Flux avalanche regimes in bulk NbTi: dynamics, threshold field, and the role of thermal coupling

I. Abaloszewa[1,*], V. V. Chabanenko[2], and A. Abaloszew[1]

[1]Institute of Physics, Polish Academy of Sciences, Aleja Lotników 32/46, 02-668 Warsaw, Poland

[2]O. Galkin Donetsk Institute for Physics and Engineering, National Academy of Sciences of Ukraine, Kyiv, Ukraine

[*]*abali@ifpan.edu.pl*

Thermomagnetic flux avalanches in type-II superconductors have been systematically studied in thin films with strong thermal coupling to the substrate, where they propagate at km/s velocities on nanosecond timescales, are controlled by electromagnetic diffusion, and exhibit a threshold field for avalanche nucleation H_{th} that increases with temperature. Although the Mints–Rakhmanov stability framework [1] anticipated a distinct, thermally controlled regime under weak thermal coupling, this regime had not been identified experimentally: isolated bulk observations in Nb and NbZr [2, 3] did not resolve individual avalanche dynamics or address the temperature dependence of H_{th}, while bulk NbTi had been investigated only by integral magnetic techniques.

Using high-speed magneto-optical imaging at frame rates up to 22,000 fps, we report the first spatiotemporally resolved observations of individual flux avalanche events in bulk NbTi — a 12 mm diameter, 0.1 mm thick NbTi disk attached to the cold finger through a nonadecane ($C_{19}H_{40}$) layer with effective thermal boundary conductance $h \sim 10^3$ W/(m^2 K) [4]. Avalanches exhibit curved and dendritic morphologies and propagate at initial velocities of 15–25 m/s, decelerating to 5–10 m/s during penetration — three orders of magnitude slower than in thin films, where they typically propagate at constant velocity or accelerate. All events follow a universal normalized velocity–distance scaling. Analysis of the timescales places the dynamics under thermal control via boundary heat removal.

The threshold field $H_{\mathrm{th}}(T)$ for avalanche nucleation decreases with temperature — opposite to the increasing trend observed in thin films. This negative slope, naturally explained by thermal runaway under slow boundary heat removal, provides the first direct experimental signature of the thermally controlled regime. Together with the velocity scaling, it identifies the thermal boundary conductance h at the superconductor–environment interface as the parameter that drives the crossover between the thermally and electromagnetically controlled regimes, with an intermediate transitional regime expected at $h \sim h_c$; we propose an estimate of the critical conductance h_c separating the two limits. These results have direct implications for flux stability and quench protection in NbTi-based superconducting magnets.

References

[1] R. G. Mints, A. L. Rakhmanov, Rev. Mod. Phys. **53**, 551 (1981).

[2] M. R. Wertheimer, J. le G. Gilchrist, J. Phys. Chem. Solids **28**, 2509 (1967).

[3] R. B. Harrison, L. S. Wright, M. R. Wertheimer, Phys. Rev. B **7**, 1864 (1973).

[4] I. Abaloszewa, V. V. Chabanenko, A. Abaloszew, Phys. Rev. B **113**, 104511 (2026).