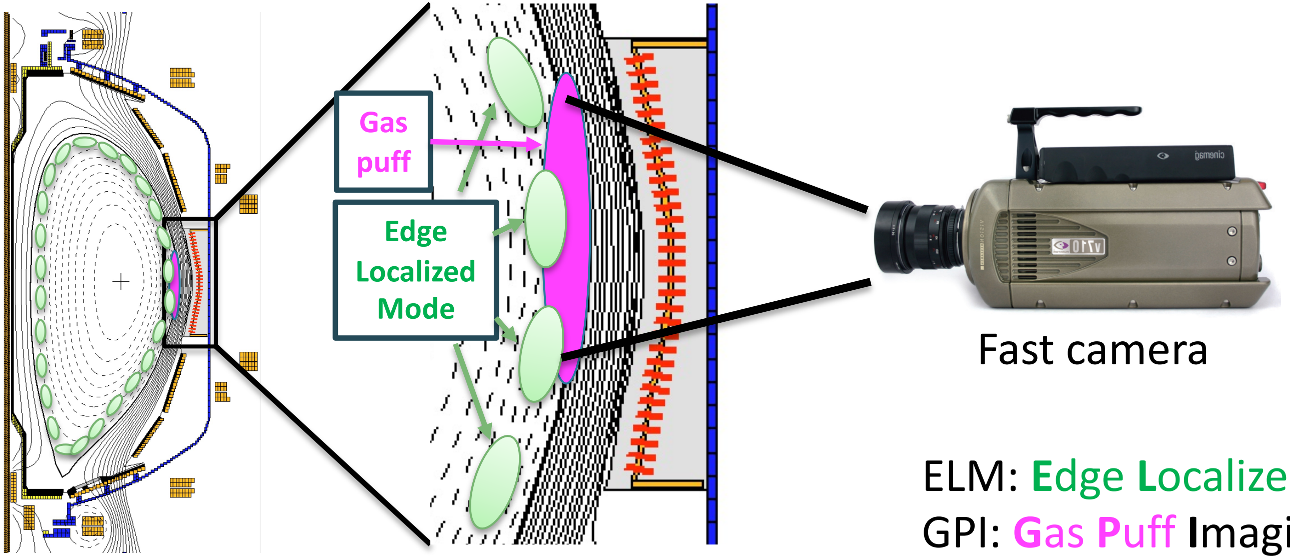
Rotational and translational dynamics of ELM filaments on NSTX

Mate Lampert

NSTX-U Monday meeting - 03/07/2022



ELM: Edge Localized Mode

GPI: Gas Puff Imaging

Outline of the talk

Introduction

- Edge localized modes
- Gas puff imaging

Methodology

- Translation and rotation estimation
- Structure fitting

Results

- Translational dynamics of ELM filaments
- Rotational dynamics

Theoretical models

Outlook and summary

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Introduction

Edge Localized Modes (ELMs)

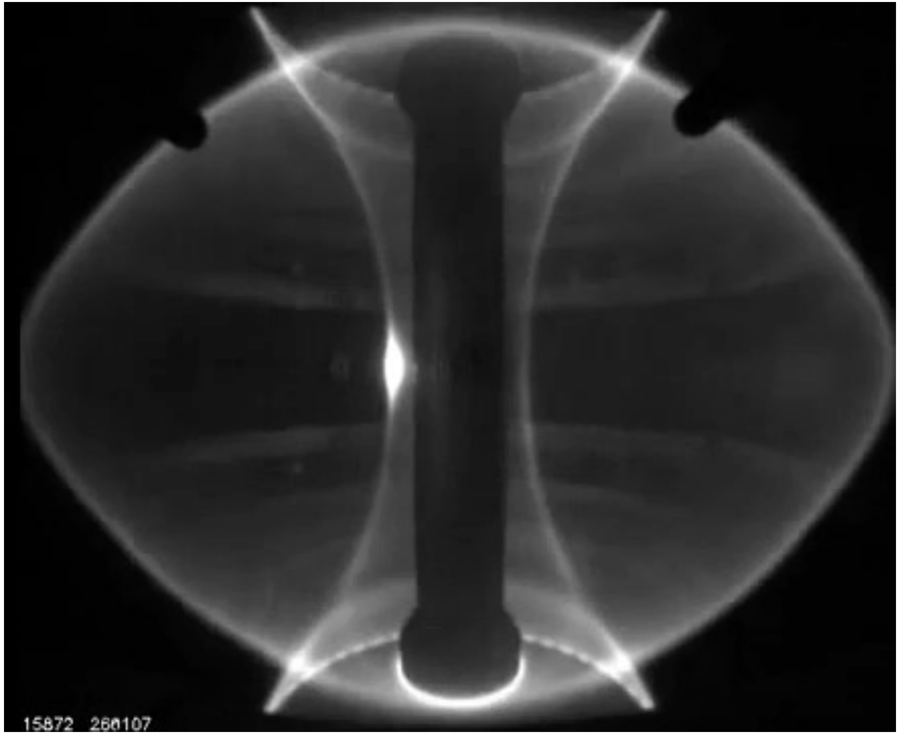
Edge **L**ocalized **M**odes are quasi-periodic instabilities at the plasma edge.

They are a **threat to tokamaks** because of high heat and particle load causing **erosion and melting of plasma facing components.**

Dynamics of the ELM crash filaments

- Characterization → physics → mitigation techniques
- Motivation for current research

Video of ELMs in MAST, #15872



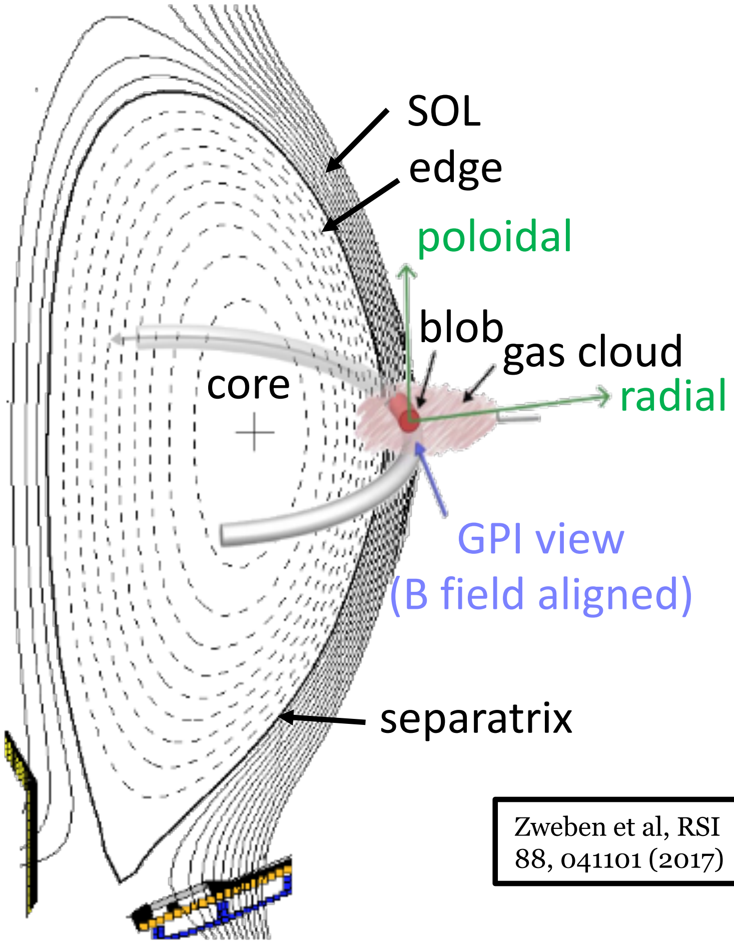
Credit: P. Ivanov, University of Oxford, 2020

Principles of GPI

- Provides 2D imaging of field aligned plasma fluctuations
- By measuring light emission from gas and plasma interaction
- A “puff” of neutral gas increases the light emission

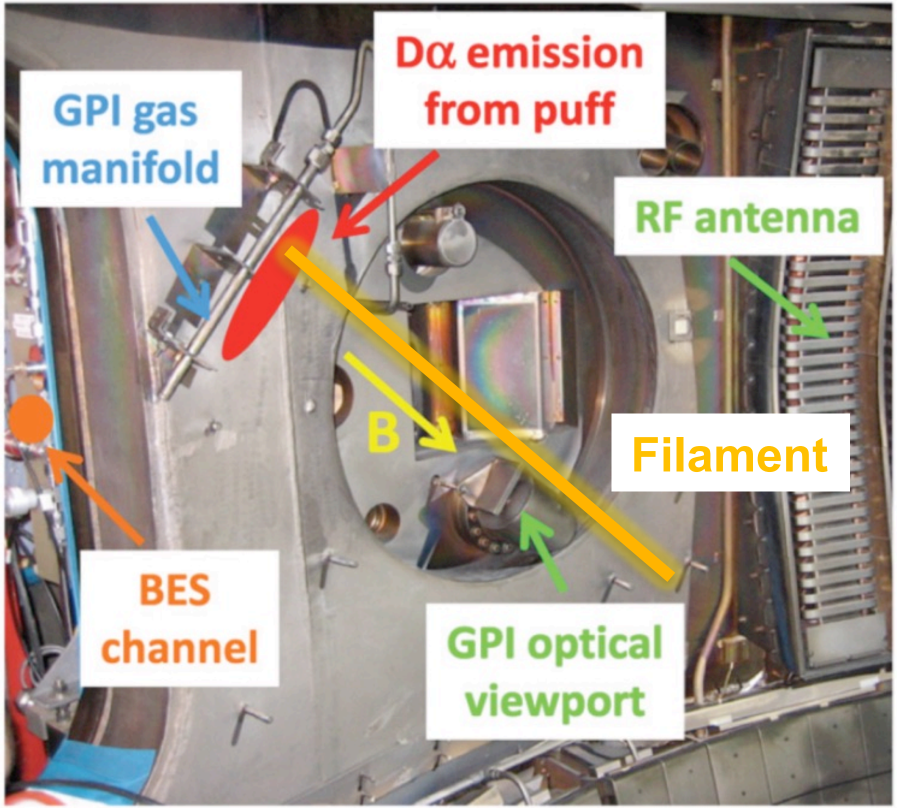
Excellent tool for characterization of turbulence in the edge and SOL

- Responds to n_e and T_e fluctuations
- Structure size, propagation, frequency spectrum, correlation length etc.



Zweben et al, RSI 88, 041101 (2017)

Gas Puff Imaging on NSTX

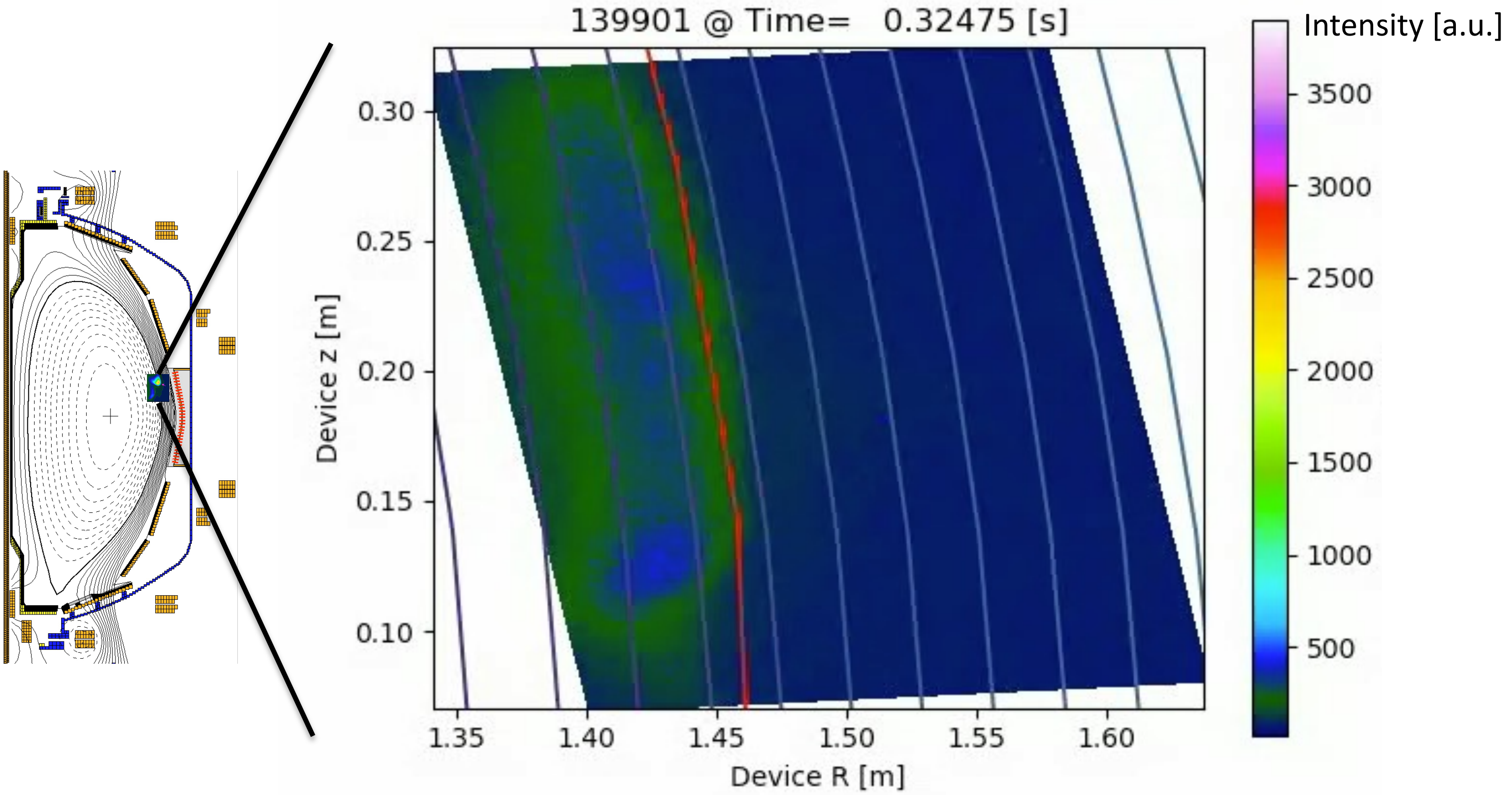


Properties of NSTX GPI

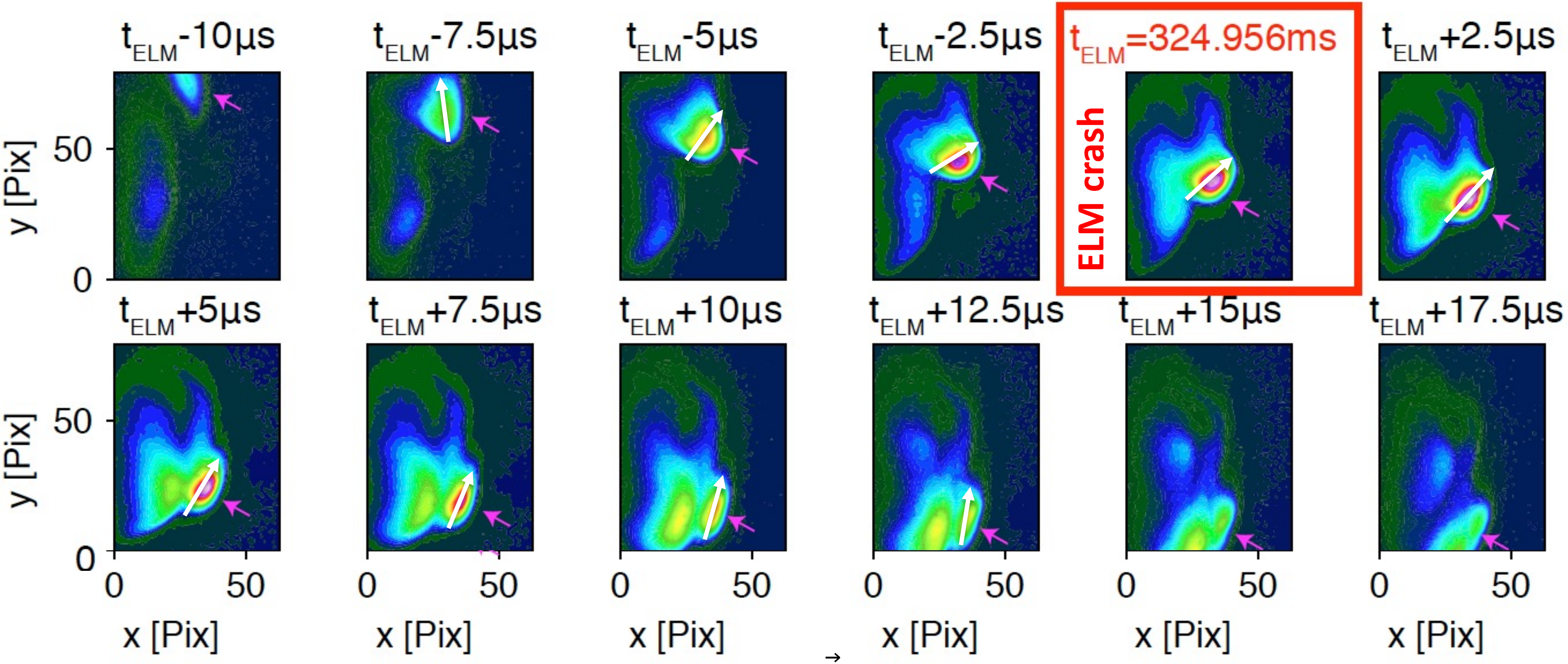
- ~ 2D gas sheet; $B_{||}$ observation
- 20cm x 30cm imaged area with
  - ~ 1cm optical resolution
  - 400 000 frames per second

[Zweben et al, PoP 24, 102509 (2017)]

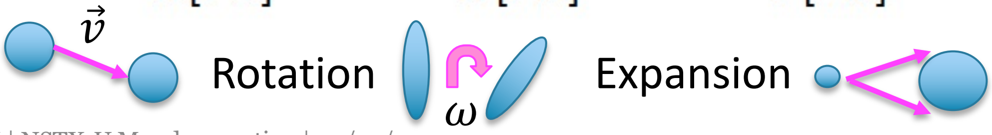
Video of an ELM burst on NSTX



Goal: Velocity and rotation estimation with sample-time time resolution



Characterized quantities: Displacement



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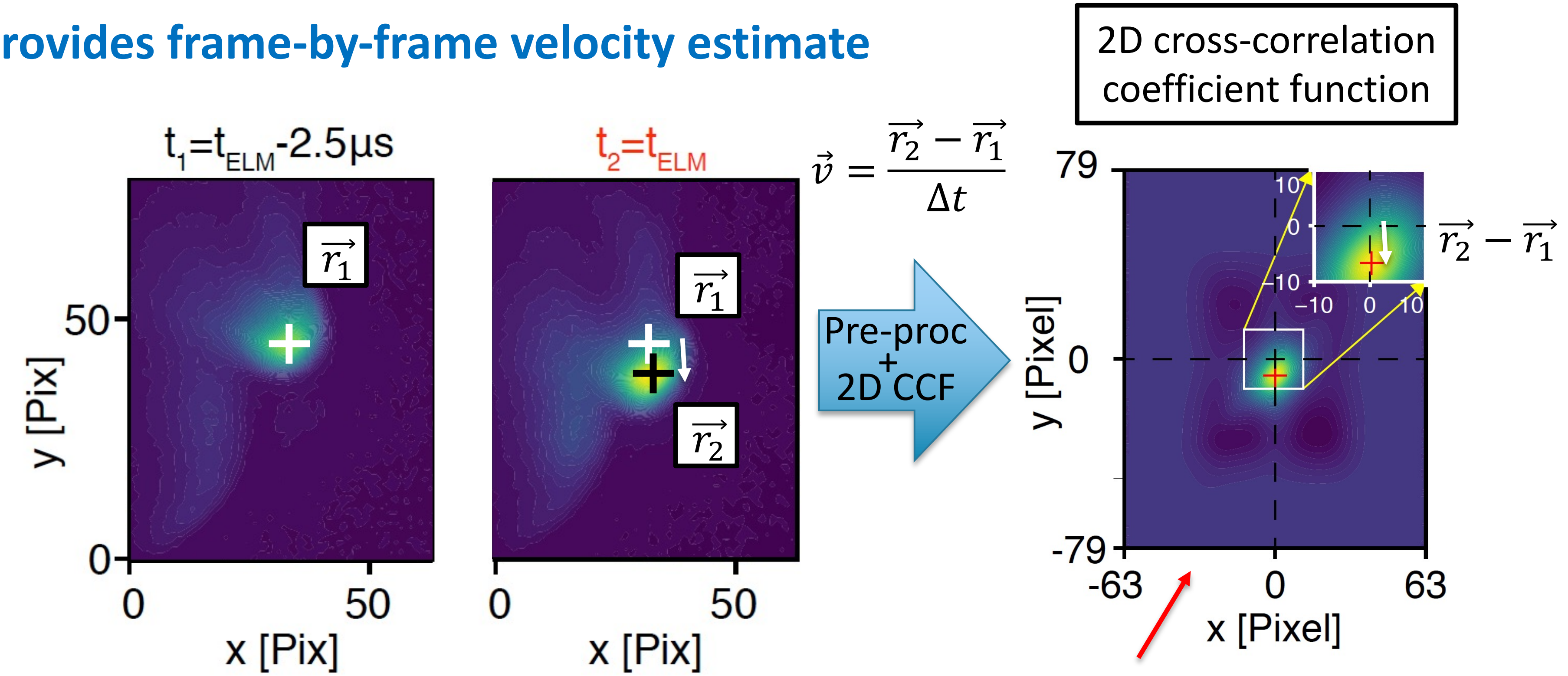
Methodology

Novel velocity estimation from 2D spatial cross-correlation

Provides frame-by-frame velocity estimate



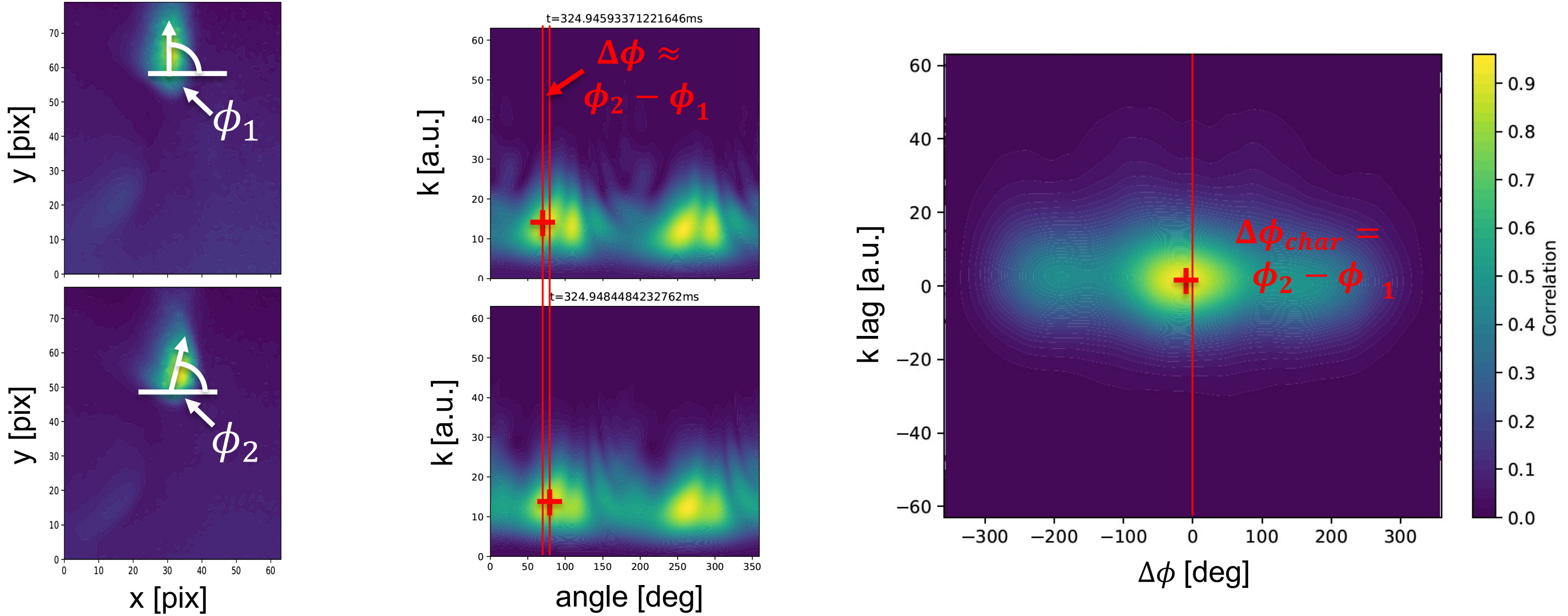
Velocity is estimated from the pixel displacement of the 2D spatial cross-correlation coefficient function.

[M. Lampert et al, RSI (2021)]

Novel angular velocity and expansion estimation from log-polar FFT and 2D cross-correlation

2D FFT magnitude spectrum of an image is **invariant to translation**

Consecutive frames → Polar FFT magnitude spectrum → 2D CCF calculation



[Publication under preparation]

CCF$_{pol}$ maximum displacement estimates characterizing **angle difference ($\Delta\phi \rightarrow \omega$)**

Log-pol transformation also provides **expansion rate**

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Results

ELM filaments characterized based on their statistical distribution

A database was built from **159 ELM events** from **77 shots** from the 2010 NSTX measurement campaign.

Workflow:

1) Calculation of each ELM filament property

- Radial and poloidal velocities, angular velocity, and the expansion rate.

2) Identifying the time of the ELM (t_{ELM}) from the GPI measurement itself

- Time of the largest change between consecutive frames

3) The distribution of each ELM filament property is calculated for each $t - t_{ELM}$ time

- Time evolution of the median and the percentiles

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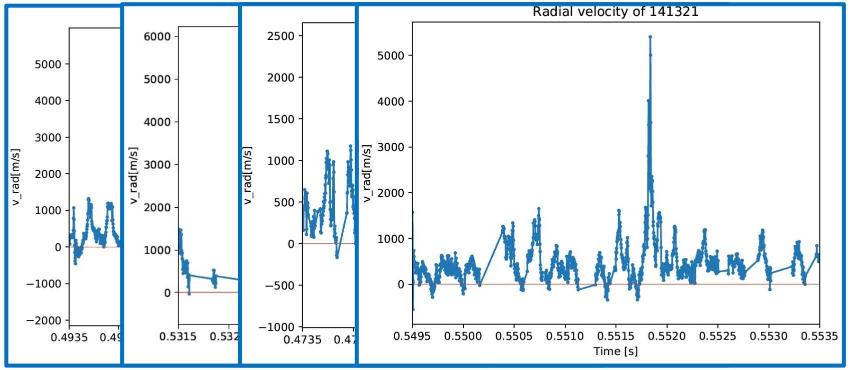

Determined parameters

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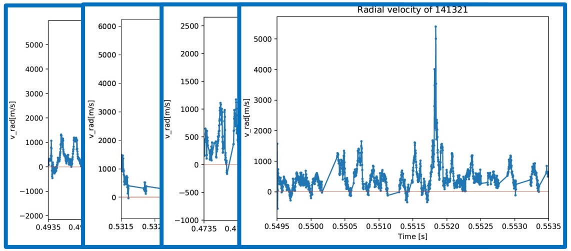

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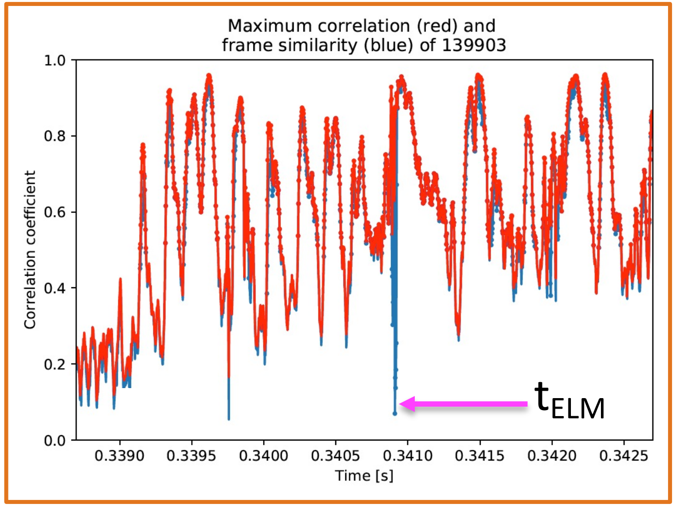

ELM time definition

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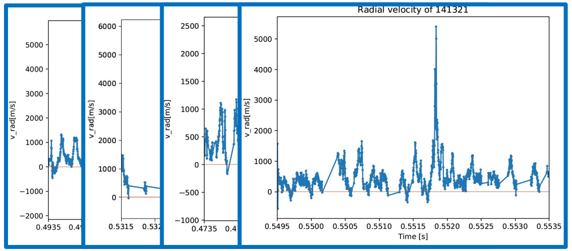

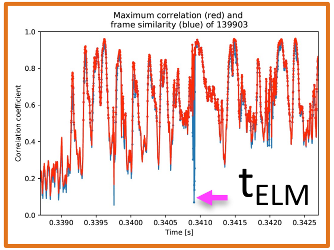

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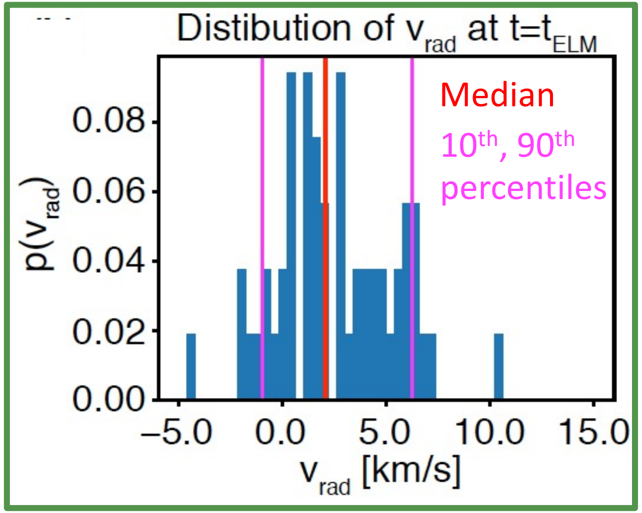
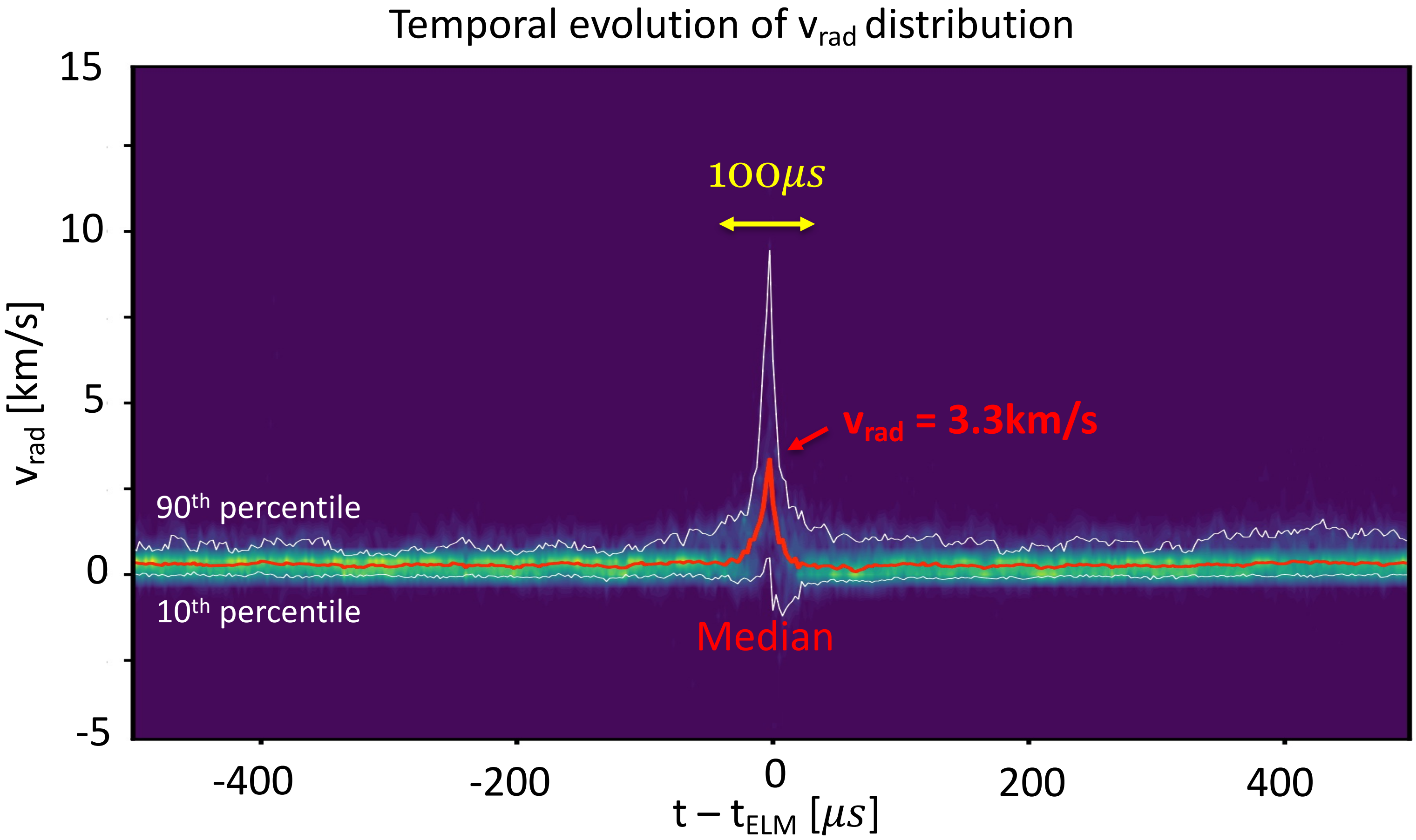
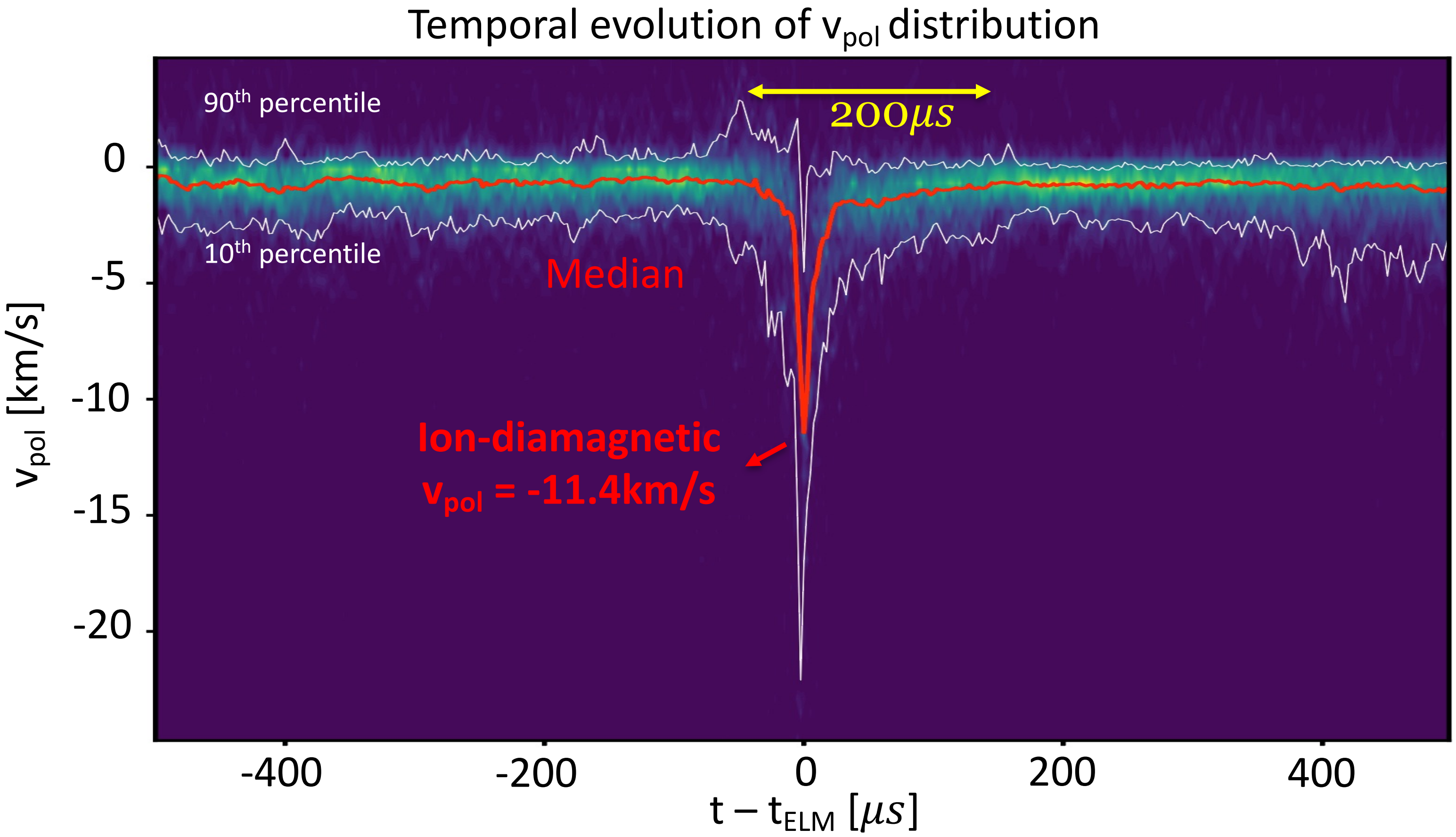


Example distribution of v_{rad}

Explosive outburst of ELM filaments are four times faster than blobs

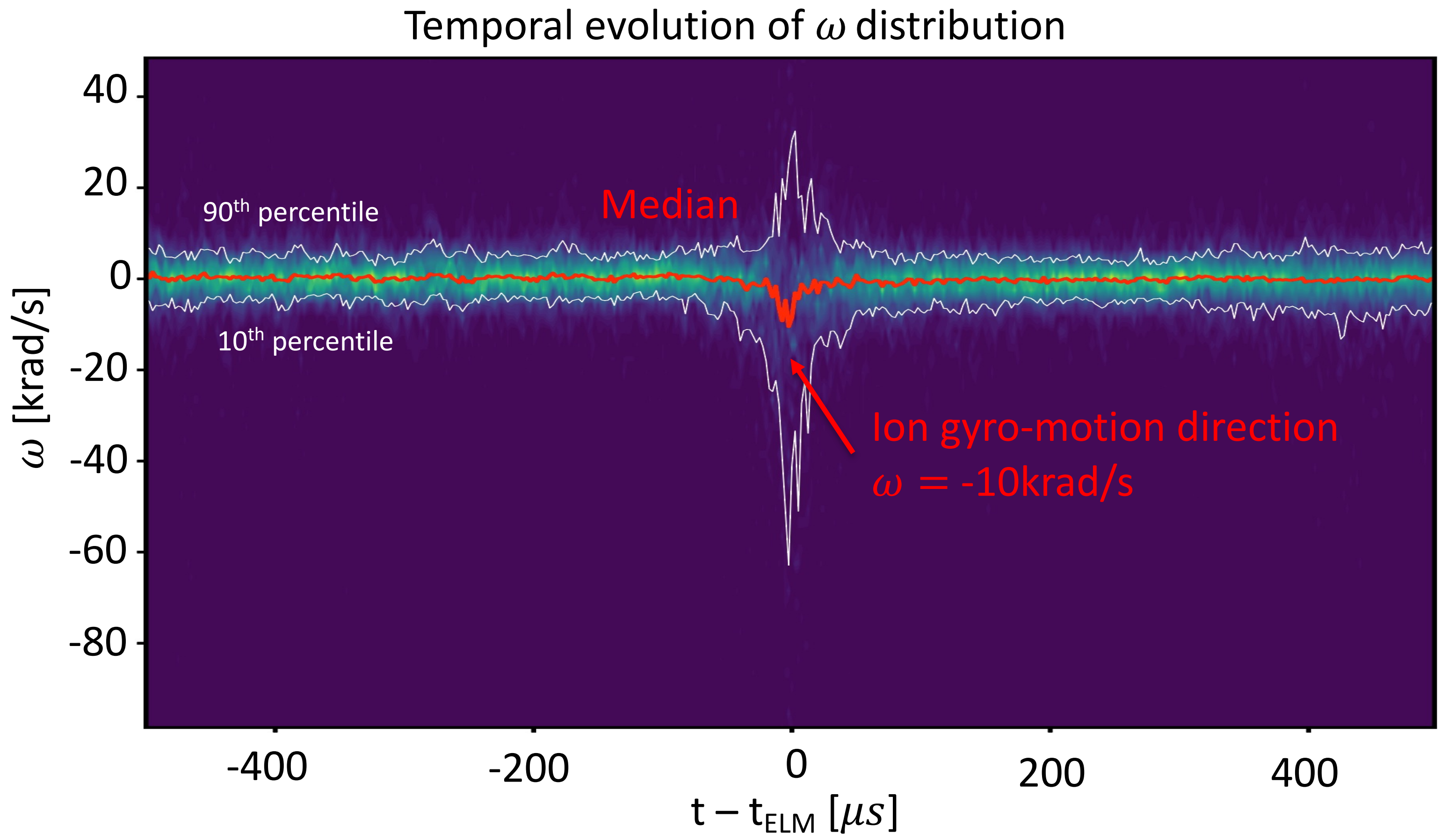


[M. Lampert et al, PoP (2021)]

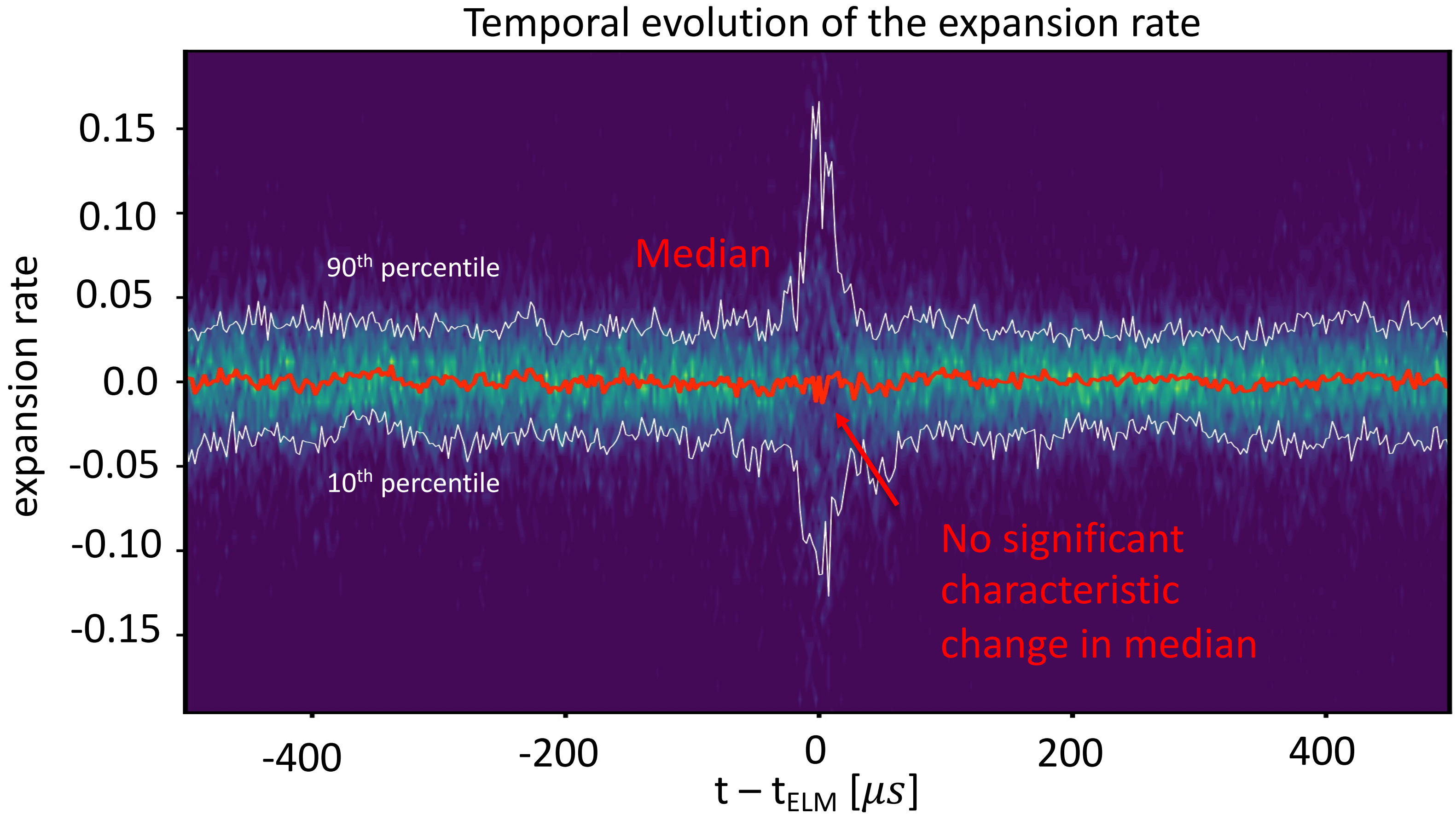


[M. Lampert et al, PoP (2021)]

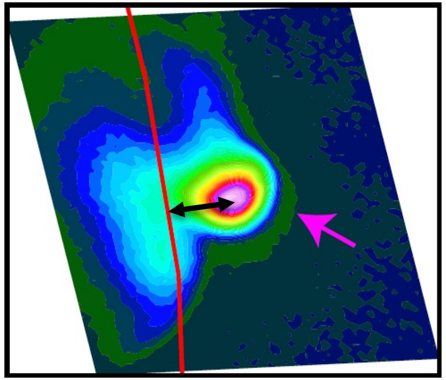
The ELM filament spins in the direction of the ion-gyro motion with 10krad/s peak median angular velocity.



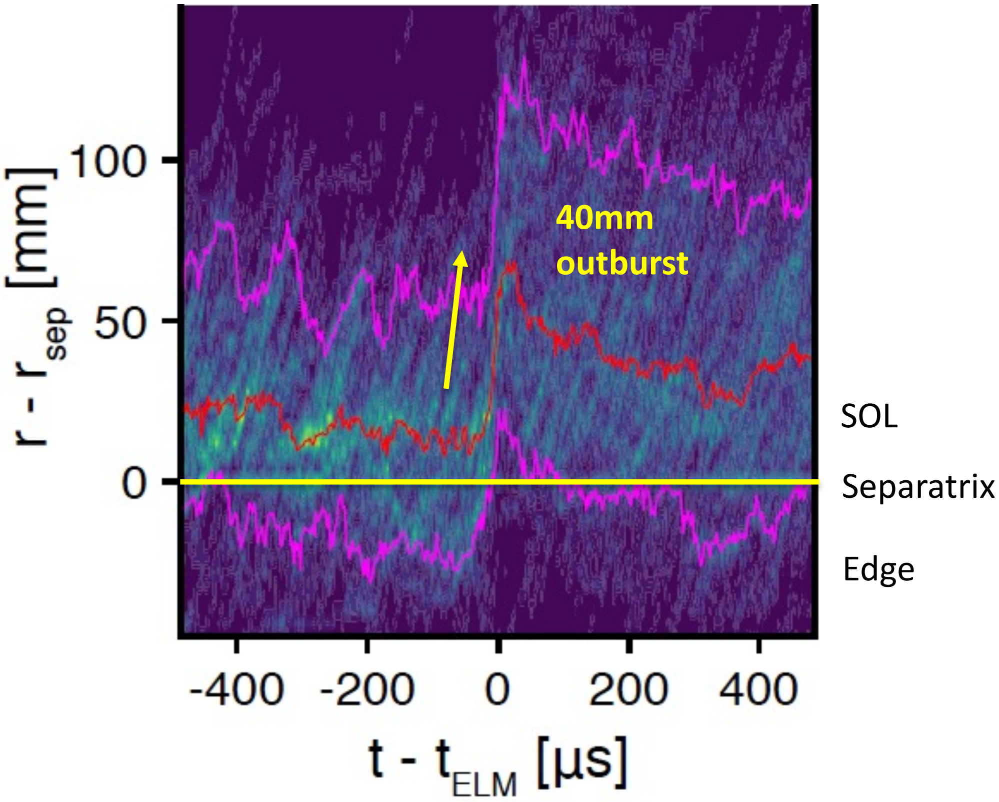
The ELM filament does not expand significantly during the ELM crash.



Example $r - r_{sep}$

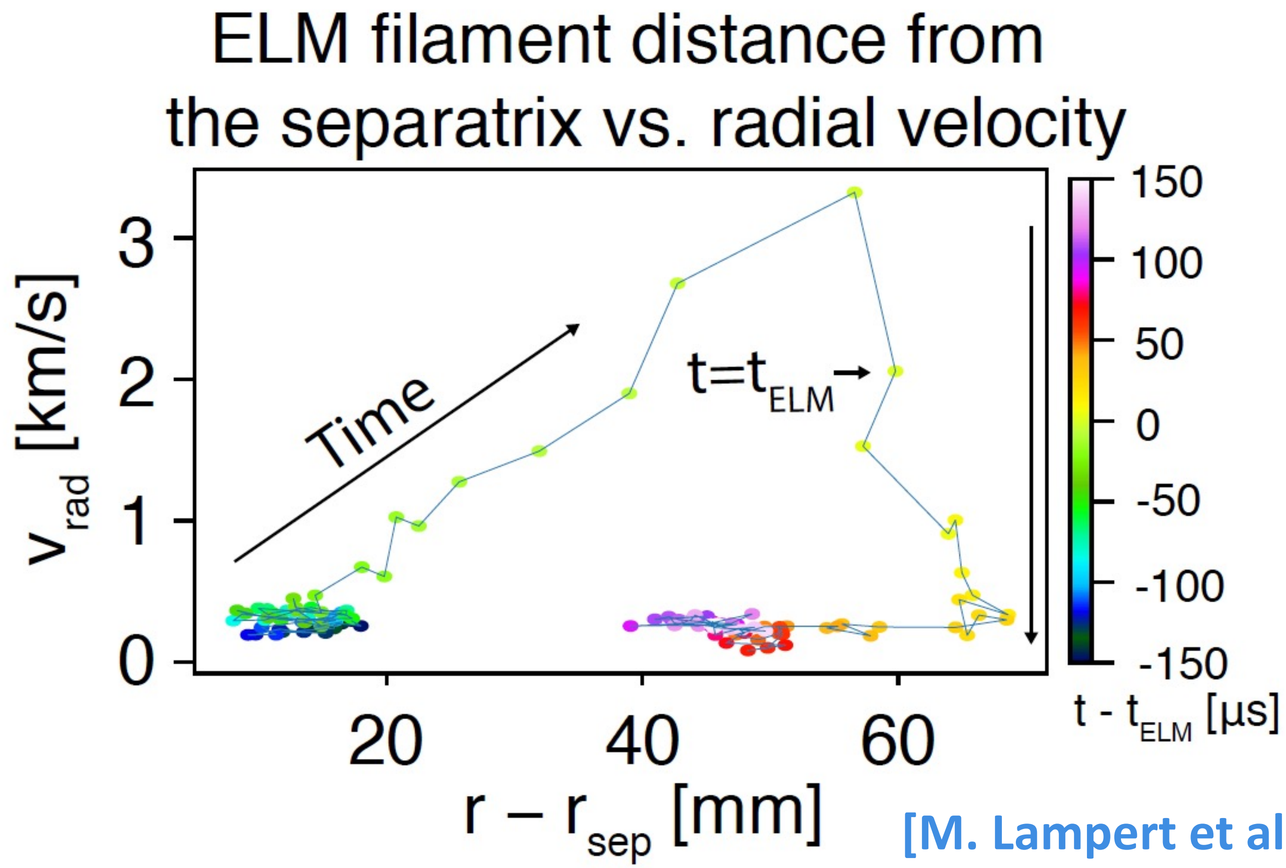


Distance between center of the ELM filament - separatrix



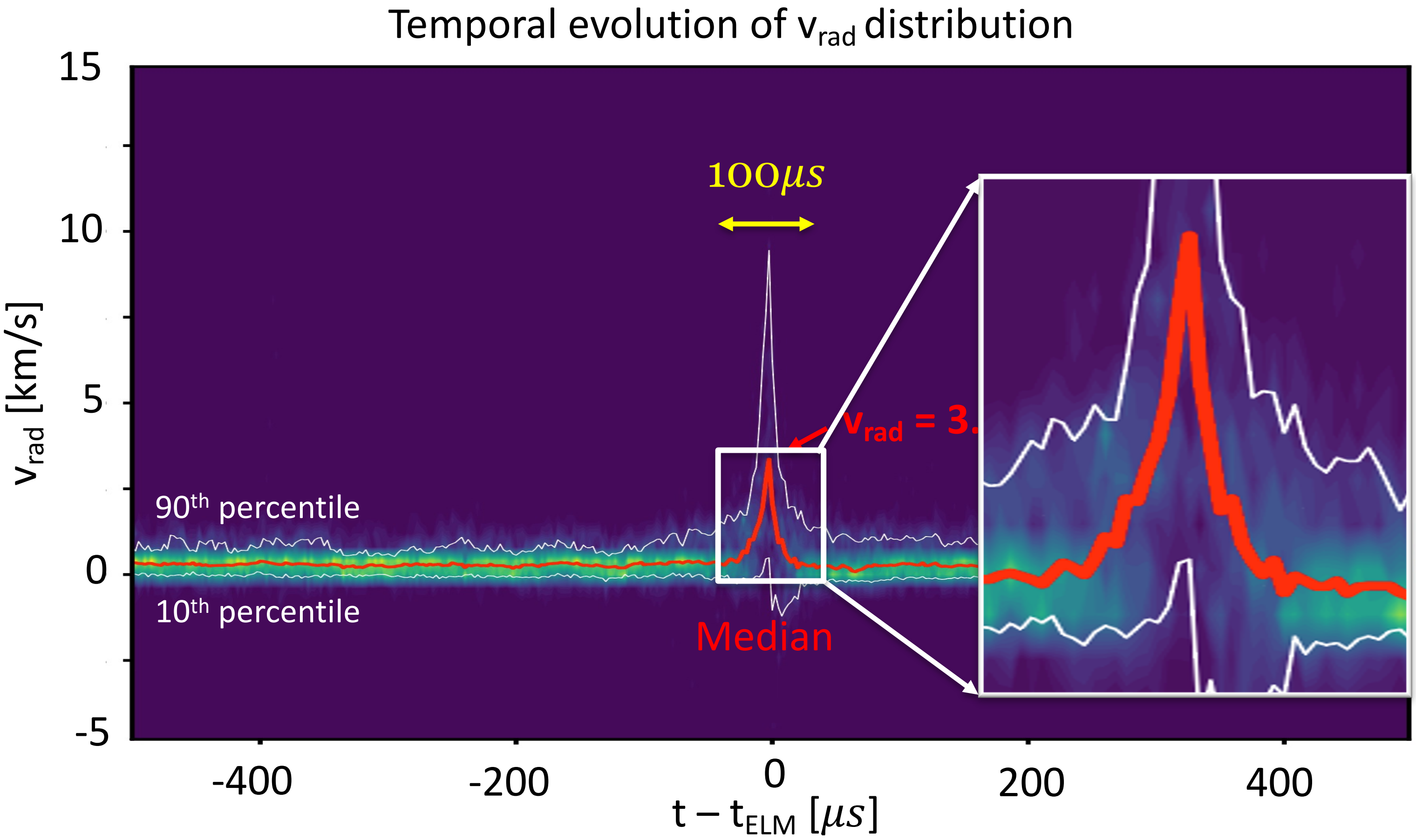
Rapid, 40mm characteristic radial outburst during the ELM crash.

The radial velocity of the filament increases linearly along its radially outwards path.



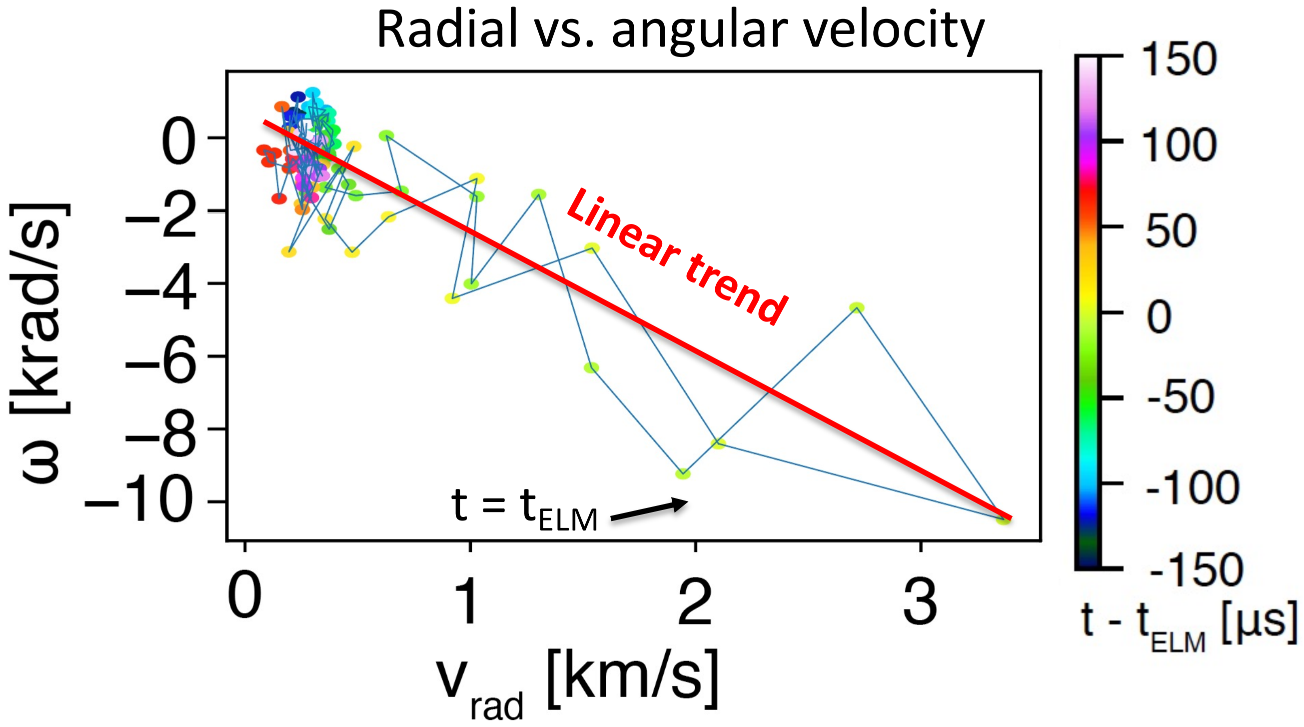
[M. Lampert et al, PoP (2021)]

Exponential time dependence of the radial velocity around the ELM crash



[M. Lampert et al, PoP (2021)]

The linear trend between v_{rad} and ω has never been seen before!



The ELM filament is **spinning** clockwise (ion gyro) during the crash

Source of the **linear trend** is under investigation.

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Connection to theory

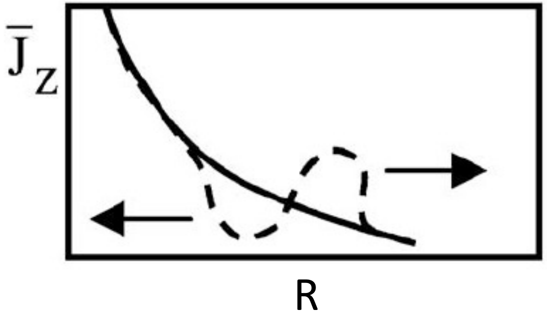
Current filament model

- Current in ELM filament
- j conservation → current hole
- Anti-parallel current repulsion
  - Thick-wire model force

Curvature-drift model:

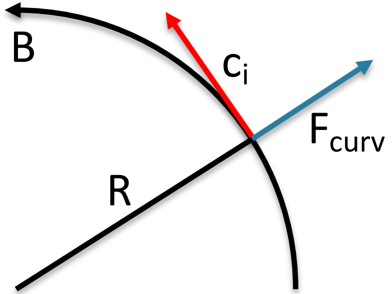
- Ion-sound speed propagation along the magnetic field lines
- Centrifugal force

Current filament

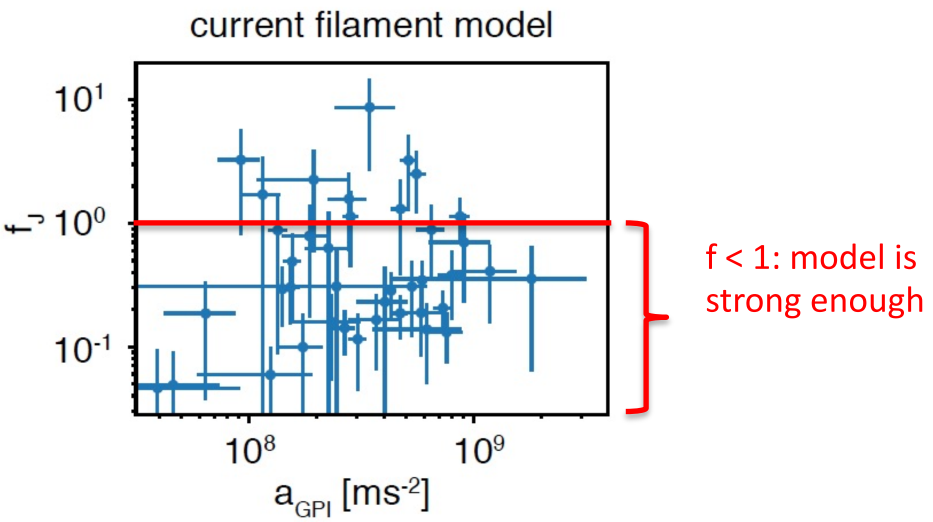


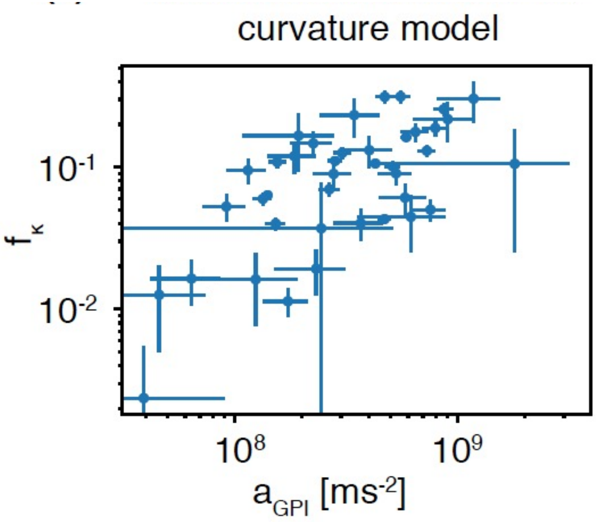
[J. Myra, PoP **14**, 102314 (2007)]

Curvature-drift



Form factors from modelled acceleration vs. GPI measurements





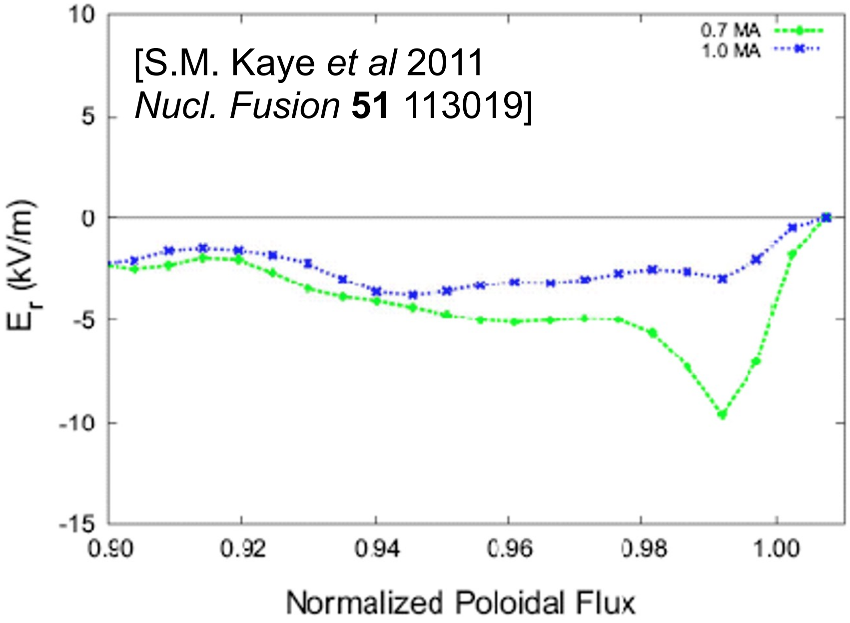
Current filament model (f_J) explains radial acceleration, circularity and coalescing.
Curvature model (f_κ) explains radial acceleration only.

The reality is a **combination of both**!

Neither can explain the linear increase of v_{rad} spatially!

Shear induced filament rotation from tilting net electric field

- **Negative and increasing** radial electric field (E_r) at the edge plasma
- $E_{f,z}$ () + E_r = **E'(net electric field) filament polarization**
- If $E_{f,z}$ and E_r are close to time-independent, **net E rotates with ω in the ion-gyro motion's direction.**
- The filament rotates with **E**



TODO:

- **v_z' needs to be estimated from background turbulence**
- The **time** the filament stays in the shear layer needs to be estimated.
- **Model to be compared with ω_{meas}**

Collaboration with Jim Myra

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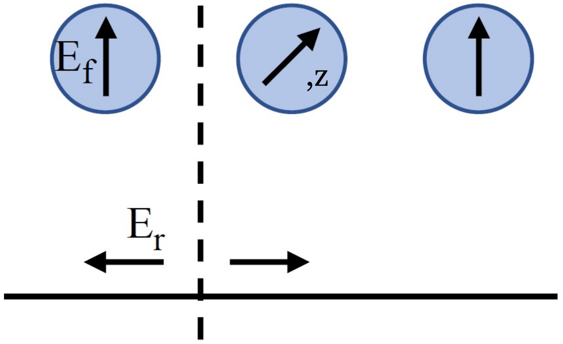

$$\tan\phi = \frac{E_r}{E_{f,z}} = \frac{E_r' d}{E_{f,z}} = \frac{v_z' d}{v_{fr}} = v_z' t$$

$$\omega = \frac{d\phi}{dt} = \frac{v_z{}'}{1 + (v_z' t)^2} \qquad t = d/v_{f,r}$$

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Ongoing work: ELM filament simulations with M3D-C1

Motivation:

The physics behind the $v_{rad} \sim \omega$ and $v_{rad} \sim r - r_{sep}$ trends and the filament birth mechanism are unknown!

Kinetic EFIT reconstruction with PyPed (Tom's tools) provides initial conditions

- Collaboration with G. P. Canal (Uni. of Sao Paulo), T. Osborne (GA), A. Diallo and A. Kleiner
- Several candidate shots (139057,141300,141309) were identified and kEFIT reconstructed

Ongoing M3D-C1 simulations: collaboration with Andreas Kleiner

- Solves the 2D/3D two-fluid extended MHD equations
- **Goal:** Qualitatively reproduce the observations and identify the driving forces behind the filament dynamics

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Summary

Summary

Edge localized modes are a threat to tokamaks due to their high heat load on the PFCs. Understanding their physics could enable novel ELM mitigation techniques.

ELM filaments were characterized in the 2010 NSTX measurement campaign **[1]** for which new data analysis methods were developed **[2].**

Results

- Radial velocity: **3.3 km/s** outwards ($3.7 \cdot v_{r,blob}$)
- Poloidal velocity: **11.4 km/s** ion diamagnetic ($4.1 \cdot v_{i,diam,max}$)
- Angular velocity: **10 krad/s** ion gyro motion direction [3]
- No significant expansion/contraction
- $\boldsymbol{v_{rad} \sim r - r_{sep}}$ **and** $\boldsymbol{\omega \sim v_{rad}}$
- **Analytical models** identified:
  - **Current-filament model**
  - **Curvature-drift model**
  - **Shear induced rotation**

[1] **M. Lampert et al,** Physics of Plasmas **28**, 022304 (2021)

[2] **M. Lampert et al,** Review of Scientific Instruments **92** (8), 083508 (2021)

[3] Rotation results: In preparation to Physics of Plasmas

Further ongoing projects

1) Alkali beam emission spectroscopy feasibility study for NSTX-U

- Successful study: absolute n_e profile measurements would be possible on NSTX-U with alkali BES
- Needs solicitation from DoE

2) Investigation of micro-tearing modes on spherical tokamaks

- Successful experimental proposal to measure MTMs on MAST-U
- Collaboration with UTA to investigate MTMs on NSTX

3) Machine-learning for structure identification and characterization in SOL imaging data

First author publications

M Lampert, A Diallo, SJ Zweben: Novel 2D velocity estimation method for large transient events in plasmas, RSI **92** (8), 083508 (2021)
M Lampert, A Diallo, JR Myra, SJ Zweben: Dynamics of filaments during the edge-localized mode crash on NSTX, PoP **28** (2), 022304 (2021)

M Lampert, S Zoletnik, JG Bak, YU Nam, KSTAR Team: 2D scrape-off layer turbulence measurement using Deuterium beam emission spectroscopy on KSTAR, PoP **25** (4), 042507 (2018)
M Lampert et al**:** Combined hydrogen and lithium beam emission spectroscopy observation system for Korea Superconducting Tokamak Advanced Research, RSI **86** (7), 073501 (2015)

Mate Lampert, Gabor Kocsis: Investigation of ELM precursors on the JET tokamak, Nukleon **V.** (2012) 112

*In the works: **M Lampert**, A Diallo, JR Myra, SJ Zweben: Rotation of ELM filaments on NSTX, To be submitted to PoP (2022)*

12 co-authored peer-reviewed publications

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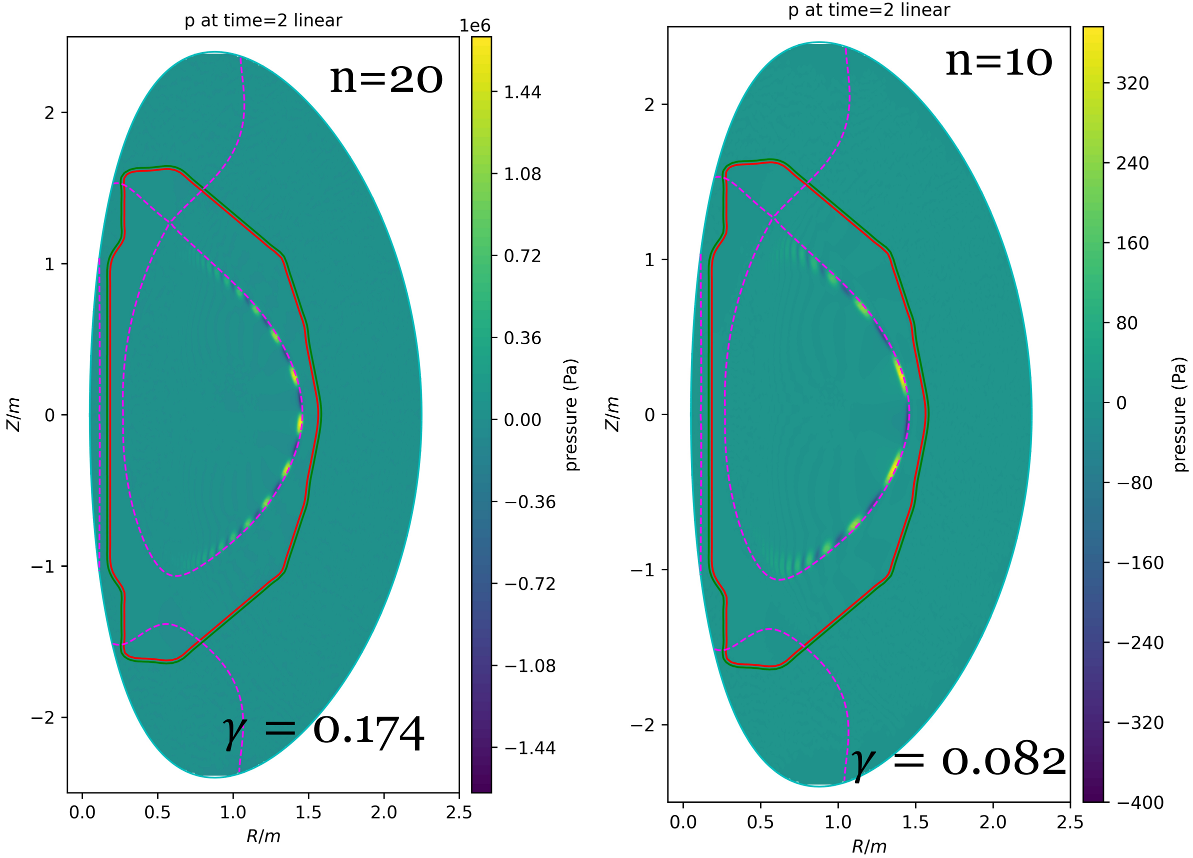
Thank you for your attention!

Backup slides

Preliminary results: Linear simulations were performed and unstable high n modes were found in shot 141309.

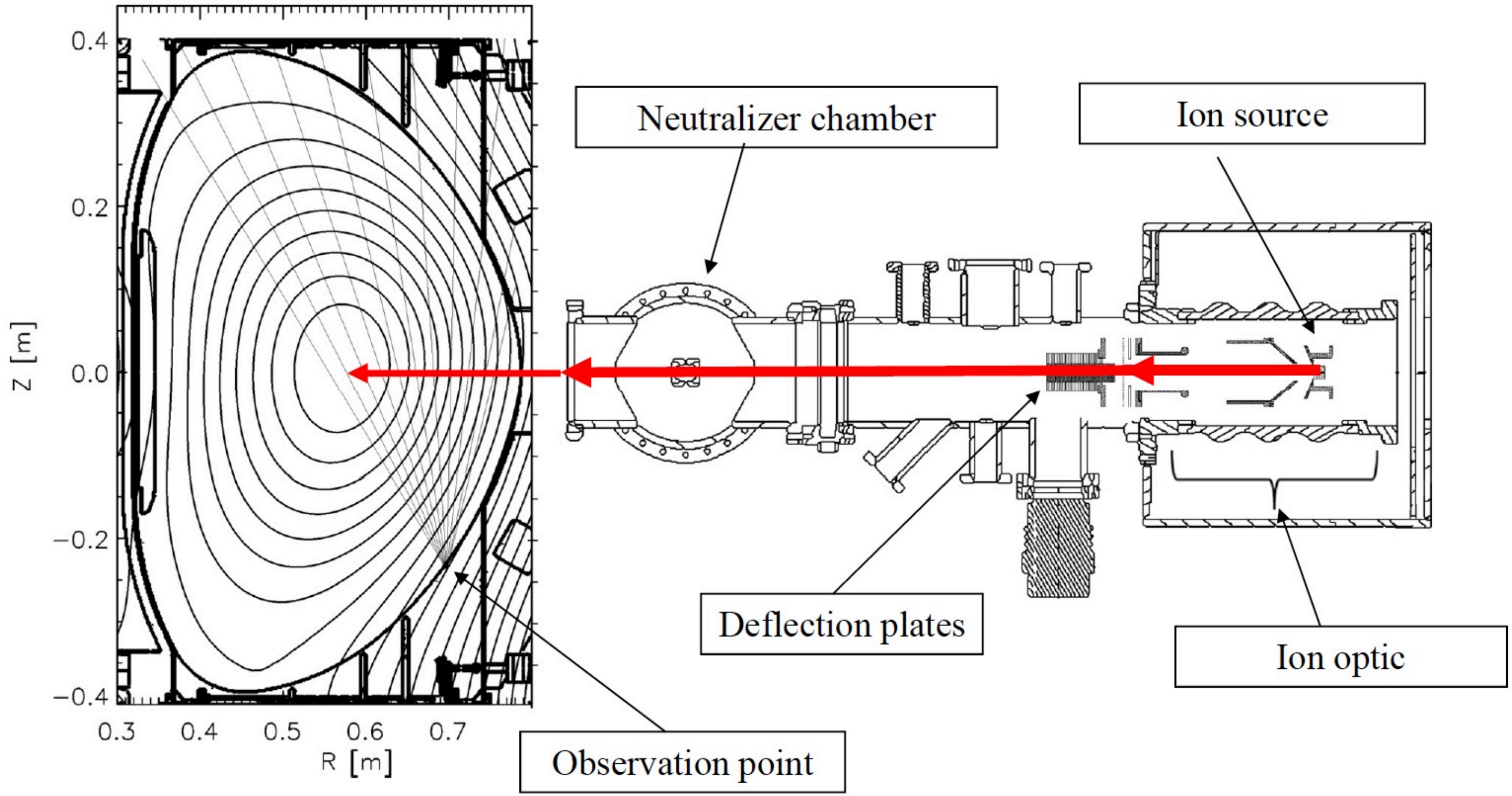


Alkali beam emission spectroscopy (ABES) for absolute n_e measurements

The NSTX-U 5year plan require high spatial and temporal resolution density profile measurements

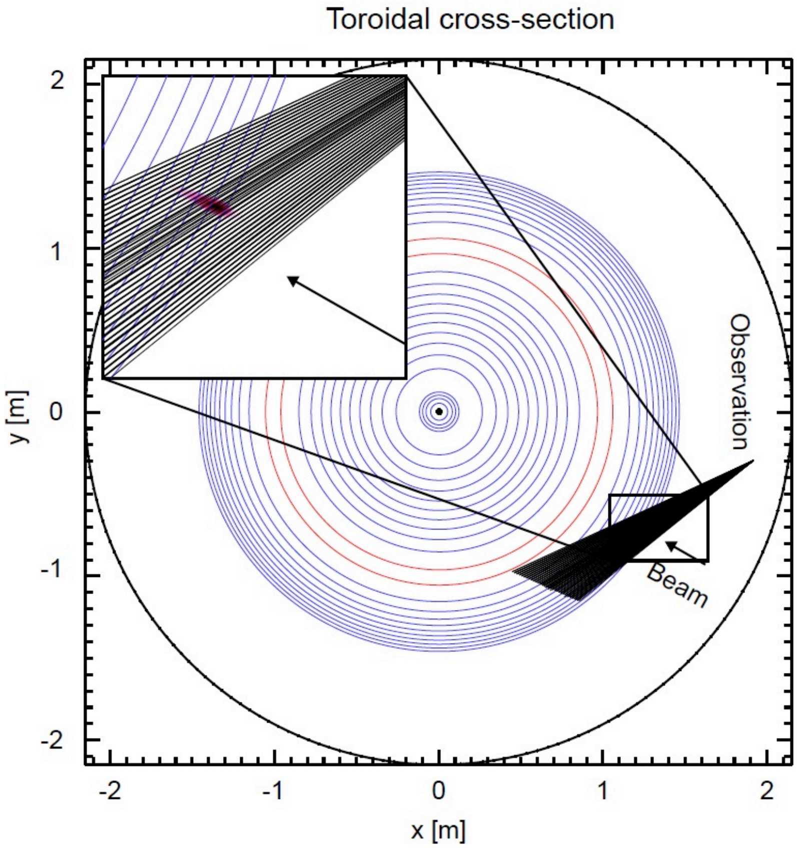
- **Objective 1 related requirement:**
  - Edge profiles **with resolution to resolve** narrow-to-wide pedestals (~cm) and temporally resolve inter-ELM evolution (~few ms)
  - Ion-scale turbulence measurements (~cm or $k_\perp \rho_s$~0.1-1, ~1 MHz), especially delta-B and **delta-n**
- **Objective 2 requires real-time profile measurements**
  - Real time MPTS and real time CHERS to improve constraints in real time equilibrium and stability calculations
  - **Real time Alkali BES could support these measurements (novel capability)**
- **Objective 3 related requirements:**
  - Edge and divertor turbulence measurements for connection to the SOL width
  - High spatial (3mm in pedestal region) and time resolution (10 kHz) of the midplane electron profiles

Absolute n_e measurement through collisional excitation of alkali beam atoms in the SOL and the edge plasma



Successful ABES feasibility study for NSTX

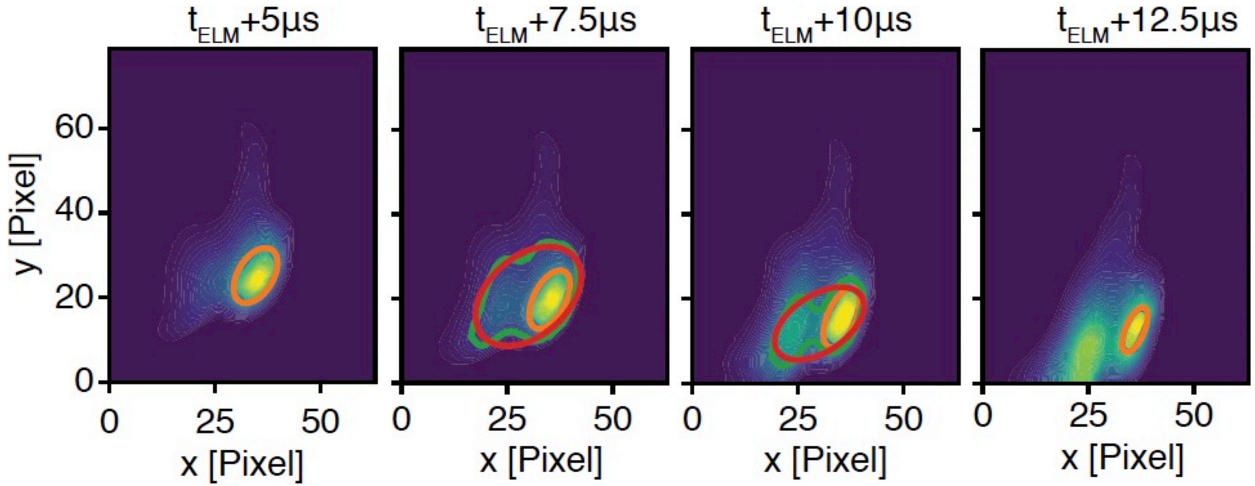
- Ports identified for beam and observation
  - High SNR: 25-140
  - $\Delta r = 7.5 - 12.5mm$
  - n_e density profile measurement up to over mid-pedestal
  - Limited fluctuation
- Smearing is close to **temperature independent**, tolerable at all densities
- Enables cm and $100\mu s$ scale absolute n_e measurements on NSTX
- **Awaiting solicitation from DoE**



Coalescing filaments

Structure identification

- Pre-processed frames → Contour paths → Find areas ≥5 enclosed paths



1st structure:
Contour (FWHM)
Ellipse fit

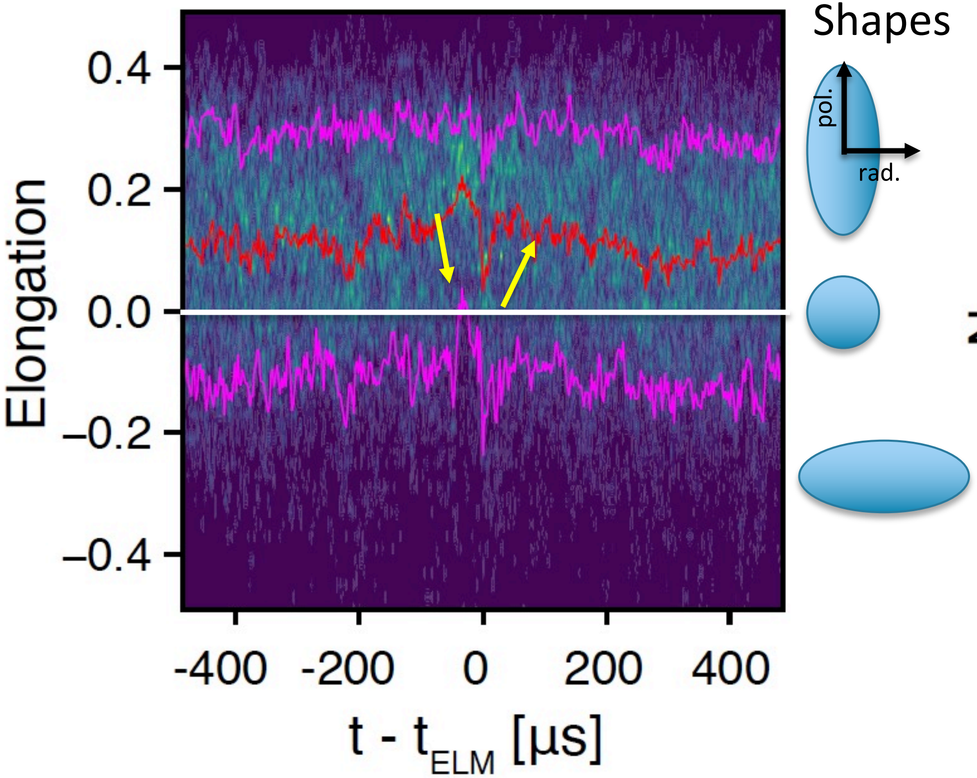
2nd structure:
Contour (FWHM)
Ellipse fit

- Ellipse fit → size, elongation, structure number, position, **distance from the separatrix (/w EFIT)**

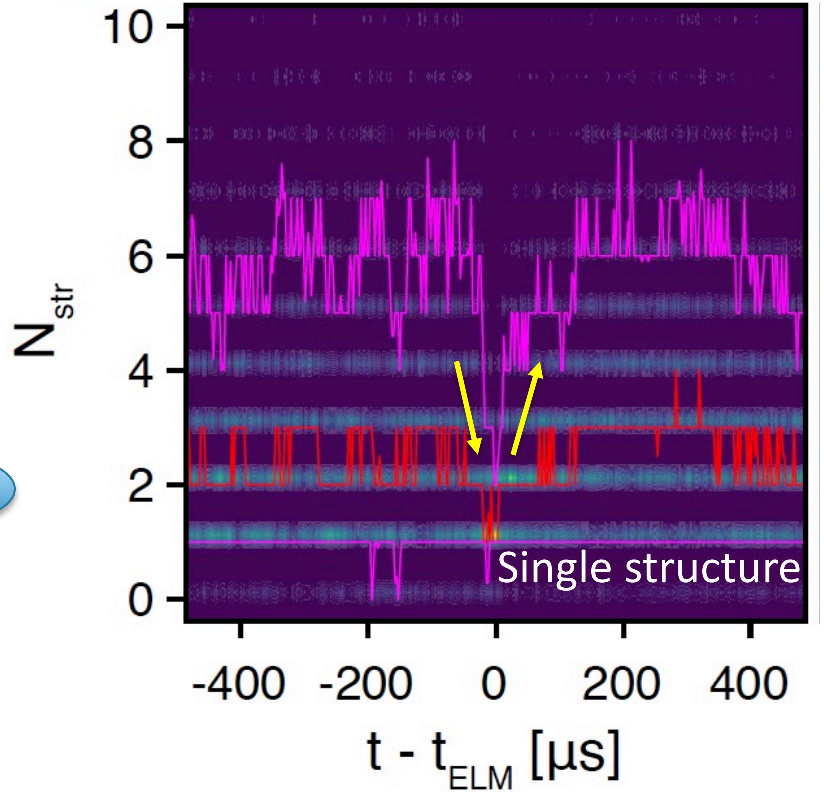
[**M. Lampert et al,** POP (2021)]

Multiple filaments coalesce into a single, circular ELM filament

$$\text{Elongation} = \frac{d_{pol} - d_{rad}}{d_{pol} + d_{rad}}$$



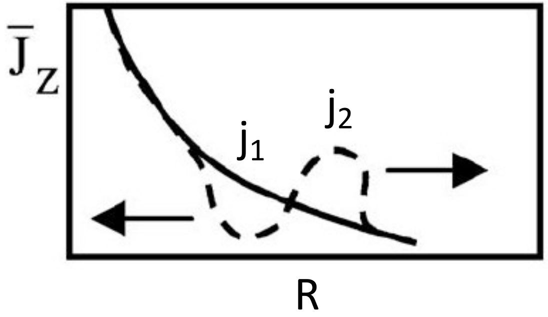
Number of structures in a frame



[**M. Lampert et al**, Physics of Plasmas **28**, 022304 (2021)]

Model details

Current filament model explains acceleration, circular shape and coalescing

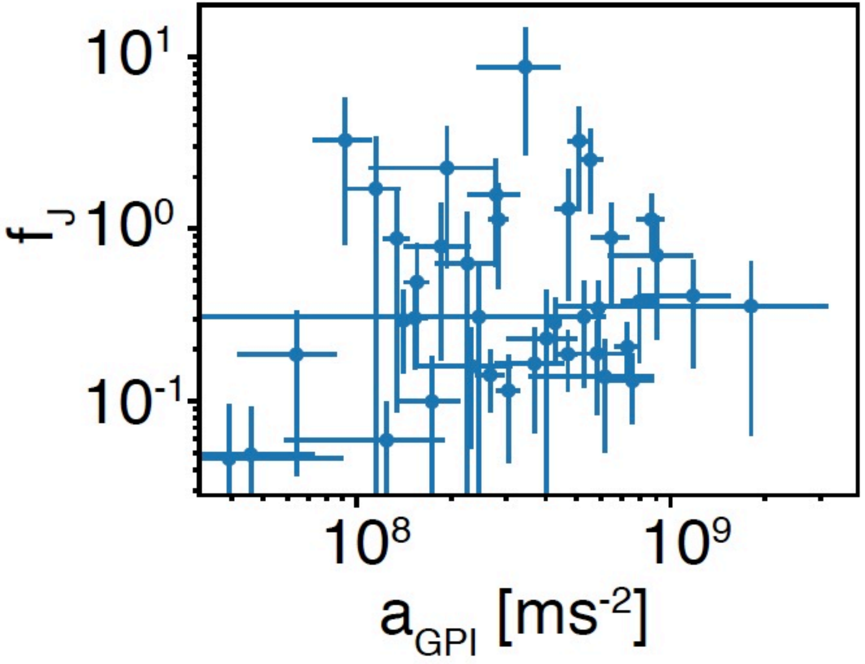


$$a_{current} = \frac{\mu_0 \pi \delta_b^2 j_1 j_2}{2\pi d \cdot m_i\, n_i}$$

$$a_{GPI} = \frac{\mu_0 \pi \delta_b^2 (f_j j_1)(f_j j_2)}{2\pi d \cdot m_i\, n_i}$$

$$f_j = \sqrt{\frac{a_{GPI}}{a_{current}}}$$

Measured acceleration vs. current filament model



Model form-factor vs. acceleration

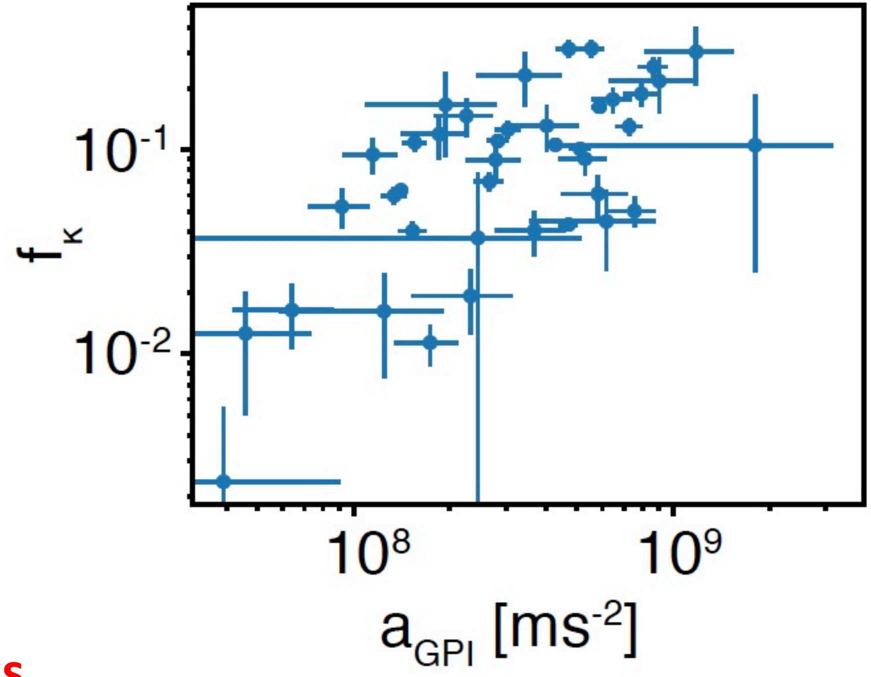
Curvature drift model explains acceleration only

$$a_{curv} = \frac{c_s^2}{R} = \frac{\gamma Z k_B T_e}{R m_i}$$

$$a_{GPI} = \frac{\gamma Z k_B (f_\kappa T_e)}{R m_i}$$

$$f_\kappa = \frac{a_{GPI}}{a_{curv}}$$

Measured acceleration vs. curvature model



Model form-factor vs. acceleration

- **Reality:**
  - **Combination of both mechanisms**

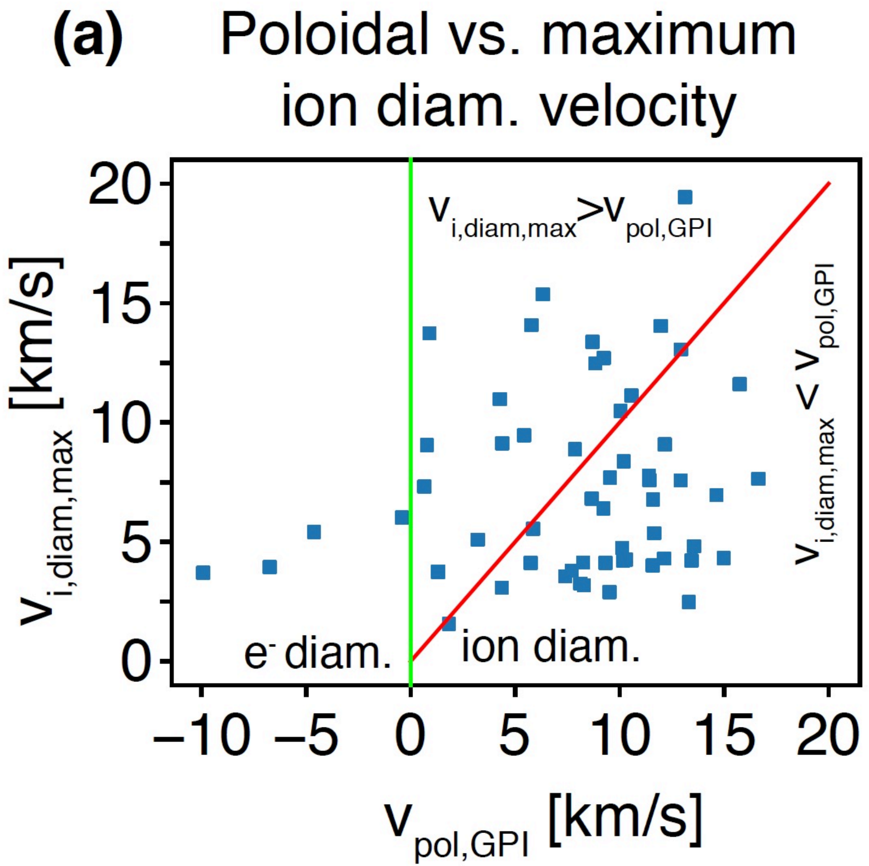
Poloidal velocity model

Model for poloidal velocity

- Filaments are born inside the separatrix
- Ion-diamagnetic velocity could determine v_{pol}

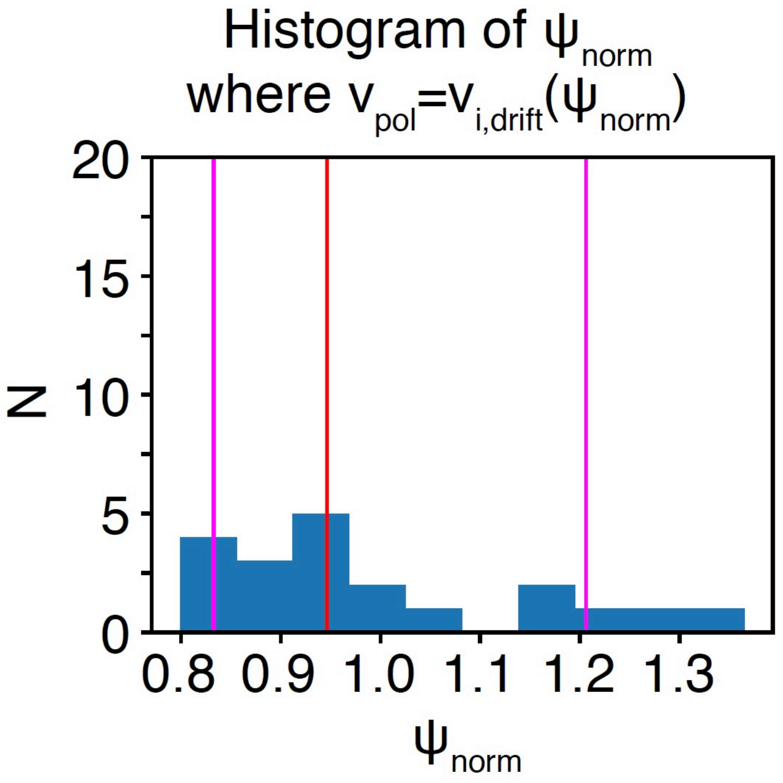
$$v_{i,diam} = -\frac{\nabla p \times B}{q n_i B^2} \approx -\frac{|\nabla p|}{q_i n_i B}$$

- Parameters from Thomson scattering and EFIT



Model for poloidal velocity

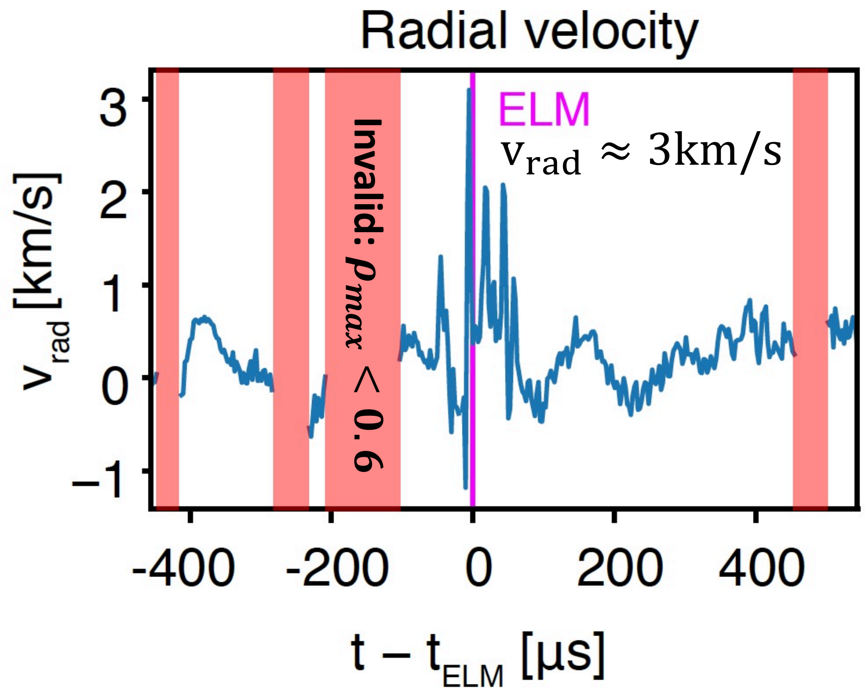
- Radial $v_{i,diam}$ profile vs. $v_{pol,GPI}$
  - Only ¼ of the events
  - Matching velocity → birthplace
  - Assumption: no other influence
    - e.g. shear layer, current-filament
- **Too large spread**
- **Too little percentage of events**

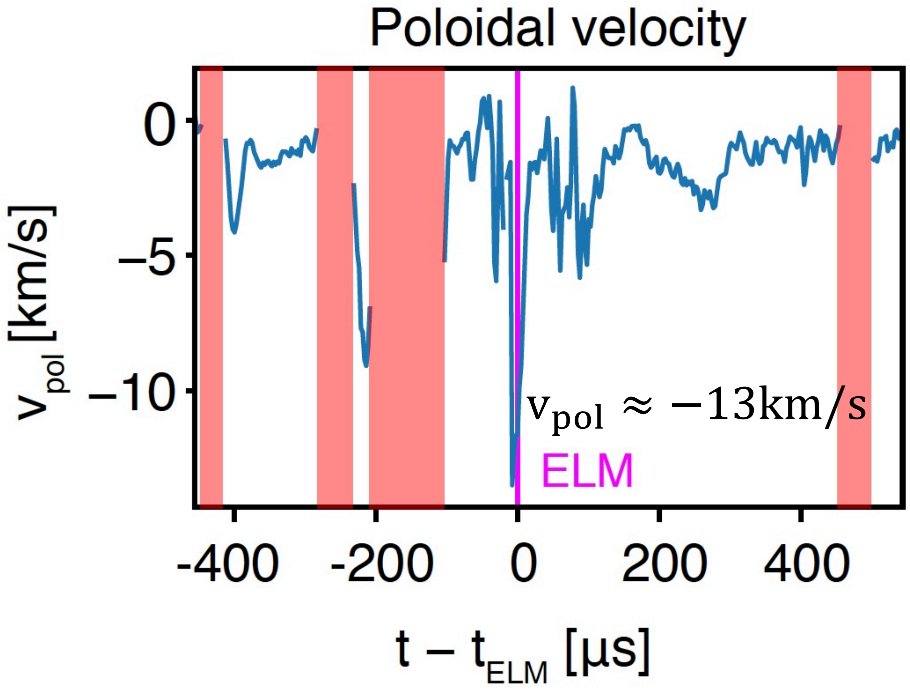


Single ELM calculation

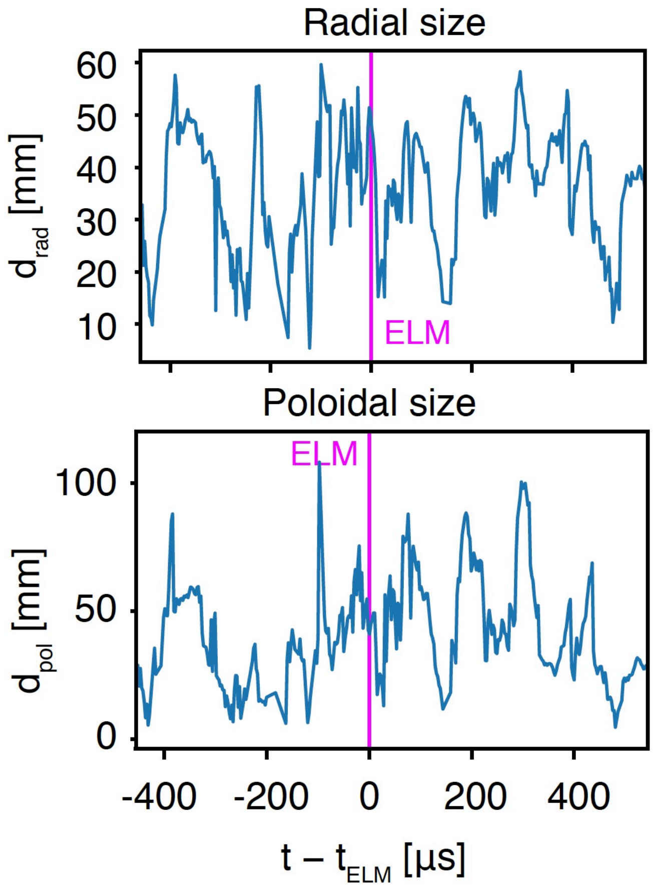
Results: 3km/s radial outburst, -13km/s ion diam. poloidal propagation

Results for 139901 @ 325ms

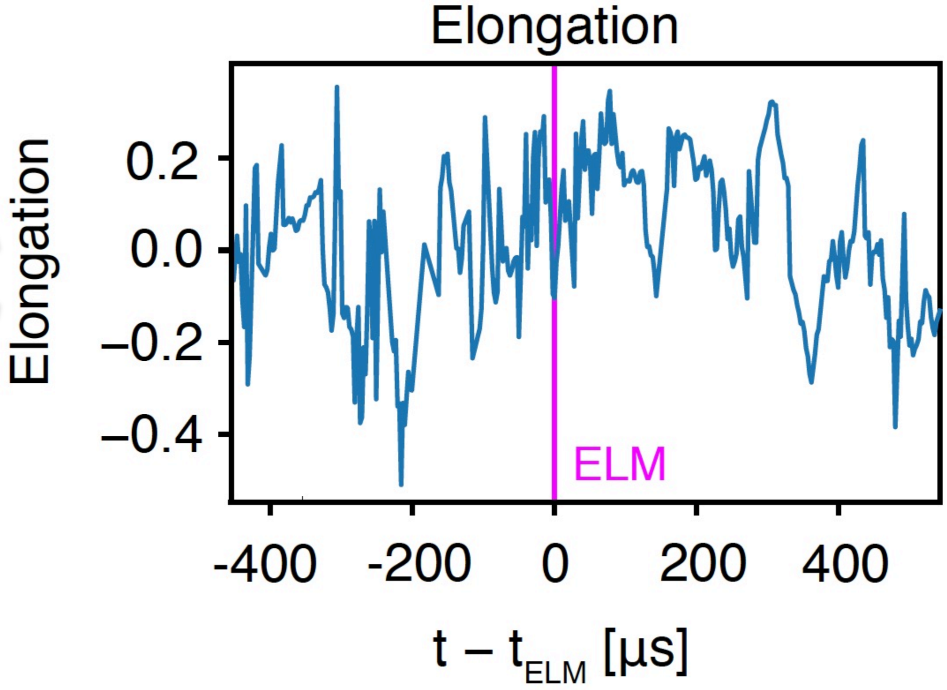




Results: No significant size change is seen

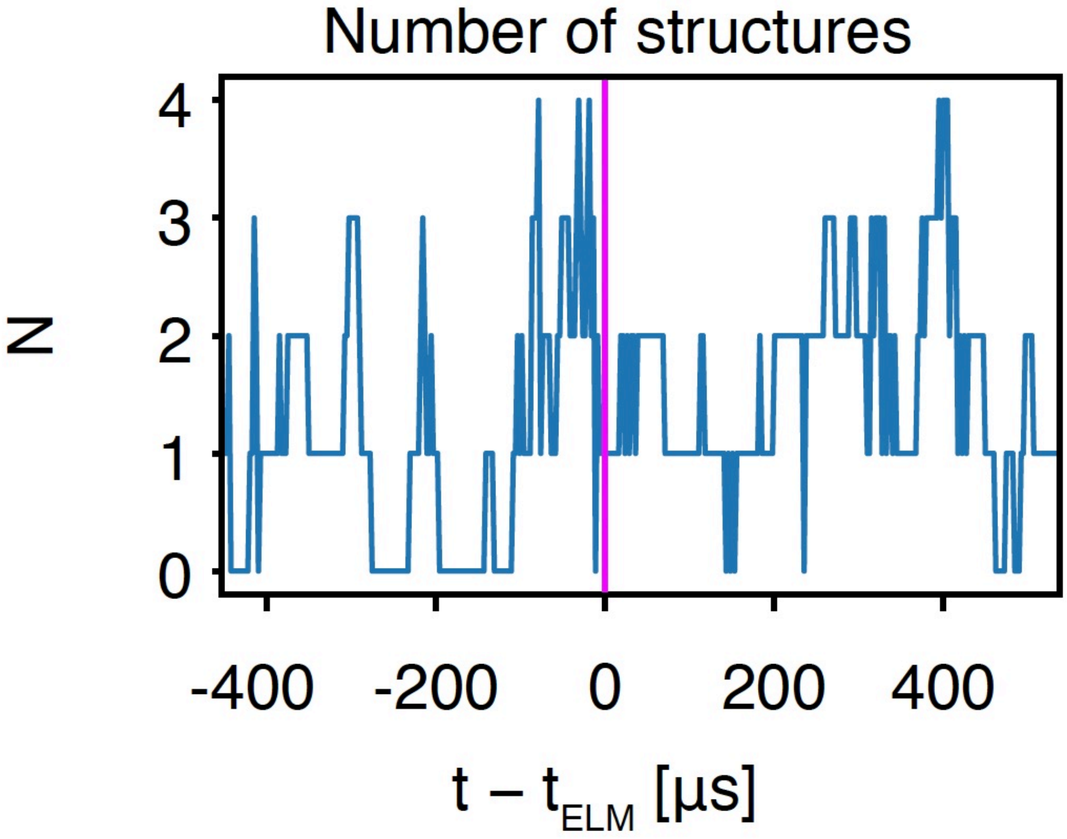


- Elongation = $\frac{d_{pol} - d_{rad}}{d_{pol} + d_{rad}}$



Results for 139901 @ 325ms

Results: **Coalescing behavior at the ELM crash**



Results for 139901 @ 325ms

Previous results: **Previous work on NSTX on ELM filaments**

Nishino et al 2002

- First observations of ELM filaments with fast camera

Maingi et al PoP 2006

- Characterization of type V ELMs

Maqueda et al PoP 2009

- Primary and secondary ELM filaments with GPI

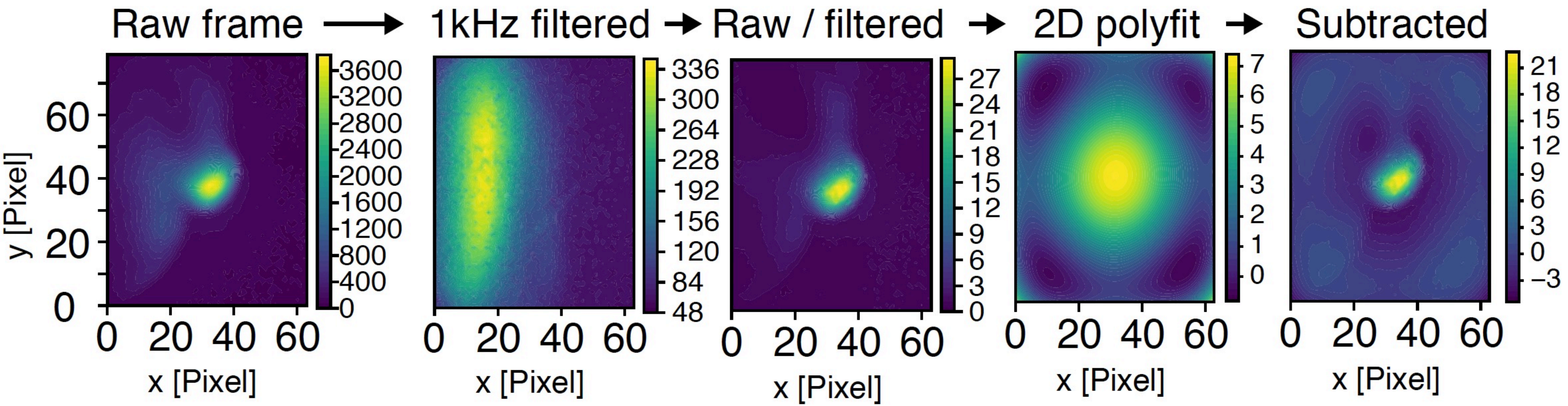
Sechrest et al 2012

- ELM precursor analysis with GPI

Current work:

- Large ELM database from 2010
  - 169 ELMs from 77 shots
- 2.5μs time resolution
  - Lower smear
- **Frame-by-frame analysis**
  - Poloidal and radial velocities
  - Structure shape evolution
  - Number of structures
- Analytical theory of dynamics
- **Extends the knowledge of ELM filaments**

- Necessary pre-processing steps for the analysis methods to work.



0th step:
Reading data
frame-by-frame

1st step: **Removing gas-cloud**
1kHz: gas cloud evolution ~ms

2nd step:
Removing low-order polynomial offset

Results: **Qualitatively similar results on other machines**

Device	Diagnostic	Measurement	v_{rad} [km/s]	v_{pol} [km/s]	d_{rad} [cm]	d_{pol} [cm]	t_{crash} [μs]	
NSTX	GPI	D_α	8	-11	-	4 - 5	300	R. Maqueda
(earlier)	Interferometry	$n_{e,int}$	-	<10 (toroidal)	10	-	400 - 1000	R. Maingi
MAST	Langmuir-probes	j_{sat}	0.75	-	7.5 - 15	-	100	A. Kirk
JET	Langmuir-probes	j_{sat}	1 - 2	-2	-	-	10 - 50	M. Endler, C. Silva
ASDEX	HFD	D_α	-	-7.5 - 14	few cm	few cm	-	M. Endler
	Langmuir-probes	j_{sat}	0.2-0.8	-	-	5-8	-	A. Kirk
	Filament-probe	j_{sat}	0.5-6	-	1-30	-	-	A. Schmid
	FFR	n_e displacement	3-4	-	-	-	few μs	J. Vicente
Alcator C-MOD	1D GPI	D_α	1	-	0.5 - 1	-	-	J. L. Terry
JT60-U	Langmuir-probes	j_{sat}	0.5-3	-	0.5 - 4	2 - 6	30	N. Asakura
COMPASS	Filament-probe	j_{sat}	1	-	-	-	200	M. Spolaore
NSTX	GPI	D_α	3.3	-11.4	3-7	3-7	100	

- Most measurements are 1D and in the SOL
- **New results**: comprehensive analysis of 2D propagation and size changes
  - Morphing into circular shape while coalescing
  - Linear dependence: distance vs. v_{rad}

- Spatial position of the maximum of the 2D cross-correlation function
- Calculated between consecutive GPI frames
  - Estimates the 2D spatial displacement
- Direct method (discreet form):
  - Calculate the spatial covariance functions:

$$COV_{(f,g)}(\kappa_x, \kappa_y, t_k) = \sum_{ij} f(x_i - \kappa_x, y_j - \kappa_y, t_k) g(x_i, y_j, t_{k-1})$$

  - Normalize it with the spatial auto-correlation functions:

$$ACF_{(f)}(\kappa_x, \kappa_y, t_k) = \sum_{ij} f(x_i - \kappa_x, y_j - \kappa_y, t_k) f(x_i, y_j, t_k)$$

$$CCCF_{(f,g)}(\kappa_x, \kappa_y, t_k) = \frac{COV_{(f,g)}(\kappa_x, \kappa_y, t_k)}{\sqrt{(ACF(f_0(t_k)) \cdot ACF(g_0(t_{k-1})))}}$$

- Easy to implement, but ~N^2 order computation time (N: number of pixels)
  - (would take 100 days to calculate for the entire database)

2D CCCF functions

- Fourier-space calculation
- The consecutive 2D GPI frames are 2D FFT transformed in space
  - Same definition for the cross-correlation coefficient functions:

$$CCCF_{(f,g)}(\kappa_x, \kappa_y, t_k) = \frac{COV_{(f,g)}(\kappa_x, \kappa_y, t_k)}{\sqrt{(ACF(f_0(t_k)) \cdot ACF(g_0(t_{k-1})))}}$$

  - The terms are calculated in Fourier-space
  - Covariance function:

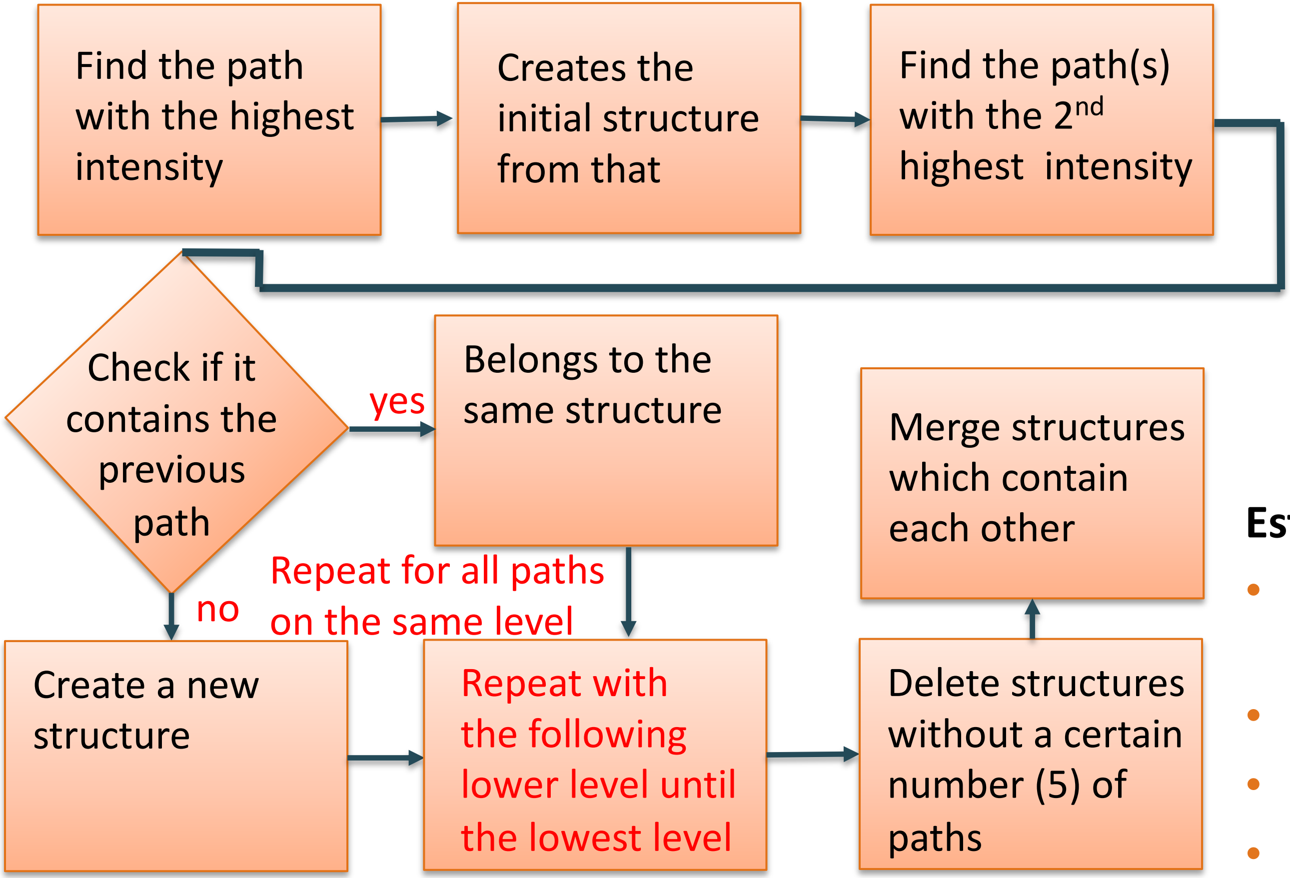
$$COV_{(f,g)}(\kappa_x, \kappa_y, t_k) = FFT^{-1}_{k_x,k_y}[FFT_{k_x,k_y}(f(x,y,t_k)) \cdot FFT_{k_x,k_y}(g(x,y,t_{k-1}))^*]$$

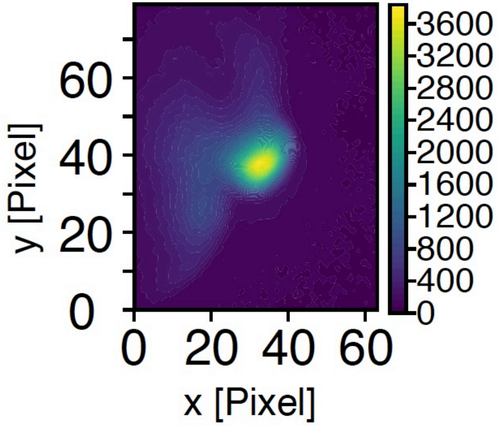
  - Auto-correlation function:

$$ACF_{(f)}(\kappa_x, \kappa_y, t_k) = FFT^{-1}(FFT(f) \cdot FFT(f)^*)$$

- About two magnitudes faster (for a 64x80 GPI image, 1 day for the database)
- Needs zero padding to prevent circular ACF, CCF
- Needs reordering to get negative, positive displacement
- Statistically equivalent to the direct method!
- Detailed derivation in Bendat-Piersol: Random Data 11.4.2 (Wiley 2010)

Methods: **Structure identification and fitting**





Estimated parameters:

- Radial, poloidal size and position (ellipse fit)
- Elongation (ellipse fit)
- Number of structures (direct)
- Velocity (tracking)

Methods: **Fitted structure movie**