

Characterization of small, Type V edge-localized modes in the National Spherical Torus Experiment^{a)}

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There has been a substantial international research effort in the fusion community to identify tokamak operating regimes with either small or no periodic bursts of particles and power from the edge plasma, known as edge-localized modes (ELMs). While several candidate regimes have been presented in the literature, very little has been published on the characteristics of the small ELMs themselves. One such small ELM regime, also known as the Type V ELM regime, was recently identified in the National Spherical Torus Experiment [M. Ono, S. M. Kaye, Y.-K. M. Peng *et al.*, Nucl. Fusion **40**, 557 (2000)]. In this paper, the spatial and temporal structure of the Type V ELMs is presented, as measured by several different diagnostics. The composite picture of the Type V ELM is of an instability with one or two filaments that rotate toroidally at $\sim 5\text{--}10$ km/s, in the direction opposite to the plasma current and neutral beam injection. The toroidal extent of Type V ELMs is typically ~ 5 m, whereas the cross-field (radial) extent is typically ~ 10 cm (3 cm), yielding a portrait of an electromagnetic, ribbon-like perturbation aligned with the total magnetic field. The filaments comprising the Type V ELM appear to be destabilized near the top of the H-mode pedestal and drift radially outward as they rotate toroidally. After the filaments come in contact with the open field lines, the divertor plasma perturbations are qualitatively similar to other ELM types, albeit with only one or two filaments in the Type V ELM versus more filaments for Type I or Type III ELMs. Preliminary stability calculations eliminate pressure driven modes as the underlying instability for Type V ELMs, but more work is required to determine if current driven modes are responsible for destabilization. © 2006 American Institute of Physics.

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I. INTRODUCTION

Performance projections for the International Thermonuclear Experimental Reactor (ITER) have highlighted the correlation between performance of the burning plasma core and the plasma temperature at the top of the H-mode pedestal. Studies examining many devices have shown^{1,2} that the highest pedestal temperature occurs at low pedestal collisionality, a region that is typically accompanied by large edge-localized modes (ELMs). Large or Type I ELMs result in a periodic exhaust of a substantial portion of the plasma stored

energy to the plasma-facing components (PFCs). Localized melting of the PFCs would occur in ITER if the ELM energy deposition were to exceed the PFC heat handling capability, which would effectively impose a limit on the PFC lifetime.³

Accordingly, the quest for high confinement regimes with no or small ELMs has received a high priority in the fusion research community. Several promising regimes have been identified that maintain the H-mode transport barrier: small, Type II ELMs from shaping⁴⁻⁶ or high density operation^{7,8}; grassy ELMs⁹; the Enhanced D_α H-mode¹⁰ and High Recycling Steady H mode¹¹; the Quiescent H mode¹²; the small, Type V ELMs¹³; and the suppression of large ELMs with externally imposed edge resonant magnetic perturbations.¹⁴ Advances in the understanding of the structure¹⁵⁻²³ of the ELMs and modeling of the underlying

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magnetohydrodynamic (MHD) instabilities^{24–31} have accompanied the progress in the identification of small ELM regimes.

ELM control research is an important part of the program in the National Spherical Torus Experiment (NSTX),^{32,33} owing partly to the importance for ITER described above and partly to the needs of long pulse operation. Spherical tori such as NSTX have limited space for an Ohmic transformer, leading to lower volt-second capabilities than higher aspect ratio tokamaks. Large ELMs can penetrate substantially³⁴ into the core of NSTX, causing an increase in plasma resistivity, an increase in the Ohmic flux consumption rate, and a decrease in the pulse length.

In this paper we discuss, for the first time, the spatial and temporal structure of small ELMs as interpreted through diagnostic signatures in NSTX. The remainder of this paper is organized as follows. In Sec. II, a comparison of flux consumption with small and large ELMs is presented. In Sec. III, the characteristics of the small ELMs as measured by several different diagnostics is presented. The results of preliminary stability calculations and implications of the diagnostic observations to certain aspects of stability theory are discussed in Sec. IV, followed by conclusions in Sec. V.

II. FLUX CONSUMPTION AND PULSE LENGTH WITH SMALL ELMs

One of the byproducts of a small aspect ratio tokamak design is the limited space available for an Ohmic transformer, which is used to inductively drive the plasma current. Consequently spherical tori such as NSTX typically possess between 10% and 20% of the inductive volt-second capability of higher aspect ratio tokamaks with comparable minor radius, such as DIII-D.³⁵ This lower volt-second capability means that the achievement of long pulse discharges requires the optimization of flux consumption, including the avoidance of large transient events such as Type I ELMs.

Large Type I ELMs in NSTX are often accompanied³⁴ by a rapid cold pulse that can propagate to the magnetic axis, reducing electron temperature and increasing plasma resistivity. To maintain constant plasma current, the loop voltage is transiently increased by the plasma control system, leading to more rapid Ohmic flux consumption. An example is used to illustrate this point. A comparison of the flux consumption between a discharge with Type I ELMs and small Type V ELMs is shown in Fig. 1. Panel (c) shows that the Ohmic coil current ramp rate began to increase at the onset of large ELMs in panel (h) for #117 425. Although #117 425 ended prematurely due to the onset of a locked mode, a plasma current (I_p) flat-top out to $t=0.8$ s is projected from the flux consumption rate prior to the locked mode. In contrast, the discharge with small ELMs maintained an I_p flat-top until $t\sim 0.97$ s, which was limited by ramp-down of the toroidal field and projected to last for another 100 ms if the toroidal field were extended, i.e., 33% longer than the discharge with large ELMs. In addition, #117 424 maintained good energy confinement relative to the global ITER 97-L scaling law³⁶ [panel (f)]. A small shape change was apparently responsible³⁷ for the difference in performance: starting from

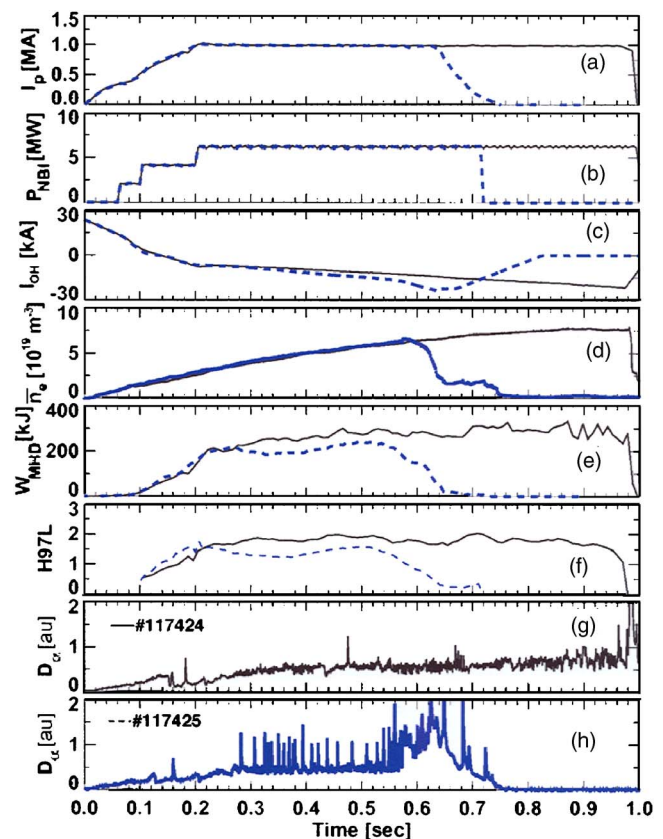


FIG. 1. (Color online) An illustration of the effect of the ELM size on pulse length: (a) plasma current (I_p); (b) neutral beam injected power (P_{NBI}); (c) current in the Ohmic transformer (I_{OH}); (d) line-average density from interferometry (n_e); (e) plasma stored energy from equilibrium reconstructions (W_{MHD}); (f) confinement time relative to the ITER 97-L global scaling law; (g) lower divertor D_α emission for small ELM discharge; and (h) lower divertor D_α emission for large ELM discharge. The solid (black) discharge has only small, Type V ELMs, whereas the dashed (blue) discharge contains large, Type I ELMs.

a balanced double null, the upper X point was pulled upward by about 4 cm in the discharge with small ELMs, such that the lower X point became the dominant one. This movement corresponds to a 0.5 cm difference of the two separatrices at the outer midplane, i.e., $\Delta_r^{sep} = -0.5$ cm. This shape dependence is consistent with the characteristics observed¹³ for Type V ELMs at lower triangularity ($\delta \sim 0.4$), although the magnitude of the increase of the upper X-point height required for small ELMs appears to be reduced at high δ .

The example shown here is not unique: at least a half dozen small and large ELM comparison discharges have been obtained in NSTX, with similar results. Thus, it is clear that the small ELMs are an important element in the achievement of a longer pulse length in NSTX. We now turn to discuss the structure of small ELMs from several diagnostics.

III. SPATIAL AND TEMPORAL STRUCTURE OF TYPE V ELMs

The interpretation of boundary phenomena is enabled by a set of diagnostics in NSTX that has been steadily growing since machine commissioning. The diagnostics discussed in

TABLE I. Diagnostic information relevant to small ELM structure and evolution.

Diagnostic	Quantity measured	Location	Specific information
Main plasma fast visible camera	Unfiltered visible light	Wide angle view inside most of the vacuum vessel	Snapshot of filament toroidal and poloidal extent
Ultra-soft X-ray arrays	USXR emission with filter dependent T_e^{\min}	Single poloidal plane, with plasma emission mainly from the edge (Fig. 3)	<ul style="list-style-type: none"> • Duration • T_e at radial origin of instability • Poloidal propagation speed and direction
Interferometers	Line integrated electron density n_e	Four toroidal chords (Fig. 5)	<ul style="list-style-type: none"> • Number of filaments • Toroidal propagation speed and direction • Excess electron density in filaments $\delta n_e^{\text{filament}}$ • Filament size L_{\perp}
In-vessel magnetics	Perturbed magnetic field at the wall δB_z^{wall}	Toroidal Mirnov array	<ul style="list-style-type: none"> • Toroidal mode number n • Duration • Toroidal propagation speed and direction • Excess current in filaments δI_z^{ELM}
Gas puff imaging	Visible light filtered for D_{α}	Outer midplane at one toroidal location, with plasma emission near the separatrix	<ul style="list-style-type: none"> • Radial/vertical size • Radial/vertical propagation speed and direction
Divertor fast visible camera	Visible light filtered for C-II	Lower X point and SOL region	<ul style="list-style-type: none"> • Number of filaments in SOL • Poloidal propagation speed and direction in the SOL

this section include (1) a fast framing wide-angle view visible camera; (2) a set of four ultrasoft x-ray (USXR) arrays; (3) several toroidally viewing interferometer chords; (4) an in-vessel toroidal Mirnov array; (5) a gas-puff imaging diagnostic; and (6) a fast framing visible camera with a tangential divertor view. Table I lists details of these diagnostics and the type of information provided by each on small ELM dynamics. Other boundary diagnostics not discussed in this paper but that provide additional small ELM data include charge exchange recombination spectroscopy (CHERS) with sub-cm spatial resolution at the edge; a passive edge rotation diagnostic; several fast framing visible cameras with a choice of bandpass filters; several infrared cameras; several one-dimensional (1-D) CCD cameras for filtered, visible light detection; a set of fast time response filter scopes; a fast reciprocating probe; and tile-imbedded Langmuir probes.

For the reader's convenience, we briefly summarize the basic picture of the Type V ELM from these diagnostics before going into the detailed discussion of each diagnostic signature. The Type V ELM appears as a single or sometimes

double filamentary helical formation aligned with the magnetic field, first appearing on the closed field lines near the top of the H-mode pedestal, and propagating toroidally in the counter- I_p direction. The filaments drift radially outward as they move toroidally, eventually appearing on visible camera images of the entire plasma and the divertor region. A summary of the observations for each diagnostic is included at the top of each subsection below for ease of reading.

A. Wide-angle fast-framing visible camera signature

The characteristic filamentary structure of a Type V ELM is perhaps best displayed with a midplane, fast-framing visible camera³⁸ using a wide-angle lens. A comparison of several different ELM types imaged with this camera was recently published¹⁹; here, we will expand on the helicity of the filament. The basic conclusion from the image is that the filament is well aligned with the total magnetic field at the edge.

Figure 2(a) shows an image of a Type V ELM filament

captured with the fast camera in a lower-single null configuration (which, nevertheless, has a second X point inside the vacuum vessel). The original image was unfiltered with a $10 \mu\text{s}$ integration time, and time slice subtraction from a nearby frame was used for contrast enhancement to highlight the ELM perturbation. Note that the impact of the ELM on the lower divertor light was not determined because the lower divertor light was saturated in both the original and background time slices. Three different open field lines corresponding to normalized poloidal flux values (ψ_N) of 1.05, 1.20, and 1.49 are overlaid for comparison in panel (a). The first field line is between the first and second X points, the second is outside the second X point, and the third is far outside the second X point and close to the radius of the limiter, i.e., the rf antenna.

This comparison suggests that the visible camera light originates mainly from the open field lines far outside of the second magnetic X point, as no helical light structure is observed around the center stack, as shown for the $\psi_N=1.05$ field line, and the helicity of the field line at $\psi_N=1.20$ does not quite match the image. Thus, it is apparent that a portion of the filament, which we will subsequently show to originate from the closed field lines, survives until it comes into contact with the nearest limiting surface at the midplane. The toroidal length of the filament from point A to point B in panel (2a) is ~ 6 m or about two-thirds of the toroidal circumference, largely independent of which the field line is used for the estimate. For comparison, panel (2b) shows a Type I ELM that was comprised of many independent filaments. We can state, albeit with limited statistics, that the small ELMs imaged with this camera are always composed of one or two filaments, i.e., far fewer than the number of filaments typically observed in large ELMs.

B. Ultra-soft x-ray signature

The USXR arrays in NSTX (Fig. 3) measure line-integrated plasma emission with intensity $I \propto n_{e,\text{edge}}^2 T_{e,\text{edge}}^{0.5}$ when used in conjunction with Be filters of thickness between 3 and $10 \mu\text{m}$.³⁹ Specifically, the 5 and $10 \mu\text{m}$ filters used for ELM studies reject emission below 400 and 600 eV, respectively, corresponding to T_e cutoffs of about 130 and 200 eV, respectively, for a Maxwellian distribution. In comparison, the NSTX H-mode pedestal T_e ranges¹⁹ from 100 to 300 eV, i.e., the USXR emission is indeed dominated by the pedestal plasma.

The variation of the filter thickness was used to localize the filament origin to the vicinity of the top of the H-mode pedestal in NSTX. To be specific, only a small fraction of the number of filaments observed with the $5 \mu\text{m}$ filter were observed with the $10 \mu\text{m}$ filter for identically programmed discharges, which suggests that nearly all the filaments originated where the T_e value was between 130 and 200 eV, i.e., the T_e range at the top of the NSTX H-mode pedestal.

From the USXR data, a composite picture of the poloidal component of motion of the filaments comprising Type V ELMs can be ascertained. The filaments enter the field of view of the USXR arrays in the lower divertor region, as indicated by the yellow circle in Fig. 3, and propagate with

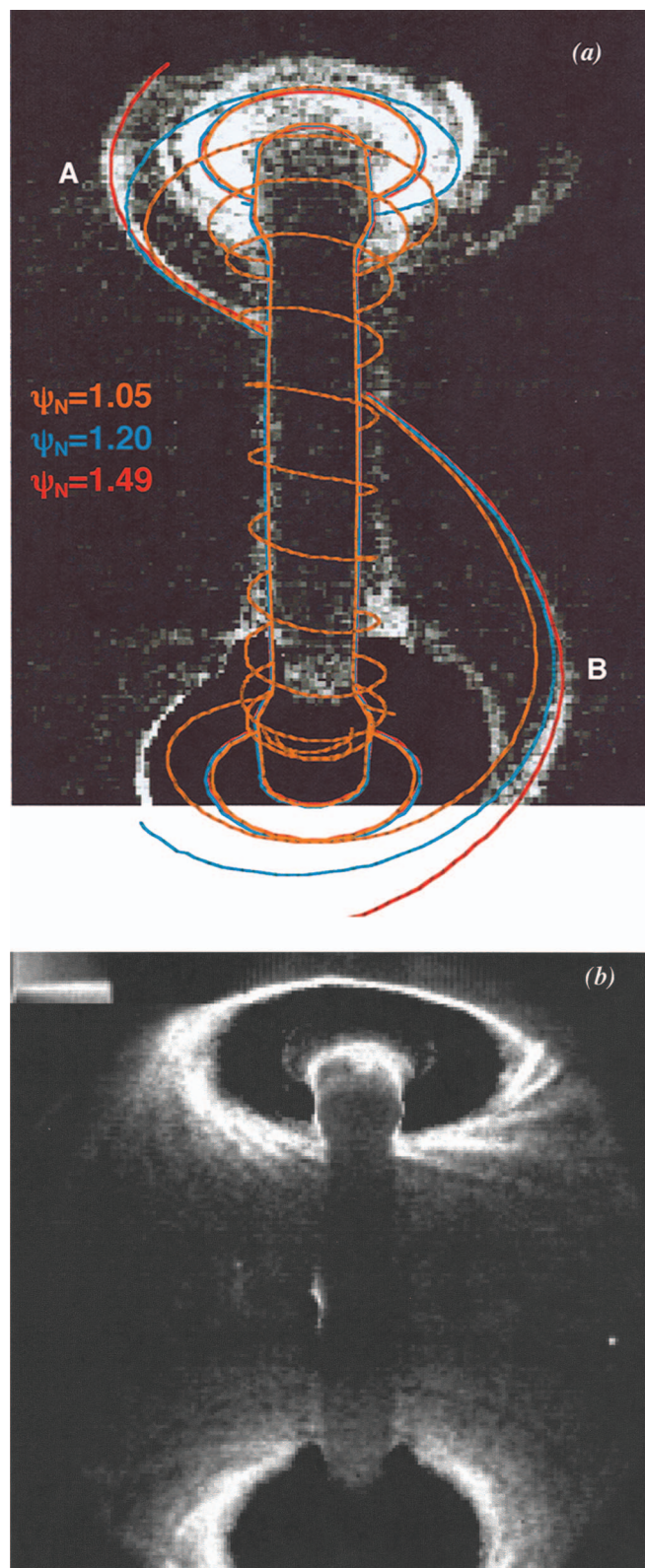


FIG. 2. (Color) Visible camera pictures in unfiltered light of a single-filament Type V ELM with a wide-angle midplane view in panel (a), as compared with a higher toroidal mode number perturbation from a Type I ELM in panel (b). The image in (a) is from #113024, using the frame at 0.52 s after subtracting a background frame from $t=0.515$ s. The NSTX center stack hardware and a set of edge field lines at the $\psi_N=1.05$, 1.20, and 1.49 surfaces are overlaid in panel (a); the distortion caused by the wide-angle lens was simulated in overlaying the hardware and field line traces onto the camera image. Panel (b) is from #112581, using the frame at 0.500 s after subtracting a background frame from $t=0.495$ s.

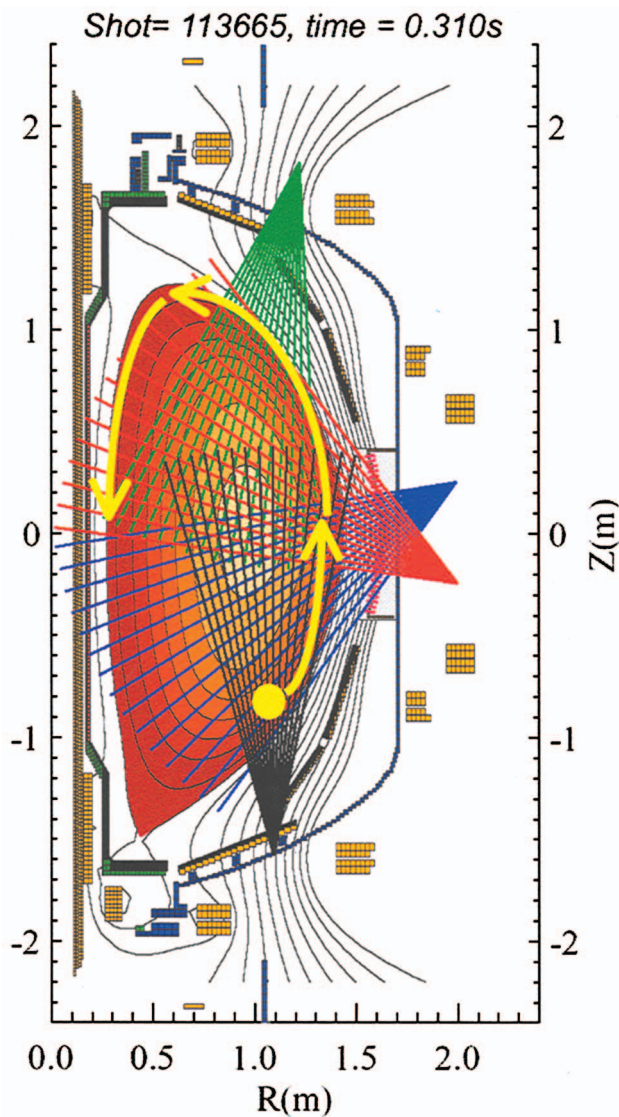


FIG. 3. (Color) View chords of the ultrasoft X-ray (USXR) arrays in NSTX. The yellow circle shows the typical poloidal location where the filamentary perturbations associated with Type V ELMs entered the field of view of the USXR arrays. All arrays are in the same (R, Z) plane. The filaments usually propagated poloidally upward away from the lower X point, as indicated by the yellow arrows.

an apparent poloidal component upward toward the outer midplane and then the top of the machine. As will be shown in subsequent sections, the filament is elongated along the field lines and its motion is more likely toroidal, yielding the observed apparent poloidal propagation observed in the USXR at this single toroidal location. For certain long-lived filaments, propagation on the high field side region down the center stack may have been observed. We now illustrate the detailed motion of a single filament in each of the USXR arrays.

Data from a Type V ELM with the $5\ \mu\text{m}$ filter on each array are shown in Fig. 4. The bright bands indicate emission above the background. The signature and movement of the filament is indicated with the arrows in each panel. We begin our discussion with the bottom panel and move upward in the apparent direction of filament motion. The filament mo-

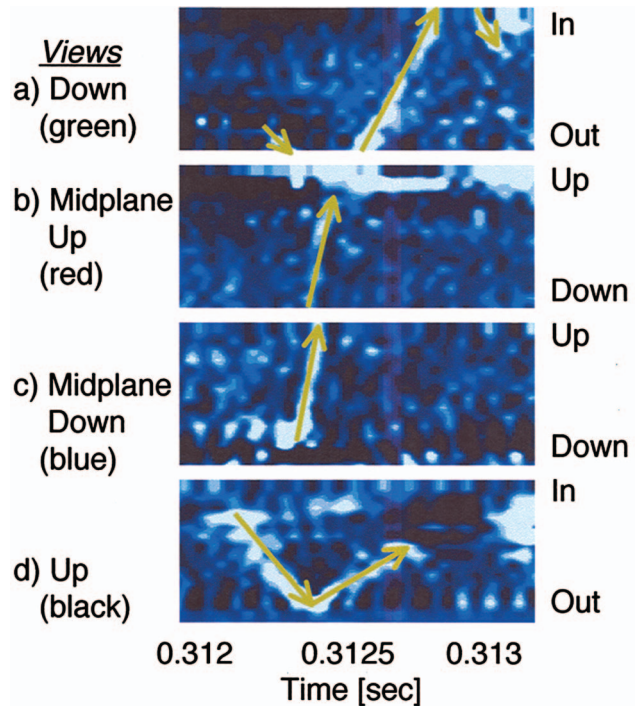


FIG. 4. (Color) Signature of Type V ELM on USXR arrays, using a $5\ \mu\text{m}$ Be filter: (a) top-mounted, downward viewing array, (b) midplane-mounted, upward viewing array, (c) midplane-mounted downward viewing array, and (d) bottom-mounted upward viewing array. The colors in the caption correspond to the colored arrays shown in Fig. 3. Data were acquired at 190 kHz and were contrast enhanced to emphasize the filament movement.

tion in panel (d) traces the shape of the letter “V” on the upward viewing array (black channels in Fig. 3) starting at $t \sim 0.3122$ s. The left side of the “V” means that the radius of the chord on which the filament appeared was increasing, as shown schematically by the yellow arrow in Fig. 3. The right side of the “V” means that the radius of the chord on which the filament appeared was decreasing. Thus, the filament propagated radially outward for ~ 0.2 ms, and then radially inward for another ~ 0.3 ms. Figure 4, panel (a) shows a similar “V” shape for the downward-viewing array (green channels in Fig. 3), except that the bottom tip of the “V” was cut off. The bottom of the “V” was truncated when the filament temporarily disappeared from the field-of-view near the outer midplane, because the chord coverage did not extend all the way to outer midplane (see Fig. 3). Moreover, panel (a) shows the left hand-side of a new “V” pattern (the right-most arrow) adjacent to the normal “V.” This new “V” shape did not connect to the other “V” shape at the top of the panel because the filament moved around the top of the plasma, again outside the field of view of the downward-viewing array. Panels (b) and (c) show the filament propagated upward from the lower divertor region to the top of the machine (red and blue channels in Fig. 3). Note the existence of a possible precursor mode in panel (c) just before the filament movement; this mode was not always present prior to filament propagation in all Type V ELMs. We also note that while the filament lifetime was ~ 0.8 – 1 ms in Fig. 4, it was typically 0.2 – 0.4 ms for most other Type V ELMs.

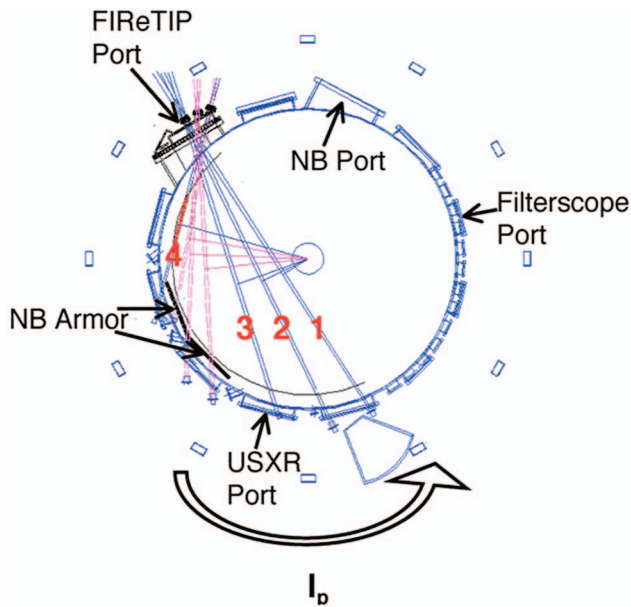


FIG. 5. (Color) Plan view of NSTX, showing the location of Far-Infrared Tangential Interferometer chords. The toroidal location of the USXR arrays and filter scopes for D_{α} measurements are also indicated.

C. Interferometer signature

The plasma electron density along several different paths is measured with the far infrared tangential interferometry and polarimetry (FIRETIP) system.⁴⁰ Figure 5 shows a plan view of the NSTX, along with the line of sight of four interferometer chords and the toroidal location of several other diagnostics and hardware. Note, in particular, that the intersection of chord #3 and the edge plasma occurs very close to the USXR diagnostic port, allowing verification that the same filament is being imaged by these two diagnostics. The excess density in the filaments above the background plasma density, and the toroidal rotation of the filaments are clearly observed on the FIRETIP chords. Given the rotation speed, an estimate of the filament toroidal length can be obtained. Finally the filament size perpendicular to the magnetic field along a flux surface can be estimated by assuming that the filament is aligned with the total magnetic field, as shown by the visible camera image in Fig. 2.

We now summarize the observations from the interferometer analysis: (1) the filaments rotate counter to the plasma current with speeds between 5 and 15 km/s; (2) the half-width of the filaments normal to the total field along the same flux surface ranges between 6 and 18 cm; and (3) about 60% of the Type V ELMs are comprised of single filaments, whereas the rest are mostly comprised of two separate filaments. The supporting data for each of these points is discussed later.

The filament shown in Fig. 4 is clearly observed as a density perturbation on the interferometers in Fig. 6. Panels (a) and (b) show the filament on a lower divertor channel and a midplane channel of the midplane-mounted downward viewing USXR array of Panel (b). Note that an excess density perturbation was observed propagating from the FIRETIP channel 1 \rightarrow 2 \rightarrow 3 from $t=0.31234$ to 0.3125 s;

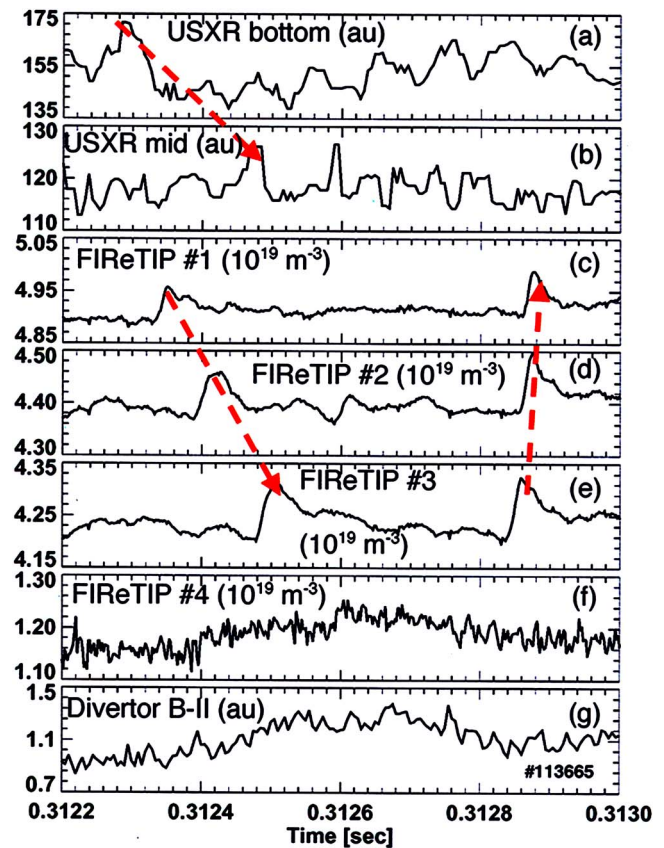


FIG. 6. (Color online) Toroidal propagation of Type V ELM observed in interferometer channels. (a) USXR channel viewing lower divertor (hup_02), (b) USXR channel viewing midplane (hup_15), (c) FIRETIP channel #1, (d) FIRETIP channel #2, (e) FIRETIP channel #3, (f) FIRETIP channel #4, and (g) lower divertor B-II line emission. The time delay of the filamentary perturbation between interferometer chords is used to estimate the ELM toroidal rotation speed, and the duration along a single chord indicates toroidal size.

the timing of the disturbance on channel 3 occurred just after the peak in panel (b) of Fig. 6, confirming that the same filament was observed. A strong perturbation was not observed on chord #4 in panel (f), indicating that the filament had a finite radial extent and had not at that time drifted out to the chord #4 tangency radius of $R=1.50$ m. Based on the known spacing between the interferometer chords at the plasma edge at $R \sim 1.4$ m, the toroidal rotation speed of the filament was between -5 and -7 km/s. Here we use the negative sign for the rotation speed because the filament rotation was in the direction opposite the plasma current, and opposite to the neutral beam momentum input direction. For reference, the measured fully stripped carbon rotation velocity near the top of the H-mode pedestal was typically ~ 10 – 20 km/s from the CHERS diagnostic in similar discharges, including the one with multiple filaments in Fig. 7 (see the following discussion). Another perturbation is seen propagating from channel 3 \rightarrow 2 \rightarrow 1 from 0.31286 – 0.31288 s in Fig. 6, apparently close to the interferometer port. From the known spacing between chords at the plasma edge, the toroidal rotation velocity is computed between -8 and -10 km/s, and it is probable that the same filament caused both perturbations.

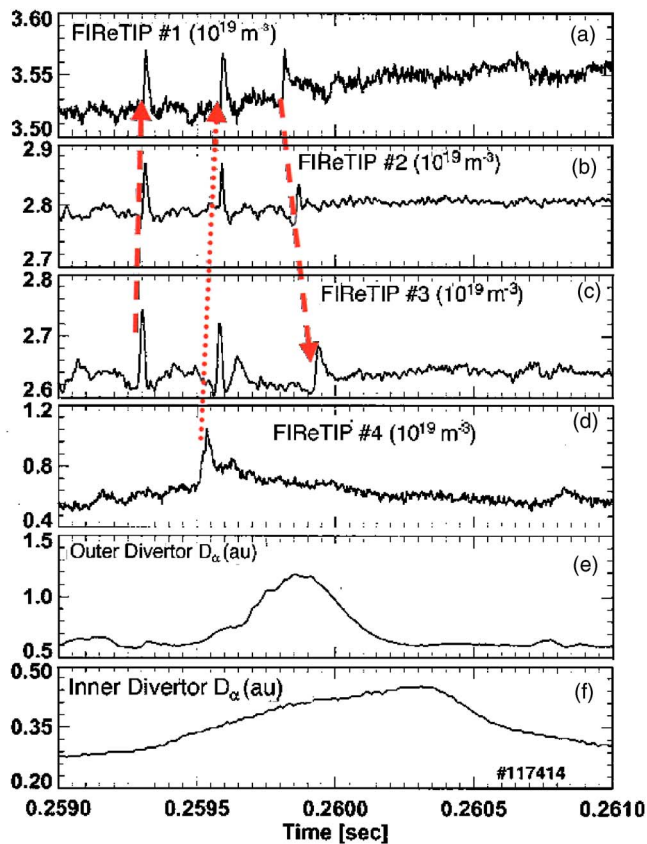


FIG. 7. (Color online) Toroidal propagation of Type V ELM observed in interferometer channels with multiple simultaneous filaments. (a) FIReTIP channel #1, (b) FIReTIP channel #2, (c) FIReTIP channel #3, (d) FIReTIP channel #4, and (e) lower, outboard divertor D_α line emission at $R = 0.79$ m, and (f) lower, inboard divertor D_α line emission at $R = 0.33$ m.

An estimate of the filament toroidal extent at the outer midplane can be obtained from the product of the width of the perturbation across each interferometer chord and the rotation speed between chords computed above; note that the 4 cm finite spot size of the FIReTIP beam is taken into account. Note that this toroidal extent is not the full length of ~ 5 – 6 m shown in Fig. 2, but rather a measure of the size of the perturbation normal to the total magnetic field along a flux surface at the outer midplane. Assuming that the filament is aligned with the magnetic field, the relation between the toroidal extent and the size normal to the field is given by the local magnetic field pitch. Using this technique, the toroidal extent at the midplane (L_ϕ) is estimated at between 18 and 30 cm for the filament in Fig. 6. The filament width perpendicular to the magnetic field along a flux surface (L_\perp) is then between 10 and 16 cm, obtained by multiplying the toroidal length by the sine of the field line pitch angle $\sim 35^\circ$. Finally, the vertical extent of the filament at the midplane (L_z) is estimated as between 13 and 20 cm, obtained by multiplying the toroidal length by the tangent of the field line pitch angle. The size and speed characteristics of the filament in Fig. 6 are summarized in Table II. An examination of several Type V ELMs yields a range of toroidal propagation speeds between -5 and -15 km/s, and a range of perpendicular widths between 6 and 18 cm. Statistical averages of toroidal speed and lengths from \sim one dozen filaments is

TABLE II. Characteristic size (half-width) and velocity of a single Type V ELM filament observed in the FIReTIP channels for the filament shown in Fig. 6, from discharge #113665. Toroidal rotation velocity (v_ϕ) was computed between the FIReTIP channel in question and the nearest one in the counterclockwise direction shown in Fig. 5. The toroidal (L_ϕ), perpendicular along a flux surface (L_\perp) and vertical lengths (L_z) are estimated as the filament passes through the outer midplane.

Channel number	Peak time (ms)	Width (ms)	v_ϕ (km/sec)	L_ϕ (m)	L_\perp (m)	L_z (m)
1 (far) ^a	312.346	0.039	—	0.18	0.10	0.12
2 (far)	312.425	0.039	-5.5	0.18	0.10	0.12
3 (far)	312.508	0.037	-6.3	0.20	0.11	0.14
3 (near)	312.861	0.039	-7.3	0.25	0.14	0.17
2 (near)	312.874	0.032	-9.8	0.28	0.16	0.20
1 (near) ^a	312.874	0.028	—	0.25	0.14	0.15

^aThe characteristics of the filament observed in the signals from channel 1 [far (near)] were computed using the channel 2 [far (near)] rotation speeds. Hear, “near,” and “far” refer to whether the filament is passing through the edge plasma close to the FIReTIP port or nearly 180° away (see Fig. 5).

displayed in Table III. Thus the filaments are elongated toroidally and poloidally relative to a plausible radial dimension of several cm, and can be thought of more as a ribbon or sheet than a cylinder, bent into a helical shape. Note that a modest acceleration of the filaments as they approach the FIReTIP port, e.g., from -6 km/s to -10 km/s, as displayed for a single filament in Table II, is commonly observed.

Multiple filaments are sometimes observed simultaneously during Type V ELMs. An example of the signatures of multiple filaments is shown in the FIReTIP data in Fig. 7. A perturbation propagating from channels $3 \rightarrow 2 \rightarrow 1$ was observed at $t = 0.2593$ s (dashed arrow), followed by another one at $t = 0.2595$ s (dotted arrow). A third perturbation propagating from channels $1 \rightarrow 2 \rightarrow 3$ was observed at $t = 0.2598$ sec (dashed arrow). The FIReTIP perturbations are

TABLE III. Average size (half-width) and velocity and standard deviations from a dozen long-lived Type V ELM filaments observed in the FIReTIP channels from discharges #113665 and #117405–#117419. Toroidal rotation velocity (v_ϕ) was computed between the FIReTIP channel in question and the nearest one in the counterclockwise direction shown in Fig. 5. The negative sign was removed from the values and indicated in the column heading for clarity. The range in values results from assuming that the filament is centered radially either at $R = 1.4$ m or at $R = 1.5$ m, i.e., about 5 cm either inside or outside of the separatrix. Note the speeds and sizes decrease for channel 2 (near) because the path length decreases in going from $R = 1.4$ to 1.5 m close to the FIReTIP port. The toroidal (L_ϕ), perpendicular along a flux surface (L_\perp) and vertical lengths (L_z) are estimated as the filament passes through the outer midplane.

Channel number	$-v_\phi$ (km/sec) σ	L_ϕ (m) σ	L_\perp (m) σ	L_z (m) σ
2 (far)	7.6–7.8 ($\pm 16\%$)	0.13–0.14 ($\pm 45\%$)	0.08–0.08 ($\pm 45\%$)	0.09–0.10 ($\pm 45\%$)
3 (far)	6.4–6.4 ($\pm 16\%$)	0.12–0.12 ($\pm 51\%$)	0.07–0.07 ($\pm 51\%$)	0.08–0.09 ($\pm 51\%$)
3 (near)	8.8–10.0 ($\pm 15\%$)	0.16–0.18 ($\pm 31\%$)	0.09–0.10 ($\pm 31\%$)	0.11–0.13 ($\pm 31\%$)
2 (near)	11.6–10.2 ($\pm 24\%$)	0.19–0.15 ($\pm 34\%$)	0.11–0.09 ($\pm 34\%$)	0.13–0.11 ($\pm 34\%$)

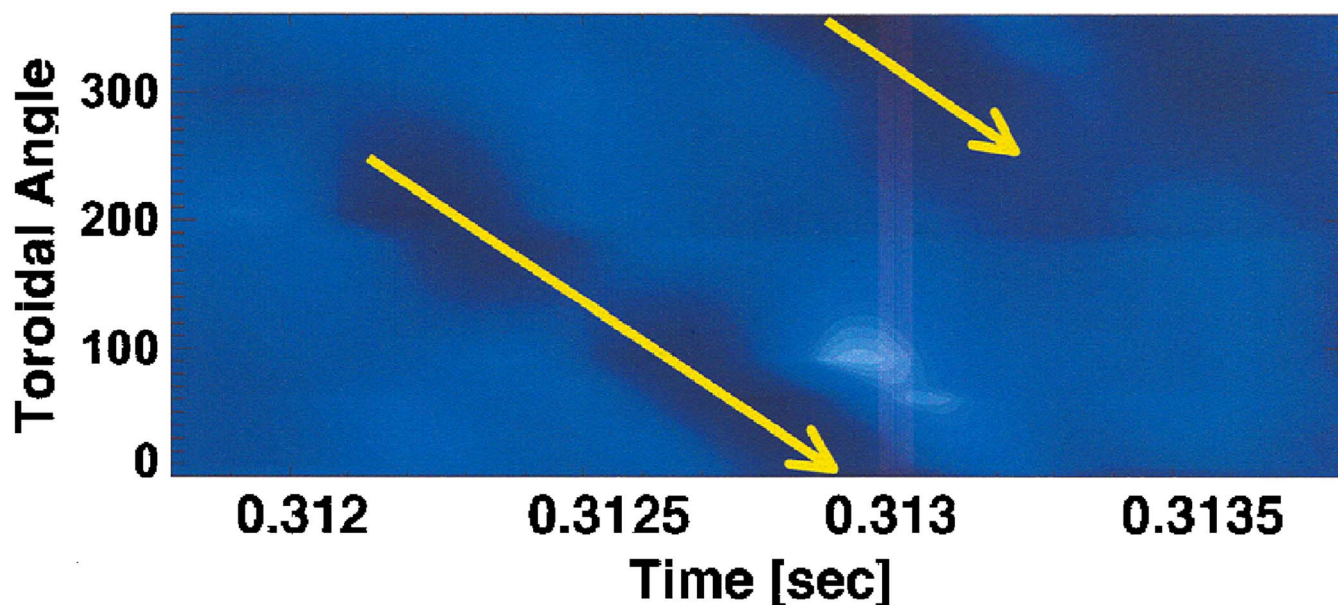


FIG. 8. (Color online) Contour plot of data from the high- n toroidal magnetics array during the Type V ELM from #113665 shown in Fig. 4. The toroidal angle shown on the y axis increases in the counterclockwise, $\text{co-}I_p$ direction shown in the plan view in Fig. 5. The toroidal motion of the filament in the counter I_p direction is highlighted by the yellow arrows.

correlated within a single peak in the outer and inner divertor D_α emission in panels (f) and (g), respectively. Based on the toroidal rotation speed computed as discussed above, it is likely that the same filament was responsible for the first perturbation and the third perturbation on the FIREtIP data, and that a second filament was responsible for the second peak. In contrast to the first perturbation, the second filament showed a clear signature on channel #4, indicating it was near or outside of $R=1.50$ the tangency radius of that FIREtIP channel. At this time, the separatrix from EFIT reconstructions^{41,42} was computed at $R\sim 1.46$ m, i.e., the second filament was in the scrape-off layer. These filaments did not have the characteristic signature in USXR emission with the Be 10 μm filter as shown in Fig. 4, indicating that the origin of the filaments occurred somewhere in the radius where the $T_e < 200$ eV.

A survey of about 50 Type V ELMs indicated that about 60% of the ELMs had a single filamentary perturbation on the FIREtIP data, whereas about 40% had two filamentary perturbations during the divertor D_α rise time. Because of the finite toroidal coverage of the FIREtIP channels, a toroidal mode number as high as $n=3$ to $n=4$ would be consistent with these multiple filament observations if the filaments were evenly distributed toroidally. This assessment of the number of separate perturbations was based on the toroidal rotation speed. If the toroidal speed between channels 1–3 far away from the FIREtIP port was within a factor of 2 of the speed between channels 1–3 close to the port, then it was assumed that a single filament could have caused the FIREtIP perturbations, otherwise at least two filaments would have been necessary. In contrast, a survey of several large Type I ELMs showed at least four separate filamentary perturbations on the FIREtIP data during the D_α rise time, consistent with a toroidal mode number $8 < n < 16$.

D. Magnetics signature

NSTX is equipped with a toroidal Mirnov array that can detect the electromagnetic signature of Type V ELMs, as well as the toroidal propagation speed and direction. In addition, the excess current carried in the filament can be estimated from the absolutely calibrated magnetic field perturbation at the wall.

We have previously shown an $n=1$ precursor⁴³ to the Type V ELM crash on the fast magnetics data; in fact, that precursor is simply the electromagnetic signature of the filament at the wall sensor. The magnetic signature and propagation of the filament from the discharge in Fig. 4 is shown in Fig. 8. The toroidal propagation speed obtained from the contour plot is $\sim 6\text{--}10$ km/s, i.e., similar to the values reported from the FIREtIP analysis in Table II. The maximum vertical field perturbation of this filament was ~ 2 G, indicating that the filament carried between 300 and 500 A of current, with the precise value depending on the actual radial location of the current centroid. This current flowed in the same direction as the plasma current and in the opposite direction of the filament motion.

E. Outer midplane gas puff imaging signatures

The poloidal and radial structure of the small ELMS just above the outer midplane was investigated with the gas puff imaging (GPI) diagnostic.^{38,44} The GPI diagnostic consists of a fast-framing, filtered visible camera viewing a neutral gas cloud from a manifold along the direction of the edge magnetic field. This results in a 2-D image of the light pattern in the radial-poloidal plane. Neutral transport calculations have shown that the visible light observed by GPI straddles the separatrix at the outer midplane.⁴⁵ We note that the GPI diagnostic has been used primarily to characterize short-lived

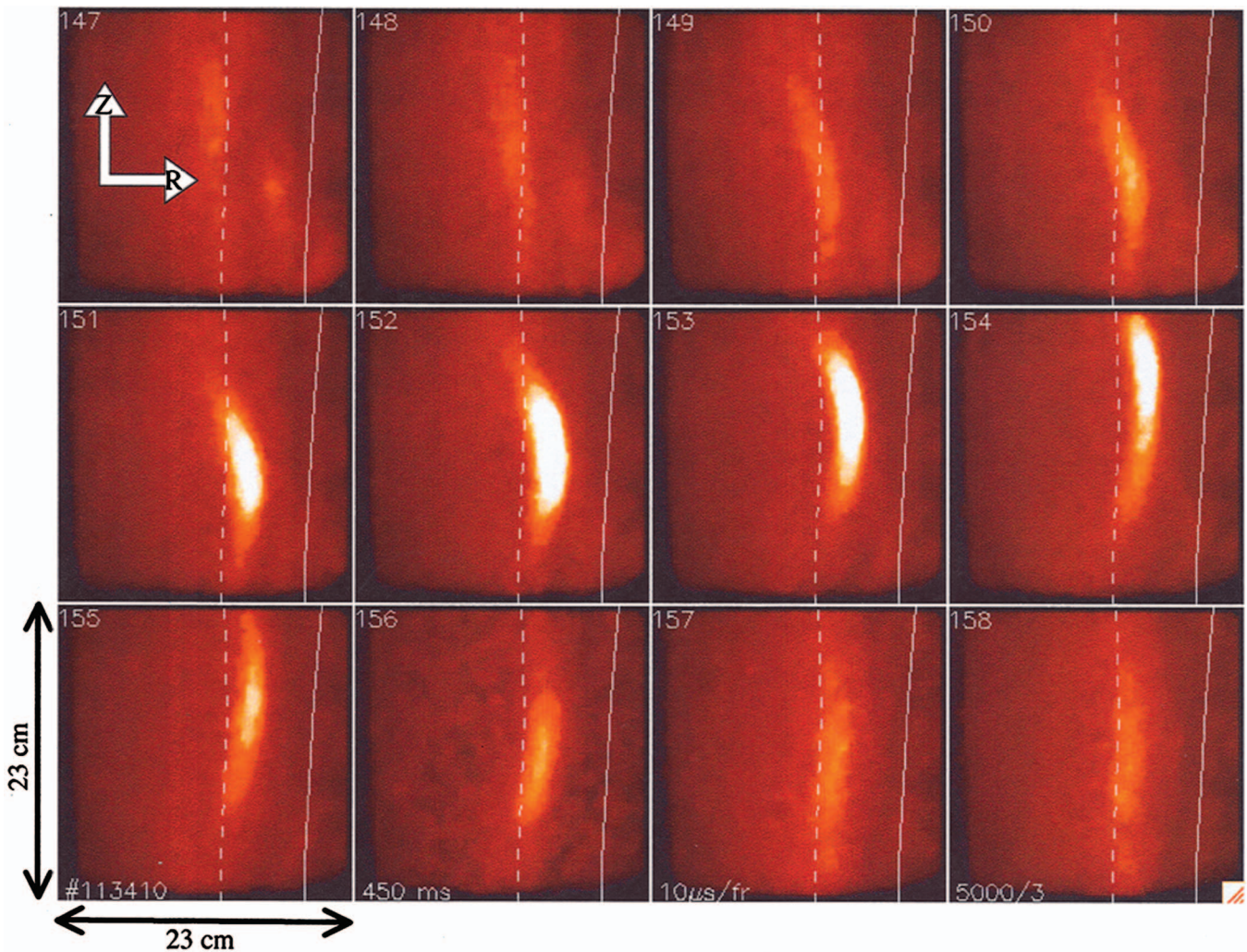


FIG. 9. (Color) Edge D_α light obtained with the gas-puff imaging diagnostic for a Type V ELM from #113410. Each frame has a $10 \mu\text{s}$ exposure, and the first frame starts at 0.451 47 s. The separatrix (as computed by equilibrium reconstruction) is indicated by the dashed line, and the shadow of the radio frequency antenna is indicated by the solid line in each frame.

($\tau_{\text{auto}} \leq 0.05$ ms) electrostatic turbulence-driven filaments, which are distinct from the electromagnetic filaments during Type V ELMs in several ways.

The vertical and radial size and motion of the filaments can be measured with GPI. Generally, we observe poloidally elongated structures with size ~ 10 – 15 cm (full-width half-max), with radial correlation lengths of a few cm. These structures differ from the normal electrostatic filaments that have comparable poloidal and radial correlation lengths.⁴⁴ When combined with the above diagnostic observations, a picture of the Type V ELM filament emerges as a ribbon-like structure, with a radial propagation speed of less than 1 km/s.

An example of a small ELM imaged with the GPI diagnostic in D_α light is shown in Fig. 9, albeit from a different discharge than for the diagnostics shown above. A poloidally extended coherent light pattern is observed in frame #149, and this structure moves first radially outward in frames #150–151, and then poloidally upward in frames #152–154. Frames #155–158 show the relaxation to the normal H-mode light emission profile. The upward motion is consistent with

the motion inferred from the USXR images in Fig. 4. The poloidal length of the coherent structure is up to ~ 15 cm in the GPI data, i.e., well within the range of vertical lengths observed for other Type V ELMs, as inferred from the interferometer data in Table III. The radial width of the light pattern associated with the ELM is about 3 cm, confirming the picture of the filament as a poloidally/toroidally extended, and radially localized ribbon-like formation. The radial propagation speed estimated from frames #149–153 is ~ 600 m/s.

Assuming that the 3 cm radial width of the structure in the GPI images is indicative of the radial width of the filament (λ_{fil}), the excess density in the filament δn_e^{fil} can be estimated as $\delta n_e^{\text{fil}}/n_e \sim \delta n_e^{\text{FIR}}/n_e \times \lambda_{\text{FIR}}/\lambda_{\text{fil}}$, where δn_e^{FIR} is the size of the perturbation on the FIR channels and λ_{FIR} is pathlength of the FIRETIP beam through the plasma. Using the density perturbations from the most perpendicular FIRETIP chord, e.g., chord #1 in Fig. 6 and 7, the density perturbation $\delta n_e^{\text{FIR}} \sim 1.4$ – 2% and plasma pathlength $\lambda_{\text{FIR}} \sim 3$ m, an excess density in the filament $\delta n_e^{\text{FIR}}/n_e \sim 140\%$ – 200% is estimated.

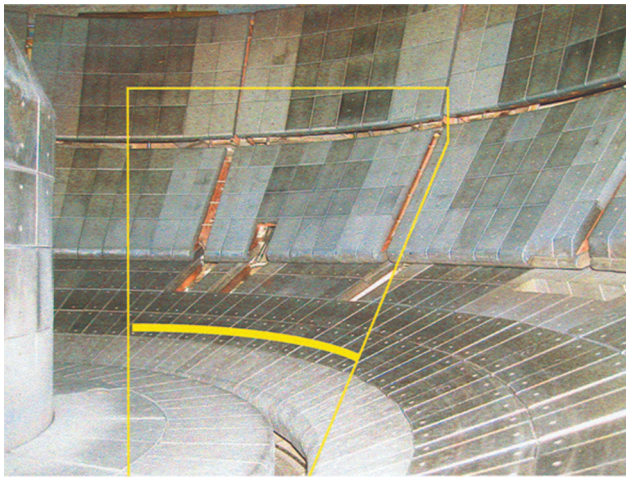


FIG. 10. (Color) Schematic representation of the NSTX lower divertor area and field of view of the fast framing divertor visible camera. The outer strike point shown in Figs. 11 and 12 is indicated here by the bright yellow band.

F. Scrape-off layer and divertor visible camera signatures

When the Type V ELM filaments drift radially outward across the separatrix, they interact with the scrape-off layer (SOL) plasma, emptying the power and particles into the divertor and wall. After crossing into the SOL, parallel flow along the open magnetic field lines to the targets competes with radial propagation across the magnetic field. Part of the ELM pulse is thought to flow at the ion sound speed to the outer target, and the remainder flows the longer way around the magnetic field lines to the inner target. This flow to each target is imaged effectively with a new fast-framing video camera⁴⁶ with a tangential view of the lower divertor, shown in Fig. 10. In particular, the poloidal propagation speed of individual filaments, along with the number of filaments within a given ELM, can be ascertained.

Figure 11 shows a set of frames during a Type V ELM in C-II light: the first signature in panel (b) is a bright band radially outboard of the outer strike point (appears as fuzz in the frame), followed by a single filamentary type perturbation propagating down the inner SOL in panels (c) and (d). We interpret the increase in light intensity as a combination of the effects of enhanced density and enhanced temperature in the filament on the carbon atomic physics; separation of the density, and temperature dependencies is beyond the scope of this paper and will be pursued in a future analysis. The X-point light pattern is affected in panel (e), but the ELM does not appear to fully connect to the inner target. Based on a correlation analysis of the filamentary perturbation down the inner SOL, the poloidal propagation speed of Type V ELMs is between 0.5 and 2.0 km/s, depending on the particular ELM. A deceleration of the poloidal speed is evident as the perturbation approaches the X point where the poloidal field vanishes. In comparison, Fig. 12 shows the SOL perturbation during a Type III (or possibly a low amplitude Type I) ELM. The first signature is a bright zone near

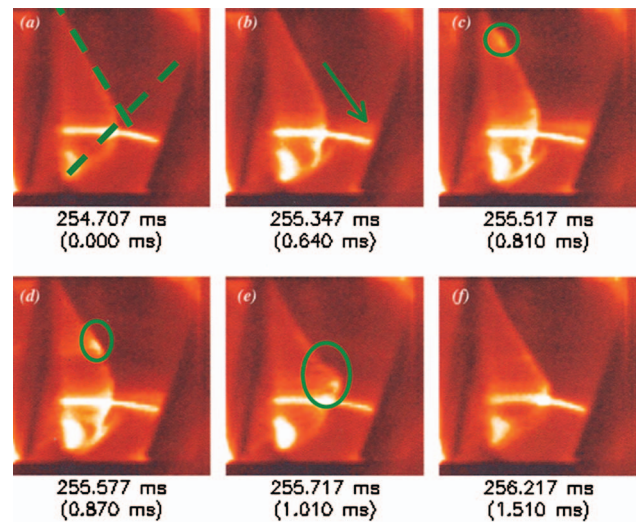


FIG. 11. (Color) Frame sequence showing signature of Type V ELM in the SOL and divertor with the fast framing camera in C-II light (filter center = 657.8 nm, full width half-max = 1.5 nm, 5 μ s exposure, 10 μ s between adjoining frames). A single filamentary perturbation is observed. The X-point geometry is overlaid in panel (a) for guidance, and the center stack is outside the field of view on the left hand side.

the outer strike point in panel (b), followed by a reconnection of the detached inner divertor leg in panel (c) near the separatrix. Panel (d) shows a complex structure comprised on many filaments moving poloidally down the inner SOL leg toward the X point. In summary, the two main differences we wish to highlight are (1) single versus multiple filaments for Type V and III ELMs, respectively, and (2) reconnection of the plasma to the inner target during a Type III ELM, but not a Type V ELM.

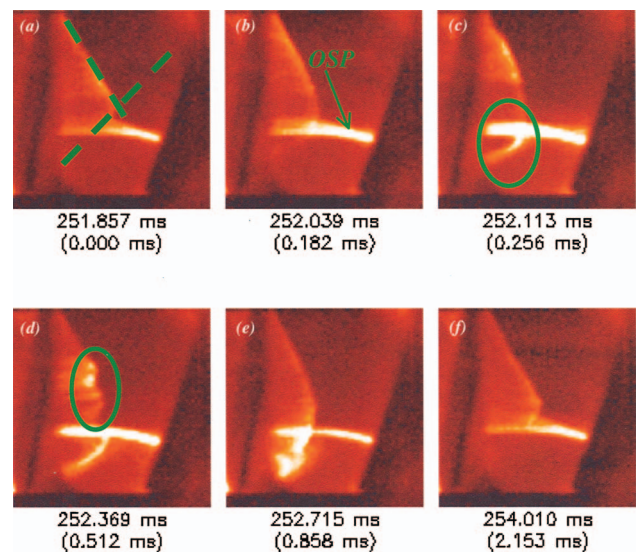


FIG. 12. (Color) Frame sequence of Type III ELM in the SOL and divertor with the fast framing camera in C-II light (filter center = 657.8 nm, full width half-max = 1.5 nm, 5 μ s exposure, 10 μ s between adjoining frames). Multiple filamentary perturbations are observed to move down the inner SOL leg. The X-point geometry is overlaid in panel (a) for guidance, and the center stack is outside the field of view on the left hand side.

IV. THEORY IMPLICATIONS AND PRELIMINARY STABILITY CALCULATIONS

We now consider the lifetime of Type V ELMs in the context of the widely accepted picture of ELMs as peeling-ballooning modes. Once the edge plasma crosses the stability boundary, theory predicts that the ballooning mode grows explosively, coalescing into one or more filaments that are ejected radially from the plasma. Indeed filament and finger-like protrusions are observed in simulations of the nonlinear MHD phase of the ballooning instability.^{28,29,47} In this picture, the filaments can expand radially until they strike a material surface at the midplane, similar to the image shown in Fig. 2(a) and first reported¹⁷ in MAST. A characteristic filament detonation time has been derived⁴⁷ as $\tau_{\text{det}} \sim (\tau_A^2 \tau_E)^{1/3}$, where τ_A and τ_E are the Alfvén time and the energy confinement time, respectively. For conditions typical of the NSTX pedestal just before a Type V ELM, $\tau_{\text{det}} \sim 0.12$ ms, which is considerably shorter than the Type V ELM filament lifetime of 0.4–1 ms. Hence, it may be concluded that the single filament of the Type V ELM is not in the nonlinear detonation phase. This conclusion has certain ramifications. In recent peeling-ballooning calculations, ELMs are correlated with intermediate- n (n =toroidal mode number) instabilities,^{26,27,30} which can sometimes coalesce into single filamentary structures during the nonlinear evolution phase of ~ 0.1 ms.³¹ The implication is that the instability responsible for the radially localized Type V ELMs *originates* as a low- n instability because it persists for ten times the expected nonlinear growth time scale. However, low- n instabilities are normally associated with perturbations of a large radial extent, expected to cause a sizable drop in stored energy, which is inconsistent with the Type V ELM characteristic of having an immeasurably small impact on stored energy.

Preliminary edge stability calculations were done for NSTX with the ELITE^{26,27} and DCON⁴⁸ codes, using a model equilibrium and the measured pedestal n_e and T_e at the onset of Type V ELMs ($t=0.245$ s) for the discharge in Fig. 7. The relevant shape and discharge parameters are given in Table IV. The edge current density was assumed to be due entirely to the bootstrap current, as calculated with the Sauter model.⁴⁹ For these input conditions, intermediate to high- n ballooning modes were found to be robustly stable. However, low to intermediate- n kink/peeling modes may be either stable or unstable depending upon the details of the assumed current profile near the separatrix. Although the underlying mechanism for Type V ELMs has not yet been clearly identified, the current-driven kink/peeling modes are a candidate for further analysis. Additional edge current density constraints on the equilibrium and several new edge Thomson channels presently being commissioned will help refine the parameters in Table IV and enable more detailed stability calculations.

V. SUMMARY, DISCUSSION AND CONCLUSIONS

We have presented evidence that small, Type V ELMs are an important ingredient of the longest pulse discharges in NSTX, and we have described the formation and evolution

TABLE IV. Discharge characteristics used in preliminary stability calculations—from #117414 at $t=0.245$ s.

Quantity	Value
Plasma current	0.8 MA
Toroidal field on axis	0.45 T
Major radius	0.85 m
Minor radius	0.62 m
Elongation	2.0
Lower triangularity	0.45
Upper triangularity	0.35
Magnetic balance (Δ_r^{sep})	-2.5 cm
Edge Z_{eff}	2.3
Central Z_{eff}	1.2
Central, pedestal n_e	2.7e19, 4.0e19
Central, pedestal T_e	0.75 keV, 0.12 keV
Central, pedestal T_i	1.0 keV, 0.12 keV
Pedestal n_e width	5%
Pedestal T_e width	3%
Pedestal T_i width	The same as T_e width
Toroidal β	8%
β_N	2.6
Internal inductance	0.7
Safety factor on axis, minimum	2.0, 2.0
Edge safety factor, q95	7.8

of the small ELMs. The small Type V ELM is composed of a small number of helical filaments: typically one or two are observed but three or four are possible due to limited spatial coverage of the diagnostics. The first sign of the ELM appears either in the ultrasoft x rays near the top of the H-mode pedestal, or as an excess density perturbation propagating toroidally in adjacent interferometer channels. Rotation speeds of ~ 10 km/s and perpendicular correlation lengths of ~ 10 cm are estimated from the interferometer data. The filaments drift radially outward as they rotate toroidally in the direction opposite the plasma current and the background plasma rotation. During the outward radial drift into the visible light region, the filaments are observed by the gas-puff imaging diagnostic as a poloidally extended but radially localized structure, confirming the picture of a ribbon-like formation. When the filaments are captured on a wide-angle camera, a clear helical structure is observed, aligned with the total magnetic field. This structure can persist into the far SOL.

Thus, a composite picture of the structure and drift of the filaments obtained from the multiple diagnostics discussed above has been obtained. The toroidal component of this motion is represented in cartoon form with field line tracing and variation of the toroidal viewing angle in Fig. 13, to simulate filament motion in the direction opposite to I_p and the NBI input direction. It is apparent from this cartoon that a diagnostic viewing in a single poloidal plane would first observe the perturbation in the lower divertor, followed by an apparent upward motion, which is precisely the pictures obtained from soft x-ray data, e.g., in Fig. 4.

After connecting with the open field lines in the SOL,

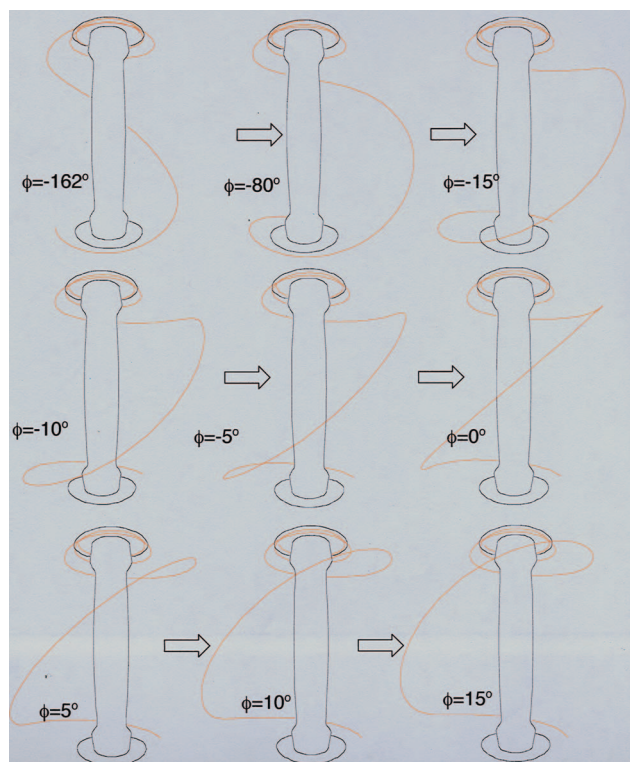


FIG. 13. (Color) Field line traces used to simulate the toroidal propagation of a Type V ELM filament, based on #113024 at $t=0.52$ s. A field line in the SOL with $\psi_N=1.12$ is viewed from several toroidal angles, simulating motion of a helical structure elongated along the magnetic field lines and propagating counter to the NBI input. The toroidal viewing angles are indicated.

Type V ELMs are observed to behave like other ELM types, i.e., the particle flux reaches the outer divertor first, followed by a perturbation down the inner SOL. Even in the inner SOL, the Type V ELMs still have only a single or double filament structure, and the ELM particle flux does not appear to reach all the way to the inner target. Note that the mechanism of interaction between the ELM flux and the SOL plasma, whether through a magnetic reconnection or through degeneracy⁵⁰ of the flux surfaces near the X point, cannot be determined from the data presented here.

Identification of the underlying instability responsible for the Type V ELM has been unsuccessful to date. The Type V ELM filaments persist for time scales much longer than the characteristic filament detonation time scales predicted by ballooning theory, which are typically $\sim 100 \mu\text{s}$ or less. Preliminary calculations indicate that the edge plasma pressure gradient is below the ideal MHD peeling-ballooning limit, but the firmness of this conclusion with regard to the current driven modes is limited by present diagnostic spatial resolution, as well as a limited knowledge of the edge current profile. Recent diagnostic upgrades will improve the input for these stability calculations, and a more concerted effort to obtain optimized data from all diagnostics simultaneously for the same set of discharges is planned.

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