Magneto-optical study of magnetic flux avalanches in Nb and NbTi

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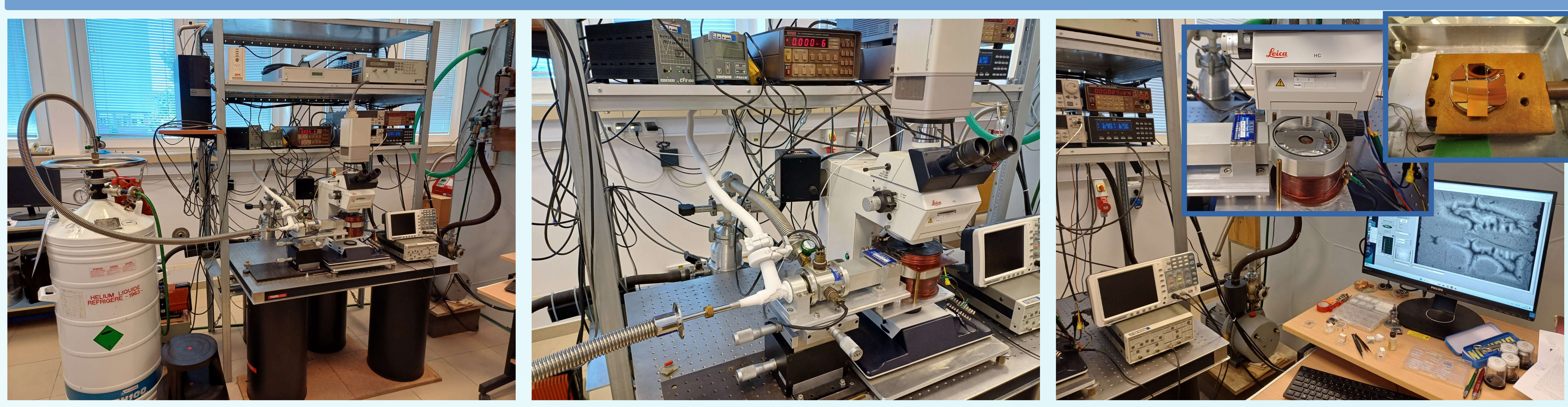
Abstract

In the present work, we have analyzed, using the magneto-optical method, the dynamic phenomena observed in thin-film and bulk superconductors with Nb and NbTi during the setting of an external magnetic field, investigated the conditions for the development of thermomagnetic instabilities (avalanches) and determined the parameters of the samples from measurements of the avalanche properties.

Magneto-optical imaging technique



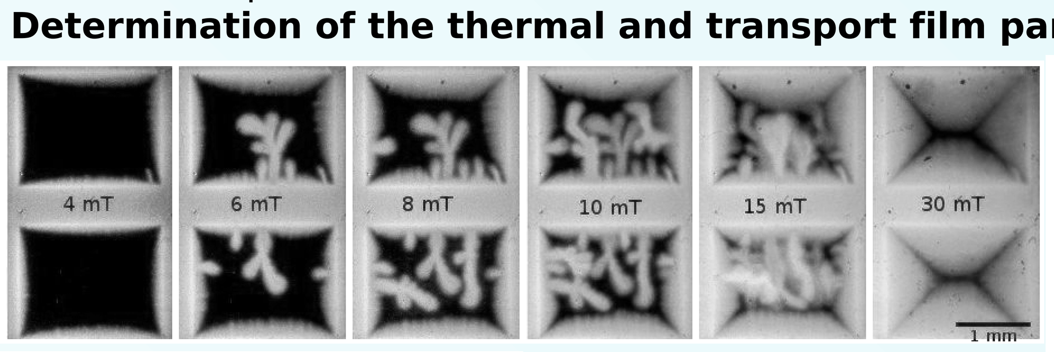
The sample is placed on a sample holder connected to a cold finger in a cryostat chamber pumped to high vacuum using a setup consisting of a turbomolecular pump and a two-stage vane pump. A liquid helium-cooled cold finger acts as a kind of cryogenic pump to further improve the vacuum in the cryostat chamber. The sample is cooled by a stream of liquid helium, which is drawn from the main reservoir of the storage dewar into the sample mount using a single-stage rotary vacuum pump. In the helium pumping system, local volumetric expansion and evaporation of helium is generated near the sample holder, allowing the temperature to decrease due to adiabatic cooling to 2.3 K in this area and to 4 K at the sample mounting point.

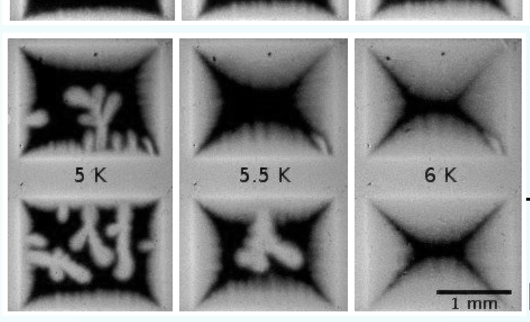
The magneto-optical (MO) method for studying superconducting materials is based on imaging the magnetic flux penetration into a superconducting sample cooled below the superconducting critical temperature. The magnetic flux is visualized using the Faraday effect in an iron-garnet indicator placed on top of the studied superconducting sample. The indicator rotates the plane of polarized light formed by the polarizer. The angle of rotation is proportional to the local magnetic field parallel to the direction of light propagation. The image of polarized light intensity corresponding to the magnetic flux distribution in the sample is recorded by a setup consisting of a polarization microscope, CCD camera and computer.

Flux avalanches in Nb films

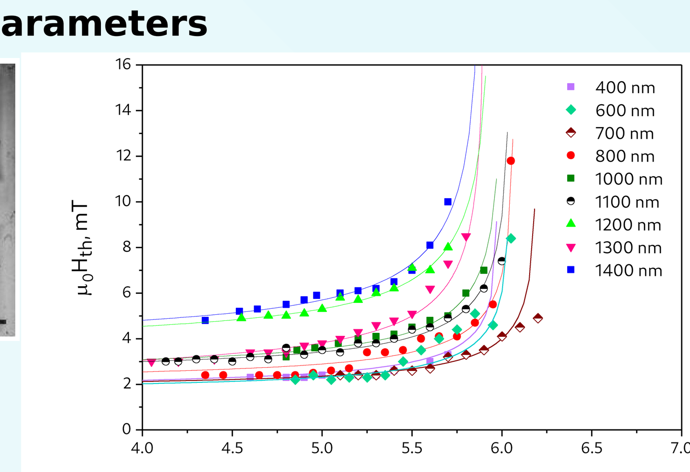
The penetration of magnetic flux into the superconducting films becomes highly inhomogeneous under certain conditions, taking the form of finger or dendritic instabilities, which develop into flux avalanches.

Determination of the thermal and transport film parameters

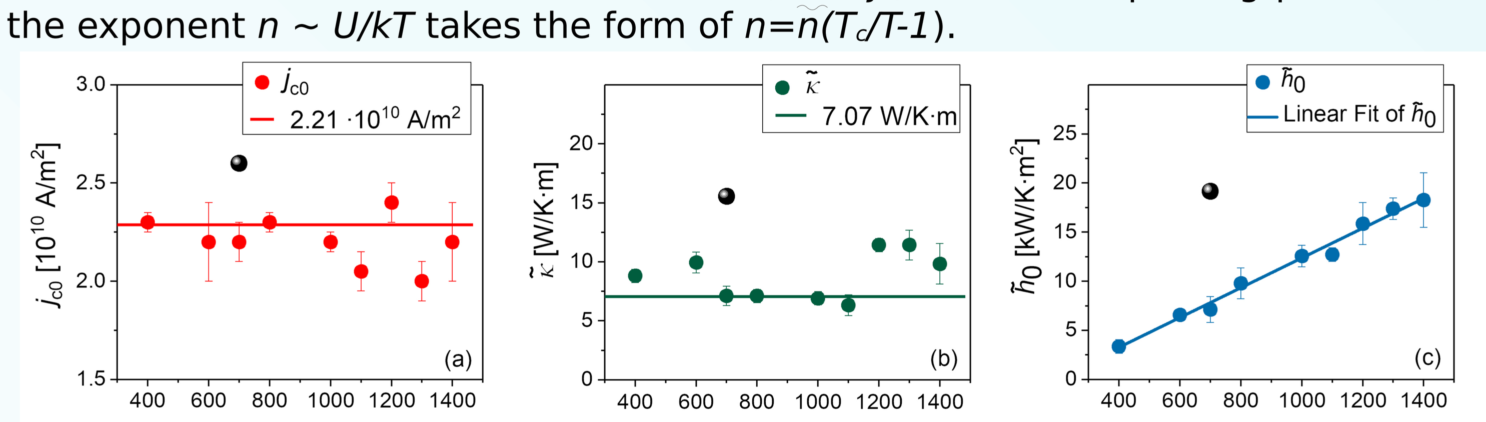




Nb on glass, 600 nm, magnetron sputtering, ← 8 mT, ↑ 5K



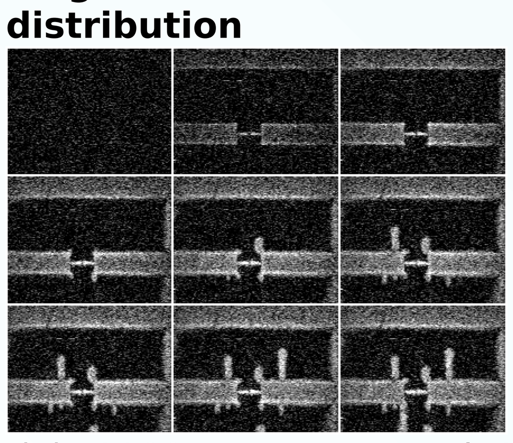
The threshold magnetic field H_{th} at which superconductor first becomes unstable: $H_{th}=\frac{j_c d}{\pi} arccosh\left(\frac{w}{w-l_{th}}\right)$, where w and d are the sample width and thickness respectively, l_{th} is the threshold flux penetration depth corresponding to H_{th} [4]: $l_{th}=\frac{\pi}{2}\sqrt{\frac{\kappa}{|j_c'|E}}\left(1-\sqrt{\frac{2h_0}{nd|j_c|E}}\right)^{-1}$. Here j_c' is the temperature derivative of the $j_c=j_{c0}(1-T/T_c)$, $\kappa=\kappa(T/T_c)^3$ is the thermal conductivity, $h_0=h_0(T/T_c)^3$ is the heat transfer coefficient between the film and the substrate, $E \propto j^n$, and with a pinning potential, $U \propto 1-T/T_c$, the exponent $n \sim U/kT$ takes the form of $n=n(T_c/T-1)$.



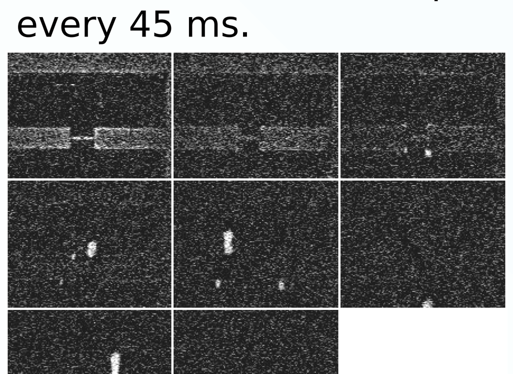
Thermal and transport characteristics of niobium-glass and niobium-sapphire systems. Color symbols: thickness dependences of j_{c0}, κ (b) and h_0 (c) for Nb films on glass. Black symbols: corresponding parameters of 700 nm Nb film on Al_2O_3.

Relaxation process of magnetic flux distribution

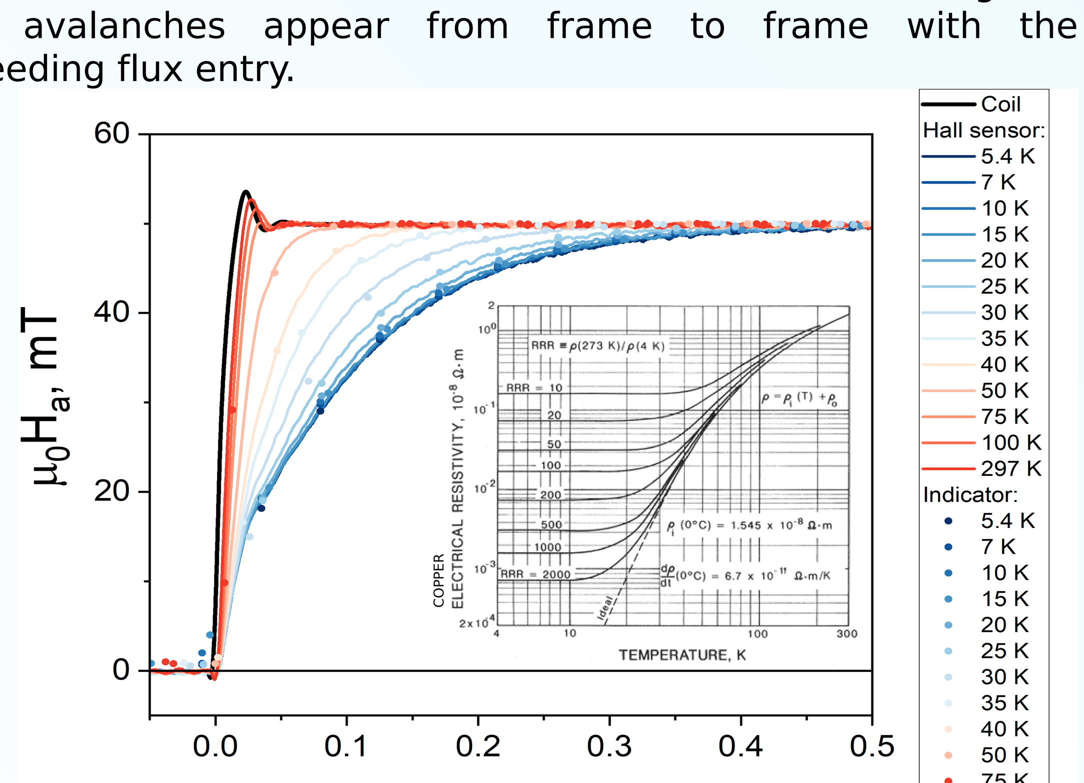
The avalanche penetration time is shorter than the time interval between two frames recorded at the highest speed that our camera can provide. At this recording speed, the image resolution is significantly reduced as the frame size of the camera is downsized to only 168×128 pixels. We do not see the gradual development of a single avalanche, but the relaxation processes accompanying switching on of the external magnetic field take about nine such frames, i.e., about 0.4 s. During this time avalanches appear from frame to frame with the proceeding flux entry.



(a) 1100 nm patterned Nb film at 4.5 K. A magnetic field of 4.5 mT is switched on between the first and second frames. Frames are captured every 45 ms.



(b) Each of the images is the difference between the neighboring images in (a).



Establishment of a local magnetic field inside the cryostat at different temperatures during the increase of the external magnetic field generated by the magnet.

Flux avalanches in bulk NbTi disc

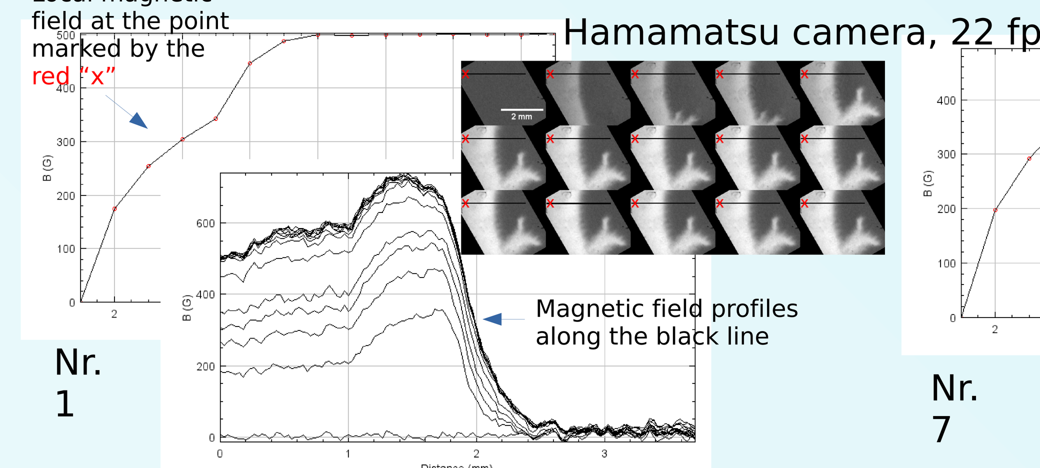
Dynamics of magnetic flux penetration into NbTi disk at switching on the external magnetic field

Relaxation processes in superconductors are described by the flux creep equation

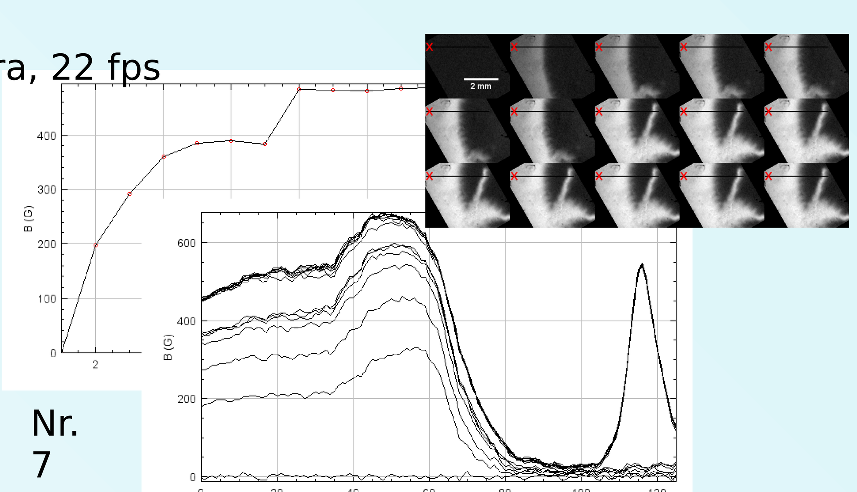
$$\Omega\mu_0\frac{dj}{dt}=-\chi_0\frac{dH_{ext}}{dt}+\Delta v_0\frac{B_{int}}{\mu_0}P(j,\ T,\ B_{int}),$$

where differential susceptibility χ_0 and the geometric factor Δ depend on the size and shape of the sample, $\Omega = M/j$ denotes the proportionality factor of current j and the magnetization M, v_0 denotes the vortex velocity, B_{int} denotes the internal field and P (j, T, B_{int}) denotes the vortex hopping probability. Larger sweep rate of external field results in larger P, less deep flux penetration and larger vortex density, which increases the impact of thermal fluctuations and avalanche development probability.

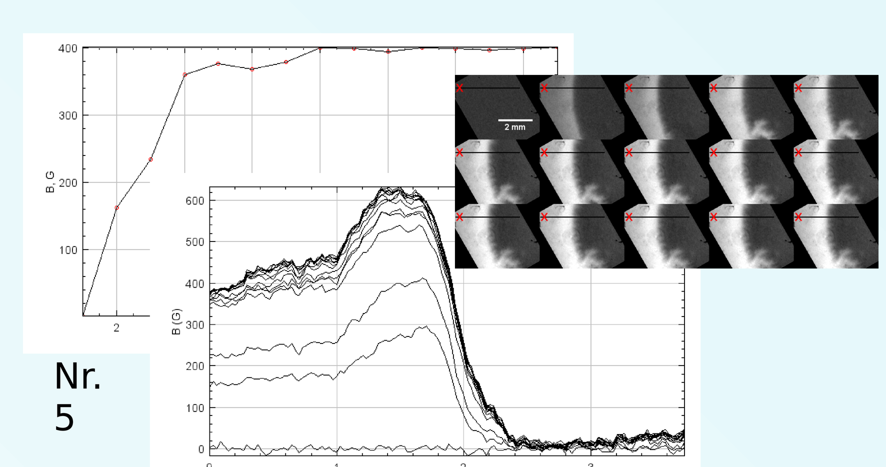
Hamamatsu camera, 22 fps



Nr. 1

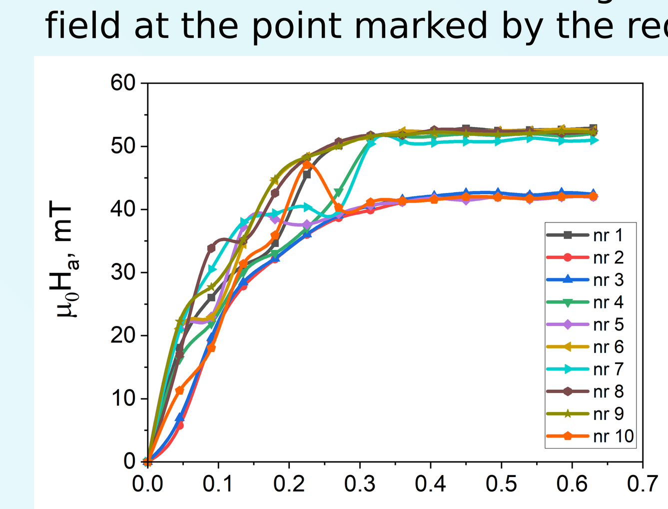


Nr. 7



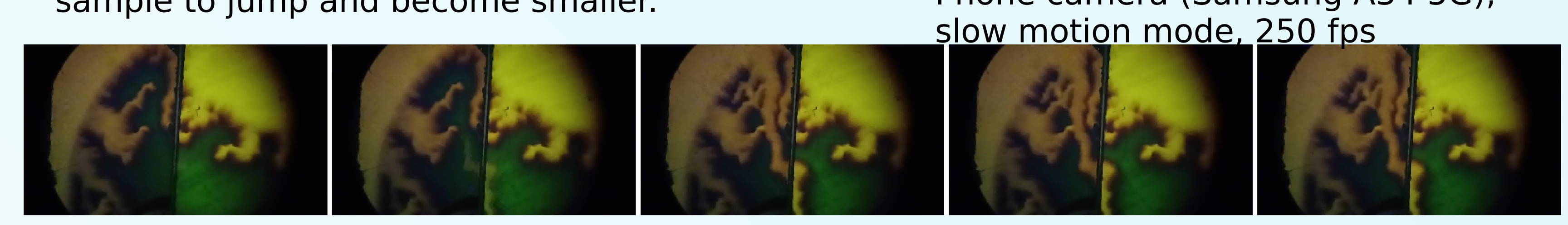
Nr. 5

Ten measurements of local magnetic field at the point marked by the red "x":



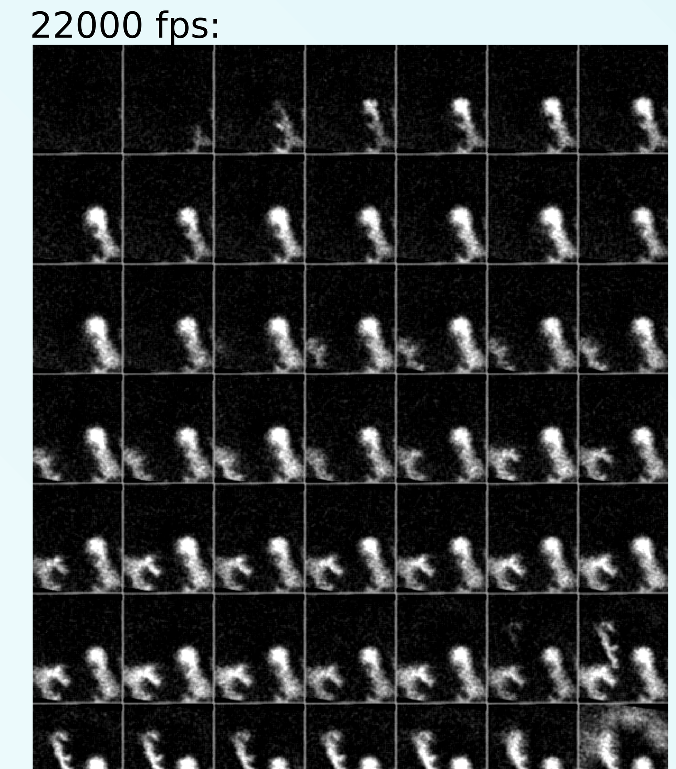
The abrupt redirection of the current causes the magnetic moment of the sample to jump and become smaller.

Phone camera (Samsung A34 5G), slow motion mode, 250 fps



Avalanche propagation velocity

22000 fps:



After cooling in an external magnetic field of 60 mT to a temperature of 6 K, -60 mT was applied. The process of avalanche entry was recorded by a Phantom fast camera.

An individual avalanche propagates about 2.8 mm in 91 μs, resulting in an **avalanche flow velocity of about 31 m/s**. The entry time of all avalanches within our field of view is about 25 ms. Previously, a spatio-temporal study was carried out to measure the avalanche speed in a 20 μm thick Nb foil by comparing the signals from Hall sensors placed on the foil 50 mm apart. The average avalanche transit time was estimated to be 0.8 ms, which gives an avalanche speed of a few cm/s. Interestingly, in thin films of MgB_2 or $YBa_2Cu_3O_{7-\delta}$, the dendrite propagation speed was estimated to be approximately 14-25 km/s.

This large value exceeds the speed of sound in these materials, and it is orders of magnitude higher than the avalanche propagation velocity in thick Nb foil and our bulk NbTi. This may indicate different scenarios of the avalanche propagation in these materials.