Structure and evolution of ELMs in the edge and SOL of NSTX

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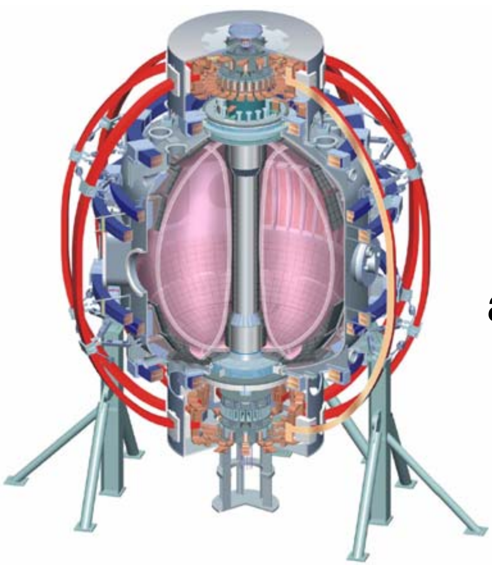

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Abstract

Edge Localized Modes (ELMs) are routinely seen during H-mode operation in NSTX. These ELMs have been characterized as large-sized Type I, medium-sized Type III, and small Type V ELMs. Recently, an experiment was dedicated to characterize the structure and evolution of these 3 ELM Types in NSTX utilizing multiple diagnostics. These diagnostics include: fast-framing digital cameras, soft X-ray arrays, edge probes (both tile-embedded and reciprocating), reflectometers and Mirnov arrays. In general, the ELM evolves from a perturbation of the edge topology that quickly develops (<30 μs) into strong filamentation that propagates both radially and poloidally/toroidally in the SOL. This ELM filamentation is then followed by an increased level of edge turbulence (and blobs) resembling, momentarily, that observed during L-mode phases. This later blob filamentation is clearly distinct from the initial ELM structures. The characteristics and differences observed in all 3 ELM Types are presented.

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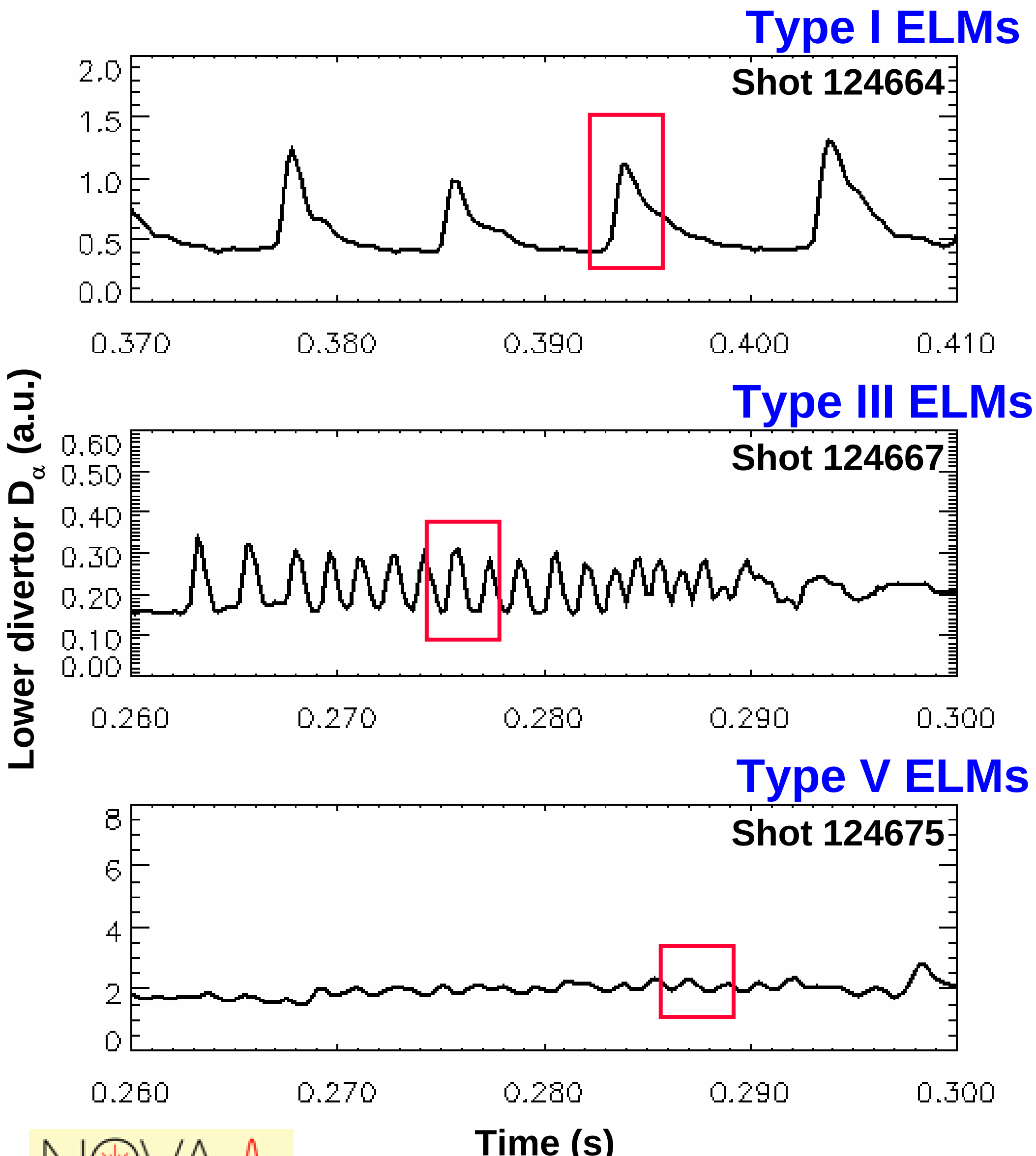
Motivation

- The structure of edge localized modes (ELMs) in the scrape-off layer is of great importance for future devices like ITER, where they can potentially affect the lifetime of plasma facing components.
- The National Spherical Torus Experiment (NSTX) is well suited with diagnostics usefull to study the structure and evolution of ELMs in the edge and scrape-off layer.

Type I, III and V ELMs are observed in NSTX



Large size ELMs ($\Delta W > 5\%$)
Close to double null configuration
NBI power above L-H threshold

Medium size ELMs ($\Delta W \sim 2\%$)
Close to double null configuration
NBI power close to L-H threshold

Small size ELMs (ΔW "small")
Lower single null configuration
Wide range of NBI powers

Other ELM characteristics in NSTX

Type I ELMs

- Frequency increases with P_{NBI}.
- Amplitude not affected by P_{NBI} but decrease with density and with δr_{sep} towards LSN.
- Generally, no electromagentic precursor.
- Inward cold pulse propagation.

Type III ELMs

- Frequency decreases with P_{NBI} and increases with density (i.e., decreases with loss power).
- Precursor with electro-magnetic signature (<40 kHz).
- No inward cold pulse propagation.

Type V ELMs

- Can coexist with Type I.
- Rotating n=1 electromagnetic mode/filament.
- Mode duration of up to 2 toroidal transit times (>1 ms) times.
- No ELM filament detachment.

NSTX ELM bibliography

- R. Maingi *et al.*, "ELMs and the H-mode pedestal in NSTX", J. Nucl. Mater. 337-339 (2005) 727.
- R. Maingi *et al.*, "Observation of a high performance operating regime with small edge-localized modes in the National Spherical Torus Experiment", Nucl. Fusion 45 (2005) 264.
- R. Maingi *et al.*, "H-mode pedestal, ELM and power threshold studies in NSTX", Nucl. Fusion 45 (2005) 1066.
- R. Maingi *et al.*, "Characterization of small, Type V edge-localized modes in the National Spherical Torus Experiment", Phys. Plasmas 13 (2006) #092510.
- R. Maqueda *et al.*, "Structure of MARFEs and ELMs in NSTX", J. Nucl. Mater. 363-365 (2007) 1000.

ELMs observed with GPI diagnostic

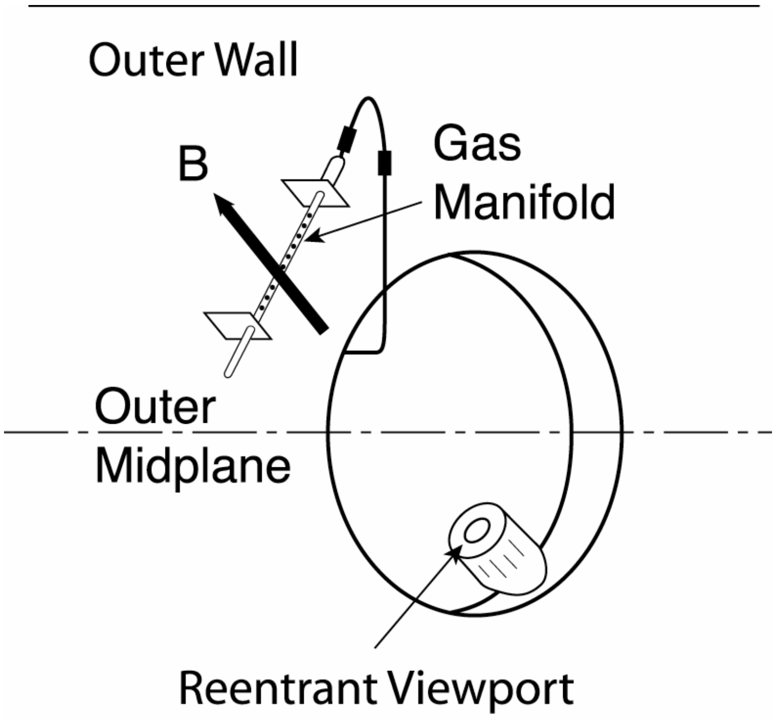
- Camera used to view visible emission from **outer edge just above midplane**.
- D_2 gas puff is injected to increase image contrast and brightness. Gas puff <u>does not perturb</u> local (nor global) plasma.
- Emission filtered for D_α light from gas puff:

  $$\mathbf{I \propto n_o F(n_e,T_e)}$$

- D_α emission only seen in range

  $\sim 5\ \text{eV} < T_e < 50\ \text{eV}$

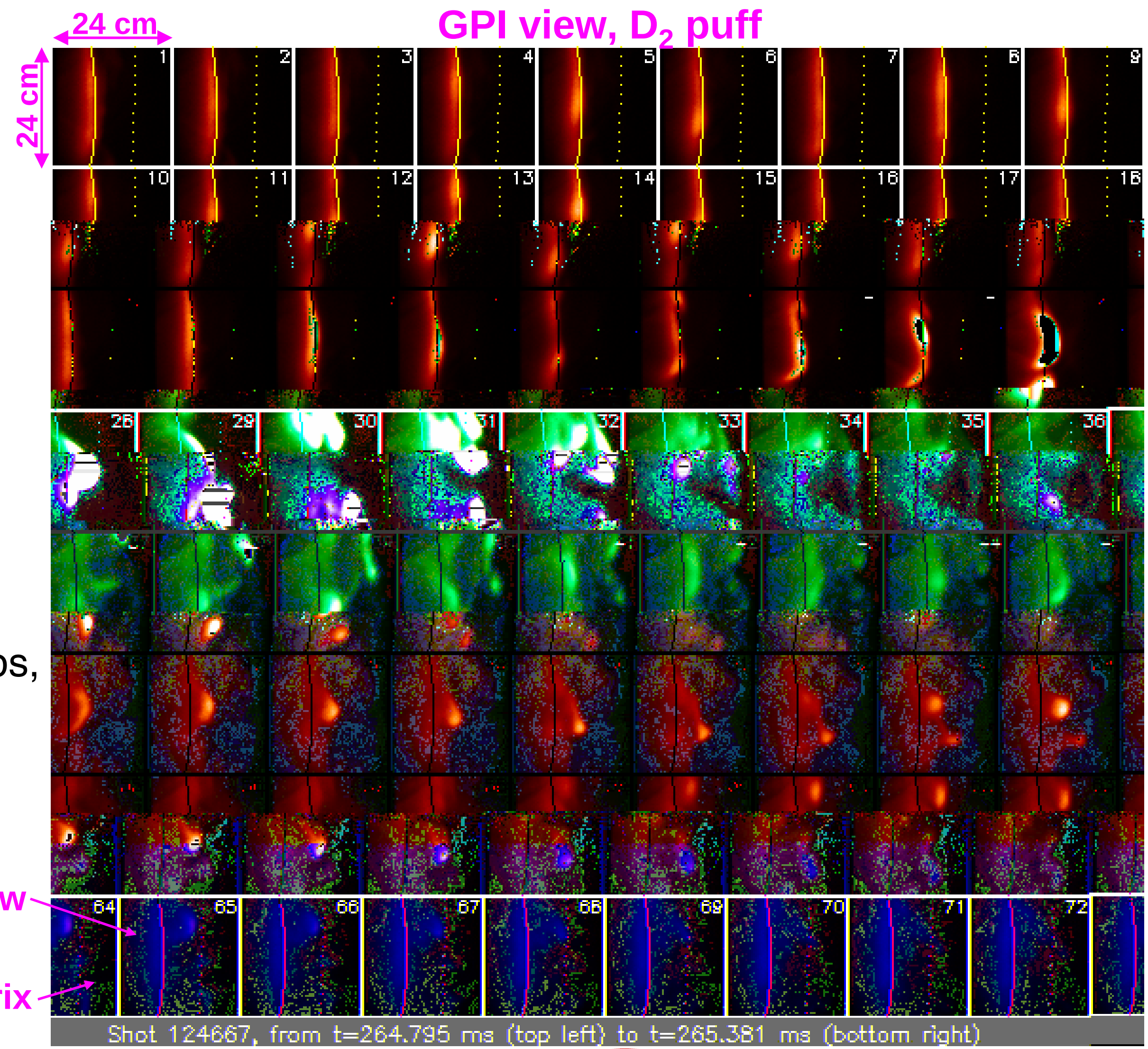
- View aligned along B field line to see 2-D structure $\perp$ B. Typical edge phenomena has a long parallel wavelength, **filament structure**.
- **Field of view covers ~24 cm of outer edge.**
- For more details: **"Gas puff imaging of edge turbulence"**, R.J. Maqueda *et al.*, Rev. Sci. Instrum. 74(3), p. 2020, 2003.



Type III ELMs

ELM filamentation after ELM onset

Type III ELM



ELM sequence

- Mode growth.
- Birth of ELM filaments.
- Filament detachment (except in Type V ELMs).
- Filament radial and poloidal/toroidal propagation in SOL – eventual interaction with plasma facing components.
- Turbulent filamentation and blobs, L-mode like.
- Recovery of H-mode edge.

D_α filter
4 μs exposures
121212 frames/s

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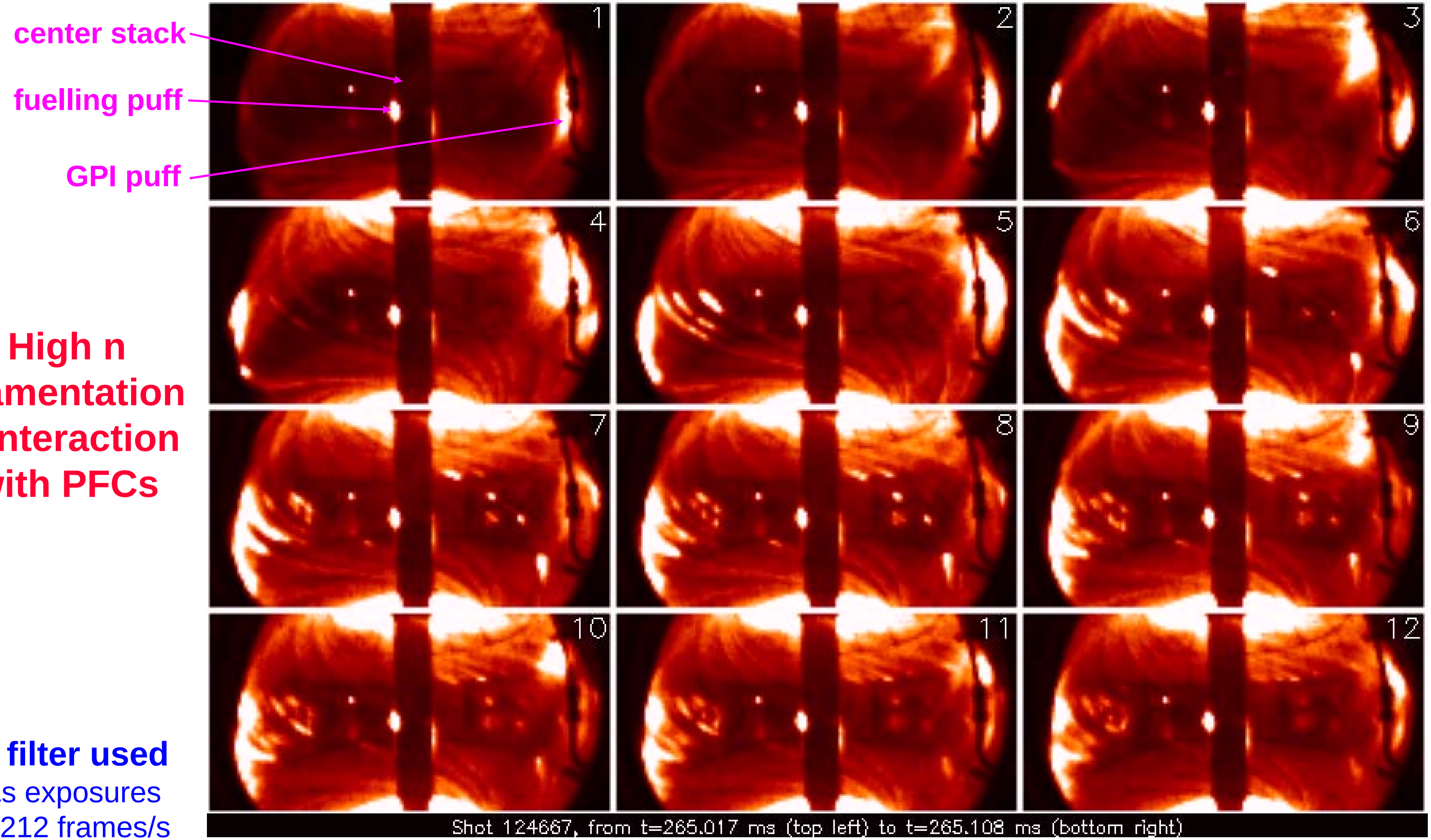
High n structure observed on wide angle view

Type III ELM



High n filamentation – interaction with PFCs

No filter used

6 µs exposures

121212 frames/s

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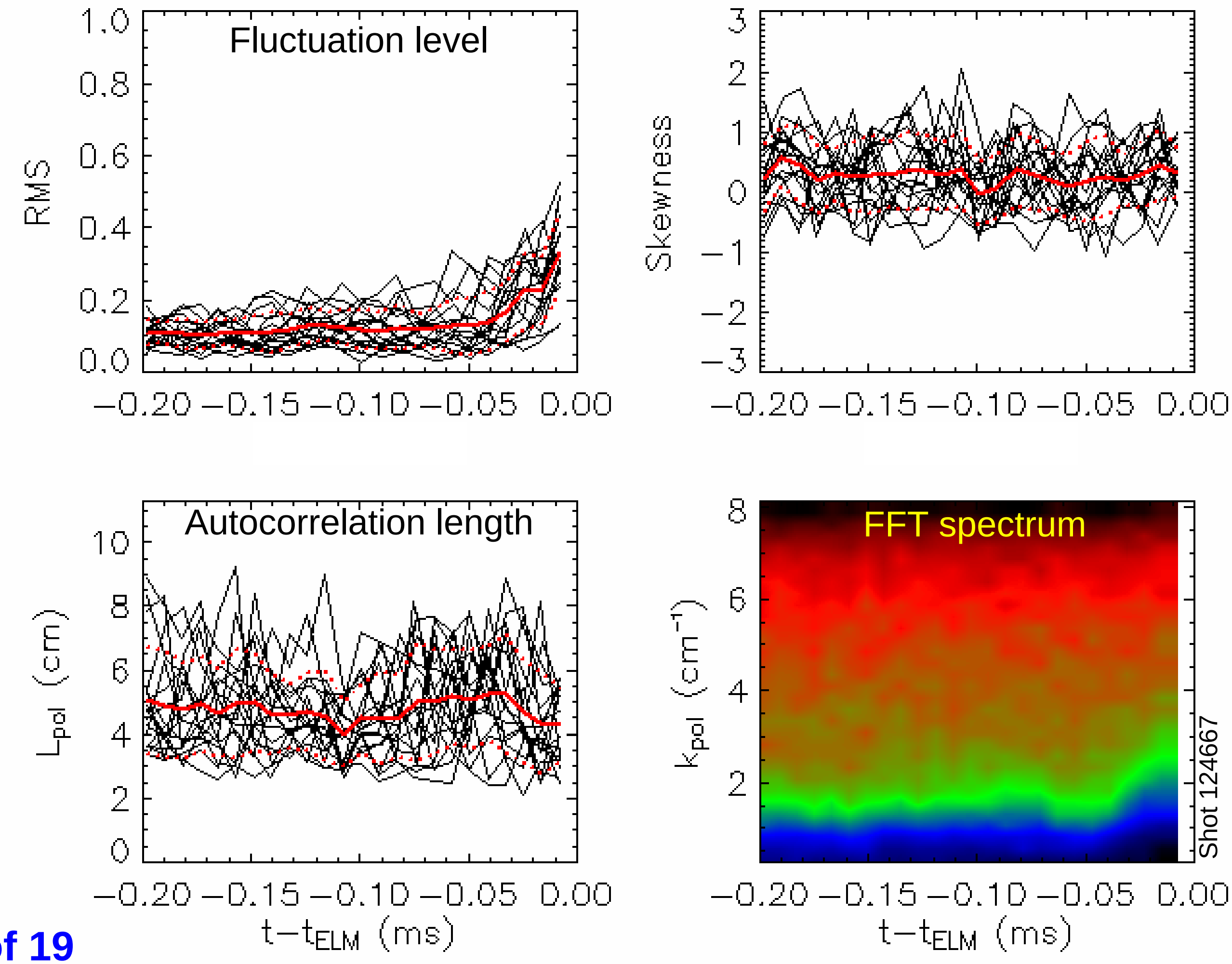
Mode growth start 40 μs before ELM filamentation

Type III ELM

- Mode growth observed in RMS fluctuation level and FFT spectrum.
- PDF (skewness and kurtosis), as well as poloidal autocorrelation length, remain unchanged.
- FFT spectrum shows increase in the 2 cm^{-1} range, broadband.

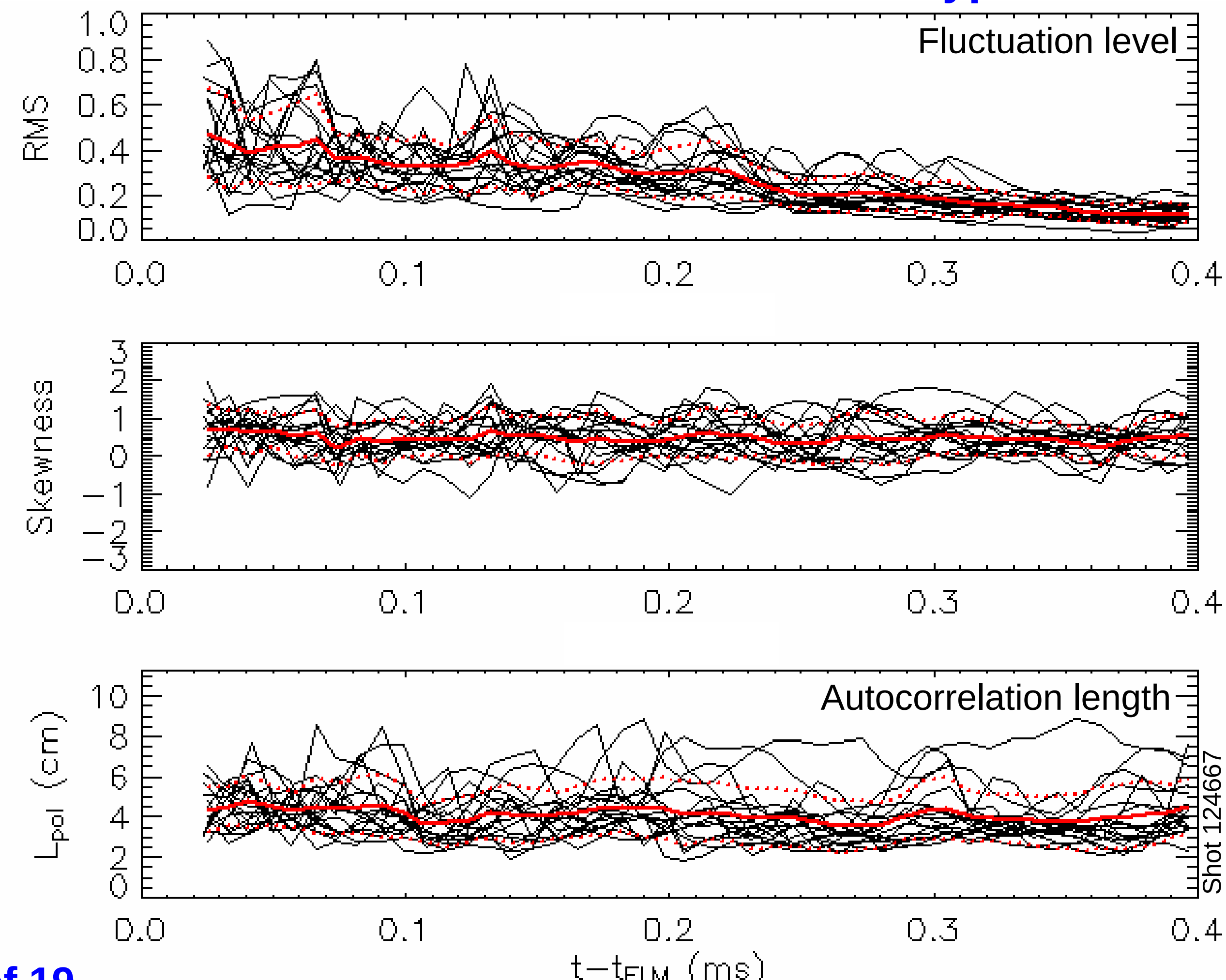


Average of 19 Type III ELMs

ELM filamentation followed by L-mode like turbulence and blobs

- Intermittency in the scrape-off layer (Δr~3.5 cm) shows decaying fluctuation level.
- Fluctuation levels of 40% RMS are characteristic of L-mode discharges [S. J. Zweben *et al.*, Nucl. Fusion 44 (2004) 134].
- Fluctuation (blobs) decay to the H-mode level of ~10% RMS within 0.3 ms.
- Fluctuation characteristics (autocorrelation lenghts and PDF skewness) are similar to “blob” activity.

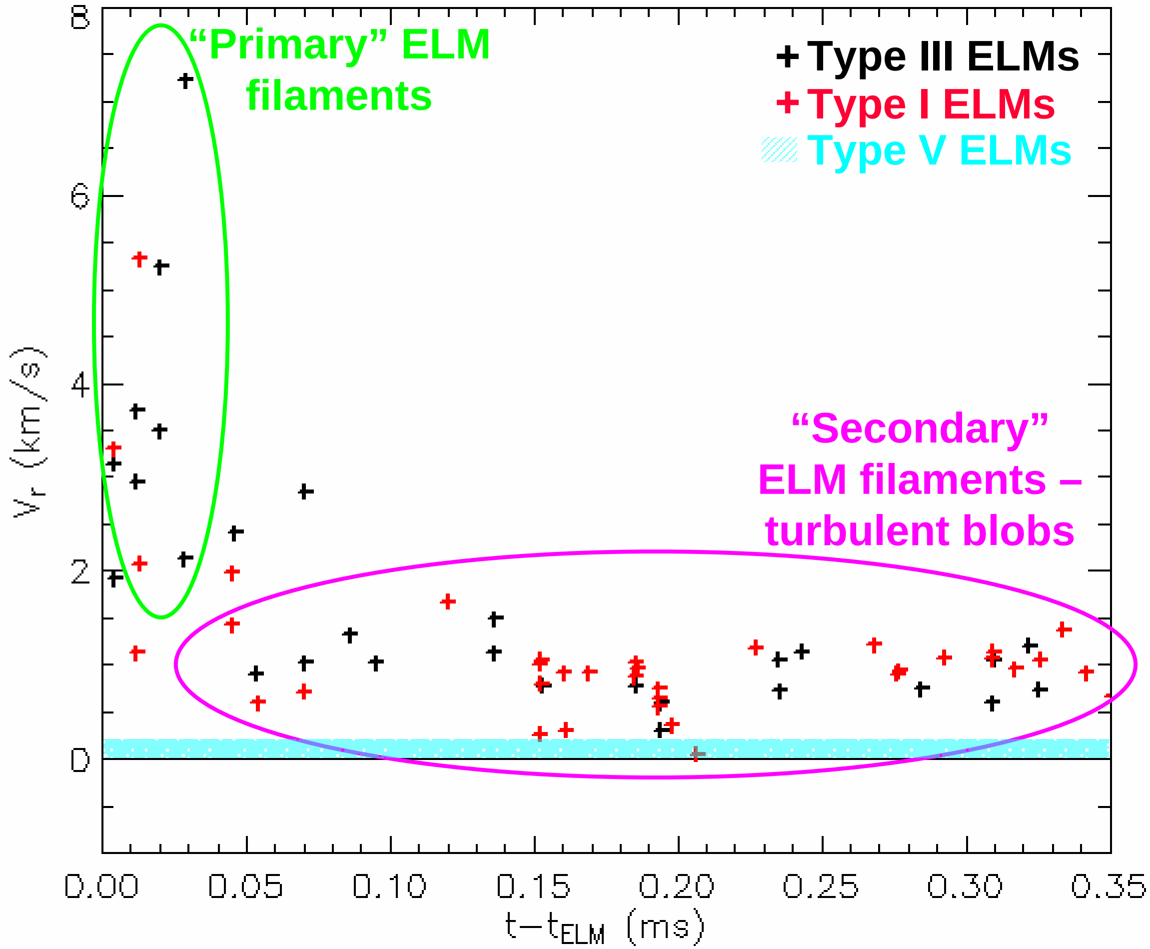
Type III ELM



Average of 19 Type III ELMs

ELM filamentation occurs within 30 μs of ELM onset

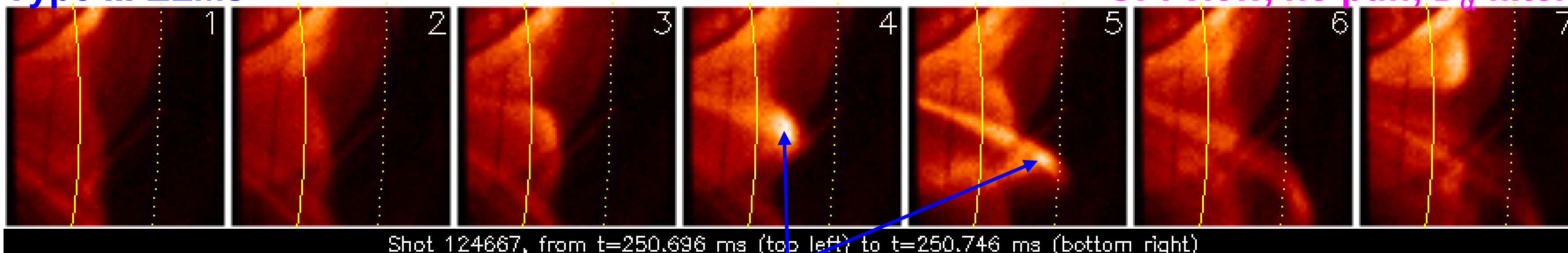
- **Primary ELM filaments** can be distinguished from turbulent "blob" filaments by their brightness, density and **radial velocity**. (See also slide #12.)
- **Secondary ELM filaments** have similar characteristics to turbulent blobs (v_r~1 km/s) and are presumably due to degraded edge confinement properties, like a temporary and local loss of the E_r well.



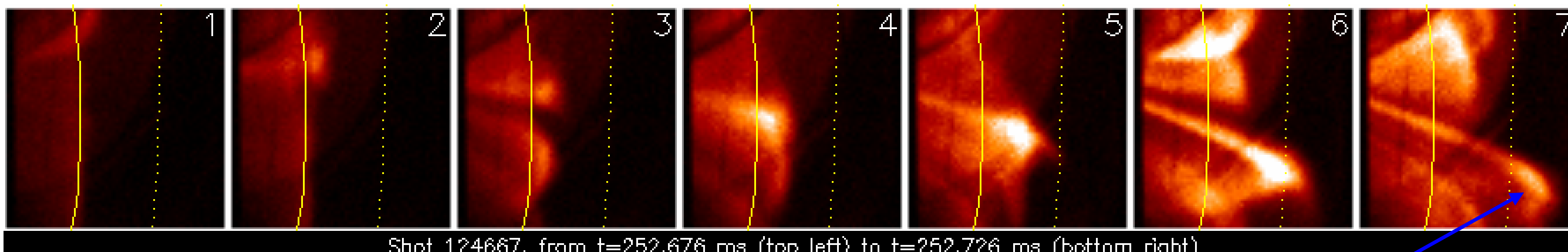
Filaments in 6 Type III ELMs and 6 Type I ELMs

Filament detachment – a non-linear, complex phenomena

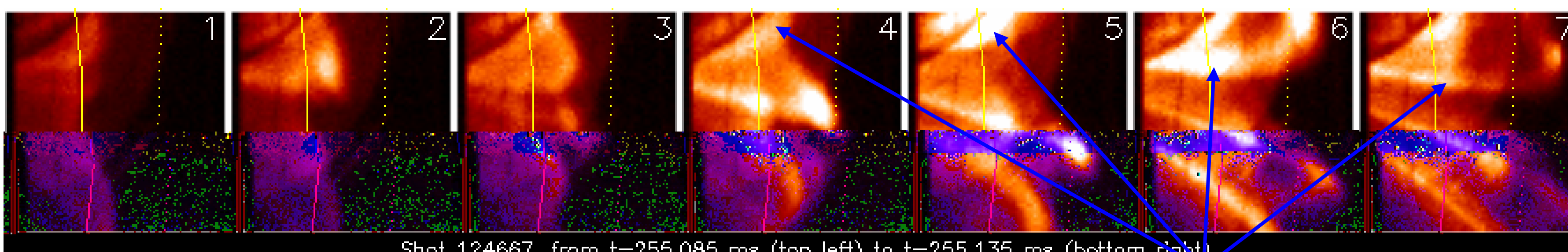
Type III ELMs **GPI view, no puff, D_α filter**



Filament detaches from mode structure



Filament propagates beyond shadow of antenna limiter (dotted line)

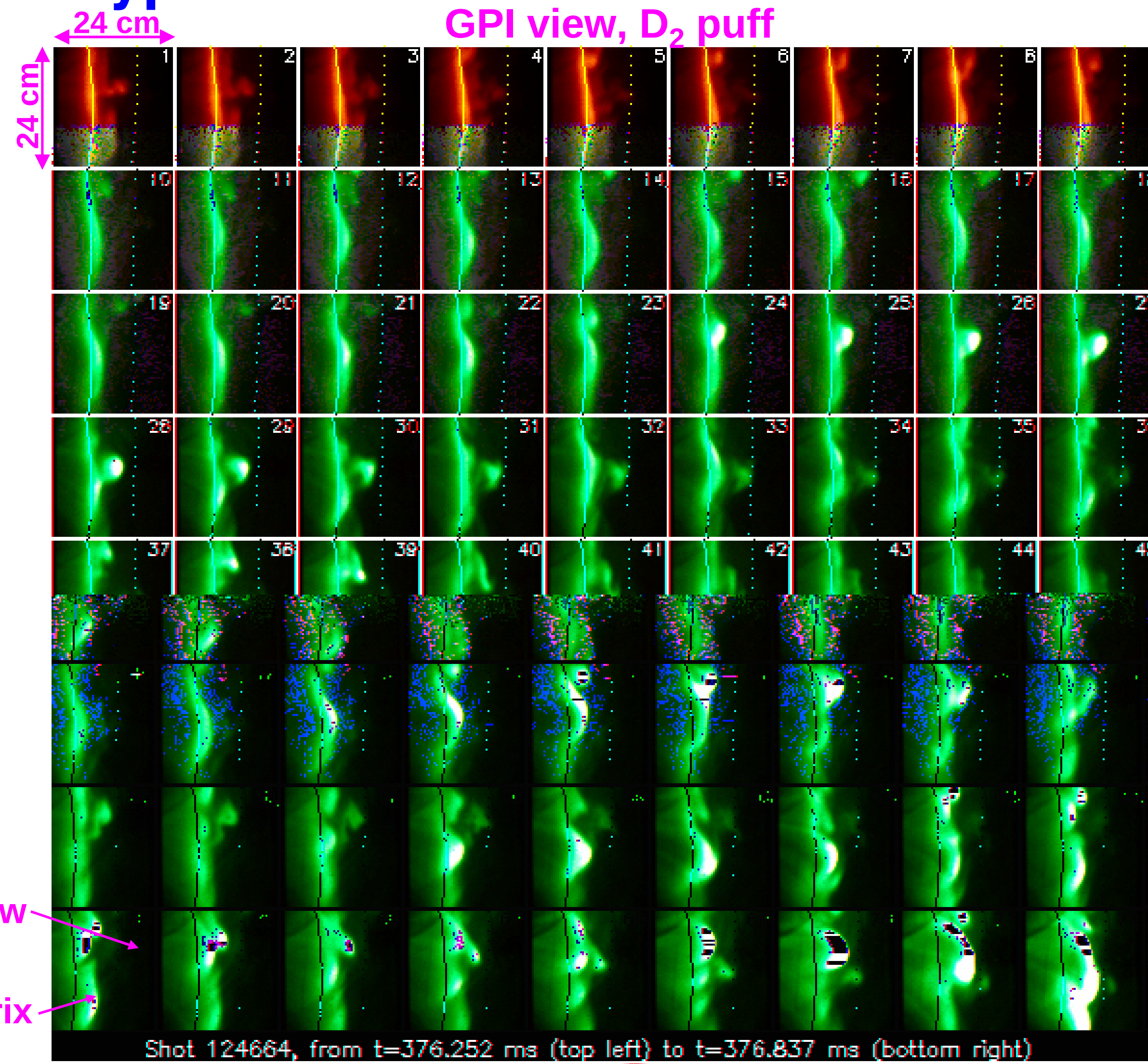


Interaction with plasma facing component follows poloidal movement of filament

Type I ELMs

Primary filament(s) not always present on GPI view for **Type I ELMs**

- Although Type I ELMs are similar to Type III ELMs, a primary filament is not always seen on the GPI view.
- Secondary filaments have same characteristics as those on Type III ELMs.

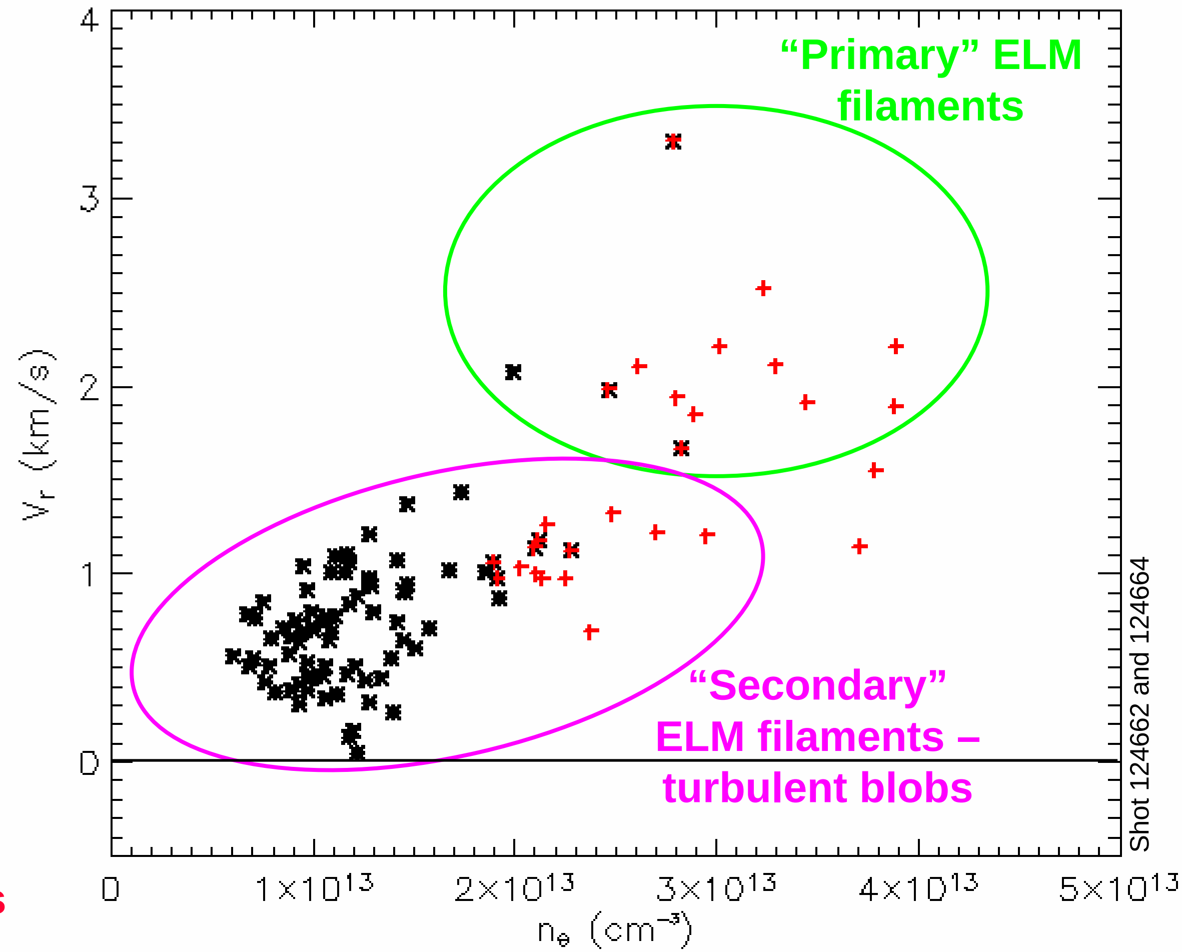


D_α filter
4 μs exposures
121212 frames/s

Radial velocities present continuum between primary and secondary (blob) filaments

Type I ELM

- The radial velocity of the filaments, both primary and secondary (blob), have a positive scaling with their density.
- The radial velocities present the same scaling characteristics, possibly due to the same ExB drive and associated physics.



Filament density

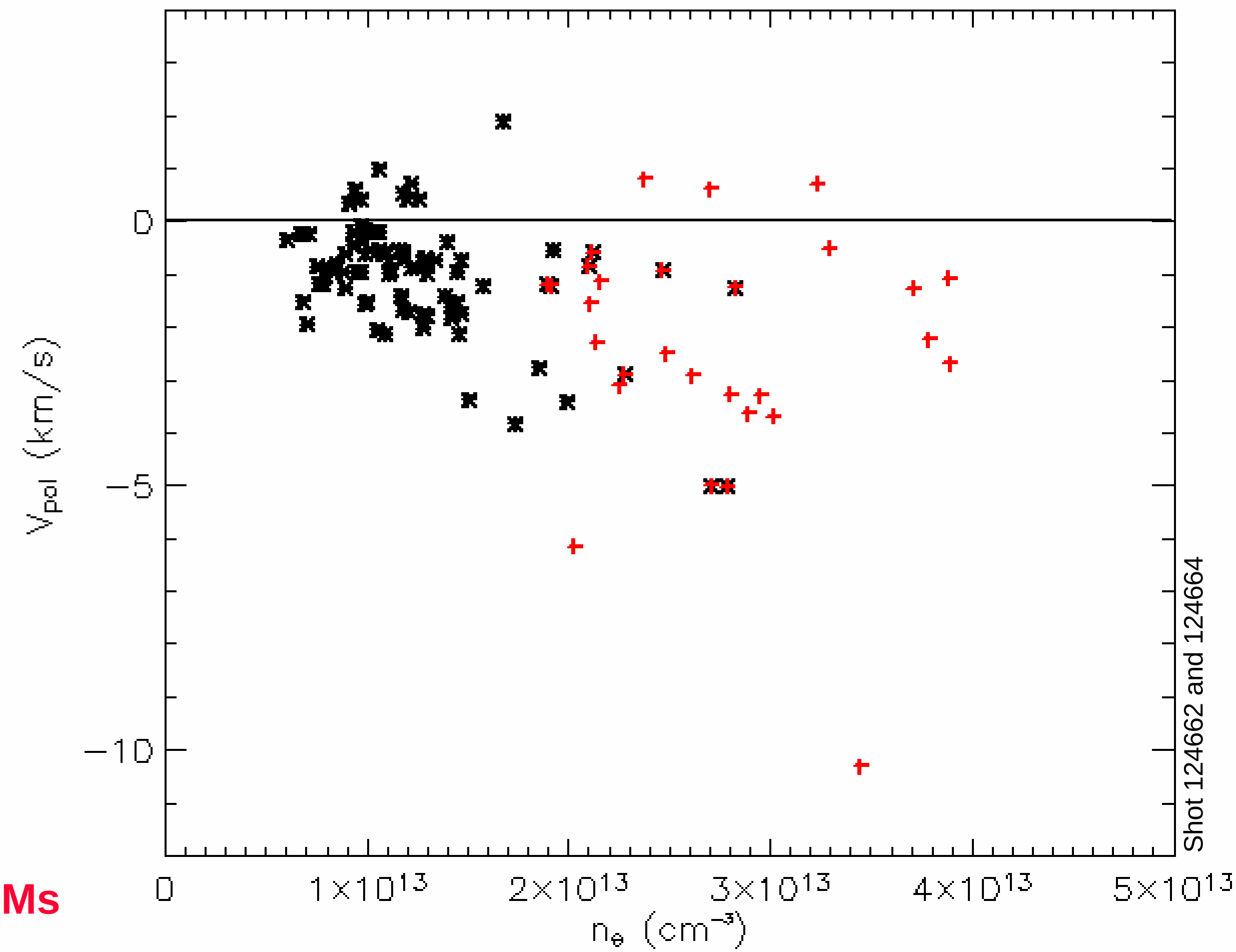
✱ All filaments, 6 ELMs

+ Bright filaments, 58 ELMs

Poloidal velocities are similar between primary and secondary (blob) filaments

Type I ELM

- Poloidal velocities and toroidal velocities are indistinguishable in the GPI field of view.
- Primary ELM filaments have a preponderance to rotate co-I_p and core plasma rotation.



⁕ All filaments, 6 ELMs

+ Bright filaments, 58 ELMs

Filament density

Evaluation of density (and temperature) within filament

Following work in J. R. Myra et al., Phys. Plasmas 13 (2006) #092509.

- The D_α image intensity (I_α) is given by:

$$I_\alpha = n_o\, A\, F(n_e,T_e)\, L$$

where	n_o	is the neutral deuterium density
	A	is the radiative decay rate
	$F(n_e,T_e)$	is the population ratio for the emitting energy levels, obtained from Degas2 modeling (D. Stotler, PPPL)
	L	is the line of sight integration length

- From the T_e and n_e profile in absence of filaments (Thomson scattering, B. LeBlanc, PPPL) $F(n_e,T_e)$ is evaluated together with $n_o\, A\, L = I_\alpha / F(n_e,T_e)$. The product ($n_o\, A\, L$) is assumed constant in time, even as filaments move by.
- Assuming filament convects plasma from its birth place as it moves in the scrape-off layer without parallel particle and energy losses then, within the filament, T_e is a function of n_e given by the pedestal profile:

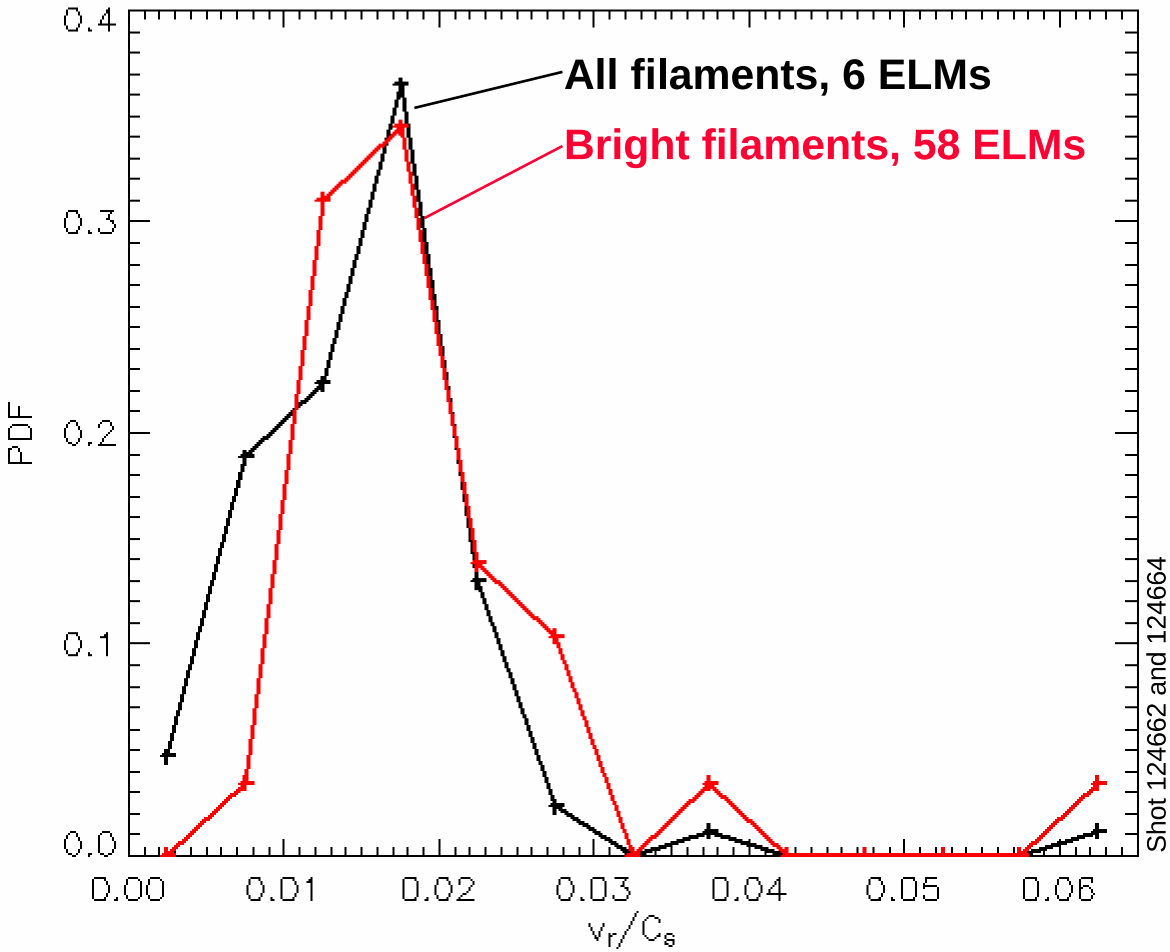
$$T_e = T_e(n_e)$$

- From the filament image intensity I_α, $F(n_e,T_e) = I_\alpha / (n_o\, A\, L)$, and with the "convection assumption" $T_e = T_e(n_e)$, this results in an unique pair of n_e and T_e values for the emitting filament.

Filaments show similar distribution respect to their normalized radial velocities

Type I ELM

- Values for density and temperature in filament are obtained (slide #14) corresponding to birth locations reaching the top of the pedestal.
- The mean radial velocities are ~2% of the ion sound speed for the plasma within the filament.



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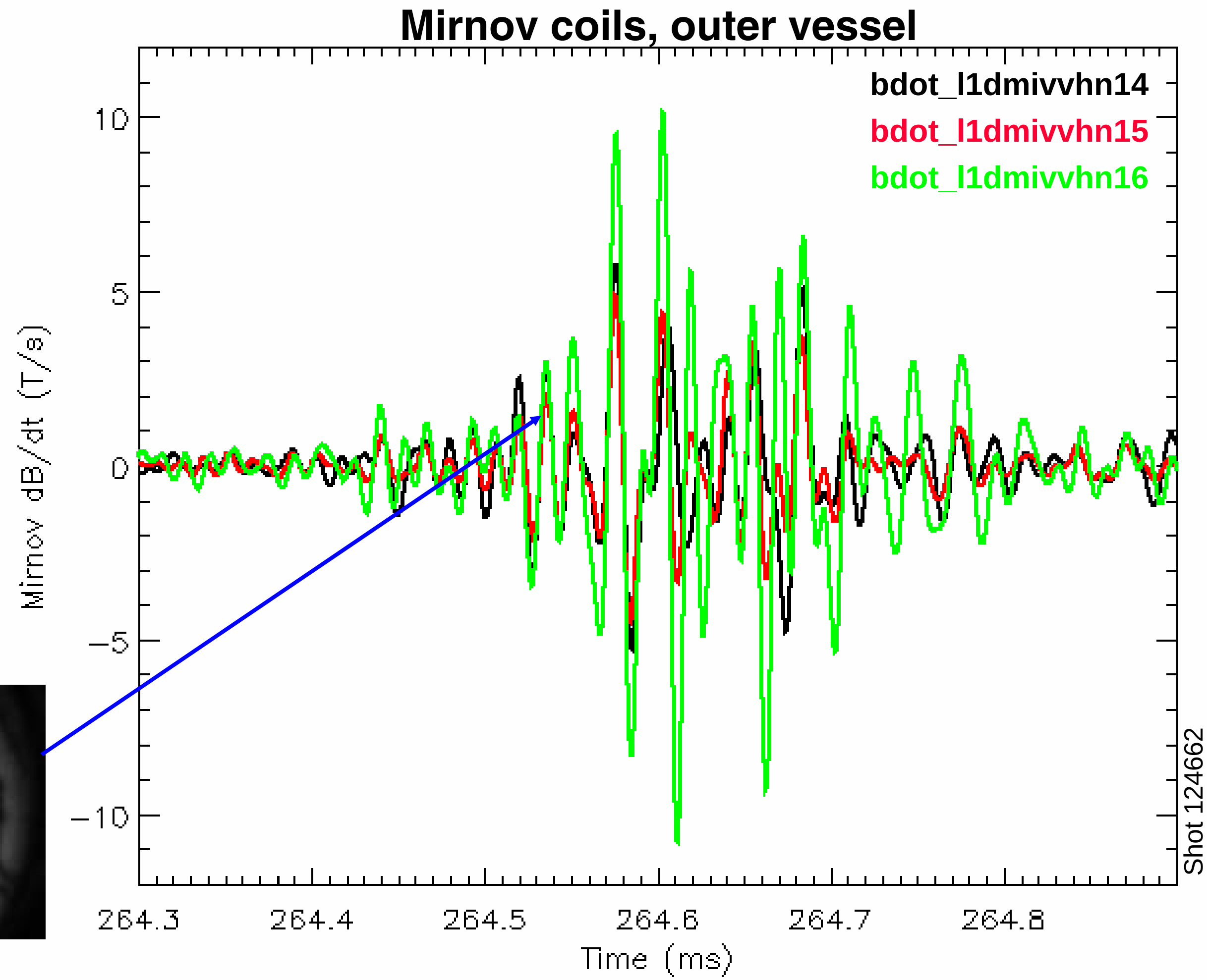
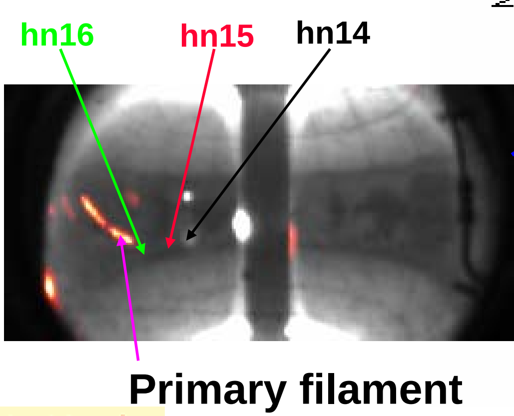
Primary ELM filaments do not show electro-magnetic signatures

Type I ELM

- Bdot signal does not show expected waveform for “approaching” current carrying filament.
- Absence of electro-magnetic signature imposes limit on current possible within filament to <500 Amp.
- Bdot coils ~12 cm away from limiter shadow.

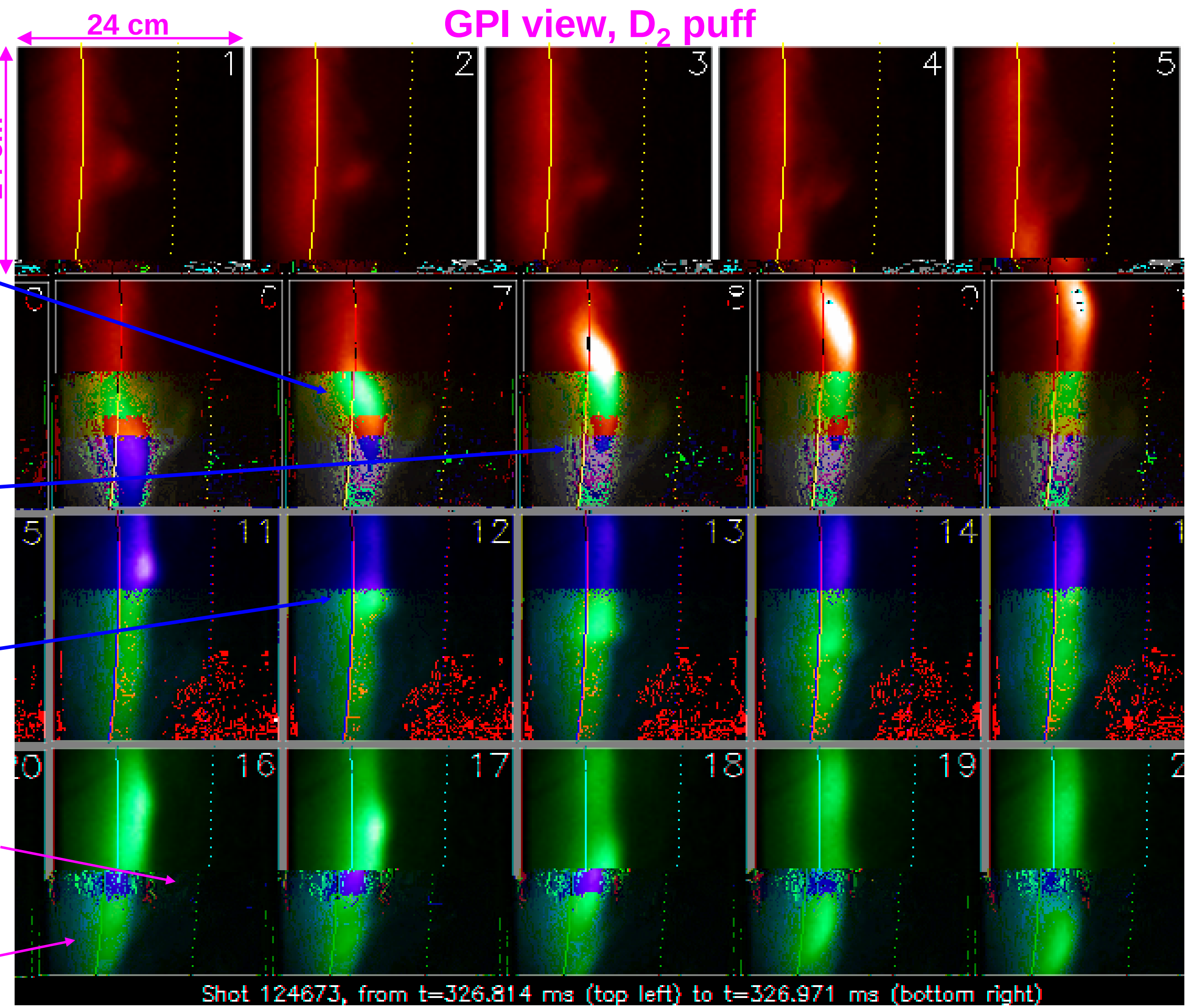




Type V ELMs

Primary filament in Type V ELM remains attached

- Primary filament consists of “lip” in flux surfaces that rotates poloidally/toroidally.
- Within a short time scale (~200 μs) T_e and n_e profiles are displaced outward, displacing the D_α emission region.
- Perturbed flux surface increases tubulence and generation of secondary filaments.



D_α filter
4 μs exposures
121212 frames/s

Type V ELM filament characteristics

- Well aligned with local magnetic field.
- Plasma within filament has similar T_e and n_e than pedestal plasma.
- Toroidal velocity: ~8 km/s (~0.9 kHz at R~1.45 m) **...counter I_P and plasma rotation**
- Radial velocity: $\leq$0.2 km/s
- Crossfield widths: ~12 cm poloidal, ~3-4 cm radial
- Current: ~400 A (~100 kA/m^2) **...co-I_P**
- Some ELMs show 2 filaments, separation might indicate n = 3-4. But... no full n = 3 or 4 structure seen on diagnostics (Mirnov array).
- Lifetime: 0.5 to 1 ms ...longer than the peeling-ballooning “detonation” time for NSTX.

R. Maingi et al., Phys. Plasmas 13 (2006) #092510

Small (Type V) ELM

n = 3-4 mode? or higher n mode? → Detonation (~0.1 ms) not (yet) seen, filament coalesce? → Long (0.5-1 ms) “stable” phase 1 or 2 filaments per ELM n = 3-4 apparent structure → **Soft** ELM crash

Enhanced transport

Movie clips

- (1) **Type I ELM**: Wide view – GPI view, D_2 puff.
- (2) **Type I ELMs**: Wide view – GPI view, D_2 puff.
- (3) **Type III ELM**: Wide view – GPI view, D_2 puff.
- (4) **Type III ELMs**: Wide view – GPI view, D_2 puff.
- (5) **Type V ELM**: Wide view – GPI view, D_2 puff.
- (6) **Type V ELMs**: GPI view, no puff.
- (7) L-mode: Wide view – GPI view, D_2 puff.
- (8) Ohmic, BEaP experiment: GPI view, D_2 puff.

Summary

- ELM filamentary structure is characterized by high density/temperature, high v_r, "primary" filaments and filaments originating in increased turbulence following the ELM, termed "secondary" filaments.
- Corollary: care should be placed in identification of ELM filaments when observing with limited spatial resolution diagnostics (like single point probe measurements).
- Type III ELMs show a higher number of primary filaments than Type I ELMs.
- Results are consistent plasma being convected by filaments from birth place in the pedestal without parallel particle and energy losses.
- Secondary filament activity has characteristics of temporary L-mode turbulence.
- In Type V ELMs the primary filaments do not detach, being much longer lived than those on Type I and Type III ELMs. General ELM characteristics are substantially different for Type V ELMs.