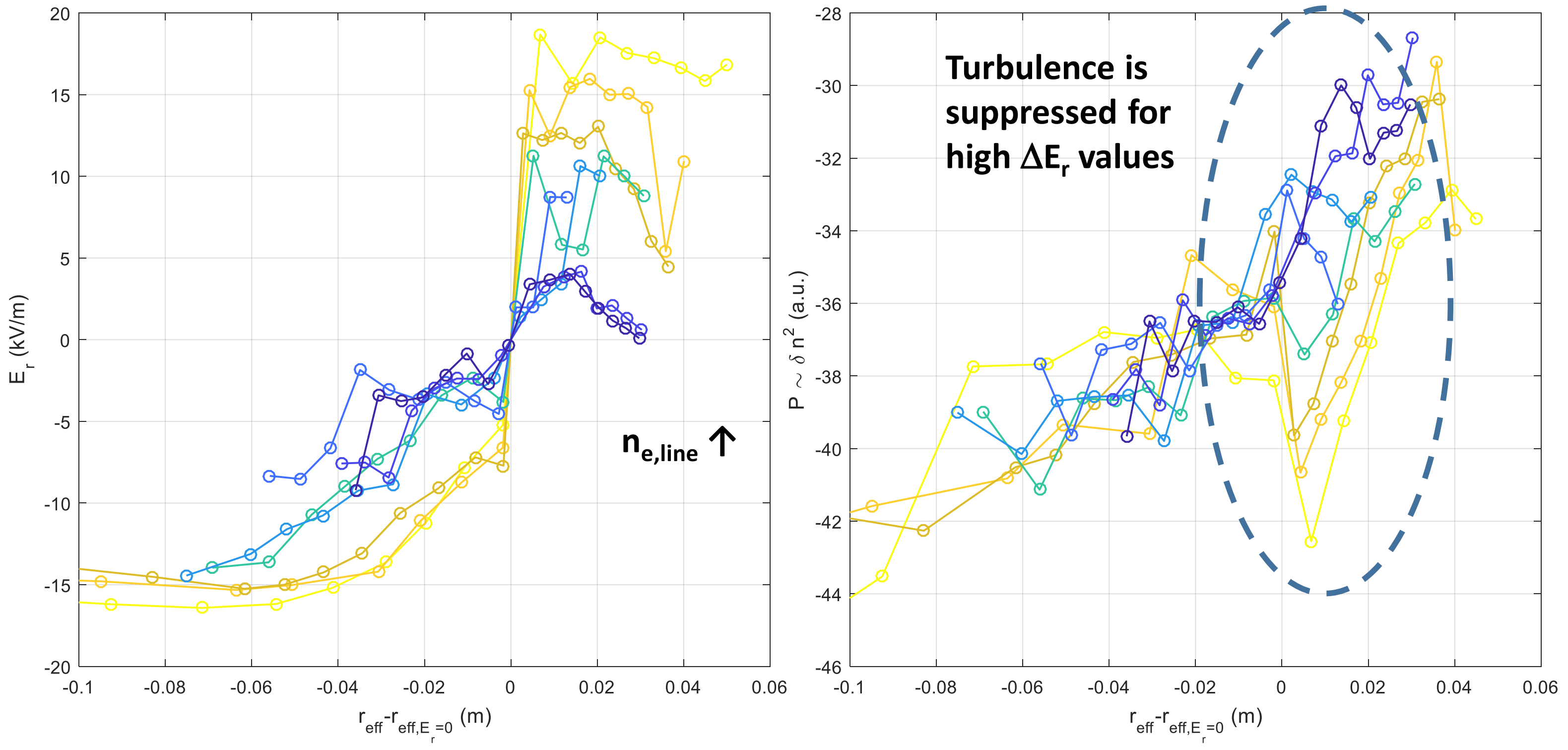
[D. Carralero]





4. SOL transport & Divertor loads – Experiments for OP2.1

- **Role of Er / Er shear for SOL turbulence and plasma performance**
  - study relation of E_r shear to SOL turbulence (and filaments, global performance) in different scenarios



[D. Carralero]