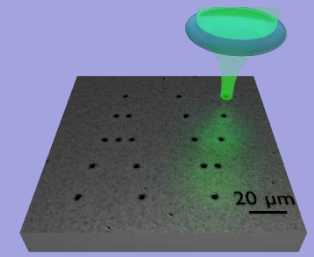


Optical methods of flux manipulation in superconductors



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University of Bordeaux, and
Institut Universitaire de France



université
de BORDEAUX

in collaboration with

M. Croitoru

Department of Physics, Federal University of Pernambuco, Brazil

B. Lounis

University of Bordeaux, LP2N, France



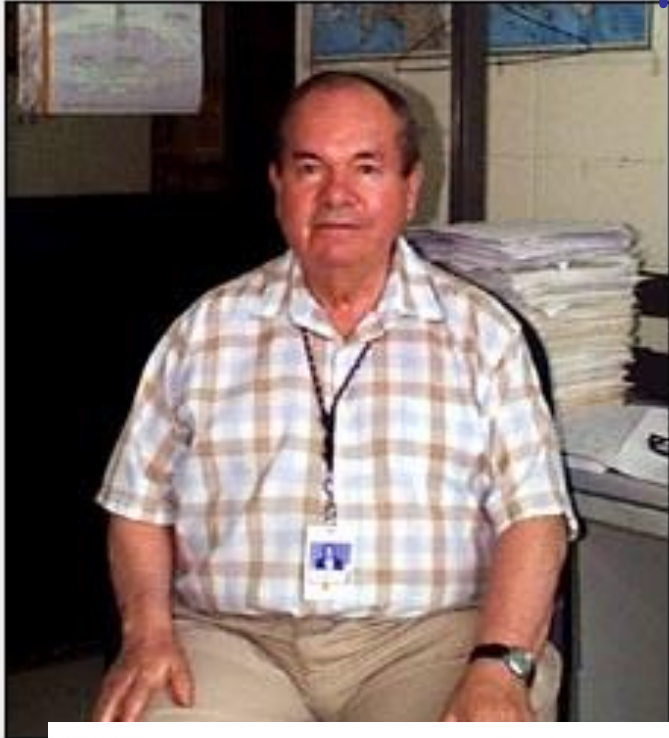
Transformations of Correlated Electronic States by Electric or Optical Impacts. International research school and workshop IMPACT – 2024

August 19 – 31, 2024 Cargèse, France

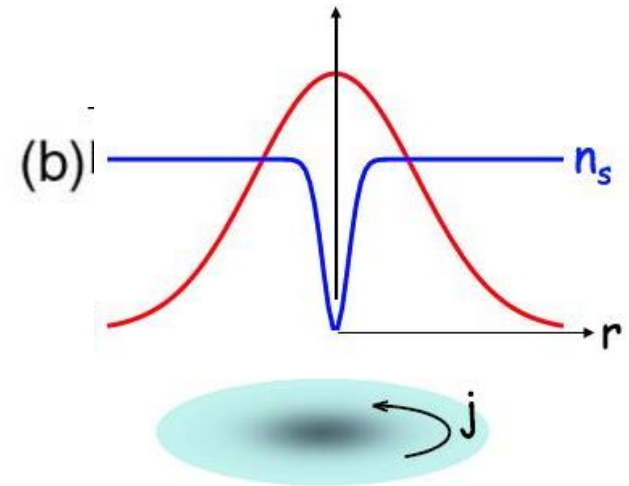
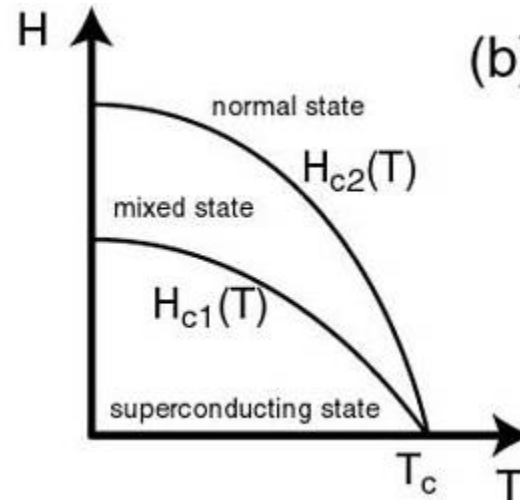
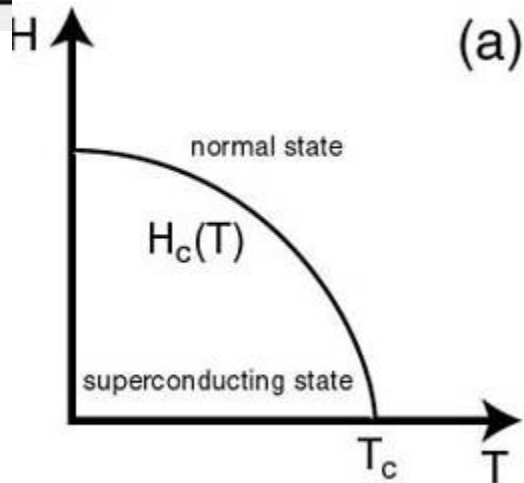
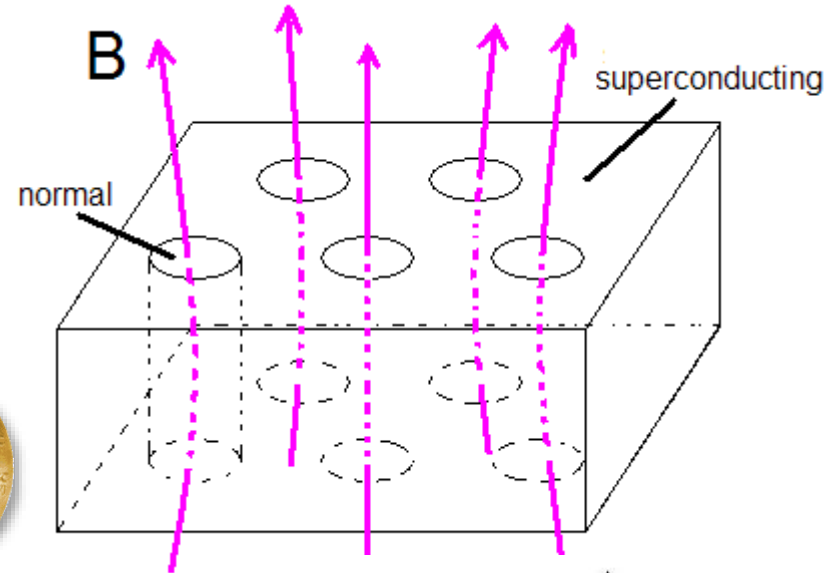
Outline

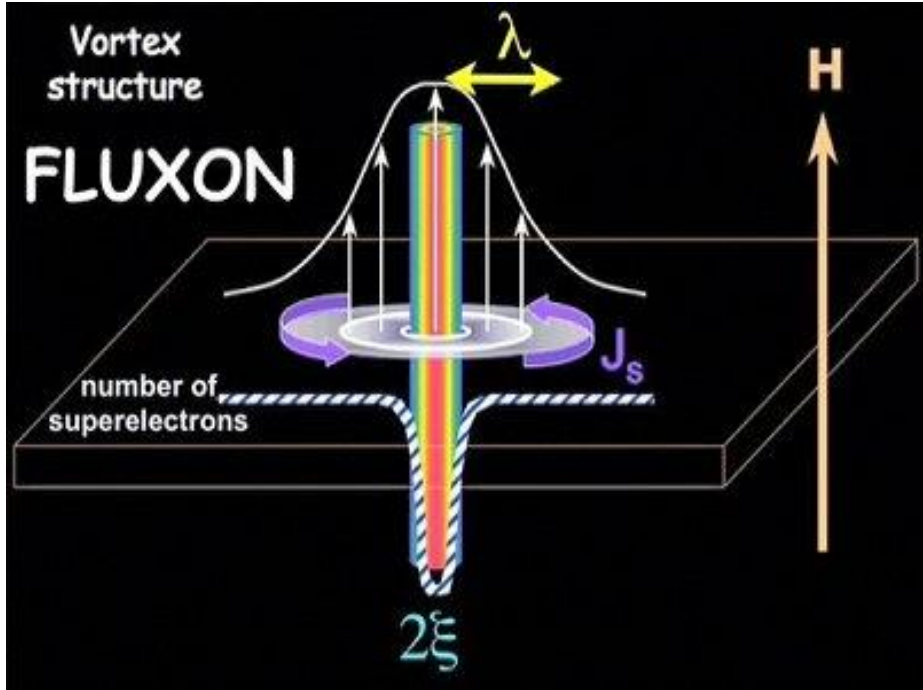
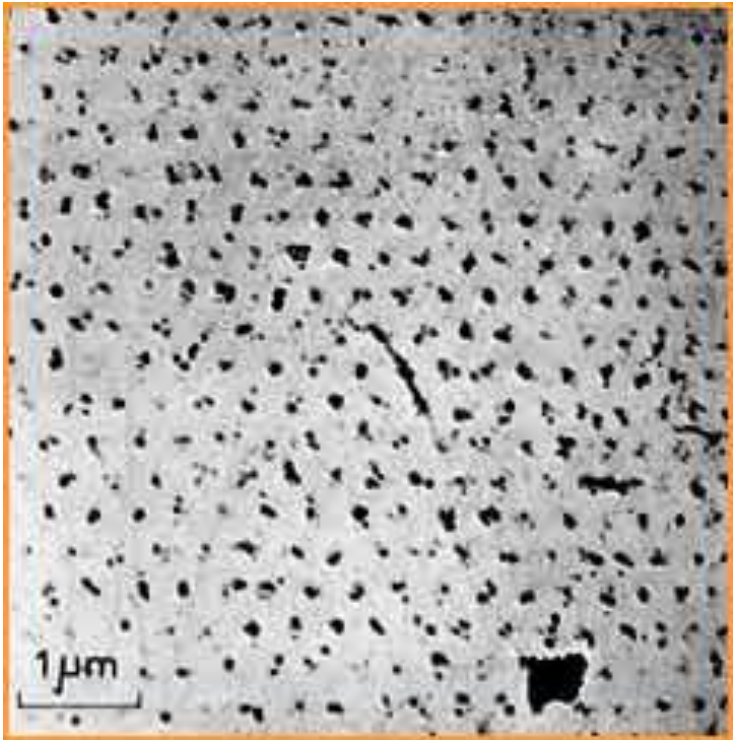
- ◆ **Vortex manipulation by focused laser beam.**
- ◆ **Spontaneous vortex-antivortex generation via the Kibble-Zurek (KZ) mechanism.**
- ◆ **Direct and inverse Faraday effects. What should we expect in superconductors?**
- ◆ **All-optical generation of the current states.**
- ◆ **On-demand switch between current-carrying states in the superconductor by controlling the helicity.**

1957: Discovery of the type II superconductivity

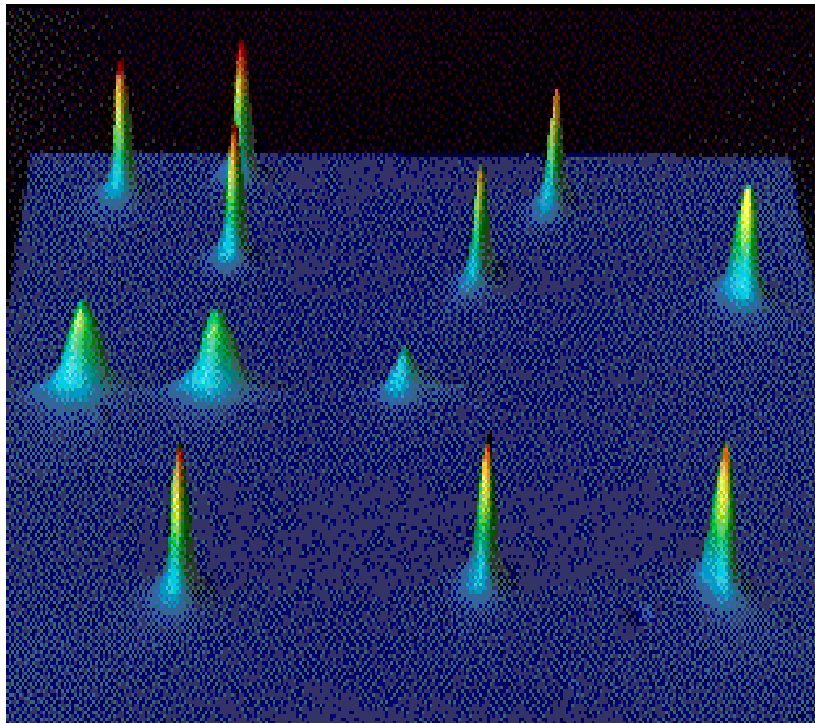


2003

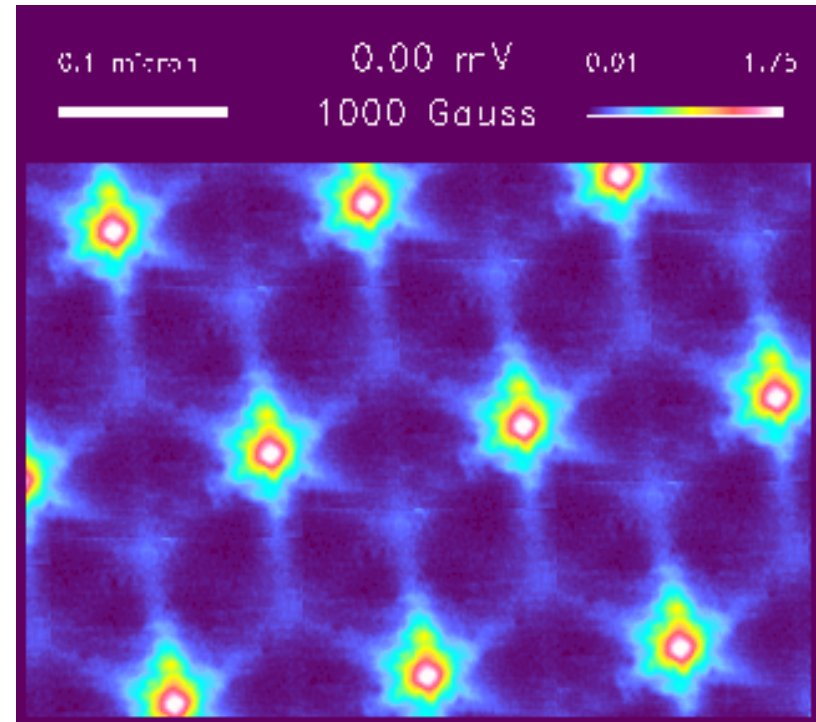




VORTICES IN SUPRACONDUCTORS



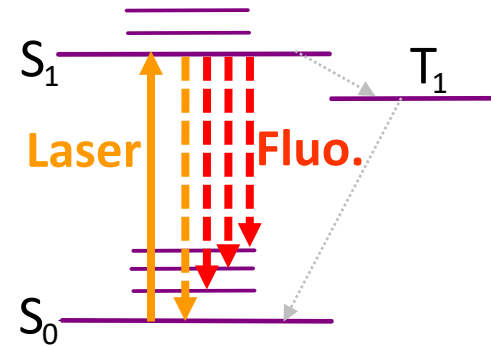
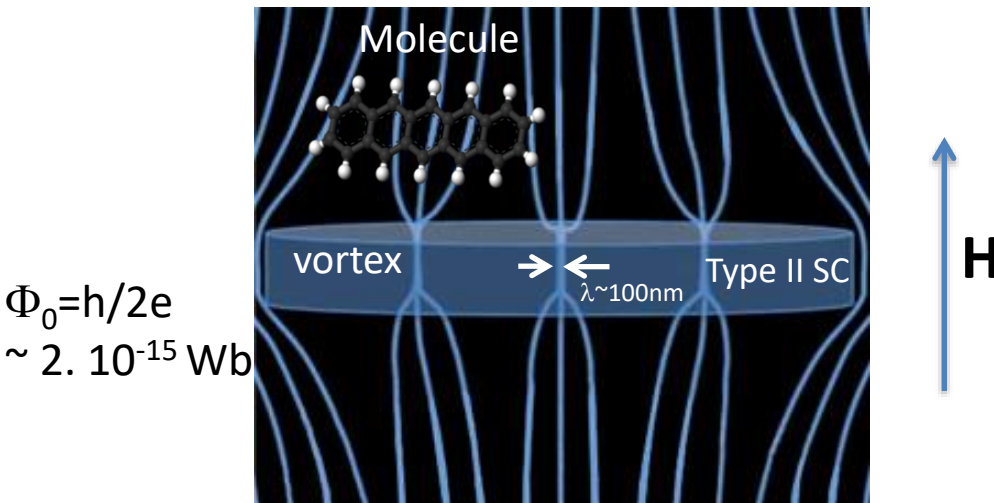
SQUID Image



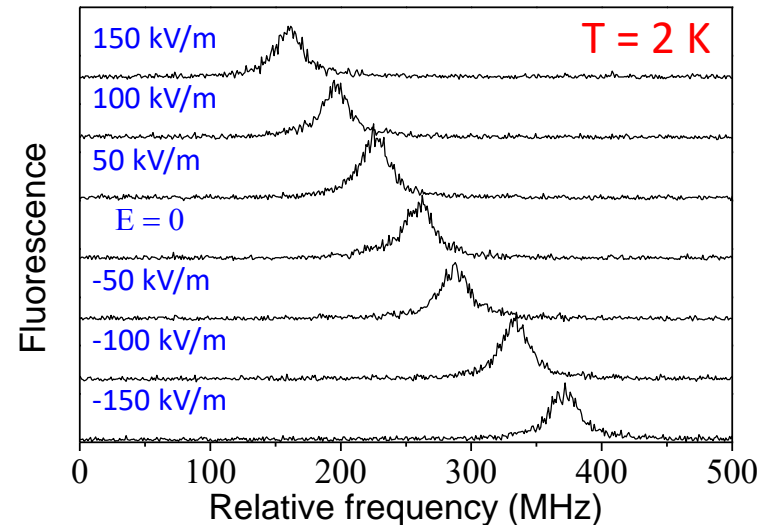
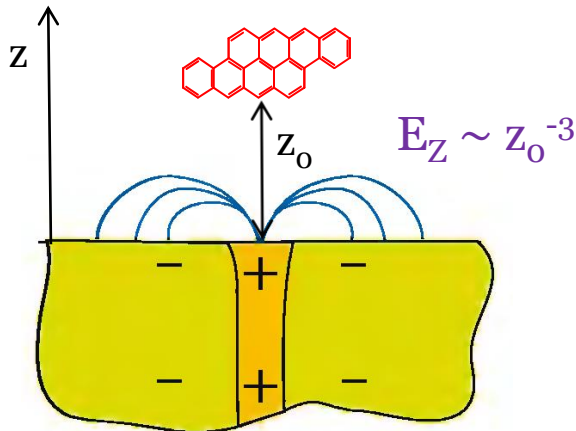
STM Image

Initial motivation

Bring a direct experimental proof of an electric charge accumulation in a vortex core, with single molecule optical spectroscopy/microscopy.



High quality factor, linear Stark effect

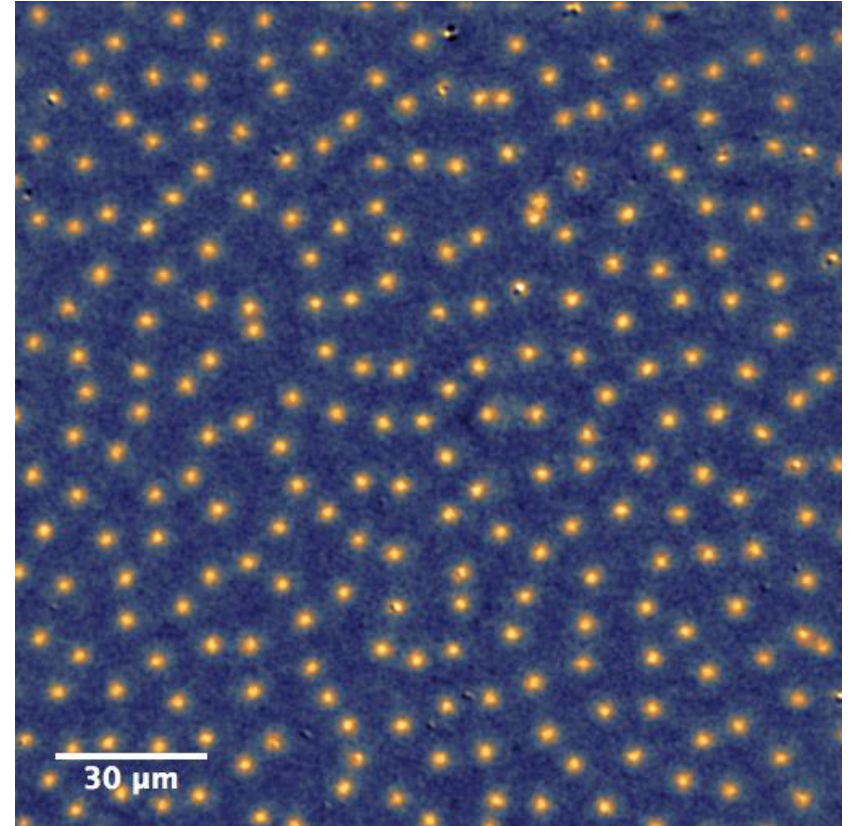
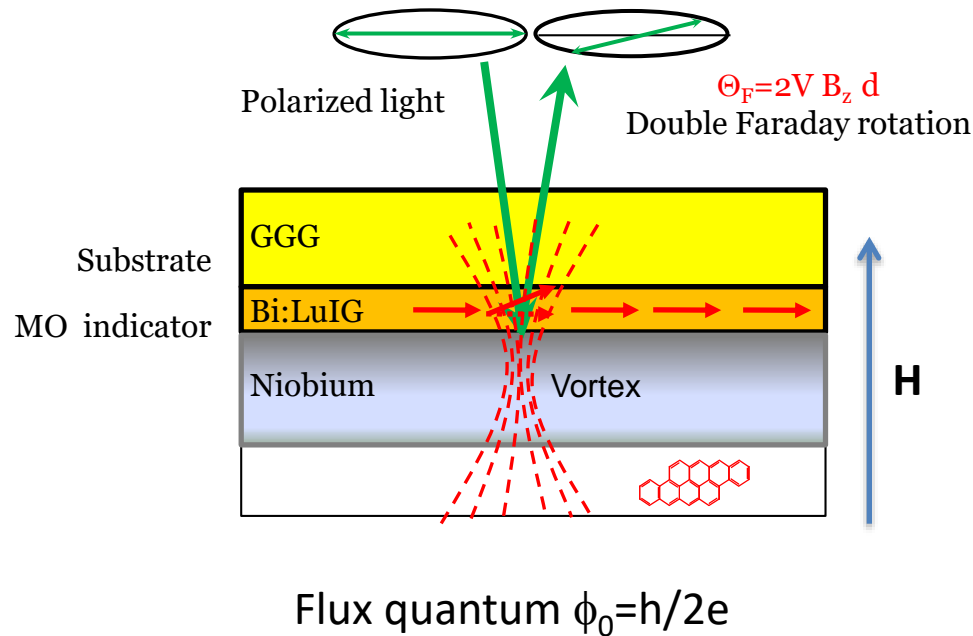


At $z_0 = 20 \text{ nm}$, $E \sim 10 \text{ kV/m}$

→ expected spectral shift by a linewidth $\sim 20 \text{ MHz}$

Magneto-optical imaging of vortices

Following *Goa et al., Rev. Sci. Instrum.* 74 (2003) 141.

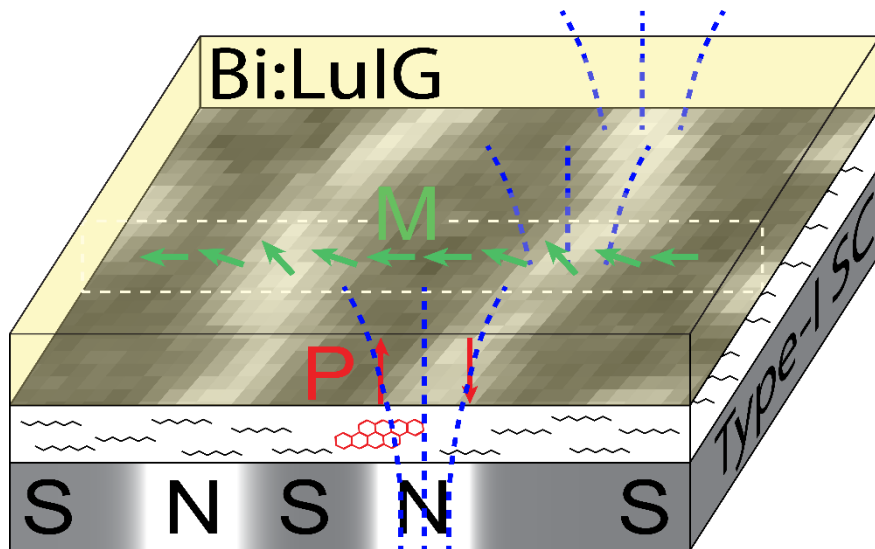


Niobium film, thickness 90 nm
 $H_{\text{ext}} = 0.22 \text{ Oe}$, $T = 4.6 \text{ K}$
Bi:LuIG, 2.5 μm thickness,
Verdet constant $0.06 \text{ }^\circ \cdot \text{mT}^{-1} \cdot \mu\text{m}^{-1}$

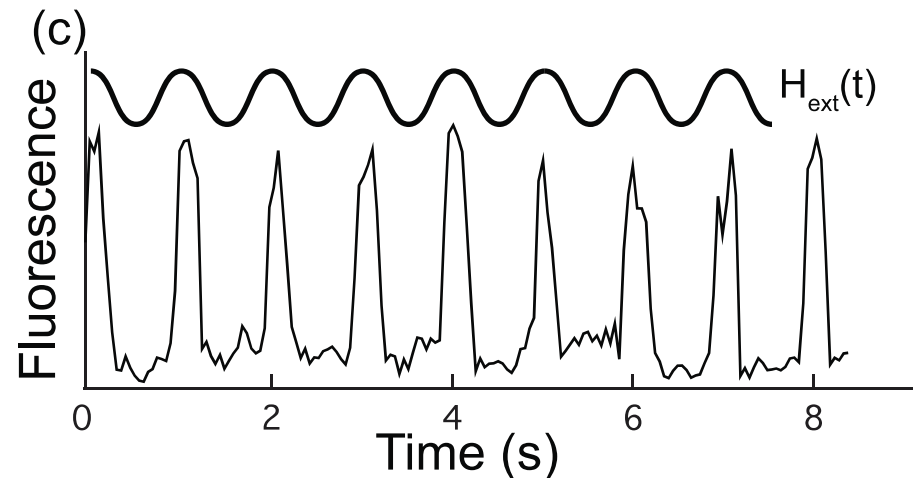
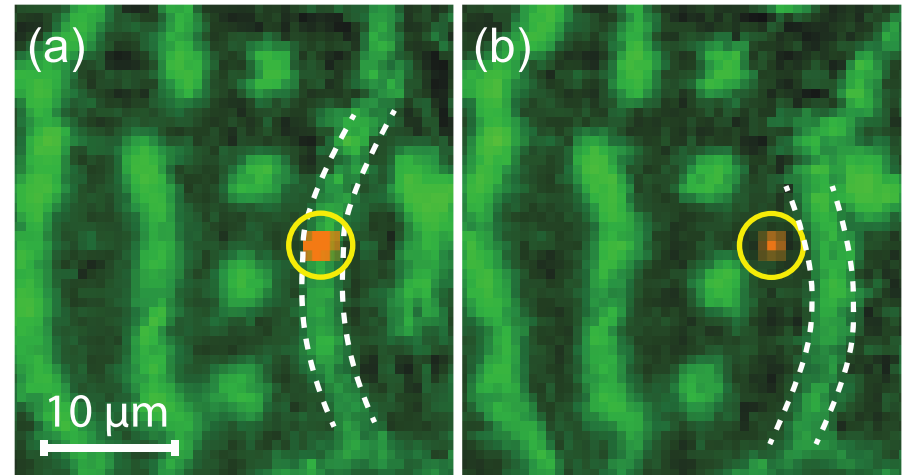
Evidence of the flexomagnetoelectric effect

In cycloid magnetic defects
such as Néel domain walls:

$$\vec{P} = \gamma \chi_e \left[(\vec{M} \cdot \vec{\nabla}) \vec{M} - \vec{M} (\vec{\nabla} \cdot \vec{M}) \right]$$

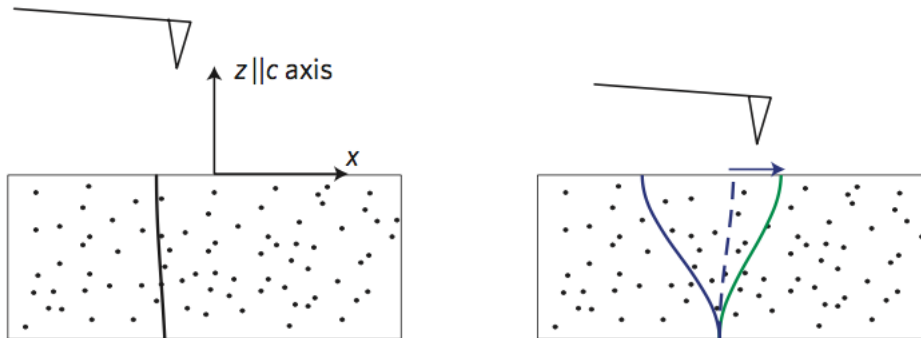


Single molecule fluorescence imaging +
Magneto-optical imaging of N, S domains

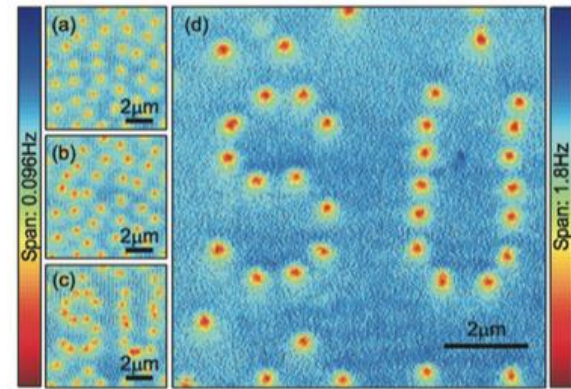


Methods for single vortex manipulation

Magnetic force microscopy

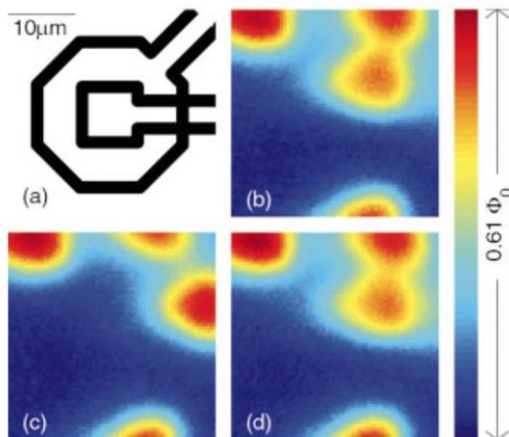


Auslaender et al. *Nat Phys* 5 (2009) 35



Straver et al., *Appl. Phys. Lett.* 93 (2008) 172514

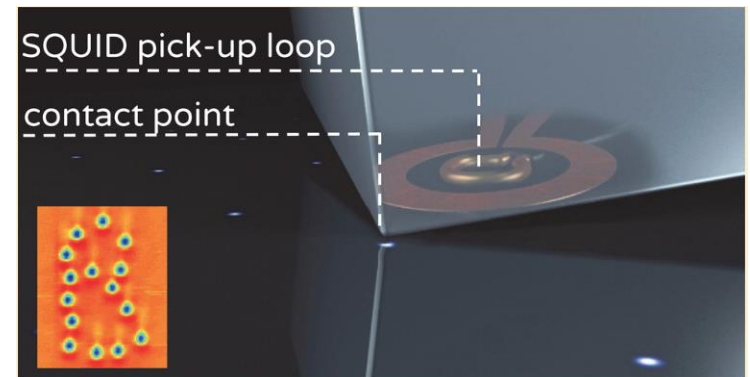
SQUID microscopy



Gardner et al., *Appl. Phys. Lett.* 80 (2002) 1010

Kalisky et al., *Phys. Rev. B* 83 (2011) 064511

Strain induced microscopy



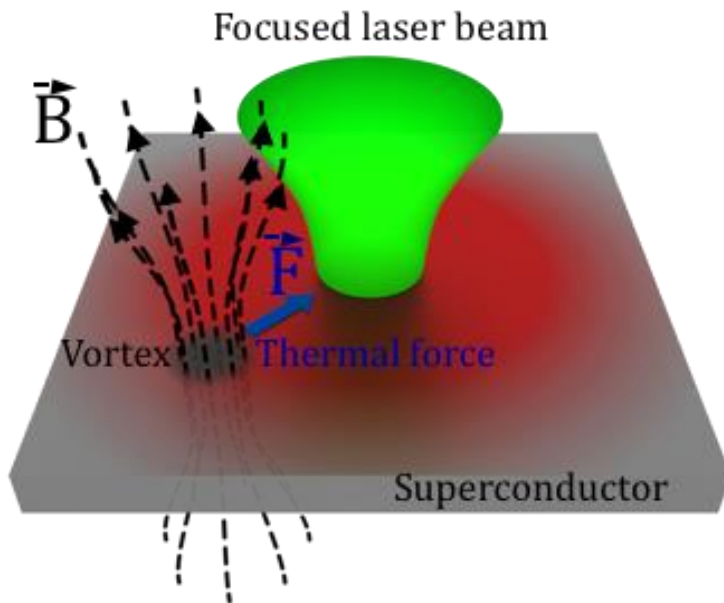
Kremen et al., *Appl. Phys. Nano Lett.* 16 (2016) 1626

Vortices in a thermal gradient

Global vortex flows induced by thermal gradients demonstrated 50 years ago.

Interpretation: vortex cores behave as entropy-carrying particles, in search for colder places.

Otter & Solomon, *Phys. Rev. Lett.* 16 (1966) 681;
Huebener & Seher, *Phys. Rev.* 181 (1969) 701.



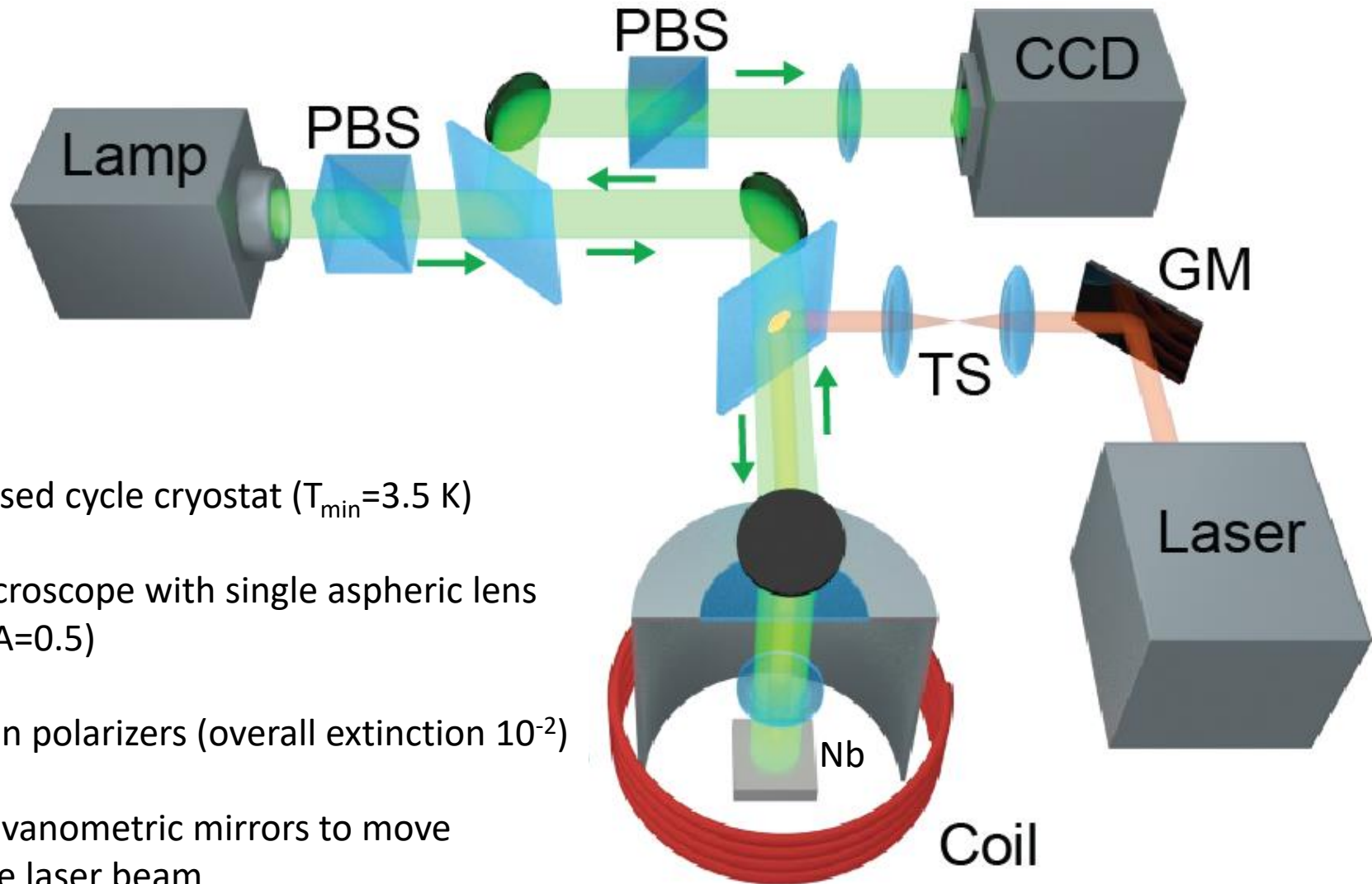
In the limit $\kappa = \lambda/\xi \gg 1$, the contribution of the core to the free energy of a vortex is negligible.

Free energy of a vortex :
$$U = \frac{\Phi_0^2}{4\pi\mu_0\lambda^2} \ln(\kappa)$$

where $\lambda = \lambda_0/\sqrt{1 - T/T_c}$ for T close to T_c .

The thermal force
$$\mathbf{F} = \frac{\Phi_0^2}{4\pi\mu_0\lambda_0^2} \ln(\kappa) \frac{\nabla T}{T_c}$$
 drives the vortex towards hot regions.

Experimental setup



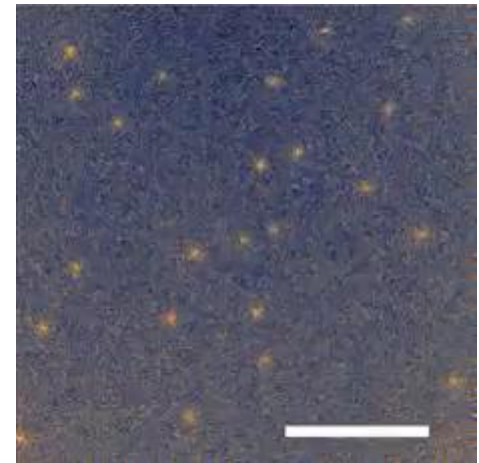
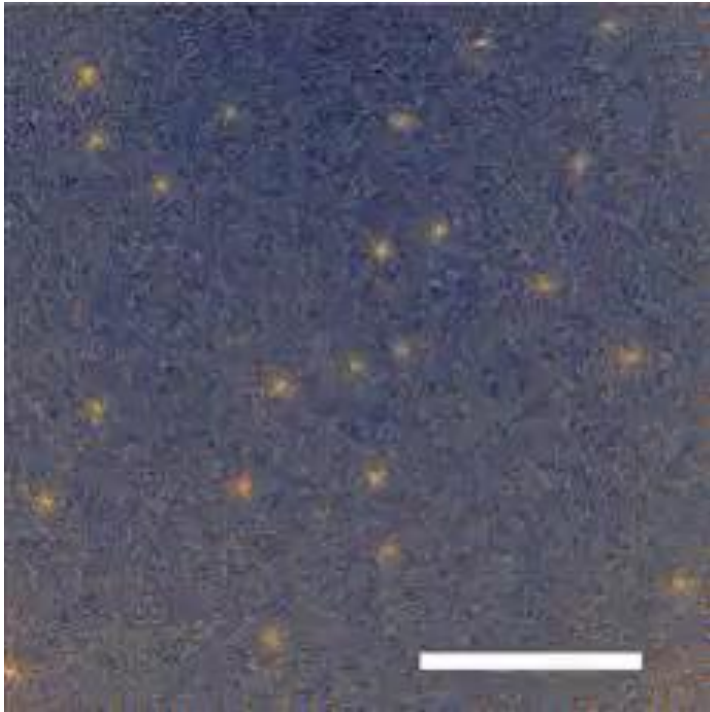
- Closed cycle cryostat ($T_{\min}=3.5$ K)
- Microscope with single aspheric lens (NA=0.5)
- Glan polarizers (overall extinction 10^{-2})
- Galvanometric mirrors to move the laser beam

Single vortex repositioning

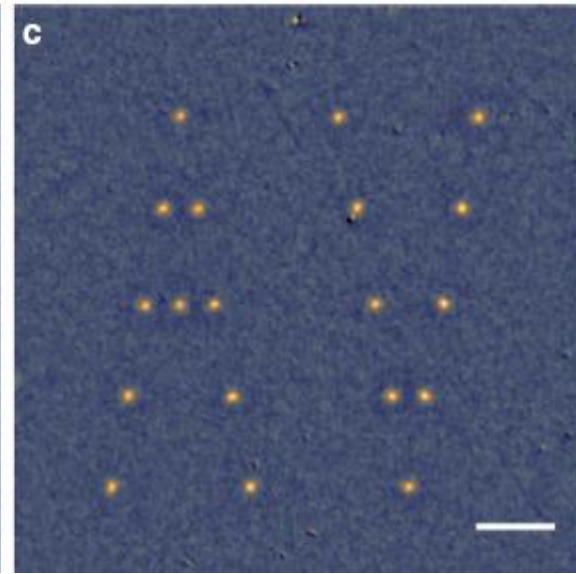
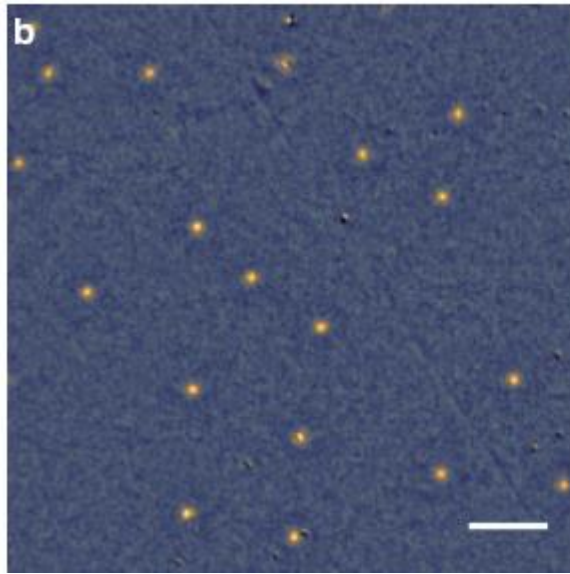
90 nm thick Nb film + Bi:LuIG indicator (2.5 μm thick)

$H_{\text{ext}}=0.02$ Oe, $T = 4.6$ K

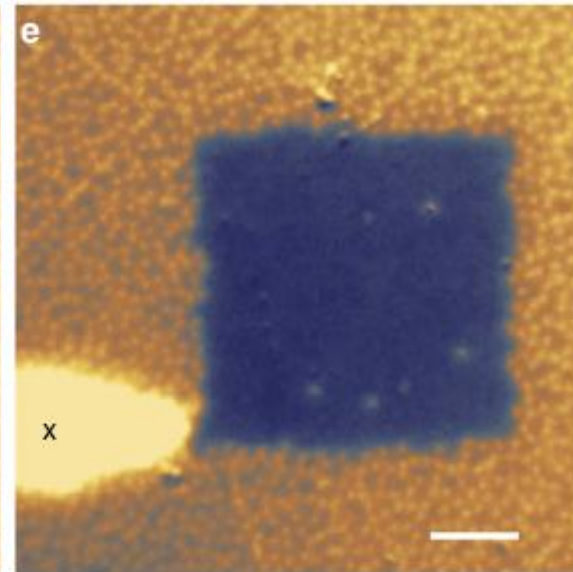
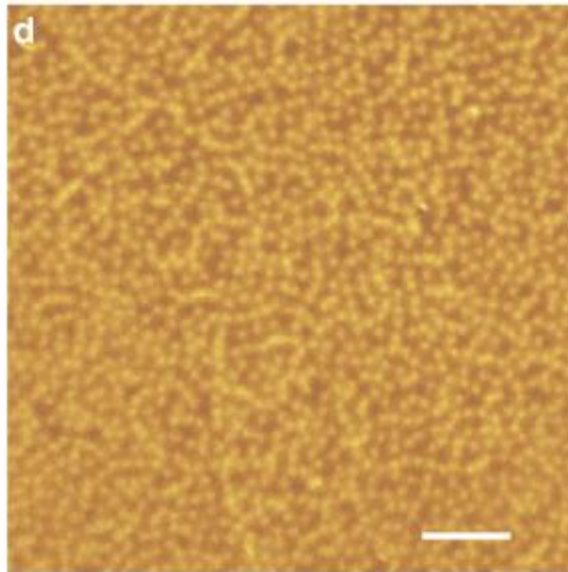
Absorbed laser power $P = 17$ μW , focused on a FWHM-diameter of 1.1 μm
(Thermal gradient up to 1 $\text{K}\cdot\mu\text{m}^{-1}$)



Veshchunov, Magrini et al.
Nature Comm.
7, 12801 (2016)



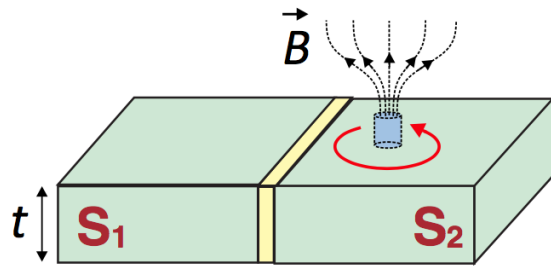
LP2N



► Abrikosov vortices manipulation

Josephson junction control

Josephson junction : two superconductors separated by a normal conductor.

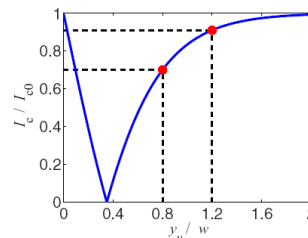
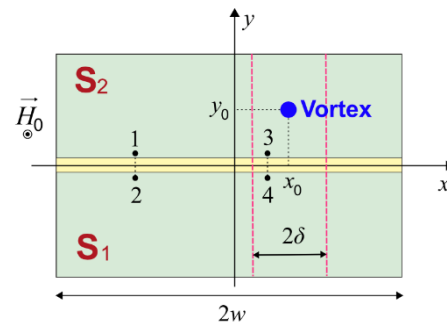


A weak link optically induced :

a 405 nm continuous laser breaks some Cooper pairs by heating the superconductors

Josephson current :

$$I_c = I_0 \sin(\Delta\phi)$$

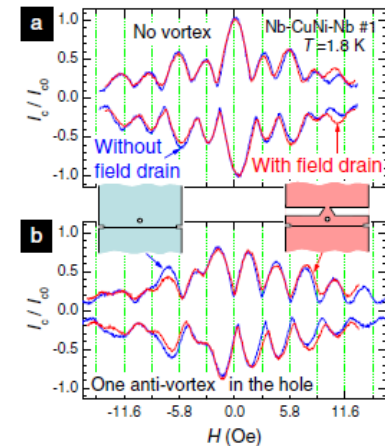
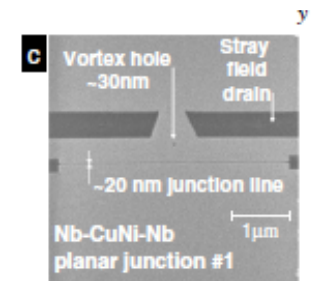


PRL 104, 227003 (2010)

PHYSICAL REVIEW LETTERS

Detection of the Phase Shift from a Single Abrikosov Vortex

T. Golod, A. Rydh, and V.M. Krasnov*



S. Mironov, E. Goldobin, D. Koelle, R. Kleiner, Ph. Tamarat, B. Lounis & A. Buzdin
Phys. Rev. B **96**, 214515(2017)

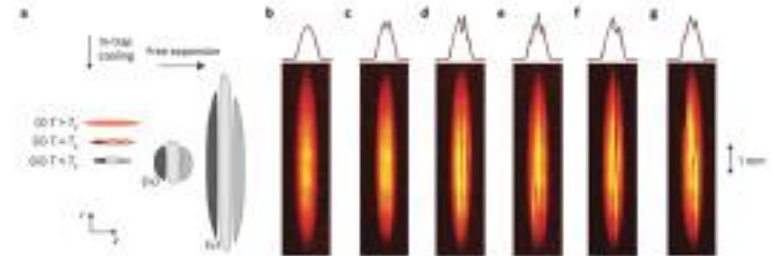
► Vortex/anti-vortex pair generation

The Kibble-Zurek Effect: spontaneous generation of topological defects

Superconductivity: a zero electrical resistance and the ejection of external magnetic fields

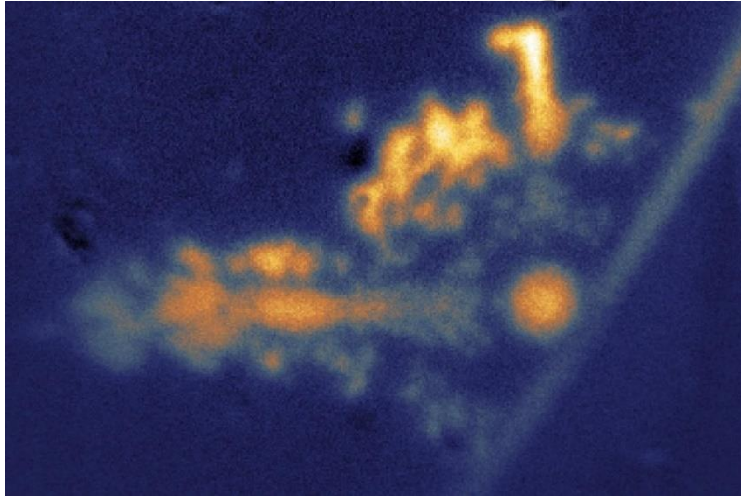


Ya. B. Zeldovich, I. Yu. Kobzarev, and L. B. Okun', Cosmological consequences of a spontaneous breakdown of a discrete symmetry, *Zh. Eksp. Teor. Fiz.* 67, 3 (1975) [*Sov. Phys. JETP* 40, 1 (1975)].



When a system crosses a second-order phase transition on a finite timescale, spontaneous symmetry breaking can cause the development of domains with independent order parameters, which then grow and approach each other creating boundary defects. This is known as the Kibble-Zurek mechanism.

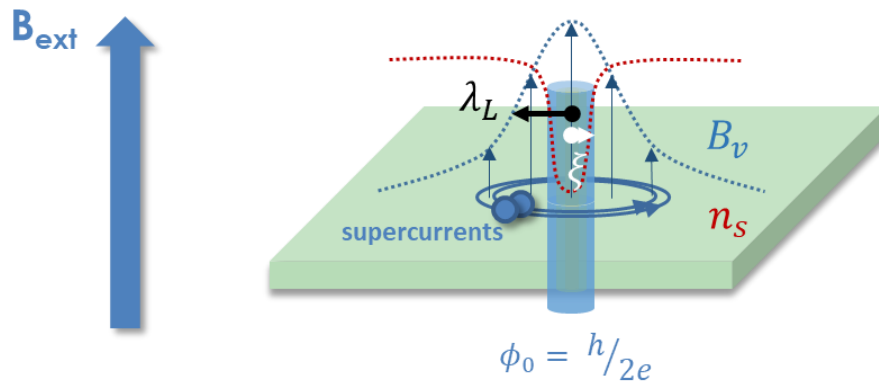
Optical generation of Abrikosov vortices by Kibble-Zurek effect



A. Rochet, V. Vadimov, W. Magrini, S. Thakur, J.-B. Trebbia, A. Melnikov, A. I. Buzdin, P. Tamarat, and B. Lounis, On-Demand Optical Generation of Single Flux Quanta, *Nano Letters* **20**, 6488 (2020).

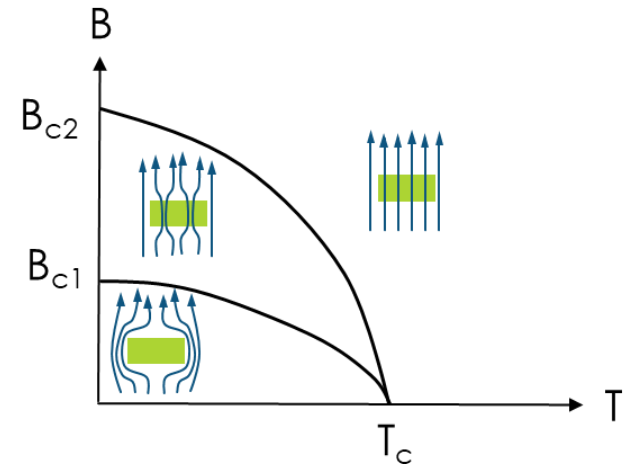
► Abrikosov vortices

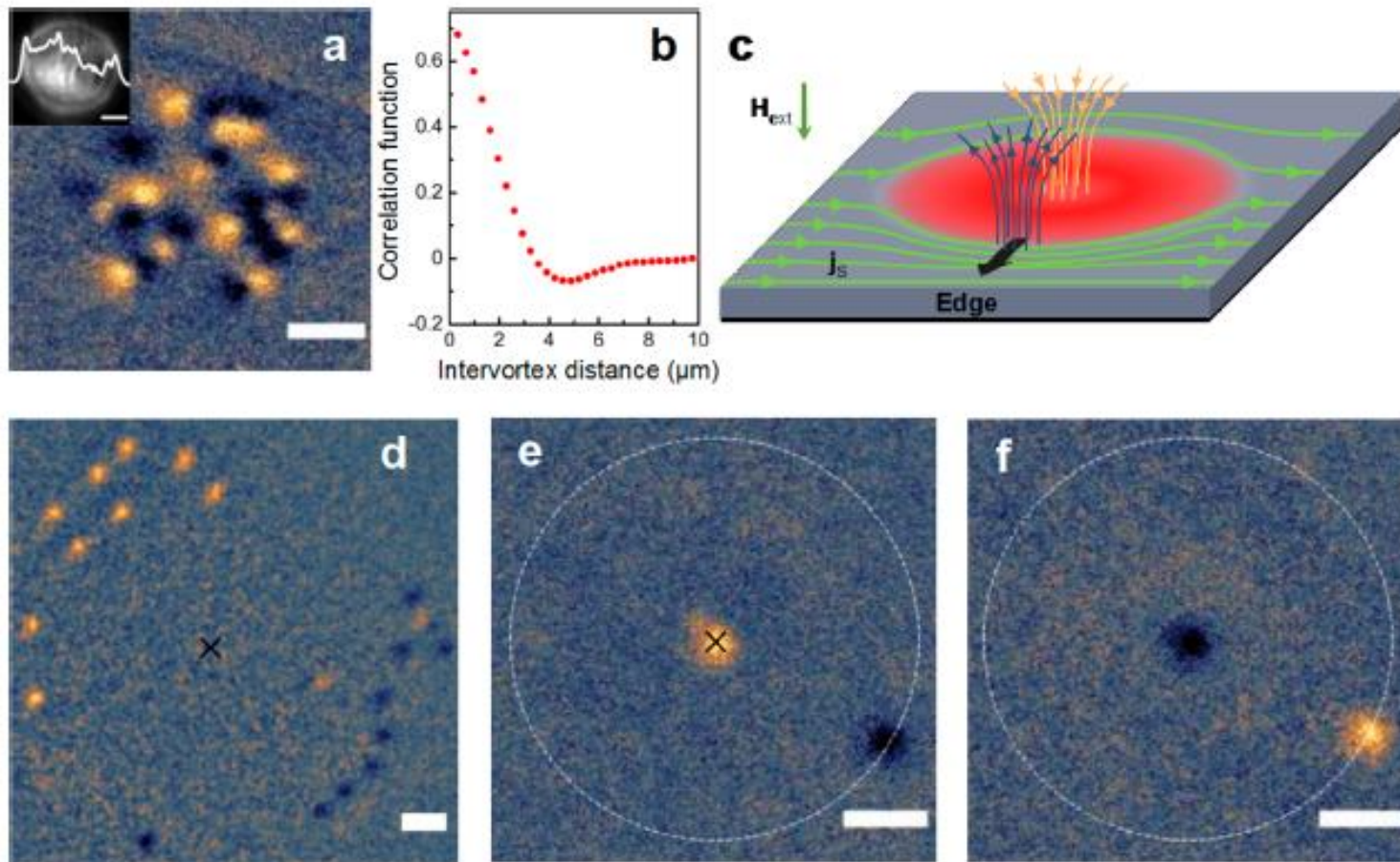
A quantum of magnetic flux



Abrikosov vortex :

A tube of magnetic flux and a loop of Cooper pair supercurrent





A. Rochet, V. Vadimov, W. Magrini, S. Thakur, J.-B. Trebbia, A. Melnikov, A. I. Buzdin, P. Tamarat, and B. Lounis, On-Demand Optical Generation of Single Flux Quanta, Nano Letters **20**, 6488 (2020).

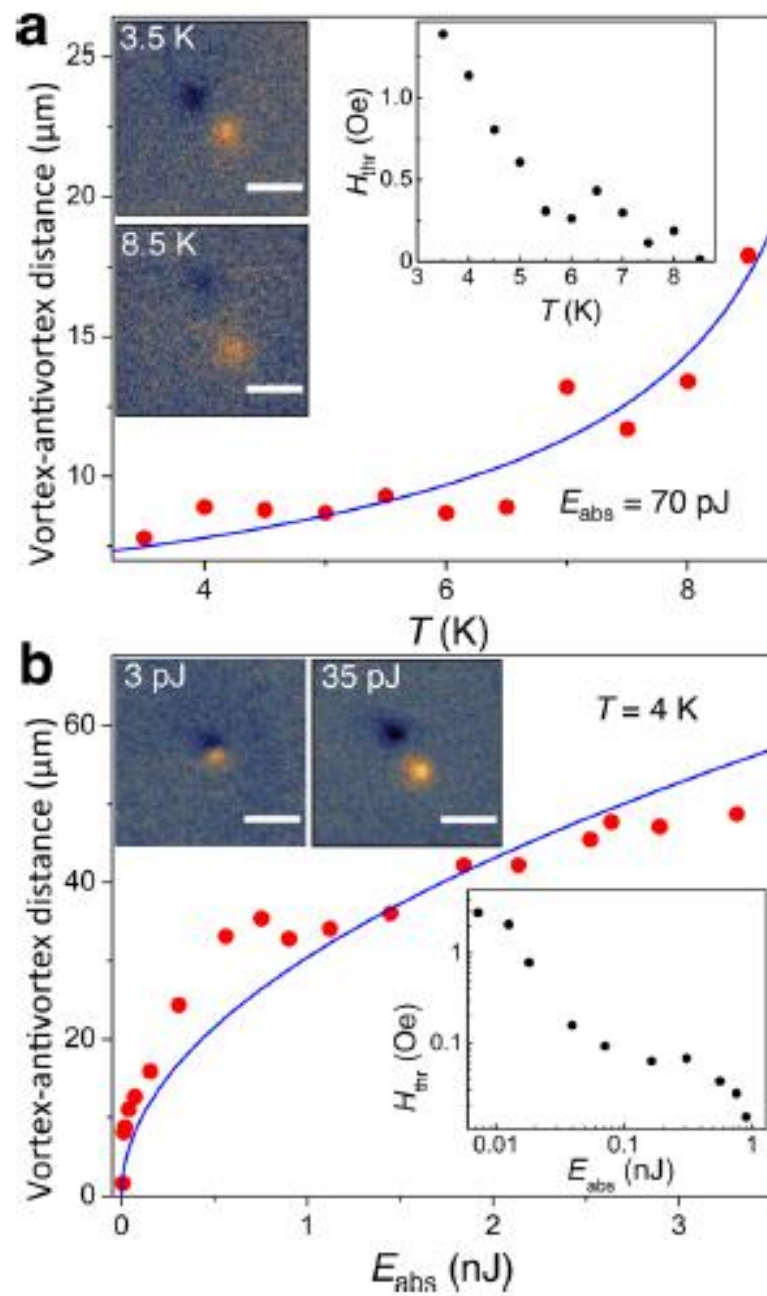


Figure 3. Control of the vortex–antivortex distance with temperature

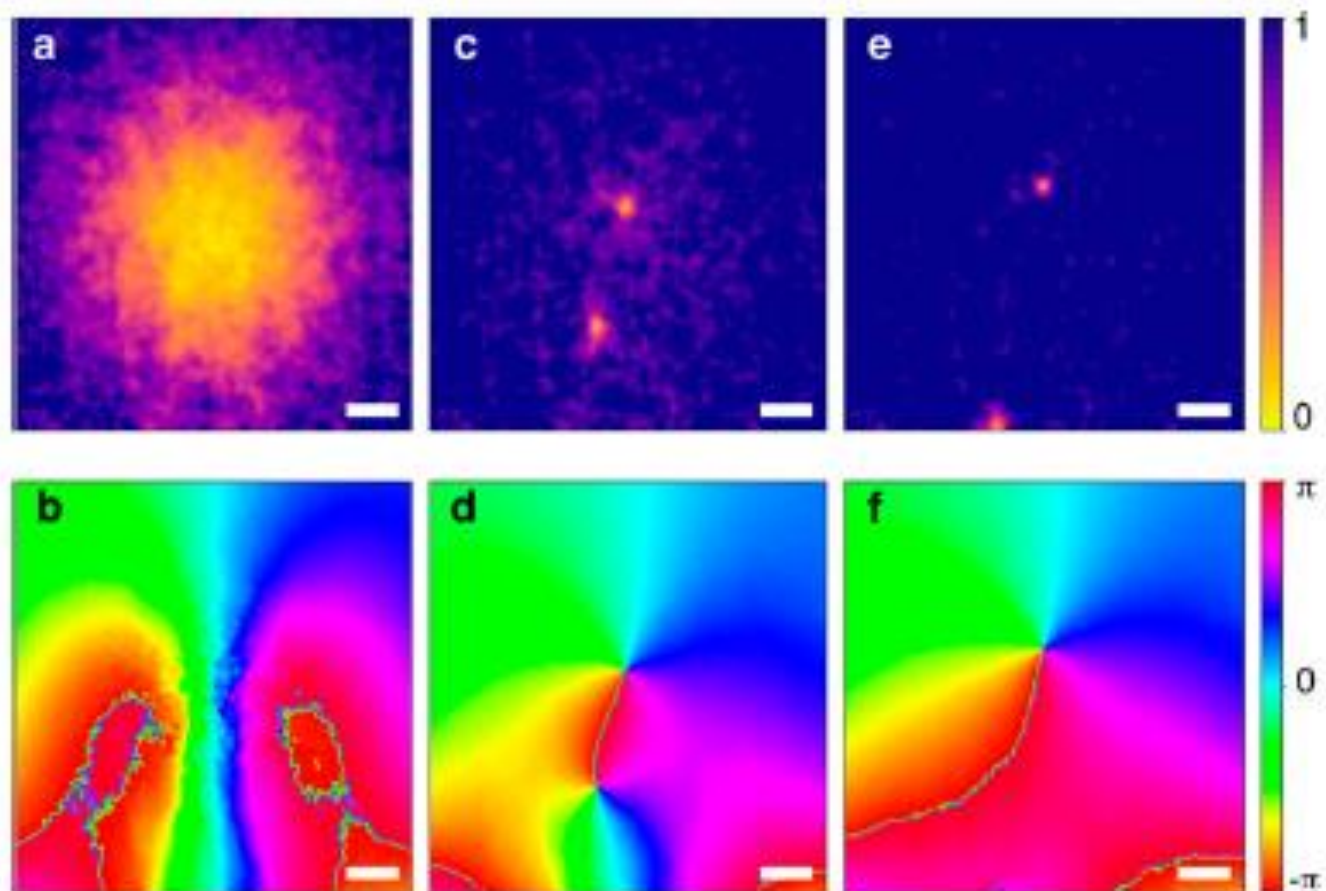
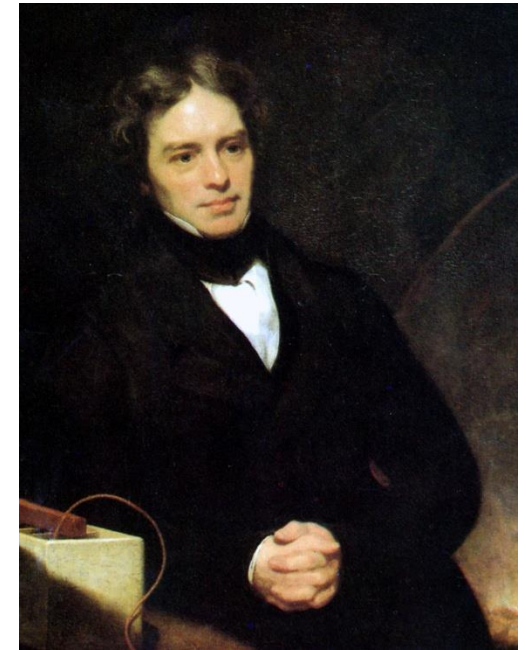
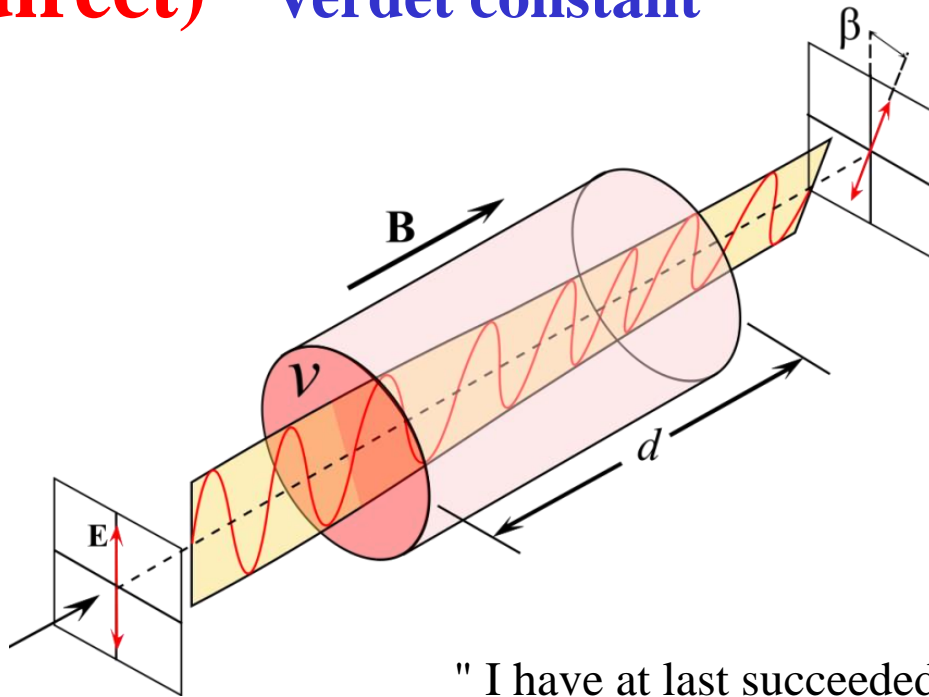


Figure 4. Numerical simulations of KZ nucleation and separation of a single vortex–antivortex pair after the application of a focused laser pulse. Computed distribution of the modulus (a, c, e) and the associated phase (b, d, f, respectively) of the order parameter in the

Faraday effect (direct) – Verdet constant



M. Faraday 1845

" I have at last succeeded in illuminating a magnetic curve or line of force and in magnetising a ray of light "

Relation to the Hall effect in conducting materials

$$\mathbf{D} = \epsilon \mathbf{E} + i [\mathbf{E} \mathbf{g}]$$

$$\vec{j} = \sigma \vec{E} + \sigma_H [\vec{H}, \vec{E}]$$

Inverse Faraday effect

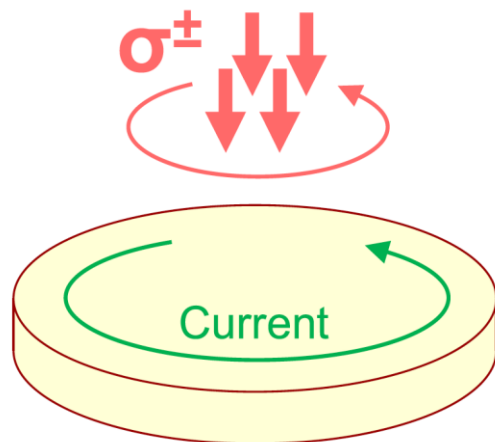


ELECTRIC FORCES IN A TRANSPARENT DISPERSIVE MEDIUM

L. P. PITAEVSKIĪ

Institute for Terrestrial Magnetism, Ionosphere, and Radio Transmission,
Academy of Sciences, U.S.S.R.

J. Exptl. Theoret. Phys. (U.S.S.R.) **39**, 1450-1458 (November, 1960)



Circularly polarized
electromagnetic wave

$$\mathbf{M} = -\frac{if}{16\pi} [\mathbf{D}\mathbf{D}^*]$$

$$M = V \frac{\lambda_0 \sqrt{\epsilon}}{2\pi c} (I_R - I_L),$$

VOLUME 15, NUMBER 5

PHYSICAL REVIEW LETTERS

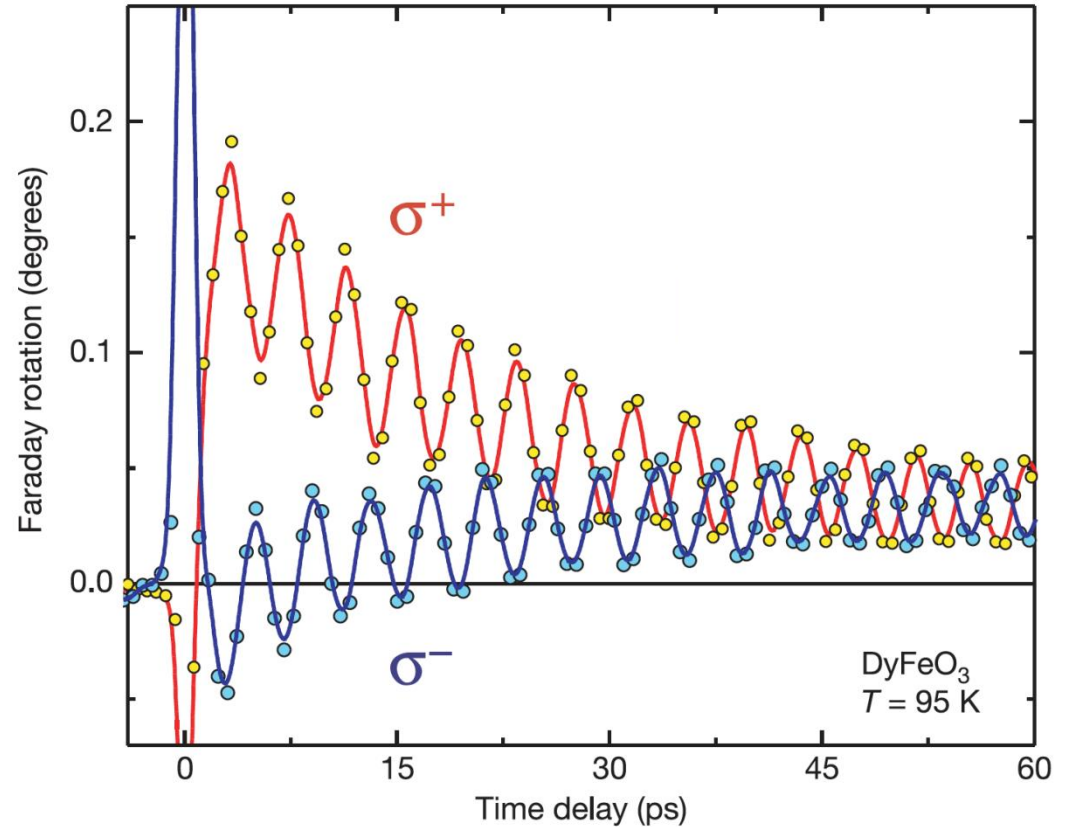
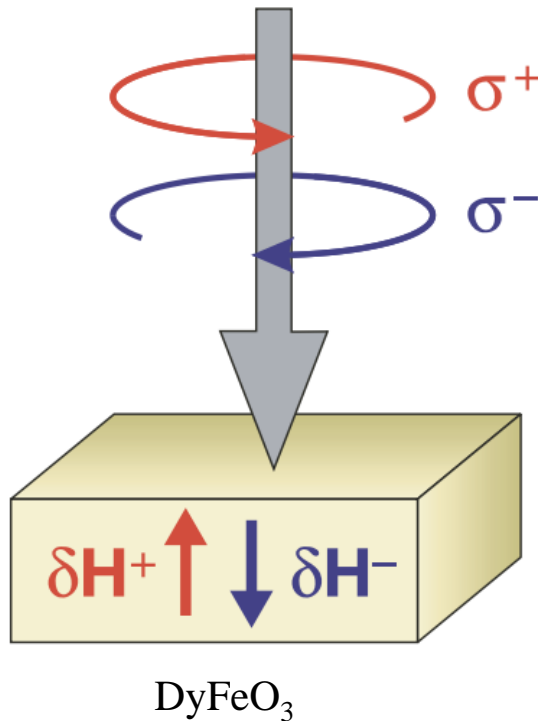
2 AUGUST 1965

OPTICALLY-INDUCED MAGNETIZATION RESULTING
FROM THE INVERSE FARADAY EFFECT*

J. P. van der Ziel, P. S. Pershan,† and L. D. Malmstrom

Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts

Inverse Faraday effect in magnetic materials



A. V. Kimel, A. Kirilyuk, P. A. Usachev, R. V. Pisarev, A. M. Balbashov, Th. Rasing, *Nature* **435**, 655 (2005)

Reviews: A. Kirilyuk, A. V. Kimel, T. Rasing, *Rev. Mod. Phys.* **82**, 2731 (2010)

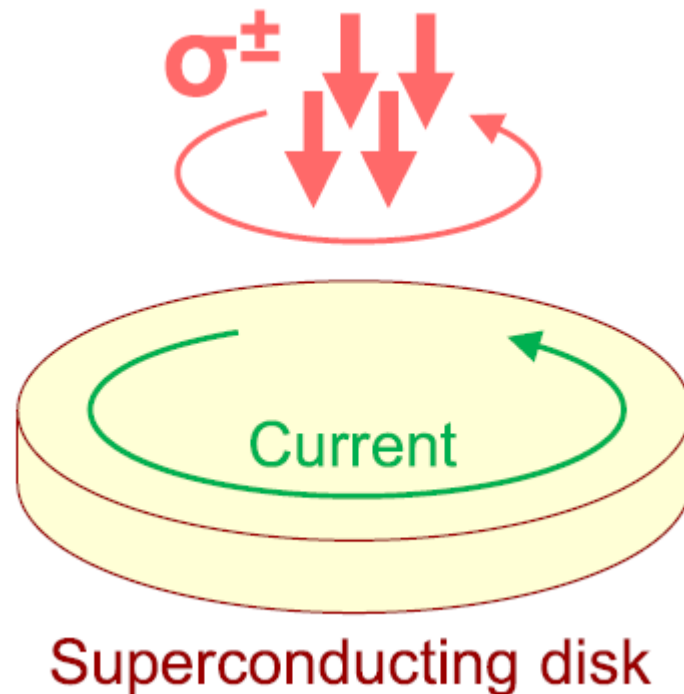
A. Kirilyuk, A. V. Kimel, T. Rasing, *Rep. Prog. Phys.* **76**, 026501 (2013)

Is it possible to induce d.c. magnetic moment and/or vortex-like state in superconductor solely by light?

PHYSICAL REVIEW LETTERS **126**, 137002 (2021)

Inverse Faraday Effect for Superconducting Condensates

S. V. Mironov¹, A. S. Mel'nikov^{1,2}, I. D. Tokman¹, V. Vadimov^{1,3}, B. Lounis^{4,5} and A. I. Buzdin^{2,6}




We need the coupling of the modes of the order parameter amplitude and phase!

Time dependent Ginzburg – Landau theory. Complex-valued relaxation constant.

$$\Gamma^{-1} \left(\frac{\partial}{\partial t} + \frac{2ie}{\hbar} \Phi \right) \Psi = \left(\frac{1}{4m} \left(\nabla - \frac{2ie}{\hbar c} \vec{A} \right)^2 - a \right) \Psi - b |\Psi|^2 \Psi$$

$$\Gamma^{-1} = \gamma_1 + i\gamma_2 \quad \gamma_2 \sim \frac{T_c}{E_F} \quad \text{Parameter of the electron-hole asymmetry}$$



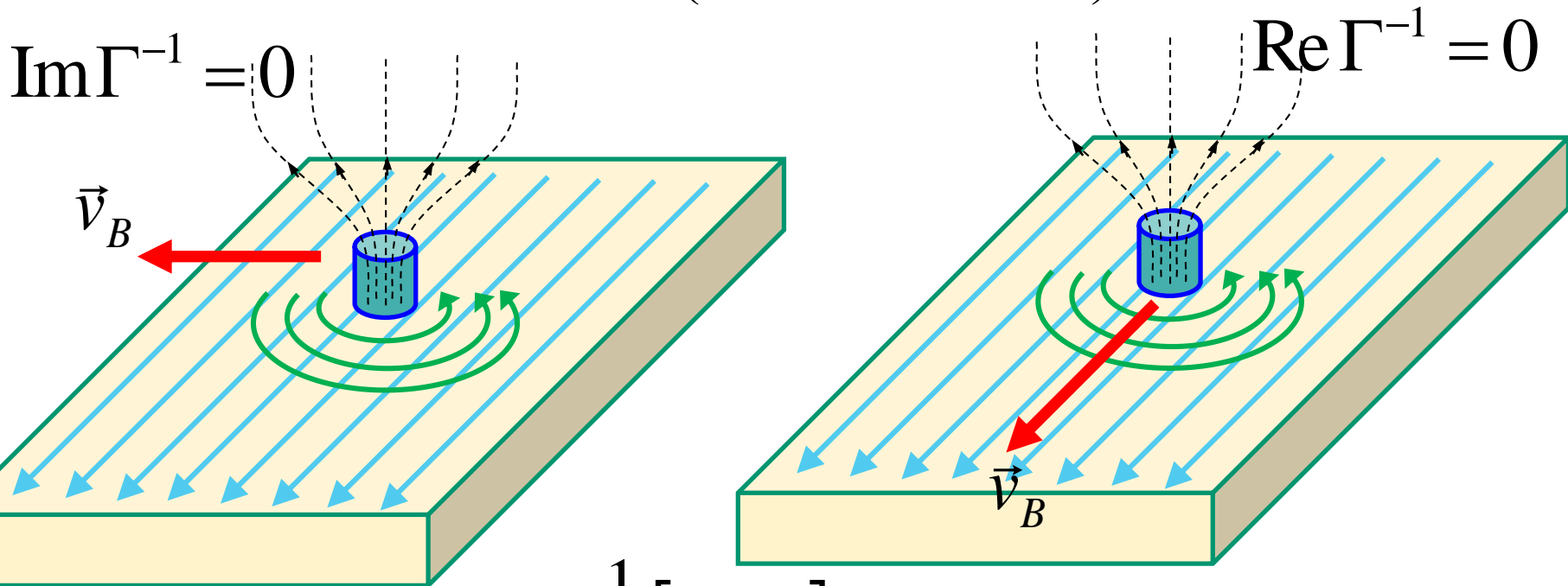
$$\tau \frac{\partial \Delta_1}{\partial t} - \nu \tau \frac{\partial \chi}{\partial t} + 2\Delta_1 - \xi^2 \nabla^2 \Delta_1 = 0$$

$$\nu = \frac{\gamma_2}{\gamma_1}$$

$$\tau \Delta_0 \frac{\partial \chi}{\partial t} + \nu \tau \frac{\partial \Delta_1}{\partial t} - \xi^2 \Delta_0 \nabla^2 \chi = 0$$

Imaginary part of the relaxation constant is responsible for the Hall effect in the vortex state

$$\Gamma^{-1} \left(\frac{\partial}{\partial t} + \frac{2ie}{\hbar} \Phi \right) \Psi = \left(\frac{1}{4m} \left(\nabla - \frac{2ie}{\hbar c} \vec{A} \right)^2 - a \right) \Psi - b |\Psi|^2 \Psi$$



A. T. Dorsey (1992)

N. B. Kopnin, B. I. Ivlev, V. A. Kalatsky (1992)

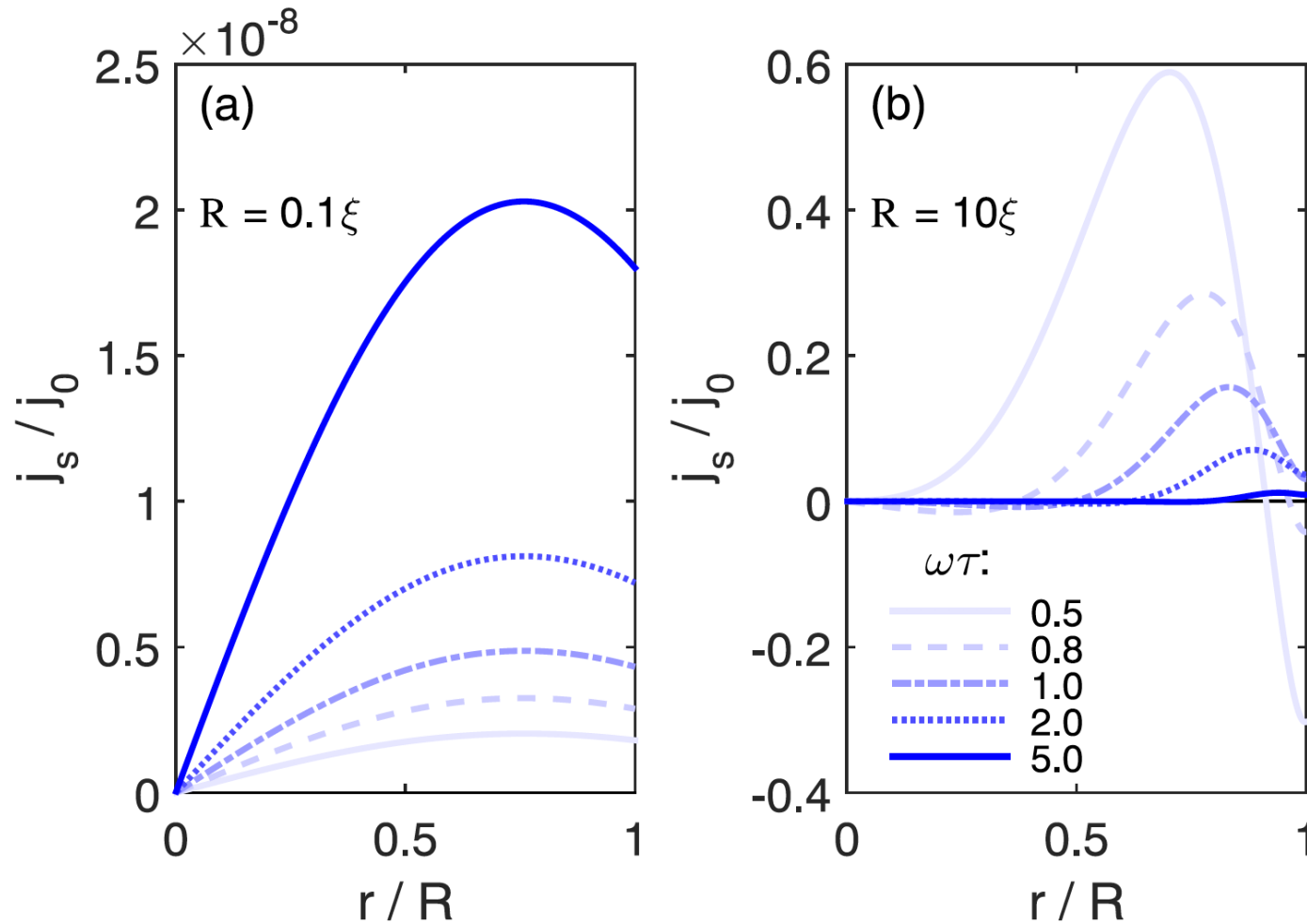
$$\vec{E} = \frac{1}{c} [\vec{B}, \vec{v}_B]$$

$$\vec{j} = \sigma \vec{E} + \sigma_H [\vec{B}, \vec{E}]$$

Now we can proceed with the inverse Faraday effect

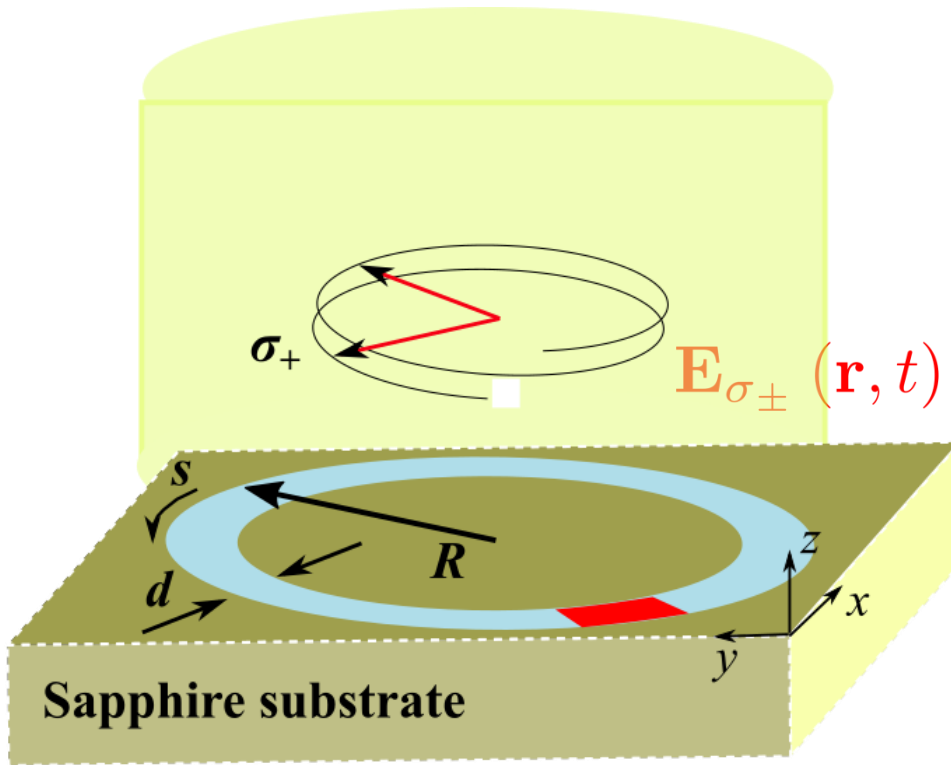
Radial profiles of d.c. current

S. Mironov et al, PRL 2021



$$j_0 = 32\gamma e^3 \Delta_0^2 E_0^2 \tau^3 / (\pi^2 \alpha^2 m^2 \xi)$$

Circularly polarized light and superconducting ring



- Circularly polarized electromagnetic wave of frequency ω and wavevector \mathbf{k} , perpendicular to the plane of the ring

$$\mathbf{E}_{\sigma_{\pm}}(\mathbf{r}, t) = E_0 \begin{pmatrix} \pm \sin(\mathbf{k} \cdot \mathbf{r} - \omega t) \\ \cos(\mathbf{k} \cdot \mathbf{r} - \omega t) \\ 0 \end{pmatrix}$$

- intensity of the radiation is supposed to be weak enough to avoid its heating effect

- The corresponding dimensionless angular component of the vector-potential

$$A_{\theta}^{\sigma_{\pm}}(\theta, t) = \frac{E_L}{\omega_L} \cos(\theta \mp \omega_L t)$$

- Dimensionless units $\omega_L = \omega \tau_{\Delta}$ $E_L = E_0 2\pi c \xi_0 / (\Phi_0 \tau_{\Delta}^{-1})$

Persistent current in the ring

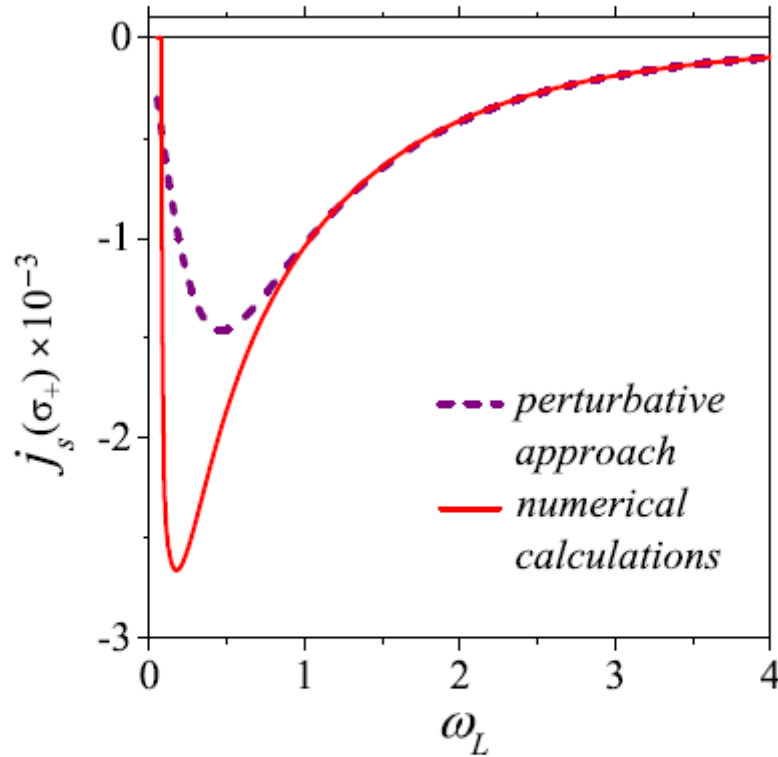
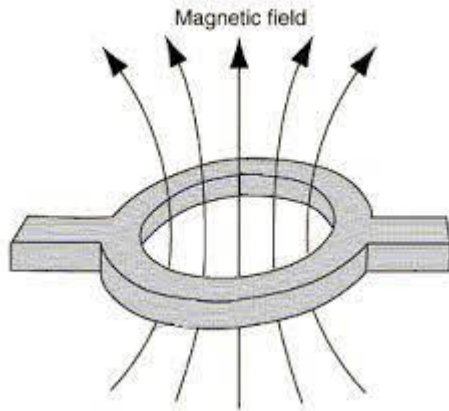


FIG. 2: Stationary current j_s averaged over the time interval $40\pi/\omega_L$, as a function of frequency ω_L of the σ_+ circularly polarized radiation with constant amplitude $E_L = 0.1$ for the sample with $\tilde{R} = 4.5$. The solid red line presents the results of numerical calculations, while the dashed line corresponds to the perturbative approach.

$$M = -M_0 \frac{\omega_L}{\rho(\rho^4 + \omega_L^2) [(2 + \rho^2)^2 + \omega_L^2]},$$

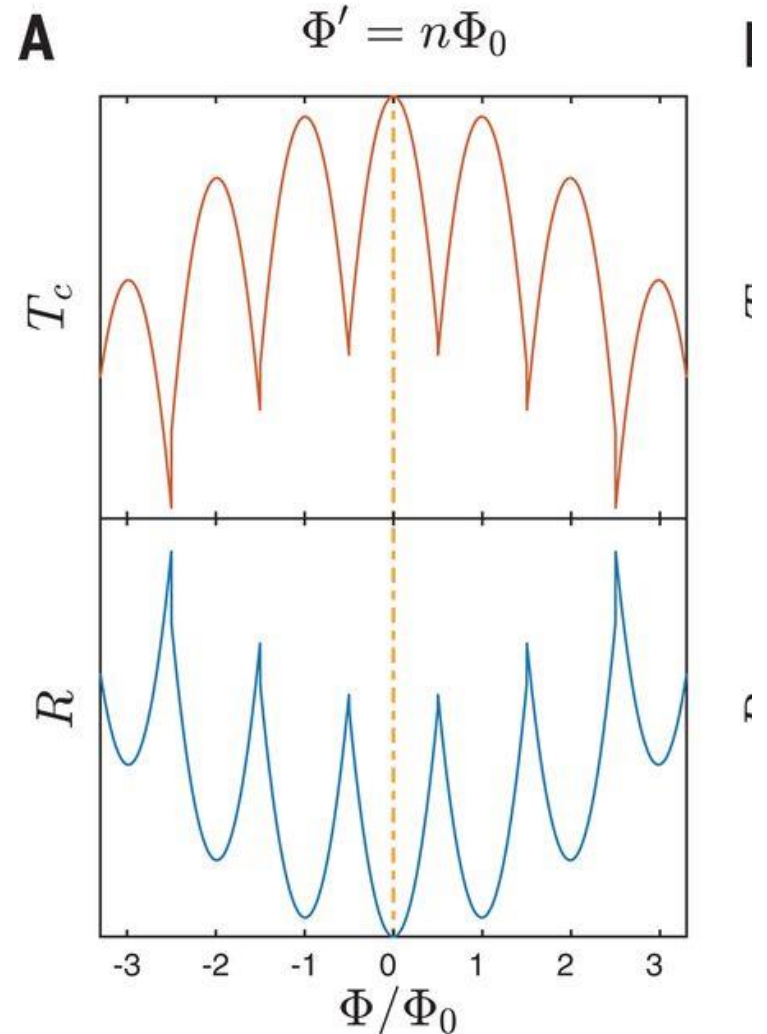
How to obtain practically 100% probability of the current state generation?

Little-Parks effect



For $\Phi = -\Phi_0/2$ the states $n=0$ and $n=1$ have the same critical temperature and the same energy and it should be easy to switch between them.

They are the current carrying states with the opposite direction of current.



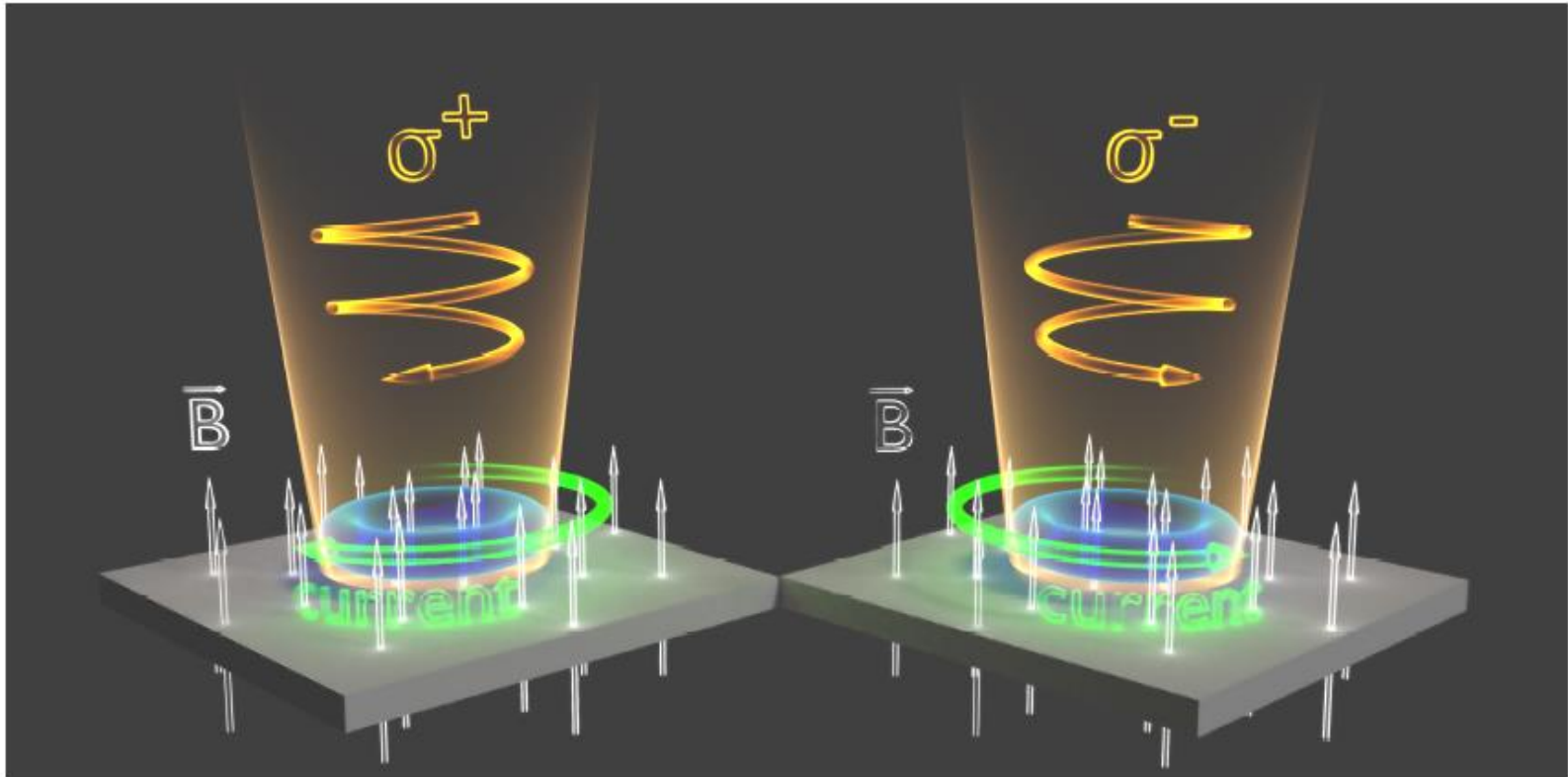


FIG. 1: Sketch illustrating the generation of the d.c. electric current in the thin superconducting ring under the influence of the circularly polarized laser beam.

Ref.: Croitoru, Mironov, Lounis, and A.B.

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Modelling with a Time Dependent Ginsburg-Landau equation

$$\Gamma_{\Delta} \frac{\partial \Delta(\mathbf{r}, t)}{\partial t} = \frac{T_{c0} - T(\mathbf{r}, t)}{T_{c0} \epsilon_0} \Delta(\mathbf{r}, t) - |\Delta(\mathbf{r}, t)|^2 \Delta(\mathbf{r}, t) - \epsilon_0^{-1} (i\nabla + \mathbf{A})^2 \Delta(\mathbf{r}, t) + \zeta(\mathbf{r}, t) \quad (4)$$

$$\Delta(\theta, t) = \sum_{n=-N_c}^{N_c} \psi_n(t) e^{-in\theta}.$$

$$\Gamma_{\Delta} \frac{\partial \psi_n(t)}{\partial t} = \left[1 - \frac{T^G(t) - T_0}{T_{c0} \epsilon_0} - \frac{1}{\epsilon_0 R^2} n^2 \right] \psi_n(t) - \sum_{l,m} \{ \psi_l(t) \psi_m^*(t) \} \psi_{n+m-l}(t) - \frac{\gamma(t)}{T_{c0} \epsilon_0} \sum_n \psi_n(t) + \zeta_n(t),$$

Averaging over 500 cooling cycles realizations

$$\psi(\theta, t) = \sum_{n=-N_c}^{N_c} \psi_n(t) e^{-in\theta},$$

For $\Phi = -\Phi_0/2$ the states $n=0$ and $n=1$ have the same energy and it is easy to switch between them.

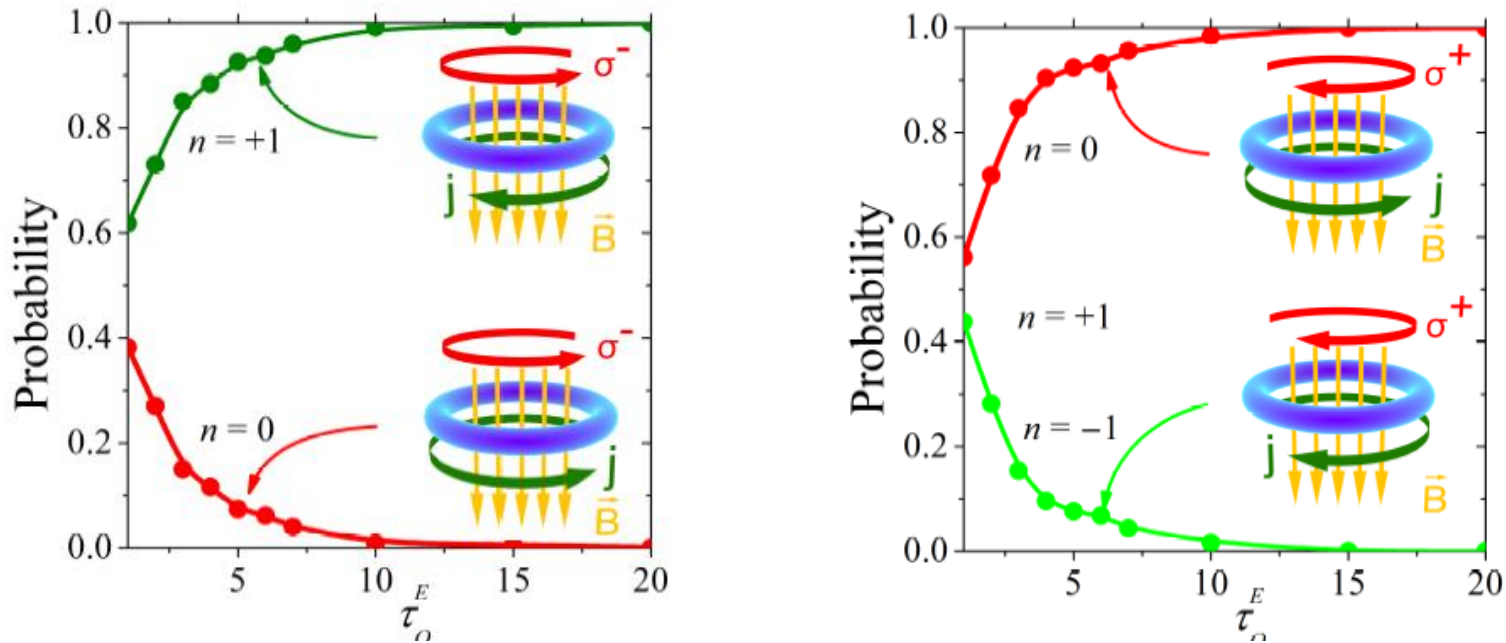


FIG. 3: Probability of a final stationary state ψ_n as a function of the decaying time τ_Q^E for $E_L/\omega_L = 0.75$ at magnetic field $\Phi/\Phi_0 = -1/2$ and polarization σ_- . Here we take $\omega_L = 1.0$ and $\tilde{R} = 4.5$.

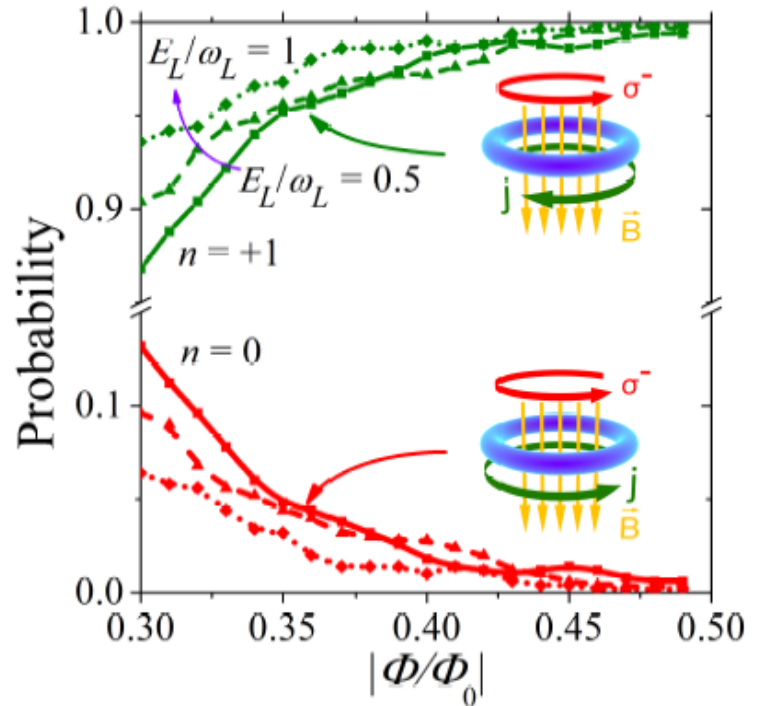
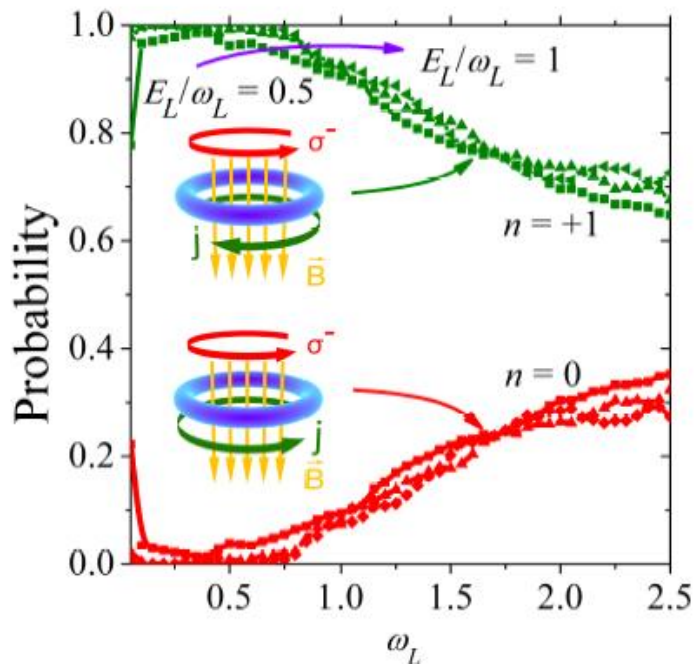
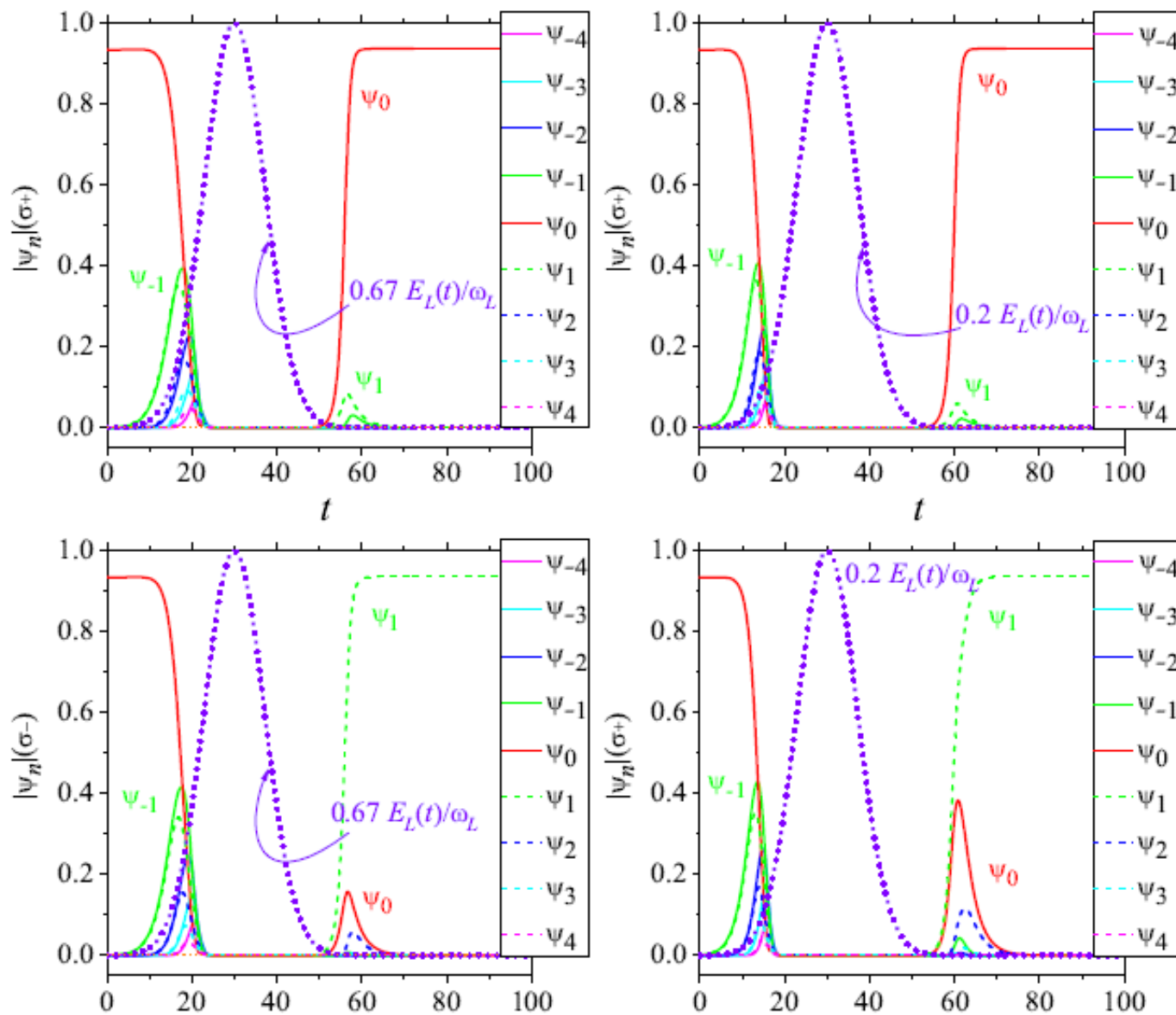


FIG. 4: Probability of the final stationary state ψ_n as a function of the radiation frequency ω_L at $\Phi/\Phi_0 = -1/2$ (top panel) and external magnetic flux $|\Phi|/\Phi_0$ at $\omega_L = 1$ (lower panel) for $E_L/\omega_L = 0.5$, $E_L/\omega_L = 0.75$, $E_L/\omega_L = 1.0$, when polarization is σ_- . Here the decaying time $\tau_Q^E = 5$ and ring radius $\tilde{R} = 4.5$.

Helicity-Controlled Switching of Superconducting States by Radiation Pulse



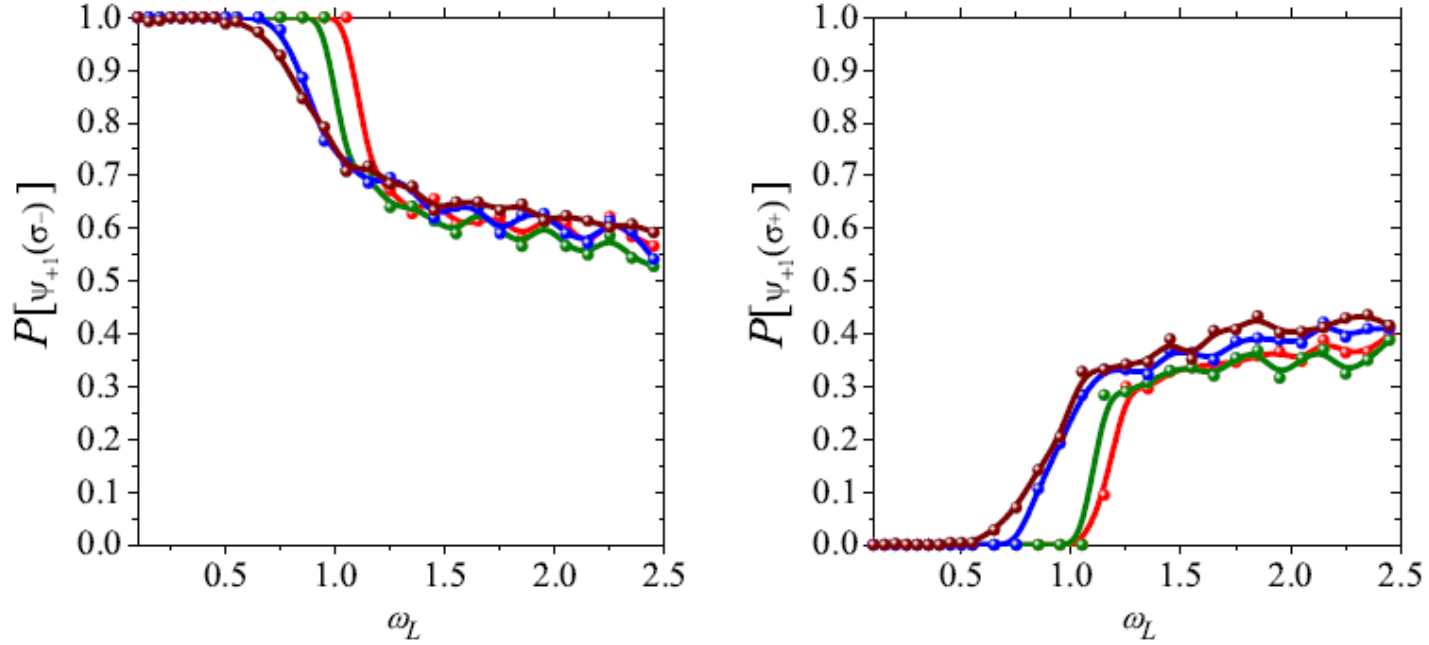
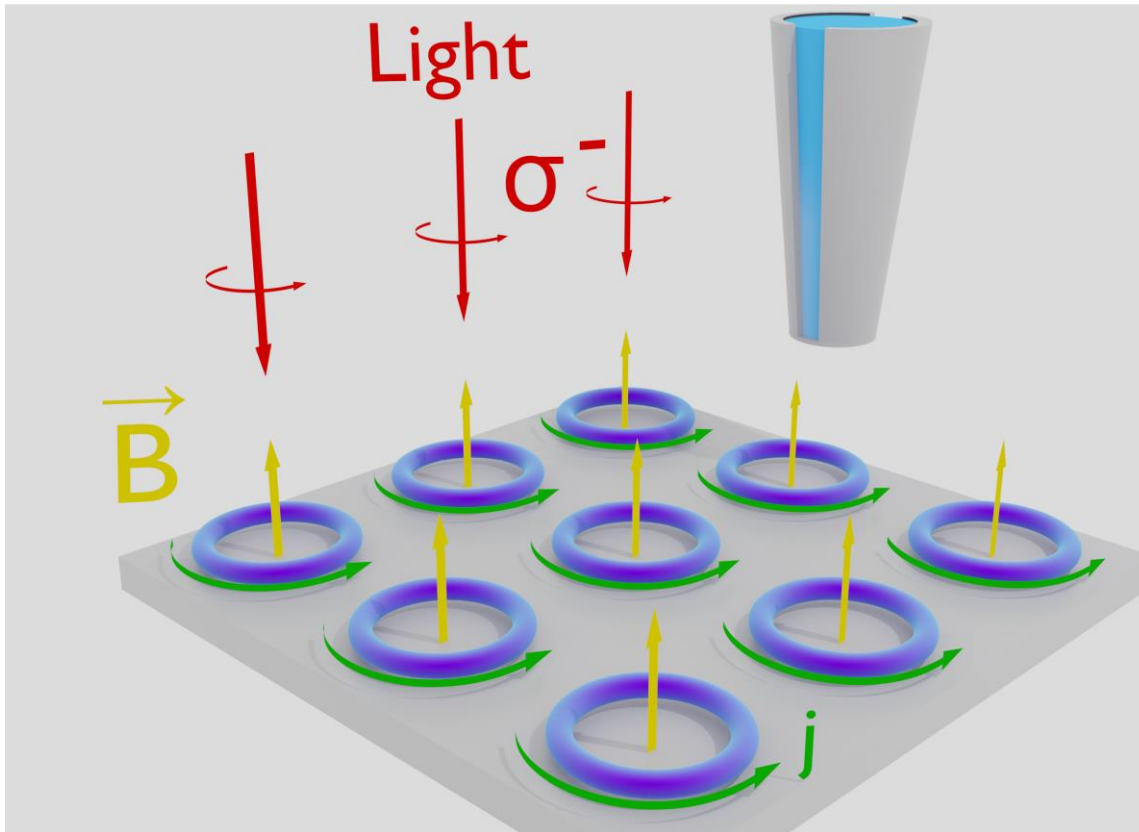
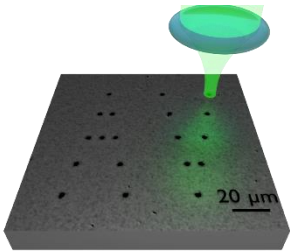


FIG. 3: Probability of the final stationary state $\psi_{n=+1}$ as a function of the radiation frequency ω_L . The radiation amplitudes are $E_L/\omega_L = 1.5$ (red curve), 2.0 (green curve), 3.0 (blue curve) and 5.0 (brown curve). The pulse's duration time (switch off) time $\tau_E = 10$. The left panel corresponds to σ_- polarization and right panel is for σ_+ polarization, external magnetic flux is $-\frac{1}{2}$. Initial state $n = 0$.

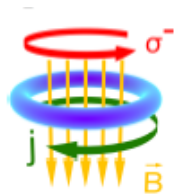


As follows from our analysis, the optimal dimensionless frequency for implementing the switching by IFE is $\omega_L \sim 0.3$, which corresponds to $\omega \sim 0.38T_{c0}\epsilon_0/\pi\hbar$. For Nb and $\epsilon_0 = 0.1$ it is $f \sim 15GHz$, while for the high- T_c superconductors this frequency is an order of magnitude larger. To avoid the heating effect due to circularly po-

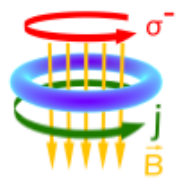
Conclusion



We suggest a method of very fast single vortex manipulation by focused laser beam.



The use of the IFE may be a very efficient tool for all-optical switching between the current states in mesoscopic superconducting systems.



All this opens the way to superconducting optoelectronics.