Mitigation of performance-limiting mechanisms in Nb3Sn films

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Supported by DOE under grant DE-SC0010081-020

Workshop on Nb3Sn SRF Science, Technology and Applications (Nb3SnSRF20), Cornell, Nov. 10, 2020.

Advantages and disadvantages of Nb3Sn

- Larger SC gaps and T_c results in a lower BCS surface resistance than in Nb

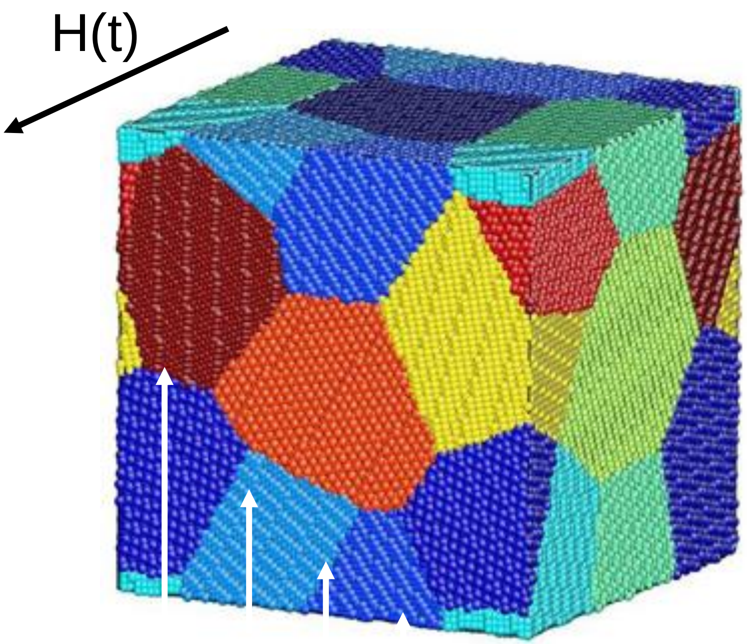
$$R_s = \frac{\mu_0^2 \lambda^3 \omega^2 \Delta}{\rho_n k T} \ln\left(\frac{9kT}{4\hbar\omega}\right) e^{-\Delta/kT} + R_i$$

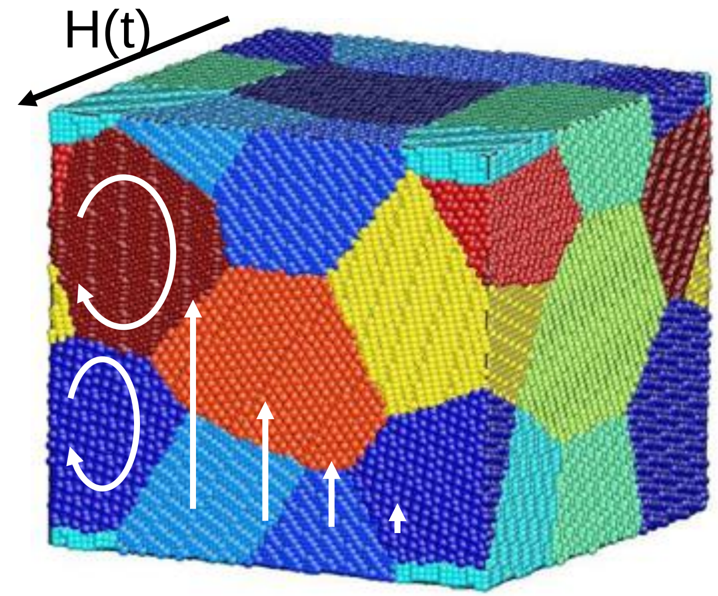
- For Nb_3Sn, one could get the same low-field R_s at 4.2K as for Nb at 2K.

- Higher critical field can translate into potentially higher accelerating gradients
- Nb_3Sn (T_c = 18K) has H_c = 540 mT versus 200 mT for Nb (T_c = 9K)

- Low Hc1 (2-10 times smaller than Hc1 = 170-180 mT in Nb)
- Current-blocking grain boundaries (GBs)
- Sensitivity of SC properties to local nonstoicheometry (segregation of Sn on weak-linked GBs)
- Low thermal conductivity $\kappa_{Nb3Sn} \sim 10^{-3}\kappa_{Nb} \simeq 10^{-2}\, W/mK$
- RF overheating in Nb3Sn layers thicker than 2-3 microns at 2K and 1-2 GHz
- Nb3Sn is more prone to flux trapping than Nb

Grain boundaries impeding SRF currents





GBs are fully transparent to the RF currents

Critical current density J_c of GB is close to J_d

No penetration of vortices along GBs

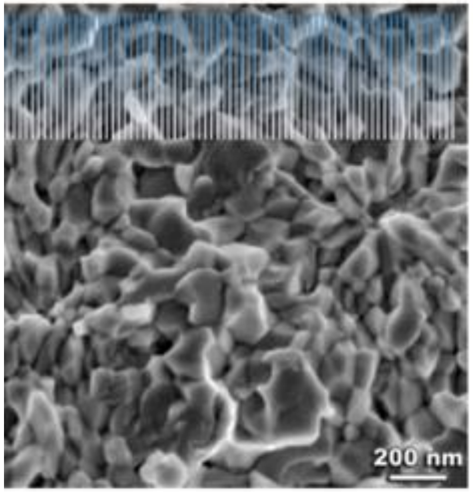
GBs are partly transparent to the RF current density

GB cannot fully transmit J(x) above a penetration field:

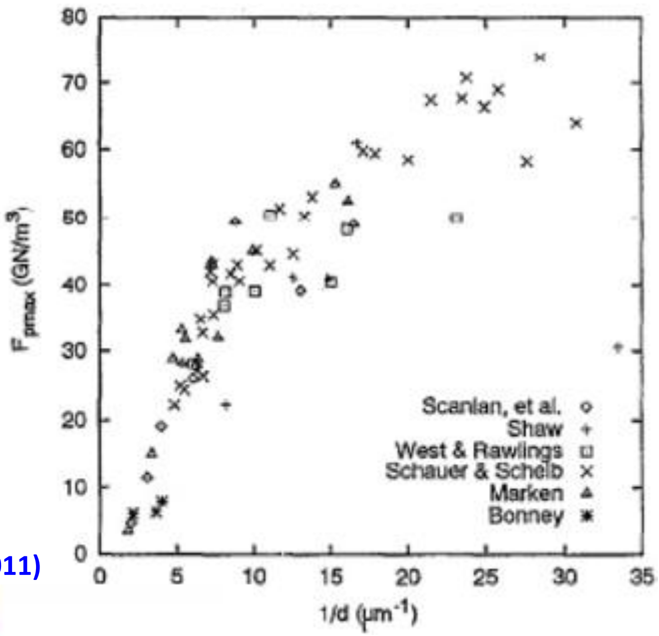
$$H > H_p \simeq \lambda J_c \simeq H_c J_c / J_d$$

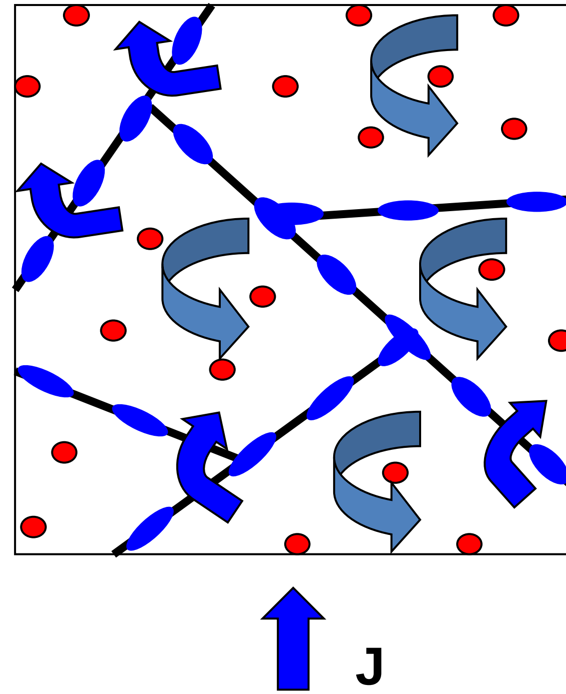
At $J_c = 0.1 J_d$, Abrikosov-Josephson vortices penetrate along GBs in Nb_3Sn at H > 20-50 mT

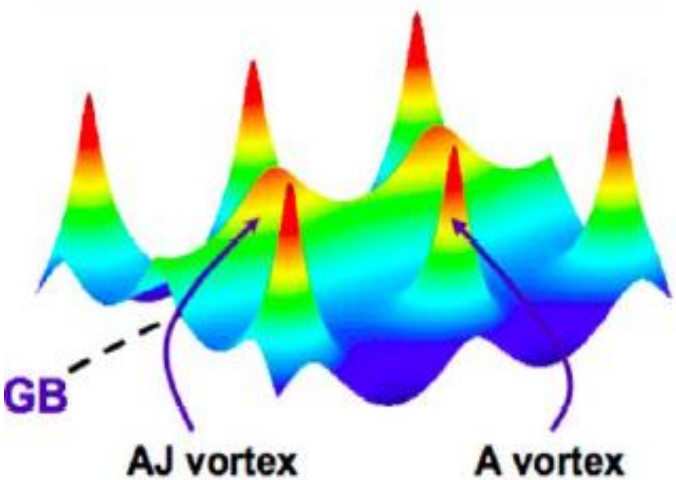
Grain boundaries pin vortices in Nb_3Sn



Durrell et al, Rep. Prog. Phys. 74, 124511 (2011)







Flux flow channels along GB

PRB 50, 13563 (1994); , PRL 88, 097001 (2002) ; PRB 65, 214531 (2002).

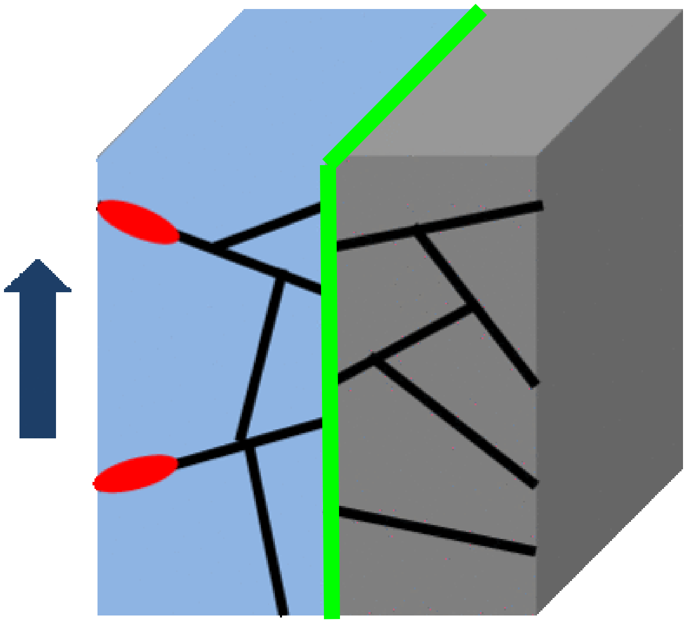
- Flux flow channels along GBs. Anisotropic pinning of vortices caged withing grains
- GBs critical current density J_c is much smaller than $J_c \ll J_d = H_c/\lambda$
- Bulk pinning force depends on the grain size d: GB partially block supercurrents

JAP 46, 2244 (1975), SUST 19, R68 (2006)

Mitigation of penetration of vortices along GBs

Sn segregation on GBs turns them into Josephson weak links

Suenaga APL 43, 791 (1983); Sandim et al SUST 26, 055008 (2013); Lee et al, SUST 32, 024001 (2018), Acta Mater. 188, 155 (2020)



Field onset of penetration for Josephson vortices

$$H > H_p \simeq \lambda J_c \simeq H_c J_c / J_d$$

Higher H_c = 540 mT for Nb_3Sn can result in better high-field SRF performance only if GBs are strongly coupled, **$J_c > 0.2J_d$**

SIS multilayers: blocking penetration of vortices in the bulk

Big reduction of RF vortex losses localized in the first thin S layer

Mismatch of GB structures in S coating layers and the Nb cavity: GB joints and I layer stop vortices

Penetration of vortices along GBs does not go beyond the first S layer

Effect of overheating on the surface resistance

Thermal feedback for trapped vortices and linear BCS:

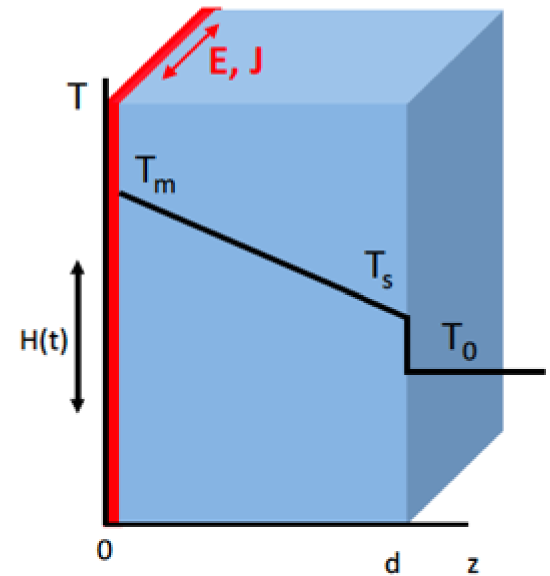
$$\left(R_i(H_a) + R_0 e^{(T-T_0)\Delta/T_0^2}\right)\frac{H_a^2}{2} = (T-T_0)g,$$

vortices BCS

Effective thermal impedance of the cavity wall:

$$g = \frac{1}{\alpha_K} + \frac{d}{\kappa}$$

Kapitza Heat diffusion



Maximum overheating and thermal breakdown field at $R_i < R_0$

$$T_b - T_0 = \frac{k_B T_0^2}{\Delta}\left(1 + \frac{R_i}{eR_0}\right)$$

$$H_b = \sqrt{\frac{2\kappa\alpha_K k_B T_0^2}{e\Delta(\kappa + d\alpha_K)R_0}}\left(1 - \frac{R_i}{2eR_0}\right)$$

Nb3Sn have larger RF losses caused by trapped vortices

Trapped vortices cause strong overheating which reduces Q(H)

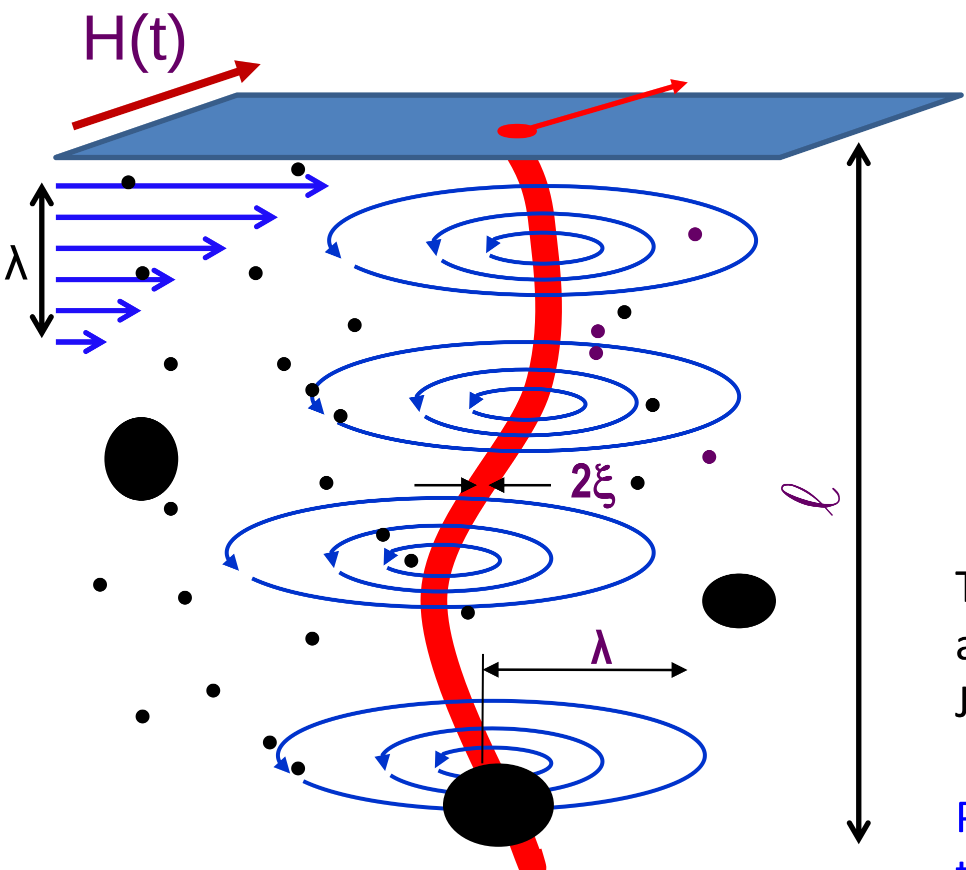
2-3 microns thick Nb3Sn film has the same thermal impedance as a 2-3 mm thick Nb

Gurevich, Rev. Accel. Sci. Technol. 5, 119 (2012)

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

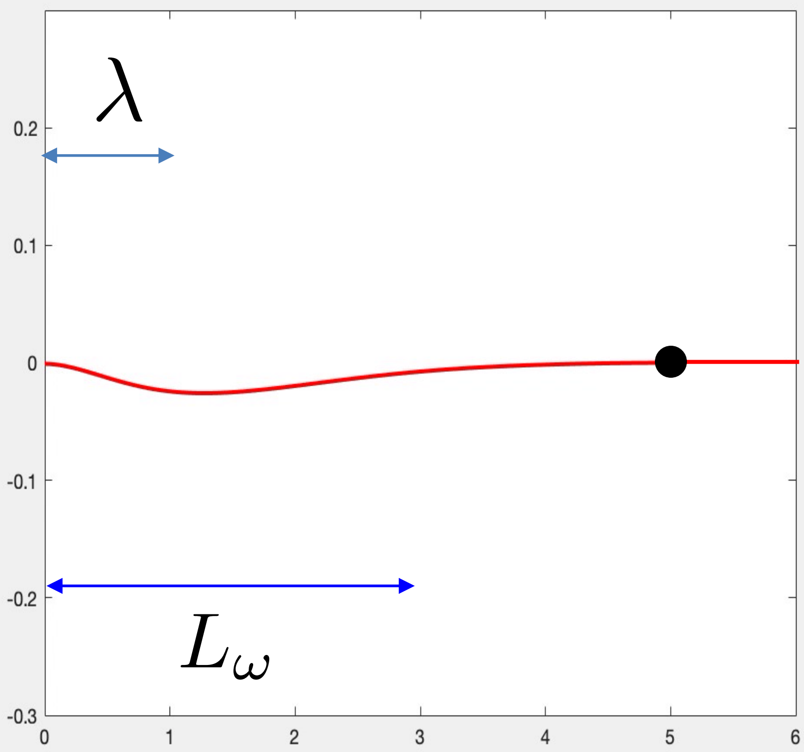
At H_a = 100-200 mT, J(0) approaches the depairing limit

$$J_d \simeq H_c/\lambda$$

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_ω can be much greater than λ.
- L_ω 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 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: $\lambda \lesssim L_\omega \lesssim \ell$

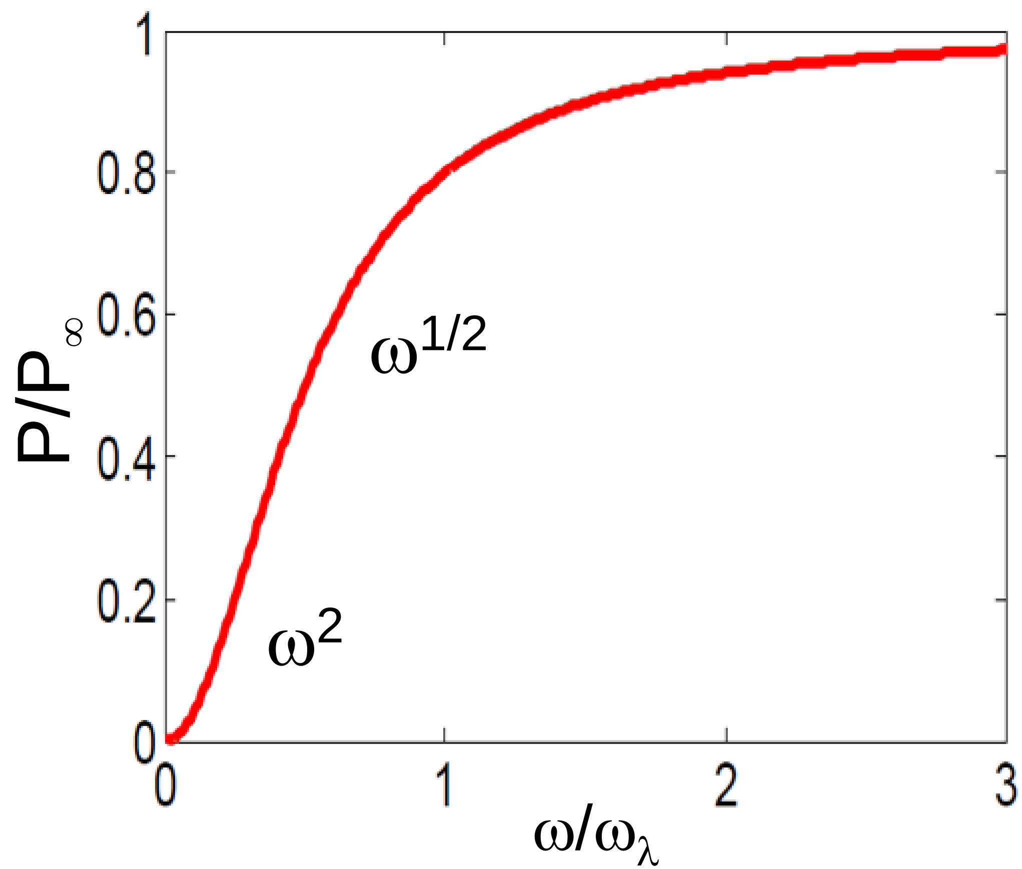
$$P \simeq \pi \mu_0^{-3/2} B_p^2 \lambda \xi \sqrt{\omega \rho_n}$$

No dependence on the pin spacing

- High ω: $L_\omega \lesssim \lambda$

$$P_{¥} = pH^2 r_n x^2 / 2l$$

No dependence on the pin spacing



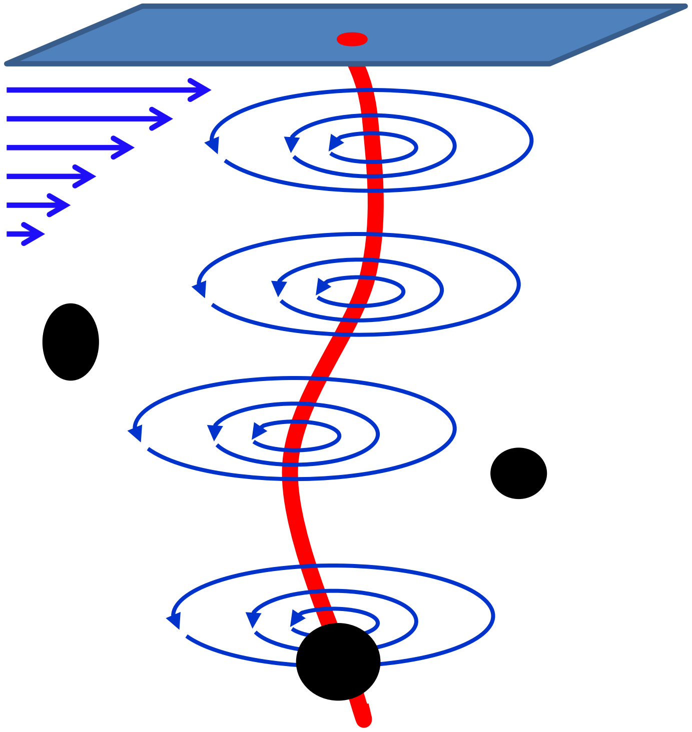
P ~ 0.13 μW at B = 100 mT and 2 GHz.

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?



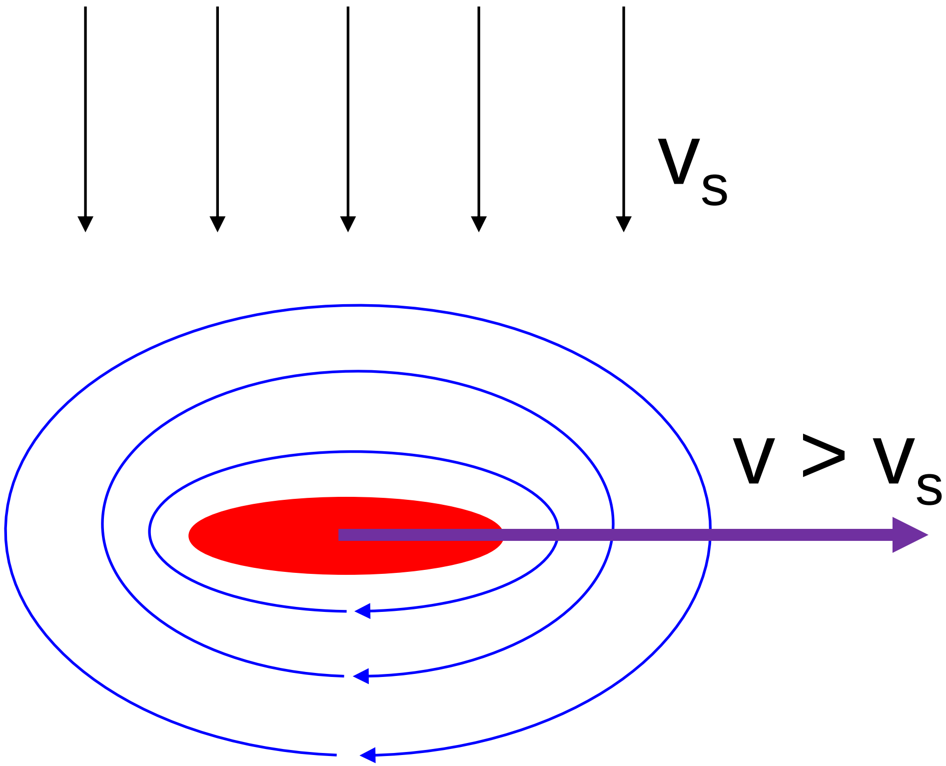
$$v \simeq \frac{J_d \phi_0}{\eta} \simeq \frac{\rho_n \xi}{2\mu_0 \lambda^2}$$

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

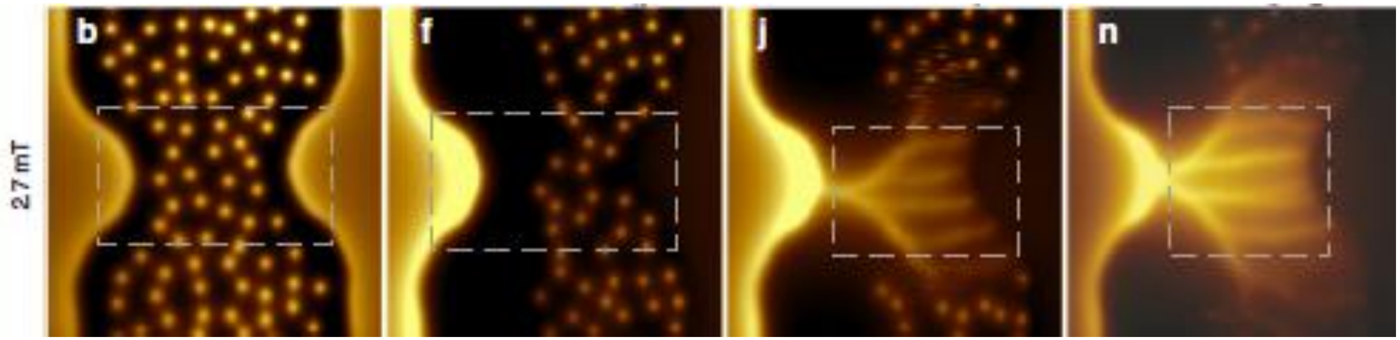
How can a vortex move faster than the current superflow which propels it?



- 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)

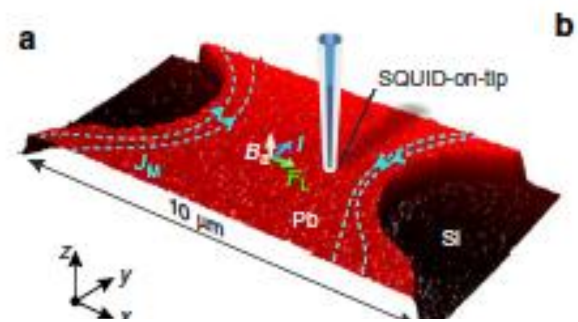
ARTICLE

OPEN

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

L. Embon[1], Y. Anahory[1,2], Ž.L. Jelić[3,4], E.O. Lachman[1], Y. Myasoedov[1], M.E. Huber[5], G.P. Mikitik[6], A.V. Silhanek[4], M.V. Milošević[3], A. Gurevich[7] & E. Zeldov[1]

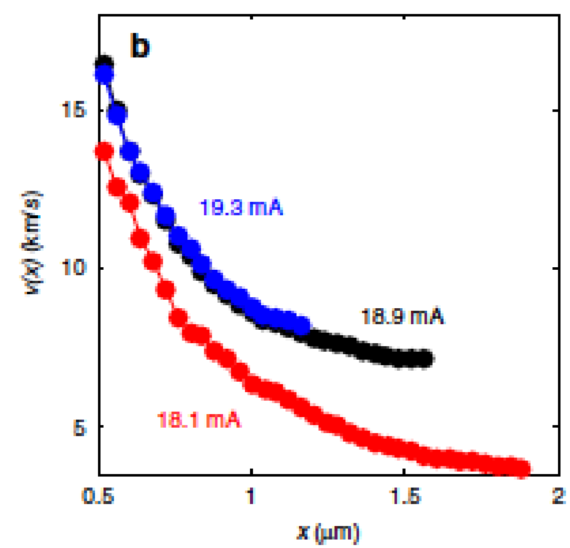
75 nm thick Pb film: imaging of penetrating vortices with a nanoscale SQUID on tip



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

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

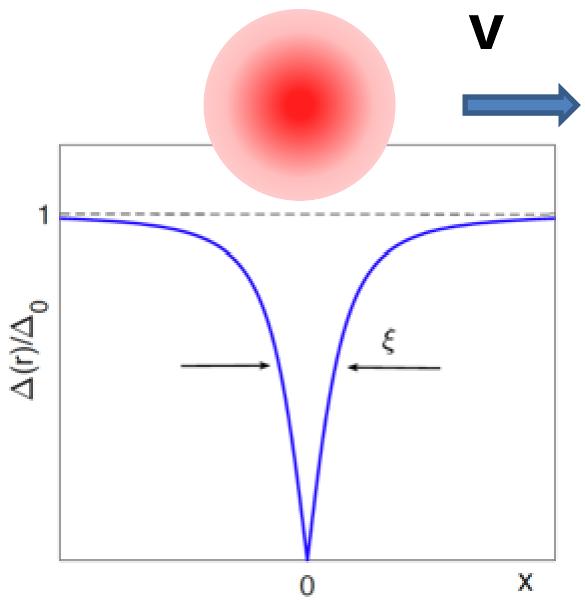


Vortices penetrate almost instantaneously through the Meissner RF layer

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

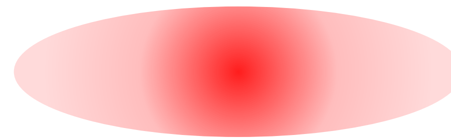
What happens to the vortex core at high velocities?

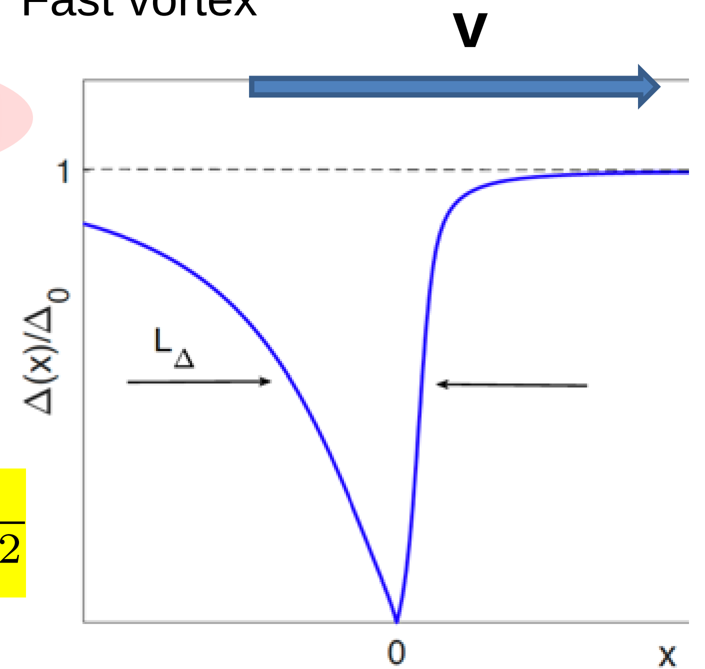
Slow vortex



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

Fast vortex





Velocity-dependent
LO vortex drag

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

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

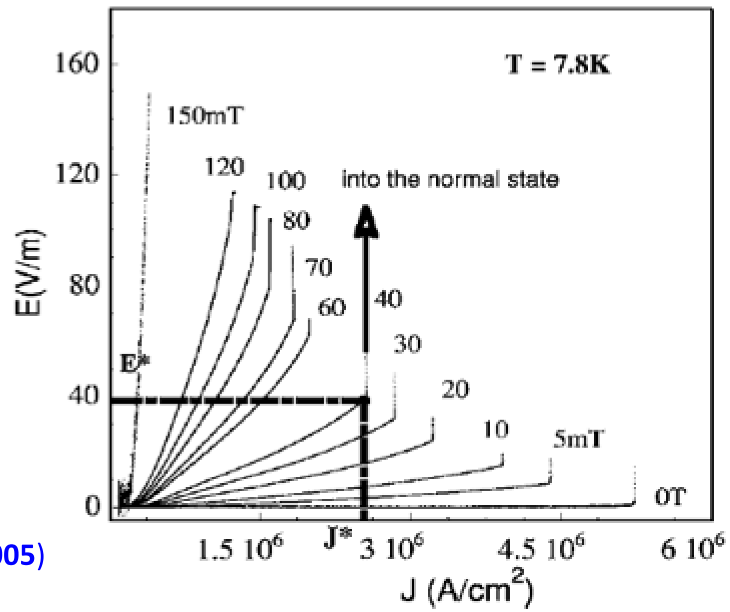
Larkin-Ovchinnikov instability

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

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

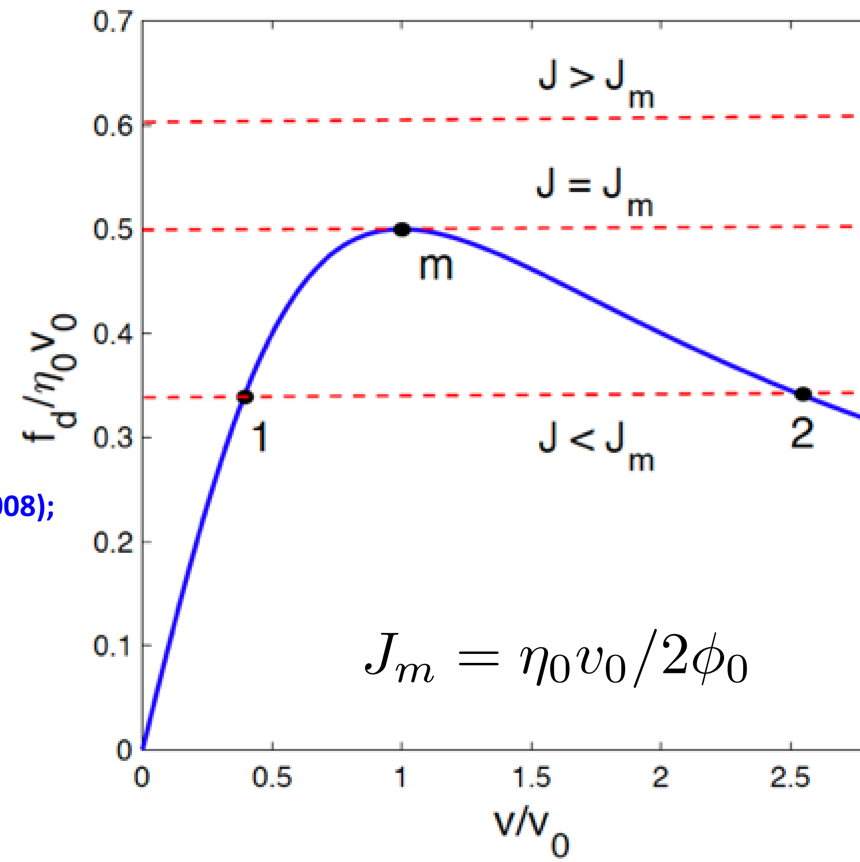
Observations on different materials:

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)



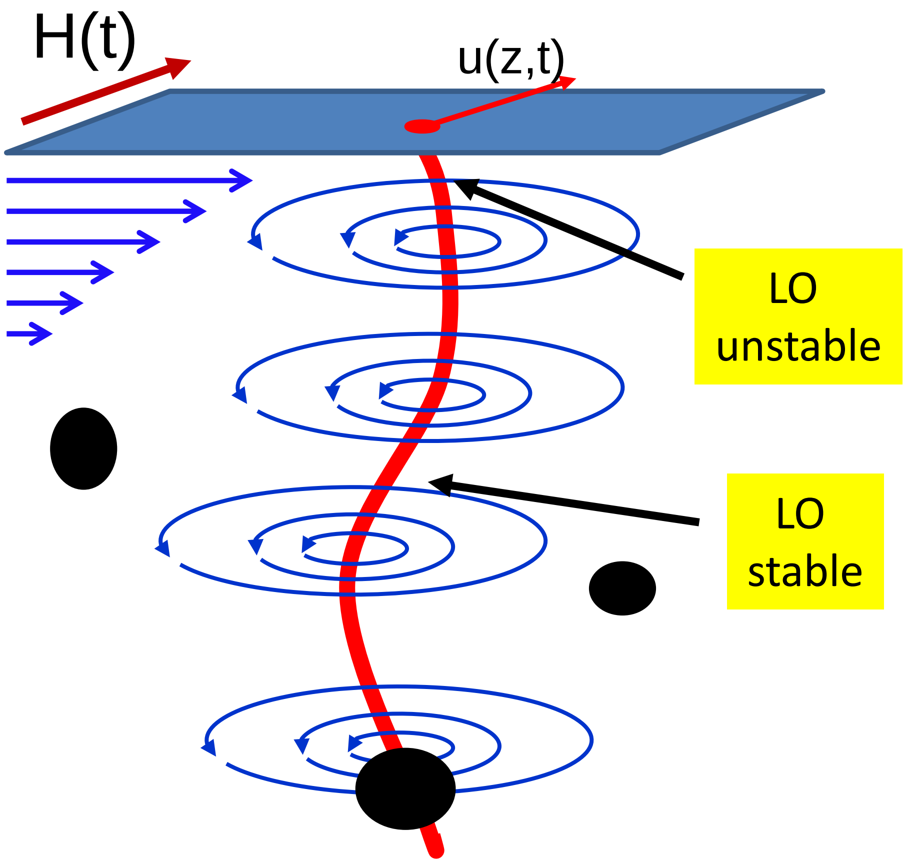
Acceleration of a runaway vortex at $v > v_0$, jumps on the V-I curves

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

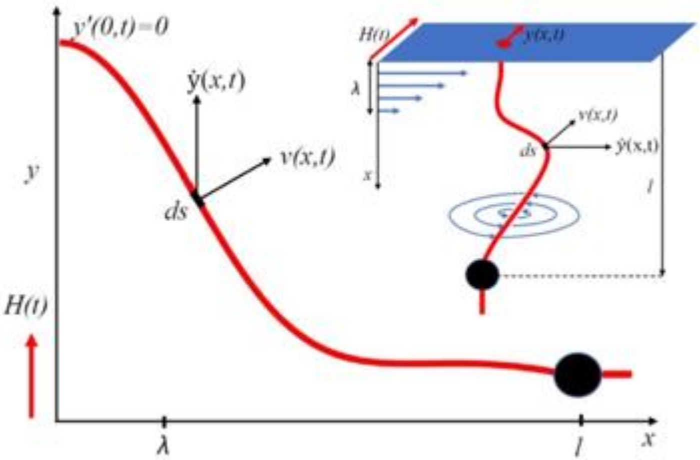
LO instability of a trapped vortex

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 << 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 $pB_0/\phi_0 = R_i H_a^2/2$:

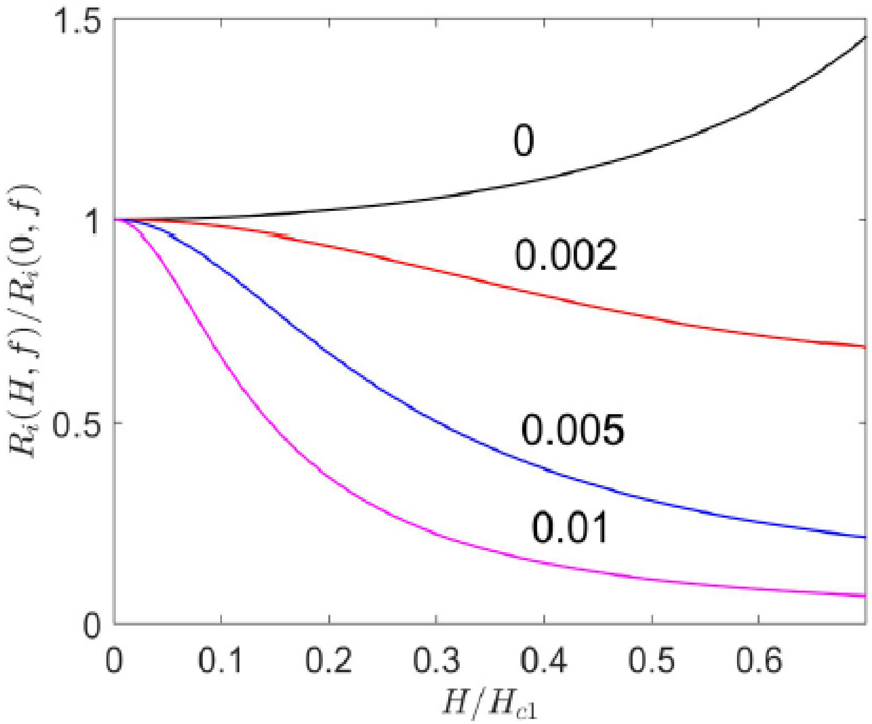
$$R_i(\beta) = \frac{R_0\gamma^2}{\beta^2}\int_0^1 dt \int_0^l \frac{(1+u'^2)^{1/2}\dot{u}^2 dx}{1+u'^2+\alpha\gamma^2\dot{u}^2}, \qquad R_0 = \frac{2\rho_n B_0}{\lambda B_{c2}}$$

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:*

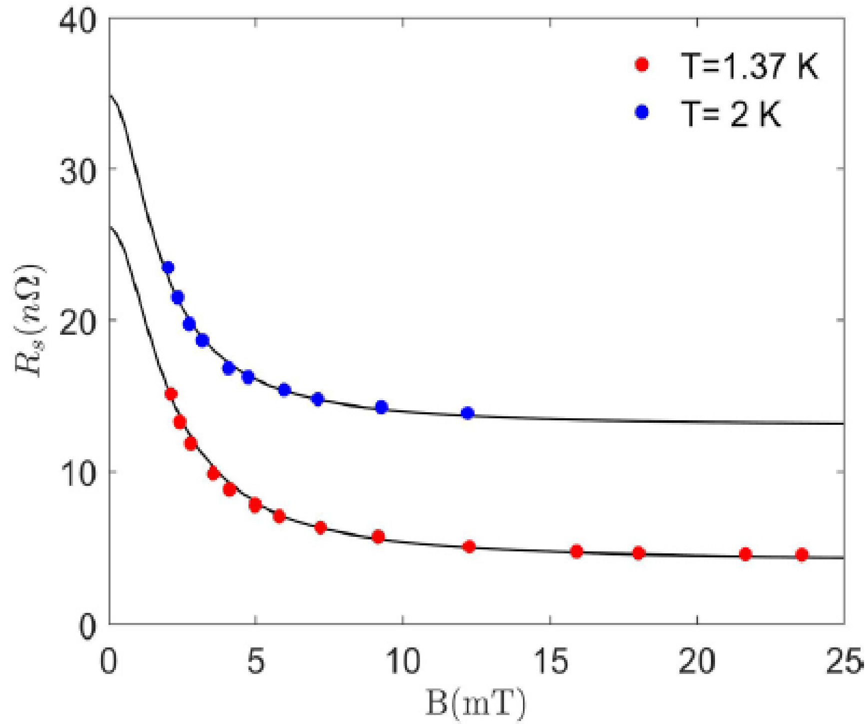
$$R_i \propto H_a^{-2}$$

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

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

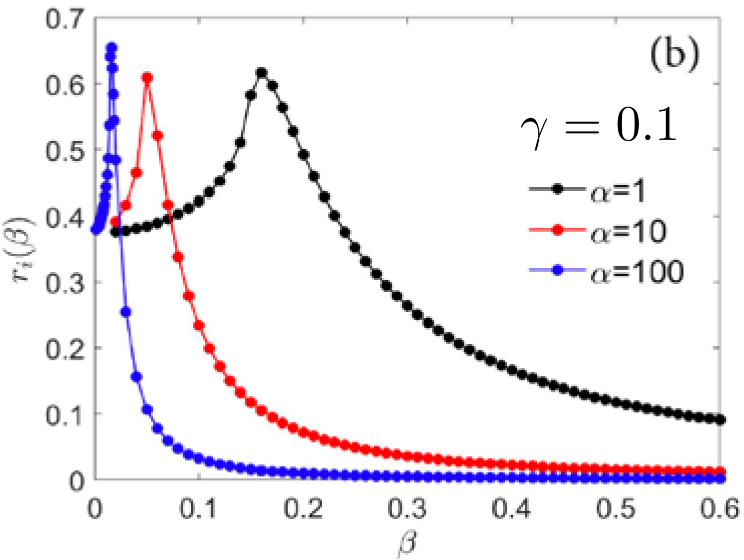


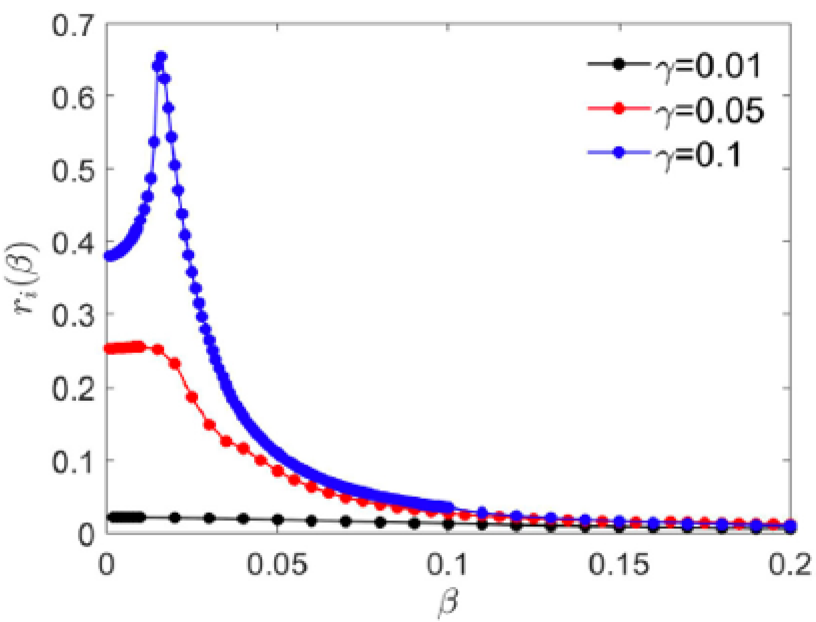
Fit to the experimental data of for a 1.47 GHz Nb cavity

Ciovati, JAP 96, 1591 (2004)

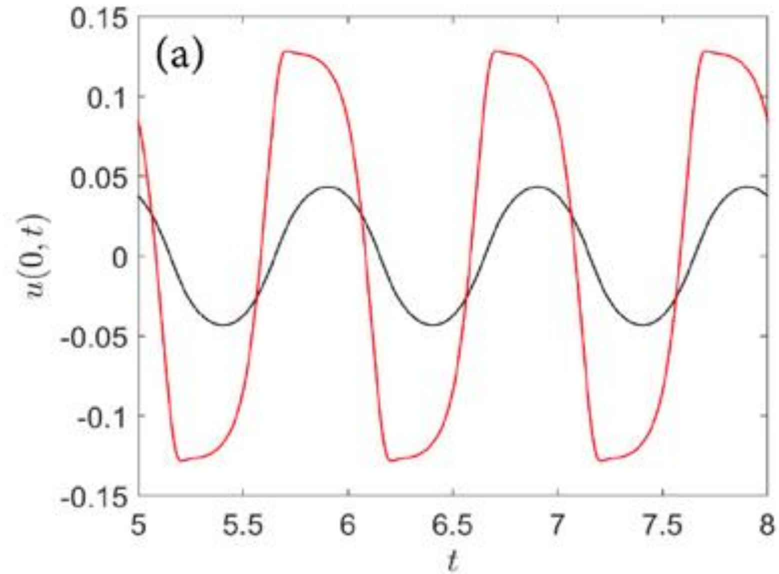
$$l = 3\lambda, \quad B_0 = 0.73\,\mu T,$$
$$v_0(2K) = 30\,m/s,$$
$$v_0(1.37K) = 35\,m/s,$$

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





$$\alpha \rightarrow \alpha\gamma^2$$

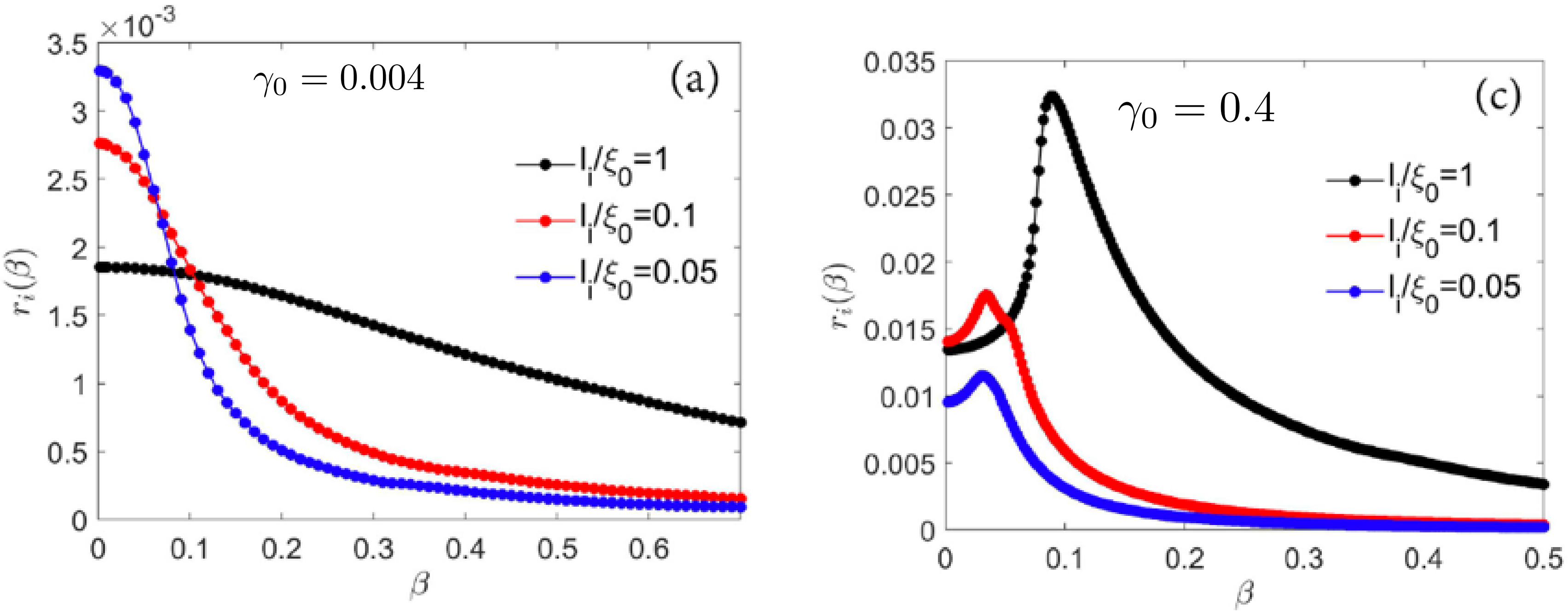


Transition from quasi-harmonic to relaxation oscillations at the peak in $R_i(H)$. The Campbell length increases with H_a:

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

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

Tuning the LO vortex dynamics by impurities

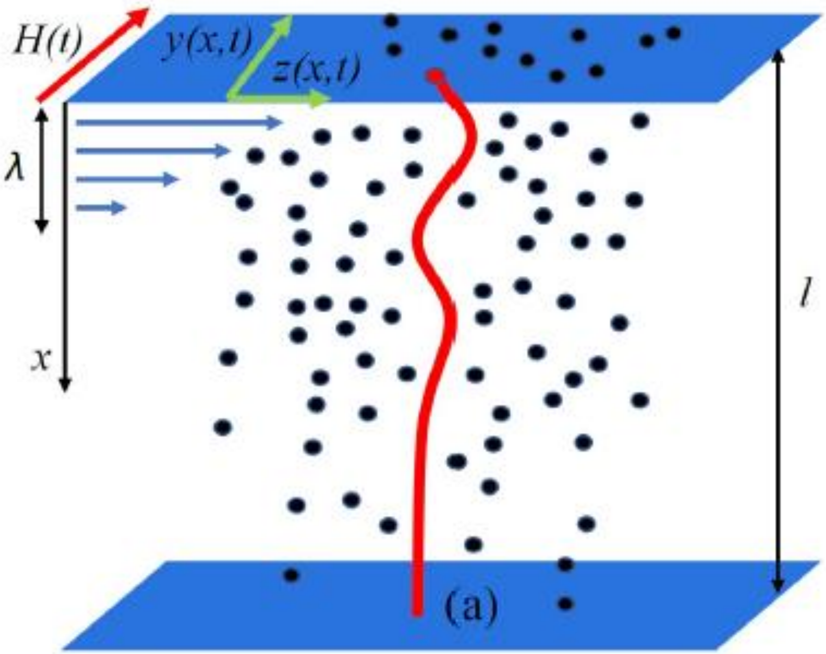


Calculated for $\alpha_0 = 1.6 \cdot 10^4, \quad l = 3\lambda_0$

- Making the surface dirtier and decreasing the impurity m.f.p. shifts the anomalous drop of the vortex surface resistance $R_i(H)$ to lower fields.
- May pertain to the low-field Q(H) drop observed on many Nb cavities

Random pinning

Pathirana and Gurevich (unpublished)



Numerical modeling of nonlinear dynamics of a curvilinear elastic vortex driven by strong RF current in a film

Mesoscopic effects in RF response for different pinning configurations

LO instability in the presence of random pinning

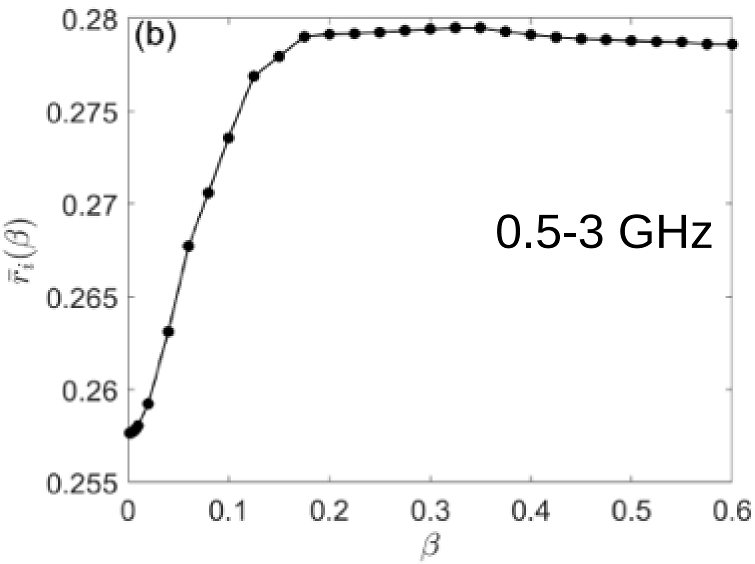
Effect of overheating

$$M\frac{\partial^2 \mathbf{R}}{\partial t^2} + \eta\frac{\partial \mathbf{R}}{\partial t} = \epsilon\frac{\partial^2 \mathbf{R}}{\partial X^2} - \nabla U(X,\mathbf{R}) - \hat{y}\phi_0 H e^{-X/\lambda}\sin\omega t,$$

$$U(X,\mathbf{R}) = -\sum_{n=1}^{N}\frac{U_n\xi^2}{\xi^2 + (X-X_n)^2 + |\mathbf{R}-\mathbf{R}_n|^2}$$

Surface resistance of trapped vortices

Mattis-Bardeen



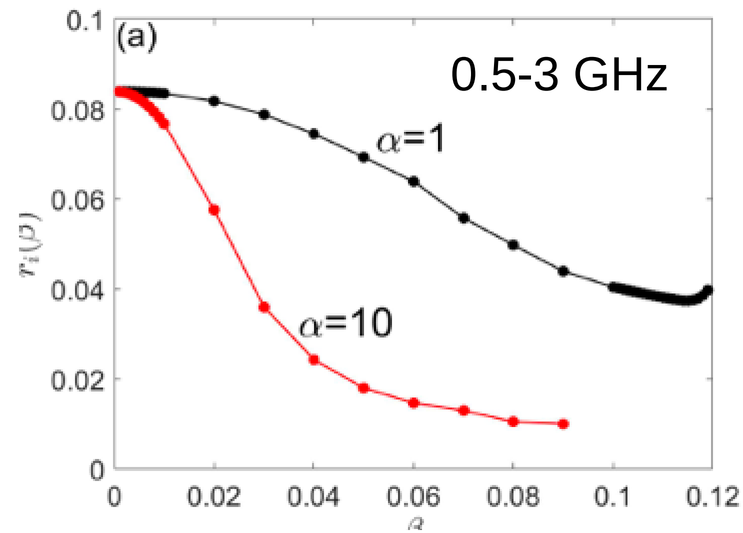
$$\beta = H/H_{c1}$$

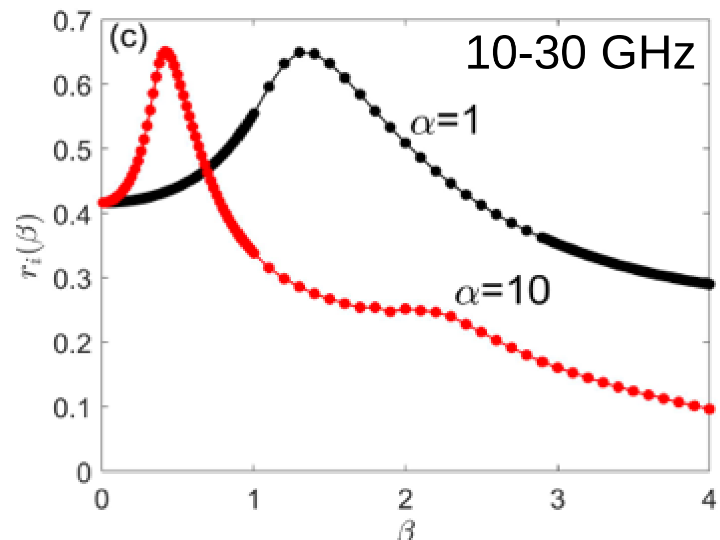
Averaging over statistical realizations of the pinning potential often (but not always) yields a linear low-field dependence of Rs(H).

Quasi-static collective pinning:

Liarte et al. Phys. Rev. Appl. 10, 054057 (2018).

Larkin-Ovchinnikov

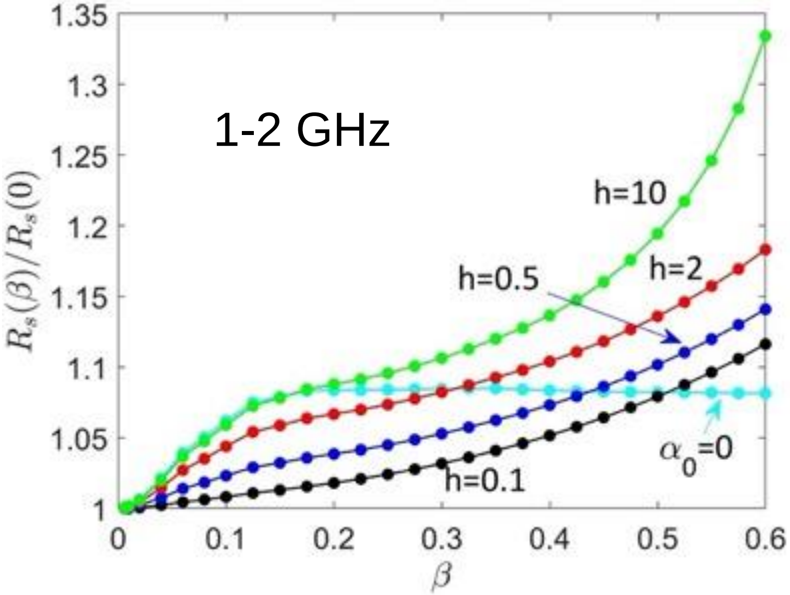




LO critical velocities: v_0 = 20-50 m/s

Overheating effects

Mattis-Bardeen

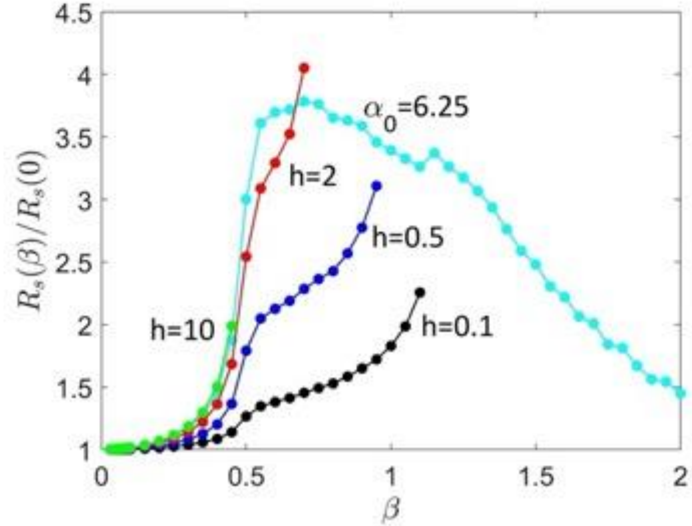


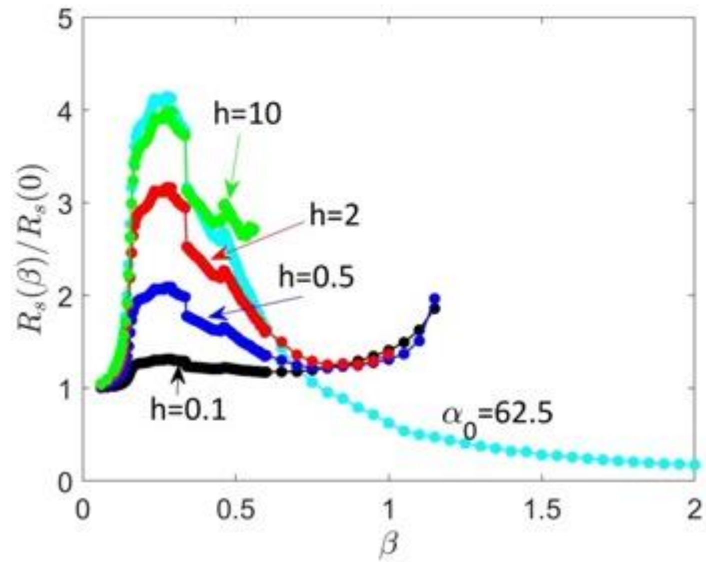
h = R_i/R_0 is proportional to the flux of trapped vortices

Quasi-linear dependence caused by heating

High-field upturn of $R_s(H)$

Larkin-Ovchinnikov





Heating mitigates the negative Q slope

Could strong pinning mitigate SRF vortex losses?

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

Taking advantage of the high-field potential of Nb3Sn requires mitigating the issues which have been taken for granted in Nb:

- Small lower critical field
- Current-blocking grain boundaries
- Sensitivity of SC properties to local nonstoicheometry (segregation of Sn on weak-linked GBs)
- Much lower thermal conductivity
- RF overheating in Nb3Sn layers thicker than 2-3 microns at 2K and 1-2 GHz
- Nb3Sn is more prone to flux trapping than Nb
- Pinning may only be effective at very low RF fields. Dense APC structures greatly increase BCS and eddy current losses.

Opportunities to probe the extreme nonlinear dynamics of trapped vortices in SRF cavities at low T. Vortex mechanism of the negative Q(H) slope.