Characterization of intermittent divertor filaments in L-mode discharges in NSTX and NSTX-U

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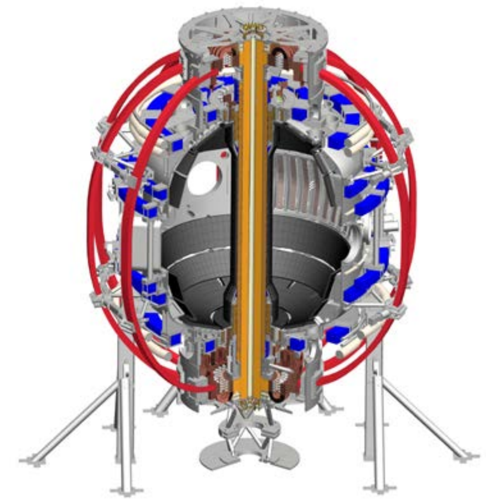
NSTX Upgrade



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Abstract

Divertor filaments due to intermittent fluctuations are studied in L-mode discharges in NSTX and NSTX-U to understand transport due to edge blobs and their role in the divertor particle fluxes.

In Ohmic L-mode NSTX discharges in a lower single null configuration, intermittent filaments on the divertor target plate were imaged through neutral lithium emission with frame rates up to 200 kHz and 1 cm spatial resolution. Broadband fluctuations (frequency spectrum decreasing for f>10kHz) up to 20-50% in RMS/mean are observed between ψ_N=1.02-1.3 (which maps to the low field side limiter). Spiral-shaped divertor correlation regions are observed up to ψ_N=1.02 and extend for over a toroidal turn. The spiral motion of the filament at the target is consistent with a radial and poloidal downward motion upstream as previously observed in NSTX H-mode discharges [Maqueda, NF 2010]. Divertor filaments are correlated with midplane blobs measured by the gas puff imaging diagnostic. The cross-correlation with midplane blobs is observed to peak at zero delay at every radius, with values up to 0.8 in the far SOL and decreasing to 0.4 at ψ_N=1.05.

In NSTX-U, a more sensitive camera with optimized throughput allowed divertor turbulence imaging using C III emission at up to f = 100kHz, enabling the study of filament dynamics along the inner and outer divertor legs in NBI-heated L-mode discharges.

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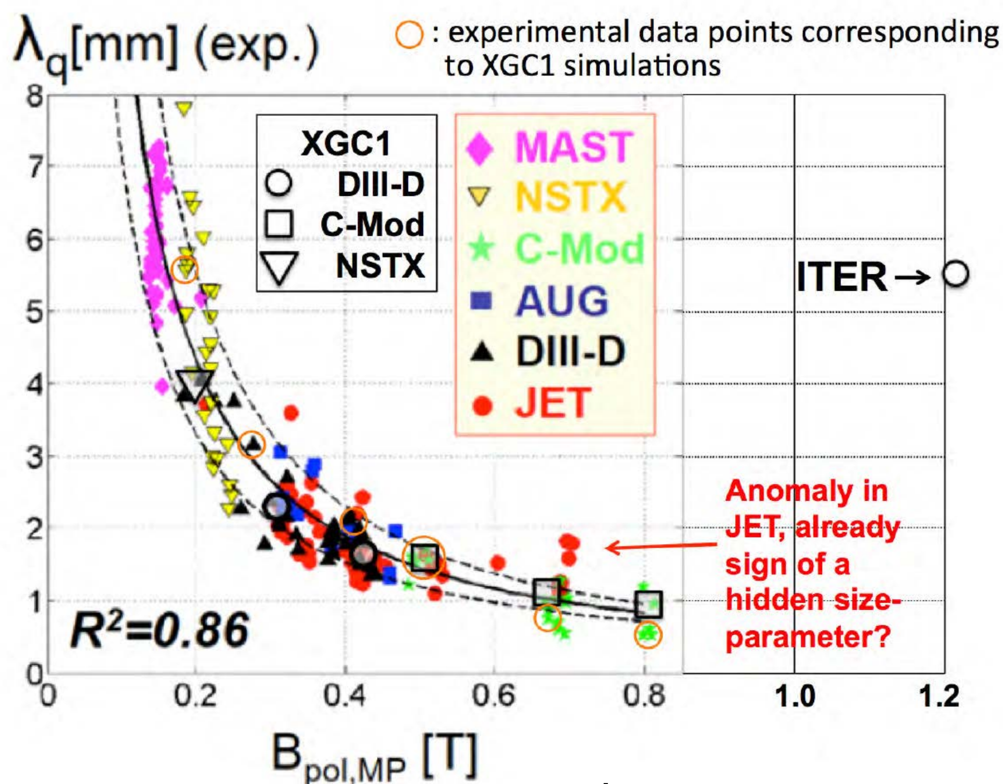
Summary/outline

- In NSTX diverted L-modes discharges, broadband divertor fluctuations in Li I emission observed with δI/I up to 30-50%
  - Fluctuations correlate with probes ion saturation current at the target and GPI upstream
  - Fluctuation statistics consistent with Gamma distribution
- Near separatrix filaments observed in NSTX-U L-mode discharges
  - Filaments appear on inner and outer leg with no correlation with upstream blobs
  - Apparent filament motion is towards X-point for both inner and outer leg

Narrow heat flux width could represents a challenge for wall materials in future reactors

- Multi machine heat flux database yields λ_q scaling [Eich, NF 2012]
  - $\lambda_q = 0.63 Bp^{-1.19}$
  - Projects to very narrow features in ITER
- Goldston's heuristic drift model consistent with multi machine scaling
  - $\lambda_q \sim I_p^{-9/8}$
  - Predicts ITER λ_q ~ 1mm
- XGC1 simulations match current tokamaks
  - <u>But predict ITER λ_q ~ 5 mm</u>



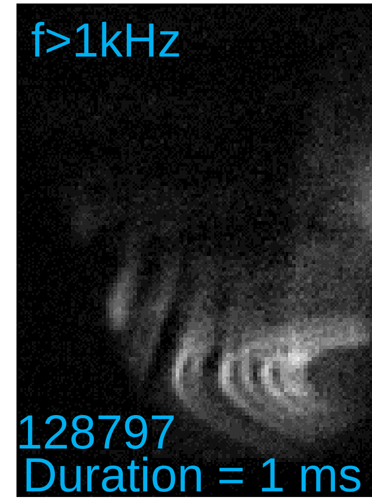
Chang, IAEA 2016

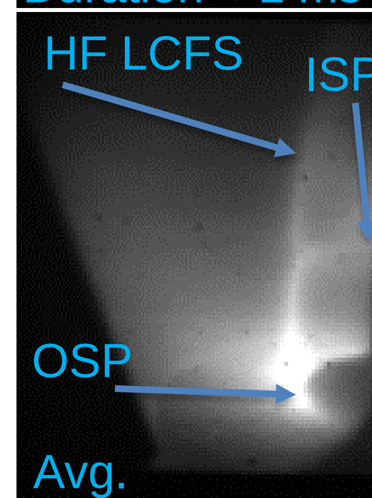
Role of turbulence vs. collisional effects in setting divertor heat flux width still unclear

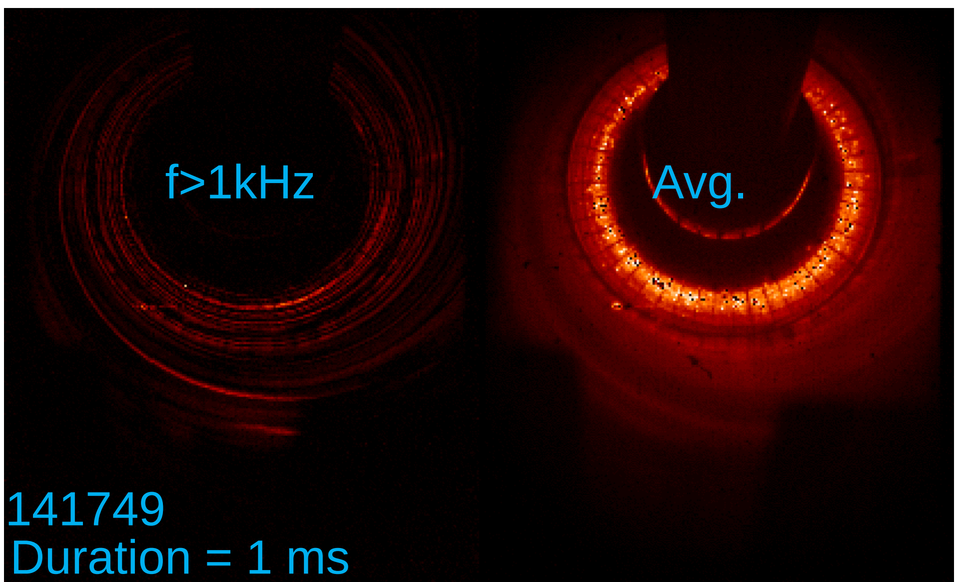
- Neoclassical effects and blobby transport can both be important in setting the heat flux width
- XGC1 simulations show blobby transport important only for JET and C-Mod and at higher fields [Chang IAEA 2016]
  - Suggests extrapolations from multimachine database incorrect for ITER
- Need to:
  - Understand contribution of turbulence to heat flux in current devices
  - Characterize divertor turbulence to help extrapolation to future devices
- In this work, characterization of far and near SOL divertor turbulence in L-mode discharges
  - Connect with previous work [Maqueda NF 2010]
  - Correlation with other diagnostics, parallel turbulence correlation
  - Comparison with other devices
  - Study role of divertor turbulence for particle fluxes fluctuations
- First step towards parameters scaling and characterization in H-mode discharges

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

- Divertor intermittent filaments studied in NSTX L-modes
- Most easily studied via neutral lithium imaging of filament footprint (as in [Maqueda NF 2010])
  - Brightest line in NSTX (with Li), atomic physics provides surface localization
  - Brightness fluctuations can be understood as being ~ $\tilde{n}_e$
  - Tangential Dα imaging can complement with poloidal filament structure

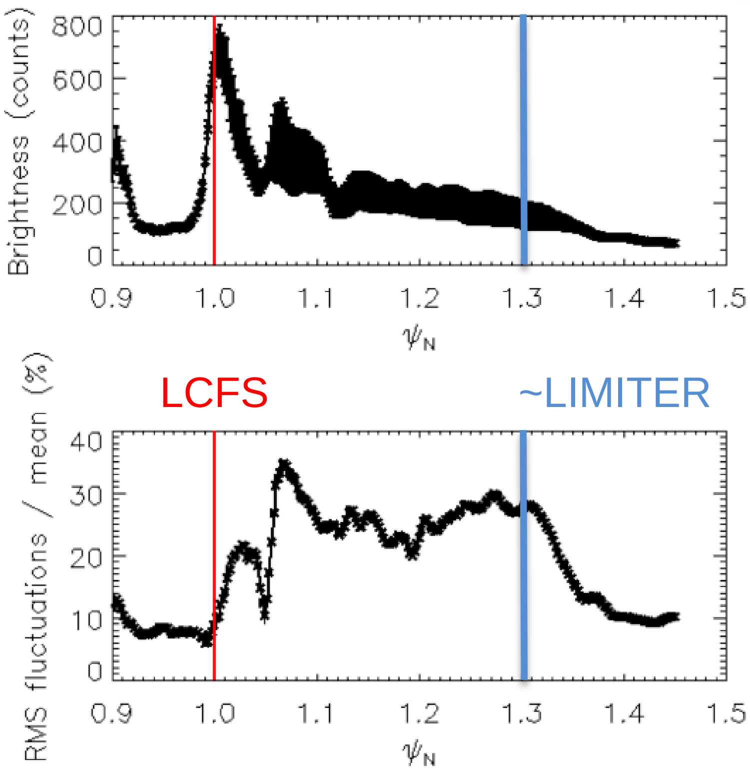


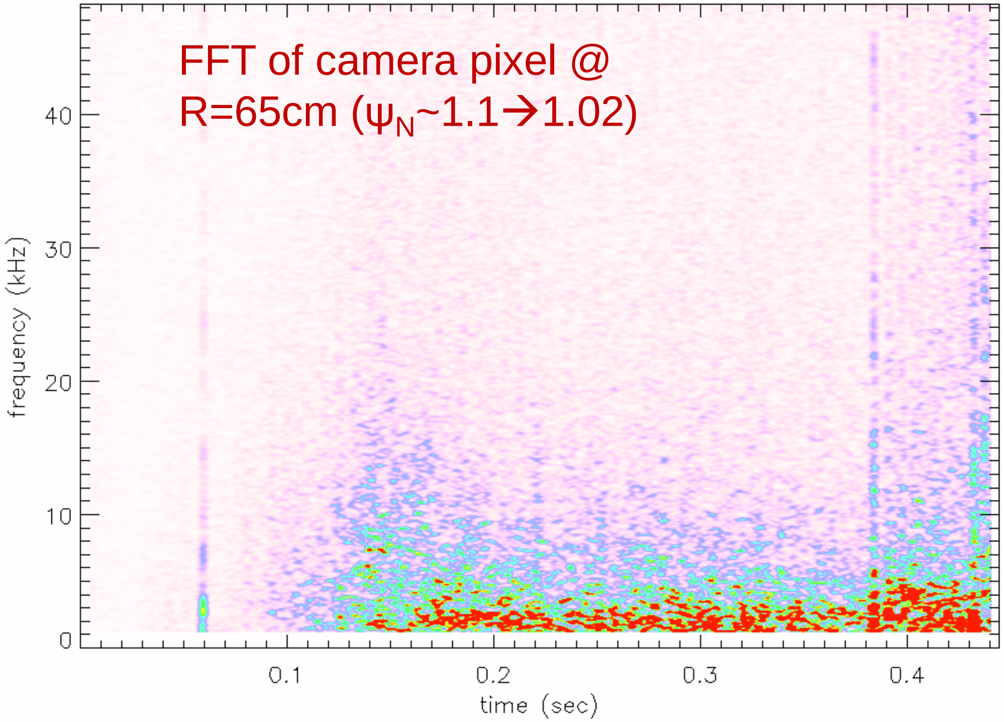




In NSTX diverted L-modes discharges divertor broadband fluctuations in Li I emission observed with δI/I up to 30-50%

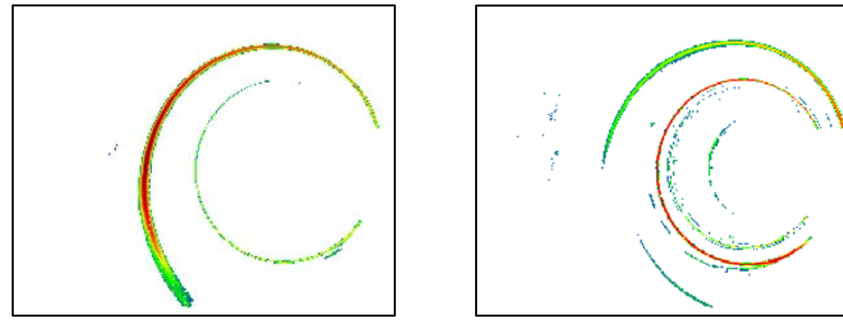
- Diverted NSTX Ohmic L-mode discharges (2010):
  - Neutral lithium emission (670.9 nm), 100kHz, 8μs exposure, 0.8 cm resolution
  - Broadband fluctuations
  - δI/I up to 30-50% in region connected to outboard midplane
    - Suggest target fluctuations related to upstream fluctuations

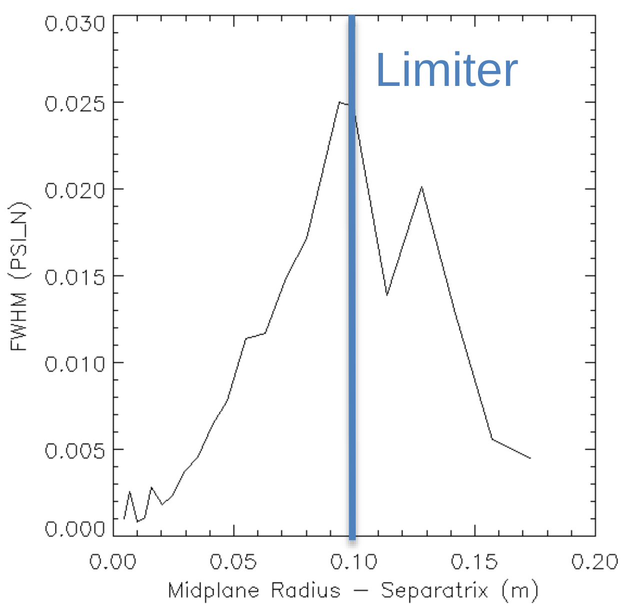


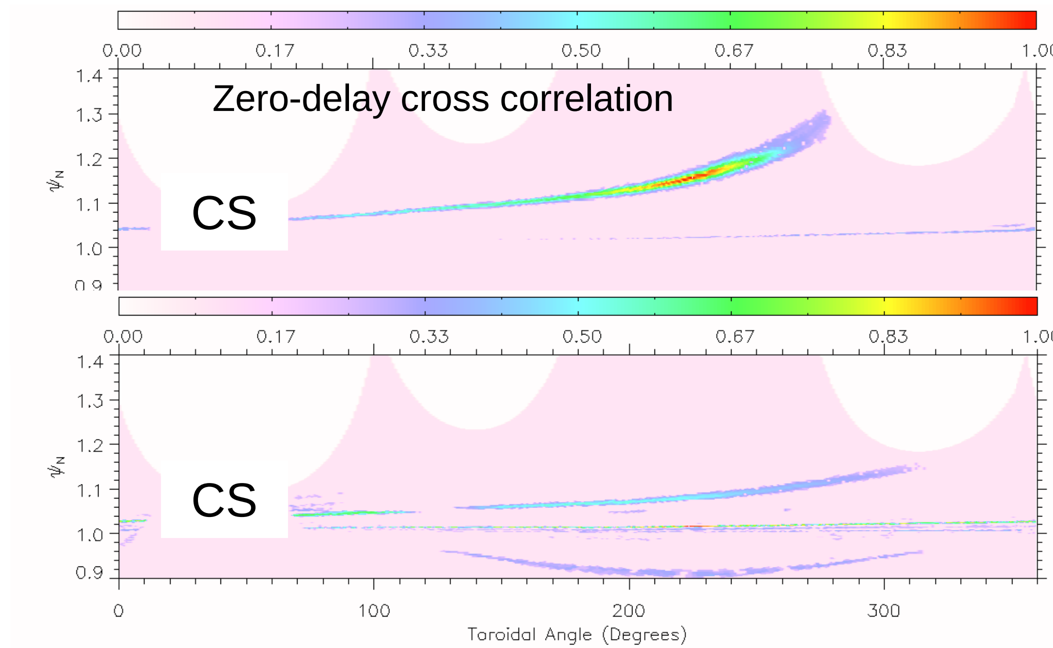


Zero-delay cross correlation shows helical correlation regions at the divertor target

- Cross correlation of single pixel with rest of image shows helical correlation regions extending over a toroidal turn
- Autocorr. ~50-100μs increasing in far SOL
- Width of cross-correlation region increases until region connecting to the limiter
  - Near separatrix features challenge camera resolution



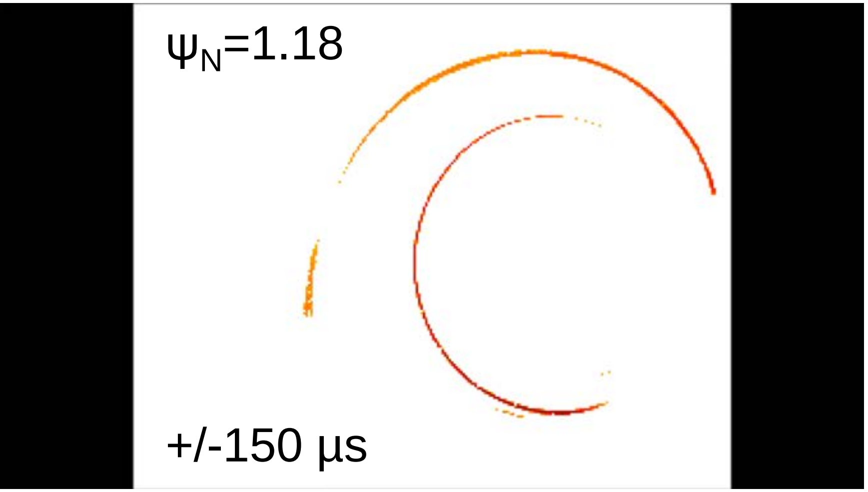


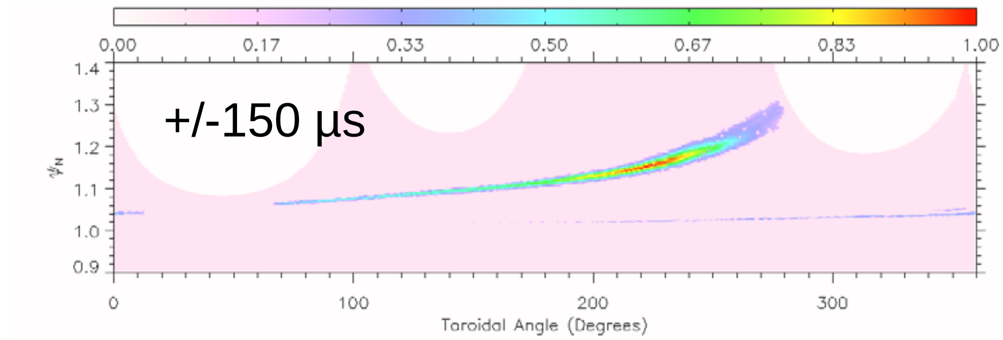


Time-delayed cross-correlation shows spiral motion consistent with upstream radial motion

- Cross-correlation of single pixel with rest of the image shows spiral motion
- Spiral motion consistent with upstream radial and poloidal motion
- Toroidal number of simultaneous filaments ~5-10
  - Inferred from unfolding of divertor image

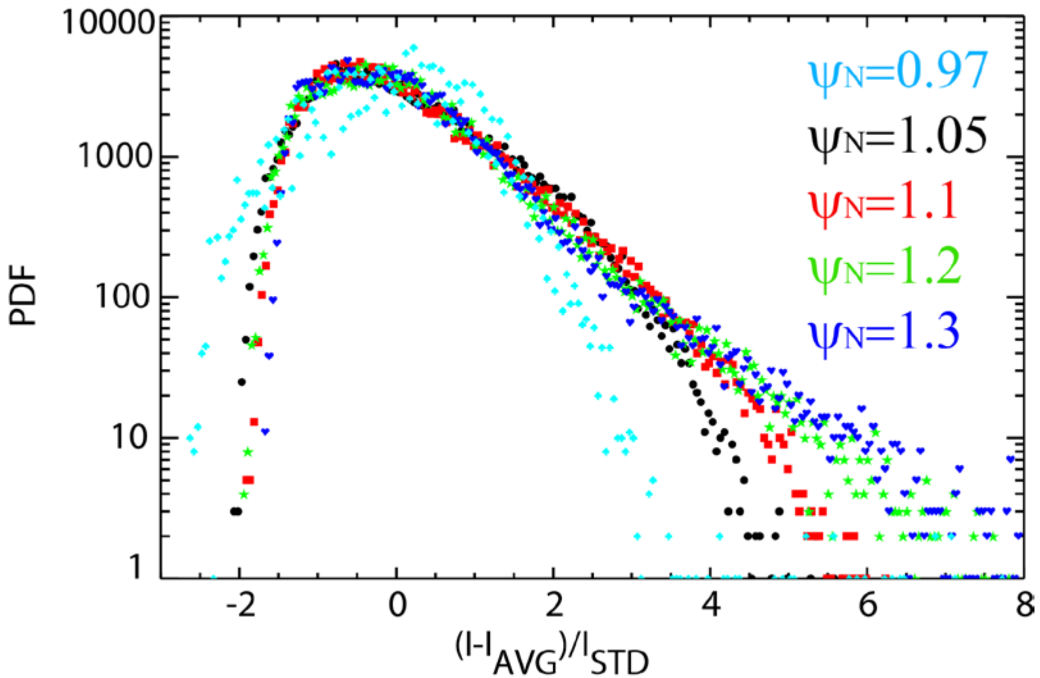
Time-delayed cross correlation

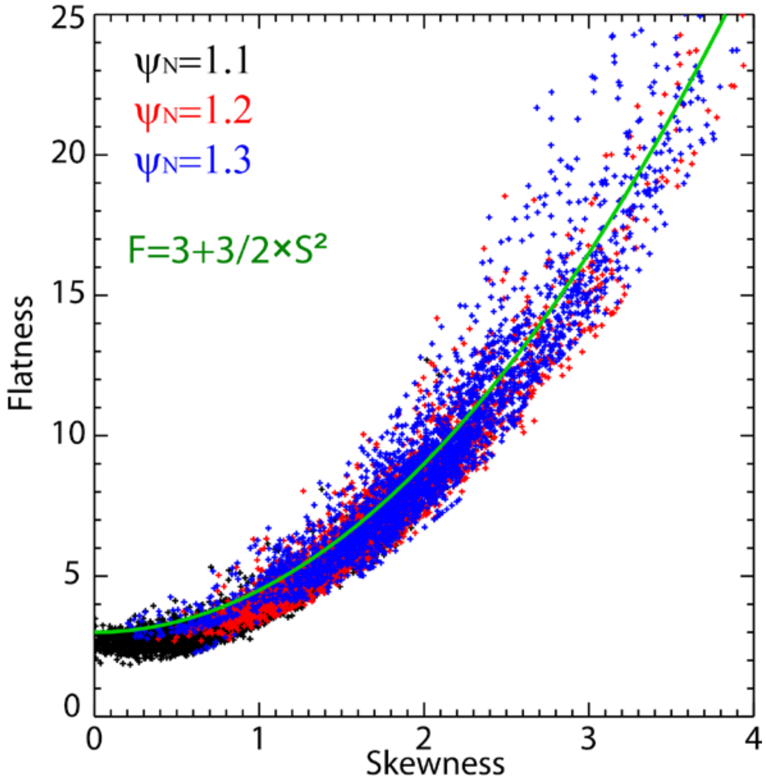




Fluctuations statistics follow properties typically observed for upstream blobby transport

- Skewness and flatness increase moving radially out in SOL
  - Also typically observed for upstream blobs in C-Mod, TCV, JET [O.E. Garcia]
- Statistical moments of fluctuations follow Gamma distribution functional form
  - Parabolic dependence of flatness vs. skewness [O.E. Garcia PRL 2012]
- Divertor fluctuations consistent with typical observations of upstream blobby transport

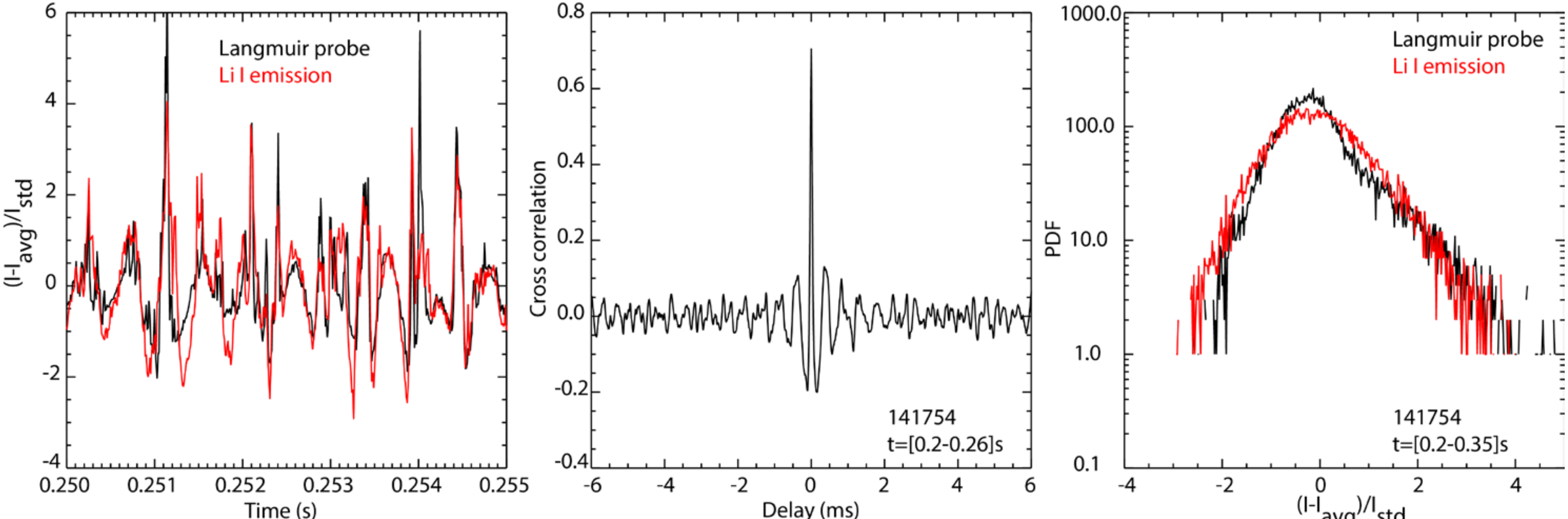




Filament footprint in Li I emission shows large correlation correlates with probe J_{sat} at target

- Correlation observed between neutral lithium emission and ion saturation current from target Langmuir probes at same (r,ϕ):
  - Filtered between 2 and 50 kHz, interpolated on camera time base
  - Cross correlation up to 0.7-0.8
  - Cross correlation peaked at zero delay
  - Comparable distribution function

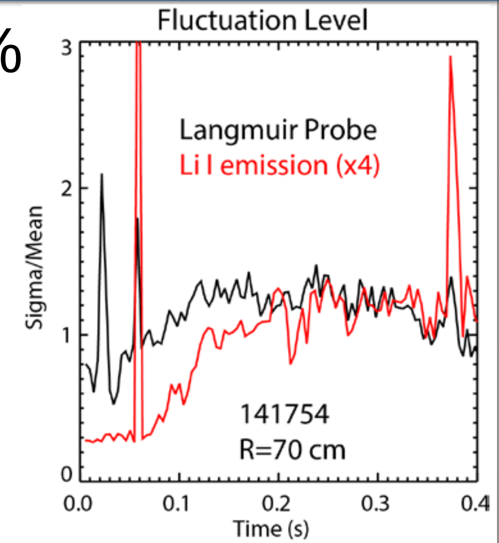
J. Kallman, M. Jaworski, V. Surla acknowledged for acquiring LP data



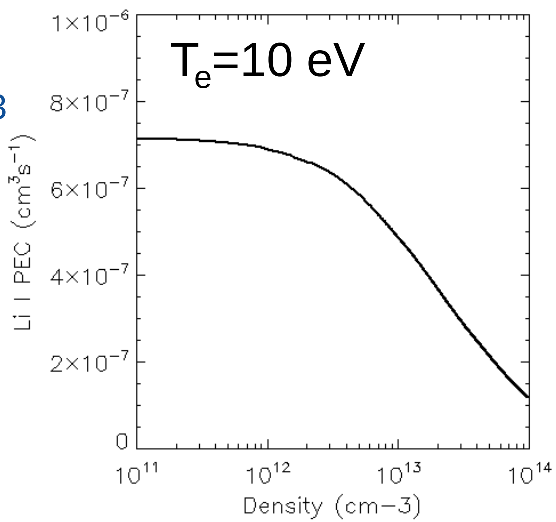
Fluctuation level in neutral lithium emission ~4x smaller than ion saturation current fluctuations

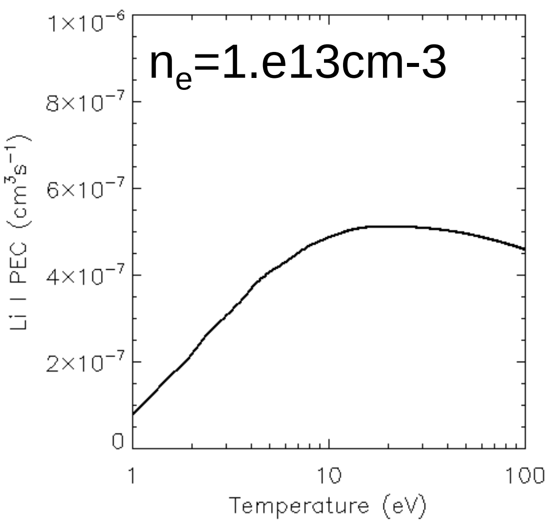
- Fluctuation level ~30% for Li I emission, ~120% for ion saturation current at same location
  - Smaller probe radial resolution (~2x)
  - Different dependence on fluctuating quantities

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



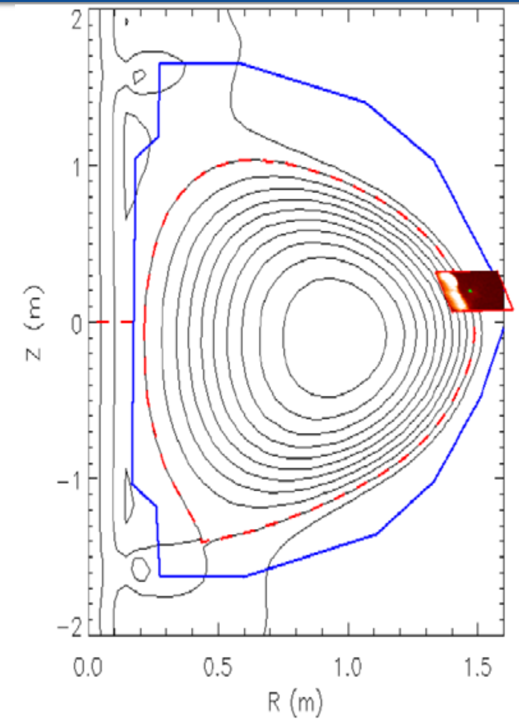
- Assuming fluctuating n_e, fixed n_{Li}
  - At T_e=10 eV, n_e=5x10^{12} cm^{-3}
    - ΔT$_e$=10% → ΔPEC =1.7%
    - Δn$_e$=20% → ΔPEC =-4%
  - At T_e=10 eV, n_e=5x10^{13} cm^{-3}
    - ΔT$_e$=10% → ΔPEC =0.4%
    - Δn$_e$=20% → ΔPEC =-15%
- But n_{Li} can also fluctuate with changes in incident fluxes, ionization

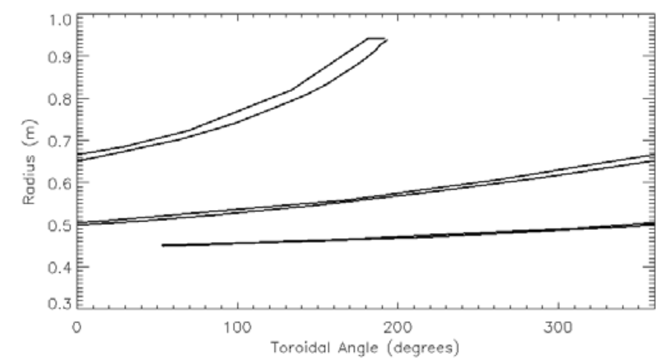




Gas puff imaging (GPI) used for upstream turbulence, correlation with target fluctuations

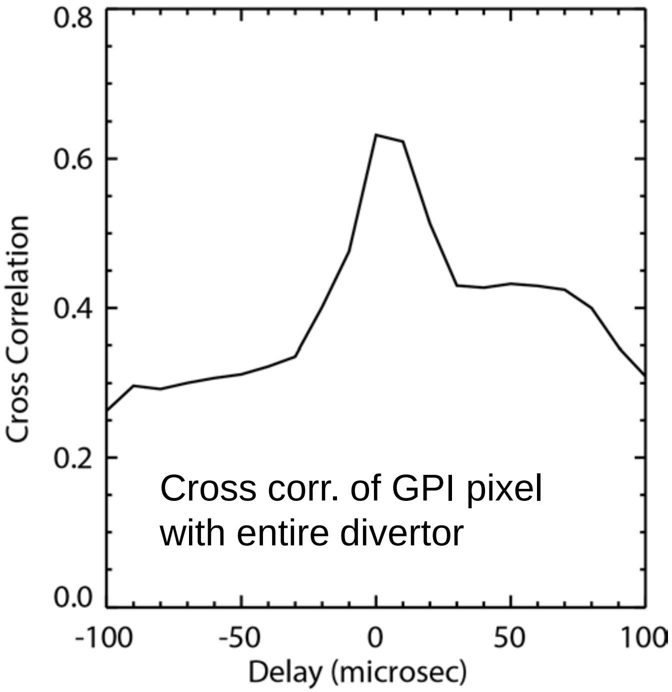
- Field aligned, D-α emission, 400 kHz, 2.1 μs exposure
- Only limited section of divertor maps to GPI
  - Additionally limited by center stack and vignetting by passive plates
  - Footprint in proximity of OSP becomes extremely narrow, below camera spatial resolution (1 cm)
- For cross-correlation with divertor filaments:
  - Filter cameras between 1 and 50 kHz
  - GPI data interpolated on divertor camera time base

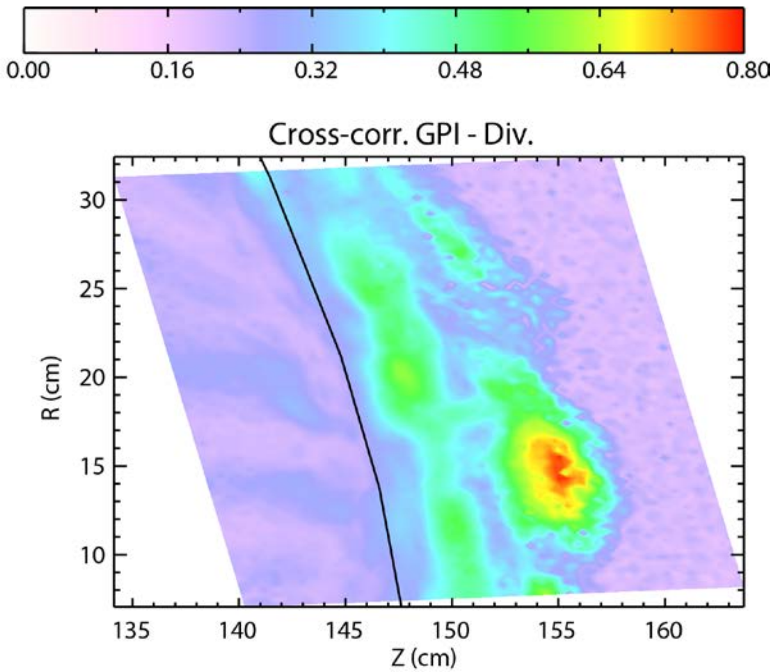




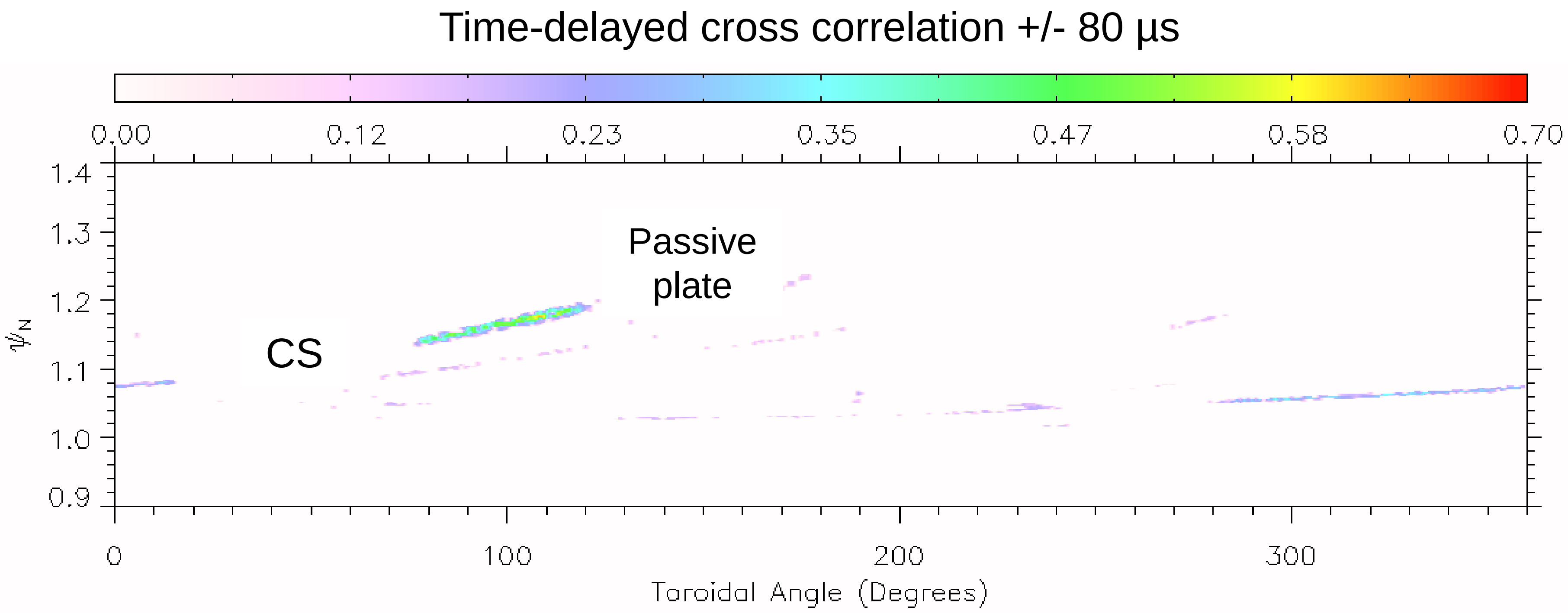
Filament footprint in Li I emission correlated with upstream blobs from GPI in far SOL

- Cross correlation with GPI up to 0.7-0.8 in far SOL in region magnetically connected to GPI field of view
  - Peaked at zero delay, as also observed in [Maqueda NF 2010]
  - No correlation features observed at ion transit time scales
  - Progressive decrease of correlation towards LCFS
  - Structures in cross correlation due to incomplete lower divertor coverage/non optimized magnetic configuration for cross correlation studies



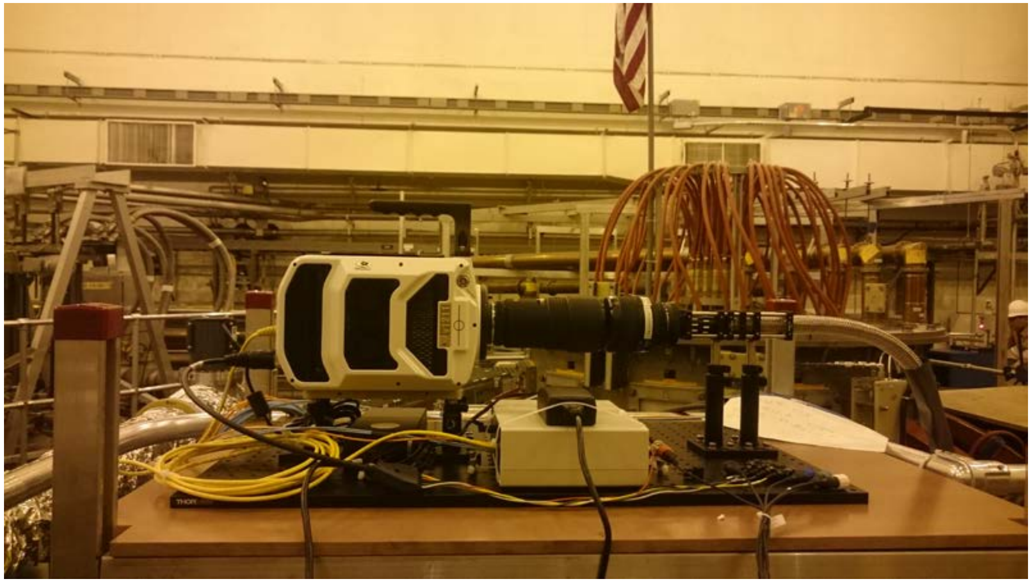


Cross correlation above random observed over all area that maps to GPI field of view



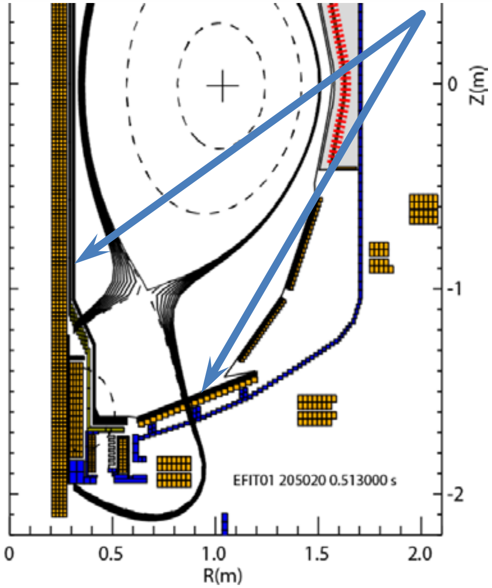
New LLNL Phantom v1211 dedicated to divertor turbulence imaging in NSTX-U

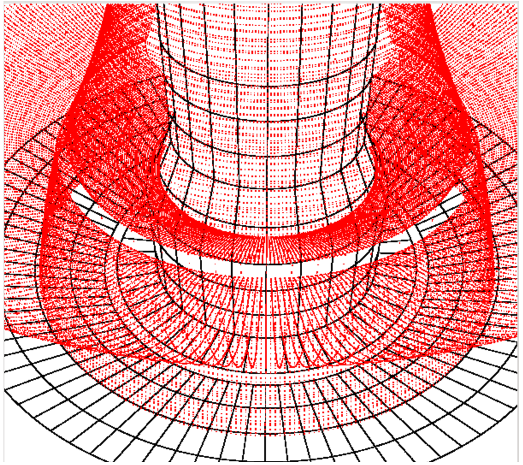
- New Vision Research Phantom v1211 camera
  - 1280x800 pixels, 28µm pixels, 12 bit
  - 5 times higher sensitivity wrt Phantom v710
  - 12 kHz @ full frame, 24GB memory, 10 Gbs Ethernet output
- Coherent fiber bundle 1000x800 10 μm fibers, 15' long
- 1:1.7 imaging on detector:
  - Collimating f=85 mm, F/1.4
  - Focussing f=50 mm, F/1.2
  - 3" bandpass filter
- Resolution:
  - 272x192 pixels
- Max fps:
  - 140 kHz



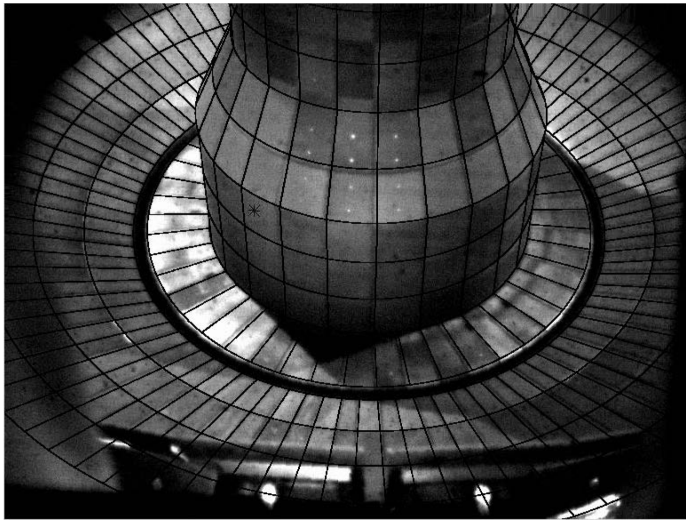
Throughput-optimized camera and high X-point L-modes enabled near separatrix filaments imaging in NSTX-U

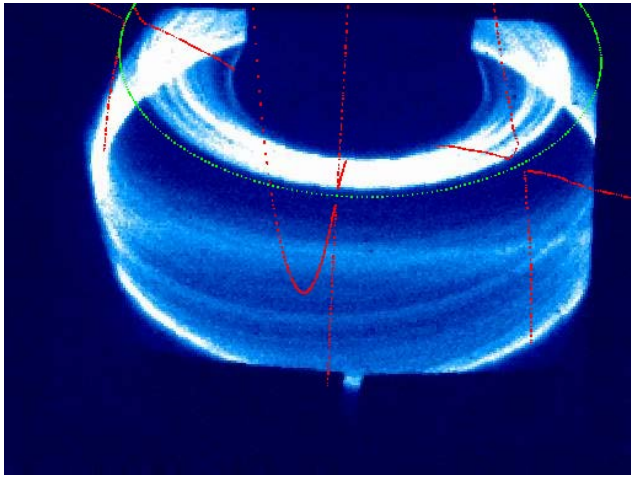
- Divertor turbulence imaging through different species/charge states provides information at different spatial locations
- Throughput-optimized setup enabled turbulence imaging via C III (up to 140kHz)
  - Filaments along divertor legs (vs. filament footprint on floor via Li I or Dα)





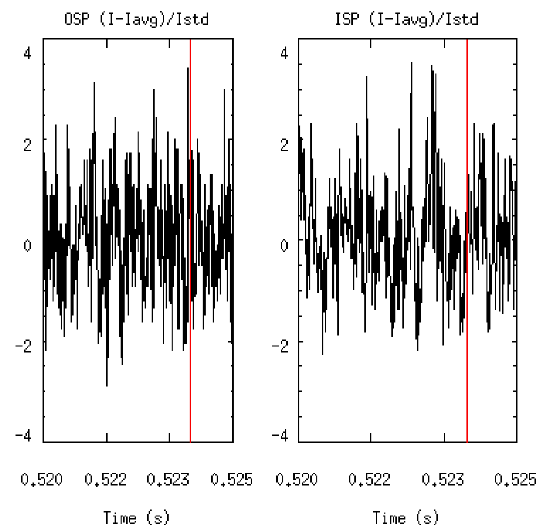
Reconstructed view + separatrix



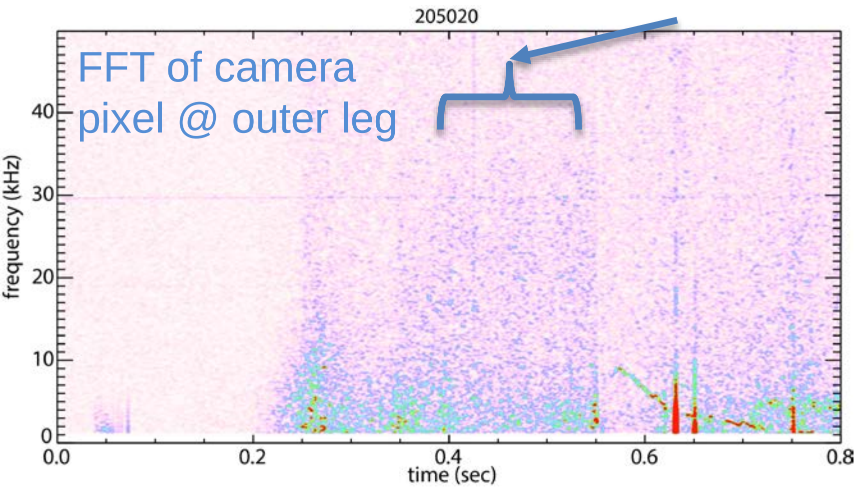


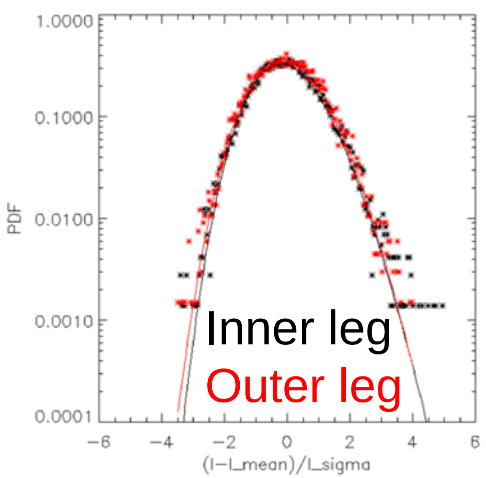
Intermittent field-aligned filaments observed in inner and outer divertor legs

- NBI-heated downward biased L-mode discharges
- Intermittent filaments observed on both inner and outer divertor leg
  - recently observed in MAST [Harrison PoP 2015] and C-Mod [Terry JNME 2016]
- FFT amplitude shows broadband fluctuations, δI/I ~10-20%
- PDF of inner and outer leg filaments show similar characteristics

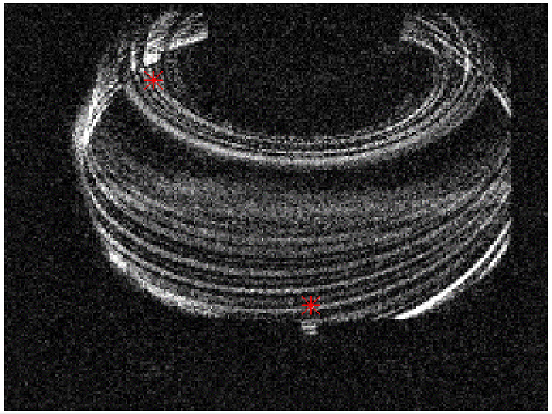


Interval in consideration



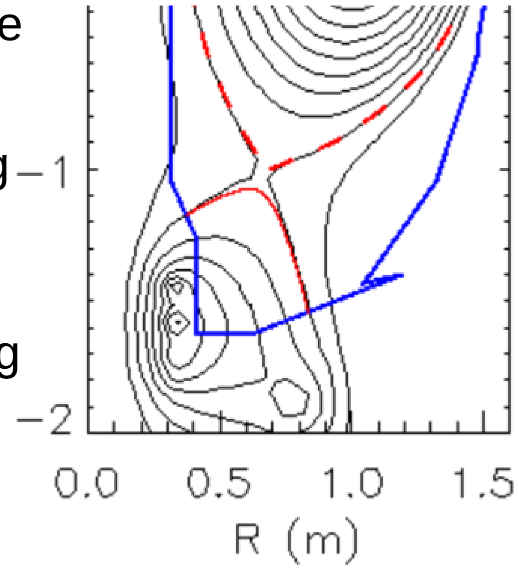


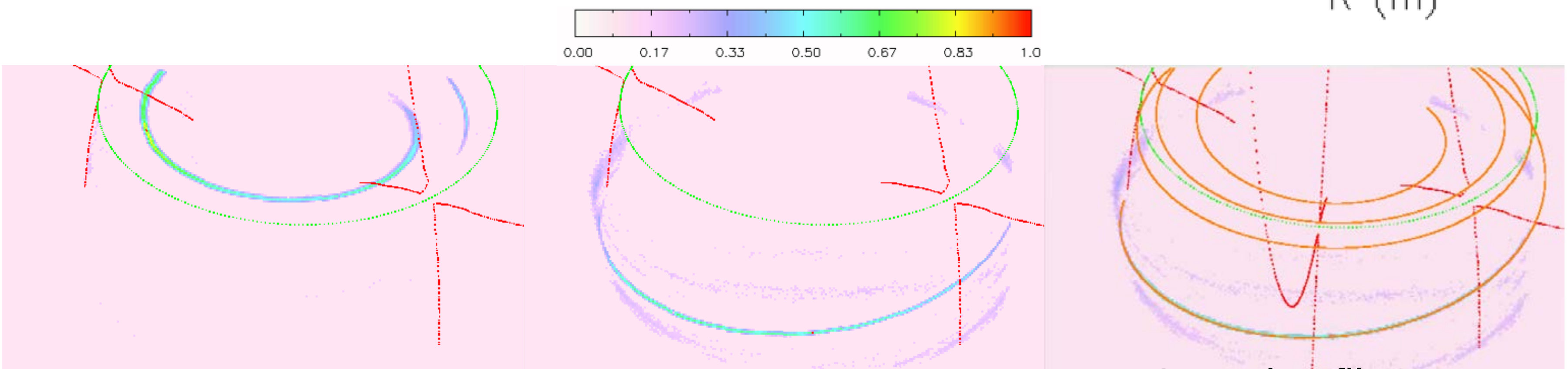
High-pass filter 1kHz



No correlation observed between inner and outer leg filaments

- Zero-delay cross correlation of single pixel with rest of image for both inner and outer leg filaments over 10ms
- Filaments are field aligned, radial localization around the leg
- Correlation > (<) toroidal turn on inner (outer) leg
- Inner and outer leg filaments are uncorrelated (despite being magnetically connected)
- Auto-correlation ~10s μs





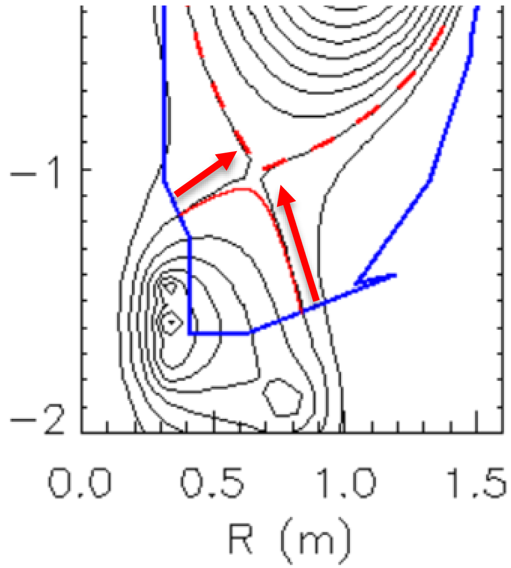
Inner-leg filament

Outer-leg filament

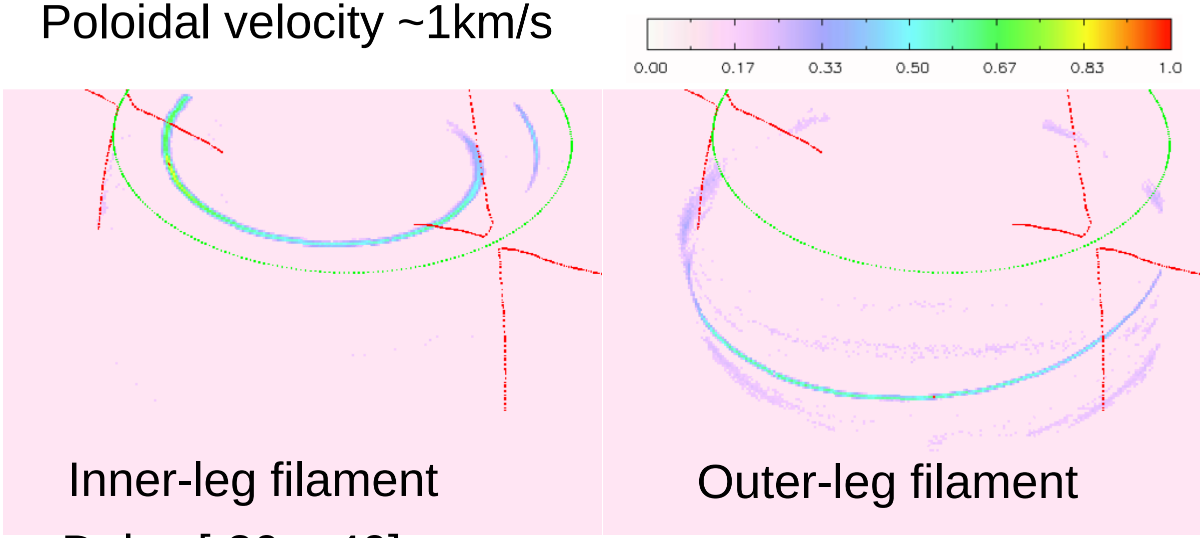
Outer-leg filament + PFR field line

Time delayed cross correlation shows opposite toroidal rotation for inner/outer leg filaments

- Time-delayed cross correlation of single pixel with rest of image to show average filament propagation
- Apparent poloidal motion for both inner and outer leg filaments towards X-point (also in C-Mod, J. Terry JNME 2016)
  - Or equivalently opposite toroidal directions.
    - Impossible to separate toroidal vs. poloidal motion
  - Inconsistent with flux tube rigid rotation (as in [J. Terry JNME 2016])



- Poloidal velocity ~1km/s

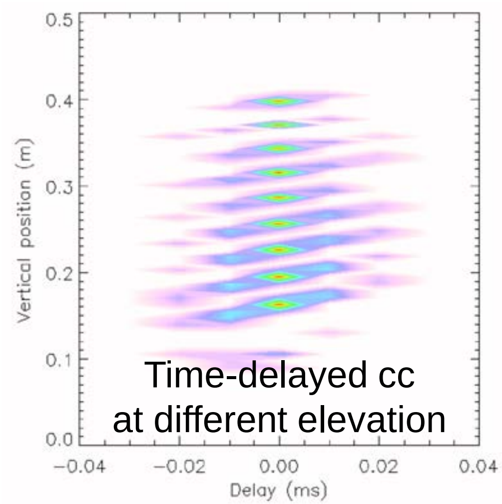


Inner-leg filament

Delay [-30, +40]µs

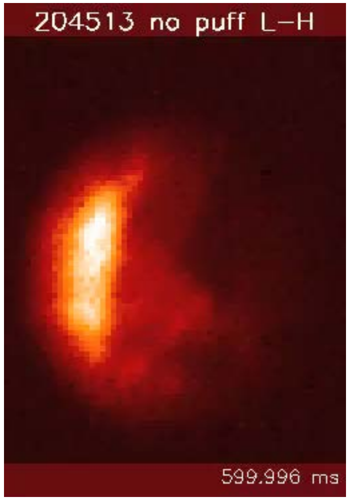
Outer-leg filament

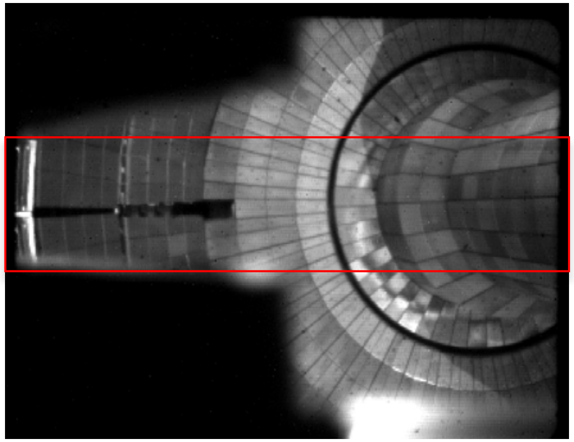
Delay [-40, +40]µs

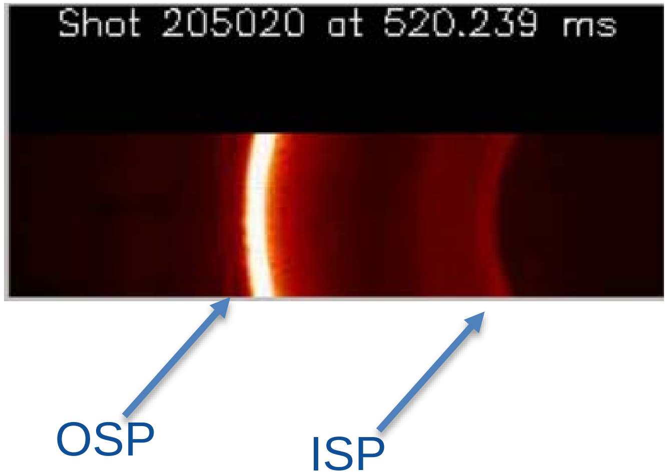


Cross correlation with other imaging diagnostics to better characterize near separatrix filaments

- GPI diagnostic in NSTX-U
  - Higher throughput (~10x)
  - No gas puff due to engineering delays
    - No spatial localization
  - Dα, 100 kHz, 9μs exposure
- Divertor fast cameras
  - Equipped with filter wheels
  - Passive Dα, 280 kHz, 3μs exposure
  - 150° from C III camera

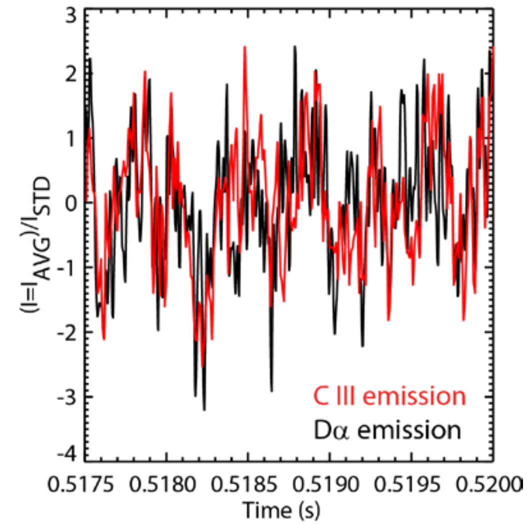


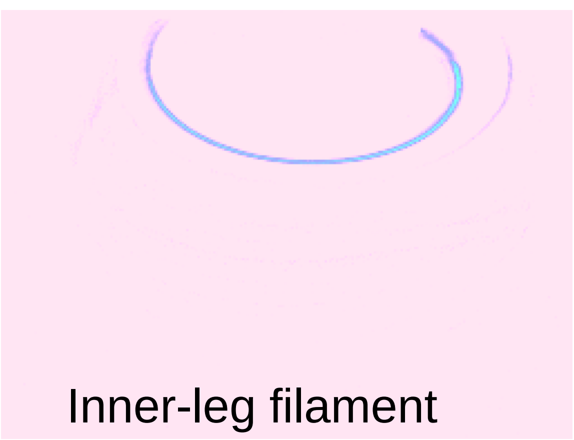




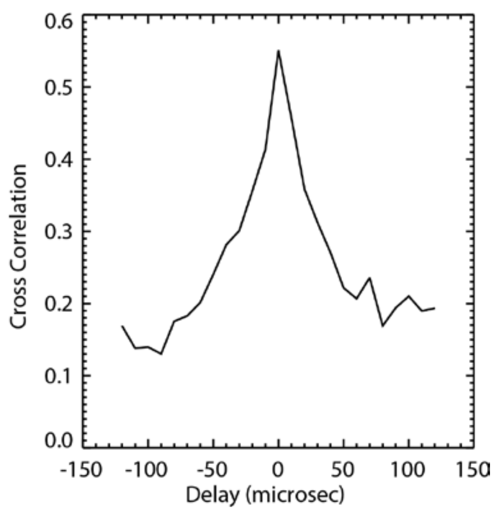
Correlation between near separatrix divertor filaments imaged in C III and Dα

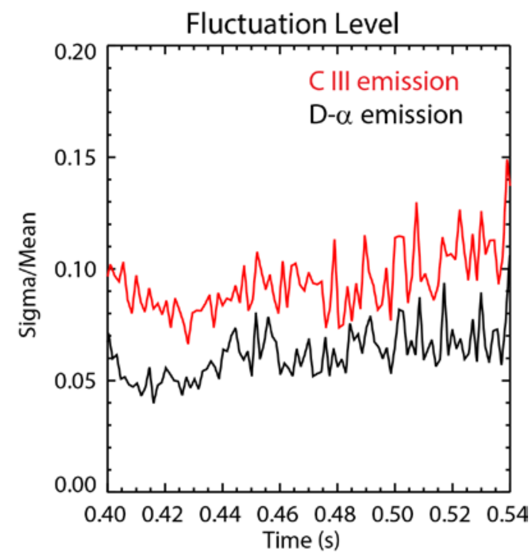
- Correlation between Dα and C III fluctuations observed for inner leg filaments
  - Cross correlation up to 0.6
  - Peaked at zero delay
  - No overlap for outer leg filaments
  - Fluctuation level 1.5x higher for C III





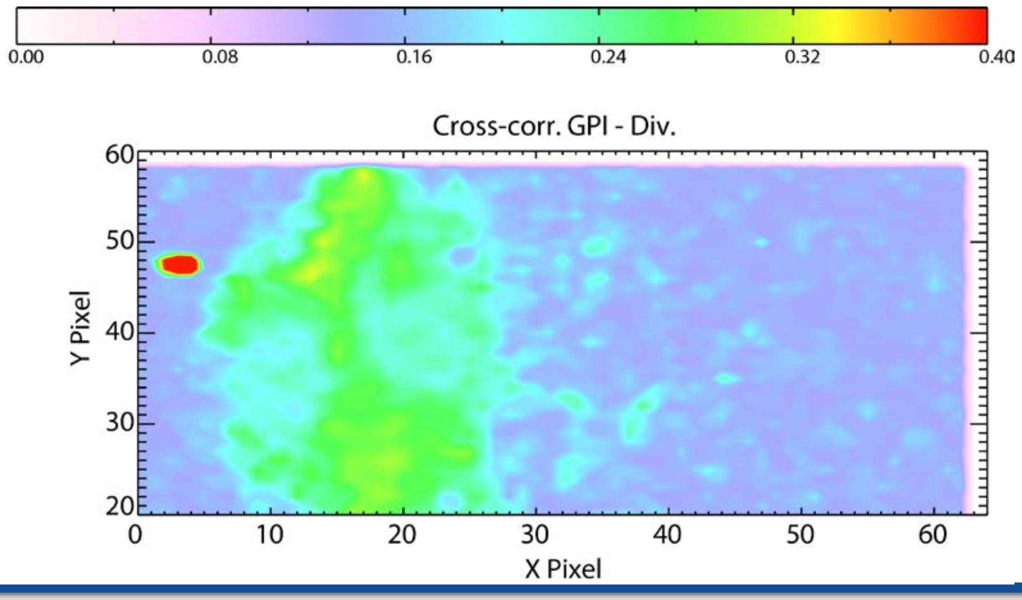
Delay [-70, +70]μs

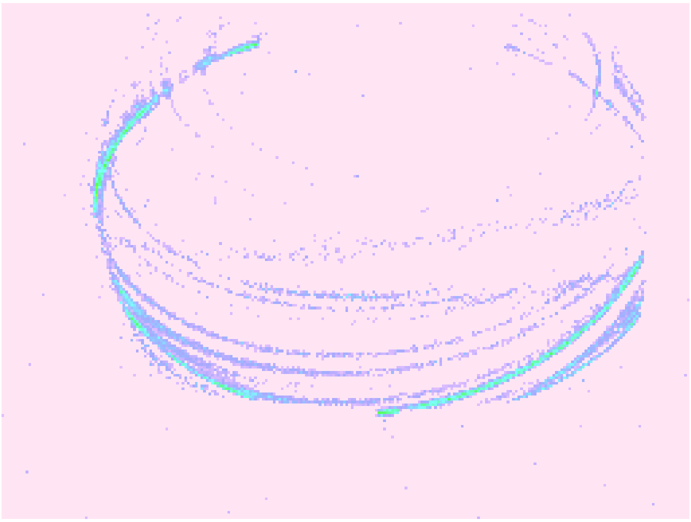




No correlation observed between near separatrix divertor filaments and GPI upstream

- No large correlation observed so far with upstream blobs from GPI
  - Cross correlation up to 0.3
  - Need post run spatial calibration to determine whether correlation is with magnetically connected filaments





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

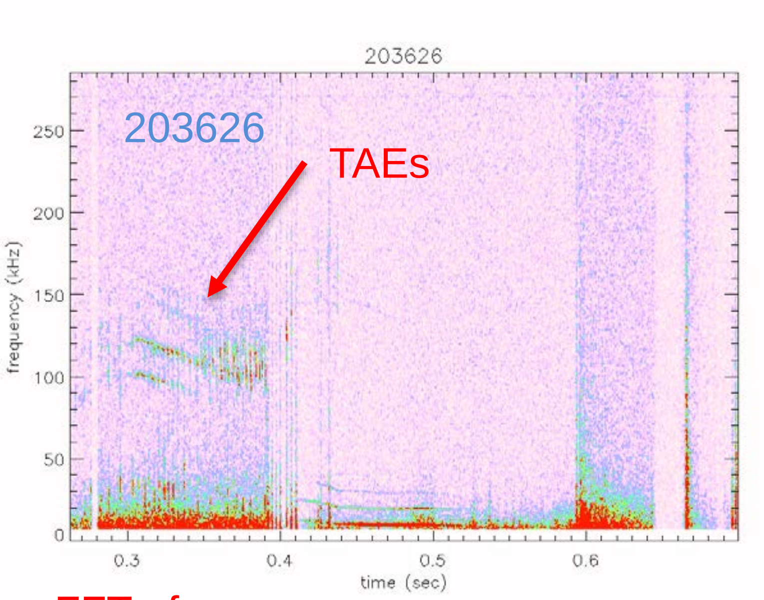
From J. Terry, JNME 2016

	C-Mod	MAST
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)
ǁ 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 ~10s μs
δI/I ~10-20 %
Speed ~1km/s

Summary and future work

- Data to analyze from the 2010 divertor high speed database + high quality GPI
- Expand work on near separatrix filaments for comparison with other devices:
  - Correlation with GPI not observed so far
  - Filaments characterization for
    - Different collisionality regimes, geometry
    - During detachment (inner SOL filaments observed)
    - Parametric dependencies
  - Apply existing models (e.g., stochastic model) or codes (XGC1, BOUT++, SOLT)
- Analyze impact of MHD modes on divertor profiles and turbulence



FFT of camera pixel @ OSP