Avalanches through windows: Multiscale visualization in magnetic thin films

Alessandro Magni*, Gianfranco Durin*†, Stefano Zapperi‡†, James P. Sethna§
*Istituto Nazionale di Ricerca Metrologica (I.N.Ri.M), Strada delle Cacce, 91 - 10135 Torino Italy
‡CNR-INFM National Center on nanoStructures and bioSystems at Surfaces (S3)
Dep.of Physics, University of Modena and Reggio Emilia, Via Campi 213/A, 41100 Modena - Italy
† ISI foundation, Viale S. Severo 65 - 10133 Torino - Italy
§LASSP, Physics Department, Clark Hall, Cornell University, Ithaca, NY 14853-2501

***Abstract*—The dynamics of domain walls motion in thin films is usually performed with magneto-optical methods, which require to detect a sequence of images in time, for different field of view. The resulting avalanche distributions give interesting hints on the magnetization dynamics, but are strongly dependent on the size of the windows chosen. Here we investigate how to properly detect the size of the single avalanches, and how to understand the finite-size effects of the boundary conditions.**

I. Introduction

The jerky motion of domain walls in soft magnetic materials, a basic example of complexity in materials science, has been the subject of a long and continuing series of studies. In bulk magnetic systems, most of the statistical properties are now understood in terms of a depinning transition of the domain wall, and many experimental results are well explained in by these theories [1]. In thin films, the motion of walls is presumably dominated by depinning as well, but our understanding of the dynamics is still at a preliminary stage. Despite the lower dimensionality, it is well known that domain walls in two dimensions often exhibit more complex structures than simple Bloch walls, and the dominant interactions important for the wall dynamics are much more complicate to be determined. Also, from the experimental point of view, the data available are still limited, although the few recent papers published using the magneto-optical Kerr effect (MOKE) have shown interesting and promising results. In 2000, Puppin [2] measured the critical exponent τ of the avalanche size distribution $P(S) \sim S^{-\tau} f(S/S_o)$ in a Fe/MgO film of 90 nm to be about $\tau \sim 1.1$, much less than the values reported in the literature for bulk systems. Later, Kim *et al.* [3] indeed measured larger values $\tau \sim 1.3$ in Co thin films of different thicknesses (5 - 50 nm). Very recently, Ryu *et al.* [4] have argued that in a 50 nm MnAs film on GaAs(001), having a Curie temperature of only about 45 ^{o}C, there is a cross-over between different universality classes driven by temperature, with the exponent τ continuously changing from 1.32 to 1.04 as the temperature is increased from 20 to 35 ^{o}C. All of these experiments rely upon measuring avalanches optically, in a small sub-window of the entire sample. Usually, windows of varying sizes are used, and the distributions are superimposed to fit the critical exponent τ over a few decades. In all these experiments, no information on the effect of the window size on the avalanche statistics is really taken into account, as, for instance, the dependence of the distribution cutoff S_o on the window sizes.

In this paper, we aim to explore some experimental issues associated with extracting avalanche statistics from optical data of this kind. First, we need to set reliable methods for extracting avalanche distributions from a series of optical images, properly taking into account the effect of background noise. This is clearly the central issue to be able to determine accurate critical exponents. Secondly, we need to investigate the proper scaling approach to address the finite-size cutoff in the avalanche sizes induced by the observation window. This will introduce further critical exponents, which are useful to unveil new information on the domain wall dynamics.

II. Avalanche distributions from a sequence of MOKE images

The determination of size of an avalanche using magneto-optics is not as simple as the one used in fluxometric measurements, which are especially suitable for bulk materials [1]. In these measurements, in fact, one detects the change of magnetization on time, and the avalanches are simply defined introducing a single noise threshold which unambiguously sets the beginning and end of the avalanche. Clearly, it is far more challenging to separate signal from noise in the richer space-time information provided by the sequence of MOKE images. Here the challenge is to find the space-time surface $\Gamma(x, y)$ separating the flipped from the unflipped spins. This problem is particularly important when extracting avalanche size distributions, where the small avalanches are crucial for in estimates of the critical exponents.

To address this question, we acquired in continuous mode the images of the motion of zig-zag domain walls on Permalloy thin films, using the high-resolution longitudinal Kerr effect, with the sample magnetized by a slowly varying longitudinal in-plane field. The microscope is a Zeiss Axioscop2 Plus, modified with additional optical elements to obtain a parallel *s*-polarized light beam exiting the objective, and with an off-axis aperture stop in the objective back-focal plane to obtain the correct Kerr angle of the light beam. The magnification is given by 20x and 10x objectives (with numerical aperture 0.40 and 0.25 respectively) which allow us to acquire images having sizes $480\mu m \times 340\mu m$ and $880\mu m X 660\mu m$. The microscope uses a Zeiss Axiocam HRm camera (14 bit, Peltier cooled), whose main bottleneck is the time needed (about 0.5-0.8 s) to transfer successive frames to the computer for storage. The field is applied with an Helmholtz coils, which allow the application of fields up to $\approx$ 20 kA/m along the light incidence plane. The observations are made under a sinusoidally varying field, with f=1mHz.

As usual with images obtained by in-plane Kerr effect, the contrast of the unprocessed images is fairly low. Therefore, prior to acquisition, a reference state is captured at saturation. After the run, the reference state is subtracted to each image to allow the observation of the magnetic state variation only. Successive steps involve smoothing and gray level normalization to enhance the image contrast [5], [6].

After this pretty standard procedure, we now need to clearly identify the domains in the images. We first attempted to make use of morphological operators (open/close, erode/dilate, tophat) or make convolutions with different matrices, as these operations are in general able to reduce the noise by using the spatial information around each pixel. As a matter of fact, these operations can be problematic, especially in reducing the number of small avalanches. For this reason, we prefer to first keep the raw images. Also the application of edge detection routines, for instance, are not really useful in determining the position of the walls. The general point is that by analyzing each image in isolation, we lose the useful information provided by the time sequence.

Indeed, a simple but effective starting point is to ignore the spatial information and consider only the evolution in time for each pixel. A significant jump in the measured intensity at that pixel represents the switching time Γ for the magnetization at that point. In fig. 1, we report an example of the gray intensity of three adjacent pixels. While it is evident that all of them switch at the same time around the 22nd frame, it is not so obvious how to perform the calculation which detects it correctly for the three sequences. For instance, as the change in the gray scale for the blue central sequence is much smaller, considering simple numerical derivative can give spurious answers. We considered a series of routines with different levels of smoothing and derivative calculation, but inevitably found that a small but non-negligible number of pixels appear to switch at the wrong time. To correct for this, we need to encode also the spatial information, using algorithms that adjust the switching time to that of adjacent pixels if they appear to be in the same avalanche except for small noise. In any case, these methods are pretty delicate, as they can reduce or eventually destroy small avalanches, which, as said, are essential for critical exponent estimation.

An example of avalanche visualization is shown in fig. 2, where we use the same color palette (from red to blue) as used by ref. [4] for ease of comparison. On the left, we show the jump sequence for a field of view of $880 \times 660\mu$m, in which we did not apply any spatial correction to the pixels, so that a certain number of incorrect switches are shown. In any case, the sequence of zig-zag domains is well detected, showing the

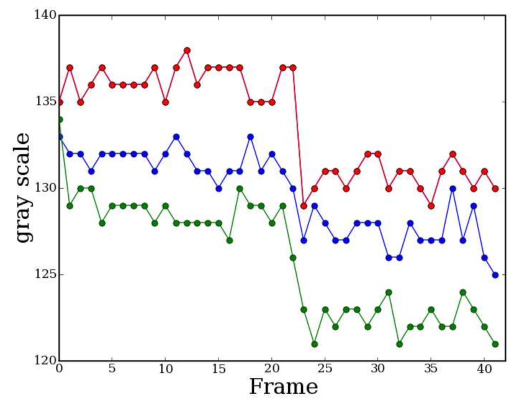

Figure 1. Time sequences of the gray scale for three adjacent pixels in a MOKE image. Visual inspection clearly recognize the pixels as having the same switching time, but numerical calculation can give spurious results due to the noise of the sequences and the reduced change of the gray level, especially for the central blue one.

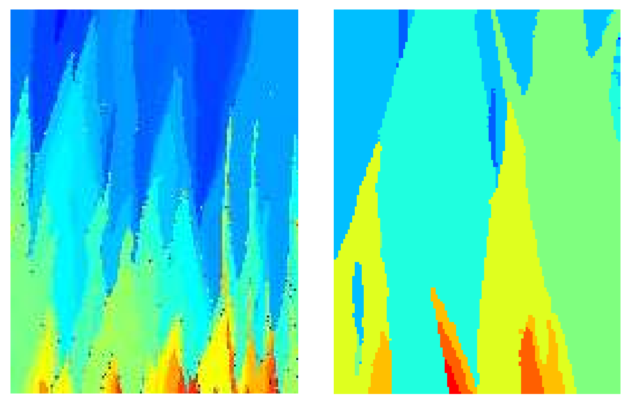

Figure 2. Jump sequences on a 170 nm permalloy thin film at two fields of view (880 $\times$ 660 μn (left), and 440 $\times$ 330). Magnetic field direction is vertical. The color code represents the time at which the jump occurs (from red to blue).

jerky character of domain wall motion. On the right, taken at a larger magnification ($480 \times 340\mu$m), we do apply the spatial correction, giving a significant decrease of incorrect switches.

In the comparison of the two images, it is clear not only that different fields of view detect different details of the domain wall jumps, but, notably, large jumps are chopped and detected as much smaller avalanches in smaller frames. In other words, the size of the window has a strong influence on the largest avalanche size which can be detected. Given that the best experiments can only measure two or three decades of avalanche sizes for a given window, it would be valuable to combine information from several window sizes; to do so we must understand the finite-size effects with windowed boundary conditions.

III. Multiscale measurements of avalanche distributions: varying the window size

To explore the effect of windows size on the avalanche distributions, we consider a model for a domain wall moving in a random environment. While the model in not completely realistic in term of the experiments, it provides a prototypical description of a self-affine interface moving in a disordered landscape. The equation of motion for the domain wall is given by

$$\frac{dh(x,t)}{dt} = H - k\bar{h} + \nu\frac{d^2h}{dx^2} + \lambda\frac{d}{dx}\left(\frac{dh}{dx}\right)^3 + \eta(x,h) \quad (1)$$

where $h(x,t)$ is the position of the domain wall,$\bar{h}$ is the center of mass of the wall that is proportional to the magnetization, $H(t)$ is a slow varying external field, k is the demagnetizing factor, $\nu\frac{d^2h}{dx^2}$ is the domain wall linear stiffness to which we added a small non-linear correction controlled by λ, and $\eta(x,h)$ is a random field describing all the inhomogeneities present in the sample. The effect of the non-linearity is crucial in two dimensions since otherwise the model would display anomalous scaling with super-rough behavior [7]. We simulate a cellular automaton version of Eq. 1 where time and space are discretized and the local velocity can assume only the values 0 or 1. The model displays an avalanche distribution with scaling exponent $\tau = 1.18 \pm 0.01$. The domain wall is found to be self-affine with a roughness exponent $\zeta = 0.65 \pm 0.05$, in good agreement with the result $\zeta = 0.63$, reported in Ref. [7].

In order to compare the model with the experiments, we restrict our analysis to the avalanches (or avalanche fractions) occuring inside square windows of linear size $L = 16, 32, 64, 128, 256$, for a system of total width $L_{tot} = 2048$. There are two empirical methods that can be used to correct for the finite window size: following Puppin [2], one can measure only the net magnetization within the window, or, in contrast, incorporate only avalanches that touch none of the borders of the window – avoiding the extra truncated avalanches. Fig. 3 shows the results of our simulation using the latter method, where only the avalanches that do not touch the sides of an $L \times L$ window are incorporated. The intricated part of analyzing this data is that the large avalanches near depinning transitions are increasingly anisotropic: an avalanche with width W will have typical height $H \sim W^{\zeta}$. If $\zeta < 1$, as in the case of eq. 1, large avalanches become short and fat. This means that the main effect of large windows is to cut off the widest avalanches, while at small window sizes a substantial number of tall avalanches may also be removed. Thus, unlike isotropic finite-size scaling, the effects of larger windows are not similar to the small windows: they are similar to smaller windows *of a different shape*.

We can analyze the data using the finite-size scaling form

$$P(S,L) = S^{-\tau}\mathcal{P}_W(S/L^{1/\sigma\nu}) \quad (2)$$

appropriate for systems with a strip geometry of width L and infinite height. Doing so, we find that the fitted exponents $\tau = 1.19 \pm 0.10$, $1/\sigma\nu = 1 + \zeta = 1.72 \pm 0.06$ are close to the theoretically expected values ($\tau \sim 1.18$ and $1/\sigma\nu = 1.63$) In contrast, we found that the distribution including also the avalanches touching the window borders has an exponent τ continuously changing with window size, slowly approaching

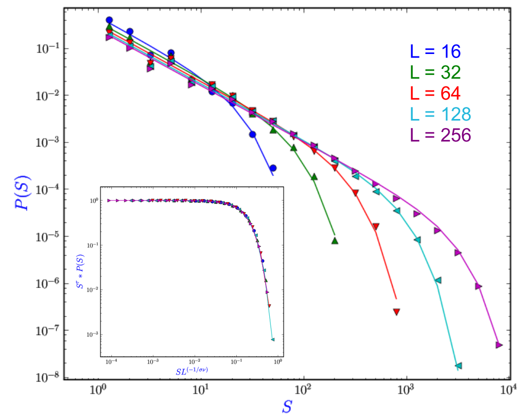

Figure 3. Distribution of avalanche sizes inside windows of different sizes L but not touching the borders of the windows. Inset shows the finite-size scaling collapse of eq. 2, with $\tau = 1.19 \pm 0.10$, $1/\sigma\nu = 1.7 \pm 0.06$.

the theoretical value only at the largest window sizes (Fig. 4). As we might expect, only for large windows which primarily throw away short-and-fat avalanches does the scaling analysis apply, with the window size acting as the strip width W.

IV. Conclusions

The experimental and theoretical analysis shown here enables us to conclude that the measurements at different window sizes must be take with care, since the extimated exponents can reflect the limited size of the windows. In particular, in the experiments, the use of a set of different magnifications, instead of being a practical limit, gives a considerable advantage, as, when statistical distributions are properly rescaled, it allows to estimate other critical exponents (i.e. $1/\sigma\nu$) which can better characterize the dynamics domain wall in thin films.

JPS would like to acknowledge NSF DMR-070167 for support.

References

[1] G. Durin and S. Zapperi, *The Science of Hysteresis: Physical Modeling, Micromagnetics, and Magnetization Dynamics*. Amsterdam: Academic Press, 2005, vol. II, ch. III "The Barkhausen noise", pp. 181–267, (Preprint on cond-mat/0404512).

[2] E. Puppin, "Statistical properties of Barkhausen noise in thin Fe films," *Phys. Rev. Lett.*, vol. 84, pp. 5415–5418, 2000.

[3] D.-H. Kim, S.-B. Choe, and S.-C. Shin, "Direct observation of Barkhausen avalanche in Co thin films," *Phys. Rev. Lett.*, vol. 90, p. 087203, 2003.

[4] K.-S. Ryu, H. Akinaga, and S.-C. Shin, "Tunable scaling behavior observed in Barkhausen criticality of a ferromagnetic film", *Nat. Phys.*, vol. 3, no. 8, pp. 547–550, 2007.

[5] F. Schmidt, W. Rave, A. Hubert, "Enhancement of magneto-optical domain observation by digital image processing", IEEE Trans. Magn. MAG-21 (1985), 1596.

[6] M. Nixon, A. Aguado, "Feature extraction and image processing", Elsevier Science and Technology Books (2002).

[7] A. Rosso, W. Krauth, "Origin of the Roughness Exponent in Elastic Strings at the Depinning Threshold", *Phys. Rev. Lett.*, vol. 87, p.187002, 2001

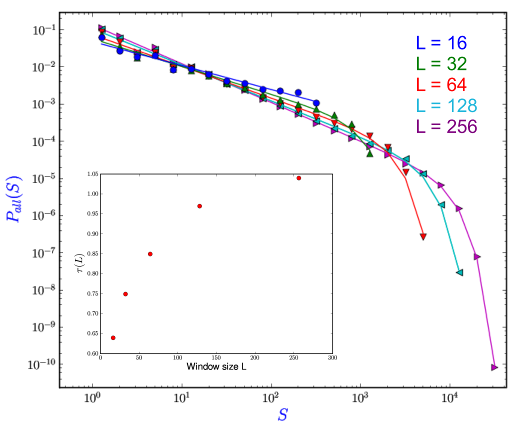

Figure 4. Distribution of avalanche sizes inside windows of different sizes L touching the borders of the windows. Inset shows the change of the fitted exponent τ with the window size L, approaching the theoretical value of $\tau = 1.18$ for large sizes.