CryoQuant

Annual Report 2025

Cryogenic Quantum Electronics

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and Fundamental Electrical Engineering
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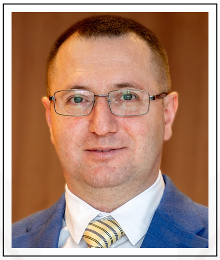
On the cover: Artistic view of a superconducting diode with periodic edge indentations, written by a focused ion beam in the group of Michael Huth, Goethe University Frankfurt, overlaid with the TDGL modelling results by CryoQuant. © Anton Pokusinskyi. For details, see the report on p. 6.

Dear Colleagues and Friends,



This year marks the first publication of our Annual Report since the establishment of the CryoQuant division in July 2024.

In Braunschweig, we operate at two locations: the ’Haus der Elektrotechnik’ and the Laboratory for Emerging Nanometrology (LENA). The research center LENA was founded in 2019 under the joint initiative ’New Research Buildings’ of the Federal Government of Germany and the State of Lower Saxony.

This year was primarily devoted to preparing the laboratories for major experimental equipment and laying the groundwork for the new group. Also, we began several research projects, and some of the obtained results are highlighted in this report.

Our group contributes to the Cluster of Excellence EXC-2123 *QuantumFrontiers*, which is entering its second funding period through 2032. We are involved in research networks, including *FLUXONICS* (European Foundry of Superconductive Electronics) and *BEACON* (Beam-Induced Nano Manufacturing).

All researchers of CryoQuant participate in the Braunschweig International Graduate School of Metrology (B-IGSM) and in the dynamic life of the Institute for Electrical Measurement Science and Fundamental Electrical Engineering (EMG).

We thank our funding supporters—the Ministry of Science and Culture of Lower Saxony (MWK Niedersachsen), German Research Foundation (DFG), Austrian Science Fund (FWF), and European Cooperation in Science and Technology (COST).

With all my best wishes for Christmas, and a Happy New Year!

Oleksandr Dobrovolskiy

Braunschweig, December 2025

Contents

The ‘Haus der Elektrotechnik‘ (left, © TeWeBs) and LENA (right, © Jan Hosan/TU Braunschweig).

Strategic Framework

Mission

We investigate the dynamics of collective excitations in superconducting and magnetic solids—fluxons and magnons—to develop novel applications in quantum electronics, sensing, and information processing. By bridging disciplines such as physics, materials science, electrical engineering, and nanotechnology, we aim to transform fundamental discoveries into practical innovations. Our research advances the frontiers of hybrid quantum systems by combining fluxonics and magnonics, and by pursuing their integration with semiconducting and photonic platforms.

Vision

Building on our work at the interface of condensed matter physics and electrical engineering, we integrate innovations from nanotechnology and materials science to advance energy-efficient, high-speed, novel computing concepts. Our vision is to drive the emergence of next-generation quantum devices and information systems that bridge fundamental phenomena with applications.

Synergy

TU President Prof. Angela Ittel and Vice President for Research Prof. Peter Hecker with the teams from the Clusters of Excellence *QuantumFrontiers* and *SE*^{2}*A*. © Kristina Rottig/TU Braunschweig.

Group Pictures

1st row: Igor Bogush, Zahra Makhdoumi Kakhaki, Anton Pokusinskyi, Roua Cheikh, Atul Mulwani,
2nd row: Neelesh Kumar, Kerstin Franke, Ralf Behme, Svitlana Babiichuk, Oleksandr Dobrovolskiy.

At the ICSM conference (May 2025), results on fluxonics and cryogenic magnonics were presented.

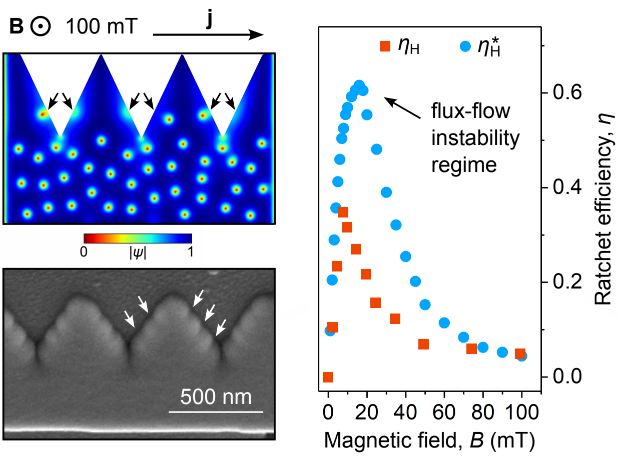
Research Highlights

Vortex ratchet effect in a NbC strip with edge indentation

Asymmetric edges create different energy barriers for Abrikosov vortex motion. Consequently, when the current polarity is reversed, vortices move more easily in one direction, producing a nonreciprocal current flow and a superconducting diode effect.

The motion of magnetic flux quanta in superconductors leads to dissipation, making its control crucial for fluxonic devices. Recently, interest has grown in the ratchet (diode) effect, which enables non-reciprocal, dissipationless currents and superconducting rectifiers, with potential applications in energy-efficient computing, memory, and switching systems. However, most approaches to superconducting ratchet systems involve patterning thin films across their entire area, and few studies have examined symmetry breaking from disparities in film edge barriers. In our work, we demonstrated that non-reciprocal current flow and vortex dynamics are observed for a superconducting NbC strip with periodic edge indentations. The notches induce current crowding and edge barrier suppression, facilitating vortex entry. Upon reversing the current polarity, we deduced a maximum ratchet efficiency of $\eta_{\mathrm{H}} \sim 35\%$ at an out-of-plane magnetic field of 16 mT, based on the difference in the depinning currents. Remarkably, the ratchet efficiency is even higher in the flux-flow instability regime, with $\eta^*_{\mathrm{H}} \sim 60\%$. Numerical simulations using the time-dependent Ginzburg-Landau equation support our findings and reveal the formation of “flux pockets”—regions where vortices become trapped between indentations—as well as diverse vortex configurations, including vortex chains, vortex jets, and vortex rivers.

The top left panel shows a snapshot of the modulus of the superconducting order parameter $|\psi|$. The bottom left panel presents a tilted scanning electron microscope image of the sample. The right panel illustrates how η first grows with increasing field, attains a maximum, and then falls as higher fields trigger additional vortex nucleation points that lessen the effect of the indentations.



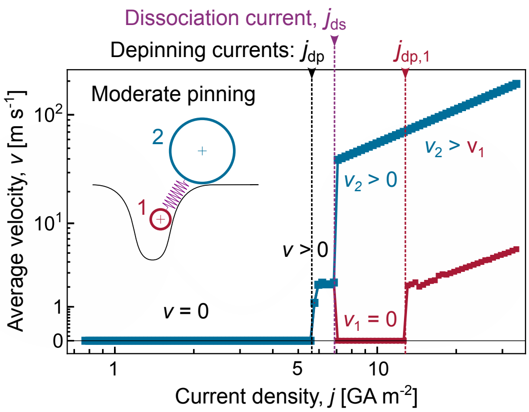
Small Methods **e01430** (2025)
Contact: A. Pokusinskyi (anton.pokusinskyi@tu-braunschweig.de)

Fractional flux quanta in two-band superconductors

Two-band superconductors host two superconducting condensates with different vortex parameters, producing unequal viscous and Lorentz forces. A transport current can displace the fractional vortex components relative to each other, and pinning sites enhance this effect by acting differently on vortices with distinct core sizes.

Two-band superconductors host vortices from superfluid condensates of different electron bands. These vortices carry a fractional flux quantum and attract each other, coalescing to form a composite vortex with the whole flux quantum Φ_0. However, due to the differences in viscosity and flux of the vortices across different bands, composite vortices may dissociate into fractional components. In our work, we theoretically explore an approach to control the dissociation of composite vortices into fractional components and their separation into stationary and fast-moving ones through dc current and pinning strength variation. To this end, we numerically solve the dynamic equation of motion for a single dc-driven composite vortex in a periodic pinning potential. As the pinning strength increases, we observe a transition from depinning followed by dissociation in the weak-pinning regime to dissociation from the pinned state in the strong-pinning regime. Under moderately strong pinning, fractional vortices from one condensate may become immobile while those from the other may even move faster than the original composite vortex just before the dissociation. The predicted pinning- and dc-controlled separation of fractional flux quanta appeals for experimental investigation and potential application in fluxonic devices.

The plot illustrates how the velocities of a composite vortex (v) and its fractional components (v_1, v_2) evolve during dc-driven dissociation under moderately strong pinning. In this case, the dissociation current j_{ds} is higher than the depinning current j_{dp} of the composite vortex but lower than that of the fractional component with the smaller core, $j_{dp,1}$. Consequently, one fractional component remains pinned and acts as an anchor for the composite vortex, making it easier to break the link between the fractional components and thereby reducing the dissociation current.



Rap. Res. Lett. **2500128** (2025)
Contact: A. Pokusinskyi (anton.pokusinskyi@tu-braunschweig.de)

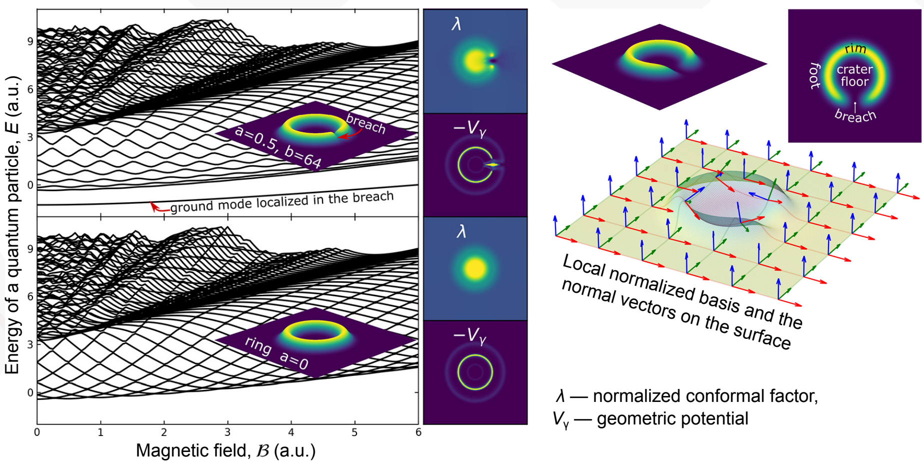
Conformal approach to simulations of curved 3D films

We develop a technique based on numerical conformal transformation. It allows for modeling 3D curved membranes by reducing them to equivalent thin, flat ones. This keeps the modeling straightforward and fast.

Three-dimensional (3D) nanoarchitectures are widely used across various areas of physics, including spintronics, photonics, and superconductivity. In this regard, thin curved 3D membranes are especially interesting for applications in nano- and optoelectronics, sensorics, and information processing, making physics simulations in complex 3D geometries indispensable for unveiling new physical phenomena and the development of devices.

In our work, we present a general-purpose approach to physics simulations for thin curved 3D membranes, that allows for performing simulations using finite difference methods instead of meshless methods or methods with irregular meshes. The approach utilizes a numerical conformal mapping of the initial surface to a flat domain and is based on the uniformization theorem stating that any simply-connected Riemann surface is conformally equivalent to an open unit disk, a complex plane, or a Riemann sphere.

We reveal that for many physical problems involving the Laplace operator and divergence, a flat-domain formulation of the initial problem only requires a modification of the equations of motion and the boundary conditions by including a conformal factor and the mean/Gaussian curvatures. We demonstrate the method's capabilities for case studies of the Schrödinger equation for a charged particle in static electric and magnetic fields for 3D geometries, including C-shaped (cf. figure) and ring-shaped structures, as well as for the time-dependent Ginzburg-Landau equation.



λ — normalized conformal factor,
V_γ — geometric potential

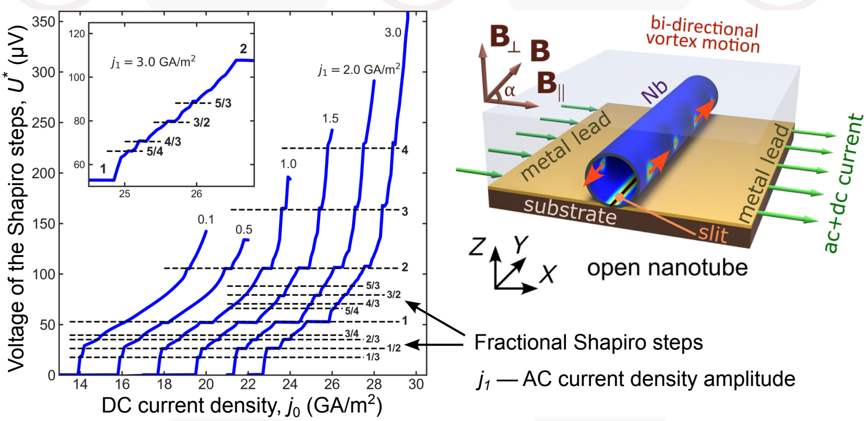
Comp. Phys. Commun. **315** (2025) 109736
Contact: I. Bogush (igori.bogus@tu-braunschweig.de)

Vortex dynamics in superconductor 3D open nanotubes

The 3D geometry of open nanotubes creates a non-uniform normal magnetic field, confining vortices to a narrow channel. This produces quasi-1D ordered motion and ac-driven frequency locking, resulting in voltage plateaus in the current-voltage curves.

The movement of magnetic flux quanta (Abrikosov vortices) in superconductors leads to dissipation and is influenced by various ordering effects arising from vortex-vortex, vortex-defect, and vortex-edge interactions. Under combined dc and ac stimuli, when the distance travelled by fluxons during an ac cycle corresponds to an integer multiple of the vortex lattice period, the superconductor's current-voltage curve displays synchronisation (Shapiro) steps. However, in planar constrictions, frequency-locking effects rely on a perfectly ordered vortex lattice and are typically observed when periodic vortex pinning arrays dominate over intrinsic, uncorrelated disorder.

In our work, we propose superconductor 3D open nanotubes as systems free of periodic disorder, where the current-voltage curves are expected to display pronounced Shapiro steps. Using the time-dependent Ginzburg-Landau equation, we attribute the predicted effect to a reduction in the dimensionality of vortex motion. Namely, rolling a planar film into a tube causes the 2D vortex array, which initially moves throughout the film, to evolve into quasi-1D vortex chains that are restricted to areas where the normal component of the magnetic field is near its maximum. The discussed effects are relevant for superconducting devices, where vortex nucleation frequency and voltage stabilization by an external ac stimulus can enhance their operation.



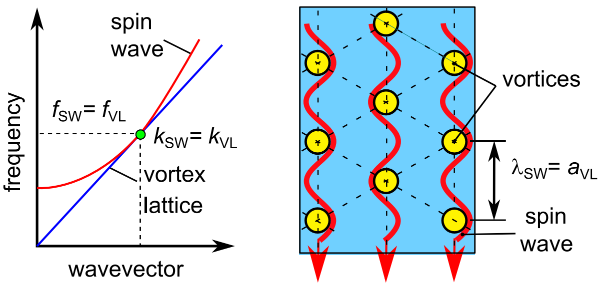
Phys. Rev. B **111** (2025) 214510
Contact: I. Bogush (igori.bogus@tu-braunschweig.de)

Moving Abrikosov vortices excite sub-40 nm magnons

Crossing of the dispersions for fluxons and magnons—fundamental eigenexcitations in superconducting and magnetic solids—allows for the unidirectional coherent excitation of propagating magnons with the shortest wavelength reached experimentally so far.

Magnons, the quasi-particles of spin waves, are promising candidates for developing wave-based computing and hybrid quantum technologies. However, the generation of short-wavelength magnons is challenging due to the lack of fast-moving excitation sources. In our work, we demonstrate magnon generation in a Co-Fe conduit, using fast-moving magnetic flux quanta (Abrikosov vortices) in a Nb-C superconducting strip, with velocities exceeding 1 km/s. Our findings showcase the generation of monochromatic sub-40 nm wavelength magnons, their unidirectional excitation, and coherent magnon-fluxon coupling. This discovery enables high-speed on-chip electrically driven magnon generation, which, moreover, by removing energy from the superconductor, sustains its low-resistive state. Our approach significantly improves our understanding of magnon excitation. It sets the groundwork for exploring other wave excitations, such as surface acoustic waves, for integration into advanced electronic and hybrid quantum systems.

In the right panel, the Abrikosov vortices in the NbC superconductor are accelerated by an electric current through the Lorentz force to move at high velocities. The resulting dynamic stray field subsequently drives coherent propagation of short-wavelength magnons with unidirectional wavevectors (k_{SW}) in the ferromagnetic CoFe thin film underneath. In the left panel, the schematic dispersion relations are shown for magnons (red parabola) and fluxons (blue straigh line). At the crossing point, the velocity of superconducting vortices (fluxons) reaches the magnon velocity, meeting the condition for magnon excitation through dynamic stray fields. At the crossing point, the spin-wave (magnon) wavevector k_{SW} equals the vortex-lattice (fluxon) wavevector k_{VL} and the magnon frequency f_{SW} (energy) equals the washboard frequency of the vortex lattice f_{VL}.



Nat. Nanotechnol. (2025), doi: 10.1038/s41565-025-02024-w
Contact: O. Dobrovolskiy (oleksandr.dobrovolskiy@tu-braunschweig.de)

Publications

Vortex ratchet effect in a NbC strip with a periodic edge indentation
F. Porrati, A. Pokusinskyi, S. Barth, M. Huth, O. Dobrovolskiy,
Small Methods **e01430** (2025).

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O. Dobrovolskiy, Q. Wang, D. Vodolazov, R. Sachser, M. Huth, S. Knauer, A. Buzdin,
Nature Nanotechn. (2025), doi: 10.1038/s41565-025-02024-w.

Quantum Escape: Kein Entrinnen ohne Supraleitung
B. Leridon, H. Suderow, S. Nicaud, J. Aarts, S. Bending, O. Dobrovolskiy,
A. Hassanien, W. Lang, F. Tafuri, A. Zaleski,
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DC-driven fractional flux quanta in two-band superconductors
A. Pokusinskyi, O. Dobrovolskiy,
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Vortex frequency locking and Shapiro steps in superconductor open nanotubes
I. Bogush, V. Fomin, O. Dobrovolskiy,
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Spin waves in magnetic nanodisks, nanorings, and 3D nanovolcanoes
O. Dobrovolskiy and G. Kakazei, in *Physics of Quantum Rings*,
(ed.) V. M. Fomin, Springer Nature, Switzerland, **2025**, pp. 277314.

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I. Bogush, V. Fomin, O. Dobrovolskiy,
Comp. Phys. Commun. **315** (2025) 109736.

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I. Bogush, R. de Braganca, V. Fomin, O. Dobrovolskiy,
Rap. Res. Lett. **2500139** (2025).

2025 Roadmap on 3D Nano-magnetism
G. Gubbiotti, A. Barman, S. Ladak, C. Bran, D. Grundler, M. Huth, H. Plank, G. Schmidt,
S. van Dijken, R. Streubel, O. Dobrovoloskiy, V. Scagnoli, L. Heyderman, C. Donnelly,
O. Hellwig, L. Fallarino, M. B. Jungfleisch, A. Farhan, N. Maccaferri, P. Vavassori,
P. Fischer, R. Tomasello, G. Finocchio, R. Clrac, R. Sessoli, D. Makarov, D. D. Sheka,
M. Krawczyk, R. Gallardo, P. Landeros, M. d'Aquino, R. Hertel, P. Pirro, F. Ciubotaru,
M. Becherer, J. Gartside, T. Ono, P. Bortolotti, A. Fernandez-Pacheco,
J. Phys: Cond. Matt. **37** (2025) 143502.

Personnel

Guests

Vladimir Fomin, Leibniz IFW Dresden

Ekaterina Pribytova, CEITEC Brno

Elina Zhakina, MPI CPfS, Dresden

Joined the group in 2025

Anton Pokusinskyi, postdoc

Zahra Makhdoumi Kakhaki, postdoc

Roua Cheikh, PhD student

Collaborations

Throughout the year, we have greatly benefited from collaborations we sincerely appreciate:

universität wien

CEITEC BRNO UNIVERSITY OF TECHNOLOGY

ADAM MICKIEWICZ UNIVERSITY POZNAŃ

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

HUAZHONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

U.PORTO UNIVERSIDADE DO PORTO

PTB Physikalisch-Technische Bundesanstalt National Metrology Institute

UNIVERSITÉ DE LORRAINE

université de BORDEAUX

UNIVERSITÀ DEGLI STUDI DI SALERNO

IFW Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden

Impression

Together with our colleagues from the Institute for Electrical Measurement Science and Fundamental Electrical Engineering, Technische Universität Braunschweig. © Tanja Coenen.

Together with our colleagues Wolfgang Lang and Bernd Aichner from the University of Vienna. Barbora Budinská and Sebastian Lamb-Camarena successfully defended their PhD theses on vortex dynamics in superconductors and on spin waves in 3D magnetic structures, respectively.

At the FluMag project meeting in Valtice, with the groups of Michal Urbánek from CEITEC Brno and Jarosław Kłos from AMU Poznań. Anton Pokusinkyi presents on fractional flux quanta.

Together with Sebastian Knauer from the University of Vienna at the Special Session on Cryogenic Magnonics at ICSM-ICQMT 2025, Olüdeniz, Türkiye.

Acknowledgements

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