Near and far SOL divertor turbulence in NSTX and NSTX-U L mode discharges

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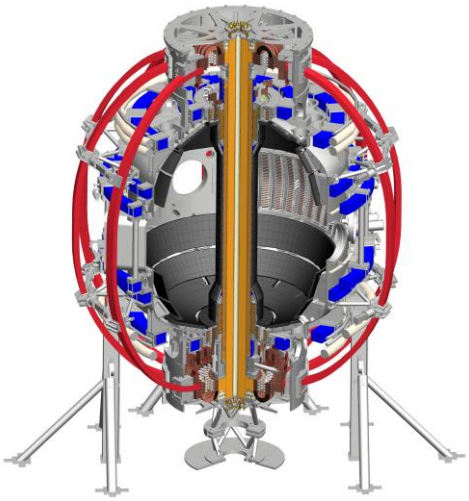
NSTX Upgrade



Fusion Energy Sciences

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PPPL

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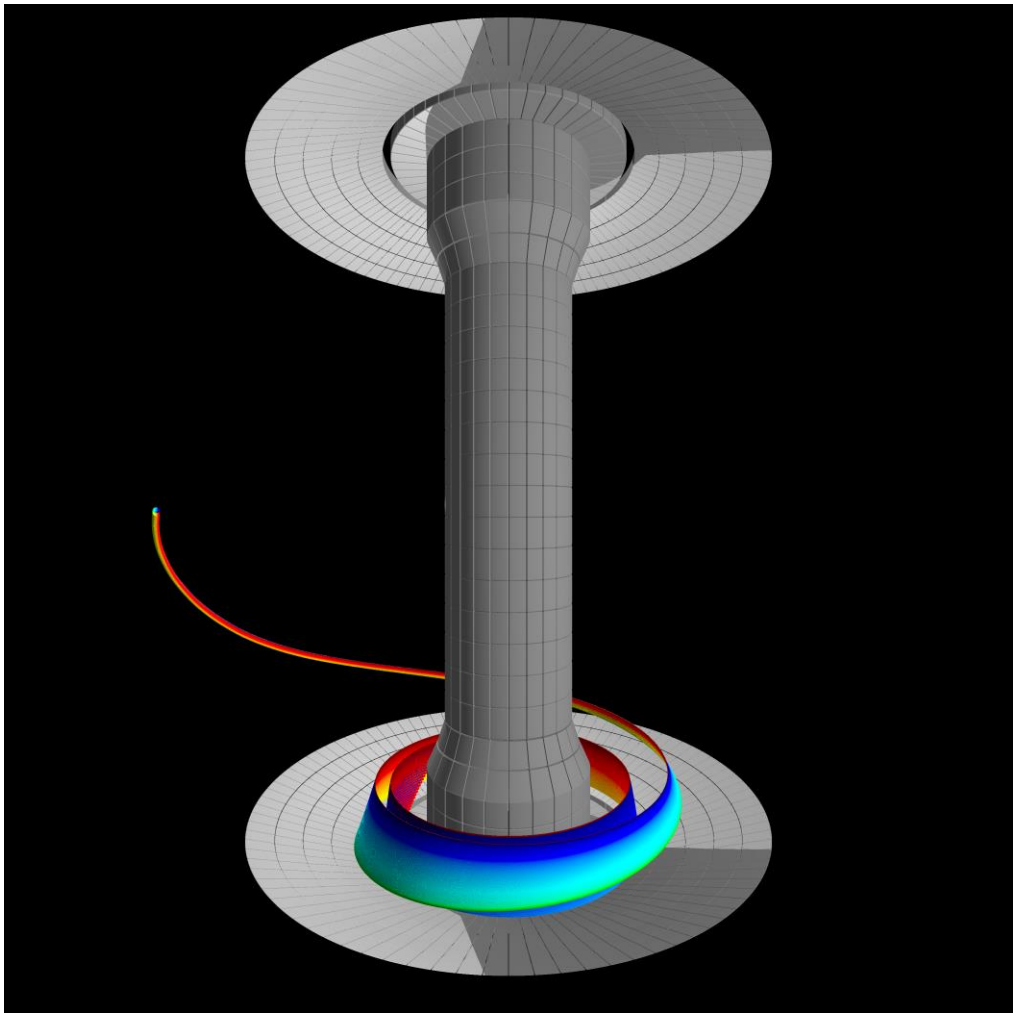
Role of turbulence vs. collisional effects in setting divertor heat flux width still unclear

- Neoclassical and turbulent transport can contribute to observed divertor heat flux width
  - Uncertainty in predictions for ITER and future tokamaks
- To increase confidence in heat flux width predictions:
  - Characterize SOL/divertor turbulence:
    - Upstream fluctuations
    - Connection of upstream turbulence to target
    - Divertor localized fluctuations
  - Compare with 3D turbulence simulations
    - Cf. current work with GBS, BOUT++, XGC1, etc.
  - Use validated simulations to extrapolate SOL widths

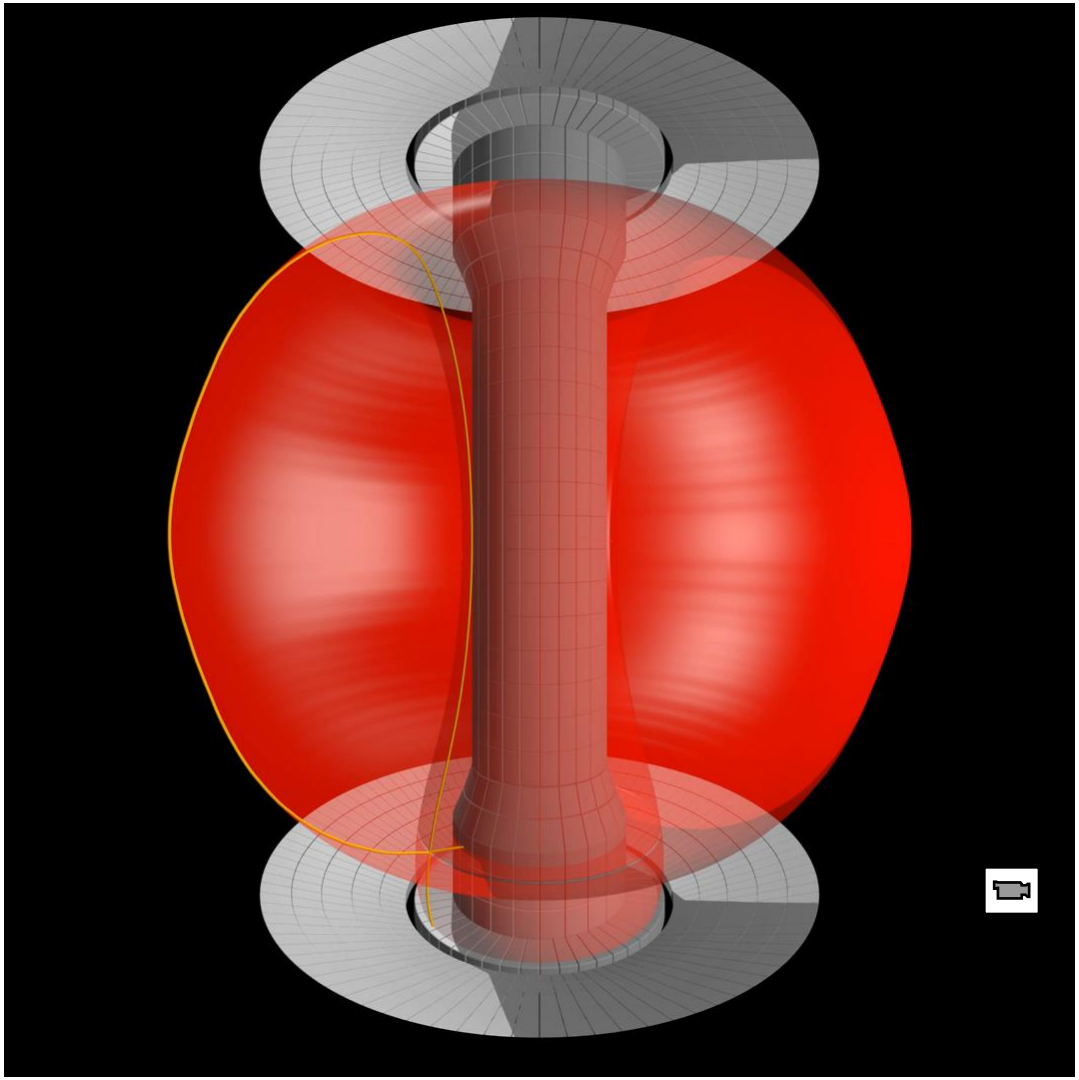
Divertor fluctuations due to upstream and divertor-localized turbulence in NSTX/NSTX-U

- Divertor fluctuations due to upstream turbulence
  - Filaments in light emission on divertor target
  - Correlation with Langmuir probes and upstream GPI
  - Extent of region with connected turbulence
- First observation of divertor-localized turbulence in NSTX-U



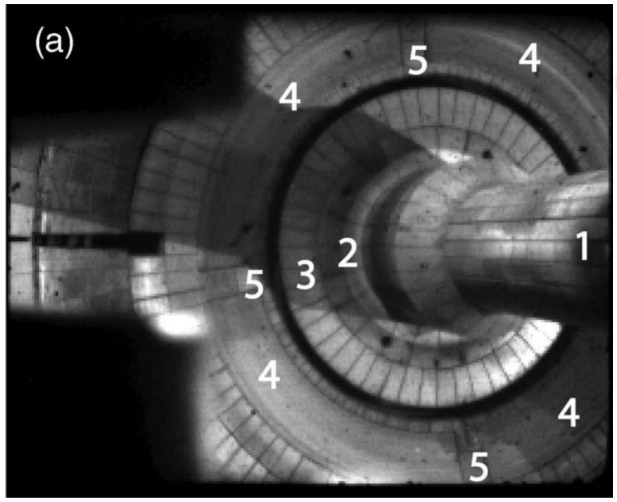
SOL flux tube with circular cross section has ribbon structure in divertor, helical footprint at target

- Flux tube with circular cross section at LFS midplane
  - Representative of blob
  - Magnetic shear leads to ribbon structures in divertor
    - Enhanced by X-point
- Flux tube elongation could disconnect turbulence from target
  - Cross section can be ~ ρ_i
  - D. Farina, NF 1993.
- Helical target footprint



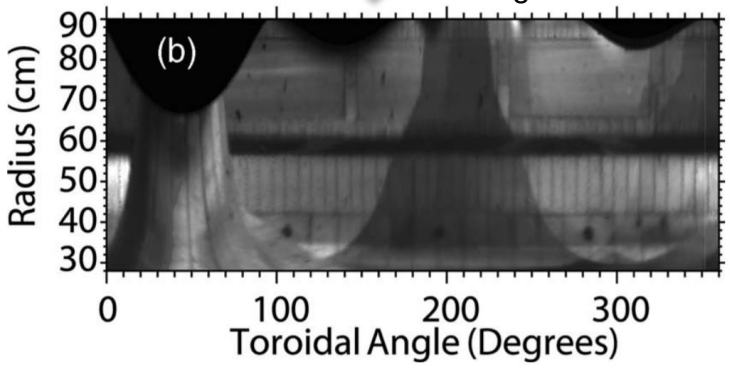
Upstream and target turbulence diagnostics for NSTX divertor turbulence characterization

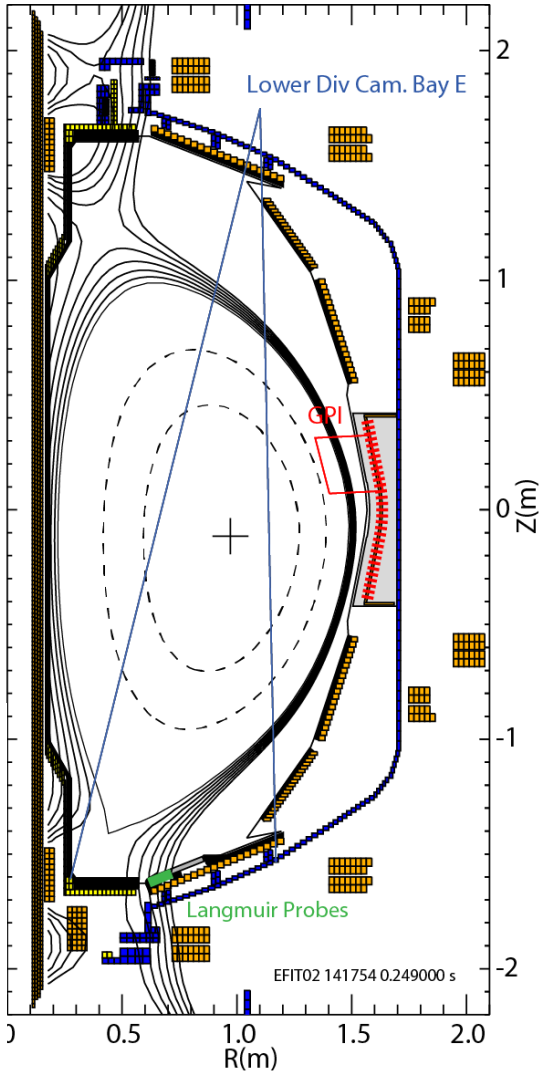
- Upstream: Gas Puff Imaging (GPI) [Zweben NF 2004]
  - Dα emission, 400kHz, 2 μs exposure, 1 cm resolution
- Wide angle divertor imaging:
  - Li I emission, 100kHz, 9 μs exposure, 0.8 cm resolution
  - Toroidal remap for easier analysis [Scotti RSI 2012]
- Langmuir probe array [Kallman/Jaworski RSI 2010]:
  - Triple probes, 250 kHz



Remapped vs (r,ϕ)

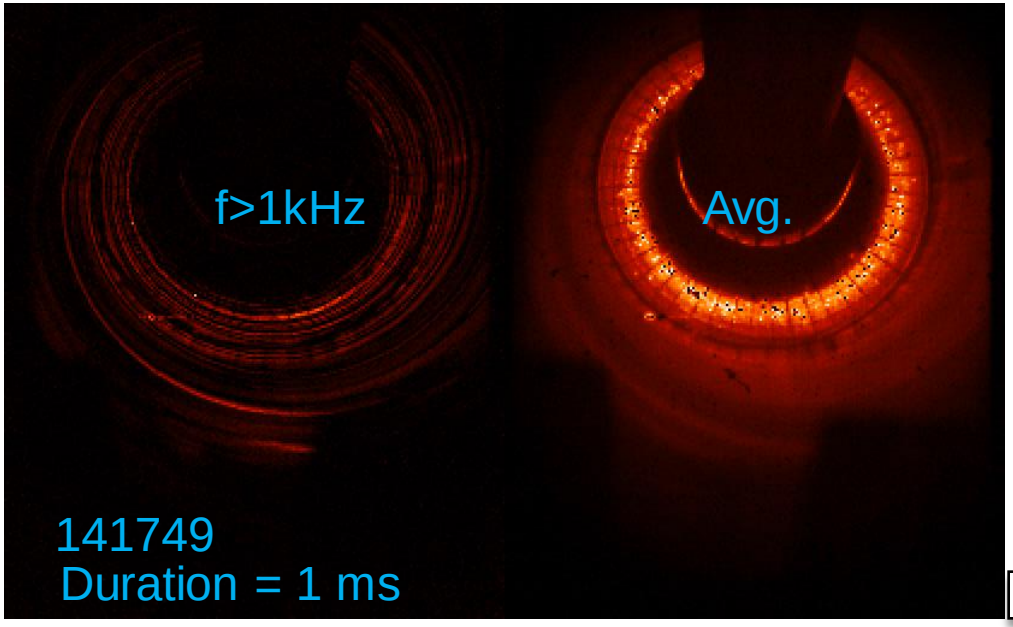
1 - Center Stack
2,3 – Inner Divertor
4 – Outer divertor
5 – Diagnostic tiles

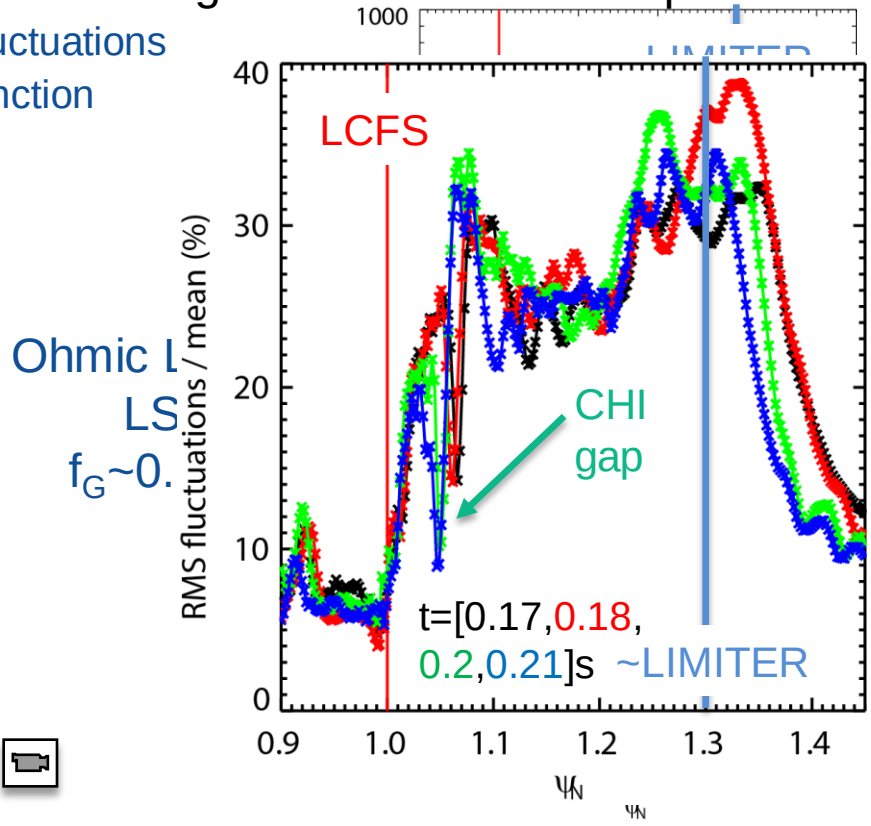




In diverted L-modes discharges, divertor broadband fluctuations in Li I emission observed with δI/I up to 30-50%

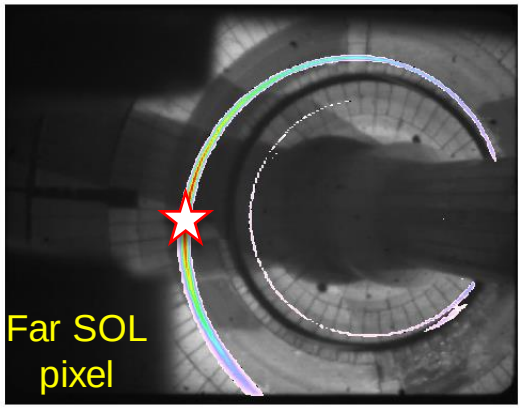
- Divertor intermittent filaments studied via neutral lithium imaging of filament footprint
  - Brightest line in NSTX, atomic physics provides surface localization (First in [Maqueda, NF 2010])
  - Brightness fluctuations can be understood as being ~ $\tilde{n}_e$
- Broadband fluctuations in Li I, δI/I up to 30-50% in region connected to midplane
  - Suggest target fluctuations related to upstream fluctuations
  - Statistical moments follow Gamma distribution function

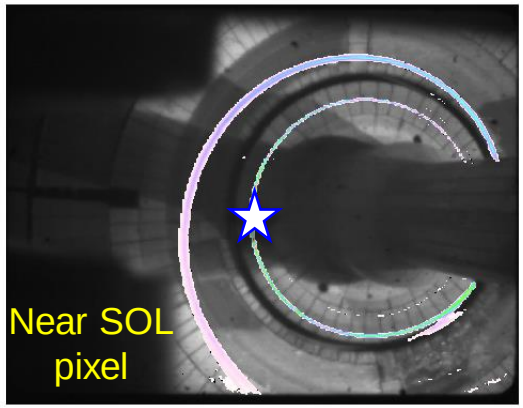


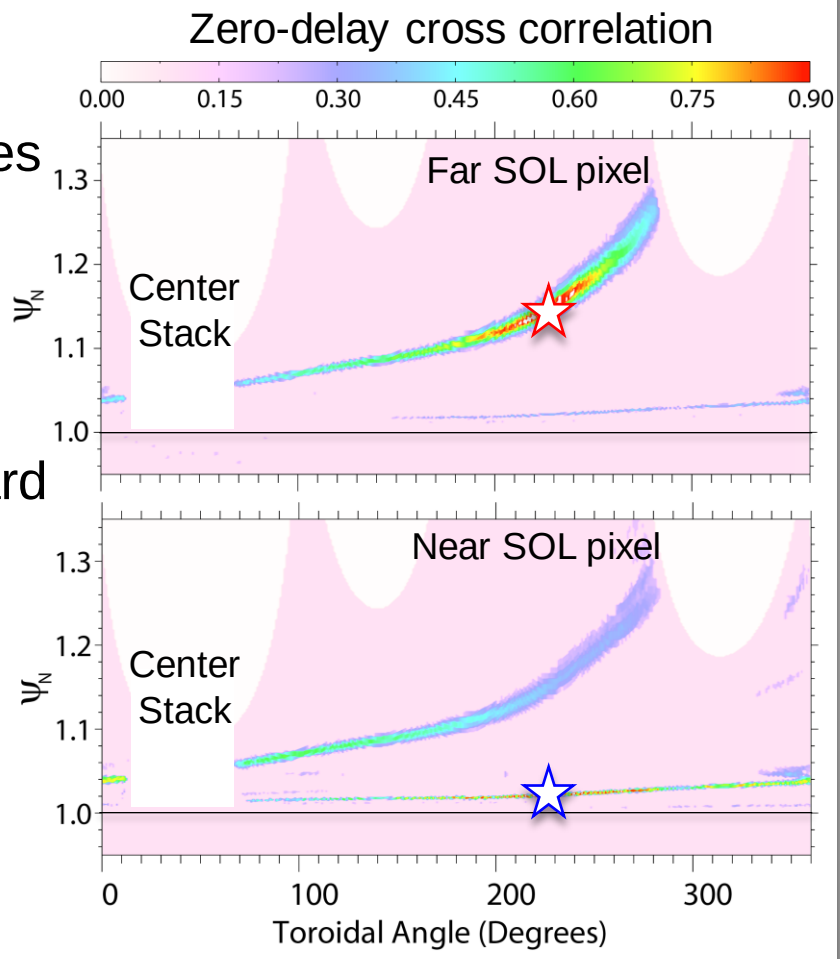


Zero-delay cross correlation shows helical correlation regions at the divertor target

- Helical correlation regions from cross correlation of pixel with rest of image
- Width of cross-correlation region decreases radially towards strike point
- Helical regions of negative correlation nearby positive correlation regions
  - As in GPI 2D cross corr. (Zweben Poster B29)
- Time delay cross correlation shows outward radial propagation along helical footprint
  - Consistent with upstream radial propagation





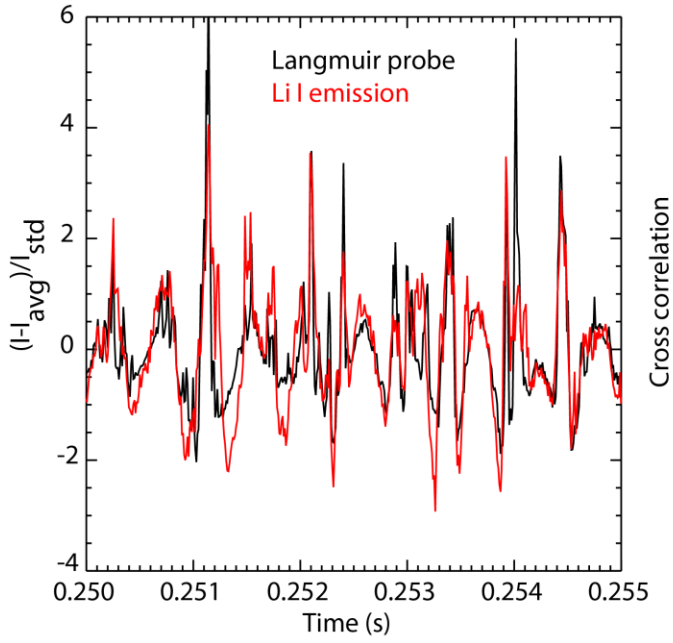


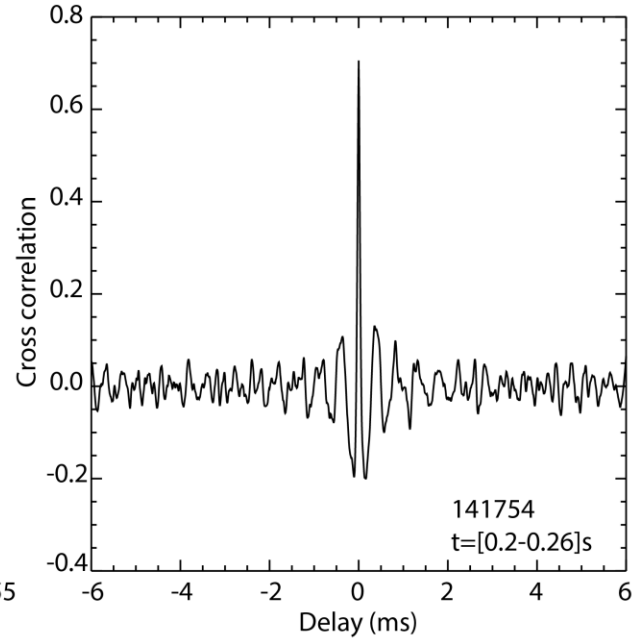
Filament footprint in Li I emission correlates with probe ion saturation current at target

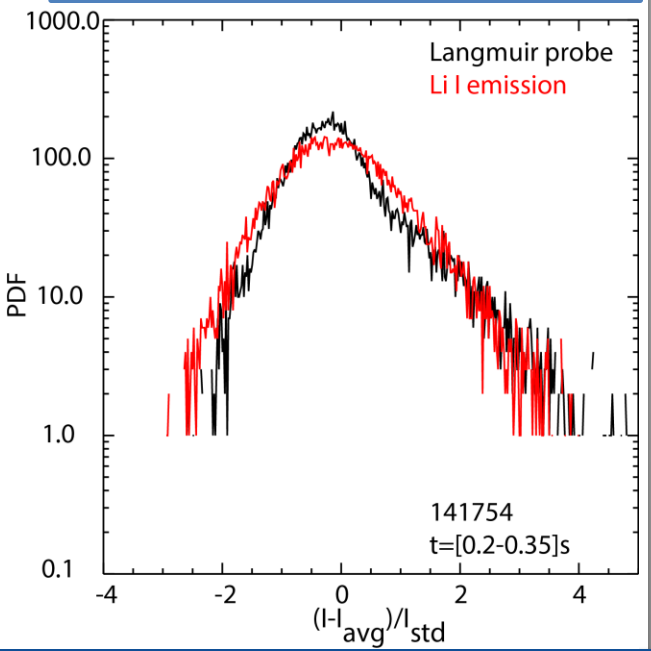
- Neutral lithium emission and ion saturation current (I_{sat}) from target Langmuir probes at same (r,ϕ) show:
  - Cross correlation up to 0.7, peaked at zero delay, comparable PDF
- Fluctuation level ~30% for Li I emission, ~100% for I_{sat} at same location
  - Smaller probe radial resolution (~2x) → smaller scales
  - Li I photon emission coefficient decreases with density

$$E_{Li} = n_e \times n_{Li} \times PEC_{Li}$$

J. Kallman, M. Jaworski, V. Surla acknowledged for 2010 LP data

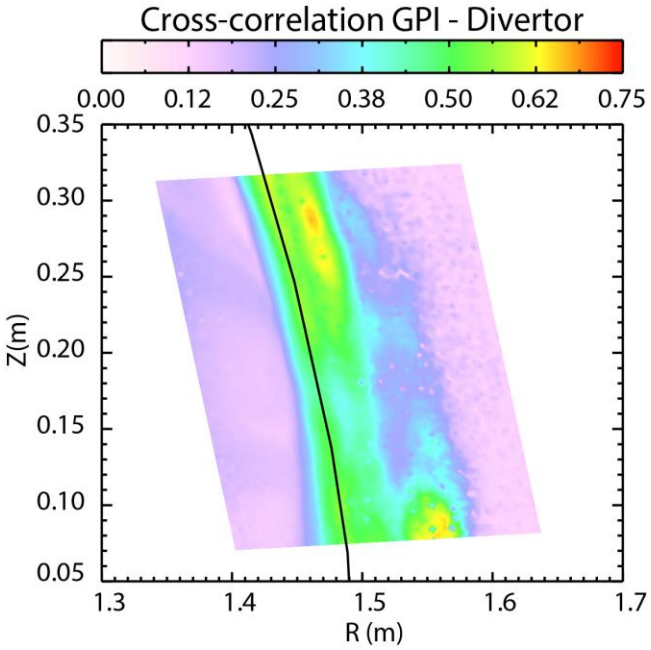


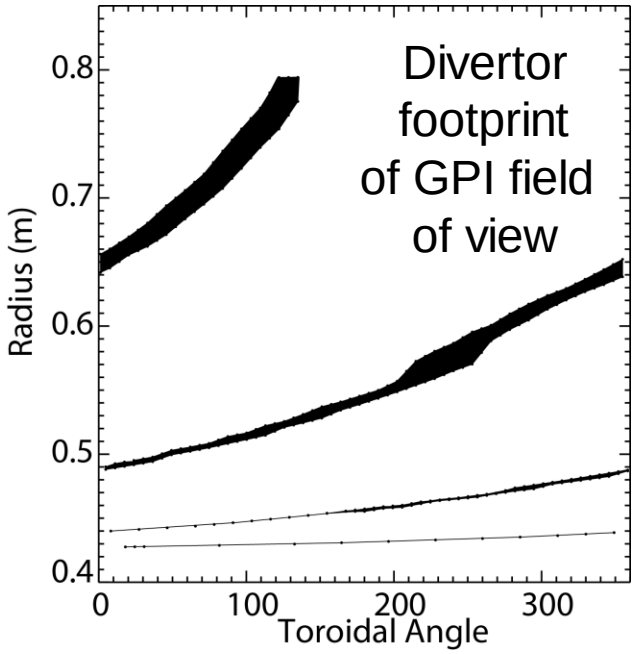


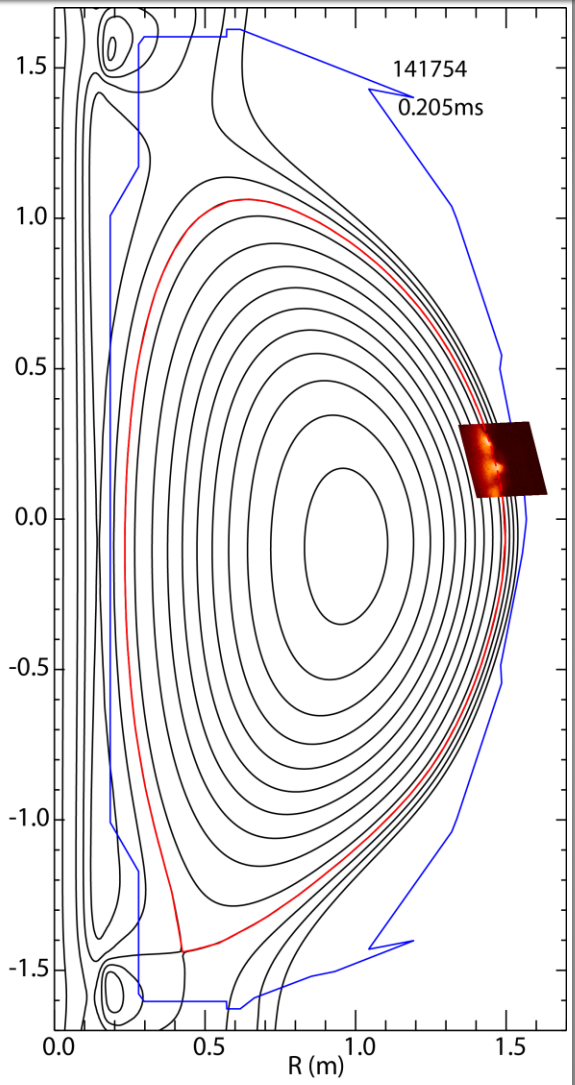


GPI correlates with divertor emission over region connected to divertor target

- GPI–divertor cross corr. up to 0.7 in connected region
  - Peaked at zero delay (9 μs exposure), as in [Maqueda NF 2010]
  - Decrease of correlation towards LCFS and beyond limiter
- GPI field of view maps to a limited section of divertor
  - Additionally limited by vignetting by center stack, passive plates
  - Footprint near OSP narrower than camera spatial resolution (1cm)

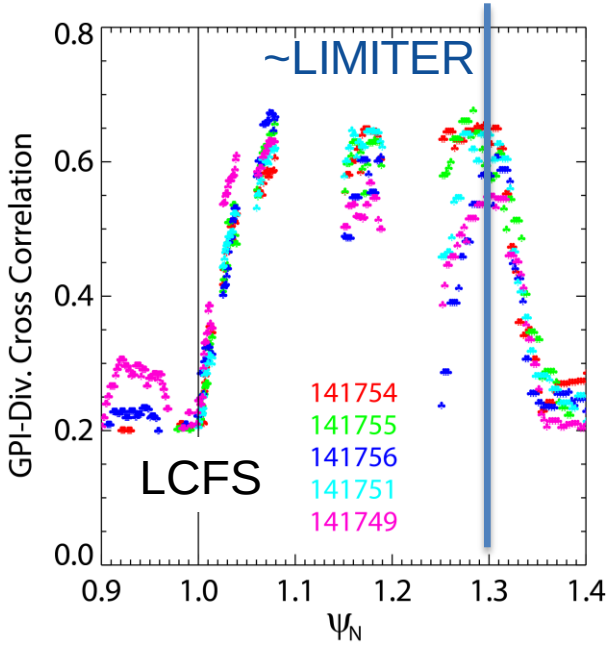


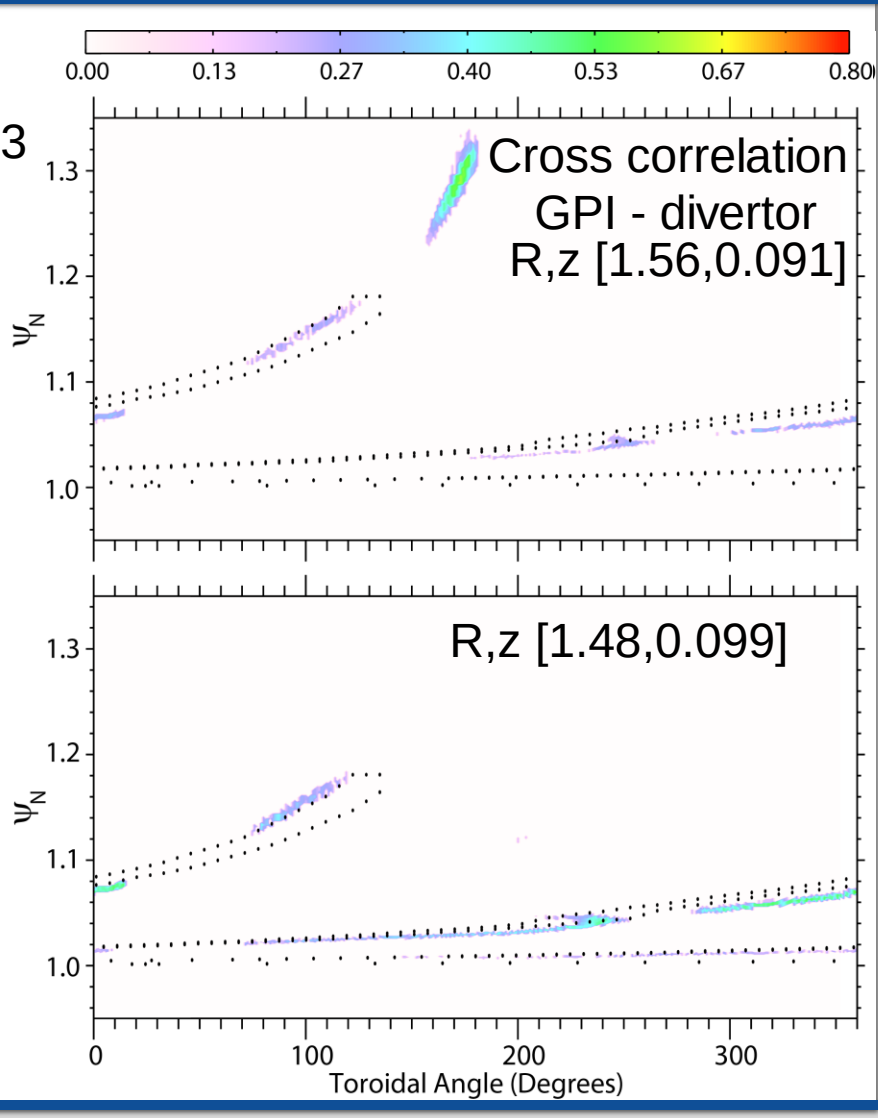




Correlation above random observed over divertor area mapping to GPI field of view

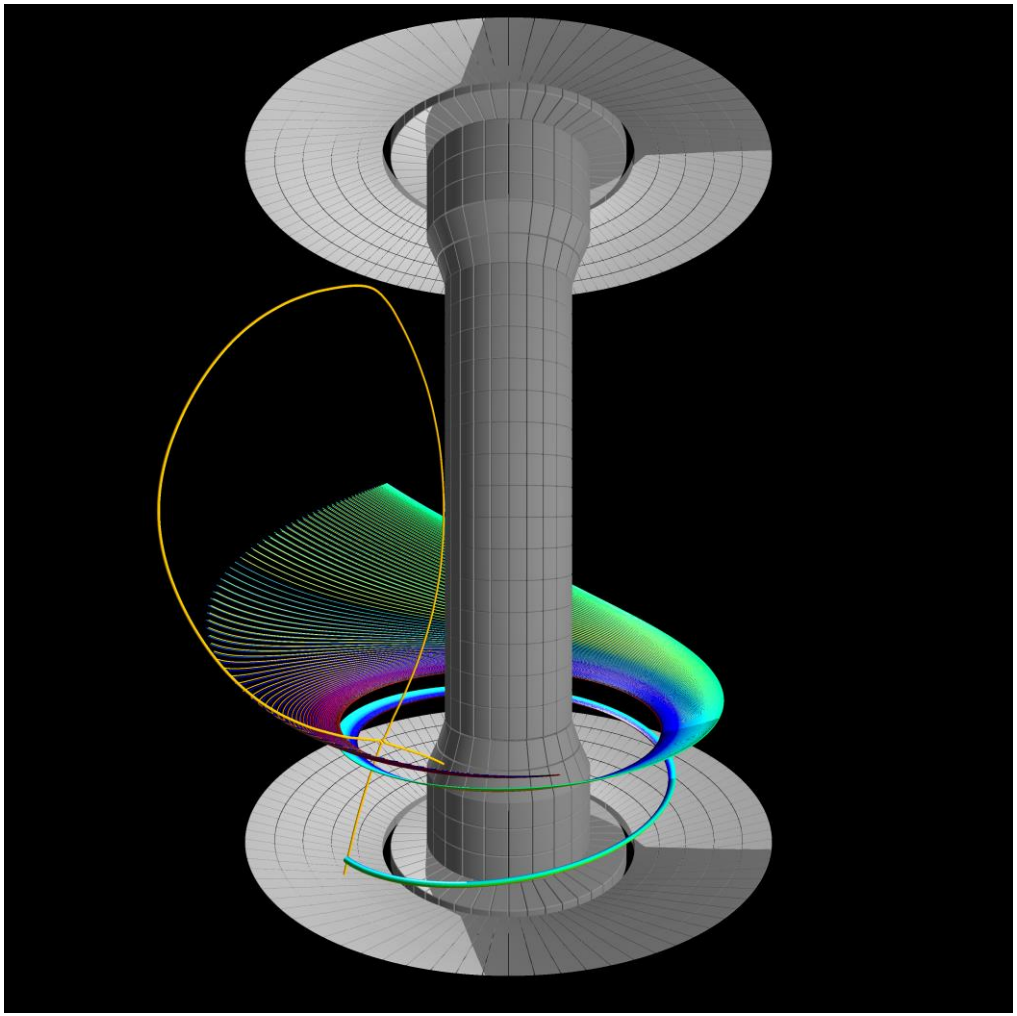
- Divertor region correlated with GPI maps to field lines within GPI field of view
- Correlation with GPI (0.65) over ψ_N~1.08-1.3
- Decrease in cross corr. towards LCFS :
  - Diagnostic limitations (narrow footprint)
  - Turbulence disconnection (D. Baver Poster B19)
- Region correlated with upstream turbulence corresponds to region with large divertor fluctuations





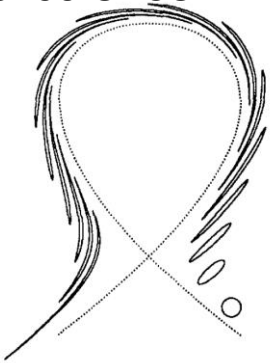
Divertor fluctuations due to upstream and divertor-localized turbulence in NSTX/NSTX-U

- Divertor fluctuations due to upstream turbulence
  - Filaments in light emission on divertor target
  - Correlation with Langmuir probes and upstream GPI
  - Extent of region with connected turbulence
- First observation of divertor-localized turbulence in NSTX-U
  - Intermittent filaments in light emission along divertor legs
  - Shape and absence of upstream correlation suggest generation in divertor legs
  - Possible additional mechanism to reduce peak heat flux

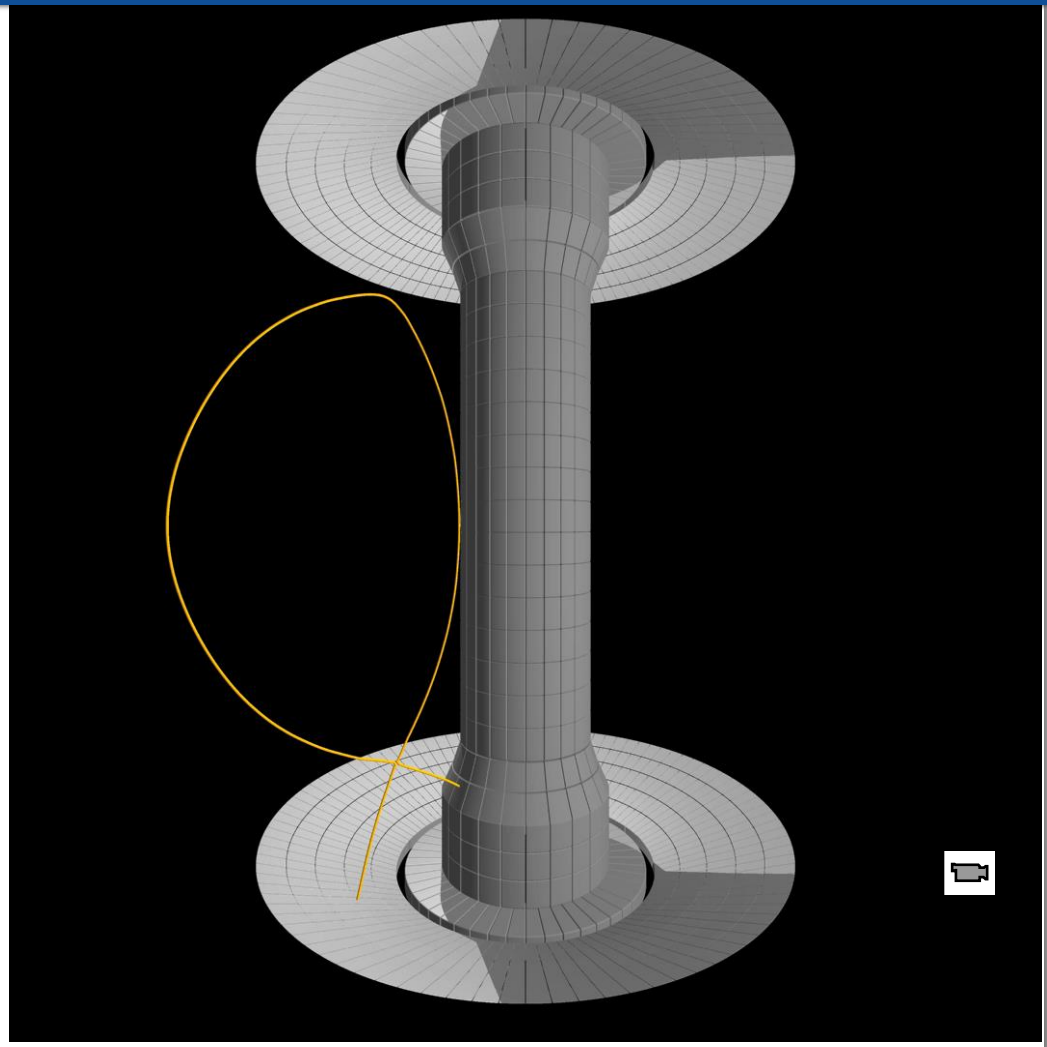


Divertor-localized fluctuations could cause further spreading of target heat flux

- Divertor-leg fluctuations theoretically studied in several papers:
  - R. Cohen, CPP 1996, 2006, NF 2007.
  - D. Ryutov, CPP 2004, 2007, PoP 2007.
- Observations in MAST and C-Mod:
  - Harrison, PoP 2015, Terry, JNME 2017.
- Circular flux tube at divertor leg
  - Representative of flute-like instability
  - Magnetic shear results in ribbon structures upstream
- Flux tube elongation possible driver for upstream disconnection of divertor turbulence

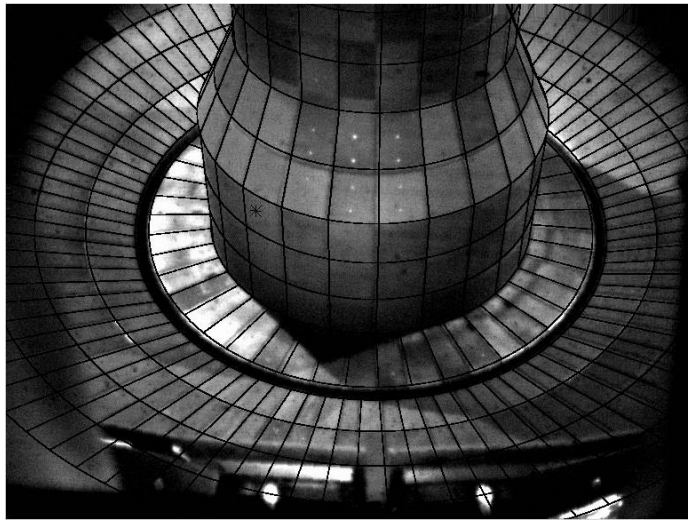


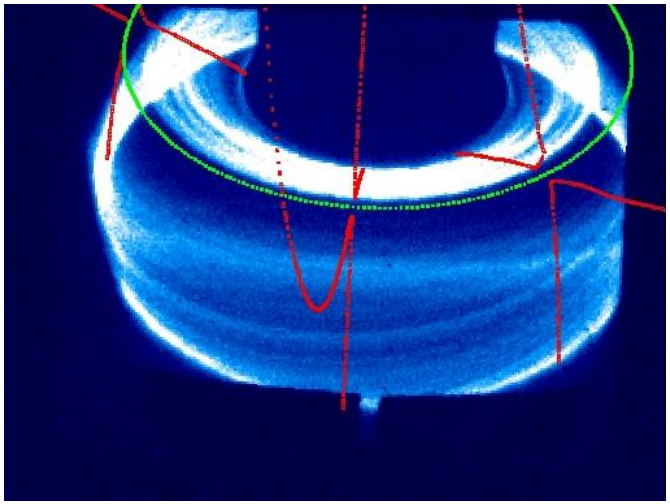
D.Farina, R.Pozzoli, D.Ryutov, NF 1993

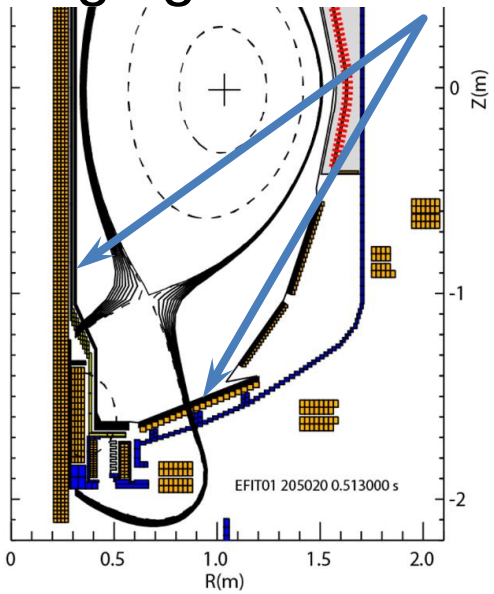


Throughput-optimized camera and high X-point L-modes enabled near-separatrix filaments imaging in NSTX-U

- New NSTX-U fast camera to study divertor fluctuations:
  - Divertor-localized instabilities, divertor filaments due to upstream blobs
- Divertor turbulence imaging through different charge states provides contrast at different spatial locations
  - Filament footprint on target via Li I
  - Filaments on divertor legs via C III (~10x dimmer than D-α)
- Throughput-optimized setup enabled 100kHz imaging via C III

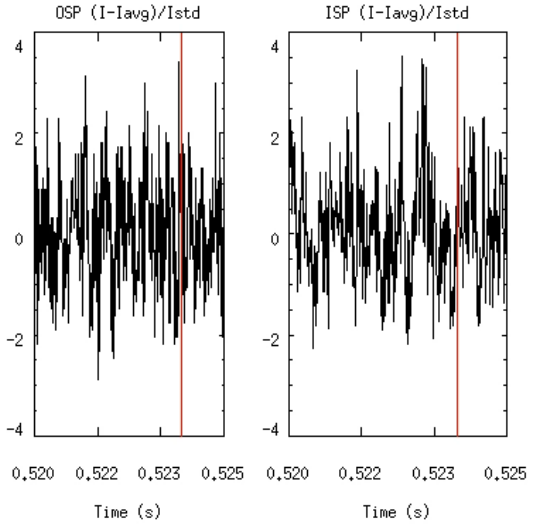




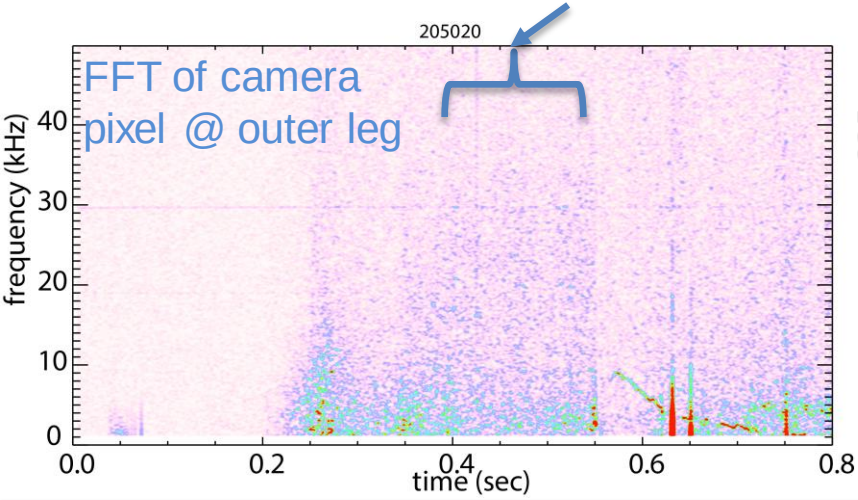


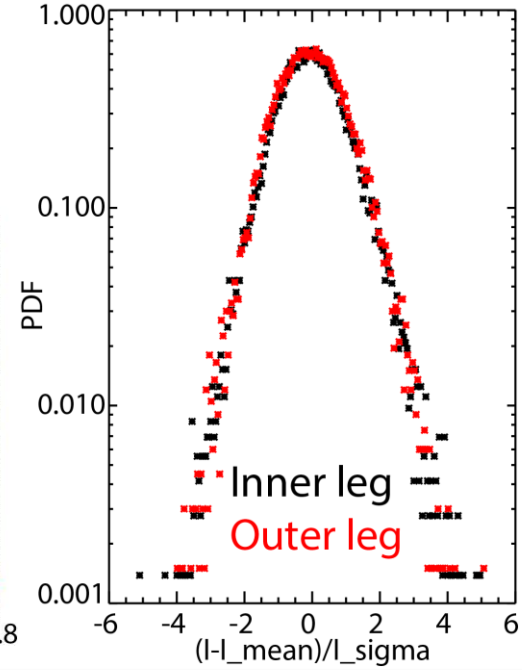
Flute-like intermittent field-aligned filaments observed in inner and outer divertor legs

- Intermittent filaments observed on both inner and outer divertor leg
  - Broadband fluctuations, δI/I ~10-20%
  - Similar PDF for inner and outer leg filaments
  - Low intermittency
- C III fluctuations correlated with Dα at same location
  - Suggests fluctuations ~ $\tilde{n}_e$

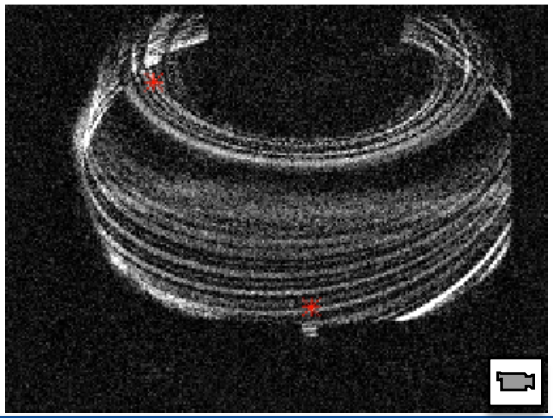


Interval in consideration



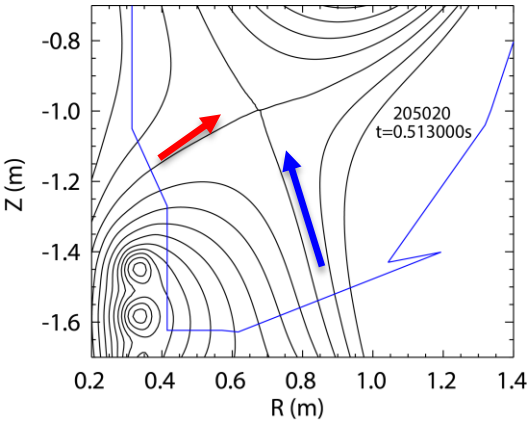


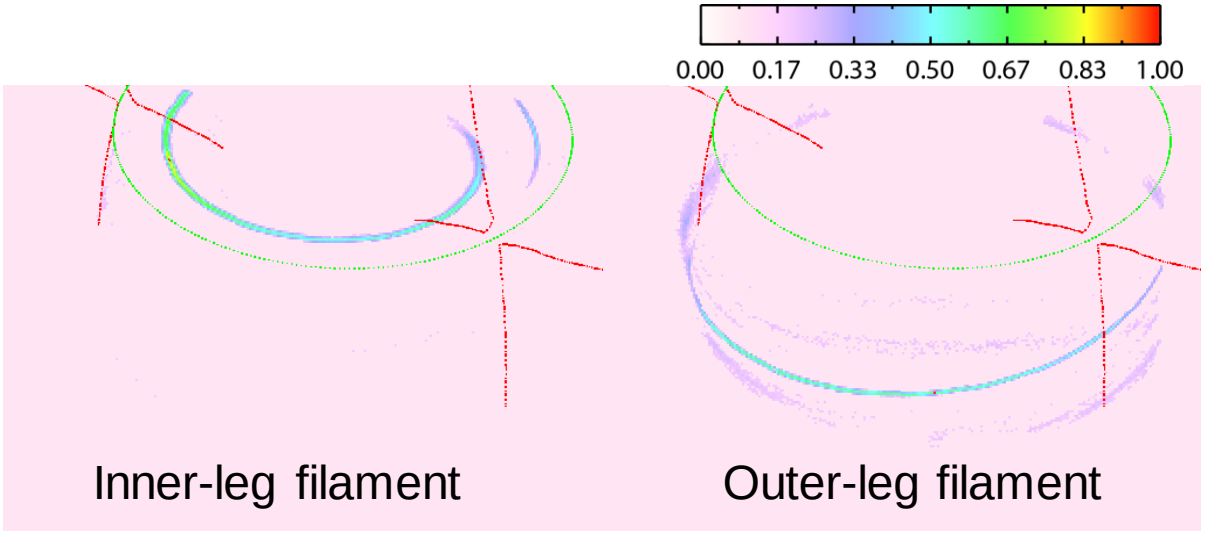
High-pass filter 1kHz

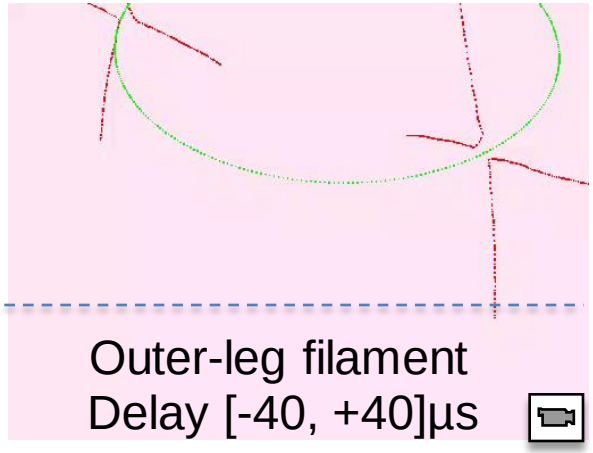


No correlation observed between inner and outer leg filaments, apparent motion towards X-point

- Zero-delay cross corr. of pixel with rest of image over 10ms
- Correlation > (<) toroidal turn on inner (outer) leg
  - Parallel correlation length ~ 3 m (due to limited C III shell?)
- No correlation between inner and outer leg filaments
- Filaments are field aligned, radially localized around leg
- Apparent poloidal motion for both inner and outer leg filaments towards X-point (also in C-Mod)
  - Or equivalently opposite toroidal directions.
- No correlation with upstream GPI







Summary

- Divertor target fluctuations in NSTX L-modes discharges due to upstream turbulence
  - Li I intermittent filaments represent footprint of upstream blobs
  - Fluctuations correlate with target Langmuir probes and GPI
  - Reduction in fluctuations and upstream correlation approaching separatrix
  - Extent of connected region in different conditions in different operational regimes to be investigated (connect to H-mode work [Maqueda NF 2010])
- Near-separatrix divertor turbulence in NSTX-U L-mode discharges
  - Intermittent filaments in C III emission
  - Filaments on divertor legs with no correlation with upstream blobs
  - Apparent filament motion is towards X-point on both legs
  - Shape, dynamics and absence of upstream correlation suggest fluctuations are generated on divertor legs