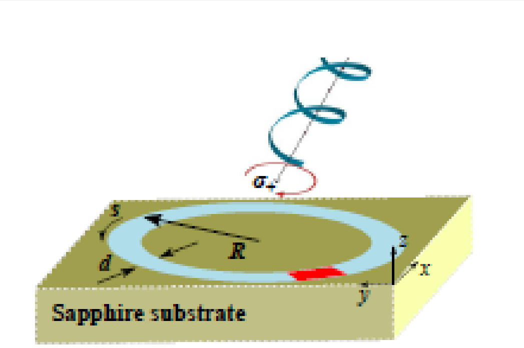

Towards the light-operated superconducting devices: circularly polarized radiation manipulates the current-carrying states in superconducting rings

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ECRYS 2022- Corse, France August 8-20 2022

Outline

◈**Direct and inverse Faraday effects. Inverse Faraday effect (IFE) in metals.**

◈ **What should we expect in superconductors?**

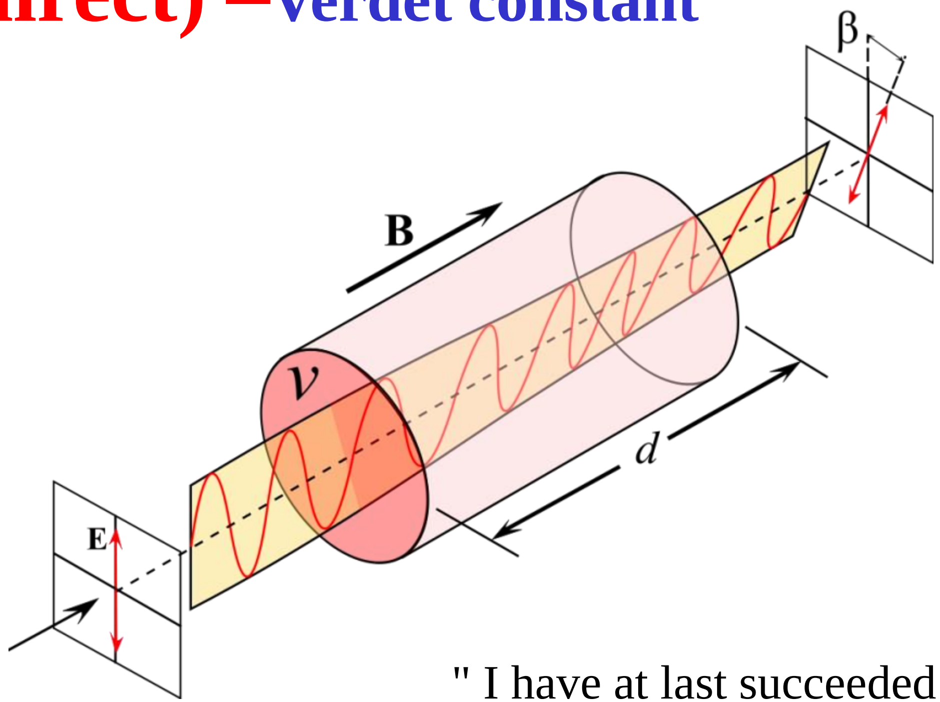
◈ **Time dependent Ginzburg – Landau equation. Hall effect and inverse Faraday effect.**

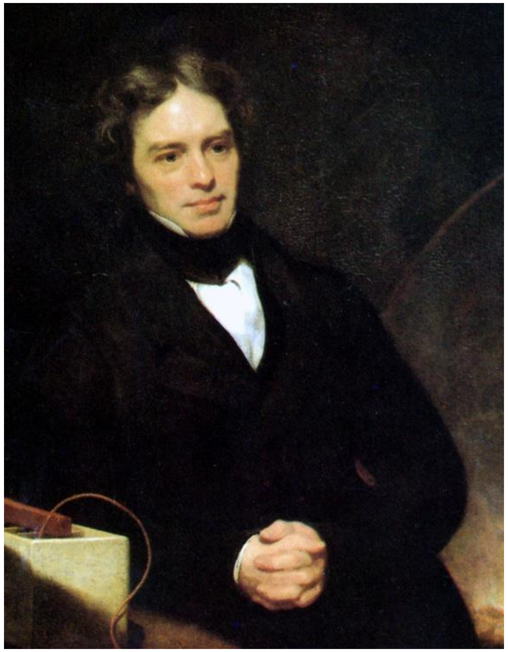
◈**All-optical generation of the current states.**

◈**How can we increase the impact of IFE? Kibble-Zurek mechanism in thin superconducting ring - spontaneous fluxoid formation.**

◈**On-demand switch between current-carrying states in the superconductor by controlling the helicity**

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 "

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

Relation to the Hall effect in conducting materials

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

Inverse Faraday effect

ELECTRIC FORCES IN A TRANSPARENT DISPERSIVE MEDIUM

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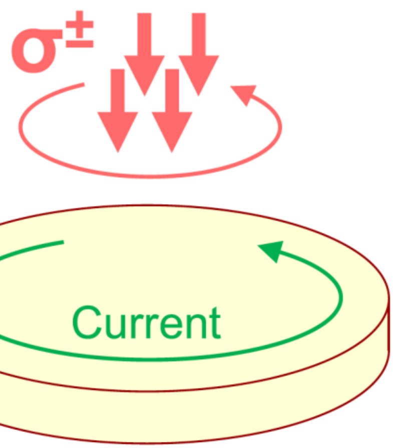
Institute for Terrestial Magnetism, Ionosphere, and Radio Transmission, Academy of Sciences, U.S.S.R.

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



Circularly polarized electromagnetic wave

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

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

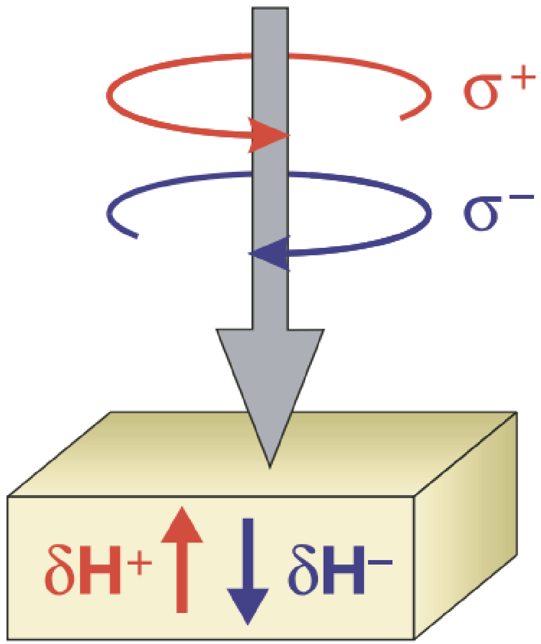
VOLUME 15, NUMBER 5 PHYSICAL REVIEW LETTERS 2 AUGUST 1965

OPTICALLY-INDUCED MAGNETIZATION RESULTING FROM THE INVERSE FARADAY EFFECT*

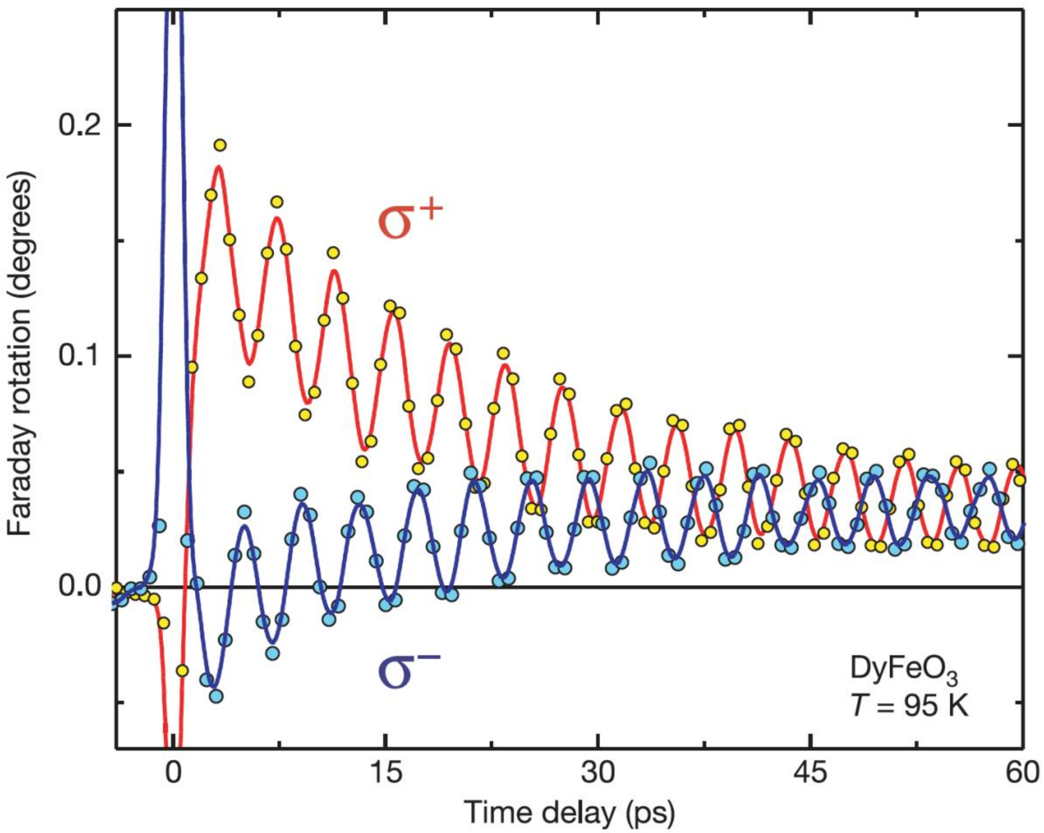
J. P. van der Ziel, P. S. Pershan,† and L. D. Malmstrom

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

Inverse Faraday effect in magnetic materials



DyFeO$_3$



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)

PRL 99, 260401 (2007)

Observation of Persistent Flow of a Bose-Einstein Condensate in a Toroidal Trap

C. Ryu,[1,2] M. F. Andersen,[1,*] P. Cladé,[1] Vasant Natarajan,[1,†] K. Helmerson,[1,2] and W. D. Phillips[1,2]

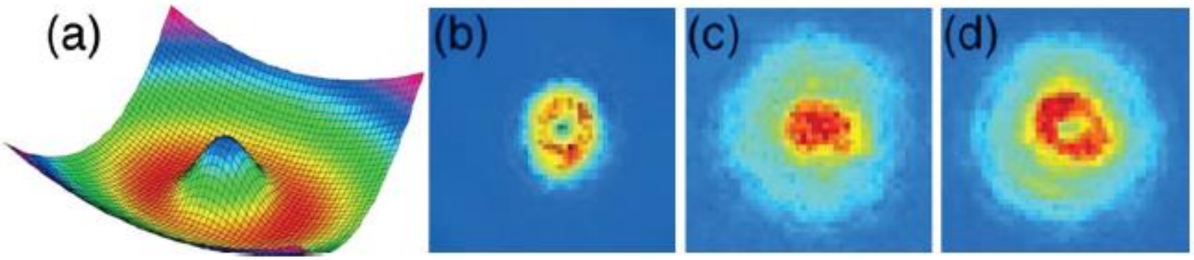


FIG. 1 (color). (a) Toroidal trap from the combined potentials of the TOP trap and Gaussian plug beam. (b) *In situ* image of a BEC in the toroidal trap. (c) TOF image of a noncirculating BEC released from the toroidal trap. (d) TOF image of a circulating BEC, released after transfer of $\hbar$ of OAM.

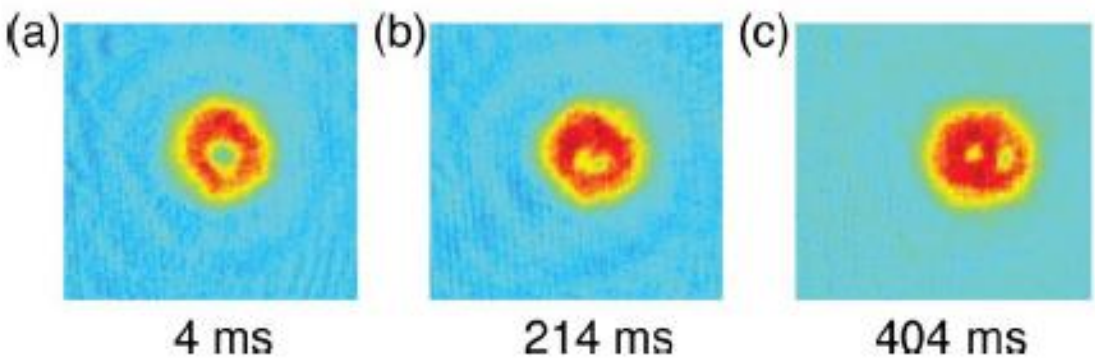
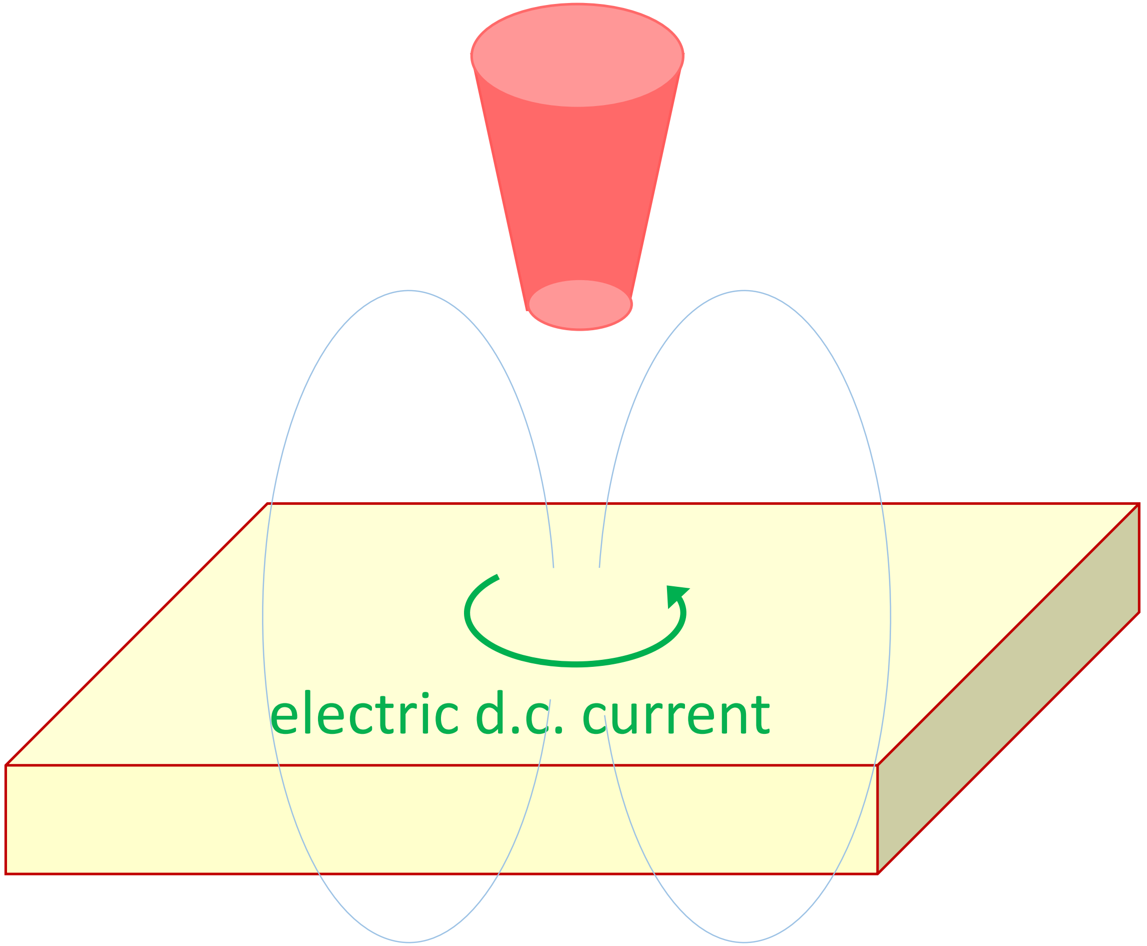


FIG. 5 (color). TOF pictures of doubly charged flow, initially stabilized for 0.5 s in the toroidal trap, for different holding times (4, 214, and 404 ms) in just the TOP trap.

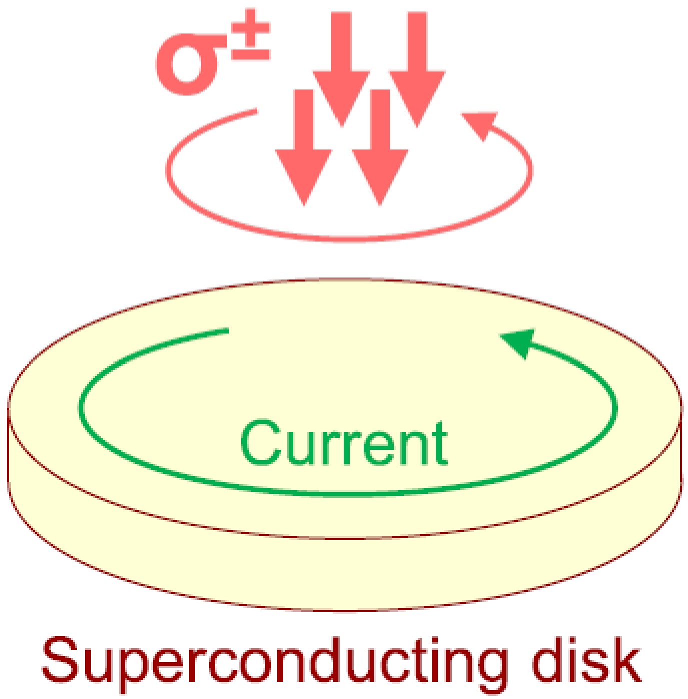
Is it possible to induce d.c. magnetic moment and/or vortex-like state in superconductor solely by light?



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

Inverse Faraday Effect for Superconducting Condensates

S. V. Mironov,[1] A. S. Mel'nikov,[1,2] I. D. Tokman,[1] 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.

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

$$\Gamma^{-1}=\gamma_1+i\gamma_2 \qquad \gamma_2\sim\frac{T_c}{E_F}$$

Parameter of the electron-hole asymmetry

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

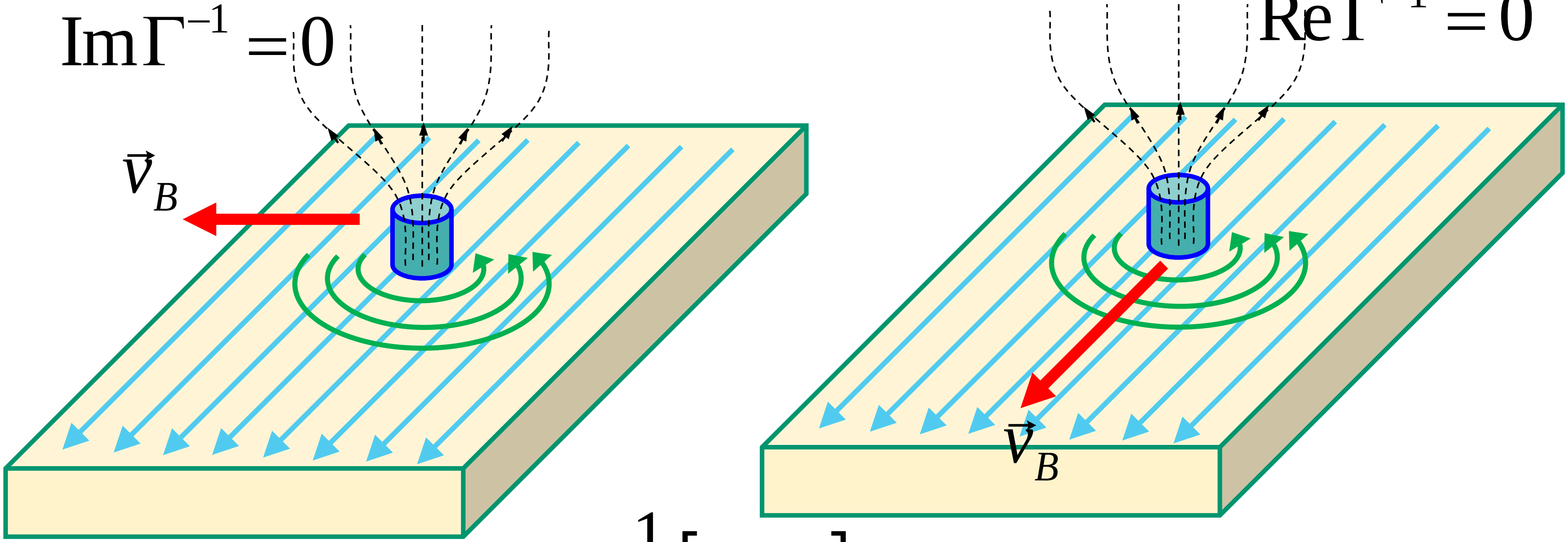
$$\nu=\frac{\gamma_2}{\gamma_1}$$

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

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

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

$$\mathrm{Im}\,\Gamma^{-1}=0 \qquad \mathrm{Re}\,\Gamma^{-1}=0$$



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

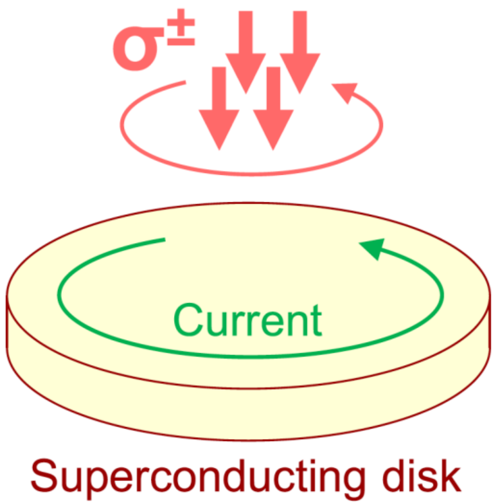
A. T. Dorsey (1992)

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

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

Now we can proceed with the inverse Faraday effect

The simplest model: small superconducting disk



$$R \ll c/\omega, \lambda, l_E$$

Electric field *inside* the disk:

$$\vec{E} = E_0 \,\mathrm{Re}\left[(\vec{e}_x + i\vec{e}_y)e^{-i\omega t}\right]$$

$$\vec{A} = \frac{cE_0}{\omega} \,\mathrm{Re}\left[(\vec{e}_y - i\vec{e}_x)e^{-i\omega t}\right]$$

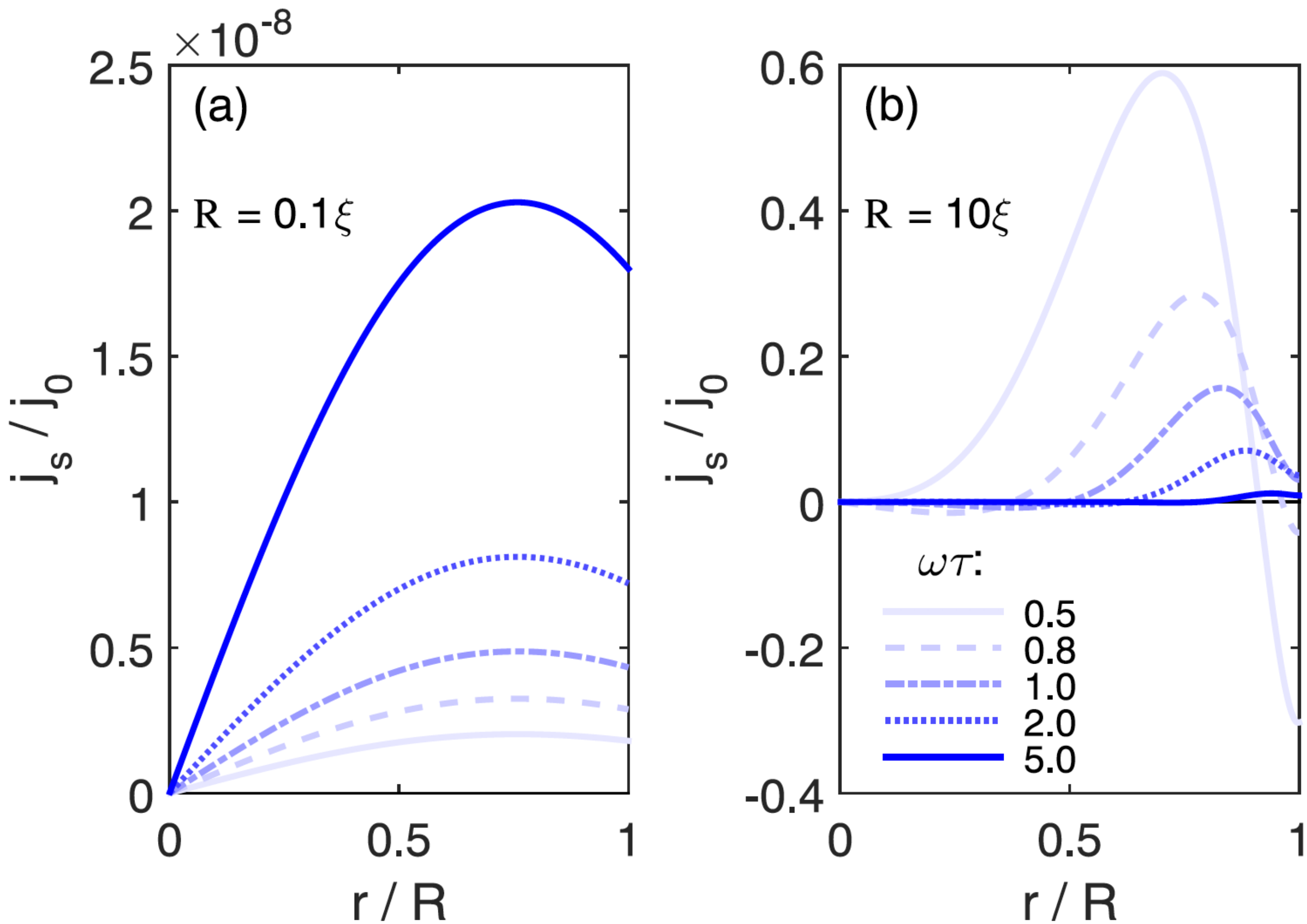
$$\left(\frac{\pi\alpha}{8} + i\gamma\right)\hbar\frac{\partial\psi}{\partial t} + \alpha(T - T_c)\psi + \xi_0^2\left(-i\nabla + \frac{2\pi}{\Phi_0}\vec{A}\right)^2\psi + b|\psi|^2\psi = 0$$

$$\vec{j}_s = \frac{2\pi\alpha T_c\xi_0^2 c}{\Phi_0}\left(i\psi^*\nabla\psi - i\psi\nabla\psi^* - \frac{4\pi}{\Phi_0}|\psi|^2\vec{A}\right)$$

$$\gamma \sim \alpha\left(\frac{T_c}{E_F}\right)$$

Radial profiles of d.c. current

S. Mironov et al, PRL 2021



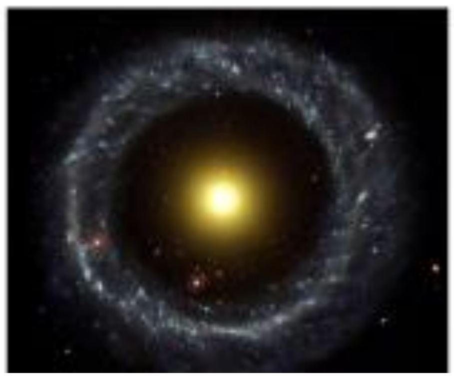
$$j_0 = 32\gamma e^3 \Delta_0^2 E_0^2 \tau^3 / (\pi^2 \alpha^2 m^2 \xi)$$

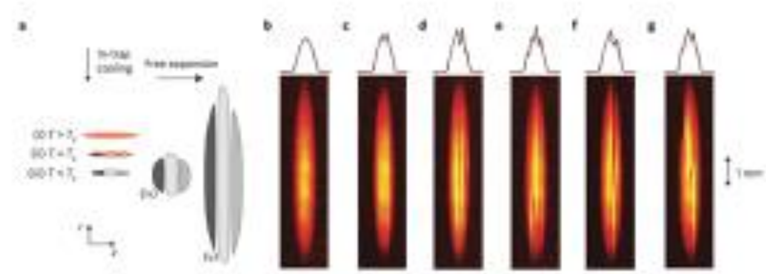
Vortex/anti-vortex pair generation

The Kibble-Zurek Effect : spontaneous generation of topological defects

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

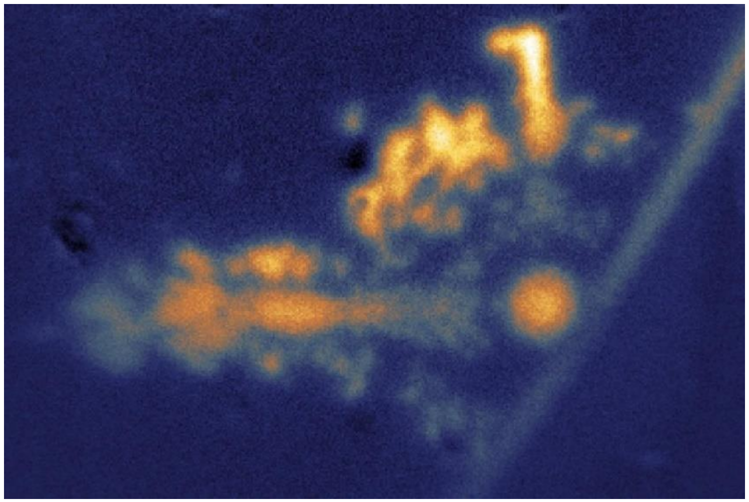
Ya. B. Zeldovich, I. Yu. Kobzarev, and L. B. Okun', Cosmological consequences of a spontaneous breakdown of a discrete symmetry, Zh. Eksp. Teor. Fiz. **67**, 3 (1975) [Sov. Phys. JETP **40**, 1 (1975)].





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.

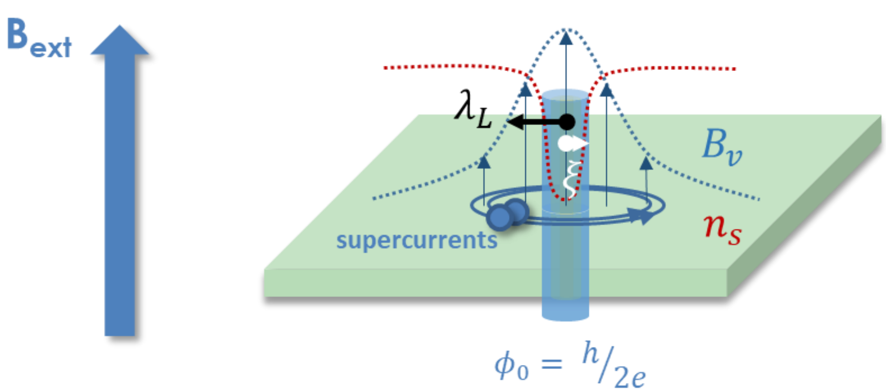
Optical generation of Abrikosov vortices by Kibble-Zurek effect



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).

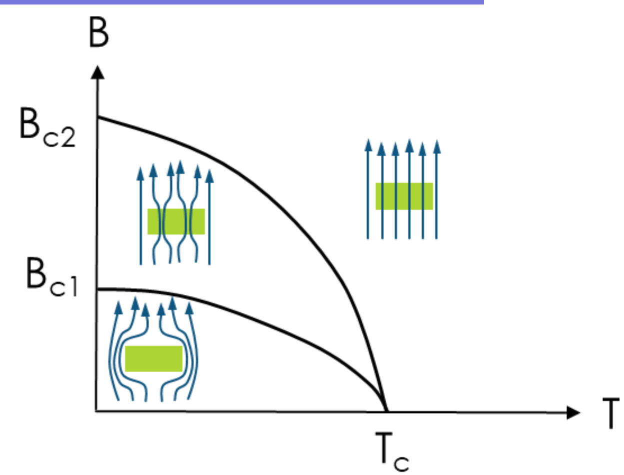
- Abrikosov vortices

  A quantum of magnetic flux



Abrikosov vortex :

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

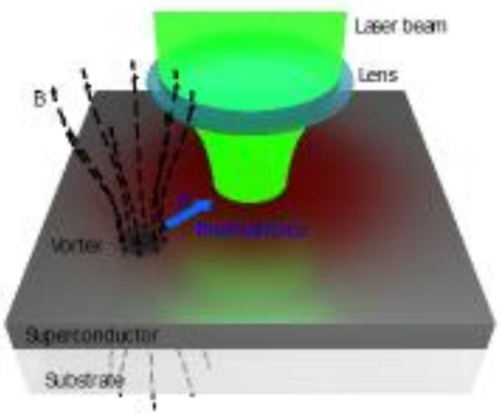


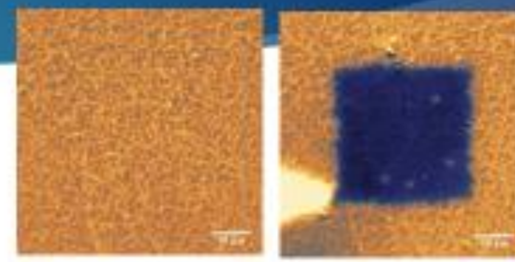
Abrikosov vortices manipulation

Optical manipulation

Experimental work on vortices :

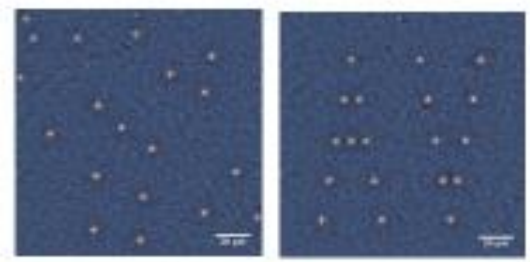
$$F_T = \frac{\phi_0^2}{4\pi\mu_0\lambda_0^2}\ln\left(\frac{\lambda_0}{\xi_0}\right)\frac{\nabla T}{T_c}$$





Removal of many Abrikosov vortices : (Nature Communication (2016))

A vortex free area produced by scanning the 561 nm laser like a vortex

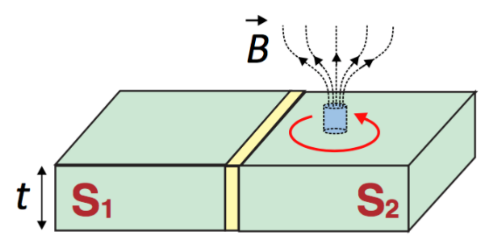


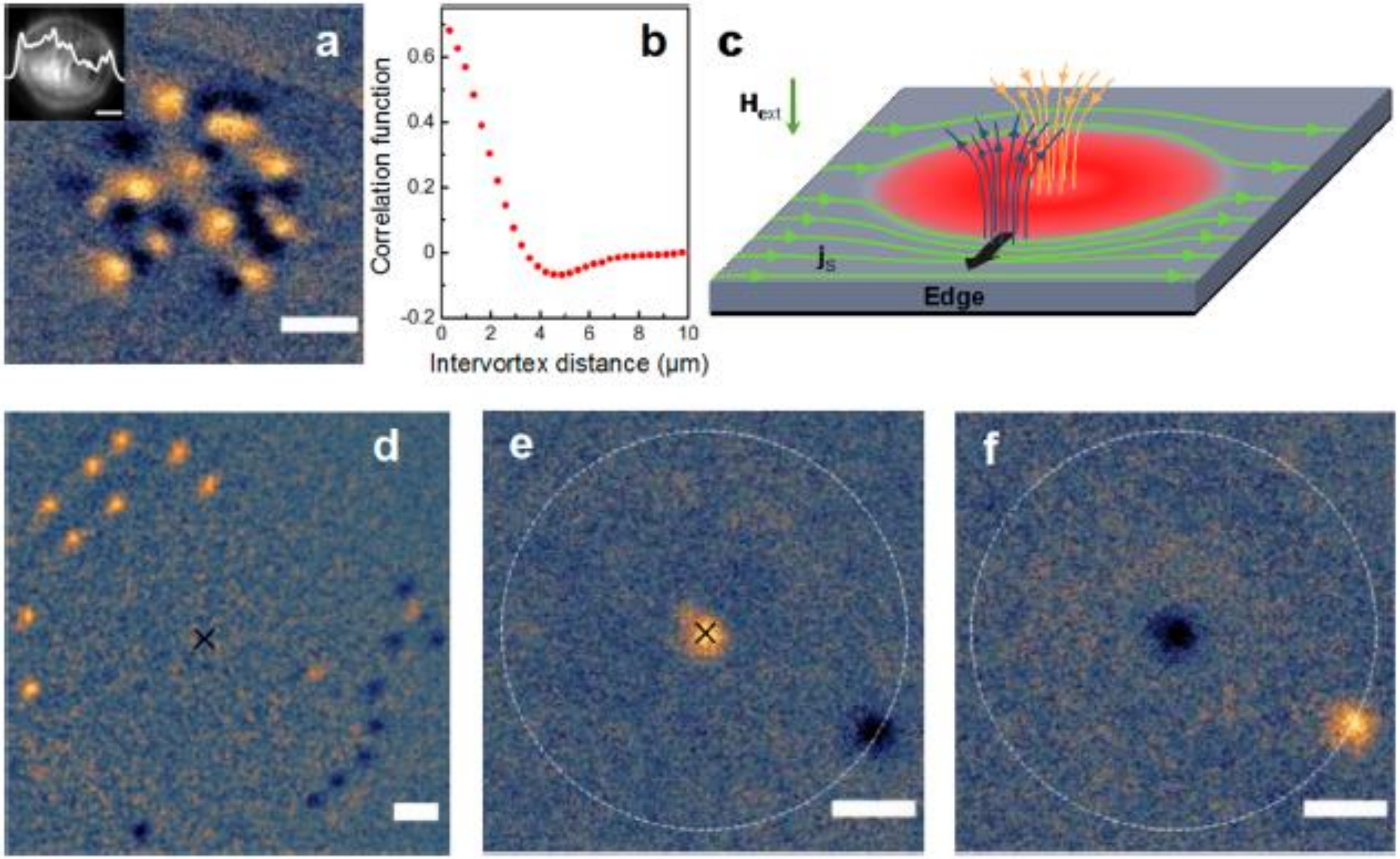
Individual displacement of vortices : (Nature Communication (2016))

A 561 nm focalized dye laser used as optical tweezers

I.S. Veshchunov, W. Magrini, S.V. Mironov, A.G. Godin, J.-B. Trebbia, A. Buzdin, Ph. Tamarat & B. Lounis

Josephson junction control





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).

KZ mechanism for a superconducting ring

PHYSICAL REVIEW B **105**, L020504 (2022)

Letter

Influence of a nonuniform thermal quench and circular polarized radiation on spontaneous current generation in superconducting rings

M. D. Croitoru,[1,2,6] B. Lounis,[3,4] and A. I. Buzdin[1,5]

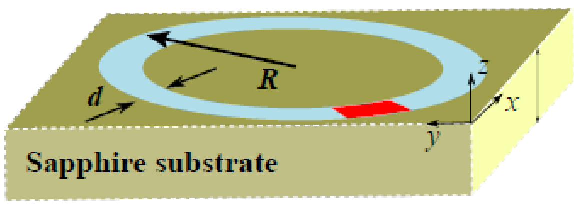
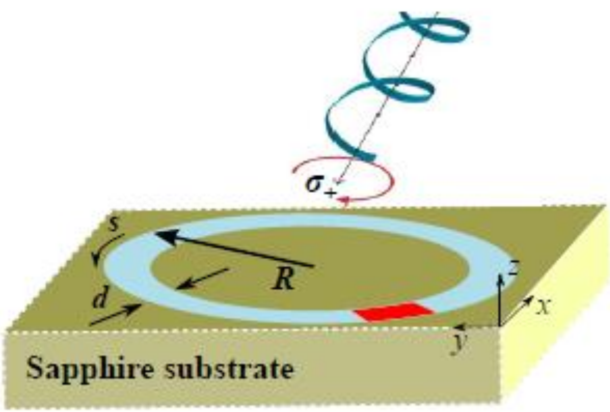


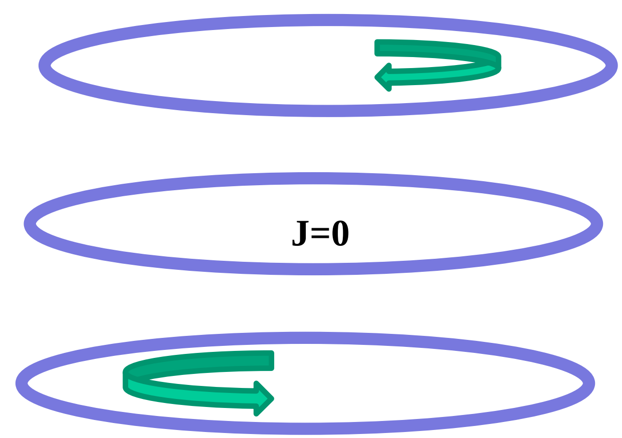
FIG. 1: Scheme of the thin superconducting ring on a substrate.

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

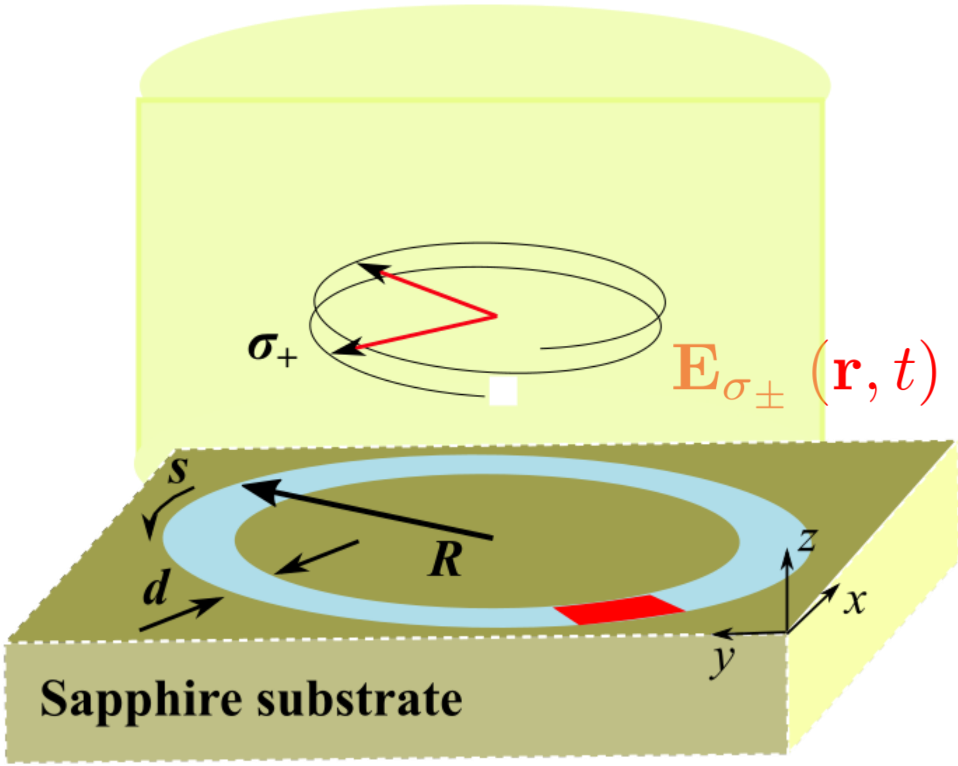
Thermal quench may be of the order of 1-4 ps

$T(t)=T_0 +\delta T\cdot\exp(-t/t_Q)$





Circularly polarized light



- Ccircular polarized electro-magnetic wave of frequency ***ω*** and wavevector ***k***, perpendicular to the plane of the ring

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

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

Modelling with a Time Dependent Ginsburg-Landau equation

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

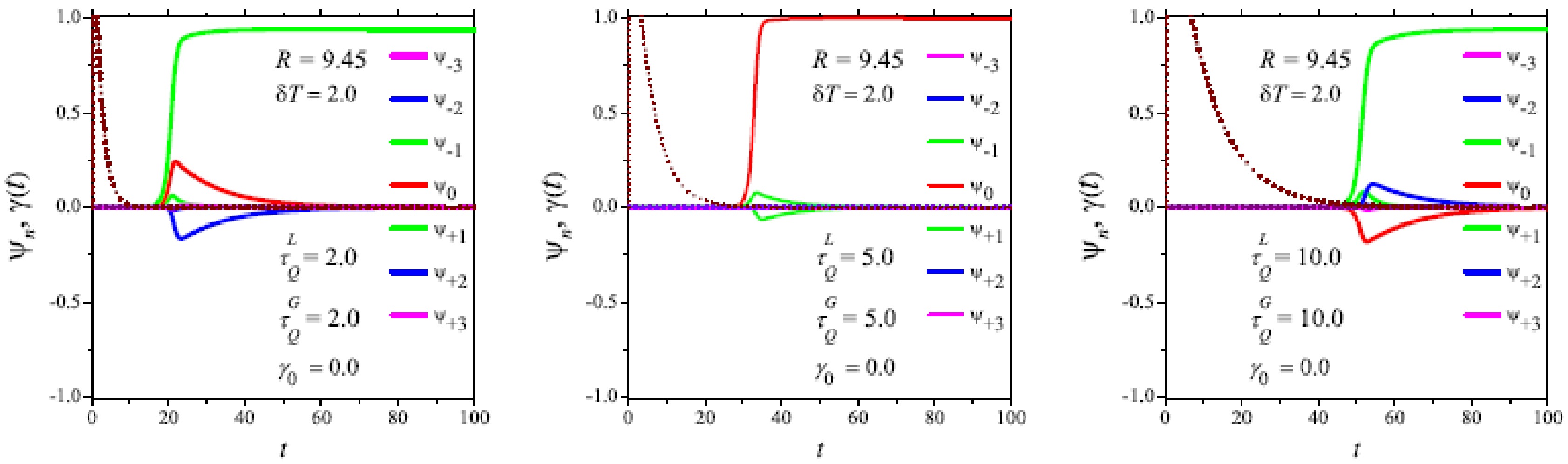
$$\Delta(\theta,t) = \sum_{n=-N_c}^{N_c} \psi_n(t)\, e^{-in\theta}.$$

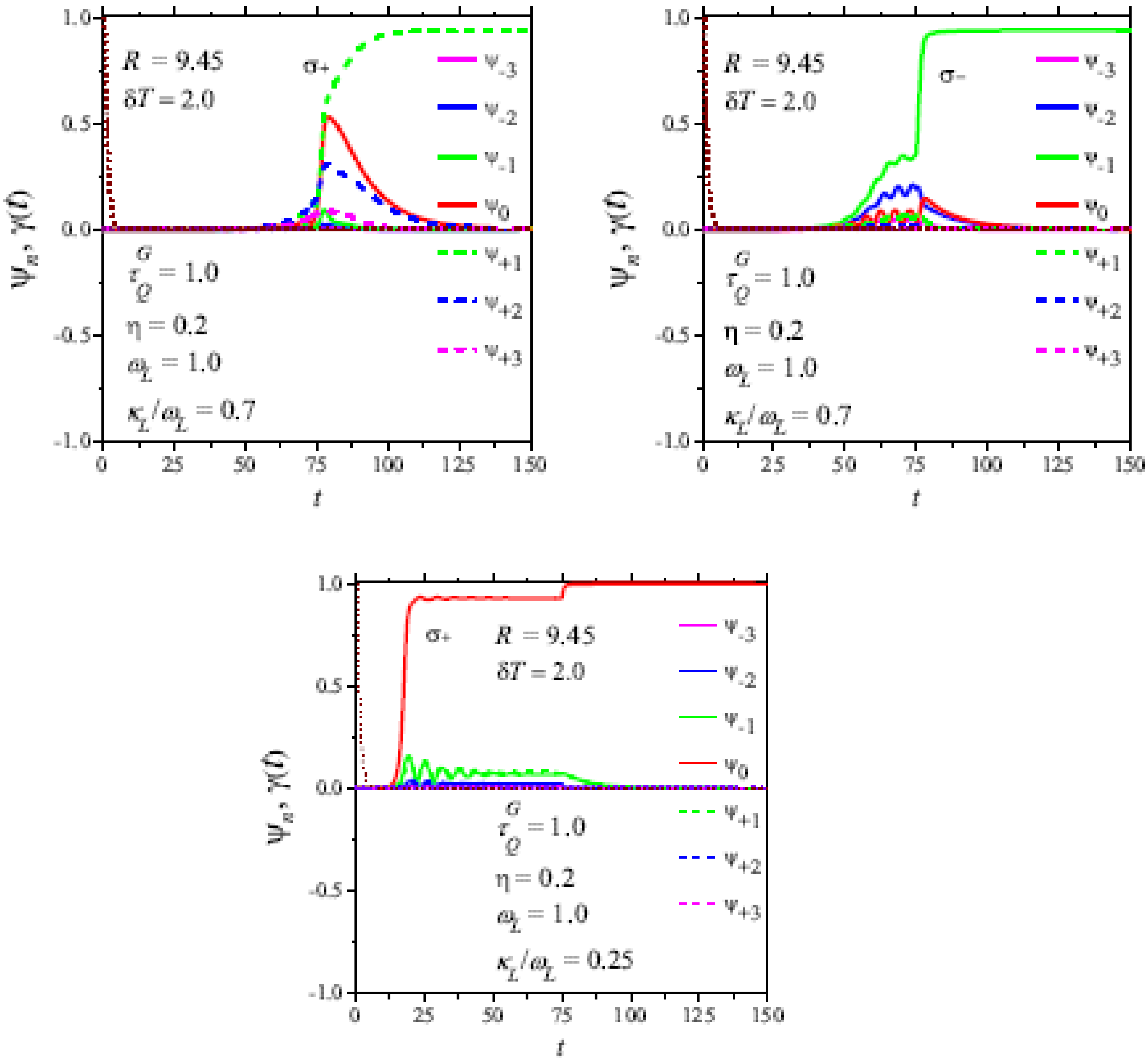
$$\begin{aligned}\Gamma_\Delta \frac{\partial \psi_n(t)}{\partial t} = & \left[1 - \frac{T^G(t) - T_0}{T_{c0}\epsilon_0} - \frac{1}{\epsilon_0 R^2} n^2\right]\psi_n(t) \\ & - \sum_{l,m}\{\psi_l(t)\,\psi_m^*(t)\}\,\psi_{n+m-l}(t) \\ & - \frac{\gamma(t)}{T_{c0}\epsilon_0}\sum_n \psi_n(t) + \zeta_n(t),\end{aligned}$$

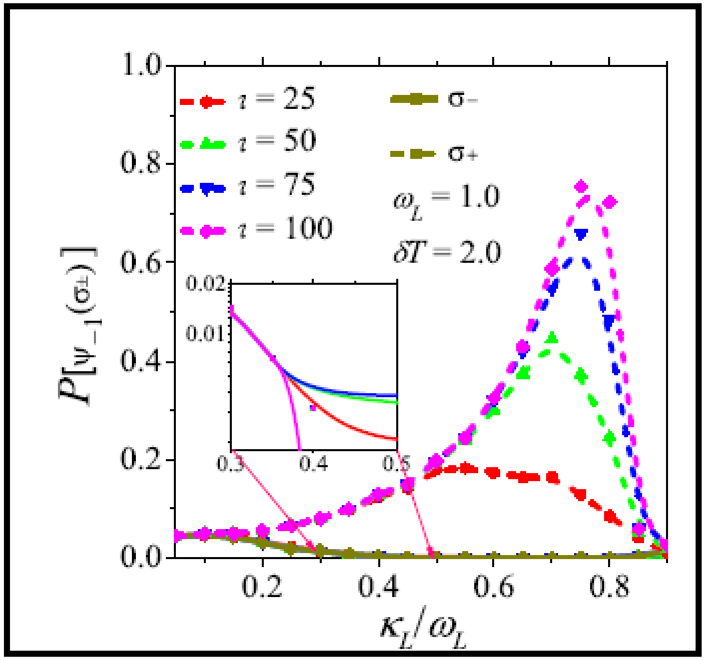
Averaging over 500 cooling cycles realizations

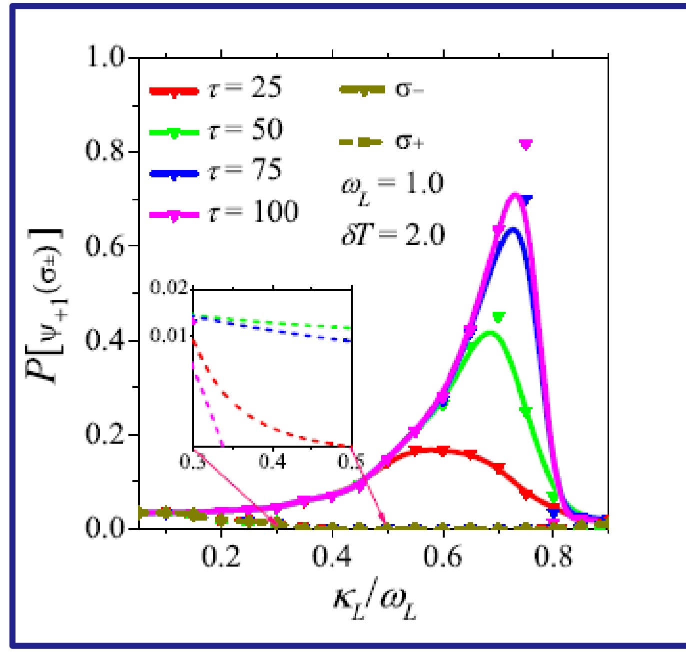
Evolution of the order parameter harmonics no circularly polarized radiation and η=0.2

For $\tau_Q^G = 1.0$ the probability to find out the state n=+-1 is around 10%




R = 9.45
δT = 2.0
σ+
ψ-3
ψ-2
ψ-1
ψ0
ψ+1
ψ+2
ψ+3
τQG = 1.0
η = 0.2
ωL = 1.0
κL/ωL = 0.7
ψn, γ(t)
t
R = 9.45
δT = 2.0
σ-
τQG = 1.0
η = 0.2
ωL = 1.0
κL/ωL = 0.7
σ+
R = 9.45
δT = 2.0
τQG = 1.0
η = 0.2
ωL = 1.0
κL/ωL = 0.25

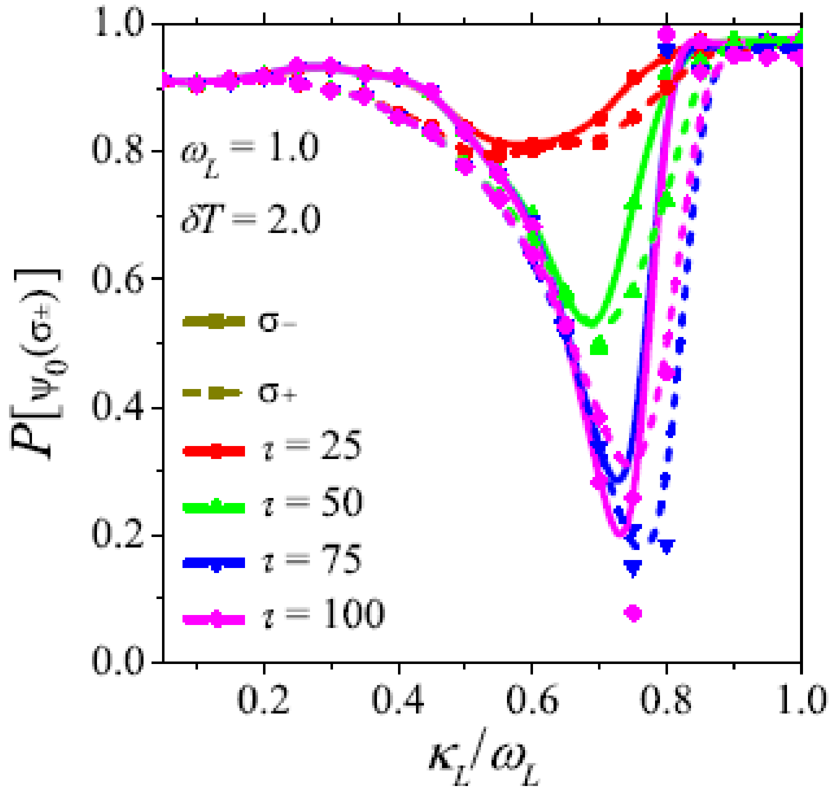




$$\kappa_L = E_L / \left(2\sqrt{\epsilon_0}\right)$$

$\omega_L = \frac{\omega \pi \hbar}{8 T_{c0} \epsilon_0} \sim 1$ corresponds in the case of Nb to the THz range of the frequencies

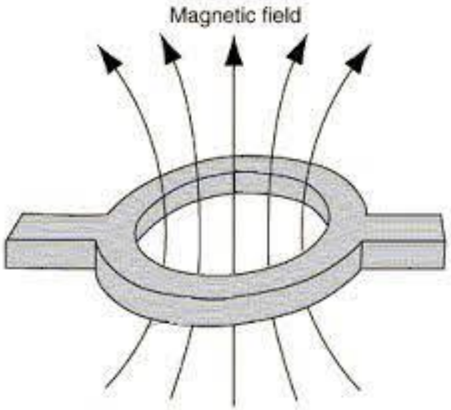
$\kappa_L / \omega_L = \frac{1}{2\sqrt{\epsilon_0}} \frac{E_L}{\omega_L} \approx 0.3$ → $I_0 \approx 3 \frac{\mathrm{mW}}{\mathrm{cm}^2}$



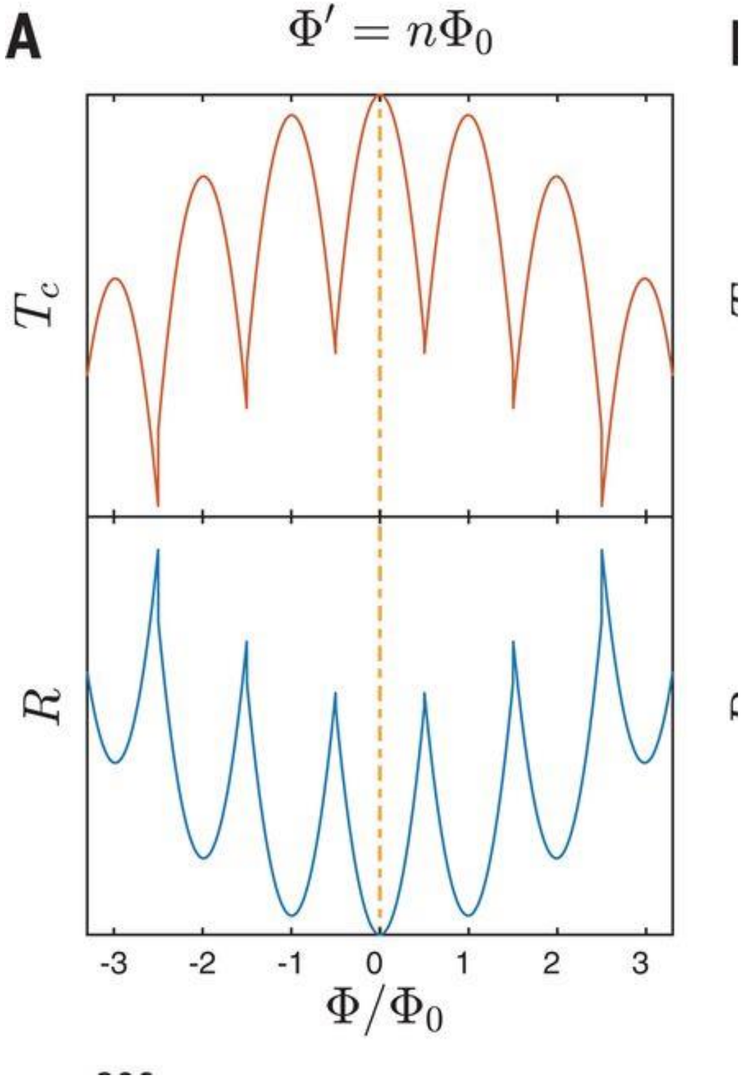
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
$\omega_L = 1.0$
$\delta T = 2.0$
σ−
σ+
$\tau = 25$
$\tau = 50$
$\tau = 75$
$\tau = 100$
$P[\psi_0(\sigma+)]$
κ_L/ω_L

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

Little-Parks effect



For **Φ = - Φ0/2** the states n=0 and n=1 have the 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.



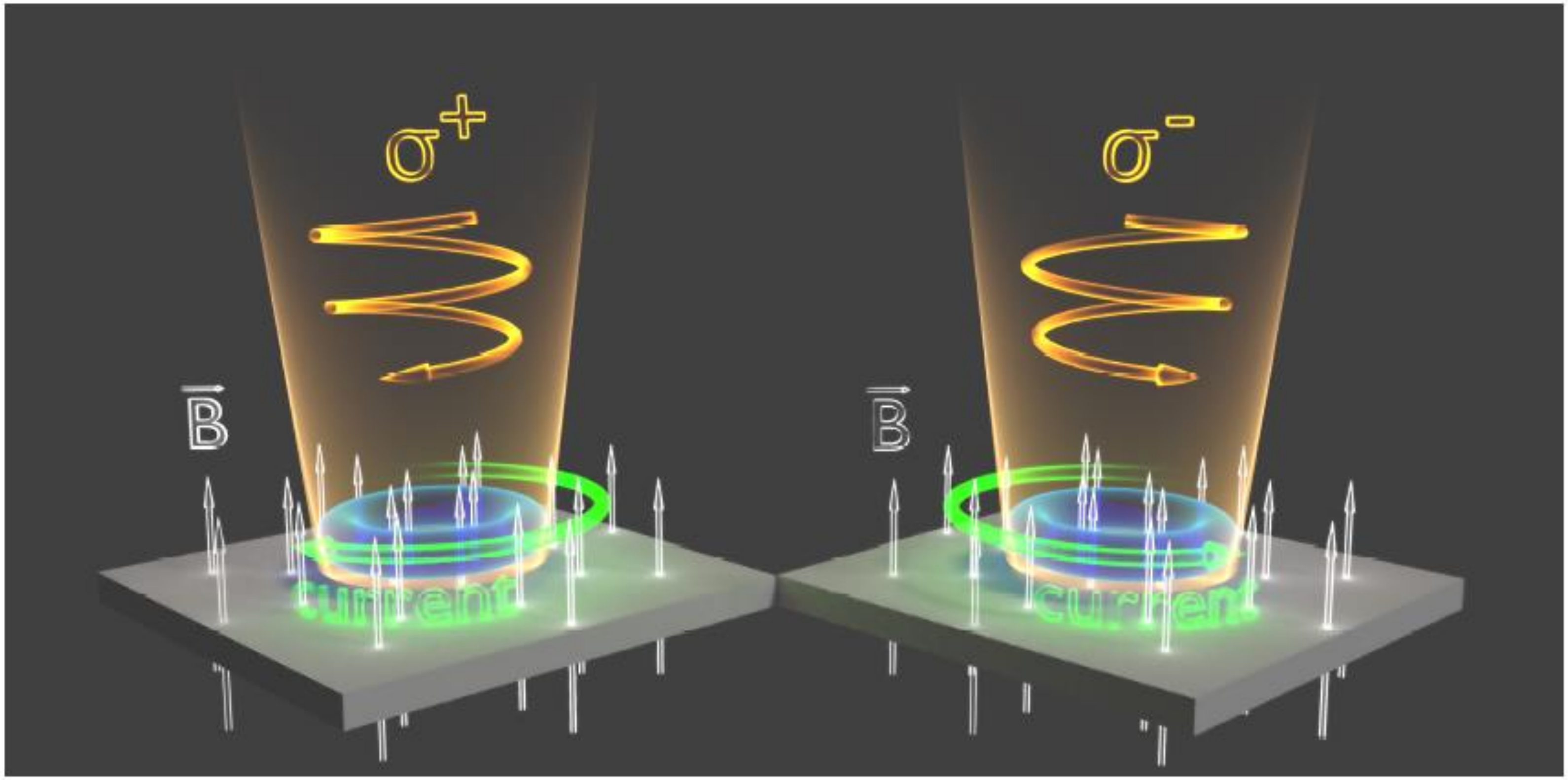


FIG. 1: Sketch illustrating the generation of the d.c. electric current in the thin superconducting ring under the influence of the circularly polarized laser beam.

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

For **Φ = - Φ0/2** the states n=0 and n=1 have the same energy and it is easy to switch between them.

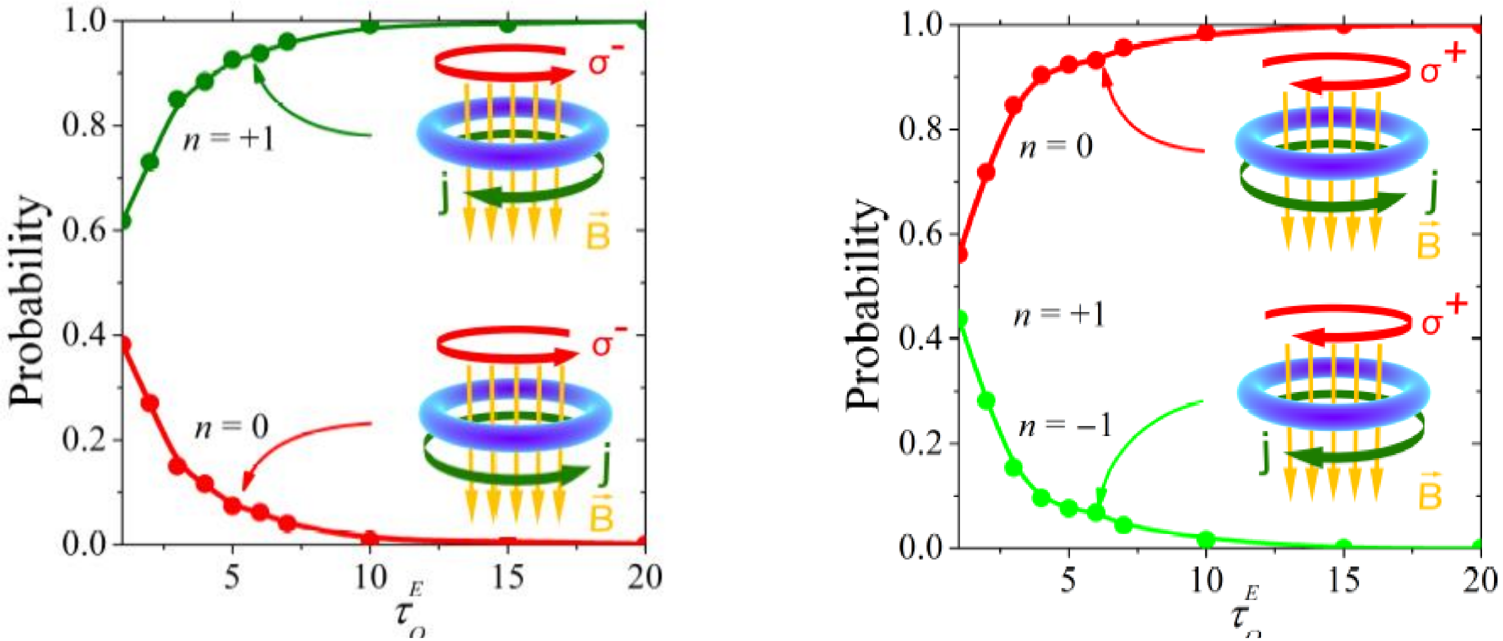


FIG. 3: Probability of a final stationary state ψ_n as a function of the decaying time τ_Q^E for $E_L/\omega_L = 0.75$ at magnetic field $\Phi/\Phi_0 = -1/2$ and polarization σ_-. Here we take $\omega_L = 1.0$ and $\widetilde{R} = 4.5$.

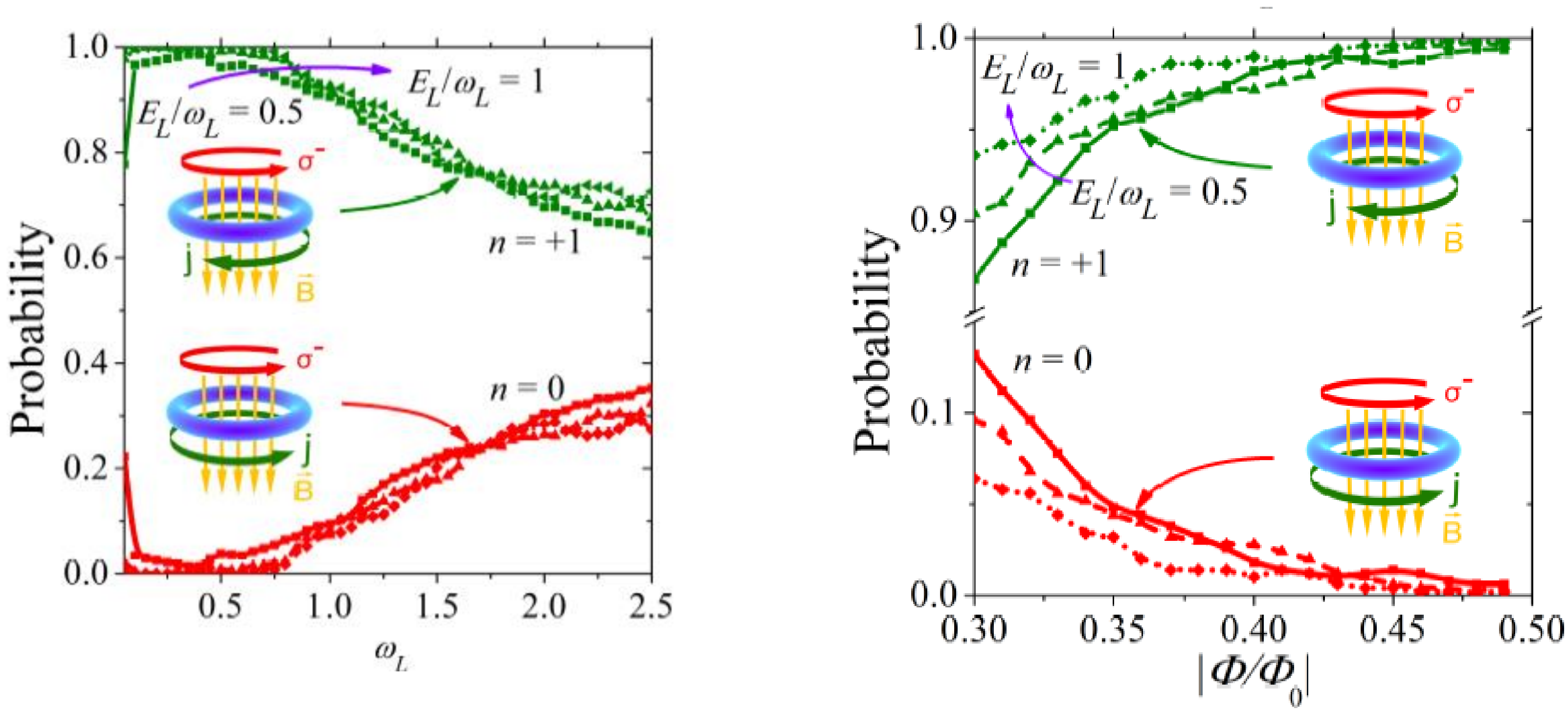
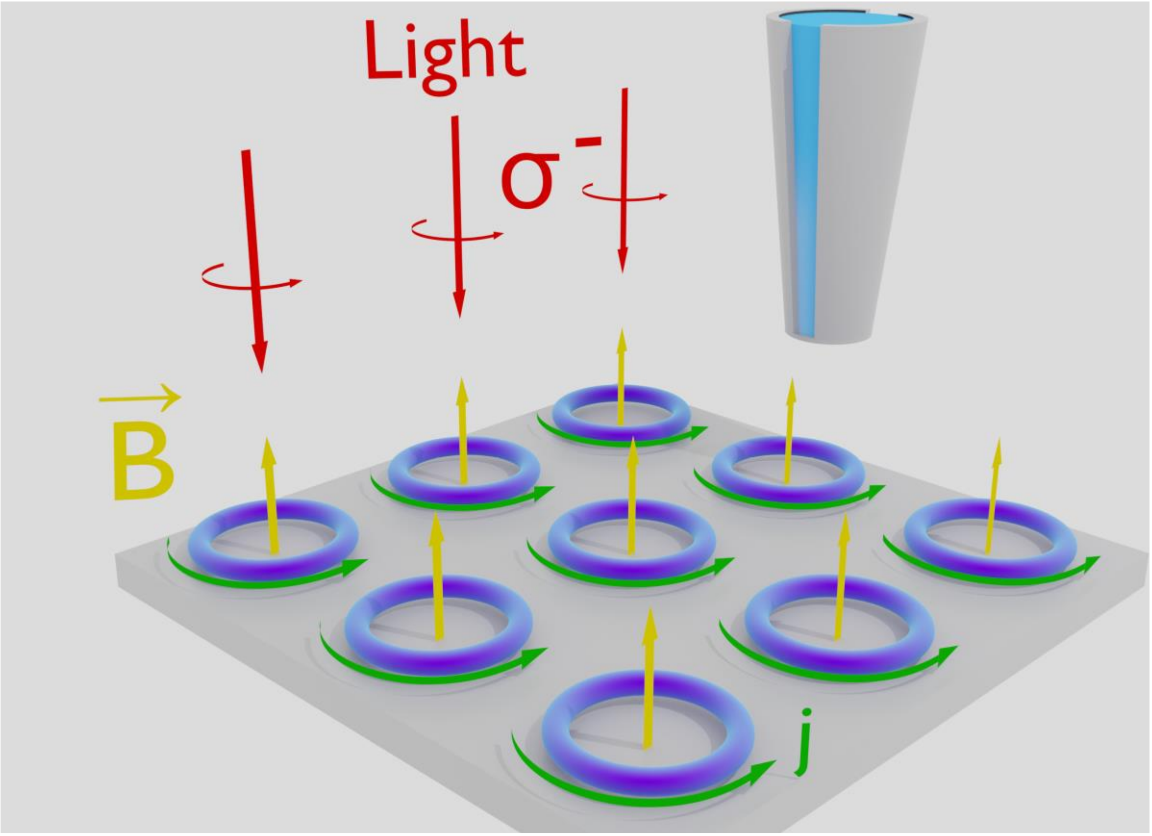
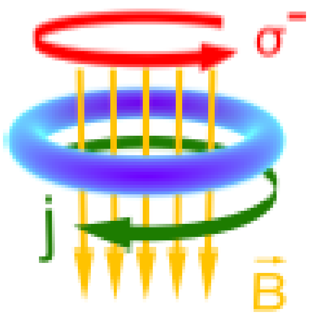


FIG. 4: Probability of the final stationary state ψ_n as a function of the radiation frequency ω_L at $\Phi/\Phi_0 = -1/2$ (top panel) and external magnetic flux $|\Phi|/\Phi_0$ at $\omega_L = 1$ (lower panel) for $E_L/\omega_L = 0.5$, $E_L/\omega_L = 0.75$, $E_L/\omega_L = 1.0$, when polarization is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

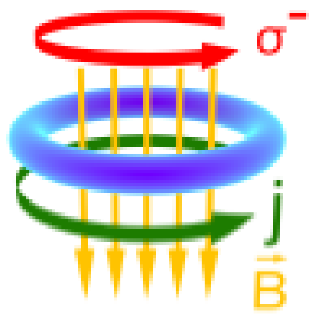


As follows from our analysis, the optimal dimensionless frequency for implementing the switching by IFE is $\omega_L \sim 0.3$, which corresponds to $\omega \sim 0.38 T_{c0}\epsilon_0/\pi\hbar$. For Nb and $\epsilon_0 = 0.1$ it is $f \sim 15GHz$, while for the high-T_c superconductors this frequency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

Conclusion



We suggest to use the IFE as a very efficient method of the all-optical switching between the current states in mesoscopic superconducting systems.



This open the way to superconducting optoelectronics.

Ref.: Croitoru, Mironov, Lounis, and A.B.
Advanced Quantum Technologies (2022)