IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March 2021.
Invited presentation Wk1MOr5A-02 was given at the virtual ASC 2020, October 30, 2020.

# Power dissipated by trapped vortices under a strong RF field and Campbell penetration depth in superconducting resonant cavities

ADVANCES IN PHYSICS, 2001, VOL. 50, NO. 8, 1249–1449

**Flux vortices and transport currents in type II superconductors***

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**Abstract**

This article is concerned with the mechanisms by which type II superconductors can carry currents. The equilibrium properties of the vortex lattice are described and the generalized driving force in gradients of temperature and field is derived using irreversible thermodynamics. This leads to expressions for thermal cross effects which can include pinning forces.

*Archie Campbell*

Alex Gurevich

Department of Physics, Old Dominion University, Norfolk, VA, USA

Supported by NSF under grant PHY-100614-010 and by DOE under grant DE-SC0010081-020

Applied Superconductivity Conference, Oct. 30, 2020.

# Campbell's penetration depth: good work always stays young and popular

J. PHYS. C (SOLID ST. PHYS.), 1969, SER. 2, VOL. 2. PRINTED IN GREAT BRITAIN

**The response of pinned flux vortices to low-frequency fields**

A. M. CAMPBELL
Department of Metallurgy, University of Cambridge
*MS. received 21st April* 1969

J. Phys. C: Solid St. Phys., 1971, Vol. 4. Printed in Great Britain

**The interaction distance between flux lines and pinning centres**

A. M. CAMPBELL
Department of Metallurgy and Materials Science, University of Cambridge, UK
*MS. received 22nd July* 1971

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **84**, 060509(R) (2011)

**Magnetic-field-dependent pinning potential in LiFeAs superconductor from its Campbell penetration depth**

Plengchart Prommapan,[1,2] Makariy A. Tanatar,[1] Bumsung Lee,[3] Seunghyun Khim,[3] Kee Hoon Kim,[3] and Ruslan Prozorov[1,2,*]
[1]*The Ames Laboratory, Ames, Iowa 50011, USA*

PHYSICAL REVIEW B **93**, 064515 (2016)

**Probing the pinning landscape in type-II superconductors via Campbell penetration depth**

R. Willa, V. B. Geshkenbein, and G. Blatter
*Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland*
(Received 18 December 2015; revised manuscript received 28 January 2016; published 23 February 2016)

PHYSICAL REVIEW B **92**, 134501 (2015)

**Campbell penetration in the critical state of type-II superconductors**

R. Willa, V. B. Geshkenbein, and G. Blatter
*Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland*

PHYSICAL REVIEW B **67**, 184501 (2003)

**Campbell penetration depth of a superconductor in the critical state**

R. Prozorov,[1,2] R. W. Giannetta,[1] N. Kameda,[3] T. Tamegai,[3] J. A. Schlueter,[4] and P. Fournier[5]
[1]*Loomis Laboratory of Physics, University of Illinois at Urbana–Champaign, 1110 West Green Street, Urbana, Illinois 61801*

PRL 115, 207001 (2015) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2015

**Campbell Response in Type-II Superconductors under Strong Pinning Conditions**

R. Willa,[1] V. B. Geshkenbein,[1] R. Prozorov,[2] and G. Blatter[1]
[1]*Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland*
[2]*The Ames Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA*

IOP PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY
Supercond. Sci. Technol. **22** (2009) 034008 (7pp) doi:10.1088/0953-2048/22/3/034008

**Coexistence of long-range magnetic order and superconductivity from Campbell penetration depth measurements**

**R Prozorov, M D Vannette, R T Gordon, C Martin, S L Bud'ko and P C Canfield**
Ames Laboratory, Iowa State University, Ames, IA 50011, USA
and
Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March 2021.
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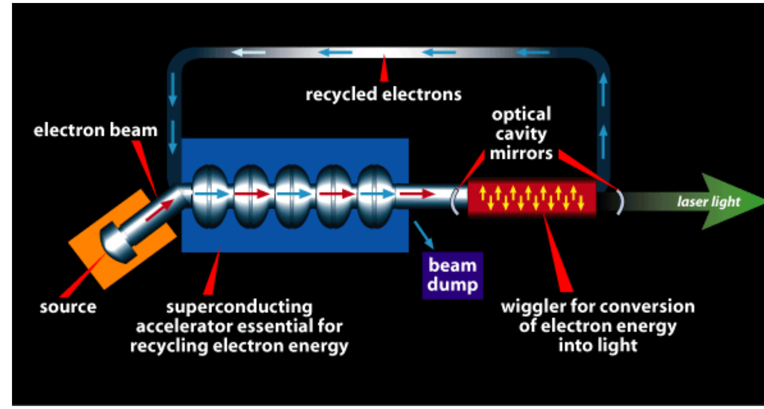
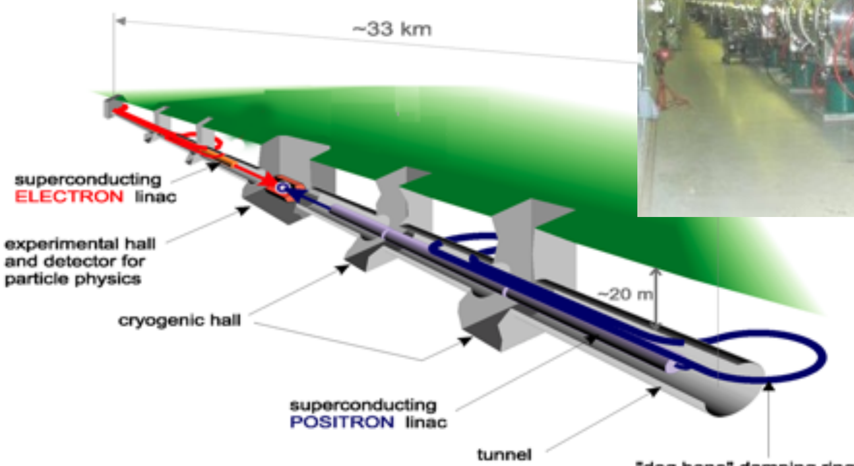
# Superconducting linac applications

Spallation neutron source (ORNL)


X-ray free electron laser




Superconducting LINAC



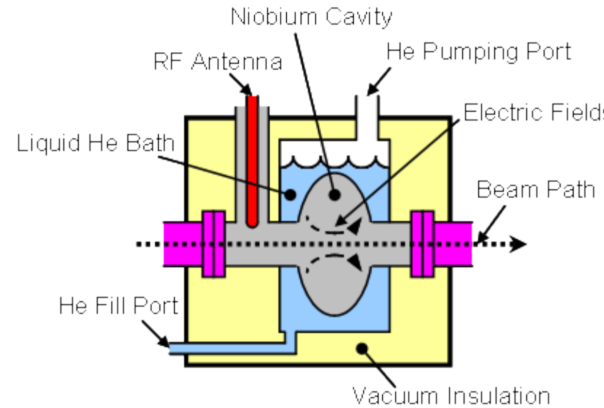

Tunable 0.25-14$\mu$m light source at JLab

Superconducting RF cavities resonating at 0.1-2 GHz

Currently made of pure niobium

Cooled by superfluid helium at 2K

Tens of thousands of these in miles long tunnels




# Definitions

$\Delta$ – superconducting gap

$\xi$ – coherence length

$\lambda$ – magnetic penetration depth

$\rho_n$ - normal state resistivity

$R_s$ - surface resistance

$Q$ – quality factor

$\omega = 2\pi f$ – RF circular frequency

$\eta_0 = \phi_0^2/2\pi\xi^2\rho_n$ - Bardeen-Stephen vortex drag coefficient

$\phi_0$ - magnetic flux quantum

$\ell$ - spacing between a pinning center and the surface

$v_0$ - Larkin-Ovchinnikov (LO) critical velocity of a vortex

$\kappa$ – thermal conductivity

$d$ – thickness of a cavity wall

$\alpha_K$ - Kapitza thermal conductance between a cavity wall and liquid He

$\epsilon = g\phi_0^2/4\pi\mu_0\lambda^2$ - vortex line tension

$g = \ln(\lambda/\xi) + 1/2$

$T_c$ - critical temperature

$B_{c1}$ - lower critical field

$B_c$ - thermodynamic critical field

$B_s$ - superheating field

$B_{c2}$ - upper critical field

# Quality factor

$$Q = \frac{\omega\mu_0 \int_V |\mathbf{H}(\mathbf{r})|^2 dV}{\oint_A R_s |\mathbf{H}(\mathbf{r})|^2 dA} = \frac{G}{\langle R_s \rangle},$$

Mean EM energy
--------------------------
Mean dissipated power

$$G = \alpha G_0, \qquad G_0 = \mu_0 c = 377\,\Omega$$

Vacuum impedance

**Surface resistance of good normal metals**

$$R_s = (\pi\mu_0 f \rho_n)^{1/2}$$

$$Q \sim 10^5 - 10^6$$

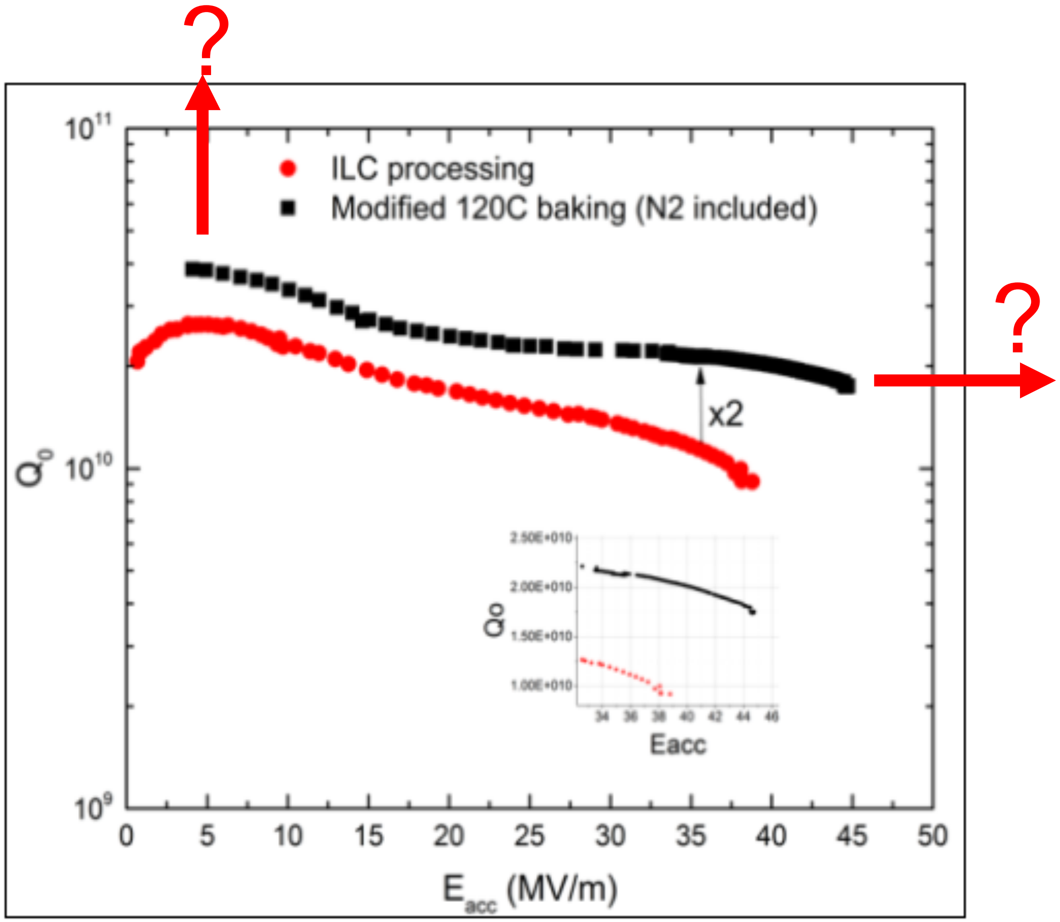
Clean Cu with
$\rho_n$ = $10^{-10}$ Ωm at f = 0.5-2 GHz
has $R_s$ = 0.5-1 mΩ

**Exponentially-small BCS surface resistance of superconductors:**

$$R_s \simeq \frac{\mu_0^2\omega^2\lambda^3}{\rho_n kT} \ln\left(\frac{9kT}{2\hbar\omega}\right) \exp\left(-\frac{\Delta}{kT}\right) \simeq 2 - 10\, n\Omega, \quad @\,1.7 - 2K,\ 1 - 2GHz$$

$$Q \sim 10^{10} - 10^{11}$$

# How good can Nb cavities be?




A. Grassellino and S. Aderhold, TTC meeting, Saclay, France (2016)

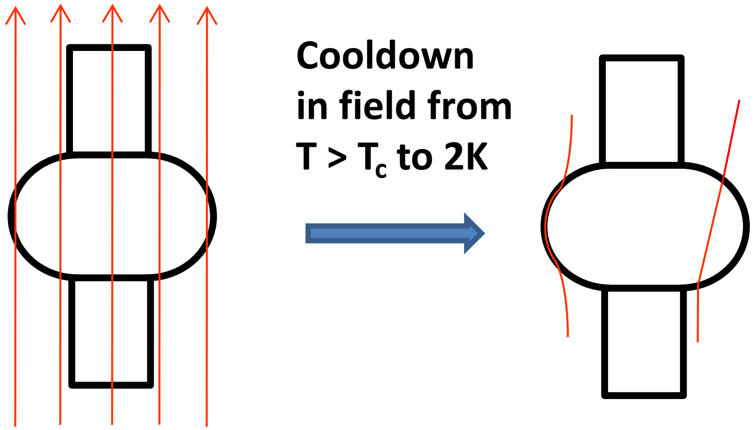
Continuous progress in improving Q(H) and $E_{acc}$ in Nb cavities.

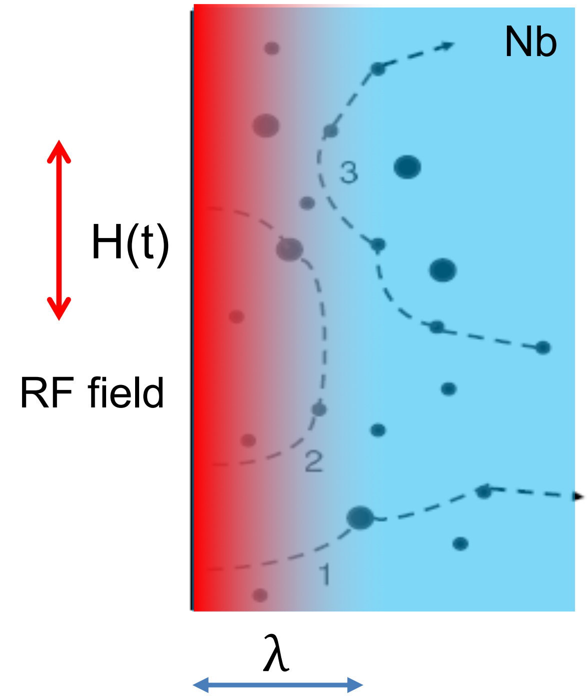
Understanding the fundamental limits of Q(H) and the SRF accelerating gradients

The RF field of H = 200 mT induces current densities at the surface close to the BCS pairbeaking limit.

High Q can only be achieved in the Meissner state with a small density of trapped vortices.

# Why are trapped vortices so bad for SRF cavities?




London penetration depth of $\approx 40$ nm << d = 3mm

- Vortices get trapped by materials defects on cooling the cavity through $T_c$ at which $H_{c1}(T)$ vanishes.
- Trapped vortices caused by Earth's magnetic field can produce $\sim 10^2$ higher RF losses than the BCS surface resistance at 2K and 1-2 GHz.
- Even good screening (1% of $H_E$) cannot eliminate trapped vortices. Temperature maps have revealed sparse hotspots of vortex bundles which reduce the quality factors and breakdown fields: **Vogt, Kugeler and Knobloch, PRAB 18, 042001 (2015); Gonnella, Kaufman and Liepe, JAP 119, 073904 (2016); Dhakal et al, PRAB 23, 023102 (2020).**

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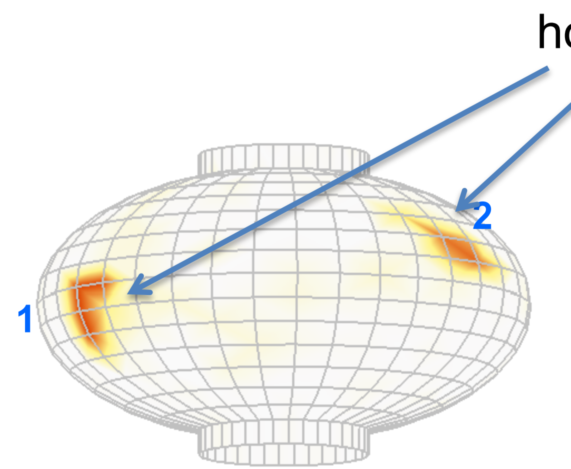
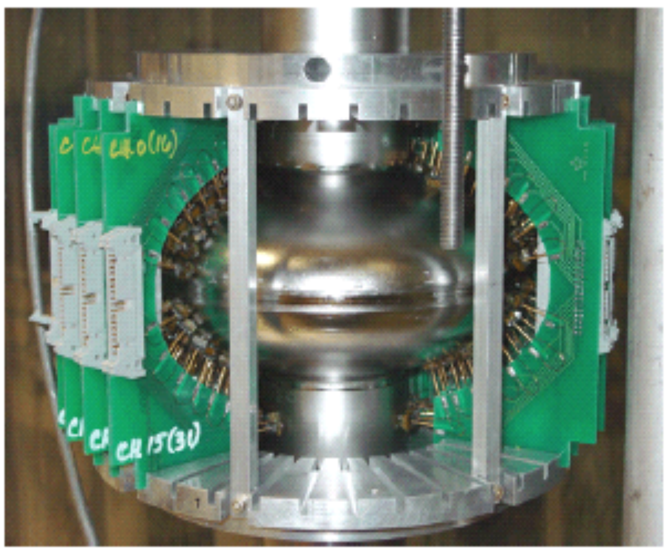
# Detection and manipulation of trapped vortices

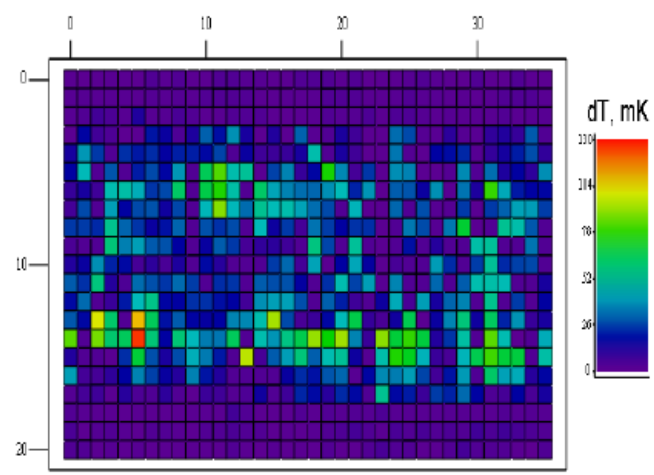
In films vortices are observed using scanning SQUID, **Kirtley, Rep. Prog. Phys. 73, 126501 (2010)**

MO imaging, STM, MF, Lorentz microscopy, …




Arrays of carbon sensors to get local temperature maps with the sensitivity of a few mK and spatial resolution of a few mm (Cornell, Jlab, FNAL)






Flushing vortices out by strong thermal gradients or scanning laser beams: **Ciovati and Gurevich, PRAB 11, 122001 (2008); Gurevich and Ciovati. PRB 87, 054502; (2013); Romanenko et al, JAP 115, 184903 (2014); Posen et al, JAP 119, 213903 (2016).**

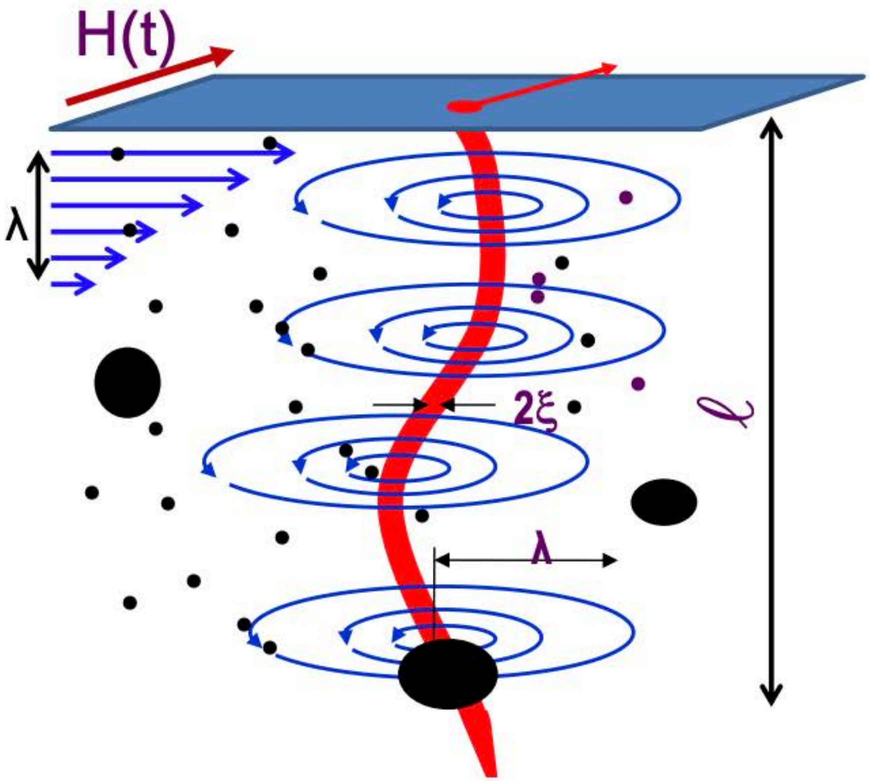
# Key issues

- Trapped vortices can produce significant losses which can be much higher than the BCS losses in SRF resonator cavities.
- Vortex losses are determined by an effective Campbell penetration depth
- New physics of superfast vortices driven by strong Meissner screening currents at the depairing limit in SRF cavities.
- How fast can vortices move? How long does it take for a vortex to penetrate a superconductor?
- Nonlinear dynamics of supersonic vortices: field-dependent RF losses, Larkin-Ovchinnikov instability, decrease of the surface resistance with the RF amplitude, …
- How much vortex dissipation can be tolerated? Can vortex dissipation be mitigated by strong pinning?

# Trapped vortex driven by RF Meissner current

An elastic vortex is driven by the Lorentz force $\mathbf{f}_L = \phi_0 \mathbf{J} \times \mathbf{z}$ perpendicular to **J**:

$$J(z,t) = (H_a/\lambda)e^{-z/\lambda}\sin\omega t$$




The surface Lorentz force is balanced by viscous drag force and bending stress

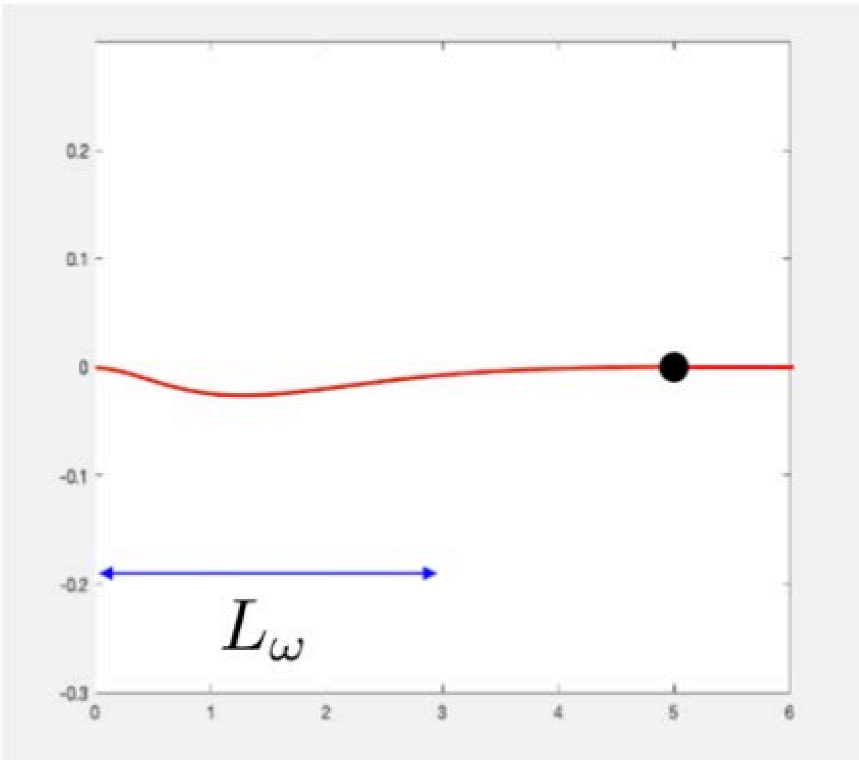
At $H_a$ = 100-200 mT, J(0) approaches the depairing limit

$$J_d \simeq H_c/\lambda$$

Typical depinning $J_c$ = 10-100 kA/cm$^2$ in Nb are some 4 orders of magnitude lower than
$J_d = H_c/\lambda$, = 500 MA/cm$^2$

Pinning is too weak to stop the vortex tip at the surface above $H > 0.01H_c$ = 2 mT

# RF Campbell length




- Campbell length $L_\omega$ can be much greater than $\lambda$.
- $L_\omega$ can be either larger or smaller than the pin distance from the surface.
  If $\ell > L_\omega$ the effect of pinning is weak

Dynamic eq for displacements u(x,t) of a vortex driven by a weak RF field $H_a << H_c$

$$\eta\dot{u} = \epsilon u'' - (H_a/\lambda)e^{-x/\lambda}\sin\omega t$$

Elastic RF ripple length – Campbell penetration depth:

$$L_\omega = \sqrt{\frac{\epsilon}{\eta\omega}} = \frac{\xi}{2\lambda}\sqrt{\frac{g\rho_n}{\pi\mu_0 f}}$$

**Clean Nb**

$$\lambda \approx \xi, \quad \rho_n = 1\ n\Omega m, \quad f = 2\ GHz$$
$$L_\omega \approx 180\ nm$$

**$Nb_3Sn$**

$$\lambda/\xi \approx 20, \quad \rho_n = 0.2\ \mu\Omega m, \quad f = 2\ GHz$$
$$L_\omega \approx 126\ nm$$

# Low-field RF power of an oscillating vortex

Gurevich and Ciovati. PRB 87, 054502; (2013)

- Low frequencies. The whole vortex segment swings: $L_\omega \gtrsim \ell$

$$P \simeq \frac{4\pi B_p^2 \ell^3 \omega^2}{3\rho_n \xi^2}$$

Decreases strongly as the pin spacing decreases

- Intermediate ω: $\lambda \lesssim L_\omega \lesssim \ell$

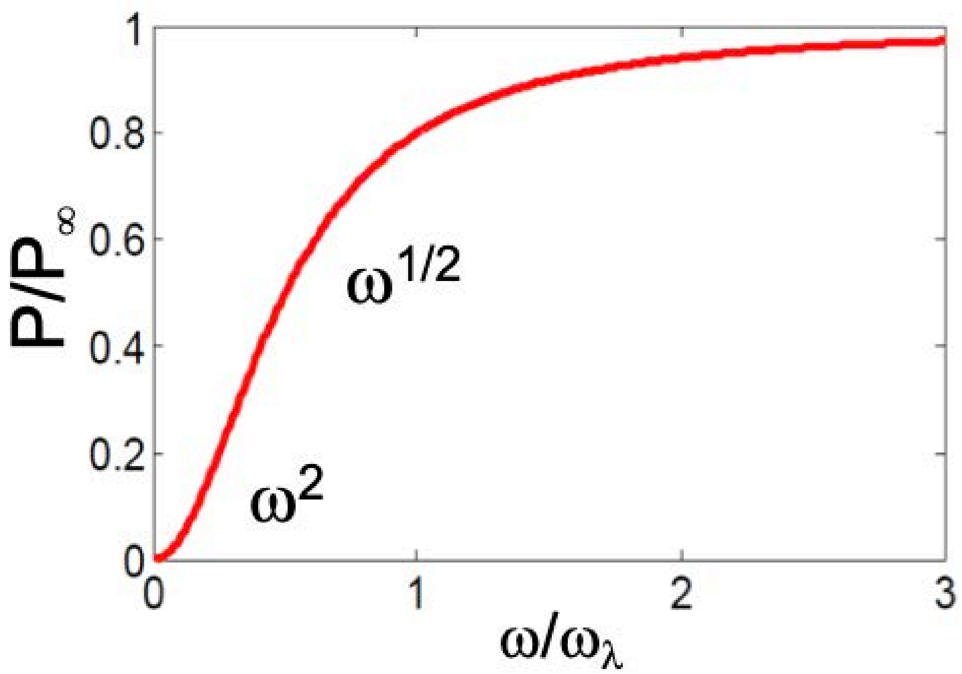
$$P \simeq \pi \mu_0^{-3/2} B_p^2 \lambda \xi \sqrt{\omega \rho_n}$$

No dependence on the pin spacing

- High ω: $L_\omega \lesssim \lambda$

$$P_\infty = \pi H^2 \rho_n \xi^2 / 2\lambda$$

No dependence on the pin spacing




P ~ 0.13 μW at B = 100 mT and 2 GHz.

Hotspots revealed by thermal maps require regions ~ few mm with ~ $10^6$ vortices

# Extreme dynamics of vortex tips at the surface

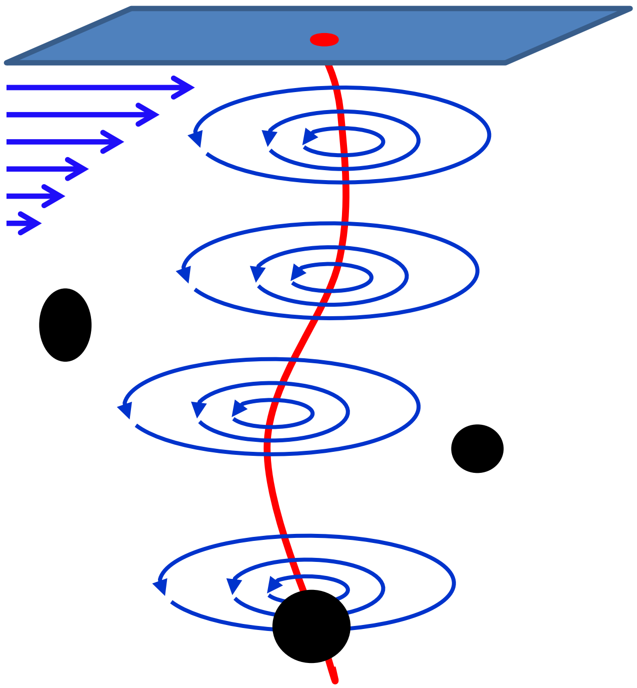
At $H = H_c$, the superflow velocity of Cooper pairs reaches the critical pairbreaking value $v_c = \Delta/p_F$ .

How fast can the vortex tip move at the pairbreaking limit?

$$v \simeq \frac{J_d \phi_0}{\eta} \simeq \frac{\rho_n \xi}{2\mu_0 \lambda^2}$$

This rough estimate yields v = 10 km/s, which exceeds both the speed of sound (2-4 km/s) and $v_c = \Delta/p_F$ = 1 km/s

How can a supersonic vortex tip remain connected to a subsonic elastic vortex line in the bulk?



SRF cavities are a unique testbed to study the extreme dynamics of a vortex driven by non-dissipative Meissner currents at the pairbreaking limit

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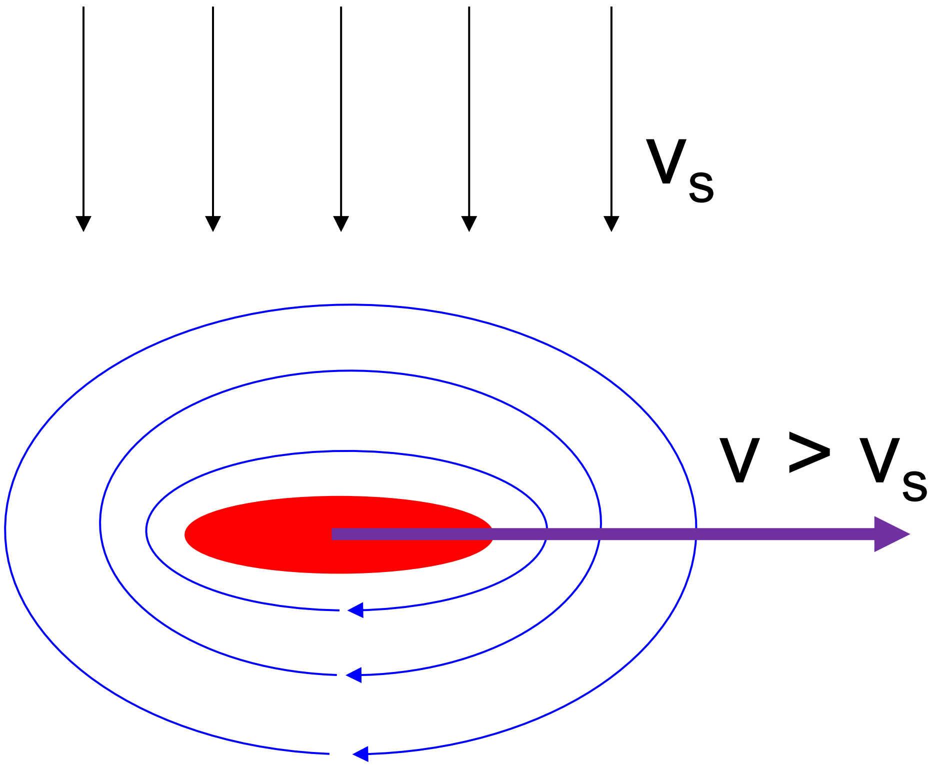
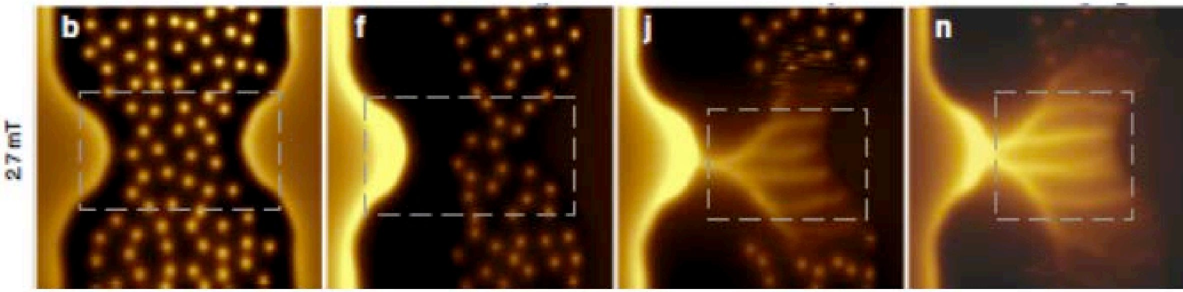
# How can a vortex move faster than the current superflow which propels it?




- Vortex core stretches along the direction of motion
- Vortex can move much faster than the drift velocity of supercurrent
- V can exceed the pairbreaking velocity

A sailboat can move much faster than the wind if drag is weak and the sail is nearly perpendicular to the wind blow.

# What does experiment say?





Nature Comm. 8, 85 (2017)

ARTICLE

OPEN

Imaging of super-fast dynamics and flow instabilities of superconducting vortices

75 nm thick Pb film: imaging of penetrating vortices with a nanoscale SQUID on tip

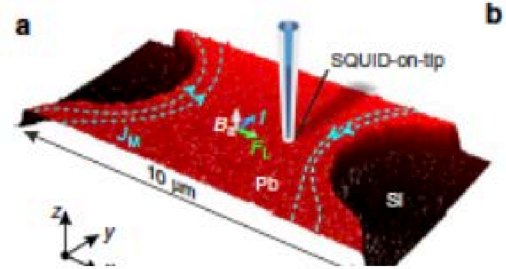
Velocities can reach **10—20 km/s** as J(x,y) at the edge reaches $J_d$ ($H = H_s$ for the SRF cavities)

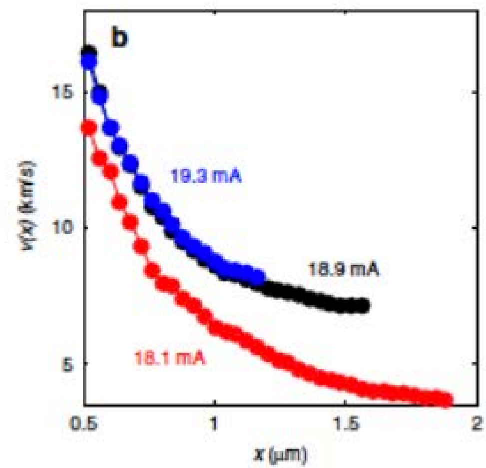
If v = 10 km/s, a vortex penetrates by the distance

$$L \simeq v/f \simeq 10\mu m \gg \lambda, \quad @\, 1GHz$$

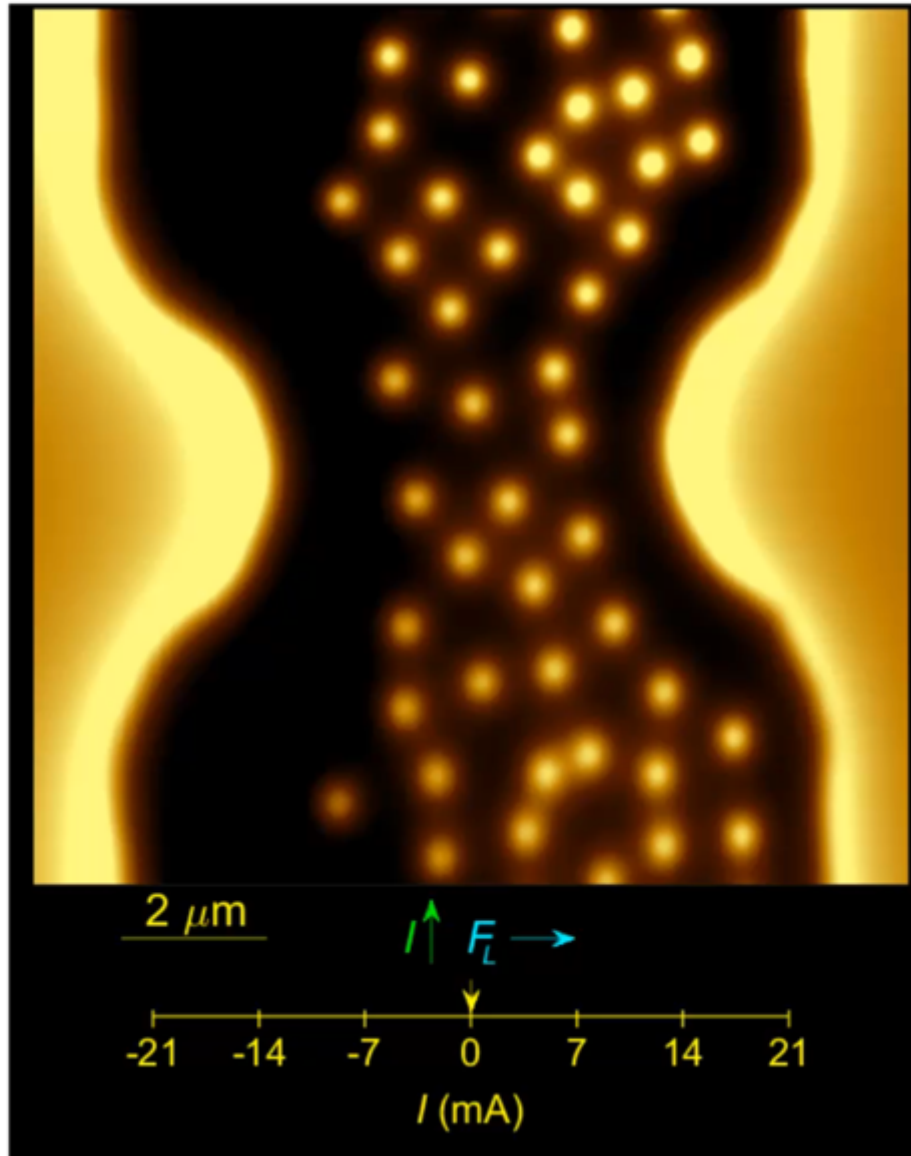
Vortices penetrate almost instantaneously through the Meissner RF layer

Hot vortex branching trees. No materials defects can stop such superfast vortices.



# Dynamics of vortex branching observed by SOT microscope

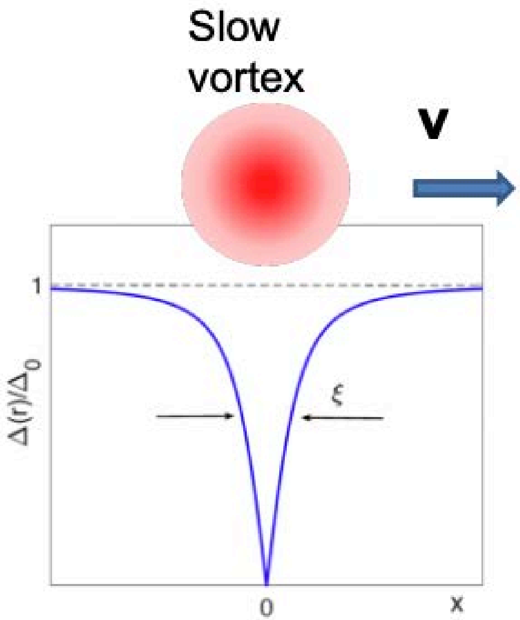



Pb bridge at $B_a$ = 27 G
SOT diameter: 225 nm
Scan area: 12 × 12 μm²
Pixel size: 40nm
Scan time: 4 min/frame
T = 4.2 K

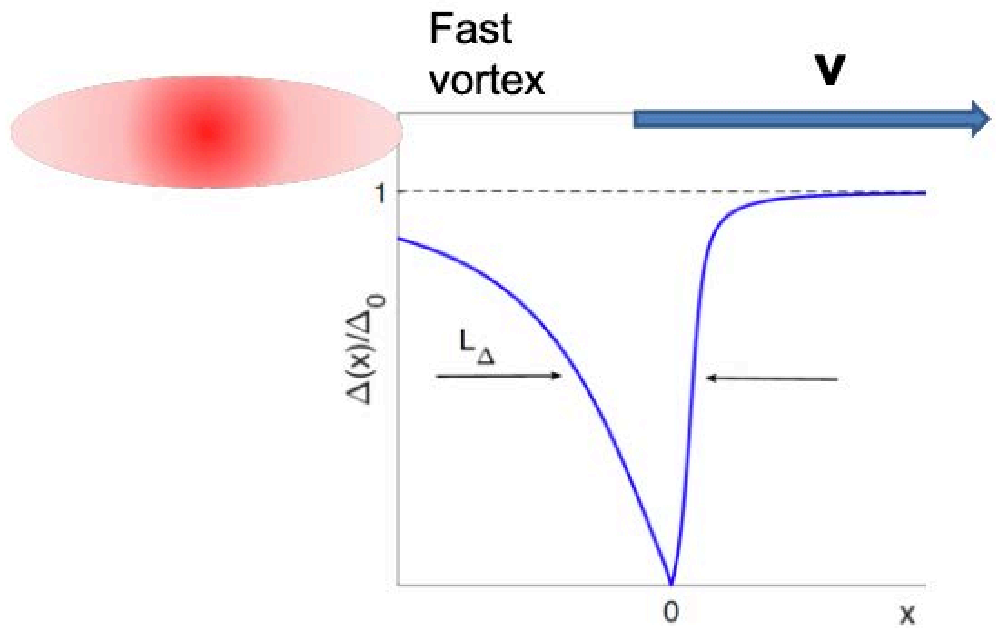
Dynamics ac 2 0:40

L. Embon et al, Nature Comm. 8, 85 (2017)

# What happens to the vortex core at high velocities?




- A nearly round vortex core of radius $\approx \xi$
- Cloud of dissipative quasiparticles is locked onto the moving core




- The core stretches along **v** as the recovery length of $\Delta(x,t)$ behind the core increases with v:

$$L_\Delta \simeq v\tau_\Delta, \quad v > \xi/\tau_\Delta$$

- A cloud of diffusive nonequilibrium quasiparticles is lagging behind the core
- Vortex drag decreases with v:

$$\eta(v) \simeq \frac{\phi_0^2}{2\pi\rho_n\xi L_\Delta}$$

# Velocity dependence of $\eta(v)$

## Larkin-Ovchinnikov mechanism

Reduction of the vortex drag due to diffusive depletion of quasiparticles in the moving core

$$\eta(v) \simeq \frac{\eta_0}{1+(v/v_0)^2}$$

LO critical velocity:

$$v_0 \sim (D/\tau_E)^{1/2}(1-T/T_c)^{1/4}$$

D is the electron diffusivity

The energy relaxation time $\tau_E(T)$ caused by inelastic e-p scattering increases as T decreases so $v_0(T)$ is expected to decrease at $T << T_c$

Larkin and Ovchinnikov. JETP 41, 960 (1975)

## Electron overheating

The drag coefficient depends on the electron temperature $T_v$ of the vortex

$$\eta(T_0) = \frac{\phi_0 B_{c2}(0)}{\rho_n}\left(1-\frac{T_v}{T_c}\right)$$

2D power balance:

$$\eta(T_v)v^2 \simeq (T_v - T_0)\kappa$$

An effective thermal conductivity $\kappa(T_0)$ contains both quasiparticle and phonon contributions

Solving for $T_v$ yields $\eta(v)$ in the LO form with

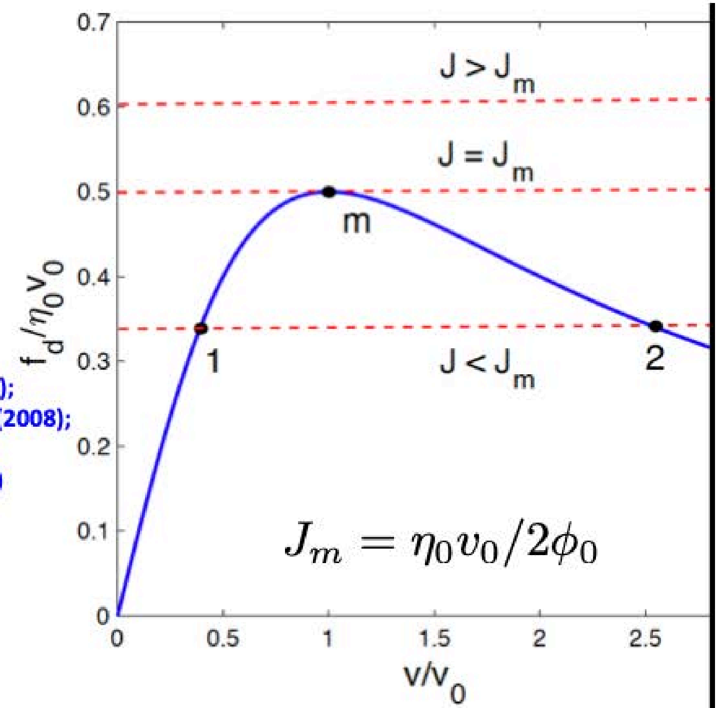
$$v_0 = \sqrt{T_c\kappa(T_0)/\eta_0(0)}$$

Bezuglyj and Shklovskii, Physica C 202, 234 (1992)
Kunchur, PRL 89, 137005 (2002)
Gurevich and Ciovati, PRB 77, 104501 (2008)

# Larkin-Ovchinnikov instability

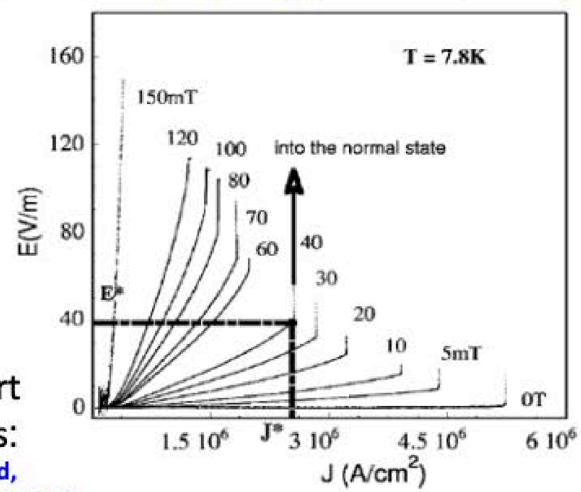
Balance of drag and Lorentz forces for a straight vortex in a thin film:

$$\frac{\eta_0 v}{1+(v/v_0)^2} = \phi_0 J$$




Observations on different materials:

Musienko et al, JETP Lett. 31, 567 (1980); Klein et al., JLTP 61, 413 (1985); Amenio et al, PRB 76, 054502 (2007); Grimaldi et al, J Phys C97, 012111 (2008); Villard et al, JLTP 131, 957 (2003); Doettinger et al, PRL 76, 1691 (1994) ; Samoilov et al, PRL 75, 4118 (1995); Bezuglyj et al PRB 99, 174518 (2019)




dc transport on Nb films:

Peroz and Villard, PRB 72, 014515 (2005)

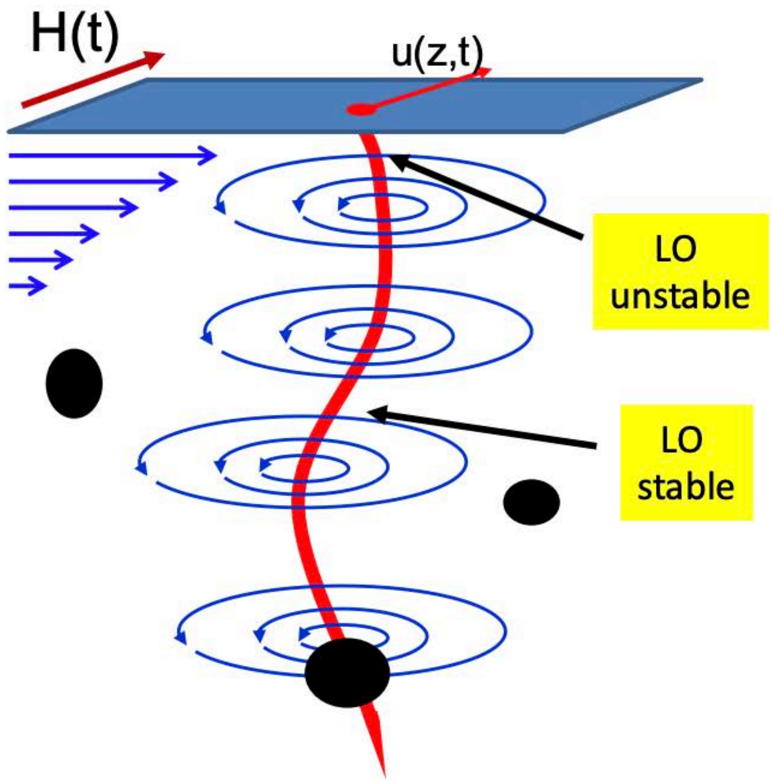
Acceleration of a runaway vortex at $v > v_0$, jumps on the V-I curves

The observed $v_0(T)$ is $\simeq 0.1 - 1$km/s near $T_c$ and decreases as T decreases.

Can be masked by heating effects

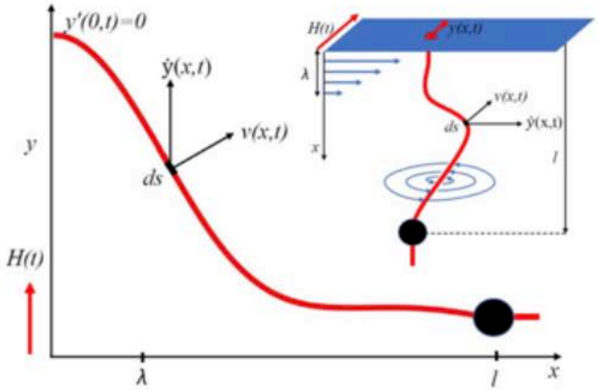
# LO instability of a trapped vortex

Since the LO critical velocity $v_0 \sim 0.1 - 1$ km/s is 1-2 orders of magnitude smaller than velocities of a vortex at H = 10 -100 mT, the LO instability can be essential in SRF cavities.




- What happens to the vortex if its fast tip is LO-unstable while the rest of the vortex is LO-stable?
- Can a vortex be shredded into disconnected pieces by strong surface current?
- Dependence of RF losses and the residual surface resistance caused by trapped vortices on the RF field.
- The extreme vortex dynamics in SRF cavities is not masked by strong overheating typical of dc transport measurements at $T \ll T_c$ .

# Nonlinear dynamic equations for a vortex




Balance of local forces perpendicular to a curvilinear vortex

$$M\dot{v} + \eta(v)v = \epsilon/R - (H_a/\lambda)e^{-x/\lambda}\sin\omega t$$

Dynamic eq. for a dimensionless vertical displacement
$u(x,t) = y(x,t)/\lambda, \quad x \to x/\lambda:$

$$\mu\frac{\partial}{\partial t}\left(\frac{\dot{u}}{\sqrt{1+u'^2}}\right) + \frac{\gamma\dot{u}\sqrt{1+u'^2}}{1+u'^2+\alpha\gamma^2\dot{u}^2} = \frac{u''}{(1+u'^2)^{3/2}} - \beta e^{-x}\sin(2\pi t)$$

Takes into account vortex inertia, and nonlinearities of the LO vortex drag and bending rigidity

$$\gamma = f/f_0, \qquad f_0 = H_{c1}\rho_n/H_{c2}\lambda^2\mu_0$$

$$\alpha = (\lambda f_0/v_0)^2, \qquad \beta = H_a/H_{c1}$$

$f_0$ = 22 GHz for Nb.

Pathirana and Gurevich, PRB 101, 064504 (2020)

# Nonlinear vortex losses and residual resistance

Dissipated power per vortex:

$$p = \int \langle \eta(v) v^2 \rangle ds$$

Surface resistance $R_i$ for the mean trapped flux density $B_0$ is obtained from $pB_0/\phi_0 = R_i H_a^2/2$:

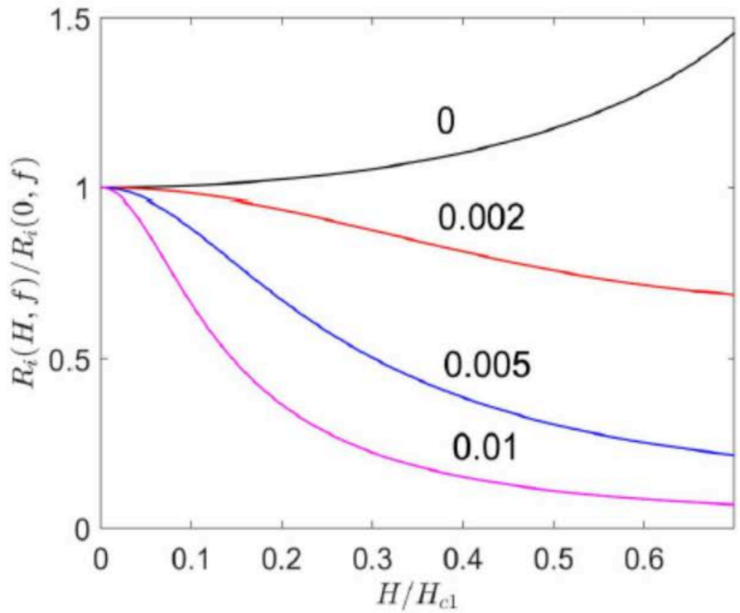
$$R_i(\beta) = \frac{R_0 \gamma^2}{\beta^2} \int_0^1 dt \int_0^l \frac{(1+u'^2)^{1/2} \dot{u}^2 dx}{1 + u'^2 + \alpha\gamma^2 \dot{u}^2}, \qquad R_0 = \frac{2\rho_n B_0}{\lambda B_{c2}}$$

For Nb at 1-2 GHz, we have $\gamma \sim 10^{-1}$, and $\alpha \sim 10^2 - 10^4$. At small f and $H_a$ the LO term in the denominator is negligible and $R_i$ is independent of Ha

As $H_a$ and f increase, $\dot{u}^2$ cancels out and $R_i$ becomes nearly *independent of frequency and decreases with the RF field:*

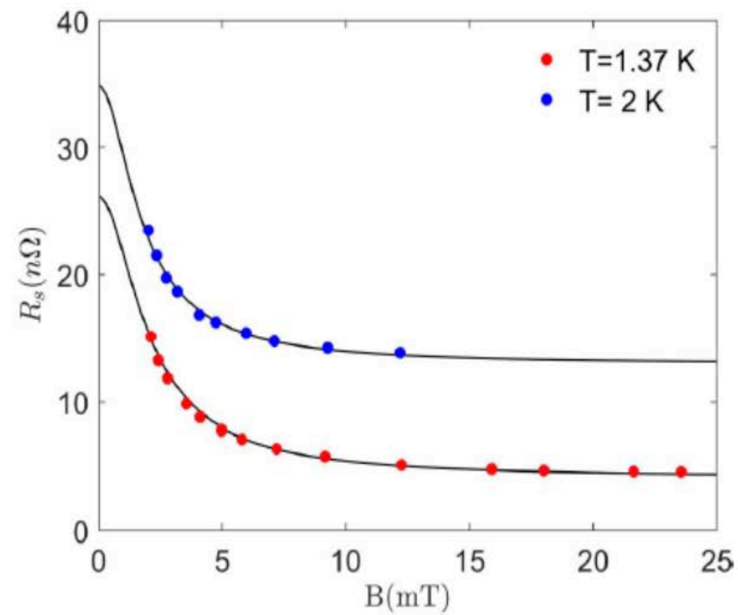
$$R_i \propto H_a^{-2}$$

# LO mechanism of the low-field Q(H) rise




The surface resistance Ri(H) starts decreasing with the field amplitude as the frequency increases. Calculated for different values of

$$\gamma = f/f_0 \text{ @ } l = 4\lambda, \ \alpha = 3 \cdot 10^3$$

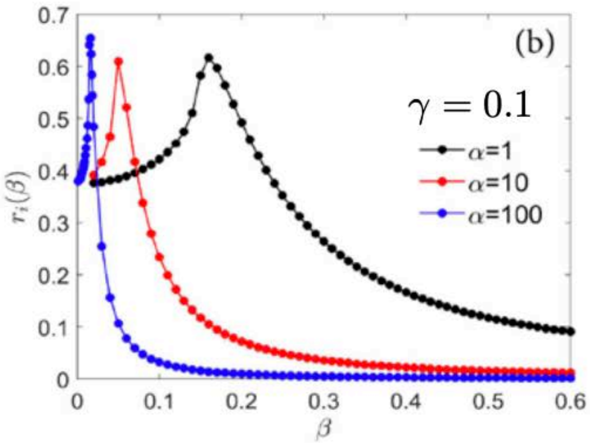



Fit to the experimental data of for a 1.47 GHz Nb cavity

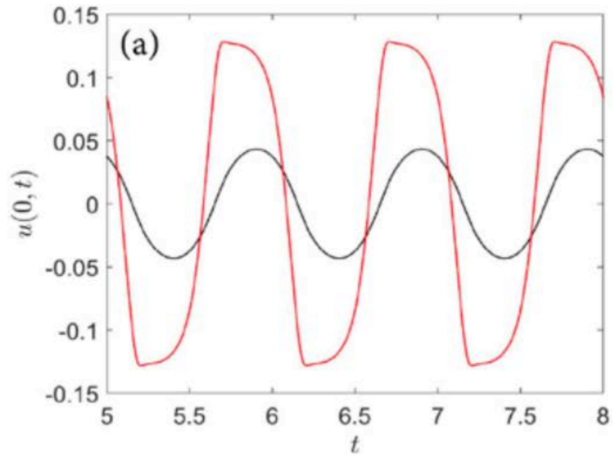
Ciovati, JAP 96, 1591 (2004)

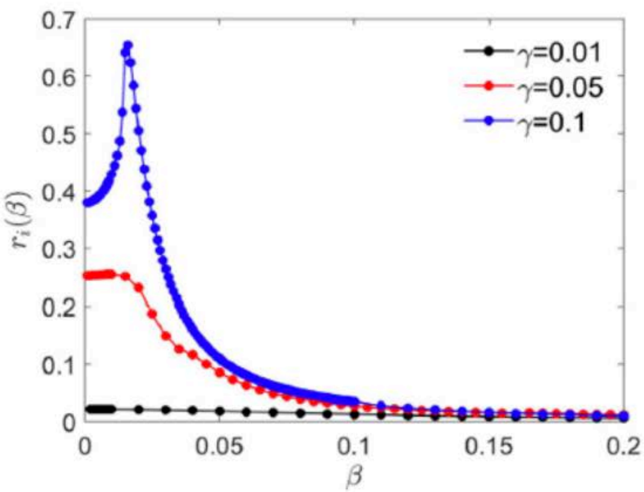
$$l = 3\lambda, \quad B_0 = 0.73\,\mu T,$$
$$v_0(2K) = 30\,m/s,$$
$$v_0(1.37K) = 35\,m/s,$$

# Effect of frequency on the field dependence of $R_i(H_a)$




$$\alpha \to \alpha\gamma^2$$



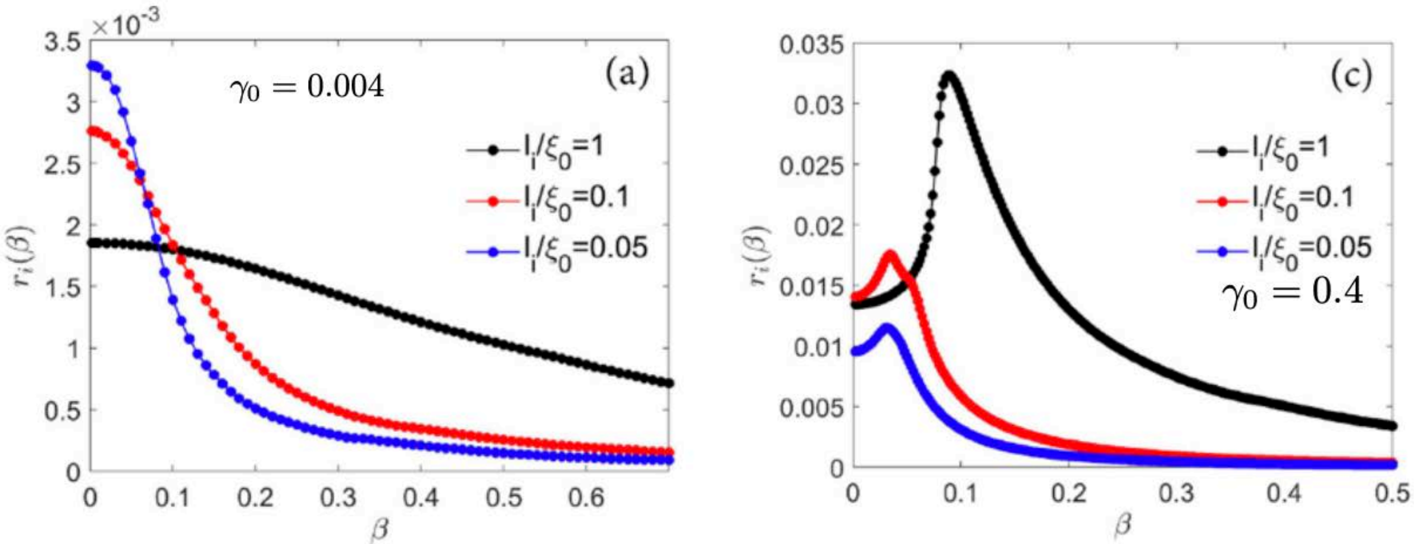




Transition from quasi-harmonic to relaxation oscillations at the peak in $R_i(H)$. The Campbell length increases with $H_a$:

$$L_\omega(H_a) \simeq \sqrt{\epsilon/\omega\eta(v)}$$

- $L_\omega(H_a,\omega) < l$ before the peak
- $L_\omega(H_a,\omega) > l$ after the peak

# Tuning the LO vortex dynamics by impurities




Calculated for $\alpha_0 = 1.6 \cdot 10^4, \quad l = 3\lambda_0$

- Making the surface dirtier and decreasing the impurity mean free path shifts the anomalous drop of the vortex surface resistance with $H_a$ to lower fields.
- May pertain to the low-field Q(H) drop observed on many Nb cavities

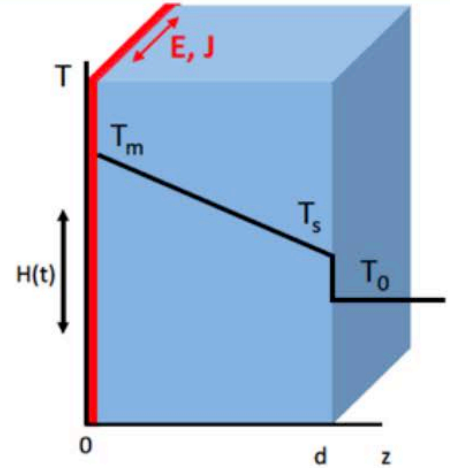
# Effect of weak overheating on the surface resistance

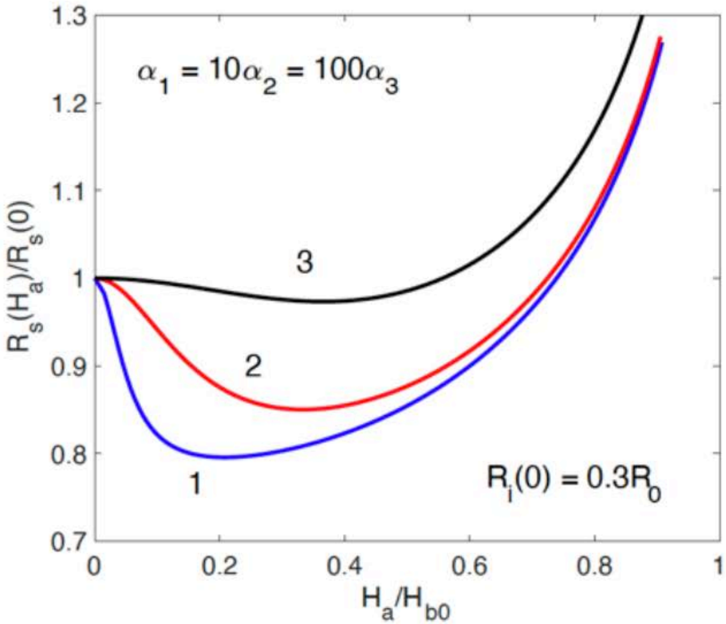
Thermal feedback for trapped vortices and BCS:

$$\left(R_i(H_a) + R_0 e^{(T-T_0)\Delta/T_0^2}\right)\frac{H_a^2}{2} = (T-T_0)g,$$

vortices BCS

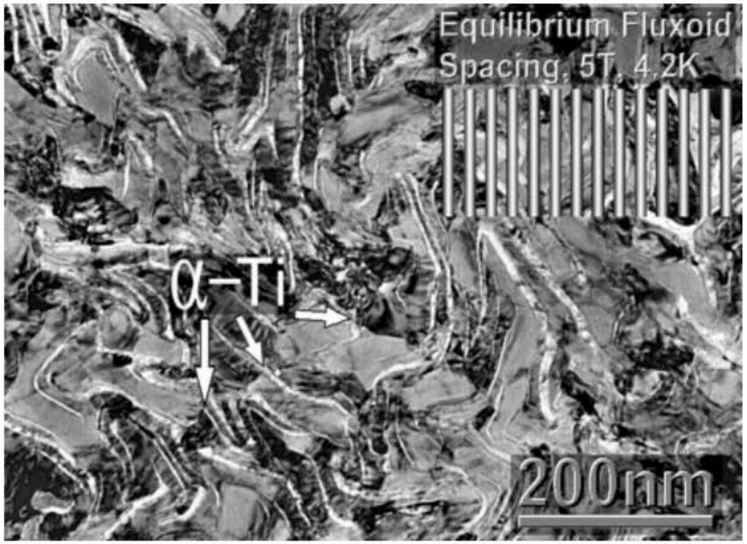
Thermal resistance of the cavity wall: $g^{-1} = \alpha_K^{-1} + d/\kappa$




- Interplay of the descending $R_i(H)$ and ascending $R_0(H_a)$ due to overheating produces a minimum in $R_s(H_a)$
- At large LO critical velocity $v_0(T)$, BCS overheating reverses the decrease of $R_s(H_a)$ with $H_a$
- Too many trapped vortices cause strong overheating which can eliminate the minimum in $R_s(H)$ as $v_0(T)$ increases with T

# Could strong pinning be effective in SRF cavities?




α-Ti ribbons in a Nb-Ti alloy **(D. Larbalestier & P. Lee)**

## GOOD

- Artificial pinning centers (APCs) which take 10% of current-carrying cross-section can produce critical current densities $J_s \simeq 0.1 J_d$
- For cavities this can only be effective below the depinning field H < $0.1H_c$ = 20 mT= 10% of the SRF breakdown field for Nb.
- Reduction of vortex losses only in a small low-H part of the field operation range

## BAD

- 10% of metallic APCs produce huge ohmic losses above the proximity effect breakdown field. Incompatible with high Q controlled by the BCS surface resistance
- 10% of dielectric APCs block the current-carrying cross section, greatly increasing the field penetration depth and the BCS surface resistance
- Above the depinning field, high Bean's hysteretic losses make high-$J_c$ SRF cavities no better than the normal Cu cavities

# Conclusions

- At RF fields of 100-200 mT tips of vortices trapped in Nb cavities can reach velocities of a few km/s approaching the speed of sound (3.5 km/s)

- Extreme nonlinear dynamics of the elastic vortex, drastic change of a hot moving vortex core, strong pairbeaking effects and nonequilibrium kinetics of quasiparticles.

- Decrease of the residual surface resistance due to the Larkin-Ovchinnikov mechanism and electron overheating in the vortex core.

- The descending field dependence of the surface Ri(H) develops as the frequency increases. A new mechanism of the Q(H) rise which can be tuned by impurities.

- Pinning at the surface can only reduce vortex dissipation at low RF fields << $H_s$.

- High-Q SRF cavities offer a unique opportunity to investigate the extreme dynamics of vortices at low temperatures.