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

NSTX-U Monday Physics Meeting

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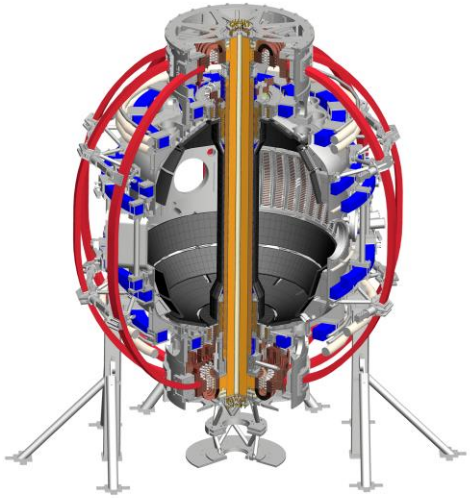
Fusion Energy Sciences

NSTX Upgrade



PPPL

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LLNL-POST-

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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
  - Relative role still unclear in existing devices
  - Leads to uncertainty in predictions for ITER and future tokamaks
    - T. Eich, NF 2012, R. Goldston NF 2012, FES Theory&Simulation Perf. Target 2016
- To increase confidence in heat flux width predictions:
  - Characterize SOL/divertor turbulence:
    - Upstream fluctuations
    - 3D structure of SOL fluctuations
    - Divertor fluctuations: divertor-localized and due to upstream turbulence
  - Compare with 3D turbulence simulations (e.g., XGC-1, BOUT++)
    - Cf. current work with GBS, BOUT++, etc.
  - Use validated simulations to understand/extrapolate SOL widths

Outline

- 3D structure of SOL flux tubes
- Divertor target turbulence in NSTX L-mode discharges
  - Why L-mode?
    - Good data set for edge turbulence diagnostics in NSTX and NSTX-U
    - Avoids complications in H-mode discharges (MHD, EHOs)
  - Connect with previous work in H-mode [Maqueda NF 10]:
    - First characterization of target filaments in NSTX
    - Identification of target filaments as footprint of blobs
    - Correlation with GPI only in far SOL (ψ_N~1.2-1.3)
- First observation of divertor-leg turbulence in NSTX-U L-mode discharges
  - Possible additional mechanism to reduce peak heat flux
  - Connect with observations from other machines (C-Mod, MAST)

Divertor turbulence due to upstream blobs in NSTX L-mode discharges

- Target turbulence due to upstream blobs in L-mode discharges
  - Broadband fluctuations in Li I emission with δI/I up to 30-50%
  - Fluctuations correlate with target Langmuir probes and GPI upstream
  - Reduction in fluctuations and upstream correlation approaching separatrix
- Divertor-leg turbulence in L-mode discharges
  - Intermittent filaments in C III emission with δI/I up to 10-20%
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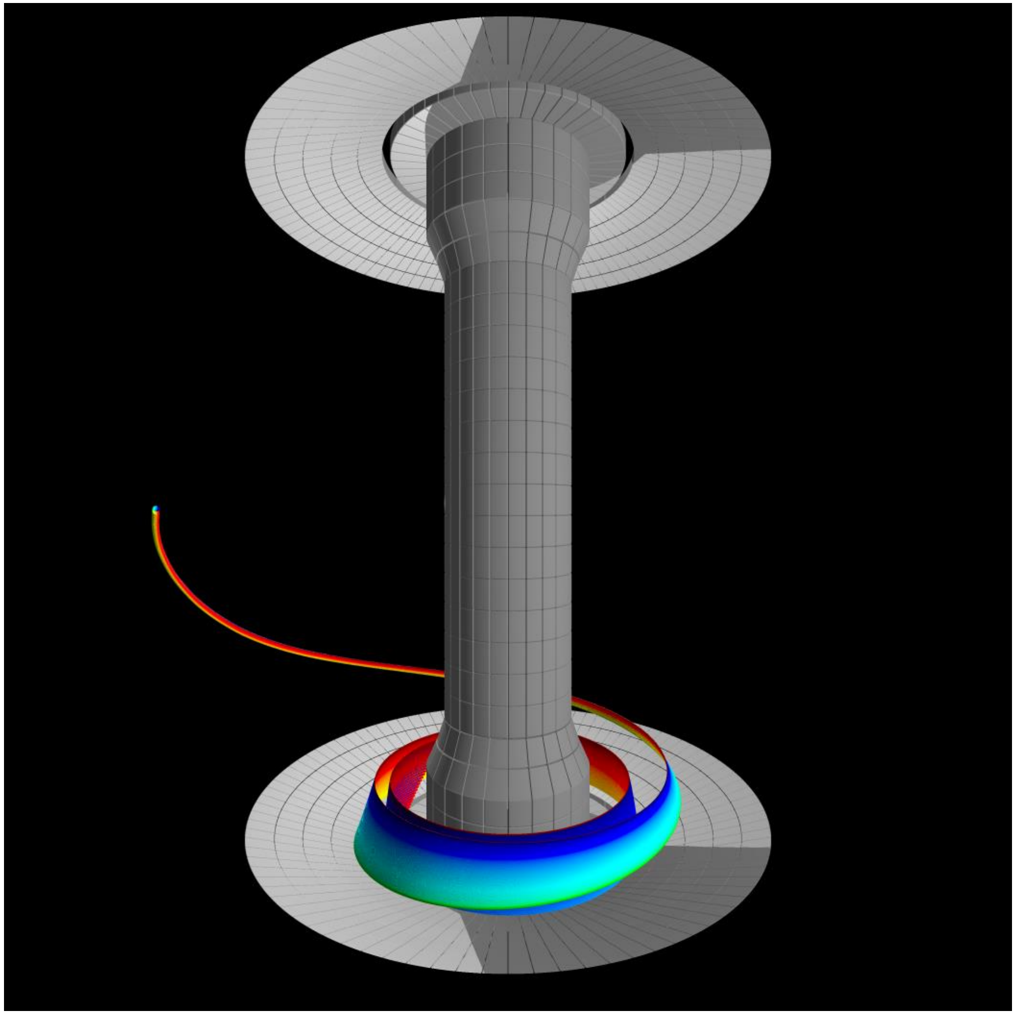
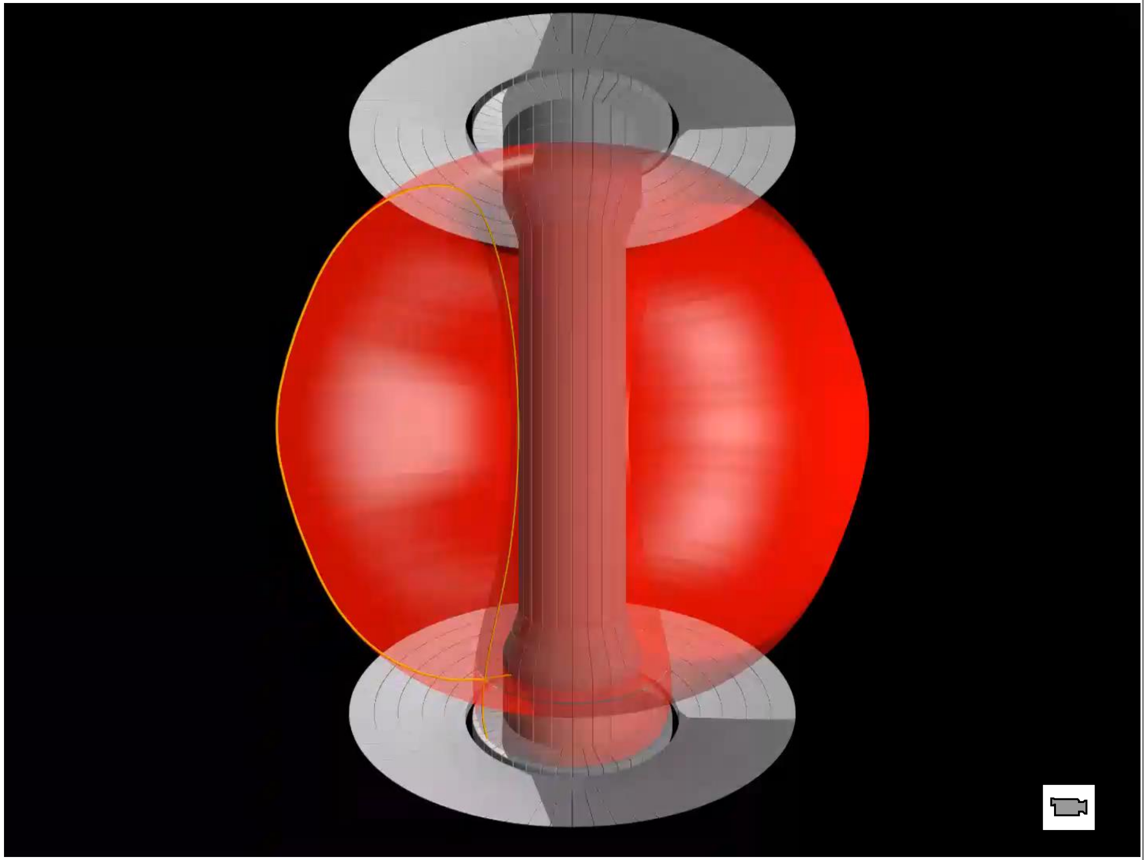


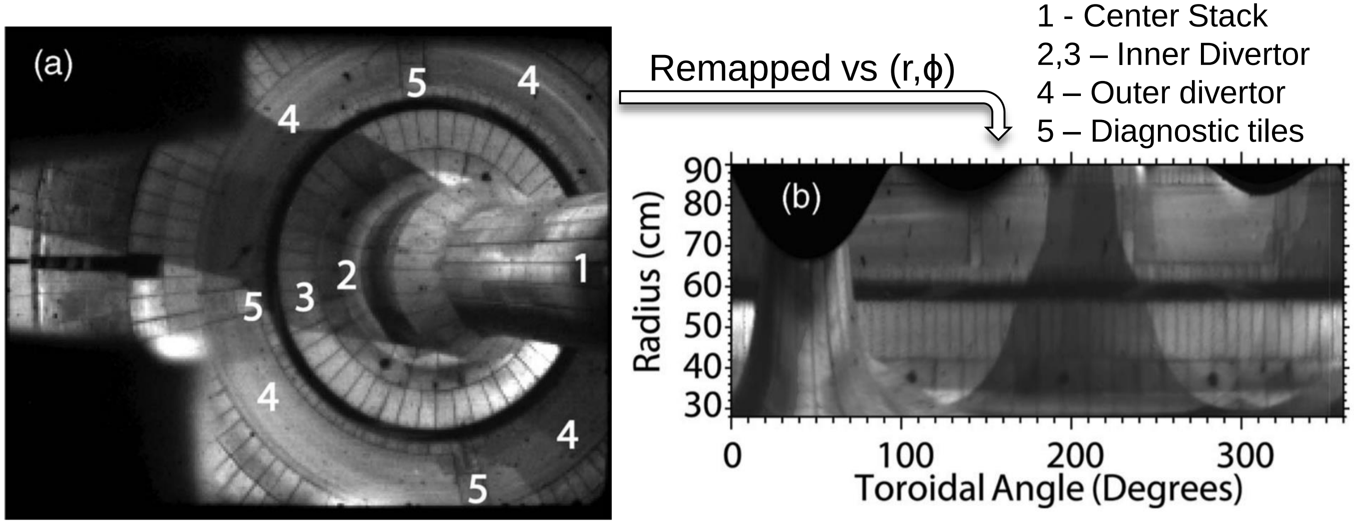
SOL flux tube with circular cross section has ribbon structure in divertor, helical footprint at target

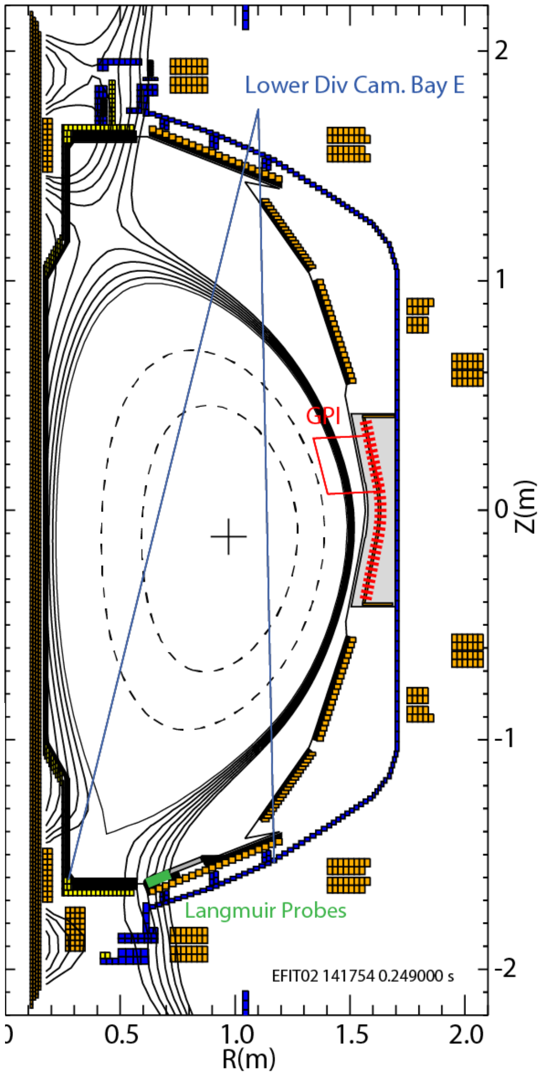
- Flux tube with circular cross section at midplane
  - Representative of LFS blob
- Magnetic shear leads to ribbon-like structures in divertor
  - Enhanced by X-point
- Flux tube elongation possible driver for disconnection of upstream turbulence from target
  - Cross section can be smaller than ion gyroradius
  - D. Farina, NF 1993.
  - R. Cohen, NF 1997.
- Helical footprint at target



Upstream and target turbulence diagnostics for NSTX divertor turbulence characterization

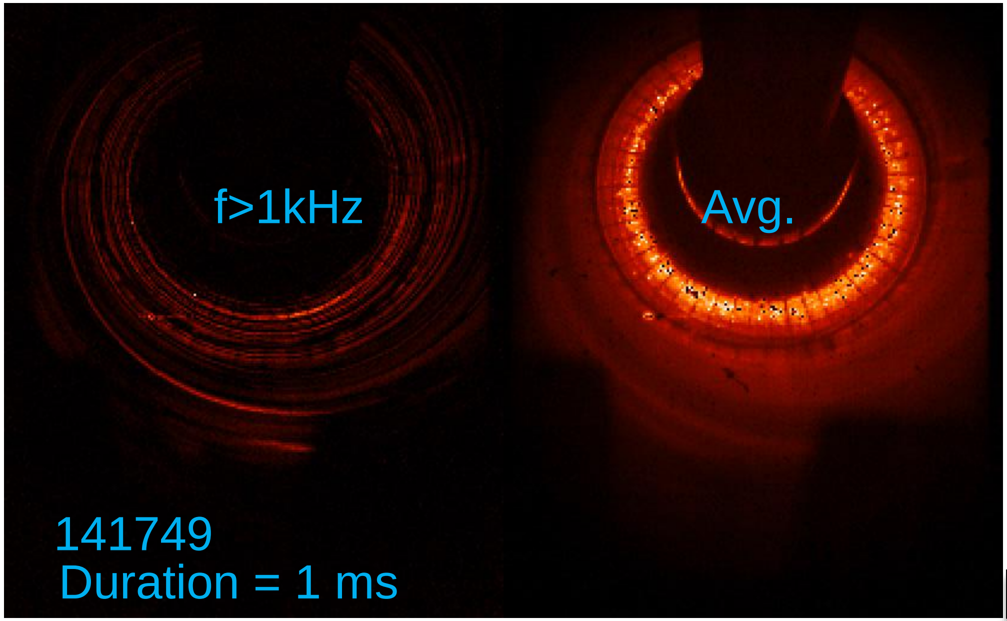
- Upstream: Gas Puff Imaging (GPI) [Zweben NF 2004]:
  - Imaging of Dα emission, 400kHz, 2 μs exposure, 1 cm resolution
    - Fast CMOS camera, Vision Research Phantom 710
- Wide angle divertor imaging:
  - Imaging of Li I emission, 100kHz, 9 μs exposure, 0.8 cm resolution
    - Fast CMOS camera, Vision Research Phantom 710
  - Toroidal remap for easier analysis [Scotti RSI 2012]
- Langmuir probe array [Kallman/Jaworski RSI 2010]:
  - Triple probes, 250 kHz

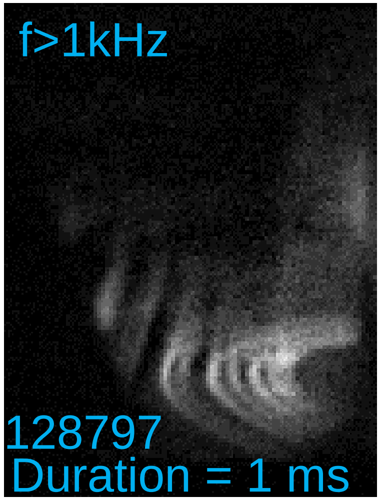


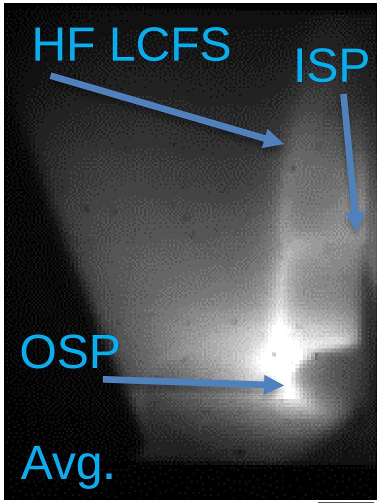


Divertor intermittent filaments routinely observed in NSTX L-mode and H-mode discharges

- Divertor intermittent filaments most easily studied via neutral lithium imaging of filament footprint
  - First done in [R. Maqueda, NF 2010]
  - Brightest line in NSTX, atomic physics provides surface localization
  - Brightness fluctuations can be understood as being ~ $\tilde{n}_e$
  - Tangential Dα imaging complements with poloidal structure

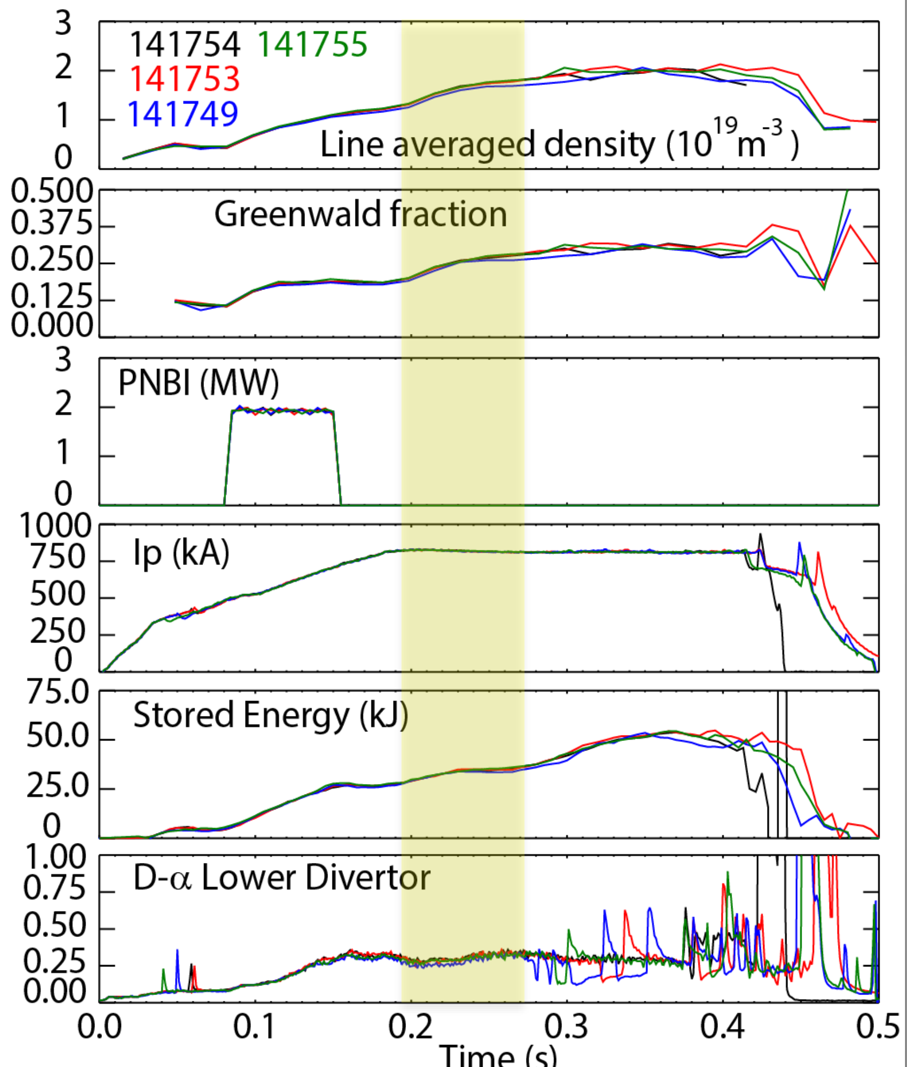


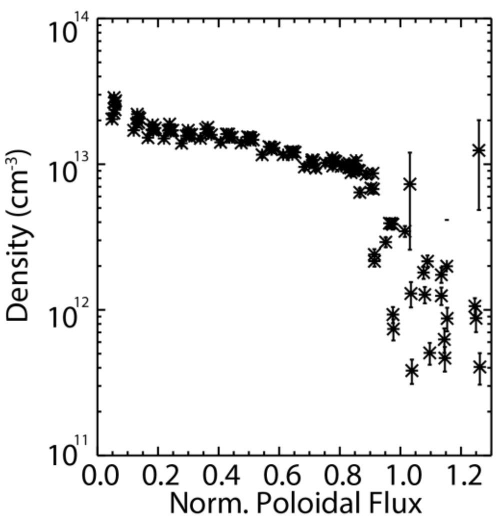


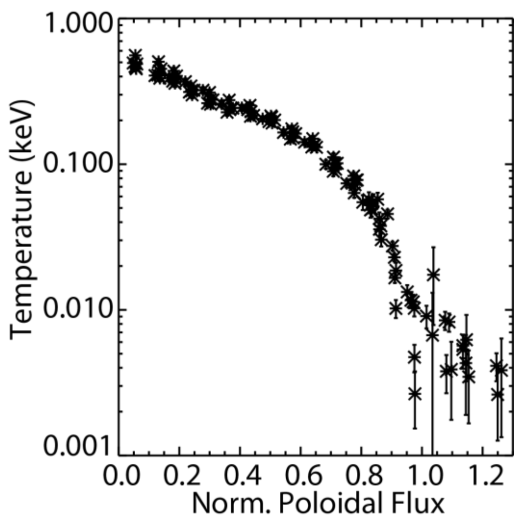


NSTX diverted ohmically-heated L-modes discharges used for divertor turbulence characterization

- Diverted NSTX ohmic L-mode discharges (2010)
  - Lower single null ($d_{r\text{-}sep}$ ~ 2 cm)
  - I_p=800kA, f_G~0.2-0.3
  - Analysis limited to L-mode intervals
  - GPI at start of flat-top (t = 0.2 s)
  - No core MHD

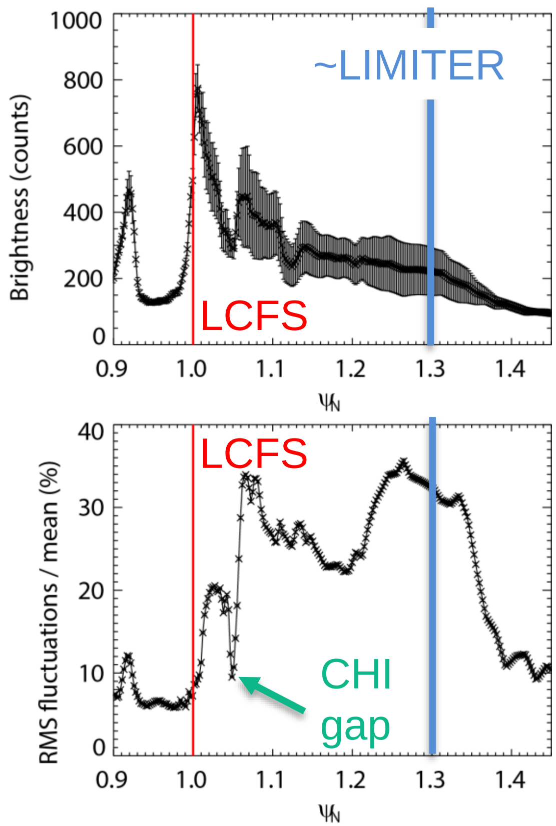


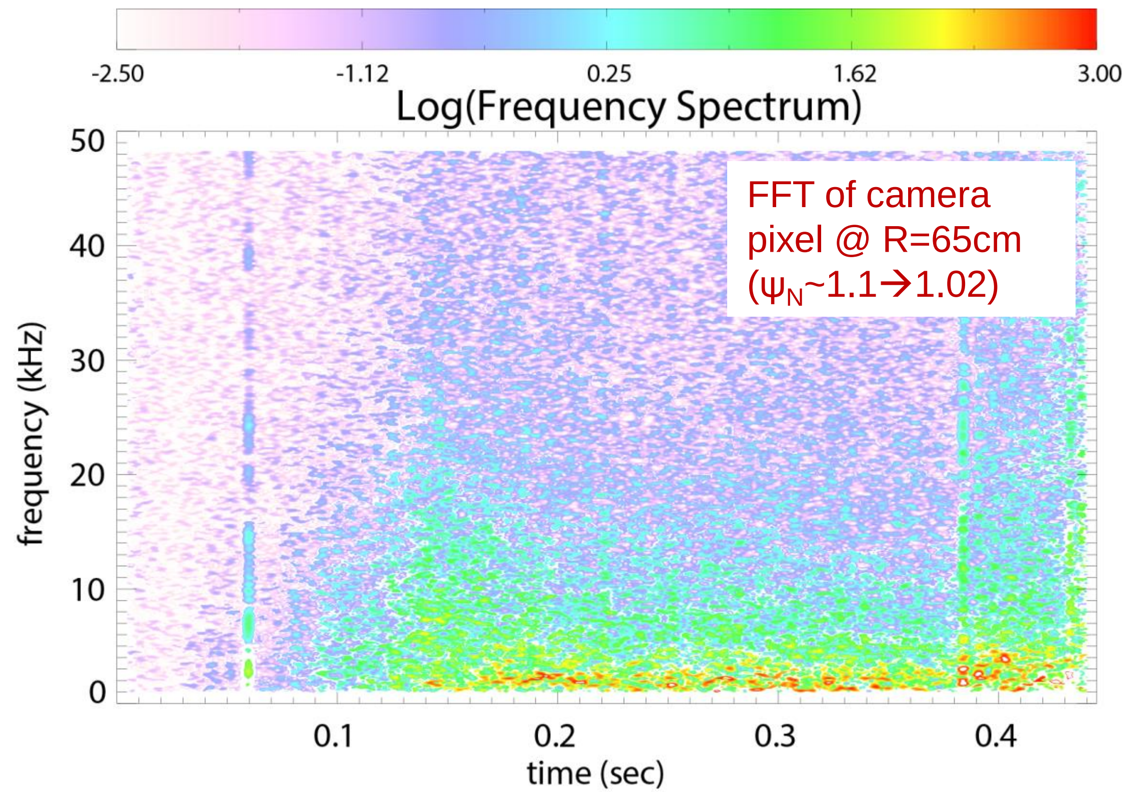




In diverted L-modes discharges, divertor broadband fluctuations in Li I emission observed with δI/I up to 30-50%

- Broadband fluctuations in Li I, δI/I up to 30-50% in region connected to midplane
  - Suggest target fluctuations related to upstream fluctuations
  - From ψ_N~1.03 fluctuations decreasing towards separatrix
  - 3 kHz feature associated to quiet turbulence periods [Zweben PoP 2010, Sechrest Pop 2011]





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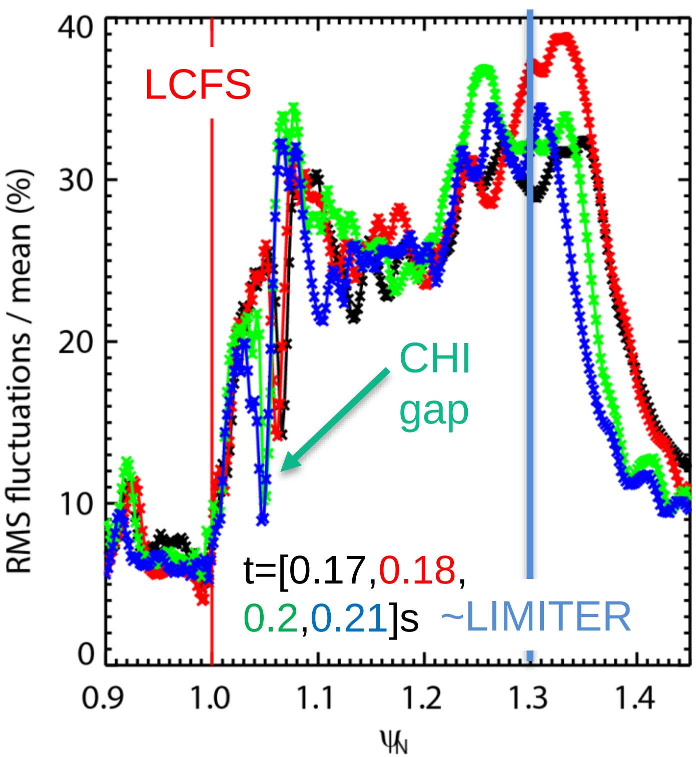
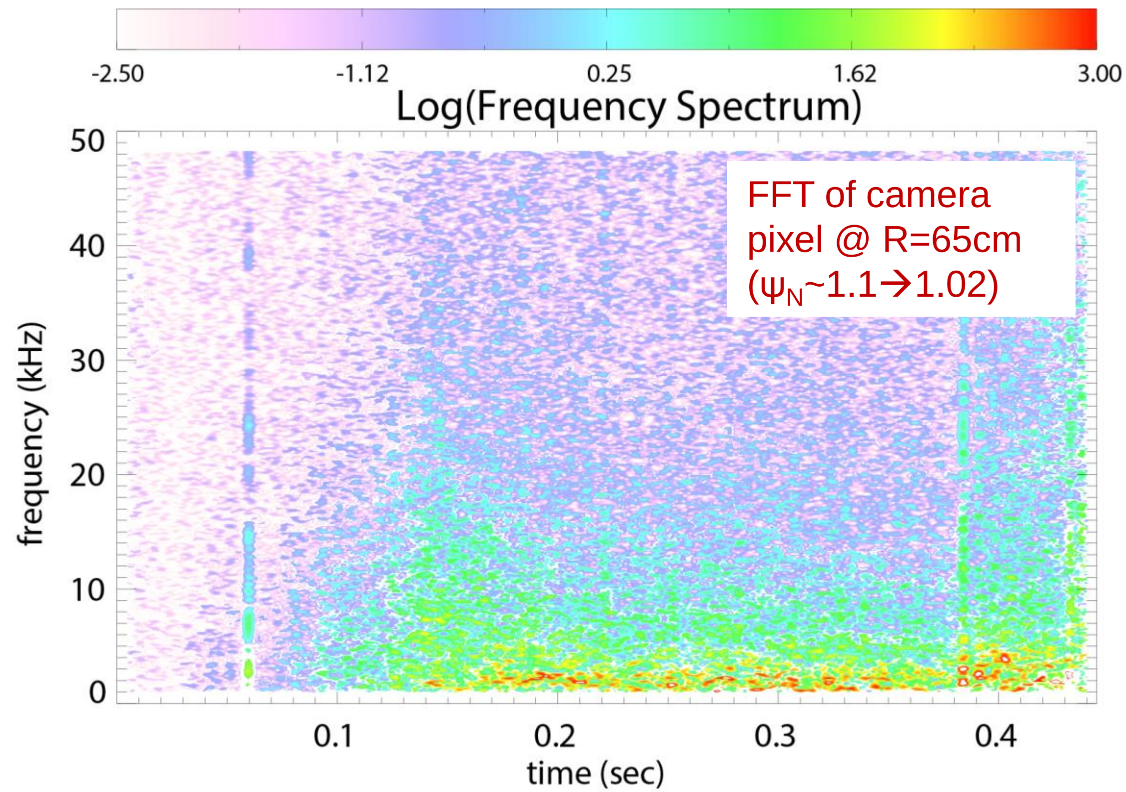
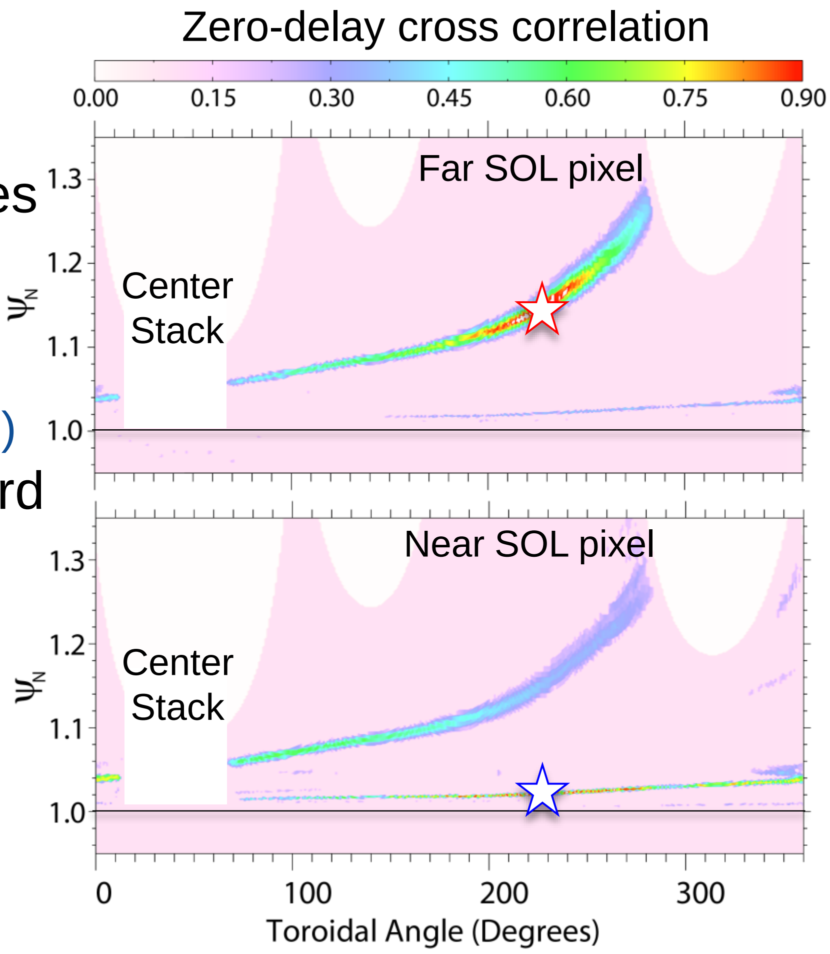
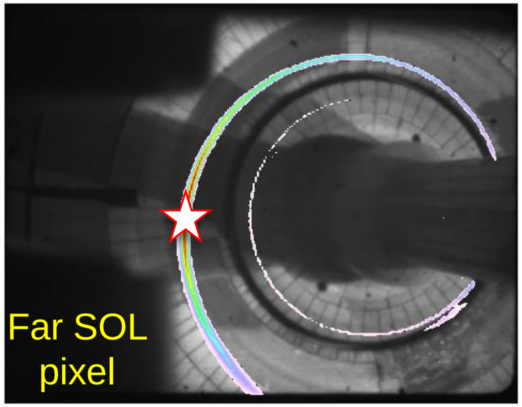


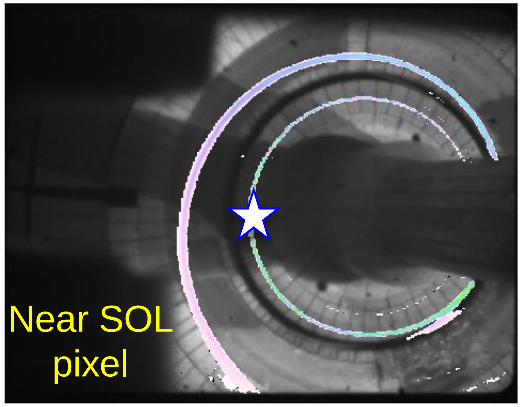


Zero-delay cross correlation shows helical correlation regions at the divertor target

- Helical correlation regions from cross correlation of pixel with rest of image
  - Autocorrelation ~ 50µs
- 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. maps (Zweben TTF17)
- Time delay cross correlation shows outward radial propagation along helical footprint
  - Consistent with upstream radial propagation

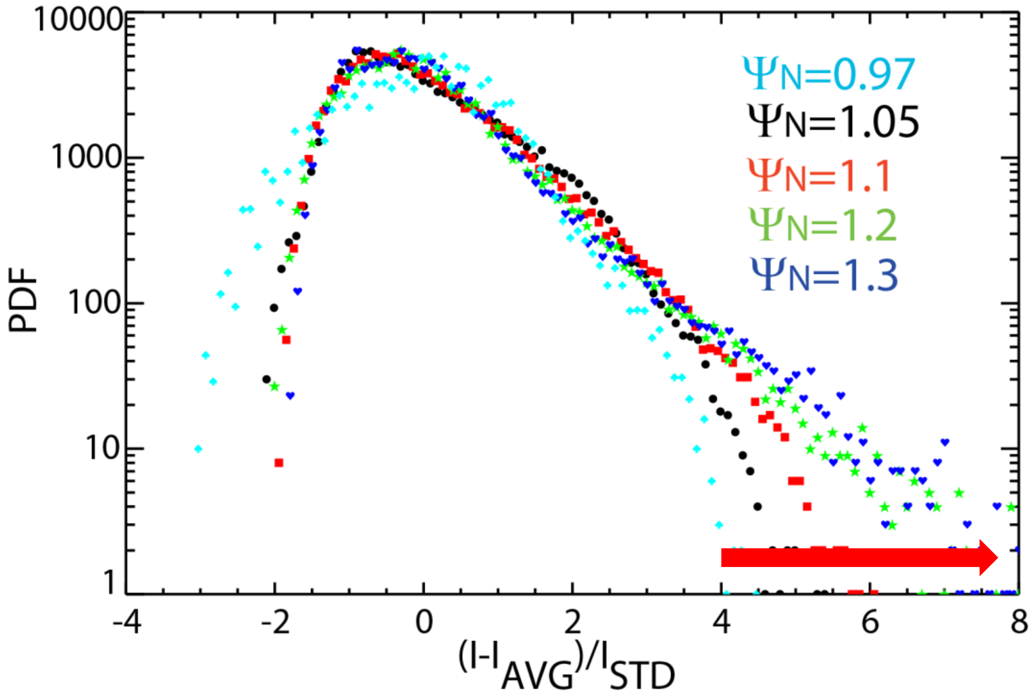


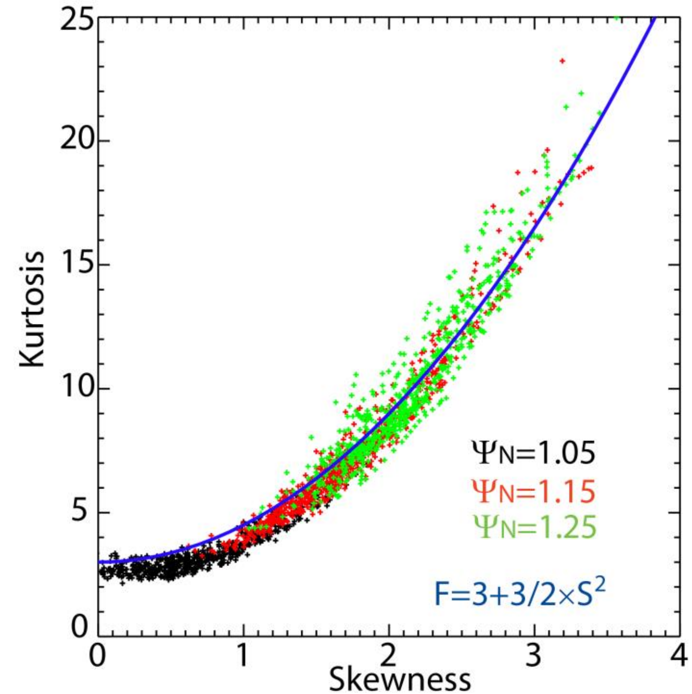




Fluctuations statistics follow properties typically observed for upstream blobby transport

- Divertor fluctuations intermittency increases moving radially out in SOL (also in Maqueda NF 2010)
  - Typically observed for upstream turbulence in NSTX, C-Mod, TCV, JET, KSTAR, etc.
- Parabolic dependence of kurtosis vs. skewness
  - Statistical moments consistent with Gamma distribution [O.E. Garcia PRL 2012]



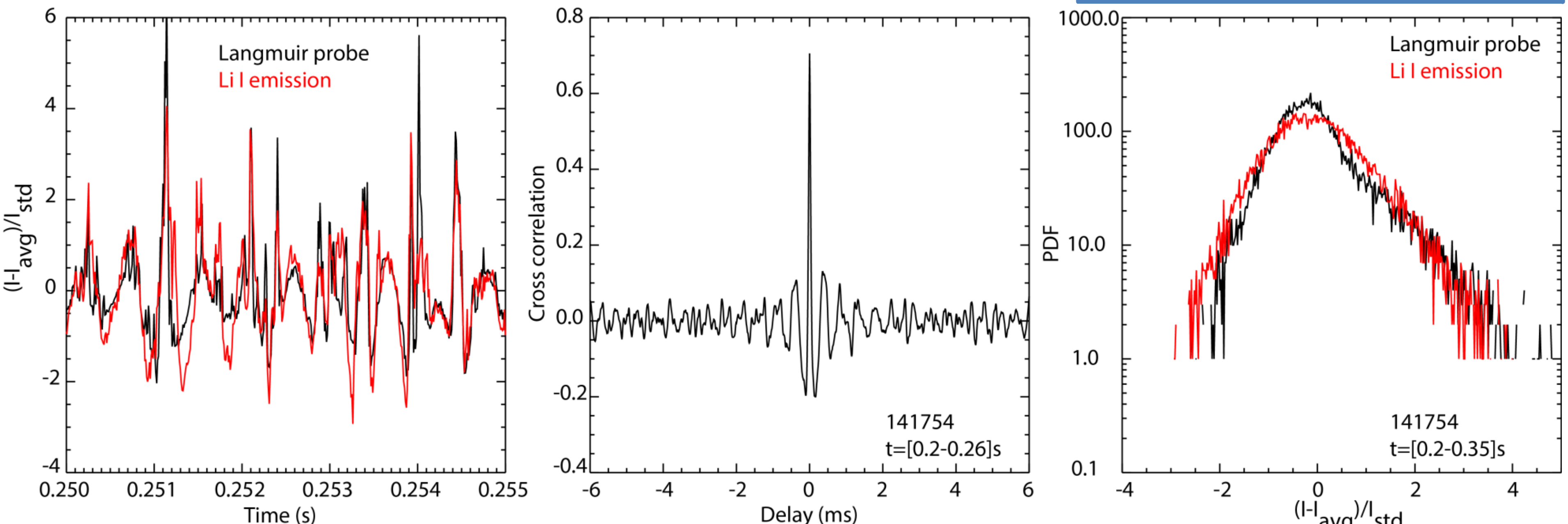


Filament footprint in Li I emission correlates with probe ion saturation current at target

- 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 (Backup)
  - Smaller probe radial resolution (~2x) → smaller scales
  - Li I photon emission coefficient decreases with density

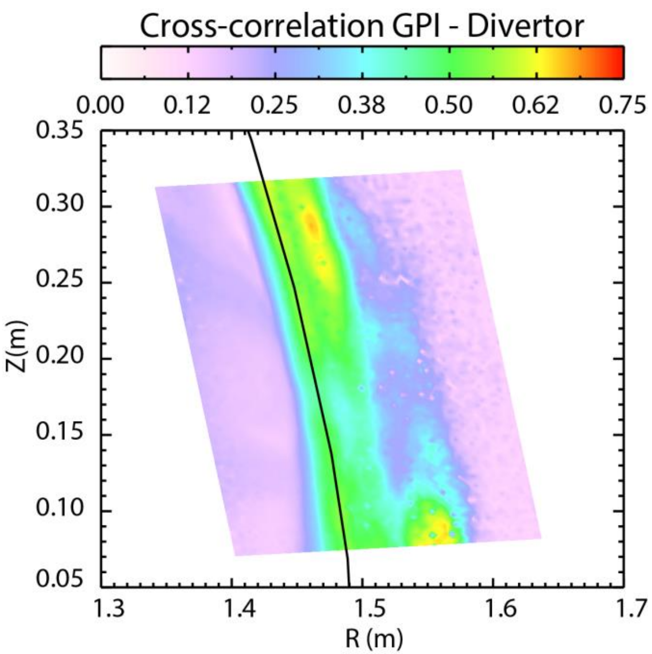
$$E_{Li} = n_e \times n_{Li} \times PEC_{Li}$$

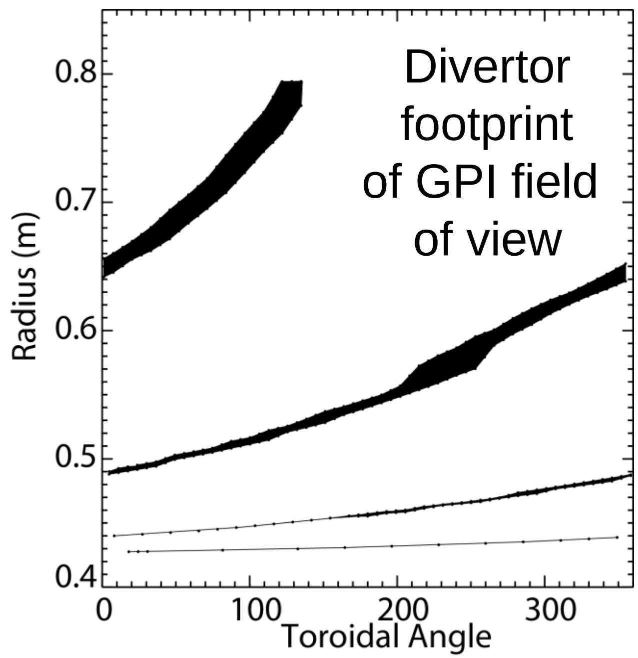
J. Kallman, M. Jaworski, V. Surla acknowledged for 2010 LP data

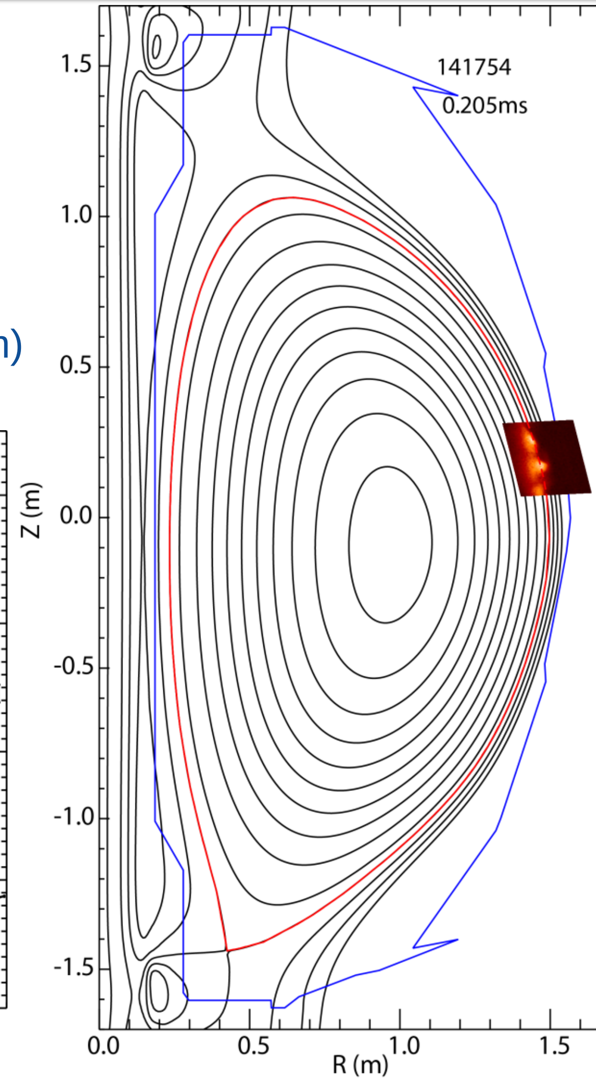


GPI correlates with divertor emission over region connected to divertor target

- 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)

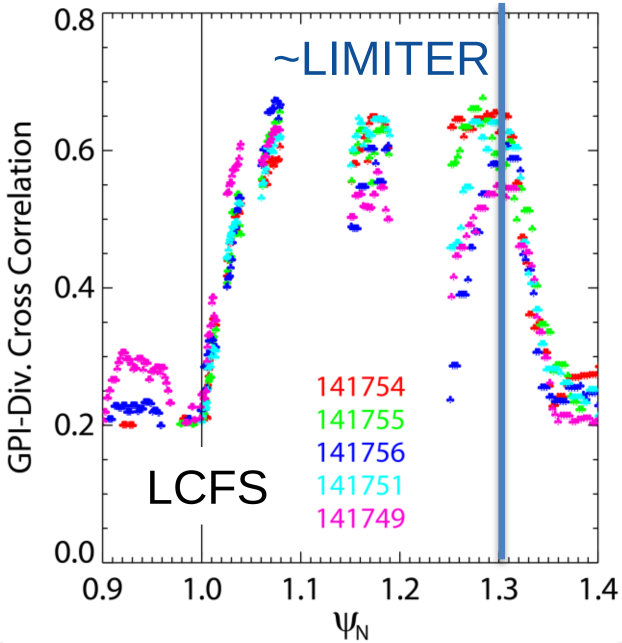


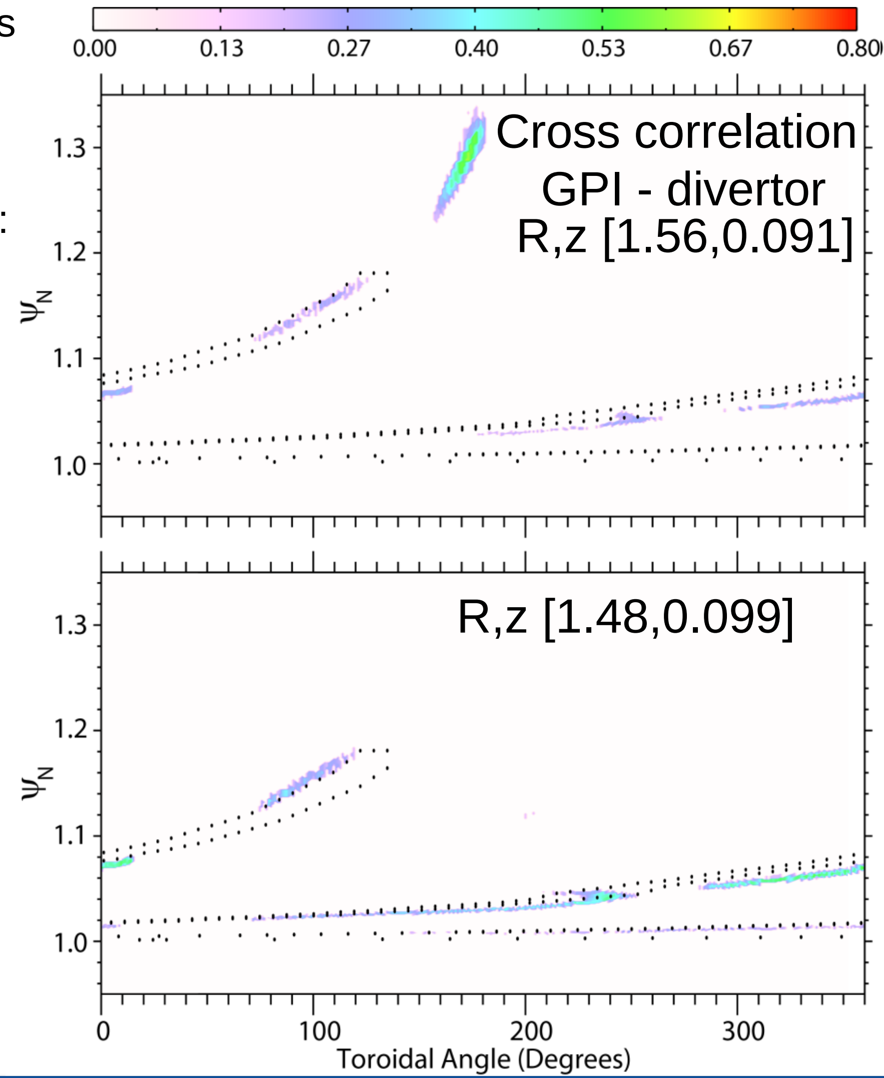




Correlation above random observed over divertor area mapping to GPI field of view

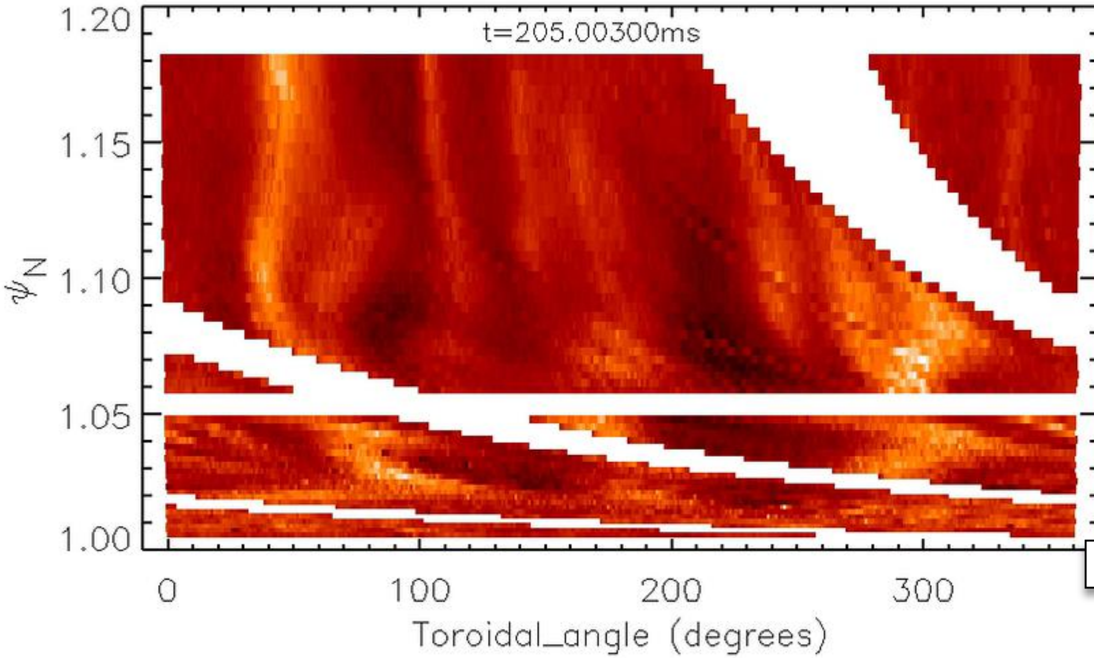
- Divertor region correlated with GPI maps to field lines within GPI field of view
  - Fluctuations are field aligned
- Large correlation (0.65) with GPI over ψ_N ~1.08-1.3
- Decrease in cross corr. towards LCFS can be due to:
  - Diagnostic limitations (narrow footprint)
  - Disconnection of divertor turbulence (e.g., via X-point)
- Region correlated with upstream turbulence corresponds to region with large divertor fluctuations





Midplane projection of divertor filaments shows radial propagation and number of filaments

- Upstream and divertor turbulence are correlated, filed aligned and with zero delay
- Wide angle divertor imaging can provide wide angle information on upstream turbulence
- Remapping divertor images upstream additional information can be derived:
  - Effective toroidal mode number, toroidal propagation, etc.
  - Can be useful for model/code validation



Divertor-leg fluctuations in NSTX-U L-mode discharges

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  - Broadband fluctuations in Li I emission with δI/I up to 30-50%
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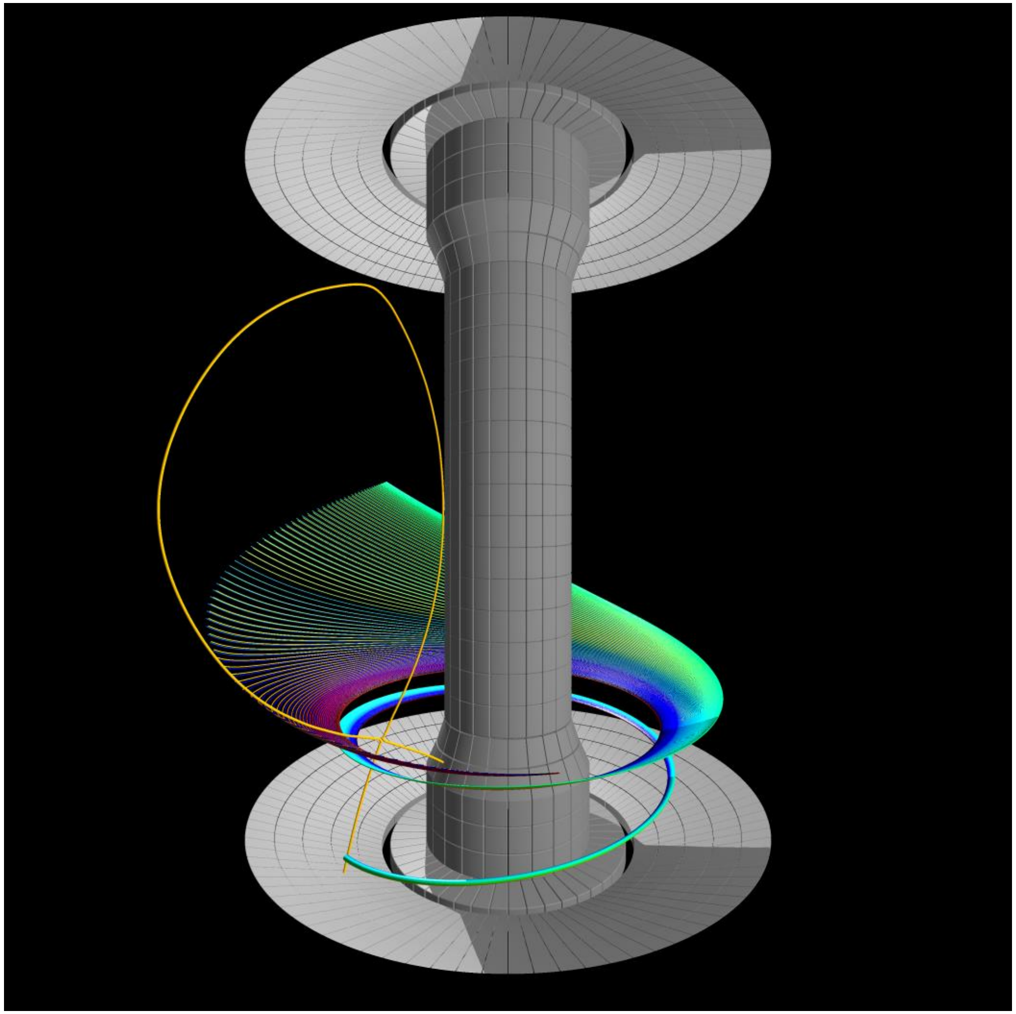
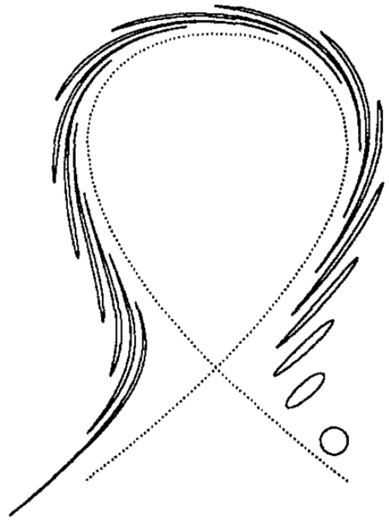


Divertor-localized fluctuations could cause further spreading of target heat flux

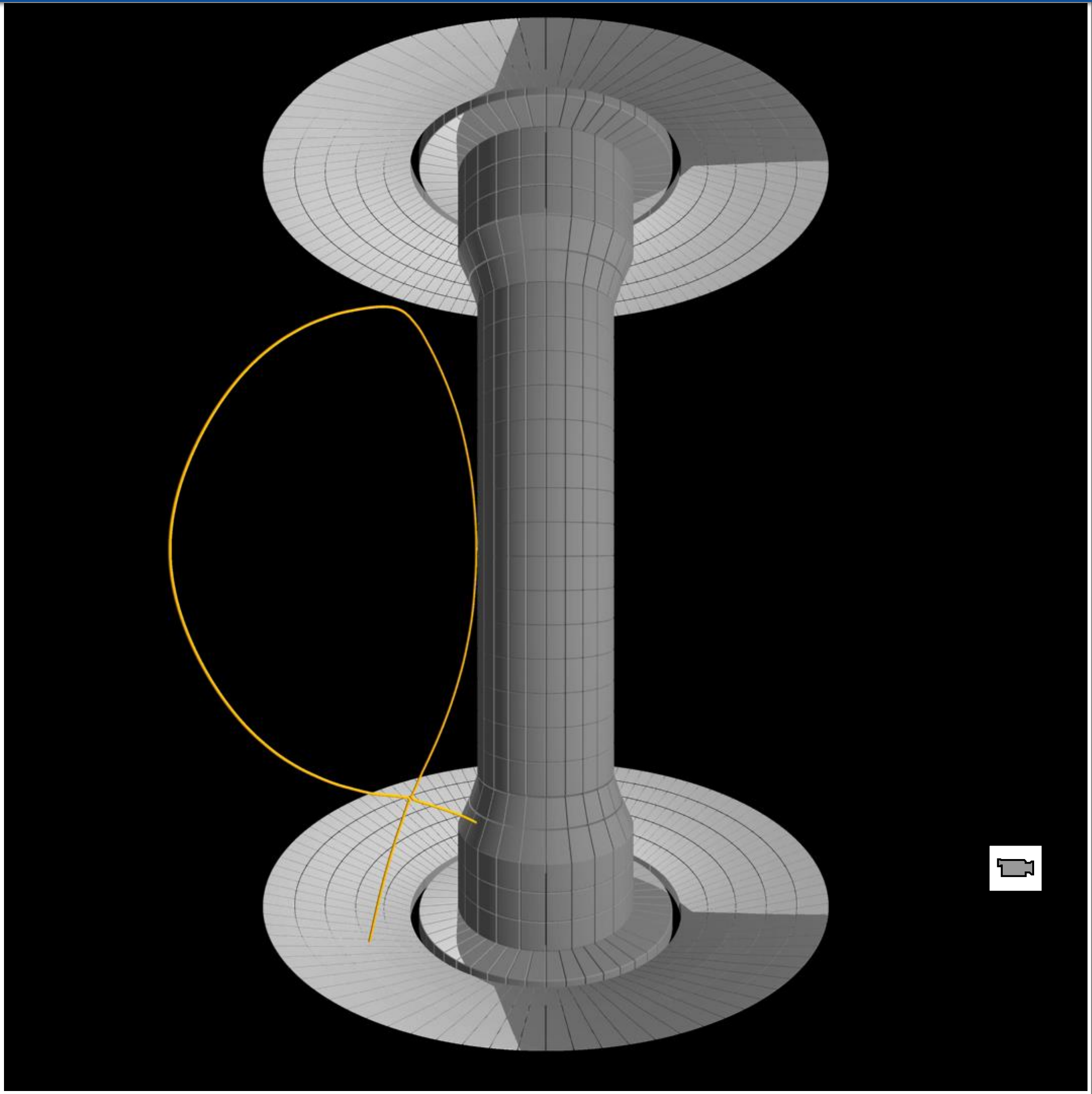
- In addition to divertor fluctuations due to upstream turbulence, divertor-localized turbulence could enhance heat flux spreading
- Divertor-leg fluctuations theoretically studied in several papers:
  - D. Farina, Nucl. Fusion 1993.
  - R. Cohen, Contrib. Plasma Phys. 1996, 2006, Nucl. Fusion 2007.
  - D. Ryutov, Contrib. Plasma Phys. 2004, 2007, Phys. Plasmas 2007.
- Recent observations in MAST and Alcator C-Mod:
  - J. Harrison, Phys. Plasmas 2015.
  - J. Terry, J. Nucl. Mater. Energy 2017.
- New fast camera installed in NSTX-U to study divertor fluctuations:
  - Divertor filaments due to upstream turbulence
  - Divertor-localized turbulence
  - Instabilities in the weak poloidal field region of snowflake divertors (“churning” mode, D. Ryutov, Phys. Scripta 2014)

X-point can cause stretching of divertor flux tubes, possibly causing disconnection

- Flux tube with circular cross section at outer divertor leg
  - Representative of flute-like divertor instability
- Magnetic shear results in ribbon like structures upstream
  - Enhanced by proximity to X-point
- Flux tube elongation possible driver for disconnection of divertor turbulence from upstream



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



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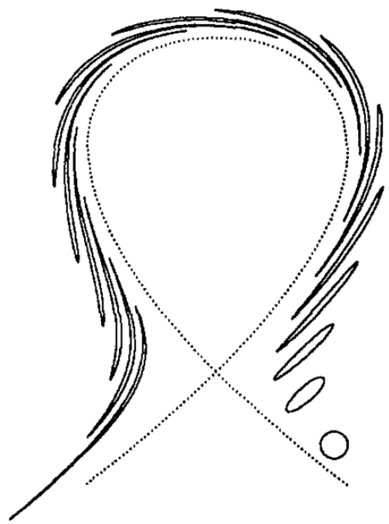

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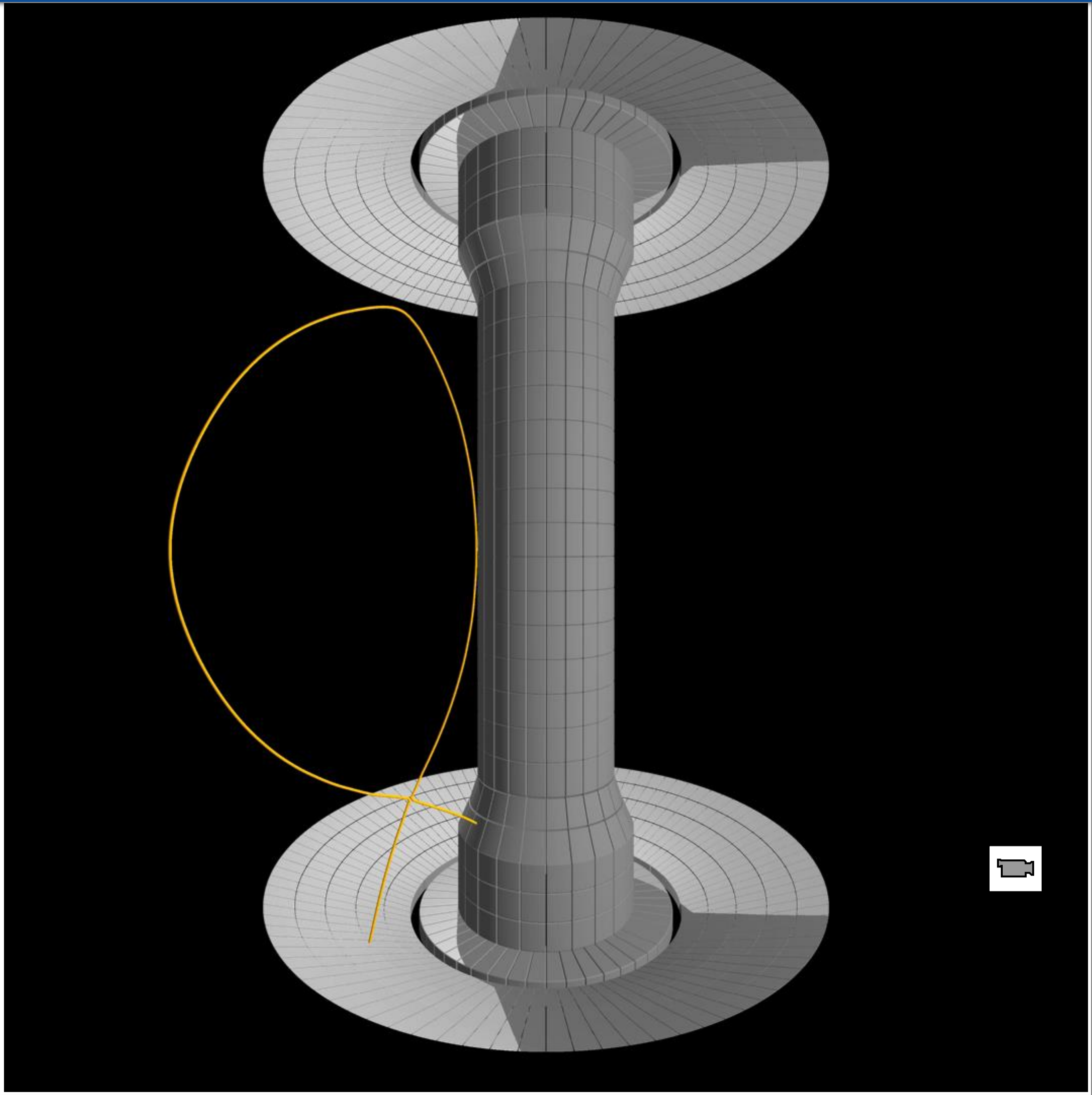
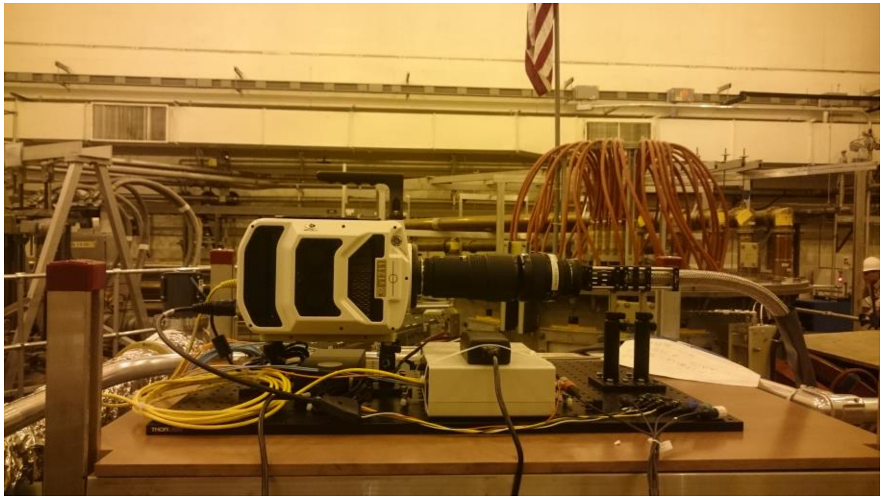


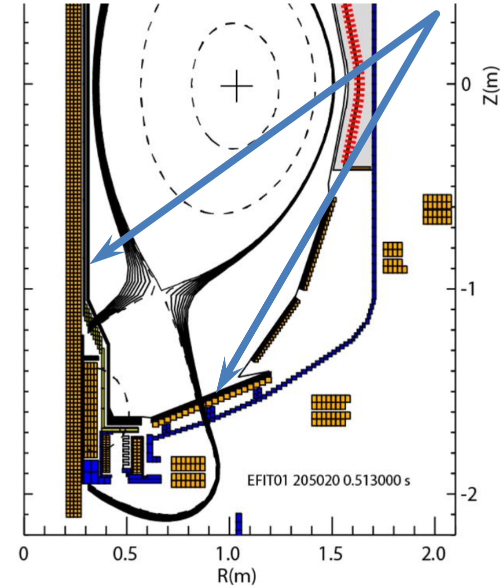
New divertor leg imaging to study divertor-localized fluctuations in NSTX-U

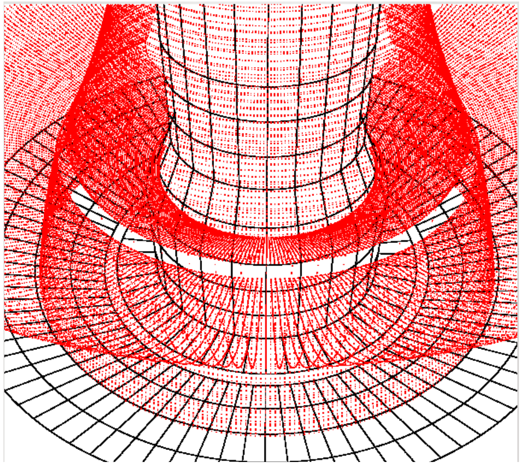
- Vision Research Phantom v1211 fast CMOS camera
  - 1280x800 pixels, 28µm pixels, 12 bit, 12 kHz @ full frame
  - 5 times higher sensitivity compared to Phantom v710
- Coherent fiber bundle 1000x800 10 µm fibers, 15' long
- 1:1.7 imaging on detector with optimized throughput:
  - Collecting f=16 mm F/1.4, collimating f=85 mm F/1.4, focus f=50 mm F/1.2
  - 140 kHz @ 272x192 pixels



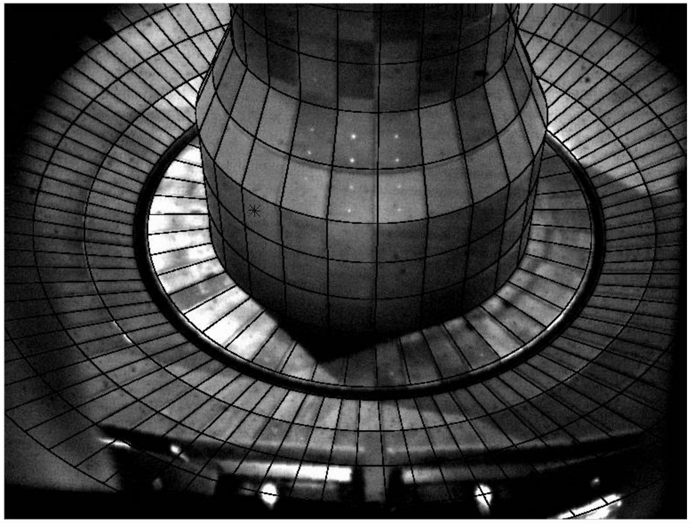
Throughput-optimized camera and high X-point L-modes enabled near-separatrix filaments imaging in NSTX-U

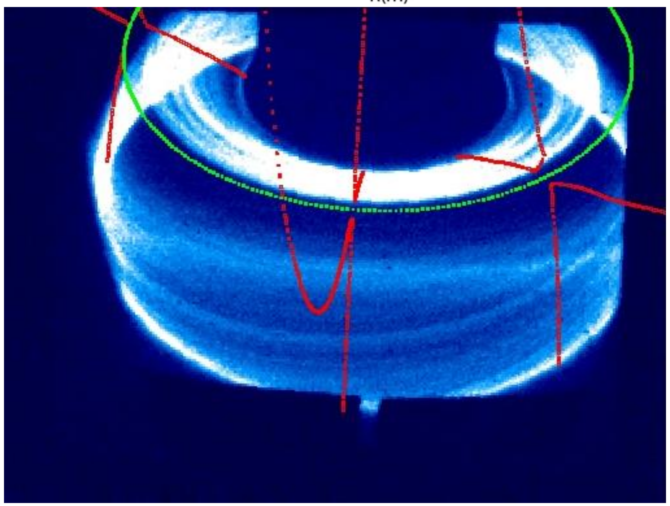
- Divertor turbulence imaging through different charge states provides contrast at different spatial locations
  - Filament footprint on target via Li I
  - Poloidal structure via Dα
  - Filaments on divertor legs via C III (~10x dimmer than D-α)
- Throughput-optimized setup enabled turbulence imaging via C III (up to 100 kHz)
  - Preliminary spatial calibration based on in-vessel structures





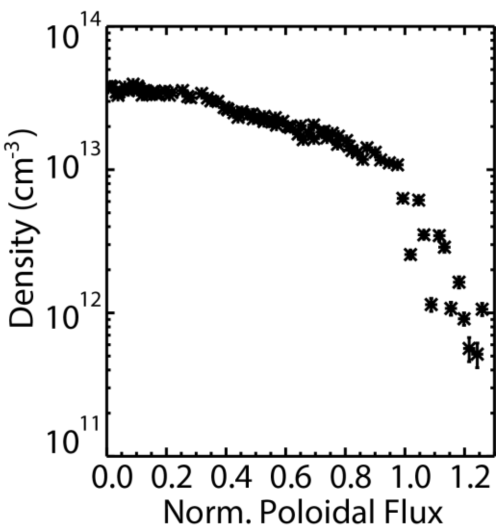
Reconstructed view + separatrix

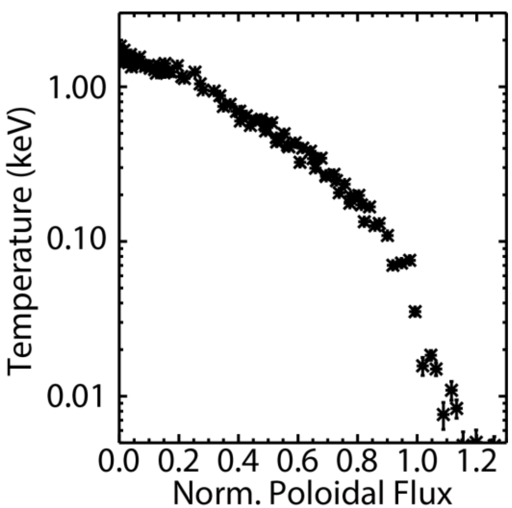


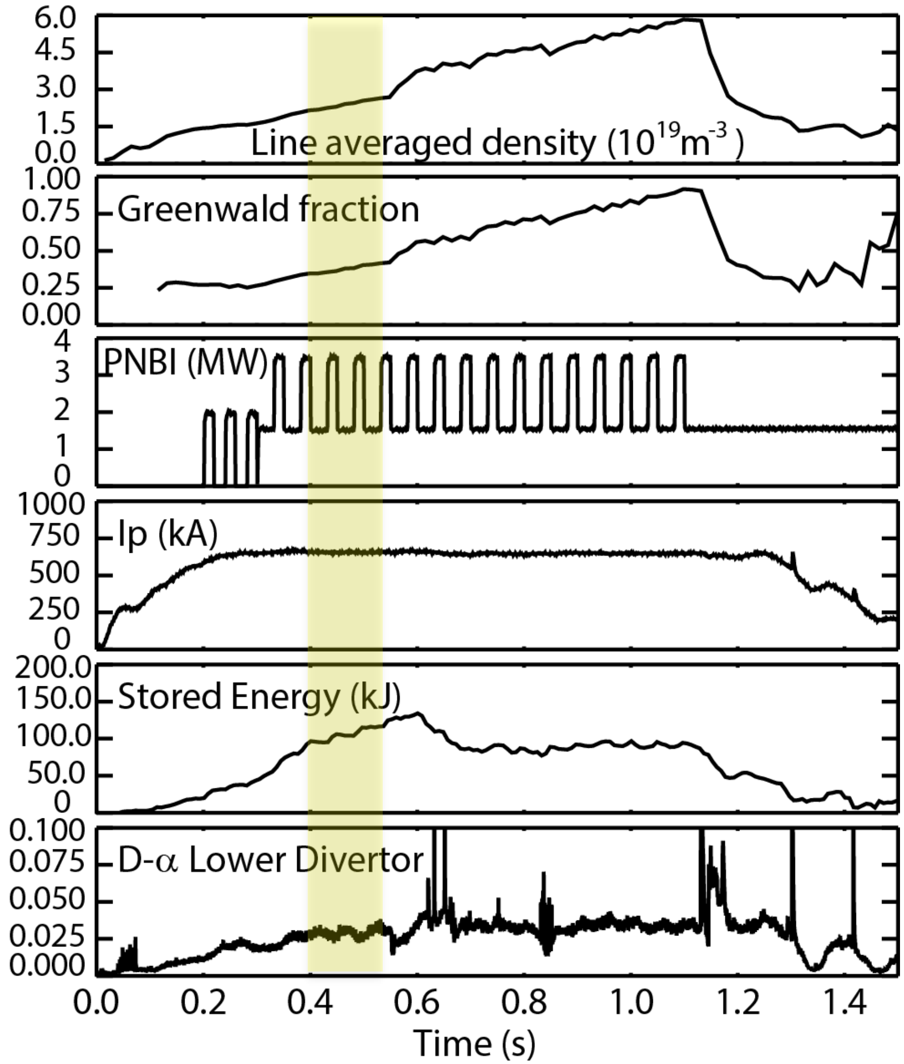


NSTX-U diverted NBI-heated L-modes discharges used for divertor turbulence characterization

- Diverted NSTX-U NBI-heated L-mode discharges (2016)
  - Lower divertor biased double null
  - I_p= 650 kA, f_G~0. 3
  - Analysis limited to L-mode interval
  - Large MHD during H-mode phase

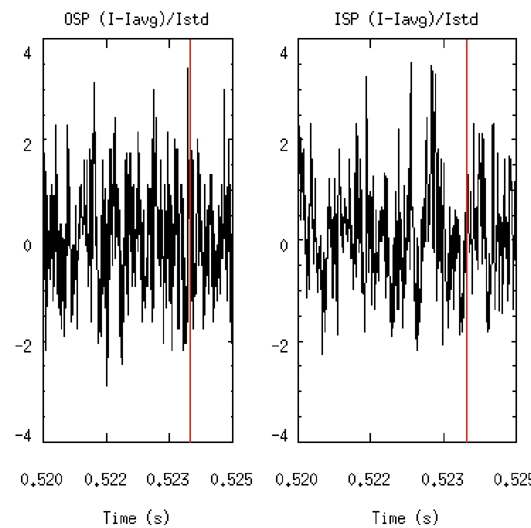




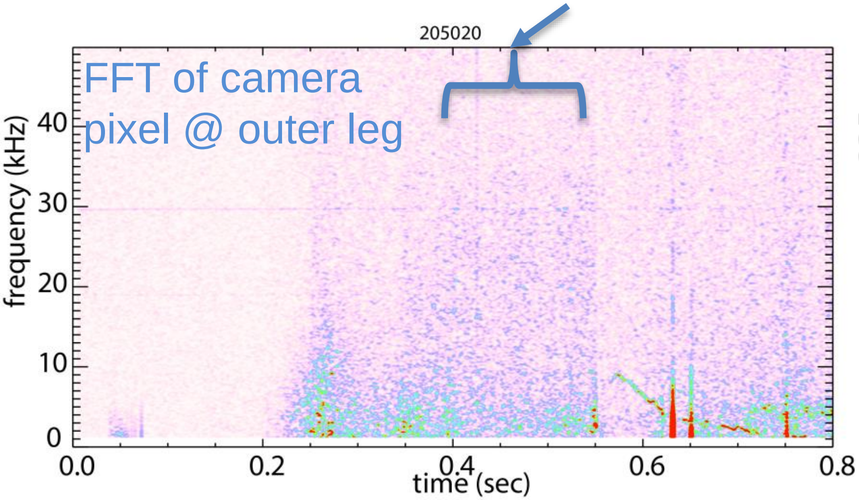


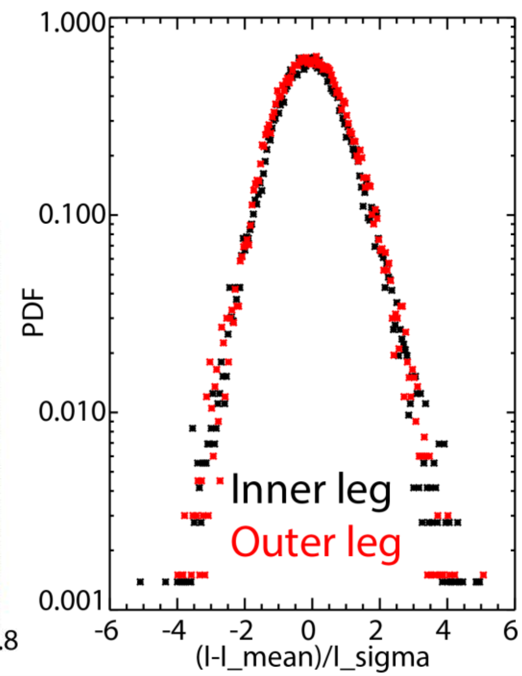
Flute-like intermittent field-aligned filaments observed in inner and outer divertor legs

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

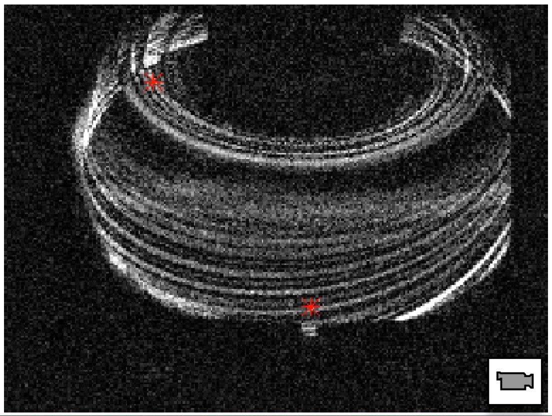


Interval in consideration



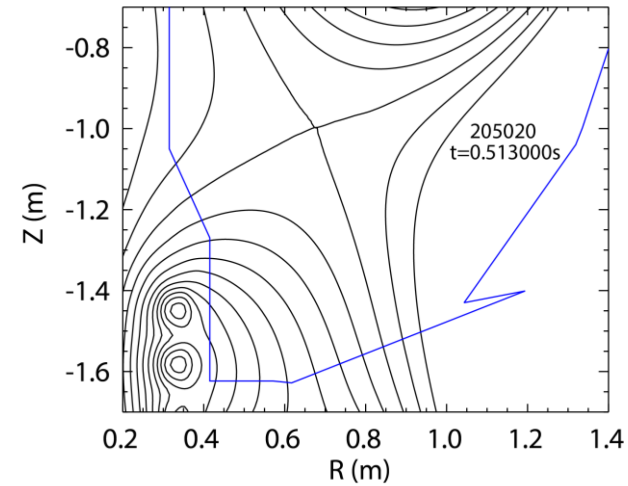


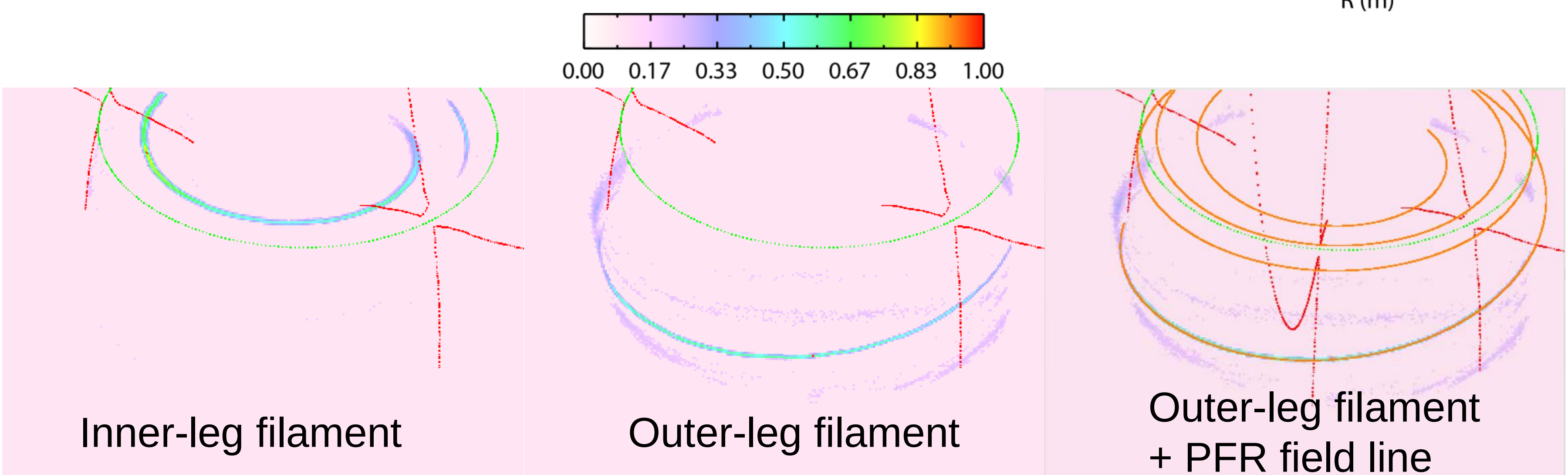
High-pass filter 1kHz



No correlation observed between inner and outer leg filaments

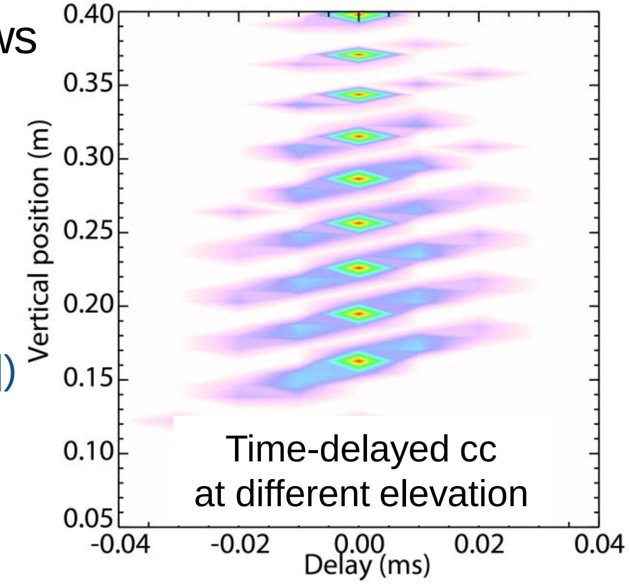
- Zero-delay cross corr. of pixel with rest of image over 10ms
- Correlation > (<) toroidal turn on inner (outer) leg
  - Parallel correlation length ~ 3 m
  - Is finite correlation due to limited C III emission shell?
  - Auto-correlation ~10 μs
- No correlation between inner and outer leg filaments
- Filaments are field aligned, radially localized around leg

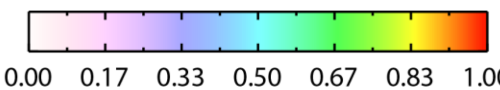


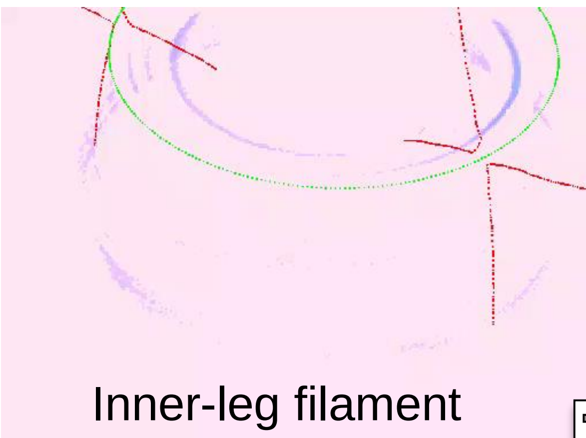


Inner and outer leg filaments rotate in opposite toroidal direction

- Time-delayed cross corr. of pixel with rest of image shows average filament propagation
- Apparent poloidal motion for both inner and outer leg filaments towards X-point (also in C-Mod)
  - Or equivalently opposite toroidal directions.
    - Impossible to separate toroidal vs. poloidal motion
  - Inconsistent with flux tube rigid rotation (also [J. Terry JNM 2017])
- Apparent poloidal velocity ~1km/s

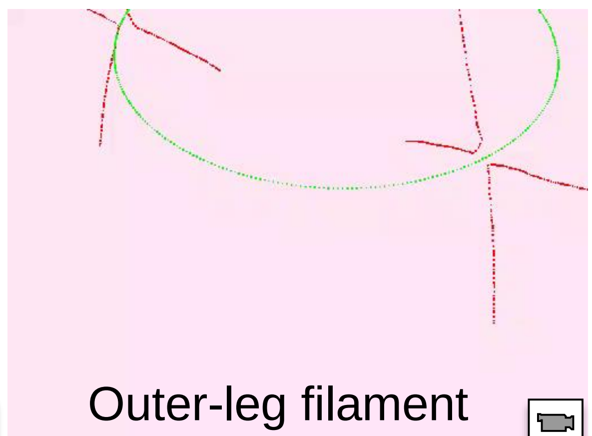






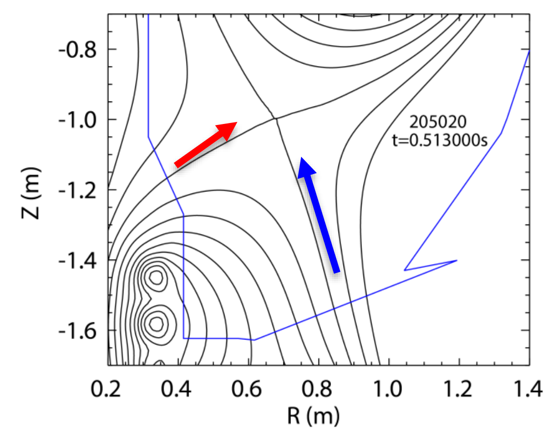
Inner-leg filament

Delay [-30, +40]µs



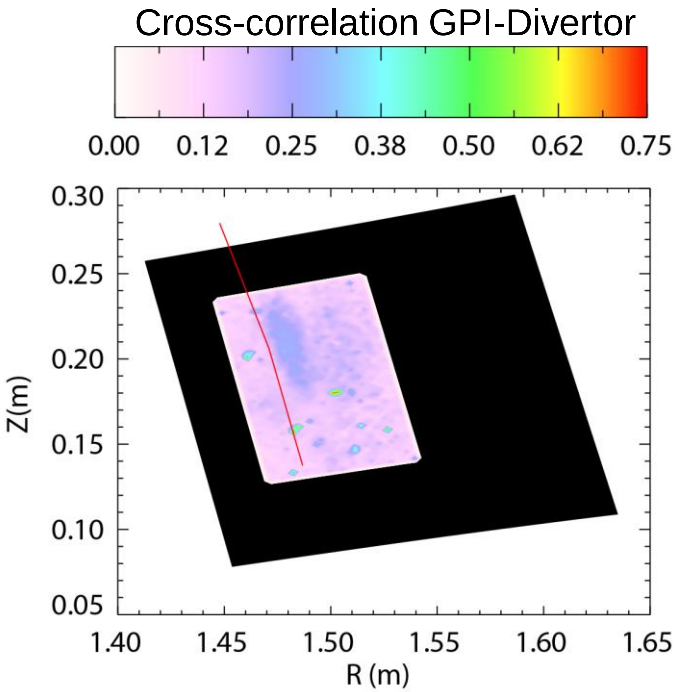
Outer-leg filament

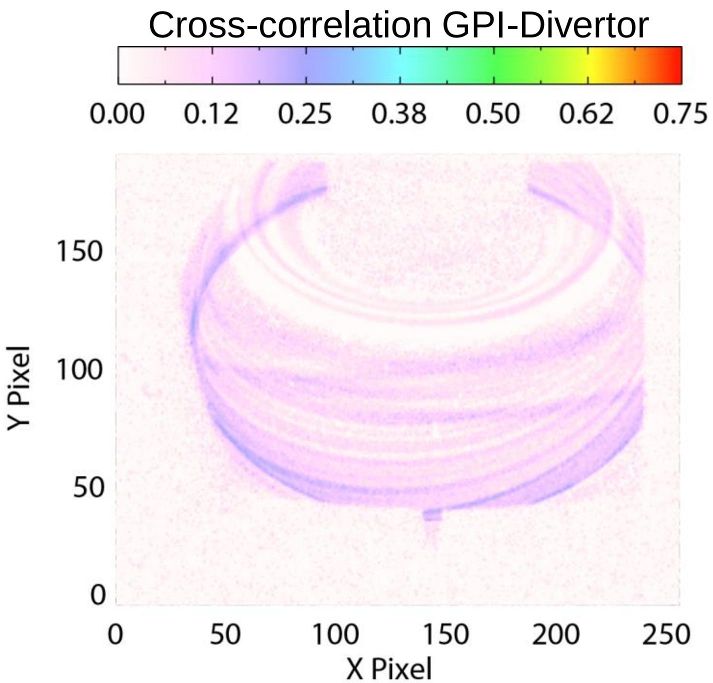
Delay [-40, +40]µs



No correlation observed between divertor-leg filaments and upstream blobs

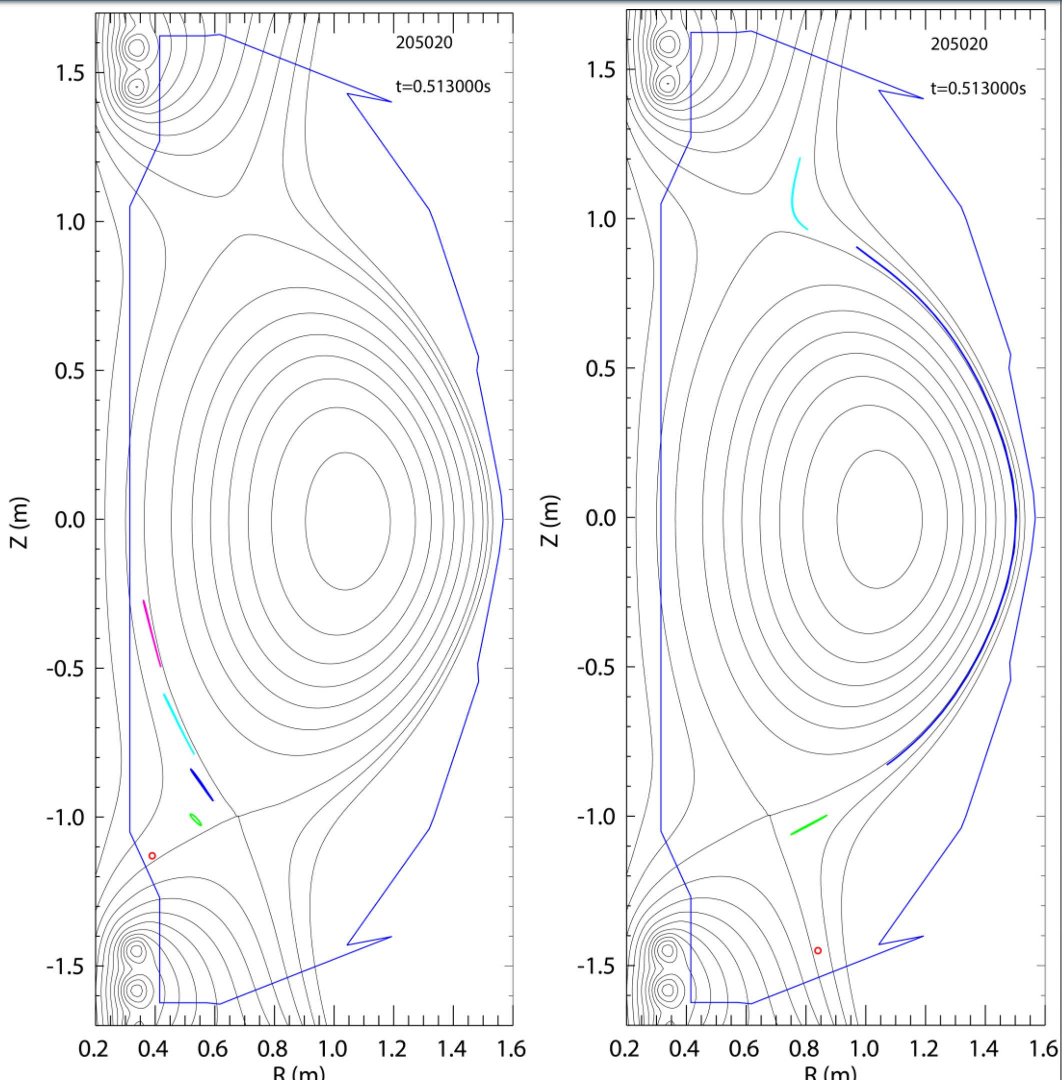
- No large correlation observed with upstream passive D-α
  - Cross correlation up to 0.3
  - Maximum correlation in the GPI field of view corresponds to axisymmetric strike point





Shape, dynamics, absence of upstream correlation suggest near-separatrix divertor filaments are generated in divertor

- Only highly elongated structures upstream map to flute-like filaments in the divertor
- Rigid flux tube rotation incompatible with motion of inner and outer filaments
- Poloidal propagation of outer divertor-leg filaments opposite to typical propagation of upstream blobs
- No correlation of divertor leg filaments with GPI



Several common features with near separatrix filaments observed on MAST and C-Mod

From J. Terry, JNME 2016

	C-Mod	MAST [Harrison, PoP 2015]
Filament location	• Along inner leg (attached conditions) • In outer leg SOL (attached conditions with Bx∇B up) • Sometimes in PFZ • Around X-point and inside LCFS (detached conditions with X-pt MARFE)	• Along inner leg (attached conditions) • Along outer leg (attached conditions) • Into PFZ from inner leg
Apparent poloidal motion at inner leg	Upward along leg ($n/n_{Greenwald}$ >0.12)	Downward along leg
Filament size ⊥ to B	~0.5 cm (~60 ρ_s)	~1-2 cm (~15 ρ_s)
ll correlation length	< one toroidal transit (<3.7 m)	> one toroidal transit (>3.9 m)
filament life-time	~10 µs (~50/ν_i)	~100 µs (~50/ν_i)

NSTX-Upgrade
Along inner leg, outer leg, inboard SOL
Apparent motion: upward along legs
Size ~1 cm
>One transit in inner leg, < one transit in outer leg
Life time ~10 µs
δI/I ~10-20 %
Speed ~1km/s

Summary

- Divertor target turbulence in NSTX L-modes discharges
  - Broadband fluctuations in Li I emission with δI/I up to 30-50% represent footprint of upstream blobs
  - Fluctuations correlate with target Langmuir probes and GPI
  - Reduction in fluctuations and upstream correlation approaching separatrix
- Near-separatrix divertor turbulence in NSTX-U L-mode discharges
  - Intermittent filaments in C III emission with δI/I up to 10-20%
  - 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

Future directions

- Determine if X-point/magnetic shear disconnects turbulence from divertor plate
  - Expand L-mode results to H-mode and comparison with previous results [Maqueda NF 2010]
- Expand camera diagnostic space-time range
  - Divertor gas puff
  - Higher spatial resolution
- Investigate turbulent contribution to heat flux
- Explore/characterize divertor leg fluctuation
  - Different collisionality regimes, geometry
  - During detachment (inner SOL filaments observed)