Scaling of average avalanche shapes for acoustic emission during jerky twin boundary motion in single-crystalline Ni_2MnGa

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[2]: *Faculty of Mechanical Engineering, Technion - Israel Institute of Technology, Haifa, Israel*

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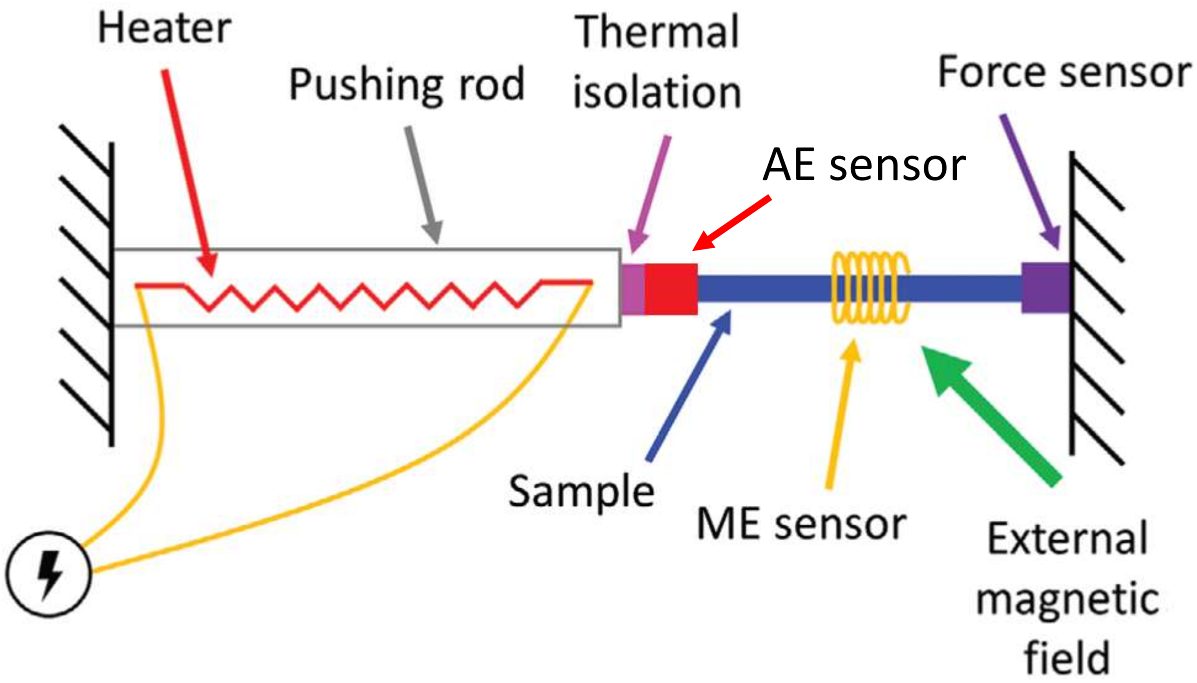
Experimental details



Overview

- 10M modulated $Ni_{50.0}Mn_{28.5}Ga_{21.5}$ single crystal Dimensions 20 mm × 3 mm × 2.5 mm
- Room temperature: fully martensitic state
- Slow compression: 2 µm/sec rate, using thermal expansion of an alumina rod
- Extrenal magnetic field: 0.08 T

Noise data acquisition:

- Magnetic coil (ME) + Piezoelectric sensor (AE)
- National instruments PCI6111 DAQ board
- 4 MSample/sec

Stress data acquisition:

- Kistler 9215A (force sensor) + 5015 (amplifier)
- National instruments PCI6071E DAQ board
- 10 kSample/sec

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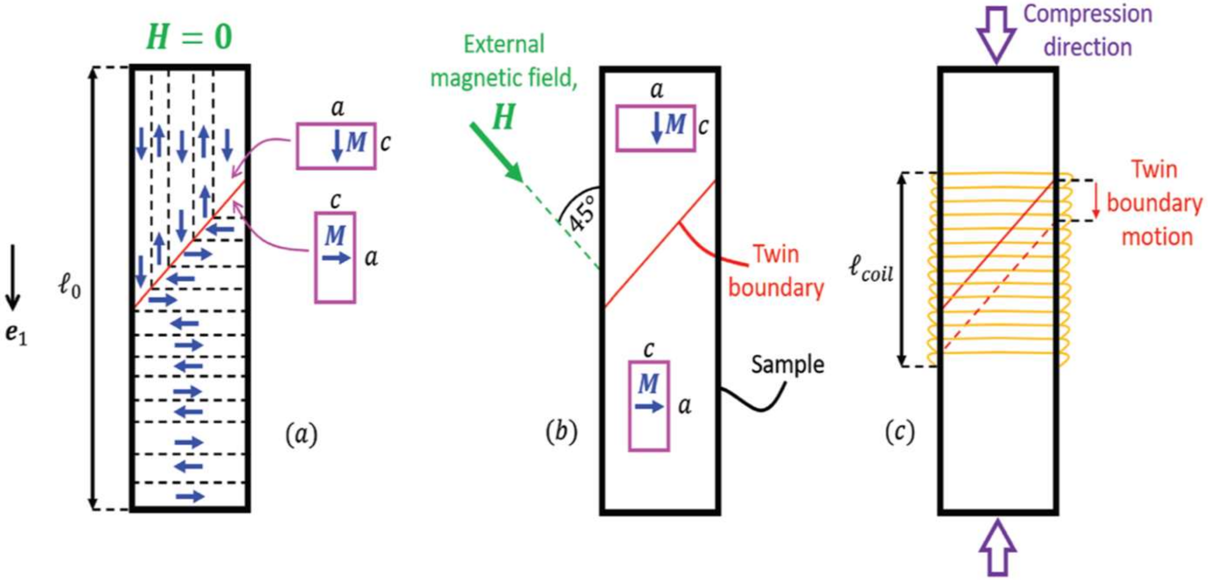
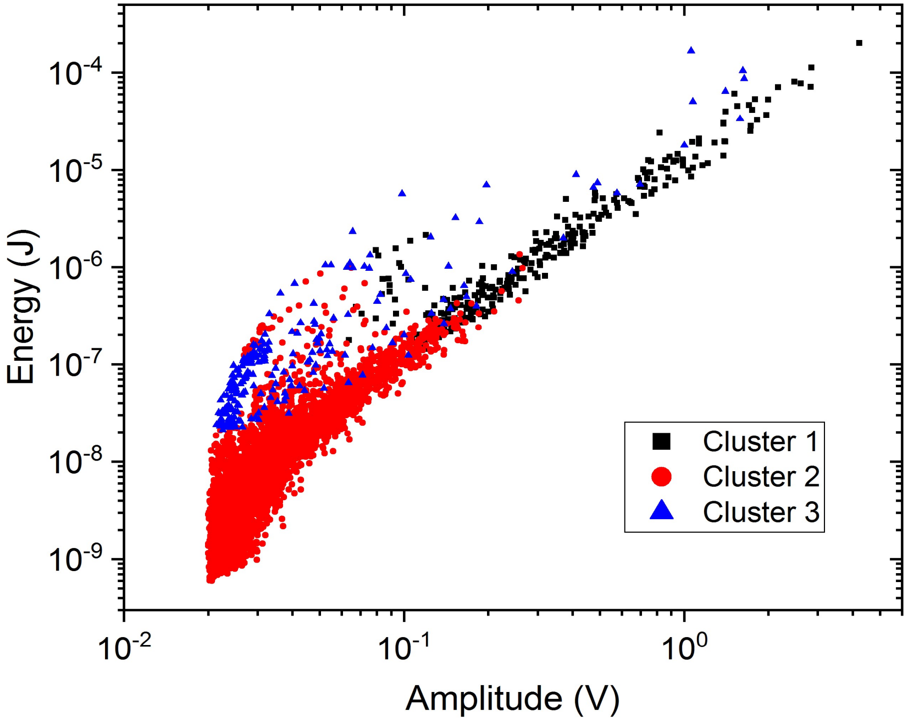
Experimental details



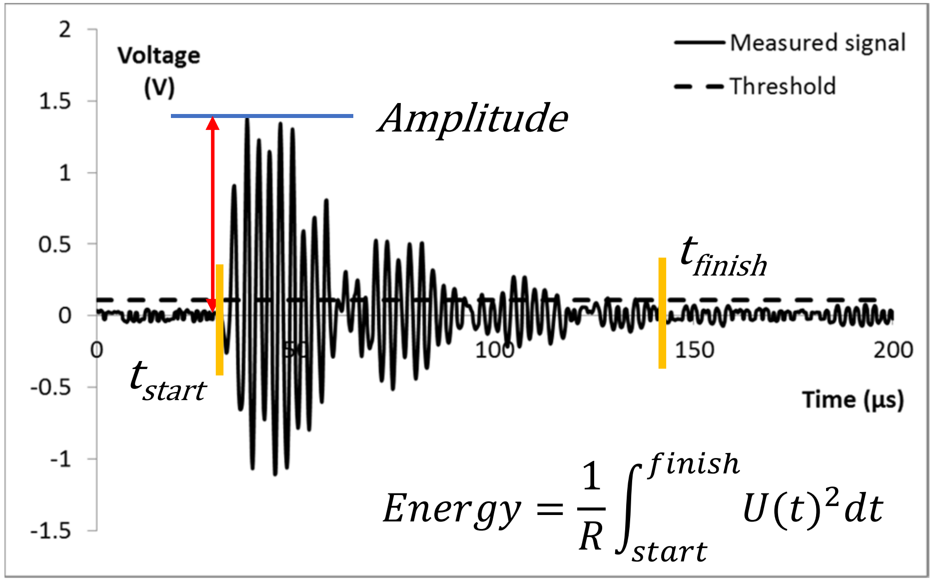
[1]: E. Bronstein, L. Z. Tóth, L. Daróczi, D. L. Beke, R. Talmon, & D. Shilo: Tracking Twin Boundary Jerky Motion at Nanometer and Microsecond Scales. *Advanced Functional Materials*, ***31*****(50)**, 2106573 (2021)

- Investigation of **single twin boundary motion**, induced by **slow compression; the magnetizations of the two neighboring twins ensure no magnetic domains at the twin boundary**
- Simultaneous measurement of **stress, acoustic emission** (AE) and **magnetic emission** (ME) to study the connection between them.
- There is a **definite agreement between** the transformed volumes calculated from **the force and the ME measurements → Ref. [1]**
- **This presentation focuses on the acoustic emission results and on the average avalanche profiles and on the scaling relations**

Processing the AE signals



[2]: E. Pomponi, & A. Vinogradov, *Mechanical Systems and Signal Processing*, ***40*(2)**, 791-804. (2013)



- Identification of AE avalanches
- Calculation of AE avalanche parameters
- Clustering [2] to eliminate false AE avalanches and background noise → ”Cluster 3”
- Statistical analysis

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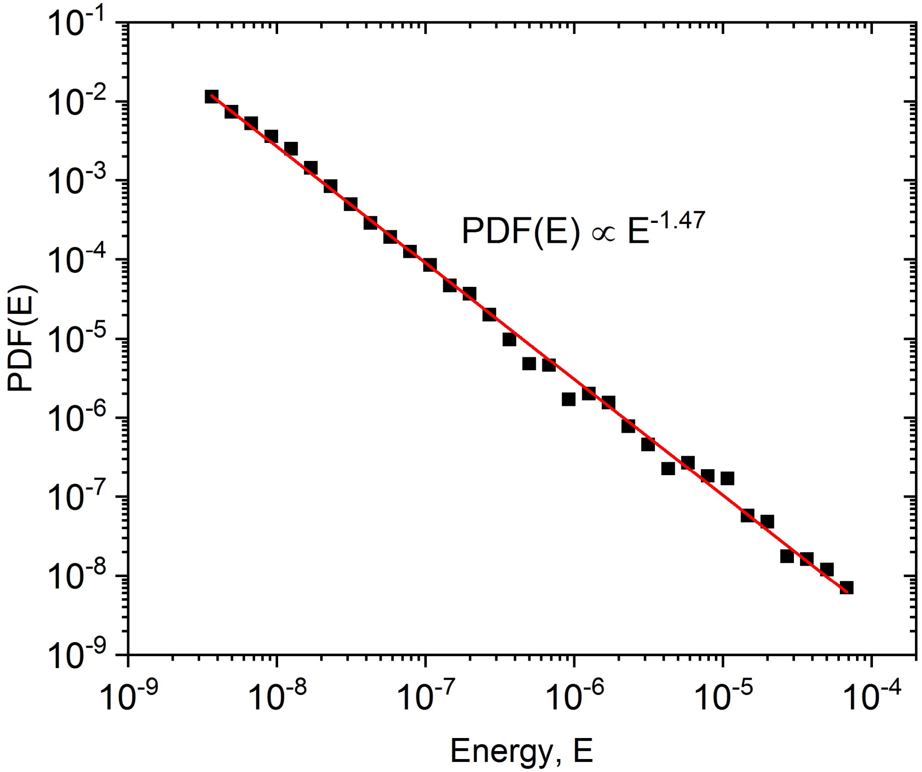
Acoustic emission results

- Crackling noise (avalanches) with power-law distribution characteristics:

$$P(x) \sim x^{-\eta} \exp\left(-\frac{x}{x_c}\right)$$

- X can be the peak amplitude, A_m, size, S, or energy, E; η is the characteristic exponent, and X_c is the cut-off value

Exponent	Magnetic emission [1]	Acoustic emission
Amplitude, α	*1.6*	1.99
Energy, ε	*1.26*	1.47
Size, σ	*0.8*	1.79



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Average shape of avalanches

- Power-law scaling relations between the above parameters (and between the exponents) were obtained:
- $E \propto A_m^x$, $S \propto A_m^\chi$, or $A_m \propto T^\xi$;
- In MFT: $x = 3$, $\chi = 2$ and $\xi = 1$.
- The focus is increasingly on the **temporal shapes of avalanches**, i.e. the average of the detected voltage signal ($U(t)$) for a given size (or duration) range of avalanches.
- Average avalanche shapes can be used when the measured voltage is **proportional to the corresponding interface velocity** v(t), characteristic for the crackling noise emission.

Average avalanche shape for fixed size

The theoretically predicted temporal shape of the avalanche is given by [3]:

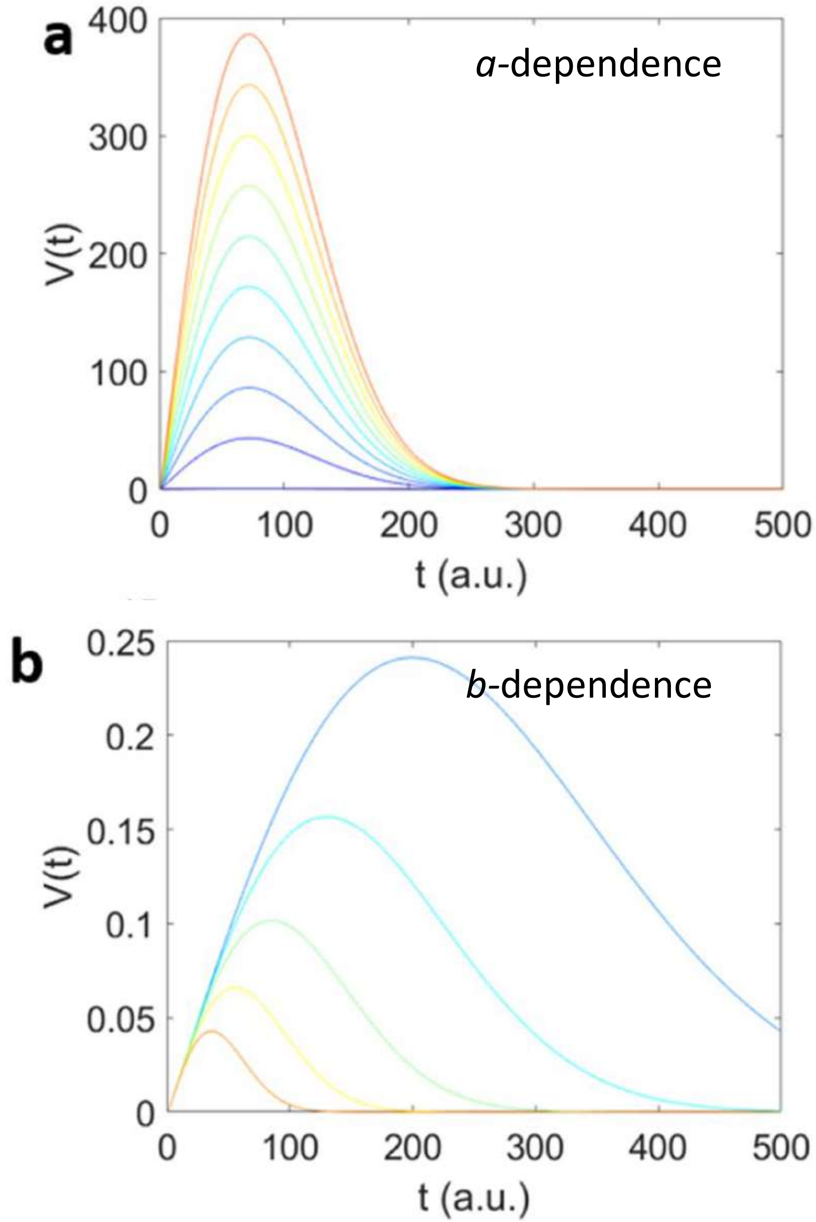
$$U(t) = at exp^{-bt^2},$$

where $b = {}^{1}/_{\tau^2}$, and τ is the characteristic time decay of the avalanche.

The above equation has maxima at:

$$t_m = \frac{\tau}{\sqrt{2}} = \frac{1}{\sqrt{2b}}$$

$$A_m = at_m e^{-{}^{1}/_{2}} = Bt_m$$



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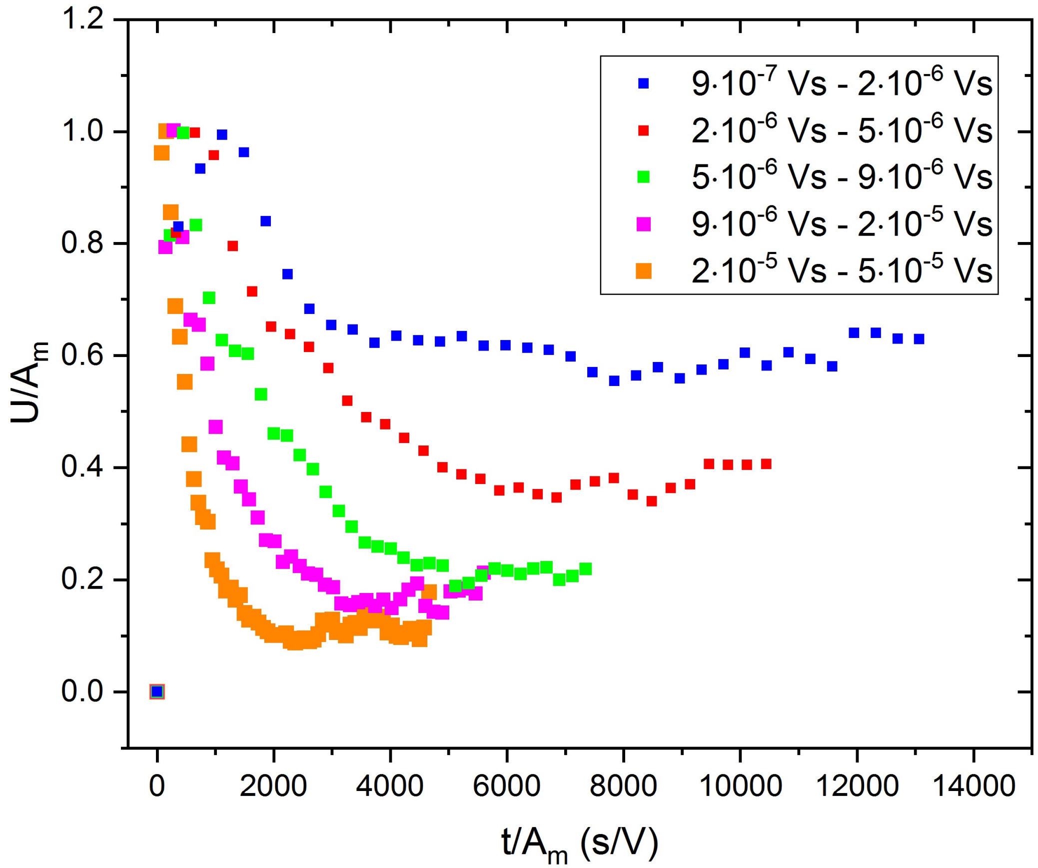
[3]: Casals, B., *et al. Sci. Rep.* **11,** 5590 (2021).

- **The average avalanche shape** has self-similar behaviour, with an appropriate normalization, they **should be scaled together**, according to a universal scaling function.
- The normalization should be performed with $\mathbf{A_m}$ and $\mathbf{t_m}$ (not distorted by the transfer function of the system [3]).
- In the experiments, t_m has high uncertainty
- Thus, **if B is constant, we can use $t_m \propto A_m$**
- **Both axis can be normalized by A_m**



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The normalization by A_m was not working, the scaling was not perfect
Which implies that **B is not constant**, and thus, a (and b or τ) are not universal constants, rather **B has a definite dependence on A_m[4]:**

$$B \propto a \propto A_m^{\varphi}$$

Thus, using $A_m = Bt_m$, we can write:

$$t_m \propto {}^{A_m}/_{B} \propto A_m^{1-\varphi}$$

Scaling the experimentaly determined avalanche shapes with A_m (voltage axis) and $A_m^{1-\varphi}$ (time axis) should produce better scaling:

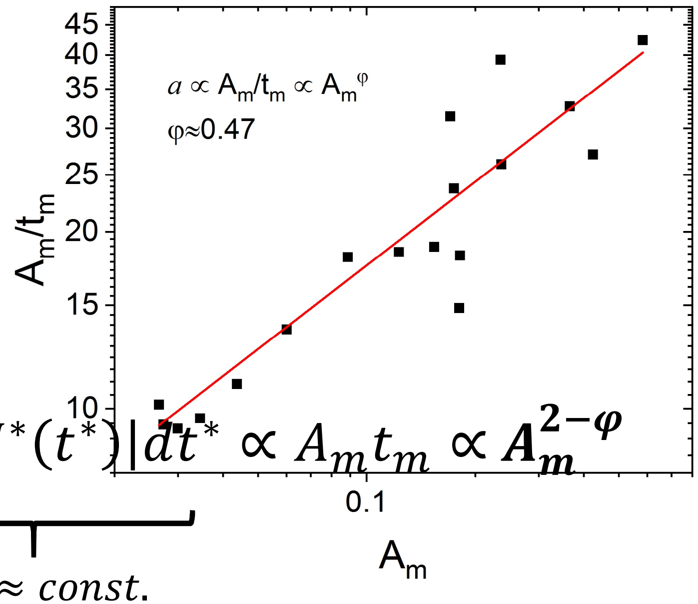
$$U^*(t^*) \propto e^{1/2} t^* \exp - \left(\frac{t^*}{\tau^*}\right)^2,$$

where $U^* = \frac{U}{A_m}$, $t^* = \frac{t}{t_m} = \frac{t}{A_m^{1-\varphi}}$, as well as $\tau^* = \frac{\tau}{A_m^{1-\varphi}}$

[4]: S. M. Kamel et al. Materials, 2022,15, 4556

How to determine ϕ?

- Directly, from the ${A_m}/{t_m} \propto A_m^{\varphi}$ scaling relation,
- $S \propto A_m^{2-\varphi}$,
- $E \propto A_m^{3-\varphi}$



$$\boldsymbol{S} = \int_0^T |U(t)|dt = \int_0^{T^*} A_m|U^*(t^*)|t_m dt^* = A_m t_m \underbrace{\int_0^{T^*} |U^*(t^*)|dt^*}_{S^* \approx const.} \propto A_m t_m \propto \boldsymbol{A_m^{2-\varphi}}$$

$$S^* = \frac{S}{A_m t_m} = \int_0^{T^*} |U^*(t^*)|dt^* = 1.65\left(1 - e^{-\frac{{T^*}^2}{2}}\right) = 1.65\left(1 - \frac{C}{A_m}\right) \qquad T^* \approx \sqrt{2ln\frac{A_m}{C}}$$

T^* goes to an asymptotic limit as C (threshold) goes to zero [4].

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[4]: S. M. Kamel et al. Materials, 2022,15, 4556

$$\left(U^* = \frac{U}{A_m}, \quad t^* = \frac{t}{t_m}, \quad T^* = \frac{T}{t_m}\right)$$

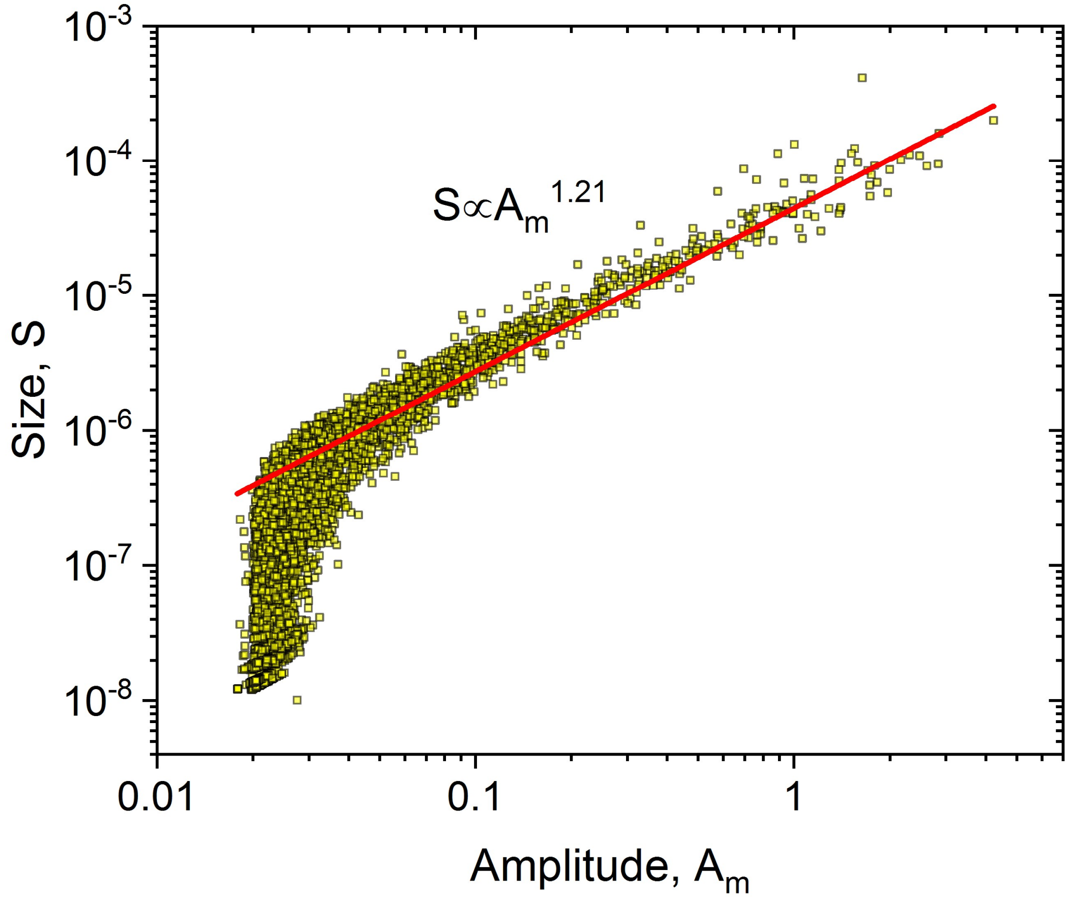
$$S \propto A_m^{2-\varphi}$$

$$2 - \varphi = 1.21$$

$$\boldsymbol{\varphi_S = 0.79}$$

From power exponents of size (σ=1.79) and amplitude (α=1.99):

$$\frac{\alpha - 1}{\sigma - 1} = 2 - \varphi = 1.24$$



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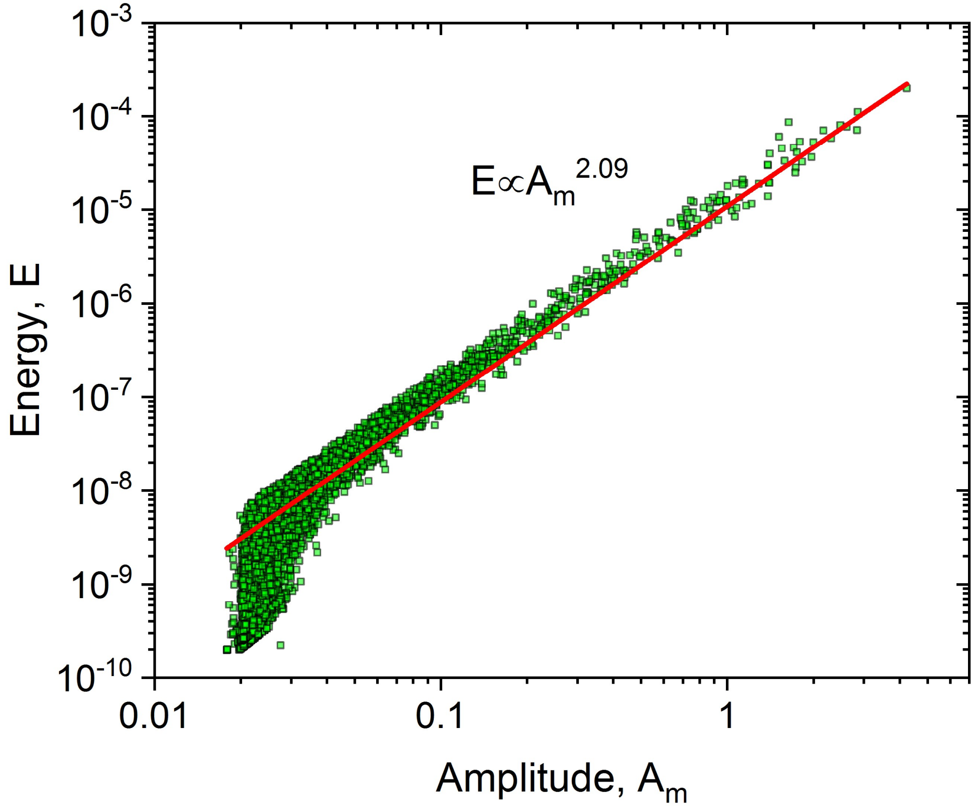
$$\boldsymbol{E} = \frac{1}{R}\int_0^T U^2(t)dt \propto \int_0^{T^*} {A_m}^2 {U^*}^2(t^*) t_m dt^* = {A_m}^2 t_m \int_0^{T^*} {U^*}^2(t^*)dt^* \propto {A_m}^2 t_m \propto \boldsymbol{A_m^{3-\varphi}}$$



$$3 - \varphi = 2.09$$

$$\boldsymbol{\varphi_E = 0.91}$$

From power exponents of energy (ε=1.47) and amplitude (α=1.99):

$$\frac{\alpha - 1}{\varepsilon - 1} = 3 - \varphi = 2.10$$

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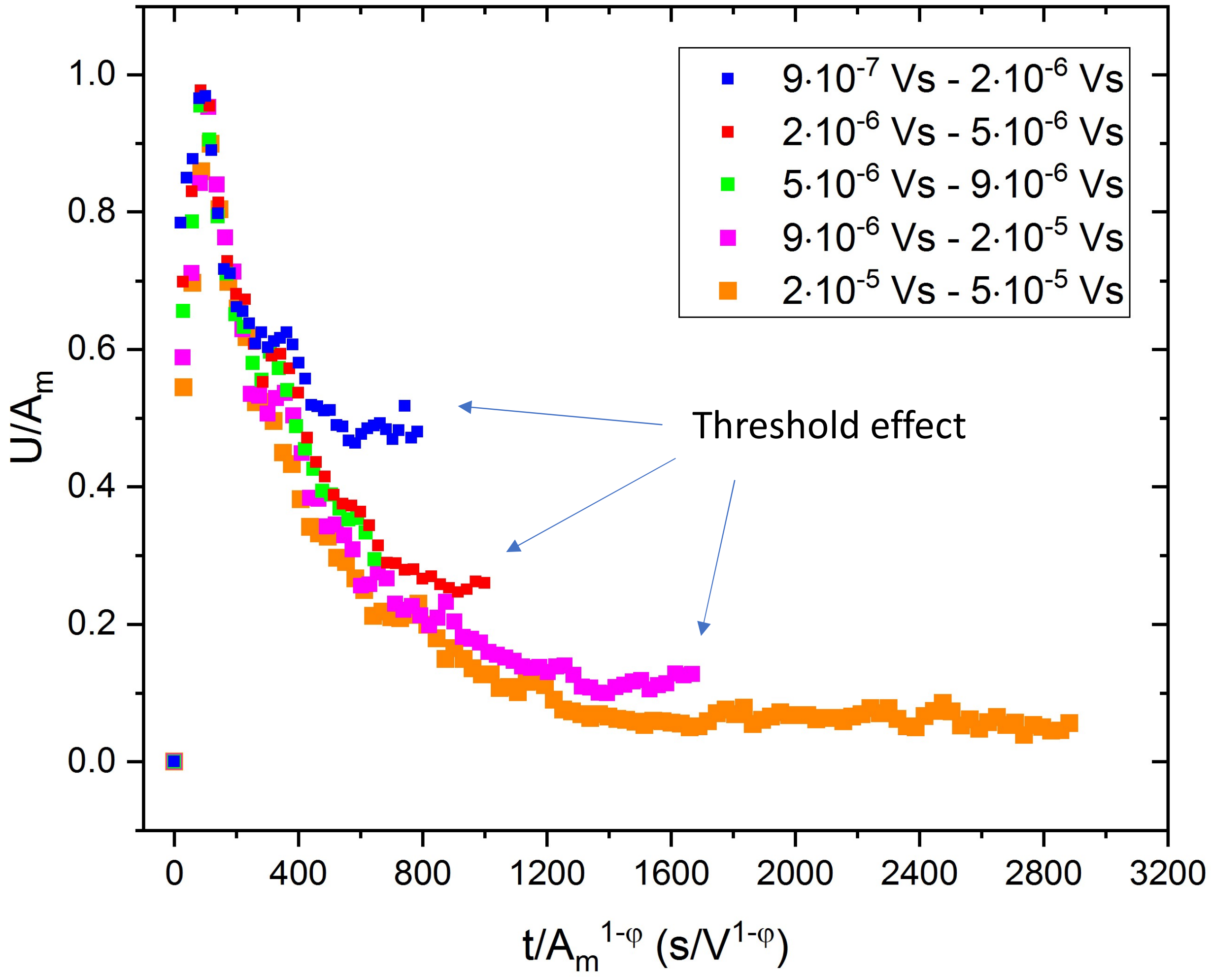
Average avalanche shapes for various fixed avalanche sizes,
Normalized by A_m and $A_m^{1-\varphi}$, φ=0.85

$$\varphi = \frac{\varphi_S + \varphi_E}{2} = 0.85$$

- Impressive scaling of the avalanches belonging to different size ranges.
- The effect of the threshold is visible near the end of the curves (especially for the smallest size range).



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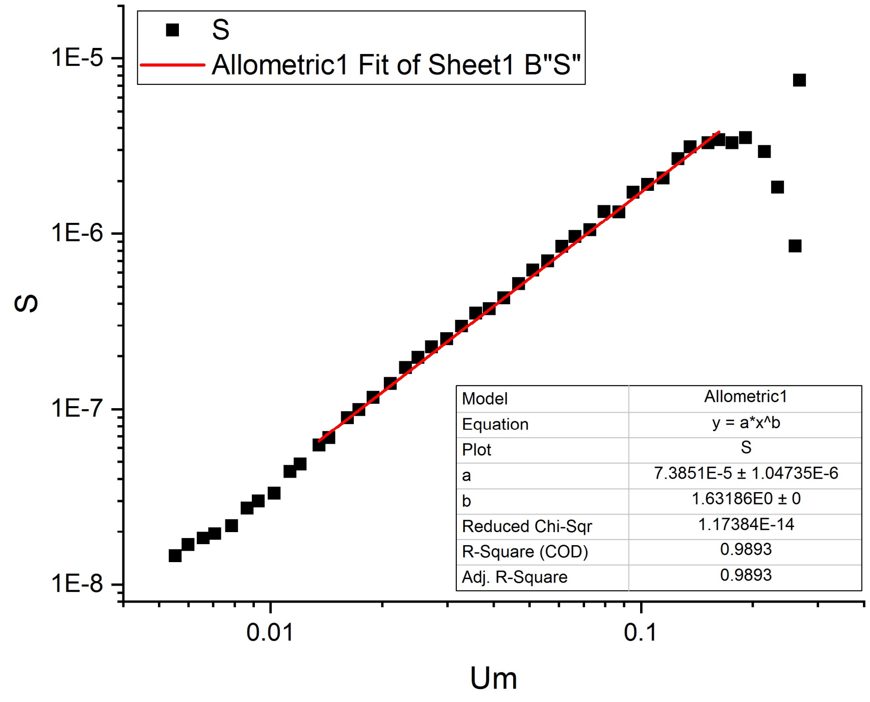
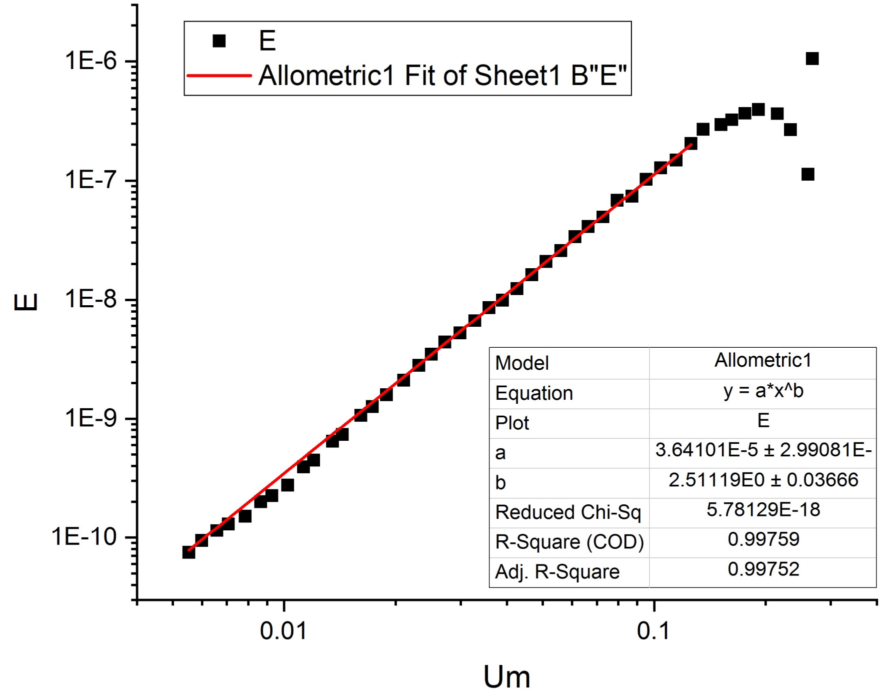
Magnetic emission





$$\frac{\partial lnS}{\partial lnU_m} \approx 2 - \varphi \approx 1.63 \qquad \varphi_S \approx 0.37$$

$$\frac{\partial lnE}{\partial lnU_m} \sim 3 - \varphi \qquad \varphi_E \approx 0.49$$

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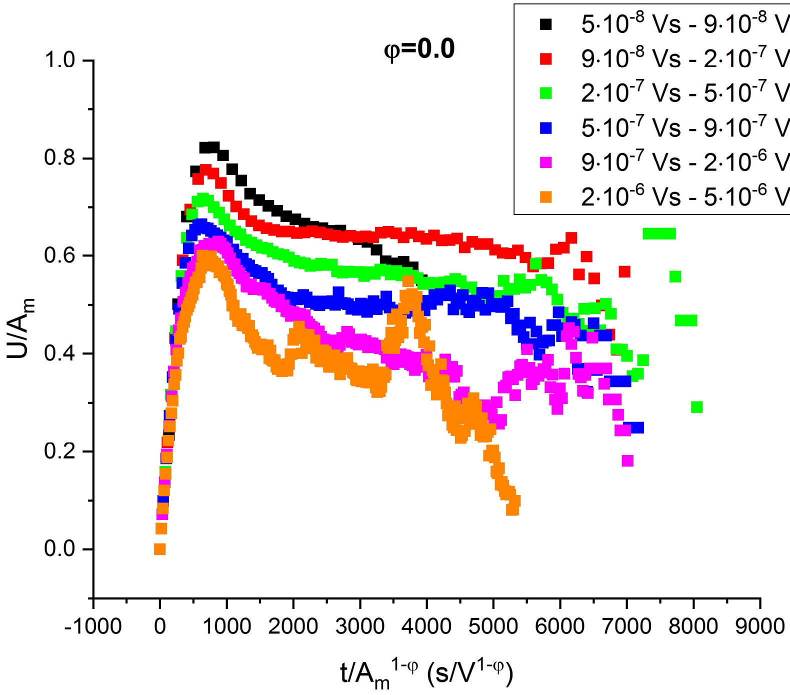
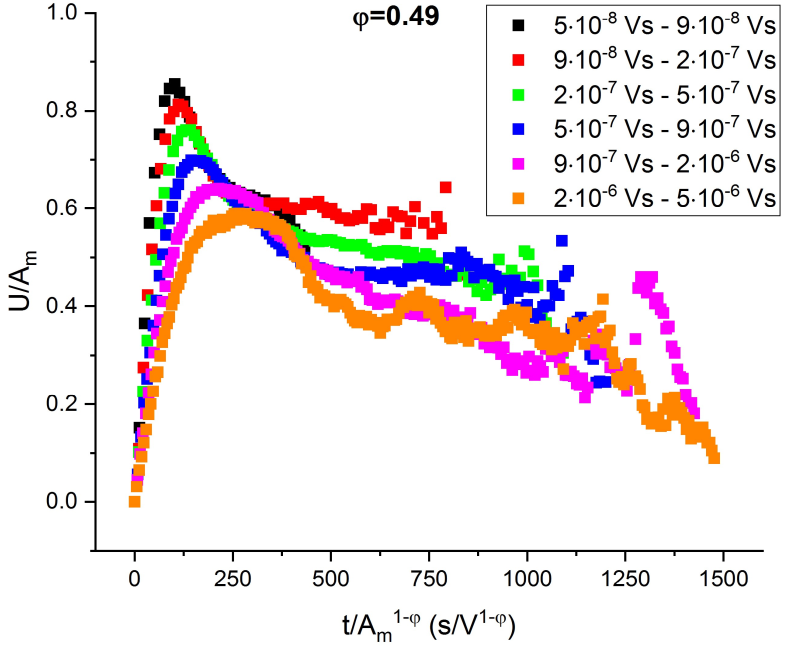


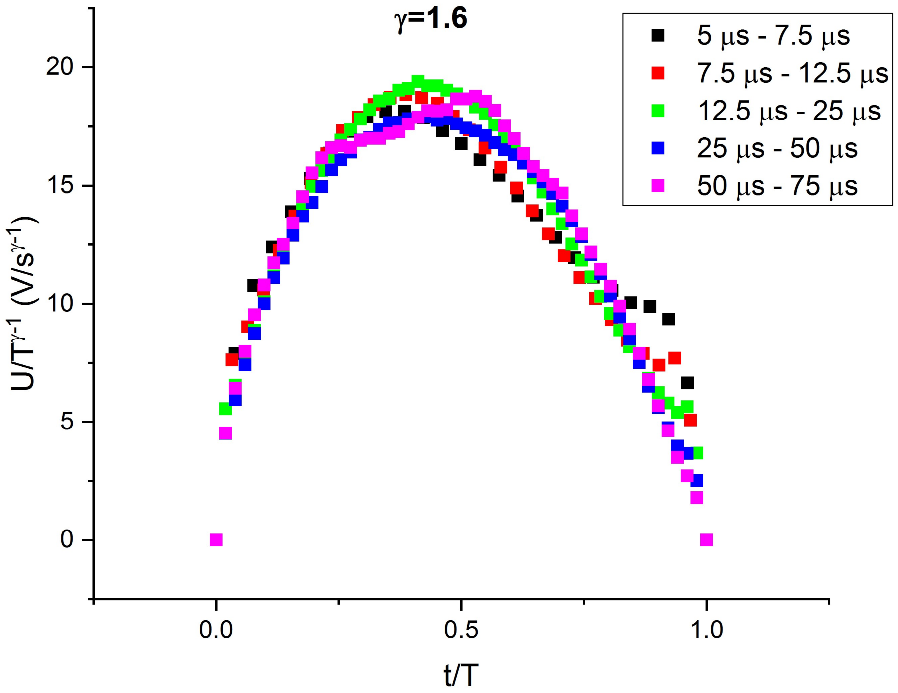


- The scaling of the magnetic avalanches is poor
- Experimental reasons: Eddy currents, …

Average avalanche shape for fixed duration [5]:

$$\langle U(t|T)\rangle \propto T^{\gamma-1}\left[\frac{t}{T}\left(1-\frac{t}{T}\right)\right]^{\gamma}\left[1-a\left(\frac{t}{T}-\frac{1}{2}\right)\right]$$

$S \propto T^{\gamma}$ → $\gamma = 1.6$



Very good scaling of the average shape for various fixed duration ranges
Visible skewness: Eddy currents

[5]: Laurson, et al. "Evolution of the average avalanche shape with the universality class." *Nature communications* 4.1 (2013): 1-6.

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