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1 Domain wall dynamics in two-dimensional van der Waals 2 ferromagnets

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19 Domain wall motion is in the core of many information technologies ranging from storage¹,
20 processing², sensing³ up to novel racetrack memory architectures⁴. The finding of magnetism

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21 in two-dimensional (2D) van der Waals (vdW) materials^{5–8} has offered a new frontier for the
 22 exploration and understanding of domain walls at the limit of few atom-thick layers. How-
 23 ever, to use 2D vdW magnets for building spintronics nanodevices such as domain-wall based
 24 logic^{9–11}, it is required to gain control of their domain wall dynamics by external driving
 25 forces such as spin-polarized currents or magnetic fields which has so far been elusive. Here
 26 we show that electric currents as well as magnetic fields can efficiently move domain walls in
 27 the recently discovered 2D vdW magnets CrI₃ and CrBr₃ at low temperatures, and robust
 28 down to monolayer. We realize field- and current-driven domain wall motion with veloci-
 29 ties up to 1020 m s⁻¹ which are comparable to the state-of-the-art materials for domain-wall
 30 based applications^{12–16}. Domain walls keep their coherence driven by the spin-transfer torque
 31 induced by the current and magnetic field up to large values of about 12×10^9 A cm⁻² and
 32 5 T, respectively. For larger magnitudes of current or field, a transition to a hydrodynamic
 33 spin-liquid regime is observed with the emission of a periodic train of spin-wave solitons
 34 with modulational instability¹⁷. The emitted waveform achieves terahertz (THz) frequency
 35 in a wide range of field and current densities which opens up perspectives for reconfigurable
 36 magnonic devices. Moreover, we found that these spin-waves can transport spin angular mo-
 37 mentum through the layers over distances as long as 10 μ m without losses for the transport
 38 of spin information. Our results push the boundary of what is currently known about the
 39 dynamics of domain walls in 2D vdW ferromagnets and unveil strategies to design ultrathin,
 40 high-speed and high-frequency spintronic devices.

41 Spin-based applications have been broadly explored for high-performance solid-state data
42 storage technologies^{18,19}. A promising strategy is to encode bits in magnetic domains walls which
43 can be controlled via applied magnetic fields and spin-polarized currents^{4,9}. Several approaches
44 for domain wall-based memory devices with a focus on the domain wall displacement have been
45 developed. From a field-controlled shift register^{9,20} up to the non-volatile multi-turn sensors²¹,
46 which are commercially available²², these emerging technologies provide a new horizon for ad-
47 vanced materials to be explored. With the discovery of magnetism in vdW layered compounds⁵⁻⁷
48 and proof-of-concept devices^{8,23-25} already showing outstanding progress toward applications, one
49 of the main challenges is the integration of 2D magnets in domain wall microelectronic platforms.

50 Due to scaling reasons and high-density requirements²⁶, competitive devices should have
51 narrow domain walls (ideally in the range of 1–10 nm), use out-of-plane magnetic anisotropy
52 materials and, in particular for memory devices, develop domain wall velocities of the order of
53 $\sim 100 \text{ m s}^{-1}$ to achieve rapid operating speed on increasing areal density^{4,27}. Sufficiently low
54 current densities ($\sim 10^6 - 10^8 \text{ A cm}^{-2}$) are also needed to guarantee low power consumption and
55 to avoid damage due to Joule heating. However, metallic layers inherently suffer with energy
56 dissipation via the conduction electrons² which make magnetic insulators better suited for domain
57 wall applications. There have been a few reports on the creation of different interfaces using
58 magnetic vdW materials^{28,29} and heavy metal overlayers (e.g. Pt, Ta) where spin-transfer torque
59 arising from charge-to-spin current conversion can effectively switch the magnetization from one
60 state to another. Nevertheless, it is unknown how domain walls behave intrinsically in 2D magnets
61 as current and fields are applied directly into the systems, and how efficient such layered structures

would be in domain-wall based functional devices.

Here we demonstrate domain-wall motion in monolayer CrI_3 and CrBr_3 by spin polarized currents and magnetic fields in a broad range of densities ($10^7 - 10^9 \text{ A cm}^{-2}$) and field (0.001–2 T). Both dynamics occur over hybrid domain walls with Néel-Bloch characteristics with a domain wall width of about $\sim 5.30 \text{ nm}$. The spin-torque induced by electric currents and magnetic fields generates a rapid rotation of the magnetization at the domain wall, hence triggering its translational motion at high velocities. We record speeds of up 1020 m s^{-1} and 100 m s^{-1} with current and field, respectively, while keeping the coherence of the wall profile through a steady motion. As the domain wall velocity approaches the maximum spin-wave group velocity, the domain wall motion start to exhibit non-linear effects with the emission of magnons at terahertz (THz) frequencies following a modulational instability behaviour. Even though no conduction electrons are present in the medium due to the insulating characteristics of CrI_3 and CrBr_3 , spin-information can be transported over distances as long as $10 \mu\text{m}$ which sets a new paradigm for spin-wave-based technologies at the ultrathin limit.

Our starting point is the investigation of the magnetic domain structures in monolayer CrBr_3 and their dynamic evolution under different temperatures and magnetic fields. The domain wall structure of CrI_3 and its cooling dynamics have recently been reported using similar theoretical framework³⁰. We use a large square flake of $0.4 \mu\text{m} \times 0.4 \mu\text{m}$ to represent a system able to be measured using imaging techniques, i.e. nitrogen-vacancy scanning magnetometry³¹. We describe the interactions using the following spin Hamiltonian:

$$\mathcal{H} = -\sum_{ij} J_{ij} (\mathbf{S}_i \cdot \mathbf{S}_j) - \sum_{ij} \lambda_{ij} S_i^z S_j^z - \sum_i D_i (\mathbf{S}_i \cdot \mathbf{e}_i)^2 - \sum_{ij} K_{ij} (\mathbf{S}_i \cdot \mathbf{S}_j)^2 - \sum_i \mu_i \mathbf{S}_i \cdot (\mathbf{B}_i + \mathbf{B}_i^{\text{dp}}) \quad (1)$$

where \mathbf{S}_i and \mathbf{S}_j are the localized magnetic moments on Cr atomic sites i and j which are coupled by pair-wise exchange interactions. J_{ij} and λ_{ij} are the isotropic and anisotropic bilinear (BL) exchanges, respectively, and D_i is the single ion magnetic anisotropy. \mathbf{B}_i and \mathbf{B}_i^{dp} represent external and dipole magnetic field sources respectively. Eq. 1 was previously found to describe accurately the magnetic properties of several 2D magnets^{30,32} including CrI_3 and CrBr_3 . Comparisons with other spin Hamiltonians such as Kitaev, bilinear Heisenberg, Ising, and Dzyloshinskii-Moriya interactions, were undertaken in refs.^{30,32} as well as in their Supplementary Information files. We take into account up to third nearest neighbors for J_{ij} and λ_{ij} in the description of CrBr_3 in Eq.1. All the parameters in Eq.1 are extracted using highly accurate non-collinear ab initio simulations taking into account spin-orbit coupling and Hubbard- U corrected density functional theory as described in Ref.^{30,32}. We ensure that fine numerical convergence within $10^{-6} - 10^{-8}$ eV is achieved in each computed parameter. We also compared the exchange parameters used in our work with those collected from the literature³³. In the context of the materials studied in our study (monolayer CrI_3 and CrBr_3), Supplementary Figure 1 clearly shows that our exchange magnitudes³² reproduce with high accuracy the critical temperatures measured. Moreover, Eq.1 provides an accurate description of the magnon dispersion extracted from inelastic neutron scattering measurements on CrI_3 ³⁴ as shown in ref.³². These results provide a firm background for the modeling of the domain wall dynamics as described here.

The fourth term in Eq.1 represents the biquadratic (BQ) exchange which involves the hopping

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101 of two or more electrons between two adjacent sites³². Its strength is given by the constant K_{ij} ,
 102 which is the simplest and most natural form of non-Heisenberg coupling. It has recently been found
 103 that several 2D vdW magnets develop substantial BQ exchange in their magnetic properties which
 104 is critical to quantitatively describe important features such as Curie temperatures, thermal stability,
 105 magnon spectra and non-trivial topological spin textures^{30,32,35,36}. The magnitude of K_{ij} for CrBr₃
 106 is 0.22 meV which is smaller than the BL exchange for the first-nearest neighbours ($J_1 = 1.66$ meV)
 107 but still sizeable to be disregarded³². In our implementation the BQ exchange is quite general and
 108 can be applied to any pair-wise exchange interaction of arbitrary range. Each system is evolved by
 109 solving the atomistic Landau-Lifshitz-Gilbert equation with a Gilbert damping $\lambda_G = 0.1$ to ensure
 110 better computational efficiency and numerical stability of the time integration. The value of λ_G is
 111 substantially higher than that (2×10^{-3}) recently measured for a parent compound³⁷ (i.e. CrCl₃)
 112 which a similar magnitude would be expected for CrI₃ and CrBr₃. The large λ_G also accounts
 113 for the possibility of free-electron doping to raise the conductivity of the system due to different
 114 processes (i.e. dopants³⁸, electric bias³⁹). Due to the inclusion of dipole-dipole interactions we
 115 explicitly include non-local damping effects in our simulations such as due to domain walls or
 116 different magnetic textures. Hence, our spin-dynamics simulations include an accurate description
 117 of the spin-interactions at the atomistic level (2–20 Å) in a multiscale framework at the lab scale
 118 (a few μm 's).

119 Monolayer CrBr₃ is thermally equilibrated above 40 K and then linearly cooled to 0 K in
 120 a total simulated time of 4.0 ns at different magnetic fields (Figure 1 and Supplementary Movies
 121 S1-S4). The time evolution of the out-of-plane magnetization M_z is utilised to study the nucleation

of the magnetic domains as it determines the easy-axis throughout the layer. For zero-field cooling
(0 mT) magnetic domains are formed for temperatures below 20 K with the free motion of the
domain walls as the temperature drops (Fig. 1a-e). As the system reaches 0 K a continuous
time evolution of the domain structures remains which results in a homogenous magnetization
over the entire crystal (Supplementary Movie S1). Even though thermal fluctuations as well as
their contributions to the energy of the system are inexistent at 0 K, other terms, such as dipolar
fields, exchange interactions and magnetic anisotropy, are still present, further contributing to the
modification of the magnetic domains. Once magnetic fields are applied to the nanosheet (Fig.
1f-t and Supplementary Movies S2-S4) this nucleation-type mechanism is accelerated with a rapid
reversal in the sign of the magnetization M_z . Indeed, a monodomain feature is observed even
in fields far below the coercivity⁴⁰ (10 mT at 5 K) for CrBr_3 . In a scenario where defects or
pinning sites are not present in monolayer CrBr_3 , magnetic domains tend to be meta-stable with
a homogeneous magnetisation throughout the surface. This is in sound agreement with recent
NV-center scanning magnetometry measurements³¹ on the magnetic domain evolution of CrBr_3
indicating that pinning effects are the dominant coercivity mechanisms.

Strikingly, the interplay between domain metastability and high magnetic anisotropy of
 CrBr_3 give additional characteristics to the domain walls (Figure 2a-b). We observe that as the
spins vary orientation from one magnetic domain to another the wall profile assumes components
of the magnetization along different in-plane directions ($M_{x,y}$) relative to the easy-axis (M_z) (Fig.
2c-d). In-plane magnetization M_x displays a variation larger than that for M_y which is mainly no-
ticed at the core of the domain wall within 1–2.5 nm. These features indicate a domain wall with

143 hybrid characteristics of Bloch and Néel type (Fig. 2e-f). We can extract the domain wall width
144 $\sigma_{x,y,z}$ by fitting the different components of the magnetization (M_x , M_y , M_z) to standard equations
145 of the form⁴¹:

$$M_j = \frac{1}{\cosh(\pi(j - j_0)/\sigma_j)}, \quad \text{with } j = x, y \quad (2)$$

$$M_z = \tanh(\pi(z - z_0)/\sigma_z) \quad (3)$$

146 where j_0 and z_0 are the domain wall positions at in-plane and out-of-plane coordinates, respec-
147 tively. The domain wall widths are within the range of $\sigma_{x,y,z} = 5.30 - 5.33$ nm. Materials with
148 high magnetic anisotropy generally stabilise such small domain wall widths but their magnetic do-
149 mains are generally stable after zero-field cooling due to long range dipole interactions. We have
150 checked that the inclusion of dipolar fields in our simulations do not change the results.

151 An intriguing question raised by the hybrid features of the domain walls in CrBr_3 and CrI_3 ³⁰
152 is the effect of magnetic fields and electric currents on the motion of domain walls. It is well estab-
153 lished that both driving forces can induce displacement of domain walls in magnetic thin films over
154 different substrates. Nevertheless, the vdW nature of the nanosheet together with the atomic thick-
155 ness (≈ 0.5 nm) may induce additional phenomena yet to be observed in 2D ferromagnets. Figure
156 3a-d shows that either fields or currents can efficiently displace domain walls in layered CrBr_3 and
157 CrI_3 magnets. The dynamics is generally initialised with a domain wall at equilibrium position
158 previously thermalized for several nanoseconds for full convergence of the spin orientations (Fig.
159 3a). The finite width of the nanowire assists in the formation of the domain walls pinned by the
160 edges. For field-induced domain wall motion, wall velocities up to $v = 70 \text{ m s}^{-1}$ and $v = 98 \text{ m s}^{-1}$

161 are recorded for CrBr₃ and CrI₃ (Fig. 4a-b), respectively. The wall moves steadily on both sheets
 162 and can be described as $v = \mu_F(B - B_o)$, where μ_F is the wall mobility and B_o is the onset field
 163 required to move the wall from structural defects or pinning⁴². The magnitudes of $\mu = 0.0343$ m
 164 s⁻¹ mT⁻¹ and $B_o = 23.89$ mT for CrBr₃ and $\mu = 0.018$ m s⁻¹ mT⁻¹ and $B_o = 13.33$ mT for CrI₃
 165 indicate that domain walls move relatively slower than those in metallic ultrathin Pt/Co/Pt films⁴³
 166 or thick magnetic insulator TmIG/Pt interfaces¹⁴ but with relatively similar onset field B_o . The
 167 domain wall moves steadily on both sheets at fields below critical magnitudes (B_c) of $B_c = 1.19$
 168 T and $B_c = 4.78$ T for CrBr₃ and CrI₃, respectively (Supplementary Movies S5-S6). For values
 169 beyond B_c different spin distributions start nucleating ahead of the domain-wall (Supplementary
 170 Movie S7-S8) and induce its collapse within a few hundreds of picoseconds after the motion ini-
 171 tiated. These spin features appear from the edges of the layers and rapidly move into the bulk of
 172 the ribbon. This behaviour is analogous to that observed in Pt/Co/AlO_x ultrathin microstructures⁴⁴
 173 and highlighted the importance of edges on the magnetic properties of 2D magnets in device in-
 174 tegration. A preference for unreconstructed edges or dangling bonds rather than on zig-zag edges
 175 (Fig. 3b at 1.50 T) has been observed in the nucleation of reversed domains during the wall dy-
 176 namics. The local variation of the exchange interactions at dangling-bonds with spins being less
 177 restricted to change their directions with an external field than at zig-zag edges is one of the main
 178 ingredients for this behaviour. This observation shall trigger further experimental studies of the
 179 atomic structure at the edges of the monolayer magnets via scanning probe microscopies^{45,46} and
 180 their connection to the device performance.

181 In the case of current-driven domain wall motion, we state that such behaviour can be ac-

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182 accomplished in two ways. First, by using an adjacent conducting layer as recently demonstrated for
 183 insulating $\text{Tm}_3\text{Fe}_5\text{O}_{12}$ on top of a Pt substrate¹⁴. Charge current will flow in the heavy metal gen-
 184 erating spin currents that exert a spin-transfer torque (STT) on the ferromagnetic material. Second,
 185 by doping the CrX_3 ($X=\text{Br}, \text{I}$) magnets in order to generate significant carriers in the host^{27,47}. Such
 186 strategies are well established and would provide a feasible platform to confirm our predictions.
 187 Indeed, we recorded domain wall velocities up to 530 m s^{-1} and 1020 m s^{-1} for monolayer CrBr_3
 188 and CrI_3 , respectively, under applied currents (Fig. 4c-d). These velocities are higher than those
 189 observed in a wide range of systems including skyrmions (100 m s^{-1})¹³, ferromagnetic semicon-
 190 ductor (Ga, Mn)As (22 m s^{-1})⁴⁷, synthetic antiferromagnets (750 m s^{-1})¹², metallic layers (380 m
 191 s^{-1})⁴⁸, Pt/CoFe/MgO and Co/Ni/Co interfaces ($\sim 10 \text{ m s}^{-1}$, 400 m s^{-1})^{16,49}, and insulating oxides
 192 (400 m s^{-1})¹⁴. It is worthwhile highlighting that low current densities within the experimental
 193 range of $10^{-8} \text{ A cm}^{-2}$ (insets in Fig. 4c-d) already resulted in domain wall speeds (i.e. 100 m s^{-1})
 194 similarly as those achieved in established racetrack platforms with more complex materials⁴. The
 195 domain walls displace freely as a function of the current density j in a viscous flow motion (Supple-
 196 mentary Movies S9-S10). The high velocities predicted for CrBr_3 and CrI_3 are only limited by the
 197 spin-wave group velocity v_g intrinsic to the systems. By using a spin-wave theory for 2D magnetic
 198 materials³², which includes biquadratic exchange and Dzyaloshinskii-Moriya interactions (DMI),
 199 we estimate from the magnon dispersion (Supplementary Figure 2) maximum values of v_g within
 200 the range of $584\text{--}891 \text{ m s}^{-1}$ for CrBr_3 and $1326\text{--}6400 \text{ m s}^{-1}$ for CrI_3 (Supplementary Figure
 201 3). These values are close to those computed from the atomistic simulations (530 m s^{-1} and 1020
 202 m s^{-1} for CrBr_3 and CrI_3 , respectively) although slightly larger. This is due to the damping of

the domain wall motion by the emission of spin-waves⁵⁰ not taken into account into the model as commented in the following.

The steady displacement of the domain walls occurs up to a certain threshold (j_w) defined as the Walker breakdown⁴². For values below j_w , the wall dynamics can be well modelled by a simple 1D model^{51,52} through a linear dependence of v and j :

$$v = \mu_I j \quad (4)$$

where μ_I is the current-driven domain-wall mobility which gives $\mu_I = 0.12 \times 10^{-10} \text{ m}^3 \text{ A}^{-1} \text{ s}^{-1}$ and $\mu_I = 0.10 \times 10^{-10} \text{ m}^3 \text{ A}^{-1} \text{ s}^{-1}$ for monolayer CrBr₃ and CrI₃, respectively. These values are of the same order of magnitude as those recorded on thin metallic interfaces⁴⁹ or permalloy nanowires⁵³ which have been studied more intensively. For values near j_w or above, the spins at the domain wall precesses inducing disruption of the wall at longer times with the nucleation of magnetic domains with a different polarisation ahead of the displacement of the domain-wall (Fig. 3c at $4.35 \times 10^9 \text{ A cm}^{-2}$). A close look at these features (Fig. 3d) indicates that they may start from both edges although dangling-bonds may induce more curvature to the domain wall since a dragging on the motion is observed generating retardation relative to the zig-zag edge. We can model qualitatively the dynamics at $j > j_w$ for both CrBr₃ and CrI₃ via the time average velocity of the domain wall^{51,52}. This suggests that the domain-wall dynamics in 2D magnets is similar as that in magnetic nanowires which allows faster integration into existing devices²⁷. We also observe that as the domain wall moves spin-waves or magnons are emitted (Fig. 4e-f). The spin frequencies driven by the field (ω_B) and current (ω_J) are in the terahertz (THz) regime with maximum magnitudes of $\omega_B^{max} = 0.43 \text{ THz}$ and $\omega_J^{max} = 0.60 \text{ THz}$ for CrBr₃ and $\omega_B^{max} = 0.50 \text{ THz}$

220 and $\omega_J^{max} = 0.66$ THz for CrI₃. These frequencies are in sound agreement with those estimate from
 221 the magnon dispersion along different points of the Brillouin zone for both halides (Supplementary
 222 Figure 3). We found that the maximum frequencies with the field are close to those at the M–point
 223 (0.47 THz for CrBr₃, and 0.57 THz for CrI₃), whereas with the applied current are around the
 224 K–point (0.63 THz for CrBr₃, and 0.64 THz for CrI₃). Indeed, the variations of ω_B and ω_J can be
 225 well fitted using:

$$\omega_B = \omega_0^B + \alpha_B B \quad (5)$$

$$\omega_J = \omega_0^J + \alpha_J j \quad (6)$$

226 where $\omega_0^B(B = 0)$ and $\omega_0^J(j = 0)$ are the onset frequencies resulting in $\omega_0^B = 0.29$ THz and
 227 $\omega_0^J = 0.31$ THz for CrBr₃; and $\omega_0^B = 0.25$ THz and $\omega_0^J = 0.43$ THz for CrI₃. We also notice
 228 that the magnitudes of ω_0^B and ω_0^J may also change due to the inhomogeneous spatial distribution
 229 of the emitted spin-waves (Supplementary Movie 11) even though with a similar behaviour with
 230 the field and current. The coefficient α_B differs moderately between both halides converging to
 231 0.13 THz T⁻¹ and 0.05 THz T⁻¹ for CrBr₃ and CrI₃, respectively, with $\alpha_J \approx 0.04$ THz 10⁻⁹ A
 232 cm⁻² being similar to both systems. On the field-driven spin-wave emission, the domain wall pre-
 233 cesses with a frequency near the Larmor frequency $\omega_0 = \gamma B$, where γ is the gyromagnetic ratio,
 234 similarly as in nanowires⁵⁴. We noticed that in both layered materials the spin wave frequencies
 235 are enclosed between odd- and even-numbered harmonics. That is, CrBr₃ is within $4\omega_0$ and $5\omega_0$
 236 ($\omega_B - \omega_0^B = 4.81\omega_0$), and CrI₃ is within ω_0 and $2\omega_0$ ($\omega_B - \omega_0^B = 1.70\omega_0$). This indicates that the
 237 spin waves and their overtones can be excited with a combination of fundamental modes which
 238 gives additional flexibility for terahertz source of magnetic signal using atomically thin layers. In

addition, the emission of spin waves electrically-driven can be associated with the Doppler effect
 on the frequency shift⁵⁵. As the domain wall moves the current changes the spin-waves disper-
 sion and incidentally causes an effective flow of the magnetic medium. This is reflected by the
 linear dependence of ω_j on j (Fig. 4f) in agreement with the spin-transfer-torque Doppler shift. A
 similar approach has been successfully used to study the effect of electric signal into magnons in
 permalloy strips⁵⁶, $\text{Ni}_{80}\text{Fe}_{20}$ wires⁵⁷ and thin films⁵⁸.

A substantially different phenomenon is observed when the domain wall is subject to large
 current densities, $j > 10^{10} \text{ A cm}^{-2}$, with the appearance of spin hydrodynamic effects in CrBr_3
 and CrI_3 . The dynamics is illustrated in Figure 5a-c where we plot line-cuts of the M_z and M_x
 components of the magnetisation at width 25 nm and selected times for monolayer CrI_3 . We
 observe that shortly after the electric pulse starting propagating into the system within 18-78 ps
 the M_x projection exhibits a wave propagating ahead of the domain wall. This amplitude tilts
 M_z into the plane and increases exponentially (Fig. 5d) until M_z is completely suppressed and
 eventually switches, nucleating a new domain wall. The first period of the wave in M_x or shock
 wave continues to propagate with no appreciable dissipation and new domain walls are nucleated
 in its wake with a certain periodicity (Fig. 5a-c). This nonlinear phenomenon is indicative of a
 modulational instability (MI) as observed in fluid dynamics^{17,59}. This type of instability occurs in
 focusing media and describes the exponential growth of waves within a band of wavevectors until
 non-linear effects favour their spatial localisation into solitons. MI are ubiquitous in dispersive
 physical problems and have been observed in several systems such as in water waves⁶⁰, nonlinear
 optics⁶¹ and Bose-Einstein condensates⁶². In magnetic materials however MI has been invoked

260 so far as a pathway for the nucleation of dissipative droplets in perpendicular magnetic anisotropy
 261 (PMA) ferromagnets⁶³, as well as the spatial localisation of high-energy magnons in PMA ferri-
 262 magnetic alloys excited with ultrafast optical pulses⁶⁴, and the disintegration of short-wavelength
 263 spin-superfluids in planar ferromagnets⁶⁵. In contrast, we find clear evidence of spin hydrodynamic
 264 behaviour manifested the onset of MI and its nonlinear dynamics driven by electrical currents in
 265 2D magnetic materials. We emphasize that the nonlinear effect observed here is fundamentally
 266 different from Walker breakdown and the subsequent precessional regime so far observed in bulk
 267 magnets.

268 We also observe that MI is visible already at 20 ps as the wavefront exhibits a transverse
 269 structure and can be more generally regarded as a spin shock wave (Fig. 6a-c). At 200 ps, there are
 270 rich transverse features in the nanoribbon, from which we can identify a modulationally unstable
 271 region where new domains are established. These domains are bounded by the trailing domain-wall
 272 (soliton edge) and the spin shock wave. At 600 ps, the shock wave is already outside our simulation
 273 profile and the domain walls continue to propagate further (see Supplementary Movie S12 for the
 274 full sequence). The salient features of the MI dynamics can be visualized in Fig. 6d by a colour-plot
 275 of the M_z component line-cuts as a function of time. After an initial translation of the domain wall,
 276 there is a split of behaviours at ≈ 0.01 ns where we can define two characteristic speeds (dashed
 277 lines in Fig. 6d). The shock wave (SW) (Fig. 6b) translates with a speed of $s^+ = 5.77 \text{ km s}^{-1} \pm$
 278 0.84 km s^{-1} which is in sound agreement with the maximum group velocity calculated for CrI_3
 279 (Supplementary Figure 3). The soliton edge exhibits a phase-shift and subsequent translation with
 280 a speed of $s_1^- = 1.33 \text{ km s}^{-1} \pm 0.002 \text{ km s}^{-1}$ (Fig. 6b). Consequently, the wavelength L of the

281 nucleated domains can be extracted from the spectral function at a constant speed, such at s^+
 282 (Fig. 6e). The obtained frequency of the wavefront or SW is computed as $\nu_{SW} = 177.5 \text{ GHz} \pm 1.25$
 283 GHz. We can immediately extract L through a simple speed and frequency relationship via $L =$
 284 $s^+/\nu_{SW} = 5.77 \text{ km s}^{-1}/177.5 \text{ GHz} = 32.50 \pm 0.23 \text{ nm}$ which is equivalent to a wave-vector of
 285 $k_{SW} = 2\pi/L = 0.19 \text{ nm}^{-1} \pm 0.00003 \text{ nm}^{-1}$. Indeed, the shock-wave speed corresponds to the
 286 group velocity of the most unstable magnon with a wave-vector given by k_{SW} .

287 The growing region bounded by the speeds s^+ and s_1^- is reminiscent to the development of
 288 dispersive shock waves (DSWs)¹⁷ which is located at the modulationally unstable region high-
 289 lighted on Fig. 6b. DSWs are ordered structures that smoothly connect the wavevectors at the front
 290 and soliton edges, and have been fully characterised for planar ferromagnets⁶⁶. However, the MI
 291 in our system induces periodic domain-wall nucleation defined by the most unstable wavevec-
 292 tor. Therefore, we can regard the scenario of Figs. 6b-c as an unstable generalization of a DSW.
 293 The periodicity of the nucleated domains leads to initially similar domain-wall speeds (parallel
 294 features in the wake of the wavefront) that are later perturbed by interactions, annihilation, and
 295 nucleation events. These can be potentially related to turbulence, thermodynamic behaviour as a
 296 soliton gas⁶⁷, or rare events such as rogue waves⁶⁰. At a later time ($\approx 0.04 \text{ ns}$), a second char-
 297 acteristic domain-wall speed $s_2^- = 0.88 \text{ km s}^{-1} \pm 0.001 \text{ km s}^{-1}$ is observed. This second speed
 298 appears to be related to an additional source of MI in the wake of the soliton-edge that opposes the
 299 current-driven torque. We can extract the frequency of this domain-wall wake (Fig. 6f) resulting
 300 in $\nu_{wake} = 6.66 \pm 1.66 \text{ GHz}$. Given the value of s_2^- , we can extract a wavelength of $132.28 \pm 32 \text{ nm}$
 301 which corresponds to the periodicity of where new domain wall appears into the system induced

302 by the wake of the domain-wall motion.

303 Interestingly, we also found that in principle there is no spatial limit for the propagation of
 304 the shock waves in the systems. Simulations undertaken at a mesoscopic level (Supplementary
 305 Figure 4) showed that once an electrical excitations is applied into the system, the transmission
 306 of short-wavelength spin waves can extend for long-distances with minor disturbance from the
 307 medium. We record lengths up to $10\text{ }\mu\text{m}$ with a group velocity above $\sim 2000\text{ m s}^{-1}$ where spin-
 308 waves can work as nanoscale information carriers. The spatial distance is at the same order of
 309 magnitude as those previously obtained in the magnetic insulator yttrium iron garnet (YIG)⁶⁸, and
 310 ferromagnetic nanowires grown on thick YIG thin-film⁶⁹, with both have been proposed as plat-
 311 forms to controllable transmission of spin information. The combination between small damping
 312 ($\approx 2 \times 10^{-3}$) in this class of 2D ferromagnets³⁷, the insulating nature of CrI_3 and CrBr_3 with no
 313 conduction electrons available to induce decay in the spin signal⁷⁰ and the relative low magnon
 314 scattering⁷¹ make magnetic layered materials a new endeavour for magnonics applications.

315 Discussion

316 The possibility to manipulate and control domain walls precisely on 2D vdW CrX_3 ($\text{X}=\text{Br}, \text{I}$)
 317 magnets opens up a pathway to design a range of novel and highly competitive applications in
 318 the thickness of a few atoms. As some of the critical parameters to domain-wall based devices
 319 are domain wall widths, which control the information density, domain wall motion, directly gov-
 320 erning access time, and pinning processes, that determine the energy consumption, 2D magnets

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show features that are fundamental for integration in novel memory technologies, such as race-track memories⁴. The large domain wall speeds achieved in both CrBr₃ and CrI₃ at the limit of 1020 m s⁻¹ compete side-by-side with the best materials used for racetrack applications (e.g. synthetic antiferromagnets¹²) where complex interfaces need to be fabricated to induce fast domain wall shifting. This remarkable result, along with recent advances in the scalable bottom-up growth of CrX₃ in the monolayer regime^{72,73}, clearly presents as an opportunity for reduction on manufacturing and time-consuming device preparation. There is still a challenge that needs to be overcome to enable current-driven excitations in these 2D magnetic halides, for instance, the enhancement of the conductivity and the consequent reduction of the current densities used to move domain walls. One route is to use doping, which is a well-known strategy that has been widely employed in other prototypical ferromagnetic semiconductors (such as (Ga,Mn)As)⁴⁷. In fact, carrier doping has been found to induce half-metallicity and enhance the ferromagnetic stability in CrI₃ monolayer^{39,74}, such that current-induced phenomena become feasible without compromising the magnetic properties. It is worth mentioning that some trade-off between conductivity enhancement and dissipation through the conduction electrons would have to be achieved for low-power consumption. It is well known that large Gilbert damping λ_G allows fast relaxation of the magnetization to equilibrium, whereas low damping enables energy-efficient processes. Several approaches⁷⁵⁻⁷⁸ were previously developed on metallic systems that may assist in the pursue of the modelling of conduction electrons on doped-2D magnets. If the electrical conductivity of CrX₃ (X=I, Br) is enhanced due to different chemical or physical processes, the values of the domain wall speeds shown in Figure 3 would be robust against such variations. Since the magnitude of

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the Gilbert damping λ_G utilised in the simulations ($\lambda_G = 0.10$) is high than that expected for CrI_3 and CrBr_3 ³⁷, we intrinsically take into account additional dissipation effects in our simulations. Furthermore, investigations to clarify the effect of different dopants, concentration and their implications on both damping and the magnetic properties of 2D magnets are promptly needed. The emission of spin waves in the THz regime and the spin hydrodynamic behaviour observed for both halides, also merit further exploration on novel information technologies. On one hand, the design of sources, detectors and prototypes functioning in the THz-gap (0.3–30 THz)⁷⁹ provides the groundwork for the developments of high-end electronics on the low-end of the electromagnetic spectrum. The ultrathin character of 2D magnets, their flexibility in generating tunable frequencies, and inexpensive sample cost relative to expensive bulky compounds⁷⁹, make vdW layered materials a playground for applications. On the other hand, the use of magnons for information carrier at the μm -scale puts vdW sheets in the roadmap of post-semiconductor spin-wave technologies. The characteristic soliton features observed on the shock-waves in both ferromagnets and consequent low dissipation indicate that magnon-based data operations may be explored for information processing. In this sense, the development of an energy-efficient spin-wave transducer through vdW materials is one of the key steps for the ultimate goal of hybrid spin-wave computing systems.

Supplementary Materials

Methods, Supplementary Figures S1–S4, and Supplementary movies S1–S12.

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361 **Data Availability**

362 The data that support the findings of this study are available within the paper and its Supplementary
363 Information.

364 **Competing interests**

365 The Authors declare no conflict of interests.

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373 **References**

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598 Figure captions

Figure 1: **Magnetic domains at different temperatures and fields.** **a-e**, Dynamical spin configurations of monolayer CrBr_3 during zero-field cooling (0 mT) at different temperatures. The out-of-plane magnetization M_z (a.u.) is used to follow the evolution of the magnetic domains from 40 K down to 0 K. **f-j**, **k-o**, and **p-t**, Similar as **a-e**, but at magnetic fields of 5 mT, 11 mT and 50 mT, respectively. Temperatures at the top row correspond to all panels in the same column. Time scale spanned up to 2.5 ns till 0 K is achieved. Further evolution are observed at later times as shown in Supplementary Movies S1-S4.

Figure 2: **Hybrid domain walls with Néel-Bloch characteristics.** **a-b**, Global and local views, respectively, of a snapshot for one of the spin configurations projected along M_z (colour map) showing the formation of a domain wall in monolayer CrBr_3 . The total strip in **a** is 400×50 nm. Only Cr atoms are showed in the honeycomb lattice arrangement of monolayer CrBr_3 . The system is at 0 K without any external fields or currents. **c-d**, Side and top views, respectively, of the rotation of the magnetization along the domain wall. Both M_x and M_y show variations along the wall altogether with M_z which indicate a hybrid character of the domain wall with Néel and Bloch features. Colours follow the scale bar in **a**. The small area around the domain wall highlighted in **a** corresponds to **c**. **e-f**, Variation of the magnetization along the domain wall projected along the in-plane components (M_x , M_y) and M_z , respectively. Fitting lines are obtained using Eqs.2-3.

Figure 3: Current- and field-induced domain wall dynamics in 2D ferromagnets. **a**, Initial domain wall configuration for monolayer CrBr₃ at no external driving forces ($j=0$, $B=0$). The domain wall is initially equilibrated for up to 4 ns to ensure convergence of the spin orientations along the wall and width. The same final configuration is utilised for both field- and current-driven domain wall motion. Similar procedure is undertaken to monolayer CrI₃. **b-c**, Snapshots of the domain wall dynamics in CrBr₃ induced by magnetic fields (0.05 T, 1.50 T) and electric currents (8.7×10^9 A cm⁻², 4.3×10^9 A cm⁻²), respectively. The edges used in the simulations are highlighted at $B=1.50$ T with dangling-bond and zig-zag at the top and bottom of the layer, respectively. Deformations observed near the domain wall at $j=4.3 \times 10^9$ A cm⁻² are highlighted by the dashed rectangle. **d**, Zoom-in of the local spin-configurations at $j=4.3 \times 10^9$ A cm⁻² with colour scale showing the variations of the spin orientations along M_z induced by the large current density.

Figure 4: Domain wall speeds and spin wave frequency. **a-b**, Calculated domain wall velocities v versus the applied magnetic field B for CrBr₃ and CrI₃, respectively. The vertical solid lines indicate the region where the nucleation of magnetic bubbles starts in each material as those shown in **b** at 1.50 T for CrBr₃. A fit using $v = \mu(B - B_o)$, where μ is the domain wall mobility and B_o is the onset field, reproduces accurately the atomistic simulation data with linear regression coefficients $R^2 = 0.99$ and a root-mean-square-error of 0.0074. The field is applied perpendicular to the surface following the easy-axis of the materials. **c-d**, Variations of v as a function of the current density j for CrBr₃ and CrI₃, respectively. Two regimes are observed in the internal dynamics of the wall before and after the Walker breakdown (j_w) with the wall motion being in steady and precessional states, respectively. We could extract $j_w^{CrBr_3} = 4.8 \times 10^9$ A cm⁻² and $j_w^{CrI_3} = 12.0 \times 10^9$ A cm⁻². Both steady and precessional regimes on the domain-wall dynamics can be modelled using a 1D model as described in the text. The insets show the velocities at lower values of current within $j \leq 8.5 \times 10^8$ A cm⁻². **e-f**, Frequencies ω_b (THz) and ω_l (THz) of the emitted spin-waves during the domain-wall motion as a function of B and j , respectively, for CrBr₃ and CrI₃. Dashed lines are corresponding fits to Eqs. 5–6. Similar data labelling applies for **e** and **f**.

Figure 5: **Modulational instability in 2D magnets.** **a-c**, Snapshots of the magnetisation along M_z and M_x magnetisation components at different times at 18 ps, 40 ps and 78 ps, respectively. **d**, Amplitude of M_x as a function of time at different current densities.

Figure 6: **Long range spin-wave propagation.** **a-c**, Snapshots of spin-dynamics at 20 ps, 200 ps and 600 ps, respectively, under a current density of $1.56 \times 10^{10} \text{ A cm}^{-2}$. M_z is used to show the variations of the domain wall with the colour scale along the length of the ribbon. A separation of the motion of the original domain wall (soliton edge) and the shock waves can be observed between a wave train (modulationally unstable) propagating throughout the system. **d**, Colour-plot of the variations of M_z with the propagation time along a $2\text{-}\mu\text{m}$ ribbon of CrBr_3 at a current density of $1.56 \times 10^{10} \text{ A cm}^{-2}$. The different line-cuts correspond to the several waveforms moving into the systems as shown in **e-g**. The dashed lines are given by $s^+ = 5773 \text{ m s}^{-1} \pm 0.84 \text{ m s}^{-1}$, $s_1^- = 1328 \text{ m s}^{-1} \pm 1.7 \text{ m s}^{-1}$ and $s_2^- = 882 \text{ m s}^{-1} \pm 1.8 \text{ m s}^{-1}$. **e-f**, Spectral density (arb. units) extracted from the fast Fourier transform of the M_z component as function of time in **d** along velocities s^+ and s_2^- , respectively. The characteristic frequencies of the shock waves and the domain-wall wake can be identified as $\nu_{SW} = 177.5 \text{ GHz} \pm 1.25 \text{ GHz}$ and $\nu_{wake} = 6.66 \pm 1.66 \text{ GHz}$, respectively.

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599 **Figures**

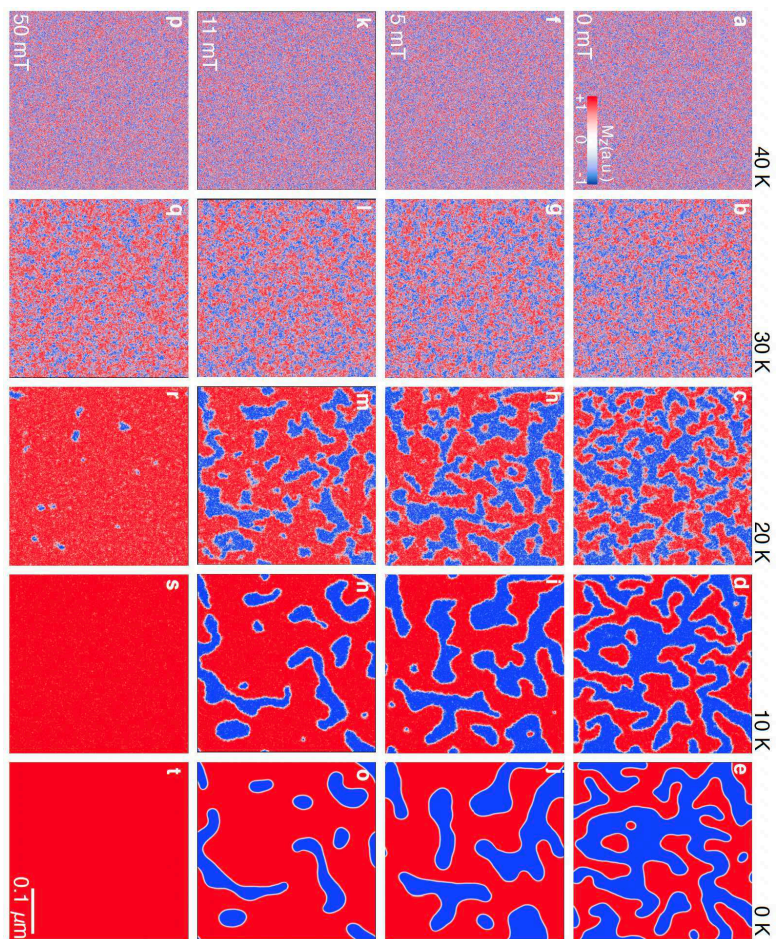


Figure 1

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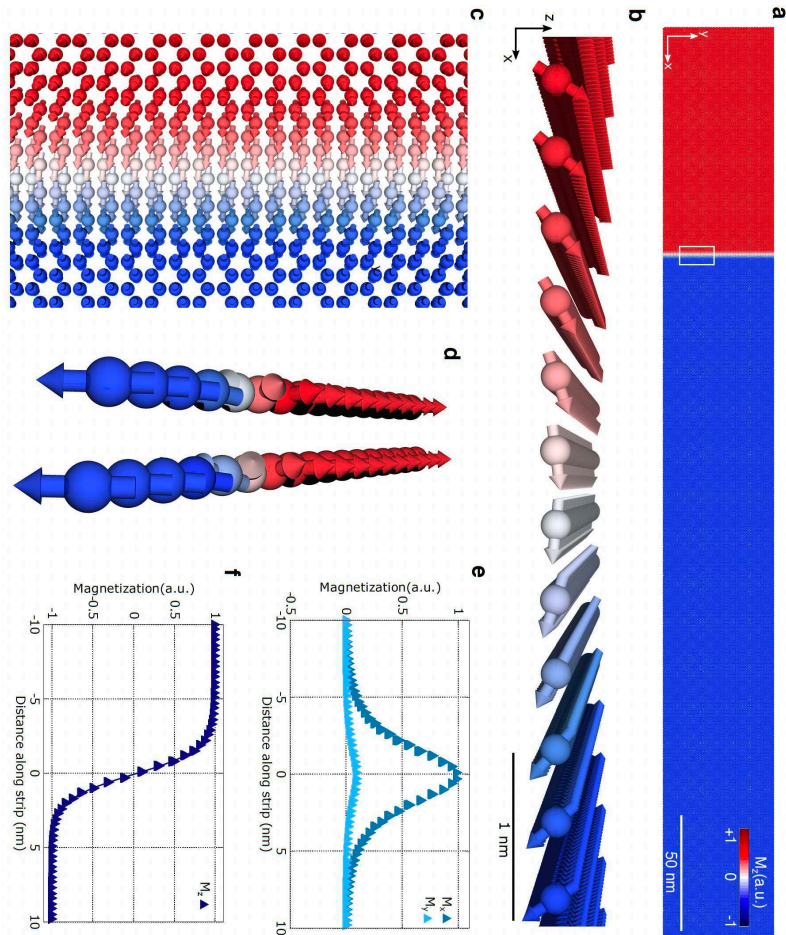


Figure 2

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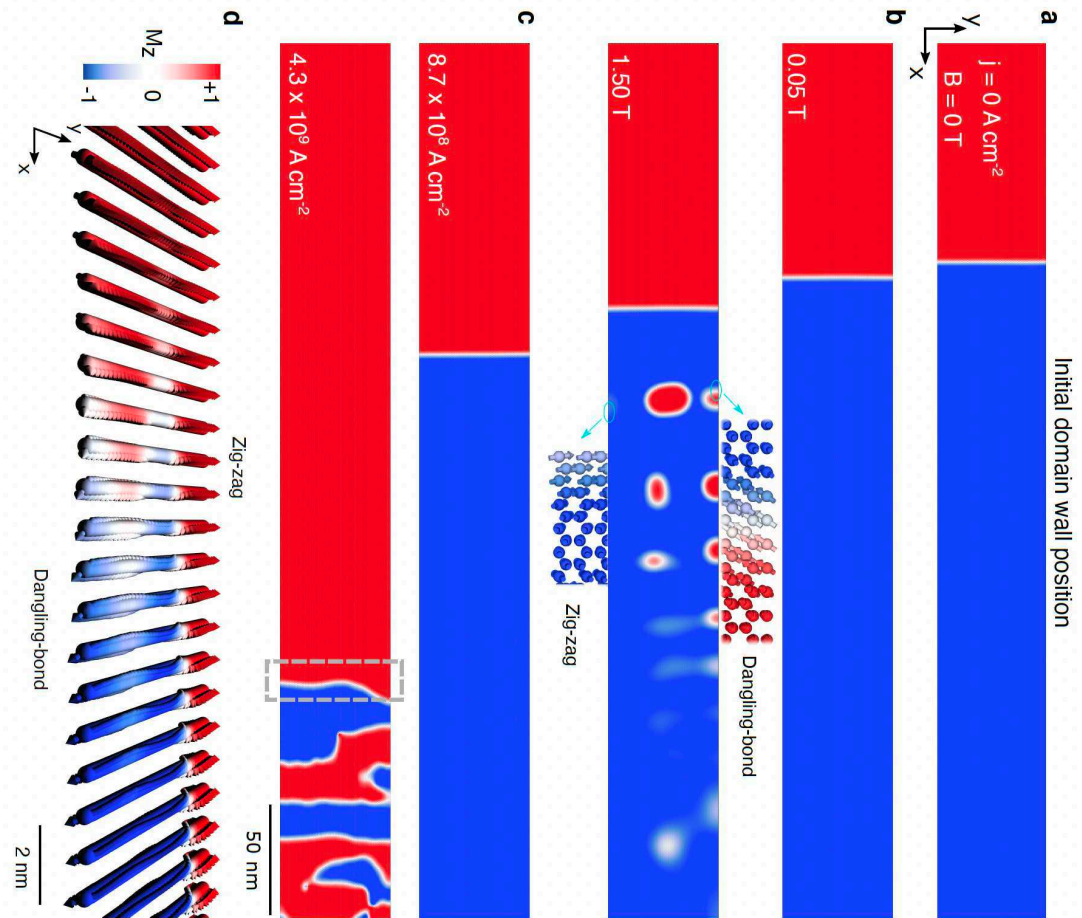


Figure 3

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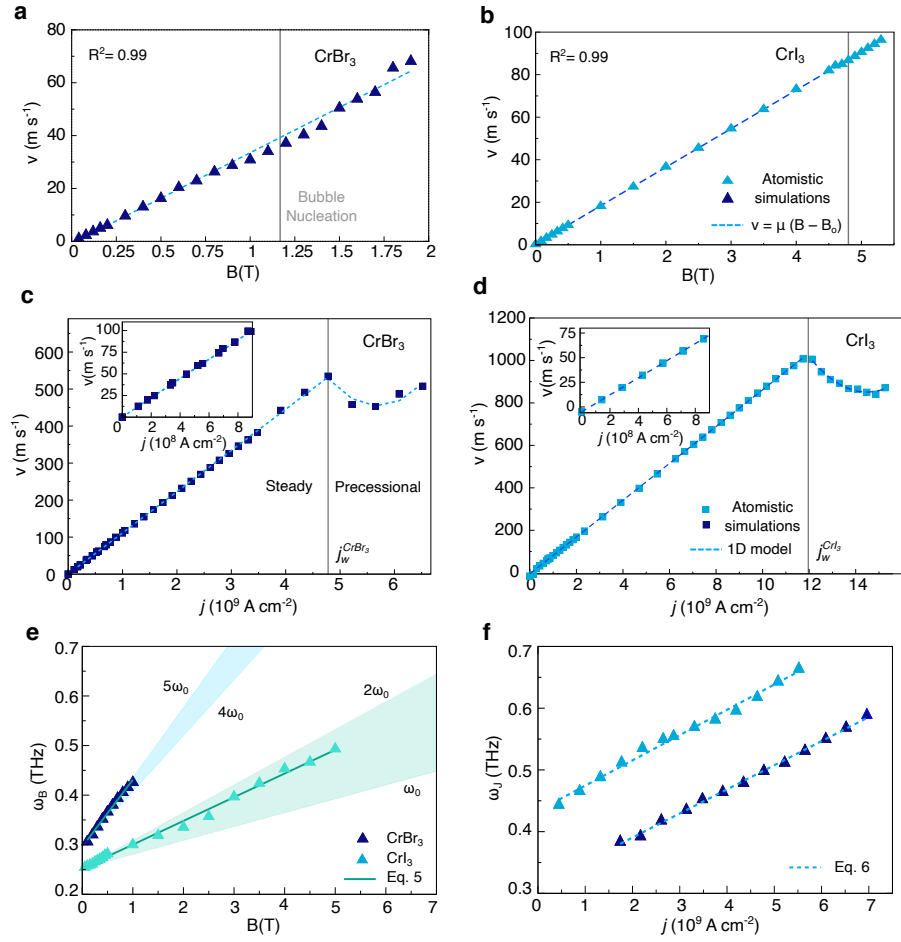


Figure 4

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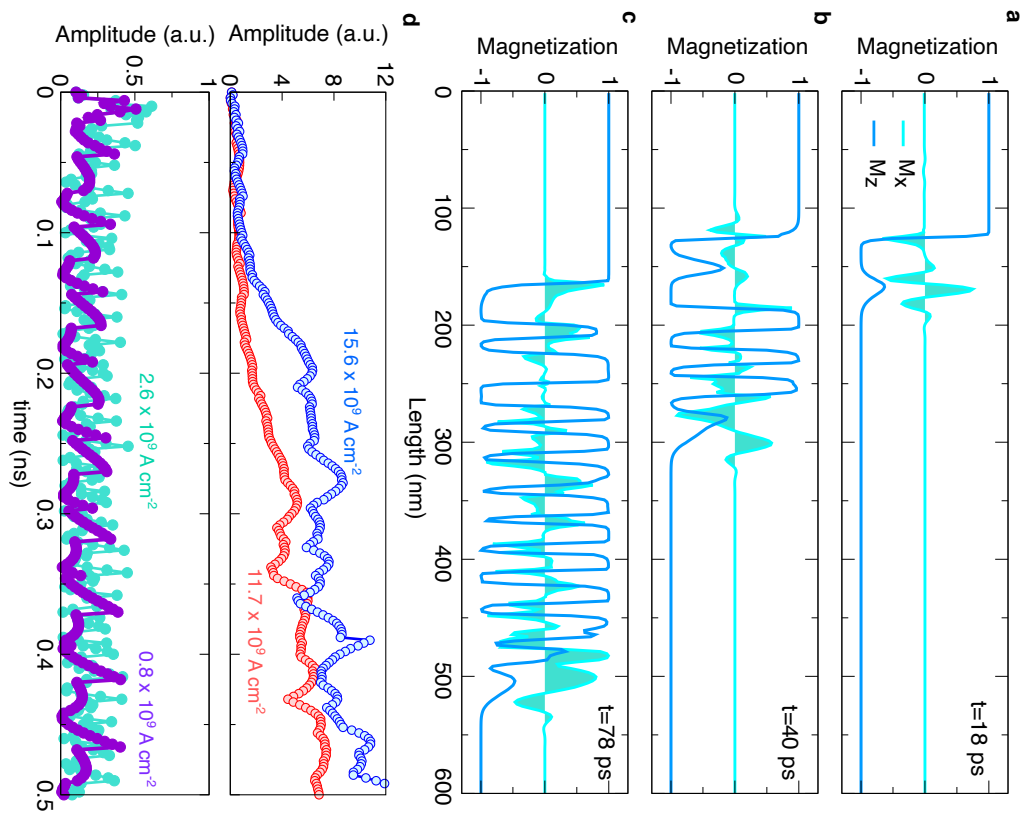


Figure 5

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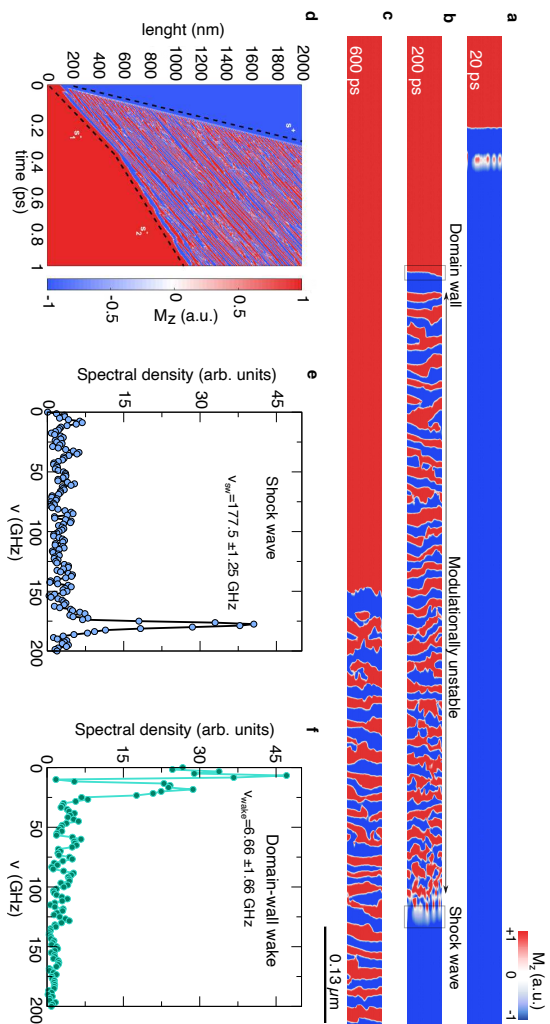


Figure 6