Avalanches driven by pressure gradients in a magnetized plasma

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The results are presented for a basic heat transport experiment involving an off-axis heat source in which avalanche events occur. The configuration consists of a long, hollow, cylindrical region of elevated electron temperature embedded in a colder plasma, and far from the device walls [Van Compernolle et al. Phys. Rev. E 91, 031102(R) (2015)]. The avalanche events are identified as sudden rearrangements of the pressure profile following the growth of fluctuations from ambient noise. The intermittent collapses of the plasma pressure profile are associated with unstable drift-Alfvén waves and exhibit both radial and poloidal dynamics. After each collapse, the plasma enters a quiescent phase in which the pressure profile slowly recovers and steepens until a threshold is exceeded, and the process repeats. The use of reference probes as time markers allows for the visualization of the 2D spatio-temporal evolution of the avalanche events. Avalanches are observed only for a limited combination of heating powers and magnetic fields. At higher heating powers, the system transits from the avalanche regime into a regime dominated by sustained drift-Alfvén wave activity. This manuscript focuses on new results that illustrate the individual contributions to the avalanche process from density and temperature gradients in the presence of zero-order, sheared flows. Published by AIP Publishing. https://doi.org/10.1063/1.5001321

I. INTRODUCTION

Avalanches are sudden events that cause major changes over an extended region of a physical system. Although the concept is commonly associated with “snow avalanches,” the general phenomena occur widely in nature and in devices built by humans. The origin of avalanches is the presence of a steep gradient in one, or more, of the parameters of the system. Often, there is a threshold value for the gradient; when it is exceeded, complex processes are triggered that relax the gradient below the threshold value. In an externally heated or fueled plasma, the sources can reestablish the gradients and further cause them to exceed the threshold; a sequence of avalanches can then occur. The behavior is intermittent and causes the parameters of the system to evolve from place to place, i.e., there is an associated “transport” that occurs. This type of intermittent phenomena is the subject of the present study.

In a previous rapid communication, it was reported that a novel heating configuration applied to a large, cold, magnetized plasma allows the exploration of avalanche-like phenomena under controlled laboratory conditions. The present, more detailed manuscript describes new experimental results that illustrate the combined effects that gradients in both density and temperature exert on driving the avalanches in the presence of zero-order flows with shear.

The manuscript is organized as follows: Section II describes the experimental arrangement. Section III identifies early changes in the temperature and density profiles, and the presence of flows and flow shear. New features of the dynamics of the avalanches are presented in Sec. IV. A discussion of the perspectives gained in these experiments, and future directions, are given in Sec. V.

II. EXPERIMENTAL SETUP

The experiment is performed on the upgraded Large Plasma Device (LAPD) operated by the Basic Plasma Science Facility (BaPSF) at the University of California, Los Angeles (UCLA). A schematic, not to scale, is shown in Fig. 1(a). The LAPD is a cylindrical device, with an axial magnetic field that confines a quiescent plasma column that is 18 m long and 60 cm in diameter. The plasma is created from collisional ionization of He gas by 70 eV electrons of a large area low-voltage electron beam, produced by the application of a positive voltage between a barium oxide (BaO) coated cathode and a mesh anode that is 50 cm away. The electron beam heats the plasma to electron temperatures in the range of 5 eV. The active phase lasts for 12 ms, and is repeated every second (1 Hz pulse rate). The present transport experiment is performed during the afterglow phase, after the active phase of the LAPD discharge is terminated. In the afterglow phase, the 70 eV beam is turned off, and the electron temperature falls below 0.5 eV within 100 μs, while the plasma density decreases on a time scale of tens of milliseconds. The time evolution of the electron density, n_e, and the temperature, T_e, in the afterglow phase is shown in Fig. 2. The shaded regions indicate the time during which the avalanche experiment is performed.

The properties of the LAPD plasmas can be sampled through vacuum ports spaced every 32 cm along the machine’s z-axis. Probes are inserted into the vacuum chamber through ball valves, which allow for 3D movement. The probes are mounted on an external probe drive system and can be moved to a prescribed position with sub-millimeter accuracy. The
The heated region along the magnetic field is about half the length. The slowing down region acts as an ideal heat source that increases the temperature of the cold, afterglow plasma. Beam electrons, injected into afterglow plasmas in LAPD, are slowed down by Coulomb collisions over a distance that is a few millimeters in radius and several meters long. Beam electrons, injected into afterglow plasmas in LAPD, are slowed down by Coulomb collisions over a region that, on average, is about 1/80 of the plasma diameter. This “temperature filament” geometry arises from the great disparity in the parallel and transverse heat conductivities of a magnetized plasma. For the narrow temperature filament, heat losses across the magnetic field, to the cold background plasma, are as important as axial losses.

In the transport experiments reported here, a larger heat source with different geometries is used. The geometry of the heat source is changed from a 3 mm diameter solid cylindrical filament to a hollow cylindrical ring with 4 cm inner diameter and 6 cm outer diameter. This corresponds to a heated region whose radial extent is about 15 ion gyroradii and 5 ion-sound lengths. The new geometry is achieved by introducing an 8 cm diameter lanthanum hexaboride (LaB₆) cathode¹³ into LAPD, opposite to the main plasma source, which is 14.7 m away. LaB₆ is a refractory ceramic material and is stable in a vacuum. It has a low work function, around 2.5 eV, and one of the highest electron emissivities known when heated to its operating temperature in the range of 1800 K. The front side of the cathode is masked-off by carbon plates to leave a ring of exposed LaB₆ with 4 cm inner diameter and 6 cm outer diameter, as shown in Fig. 1(b).

When the LaB₆ disk is biased with respect to an axially distant anode, electrons are emitted from LaB₆ in the form of a hollow cylindrical “ring.” With the discharge voltage applied between the LaB₆ cathode and the distant anode being kept below the ionization potential for the helium fill gas, i.e., ≤ 25 V, the ring source produces a hollow, cylindrical high pressure region embedded in the background cold plasma, as shown in Fig. 1(c). The spatio-temporal evolution of the heating profiles generated by such a configuration has been investigated with a Braginskii transport code, and found to be consistent with the experimental observations during the classical stage of development, determined by Coulomb collisions.

The transport of electron temperature and plasma density is measured as a function of heating power at a fixed magnetic field of 1000 G. Heating power is changed by varying the voltage bias applied between the LaB₆ source and the distant anode. At low heating powers (bias ≤ 10 V), the system immediately develops a fluctuation-free period, which is relatively insensitive to the experimental observations during the classical stage of development, determined by Coulomb collisions. At higher heating powers (bias ≥ 18 V), the system immediately develops large amplitude drift-wave turbulence. At intermediate heating rates (10 V ≤ bias ≤ 18 V), however, the system exhibits fluctuation-free periods, well-described by classical transport, interlaced with intermittent, profile collapses brought about by the drift-wave fluctuations. The results presented in this manuscript focus mainly on the dynamics of the outer gradient region for these intermediate heating rates. In this paper, the start of the heating pulse is taken as t = 0 and the axial location of the LaB₆ cathode as z = 0. The heating pulse typically lasts for 10 to 20 ms.

III. RADIAL PROFILES AT EARLY TIMES

The radial profiles of electron density, electron temperature, electron beta (pressure), and the pressure gradient, at an early time (t = 1 ms) after the LaB₆ source is turned on, are
shown in Fig. 3, for an axial location $z = 2.56 \text{ m}$. The bias voltage on the source is 14 V. The profiles are normalized to the values prior to the start of the heating pulse, i.e., uniform $T_{e0} = 0.25 \text{ eV}$ and uniform $n_{e0} = 6 \times 10^{11} \text{ cm}^{-3}$. The dotted lines indicate the radial position of the inner and outer edges of exposed LaB$_6$. The electron temperature profile is peaked on field lines connected to the LaB$_6$ source, achieving a maximum value close to 1 eV, while the background temperature is 0.2 eV. The plasma density is similarly peaked on field lines connected to the LaB$_6$ source. The observed increase in $T_e$ is 0.2 eV. The plasma density is similarly peaked on field lines after the voltage is applied is not expected to arise from pure heating conditions at these small voltage levels. The density increase is conjectured to be a consequence of a change in the axial flow because the calculated increases due to any residual ionization are far smaller than the values observed. It should be noted that before the LaB$_6$ source is turned-on, the cold, afterglow plasma density streams out to the boundaries of the machine at the sound speed, including a flow towards the LaB$_6$ source. After the voltage is applied, however, a new axial flow is set up opposite to this ambient, afterglow outflow. In a sense, this effect acts as a plug, thereby locally increasing the density. Additional contributions to the density enhancement can result from cross-field pinching due to the ion drag-force associated with neutral collisions and also from the ion polarization-drift due to the rapid turn-on of the accelerating voltage. A detailed assessment of the contributions of each of these mechanisms requires a future dedicated study of the local flows. The resulting peaked profiles in temperature, due to heating, and in density, due to the plug effect, result in a sharply peaked pressure profile within the ring region. The electron $\beta$, defined as the ratio of the electron kinetic pressure to the magnetic pressure, is on the order of $10^{-4}$. Figure 3(d) shows the cross-field pressure gradient of $\beta$, normalized to the pre-heating value of $\beta_r$. The outer pressure gradient is a factor of two larger than the inner pressure gradient, the former therefore expected on “intuitive grounds” to be more unstable. But, in fact, the results of a detailed eigenmode analysis$^{14}$ shows that, in the absence of flows, the growth rates of the corresponding inner and outer eigenmodes do not differ significantly.

One important difference with previous transport experiments using a 3 mm beam is that the discharge voltage is now applied to an extended area, since it is applied to both the LaB$_6$ ring and the carbon masks holding the LaB$_6$, the two being in electrical contact with each other. The application of the negative potential bias to LaB$_6$ and masks not only results in the predicted temperature changes downstream, but also sets up a radial plasma potential profile. Figure 4 shows the radial plasma potential profile measured with respect to the machine wall. The dashed vertical lines indicate the radial extent of the LaB$_6$ source, i.e., points between the dotted lines map back along field lines to the LaB$_6$ source. The edge of the carbon masks is at $r = 7 \text{ cm}$. The plasma potential decreases from the geometric center to a minimum near the inner-edge of the LaB$_6$ ring, and then it increases steadily over a large radial extent beyond the heated region. Near the edge of the LaB$_6$ mask, the plasma potential approaches its background value ($\simeq 2 \text{ V}$) far from the source at $r > 10 \text{ cm}$. This results in a radial electric field and associated azimuthal $E \times B$ flows, shown in Fig. 4. These flows are in the electron diamagnetic direction, and are oppositely directed inside and outside the ring filament. The largest flows are measured on the outside gradient. Flow shear is defined$^{15-17}$ as

$$\gamma_s = r \frac{\partial}{\partial r} \left( \frac{\nu_h}{r} \right),$$

which results in a null-shear for a rigid-body rotation. The full definition of Eq. (1) is used, since the approximate formula of $\gamma_s = \partial \nu_h / \partial r$ in slab geometry, invoked by many authors, is not valid here because of the relatively small radial extent of the ring filament. A profile of flow shear is shown in Fig. 4. Two regions of strong shear exist; the strongest shear occurs near the inner edge of the ring filament, and a weaker shear (by a factor of 2) occurs on the outside.

![FIG. 3. Early radial profiles 1 ms after the start of the heating pulse. (a) Electron temperature. (b) Electron density. (c) Pressure. (d) Pressure gradient. Quantities are normalized to their values prior to start of the heating pulse, i.e., uniform $T_{e0} = 0.25 \text{ eV}$ and uniform $n_{e0} = 6 \times 10^{11} \text{ cm}^{-3}$. A dual spatial display is given. In the top, the distance is in absolute cm, while in the bottom, the radial distance is scaled to the relevant physical quantity, i.e., the ion-sound length.](image_url)
gradient. The plasma potential, flow and flow shear all scale linearly with the applied potential to the LaB$_6$ source, in the experimental range of 10 V to 16 V. It is important to recognize that the flows in this experiment are imposed by the boundary conditions at the LaB$_6$ source; they are not driven by turbulent fluctuations (e.g., zonal flows$^{18}$).

**IV. AVALANCHE DYNAMICS**

Figure 5 shows typical time traces of ion saturation current ($\sim n_e \sqrt{T_e}$) measured at different radial locations across the hollow ring filament, at a distance $z = 3.6$ m from the source. The time traces show the characteristic evolution on the outer gradient in the top panel, on field lines connected to LaB$_6$ in the middle panel and in the center ($r = 0$ cm) of the filament in the bottom panel. Time is displayed in ms on the bottom, and is scaled to $L/c_s$ on the top, where $L$ is the distance between the LaB$_6$ source and the anode.

![Sample time traces of ion saturation current](image)

FIG. 5. Sample time traces of ion saturation current, (a) at the outer gradient, (b) on a field line connected to LaB$_6$ and (c) at the geometric center of the ring, i.e., $r = 0$. Time traces were obtained from different plasma shots. Time is displayed in ms in the bottom, and is scaled to $L/c_s$ in the top, where $L$ is the distance between the source and the anode.

The stability of the inner gradient, manifested by the lack of fluctuations in the bottom panel of Fig. 5 for times $t < 10$ ms, is conjectured, but not yet validated theoretically, to be a consequence of the zero-order flows and flow shear. During the time the intermittent pulses are occurring on the outer gradient, a steady decrease in ion saturation current is observed, which is largely due to the afterglow density decay. As a result, the conditions in the inner gradient change (the magnitude of the gradient increases and modifications in the flow and flow-shear occur) that eventually permit the inner region to become unstable, as expected from the no-flow calculations.$^{14}$ After the inner gradient becomes unstable, the system suddenly enters a new phase, colored in blue in Fig. 5, in which individual avalanches are no longer visible. This new phase is characterized by sustained turbulence on both the inner and the outer gradient. The pressure on the outer gradient is typically lowered, while the pressure in the inner gradient region jumps up quickly to similar levels. It results in a relaxed pressure profile, with a nearly flat density profile, but a peaked temperature profile on field-lines connected to the LaB$_6$ source where the heating continues. The remainder of the paper focuses on the dynamics of the outer gradient during the early phase (colored red), while the transition to the new phase (colored blue), and the long-term, sustained turbulence, will be discussed in a future publication.
The bottom panel of Fig. 6 shows a zoom-in on one of the avalanches on the outer gradient, colored red in the top panel of Fig. 6. This avalanche exhibits two dynamic scales; fast fluctuations with the frequency around 40 kHz and a slow increase/decrease on a time scale of hundreds of microseconds. The 40 kHz fluctuations are attributed to the predicted drift-Alfvén waves which have also been well-documented in the small filament studies. Over-plotted on the oscillatory time trace in the bottom panel of Fig. 6 is a low-pass-filtered trace which highlights the average evolution of the ion saturation current.

A complication arises in the study of individual avalanches because the time at which an avalanche occurs varies from one plasma shot to the next. As mentioned earlier, the spatial profiles in LAPD are typically acquired by moving a probe to a number of points on a user-defined grid over the course of many plasma shots. In order to combine together the data acquired during different plasma shots, a stationary reference probe is needed to provide a proxy that an avalanche is occurring. For this purpose, a fixed probe is positioned on the outer gradient, and axially upstream, or downstream, from the moving probe that gathers the profile information. Ion saturation currents collected by the reference probe are used to provide a “timing reference” of an avalanche event. For each plasma shot, the occurrence time of a local maximum in the drift-Alfvén wave fluctuations is identified near the maximum of the low-pass-filtered signal collected by the reference probe. The data on the moving and reference probes are retained and saved, for a 1 ms time-interval, before and after, for each avalanche event. The zero of time used in the displays is then, effectively, the time origin for all signals associated with the selected avalanche event.

The 2D reconstruction of a single avalanche event is shown in Fig. 7. The top panels show the ion saturation current evolution at times prior to the avalanche, during the initial stages of the avalanche, and during the late stage of the avalanche when the outer pressure gradient has collapsed. Clearly visible are the "arms" of the drift-waves on top of the ring-shaped profile. The middle panels of Fig. 7 show the high-pass-filtered ion saturation current, i.e., it shows the drift-wave fluctuations by itself. The drift-wave fluctuations have an $m = 5$ dependence, which corresponds to the most unstable mode on the outer gradient, based on linear eigenmode analysis. It is important to note that these are azimuthally propagating drift-waves, and which simultaneously, are seen to propagate radially outwards (see also the discussion of Fig. 12). The azimuthal velocity is larger by a factor of ten than the radial velocity of the avalanche. Panel (c) of Fig. 7 shows the percentage change in the
average-profile evolution, obtained from the low-pass-filtered ion saturation current. When the drift-waves attain a sufficiently large amplitude, the average pressure-profile is modified; the plasma pressure increases on the outer gradient and decreases at the ring-filament. The change in the average-profile becomes more pronounced as the avalanche-event progresses in time, with the pressure increases advancing radially outward. Eventually, the outer pressure profile collapses and the drift-waves decay (not shown in Fig. 7). After the profile collapses, the system enters a recovery phase. Since the LaB$_6$ source is continuously on, the higher temperature at the ring-filament can be reestablished. The increases in the temperature and the density at radial locations outside the ring-filament, due to the avalanche event, decay by parallel transport along the magnetic field to the end boundaries of the machine. As seen from the sequence in the left column of Fig. 7, while the drift-wave fluctuations are absent, the system nearly recovers to its pre-avalanche state. This is a consequence of the sustained external heating and the self-consistent density rearrangement driven by flows. It should be emphasized that in this experiment, the avalanche dynamics is a fully 3D process. The avalanches are carried by azimuthally propagating drift-Alfvén waves, causing profile modifications and radial transport of density and temperature. Parallel transport then governs the recovery phase. The avalanche dynamics shown so far are in terms of the ion saturation current which can have contributions from both $T_e$ and $n_e$. To separate these individual contributions, a different technique is implemented. Measurements of $T_e$, $n_e$, and the electron plasma pressure are obtained from a technique known as “Langmuir-probe sweeps.” But, acquiring standard Langmuir sweeps during these intermittent events is cumbersome, since the standard Langmuir sweeps (sweep time $\geq 25 \mu s$) take too long to resolve the fast dynamics of an avalanche event. To overcome this shortcoming, the technique of “reconstructed sweeps” is applied. In this method, the voltage on the probe is kept fixed during an entire plasma shot. The current to the probe is recorded for 10 plasma shots at a given voltage, and then the probe bias-voltage is incrementally raised for the next 10 plasma shots. Over the course of many plasma shots, the probe current is acquired at several incremental probe voltages, and a statistical I-V Langmuir curve can be reconstructed for each selected time.

Figure 8 shows an example of the reconstruction of a single avalanche event from the Langmuir sweeps. Shown is the change in normalized pressure $\delta p$, i.e., the change in the pressure compared to the pre-avalanche pressure. A number of time traces at different radial locations on the outer gradient are shown. Each trace is displaced by an amount proportional to its radial position. At around 2.4 ms, a disturbance in the pressure profile is seen to start to grow on the outer gradient. The avalanche is first observed at $r = 3.3$ cm, which corresponds to the location of the largest pressure gradient on the outer region. The avalanche front moves radially outward at a speed of around $10^4$ cm/s, which is about 10% of the sound speed. The avalanche front reaches out to $r = 5$ cm, which is well outside the heated region, as seen from Fig. 3. The avalanche front ends when the hot material moved from the interior of the ring reaches field lines that are not heated. At these large radial positions, the transported plasma cools rapidly by axial thermal conduction to the end boundaries.

The temperature and density evolution during a reconstructed avalanche event are displayed in Figs. 9 and 10, respectively. Color contours of $T_e$, $n_e$, and the electron pressure are shown as a function of radius and time. The contour displays are supplemented with radial line profiles pre-avalanche and during the avalanche, at the bottom of the figures. The times at which the profiles are shown are indicated by horizontal lines in the contour display. Also shown on the right-hand side are time traces at two locations, inside the ring-filament and at the outer gradient. Vertical lines in the contour plot indicate
these locations. The avalanche sets in around $t = 2.4\text{ ms}$. Both density and temperature are transported radially outwards during the avalanche, reaching out as far as $r = 5\text{ cm}$, as is clear from the contour plot and the line profiles. At the ring-filament, i.e., on field lines connected to the LaB$_6$ source, there is a density decrease of approximately 25% during the avalanche event, whereas the temperature shows little change at the ring-filament.

The biggest difference in the evolution of $n_e$ and $T_e$ is the recovery after the avalanche. The temperature profile recovers rapidly within tens of microseconds. The decay of the increased temperature on the outer gradient, i.e., on field lines not connected to the heat source, is rapid due to parallel heat conduction. Similarly, the large parallel heat conduction maintains the elevated electron temperature at the ring-filament due to the continuous injection of low-energy electrons from the LaB$_6$ source. In fact, it can be seen that the electron temperature at the ring-filament exhibits a small increase after the avalanche, likely due to decreased density at the ring-filament, while the heating power remains constant. The power per particle is, therefore, increased and results in a slight increase in electron temperature. The density profile recovers at a much slower rate. The increased density on the outer gradient decays through parallel outflows at the sound speed. Figure 10 shows that the recovery time on the outer gradient is on the order of one millisecond, much slower than the electron temperature recovery of tens of microseconds. The density at the ring-filament recovers on a similar time scale. It is not clear, however, how that recovery takes place. It is likely due to a replenishing of the density by parallel flows. Additional measurements at multiple axial locations are needed to shed light on the density recovery. It is instructive to note that the time between avalanches (cf. Fig. 5) is similar to the recovery time of the density profile. This indicates that the density profile is the main driver of the avalanche dynamics. The long density recovery time compared to the rapid profile collapse during an avalanche is the reason why the time trace of Fig. 5 shows such clean intermittent behavior.

The role of drift-waves in the radial propagation of the avalanche is examined in Figs. 11 and 12. Ion saturation current measurements are high-pass-filtered to single out the dynamics of the drift-waves. The top panel of Fig. 11 shows, in a color-coded format, the temporal evolution of the pressure profile ranging from pre-avalanche conditions through the late stages. The corresponding evolution of the profiles of fluctuation amplitude appears in the bottom panel of Fig. 11. Several snapshots in time are shown: pre-avalanche in black, early stages in purple, and late stages in blue and red.
The displays of Fig. 11 indicate that in the pre-avalanche stage, wave activity is present near the point of largest gradient, but only on the outer gradient of the ring-filament. The modification of the mean pressure-profile is seen to follow the rapid growth in the wave activity. Within a few drift-wave cycles, a shoulder appears on the pressure profile. This feature is associated with a radially propagating, steep front. During this expansion, the wave activity is concentrated in two separated regions: at the pre-avalanche location of the largest gradient and at the edge of the propagating front. In the late stage, when the profile collapses, the drift-wave activity subsides.

Figure 12 presents the same data in a different format. Here, time traces of the high-pass-filtered data are shown at several radial locations on the outer gradient. Each trace is displaced according to its radial location (cf. right hand side vertical axis). The solid black line represents the location on the outer gradient where the pressure profile is the steepest. This location is extracted from the “reconstructed” Langmuir sweep measurements using low-pass-filtered data, i.e., from the average-profile evolution. Prior to the growth of drift-waves, the location of the largest gradient is fixed. Drift-waves grow first near the largest gradient. As the waves increase in amplitude, the average-pressure profile is modified, and as the radial location of the largest gradient moves outward, the drift-waves adjust to the steepening front. In turn, the electric field of the waves causes the radial convection of temperature and density into the colder and less dense regions at the periphery of the ring-filament. The drift-waves, in a sense, are the propagators of the avalanche. Once the pressure gradient is relaxed, the fluctuations rapidly disappear and the system enters a recovery phase.

The interplay between the drift-wave fluctuations and the average-profile evolution is best summarized in Fig. 13. This 2D display is effectively a phase-space diagram in which the coordinates \((x, y)\) of a point are labeled by the amplitude of the fluctuation \(y\) and by the magnitude of the pressure gradient \(x\), both measured at a representative spatial location and at a given instant of time. The spatial location chosen is \(r = 3.3\) cm, corresponding to where in the pre-avalanche stage, the pressure gradient is the largest. The time when an \((x, y)\) point is measured is indicated by different colors along the trajectory of the curve shown in Fig. 13. The time-scale is in units of the period of a drift-wave, with the running value indicated by the color bar. It is seen from the path followed by the curve in Fig. 13 that at the onset of the avalanche, the pressure profile exhibits a large gradient. Fluctuations rapidly grow, and at the same time, the pressure gradient collapses. Once the gradient has collapsed, the fluctuation amplitudes diminish. The system then enters a quiescent state with nearly no fluctuations, and the pressure profile recovers and becomes steeper again. It is noteworthy that the avalanche event, i.e., collapse of the pressure profile, is very rapid and takes place in approximately ten drift-wave periods (light-blue to yellow-green colors).

The onset of the avalanches has the signature of a critical-gradient event. Figure 14 shows the long-term evolution of the outer pressure gradient for a 12 V bias voltage on the LaB\(_6\) source. These data are low-pass-filtered such that individual avalanche dynamics are not distinguishable. It is seen from Fig. 14 that for 2 ms after the external heating is applied, the gradient increases linearly in time. But after that, there is a sudden saturation. It is around this time when the first avalanche is observed. In the saturated stage \((t > 2\) ms\), numerous intermittent avalanches occur. It appears that the system settles into a near steady-state with a self-consistent gradient, which may be interpreted as a manifestation of a “critical-gradient”. It should be noted that the fact that the plasma resides close to a critical gradient for a relatively long period of time is not necessarily due to a similar process as in snow avalanches. It could very well be a hint to a hidden parameter which is still evolving until an instability criterion is fulfilled. For example, in Edge Localized Modes (ELMs) observed in tokamak devices, it is the plasma current profile and the width of the steep pressure gradient region that evolve until the instability is released.

The onset of the avalanches is associated with the rapid growth of drift-waves on the outer gradient, as detailed previously. Therefore, the critical-gradient for the avalanche event is in effect the pressure gradient at which the drift-waves become unstable. The profile remains quiescent and stable to drift-waves for long periods of time before the first avalanche and in-between avalanches. It is conjectured that

![FIG. 13. Fluctuation amplitude in the outer gradient plotted as a function of the magnitude of the outer pressure gradient, at \(r = 3.3\) cm, and color-coded by the time given in drift-wave periods.](image)

![FIG. 14. Long-term evolution of the outer pressure gradient showing critical-gradient behavior. The clear break in the initial slope corresponds to the first avalanche event. Time is displayed in ms in the bottom and is scaled to \(L_{cs0}\) in the top.](image)
flow shear, imposed by the axial boundary condition at \( z = 0 \) (cf. discussion on Fig. 4), plays a major stabilizing role in the onset of the drift-waves. Preliminary results for various heating rates and magnetic fields indicate that the larger the flow shear is in the system, the larger the pressure gradient needs to be in order for the first avalanche to occur, i.e., when the drift-waves become unstable. Clearly, flow shear plays a major role in the dynamics of the avalanches. Future publications will focus more on the dynamics of the flow and the flow shear during individual avalanche events.

V. CONCLUSIONS

This manuscript presents new experimental information about the properties of avalanche events in magnetized plasmas and the associated transport of temperature and density. This is a topic that has received very limited study in the laboratory because of the challenging constraints necessary to generate suitable avalanche conditions, and the need for adequate diagnostics. A prior rapid communication\(^1\) demonstrated a heating configuration in which avalanche events can be investigated under controlled conditions. The present study uses such a configuration in conjunction with more advanced diagnostic techniques to isolate the individual contributions of temperature and pressure gradients in the evolution of the avalanche events. The use of reference probes to generate proxy indicators of when an avalanche starts has allowed the reconstruction of the 2D evolution of a single avalanche event, as shown in Fig. 7. This methodology is necessary because the start of an individual avalanche is not under experimental control. The implementation of the “Langmuir sweep-technique” has elucidated the different evolution followed by the temperature and density profiles during an avalanche, as documented in Figs. 9 and 10.

The picture that emerges from the detailed measurements is that drift-Alfvén waves are the underlying drivers for the avalanche events, and the overall causal sequence is in general agreement with the results of a modeling study.\(^2\) The rapid rearrangement of the zero-order profiles occurs within a few cycles of the growing waves. It is measured that during the evolution of an avalanche, the poloidally propagating waves move radially outward, tracking the expansion of the pressure profile at speeds below the sound speed, as seen in Fig. 12. A phase-space diagram, Fig. 13, has been constructed that clearly demonstrates the close interplay between the average pressure gradient and the wave fluctuations during an avalanche.

A significant insight gained in the present experiment is that zero-order flows associated with the creation and maintenance of the pressure gradients by the external heating source play an important role in the avalanche dynamics, as indicated by Fig. 4. It appears that the measured “zero-order flow-shear” is responsible for the surprising stability of the inner pressure gradient, since, in its absence, the theoretical prediction\(^3\) is that this region should experience avalanche events in a manner analogous to that observed in the outer pressure gradient. Preliminary results, not presented in this manuscript, corroborate this conjecture, but a rigorous assessment requires a future study using dedicated flow diagnostics.

Another important insight made clear from the present investigation is that, in spite of the relatively long extent (~10 m) of the heated ring-filament, the dynamics of the avalanches is a fully 3D process. This feature is particularly evident in the manner in which the pressure profile recovers after it is modified by an avalanche event, as seen from Figs. 9 and 10. The rapid recovery of the temperature profile is consistent with the predictions of a Braginskii transport code,\(^4\) but the return of the density profile nearly to its pre-avalanche shape is not understood. Evidently, complex flows develop that allow fueling from distant regions to reestablish the density profile, because at the low voltages applied, ionization is negligible. This suggests the need for a dedicated study that maps the evolution of 3D flows, which requires the deployment of numerous Mach probes.

Finally, as shown in the bottom panel of Fig. 5, the stability of the inner gradient is found to disappear abruptly, late in the evolution, after surviving several avalanche events in the outer gradient. When this inner region collapses, the system evolves into a new regime of sustained turbulence. The processes through which this transition occurs pose a challenge for future experimental and modeling studies.

In summary, this study advances the understanding of “what is” an avalanche in a magnetized plasma, but it also identifies new surprising features of transport in magnetized plasmas that require further investigation.

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