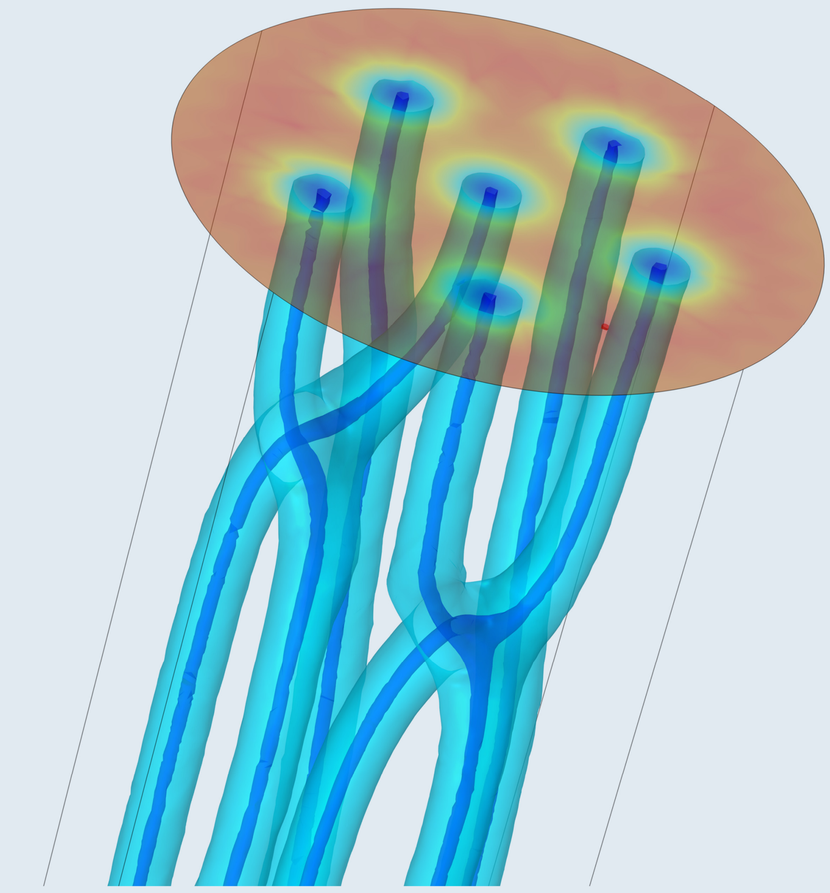


Visualization of Vortex Dynamics in Nanoscale Superconductors Using COMSOL Multiphysics®

Time-Dependent Ginzburg-Landau (TDGL) simulations visualize vortex penetration, nucleation, photon-induced dynamics, and three-dimensional vortex dynamics in nanoscale superconductors.

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Overview

Numerical simulations of the electromagnetic responses of nanoscale superconductors under transport currents and magnetic fields are performed using COMSOL Multiphysics® [1]. The simulations are based on the time-dependent Ginzburg–Landau (TDGL) equations, which describe the temporal evolution of the complex superconducting order parameter [2,3]. The equations are implemented using the Coefficient Form PDE interface without dedicated superconductivity modules. Four representative systems are examined: a superconducting disk in an external magnetic field [4,5], a current-carrying superconducting nanostrip [6,7], a current-biased nanostrip after photon absorption [8,9], and a three-dimensional superconducting nanowire [10,11].

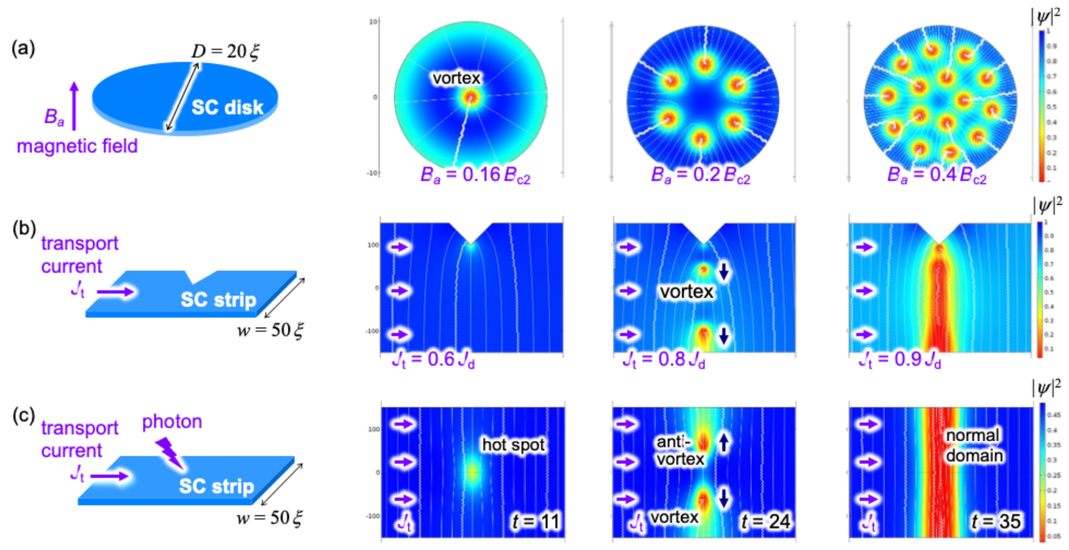


Fig 1. Two-dimensional TDGL simulations (ξ ~ nm). (a) Vortex penetration into a superconducting disk under a perpendicular magnetic field. (b) Current-carrying superconducting nanostrip with a notch. (c) Photon-induced dynamics in a current-biased superconducting nanostrip.

TDGL Model and COMSOL Implementation

The time-dependent Ginzburg–Landau (TDGL) equations [2,3] describe the temporal evolution of the complex superconducting order parameter. They are implemented using the Coefficient Form PDE interface in COMSOL Multiphysics® [1], without dedicated superconductivity physics modules. Two- and three-dimensional models are used to investigate vortex dynamics in superconducting disks, nanostrips, and nanowires.

TDGL equations for the order parameter ψ, the vector potential $\boldsymbol{A}$, and the scalar potential Φ are given by

$$\tau_0\left(\frac{\partial}{\partial t}+i\frac{2\pi}{\phi_0}\Phi\right)\psi=\xi^2\left(\boldsymbol{\nabla}-i\frac{2\pi}{\phi_0}\boldsymbol{A}\right)^2\psi+(1-|\psi|^2)\psi,$$

$$\frac{1}{\mu_0}\boldsymbol{\nabla}\times\boldsymbol{\nabla}\times\boldsymbol{A}=\frac{1}{\mu_0\lambda^2}\mathrm{Im}\left[\psi^*\left(\frac{\phi_0}{2\pi}\boldsymbol{\nabla}-i\boldsymbol{A}\right)\psi\right]-\sigma_n\left(\frac{\partial\boldsymbol{A}}{\partial t}+\boldsymbol{\nabla}\Phi\right),$$

where i is the imaginary unit, μ_0 the vacuum permeability, ϕ_0 the flux quantum, τ_0 the time constant, ξ the coherence length, λ the penetration depth, and σ_n the normal conductivity.

Results

- Magnetic-field-induced vortex penetration [Fig. 1(a)]:
  Vortices penetrate from the disk edge and eventually form a vortex lattice.
- Defect-induced vortex nucleation [Fig. 1(b)]:
  Current crowding promotes vortex nucleation at the notch, followed by vortex motion across the strip.
- Photon-induced dynamics [Fig. 1(c)]:
  Photon absorption locally suppresses superconductivity and induces a vortex–antivortex pair, whose motion can trigger a normal domain across the strip.
- Three-dimensional vortex dynamics [Fig. 2(b)]:
  Under longitudinal magnetic field and transport current, helical vortices emerge and undergo cutting and reconnection, accompanied by voltage pulses.

These simulations demonstrate that COMSOL Multiphysics® provides a flexible platform for visualizing complex vortex dynamics and superconducting-to-normal transitions in nanoscale superconductors.

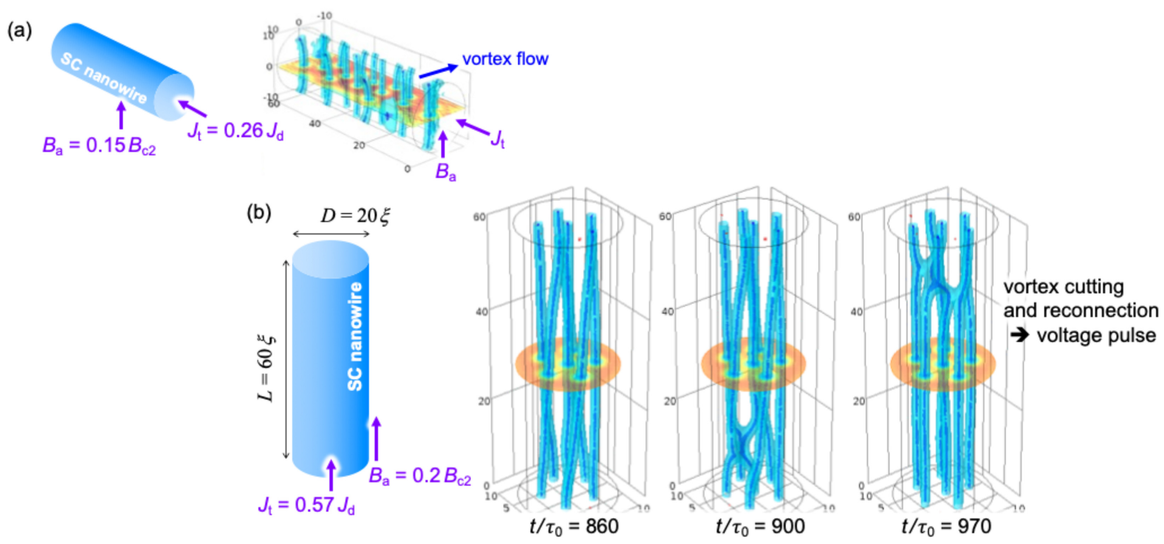


Fig 2. Three-dimensional vortex dynamics in a superconducting nanowire carrying a transport current under (a) transverse and (b) longitudinal magnetic fields. Helical vortices undergo cutting and reconnection in the longitudinal-field configuration. Representative configurations at t/τ_0 = 860, 900, and 970 are shown.

References

[1] COMSOL Multiphysics® v. 6.4, COMSOL AB, Stockholm, Sweden (2025).
[2] A. Schmid, "A Time Dependent Ginzburg–Landau Equation and Its Application to the Problem of Resistivity in the Mixed State," Phys. Kondens. Mater. **5**, 302 (1966).
[3] M. Tinkham, "Introduction to Superconductivity," 2nd ed., McGraw-Hill, New York (1996).
[4] A. K. Geim et al., "Phase transitions in individual sub-micrometre superconductors," Nature **390**, 259 (1997).
[5] V. A. Schweigert and F. M. Peeters, "Flux penetration and expulsion in thin superconducting disks," Phys. Rev. Lett. **83**, 2409 (1999).
[6] J. R. Clem and K. K. Berggren, "Geometry-dependent critical currents in superconducting nanocircuits," Phys. Rev. B **84**, 174510 (2011).
[7] D. Y. Vodolazov et al., "Defect-controlled vortex generation in current-carrying narrow superconducting strips," Supercond. Sci. Technol. **29**, 025002 (2016).
[8] A. N. Zotova and D. Y. Vodolazov, "Photon detection by current-carrying superconducting film: A time-dependent Ginzburg–Landau approach," Phys. Rev. B **85**, 024509 (2012).
[9] G. N. Gol'tsman et al., "Picosecond superconducting single-photon optical detector," Appl. Phys. Lett. **79**, 705 (2001).
[10] J. F. Blackburn, A. Campbell, and E. K. H. Salje, "The force-free case in three-dimensional superconductors: a computational study," Philos. Mag. B **80**(8), 1455 (2000).
[11] V. Vlasko-Vlasov et al., "Flux cutting in high-Tc superconductors," Phys. Rev. B **91**, 014516 (2015).

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