EFFECT OF MEAN FREE PATH ON NONLINEAR LOSSES OF TRAPPED VORTICES DRIVEN BY A RF FIELD*

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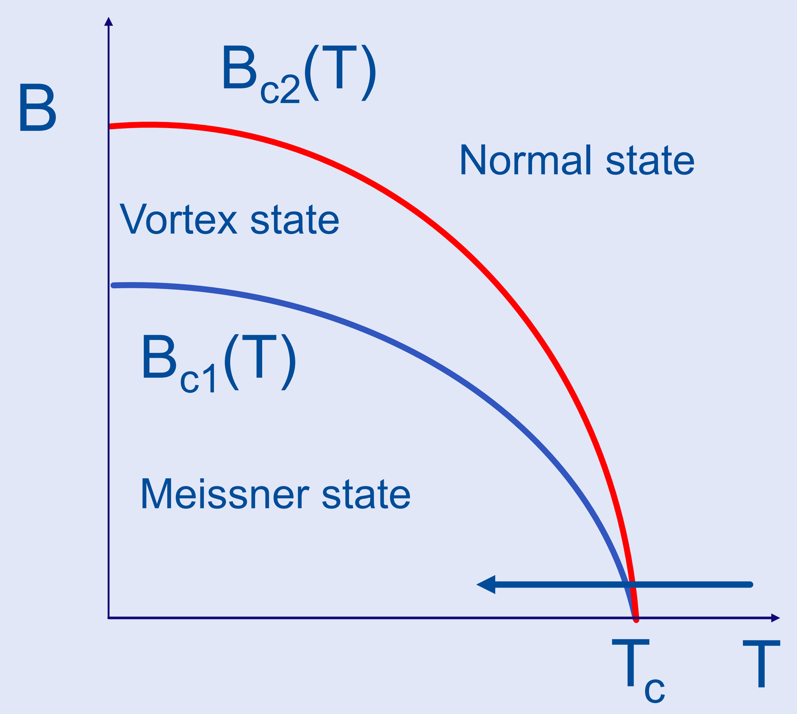
ABSTRACT

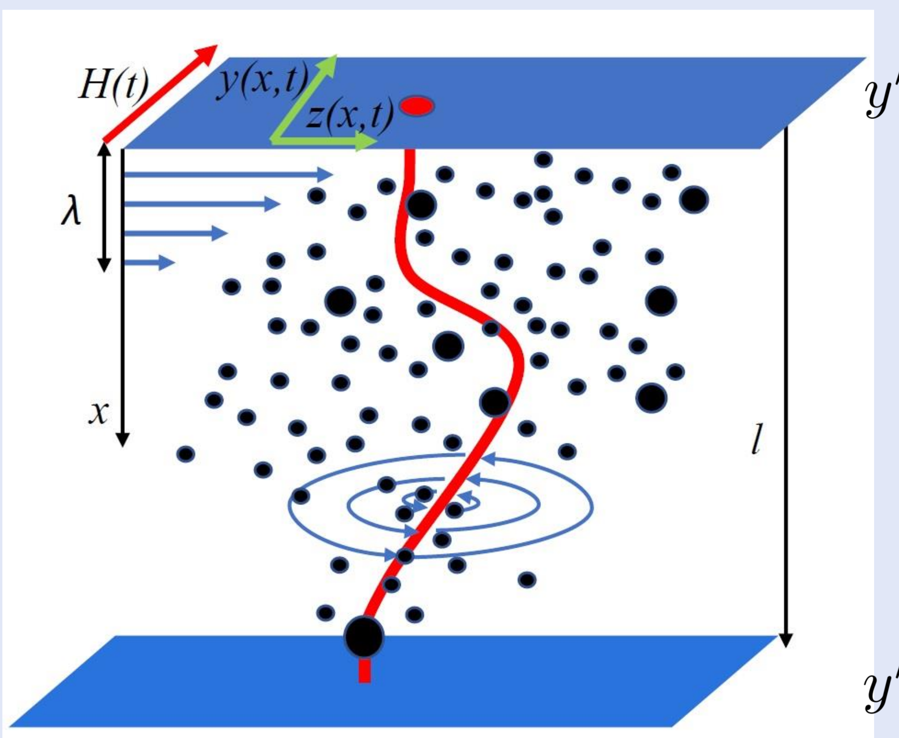
We report extensive numerical simulations on nonlinear dynamics of a trapped elastic vortex under rf field, and its dependence on electron mean free path l_i. Our calculations of the field-dependent residual surface resistance $R_i(H)$ take into account the vortex line tension, the linear Bardeen-Stephen viscous drag and random distributions of pinning centers. We showed that $R_i(H)$ decreases significantly at small fields as the material gets dirtier while showing field independent behavior at higher fields for clean and dirty limit. At low frequencies $R_i(H)$ increases smoothly with the field amplitude at small H and levels off at higher fields. The mean free path dependency of viscosity and pinning strength can result in a nonmonotonic mean free path dependence of $R_i(H)$, which decreases with l_i at higher fields and weak pinning strength.

GENERATION OF TRAPPED VORTICES [1]

- Vortex state is favorable at $B > B_{c1}(T)$ but because $B_{c1}(T_c) \to 0$, vortices can be generated in the cavity during the cool-down through T_c
- Most of the vortices exit as T it reduced below T_c but some vortices get pinned by materials defects.
- Trapped vortices contribute to the residual surface resistance
- How does the vortex residual resistance depend on B, mean free path, frequency (f), pinning distribution and their strength?



DYNAMICS OF A TRAPPED VORTEX UNDER RF CURRENT



$$y'(0,t) = z'(0,t) = 0$$

$$y'(l,t) = z'(l,t) = 0$$

Dynamic equation for the local velocity normal to a flexible vortex line:

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

- M-vortex mass, η- viscosity, ε- line tension, **R=[Y(X,t),Z(X,t)]** is the ac displacement of the vortex with the ε, F- amplitude of the rf driving force
- The core pinning of the vortices is modeled by:

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

- U_n are determined by the gain in the condensation energy in the vortex core at the pin

Dynamic equations for the dimensionless vortex displacement $y = Y(X,t)/\lambda_0$, $z = Z(X,t)/\lambda_0$:

$$\gamma\dot{y} = y'' - \sum_{n=1}^{N} A_n(x,\mathbf{r})(y-y_n) + \beta sin(2\pi t)e^{-x/\Gamma},$$

$$\gamma\dot{z} = z'' - \sum_{n=1}^{N} A_n(x,\mathbf{r})(z-z_n),$$

$$\gamma = \frac{g_0\Gamma^4 l_i f}{g\xi_0 f_0}, \qquad f_0 = \frac{H_{c10}\rho_{n0}}{H_{c20}\lambda_0^2\mu_0},$$

$$\Gamma = (1+\xi_0/l_i)^{1/2}, \qquad \beta = \frac{g_0\Gamma H}{gH_{c10}},$$

$$A_n = \frac{g_0\Gamma^5\zeta_{n0}}{g\left[1+\Gamma^2\kappa_0^2(x-x_n)^2+\Gamma^2\kappa_0^2|\mathbf{r}-\mathbf{r}_n|^2\right]^2},$$

$$\zeta_{n0} = 2\kappa_0^2 U_n/\epsilon_0,$$

$$g_0 = \ln\frac{\lambda_0}{\xi_0}+\frac{1}{2}, \qquad g = \ln\frac{\lambda_0\Gamma^2}{\xi_0}+\frac{1}{2}.$$

λ_0 - London penetration depth in clean limit
time is in units of rf period
l is in units of λ_0
N_v - number of vortices
ρ_0 – normal state resistivity in clean limit
H_{c10}, H_{c20}- Lower and upper critical fields in clean limit

Dimensionless surface resistance:

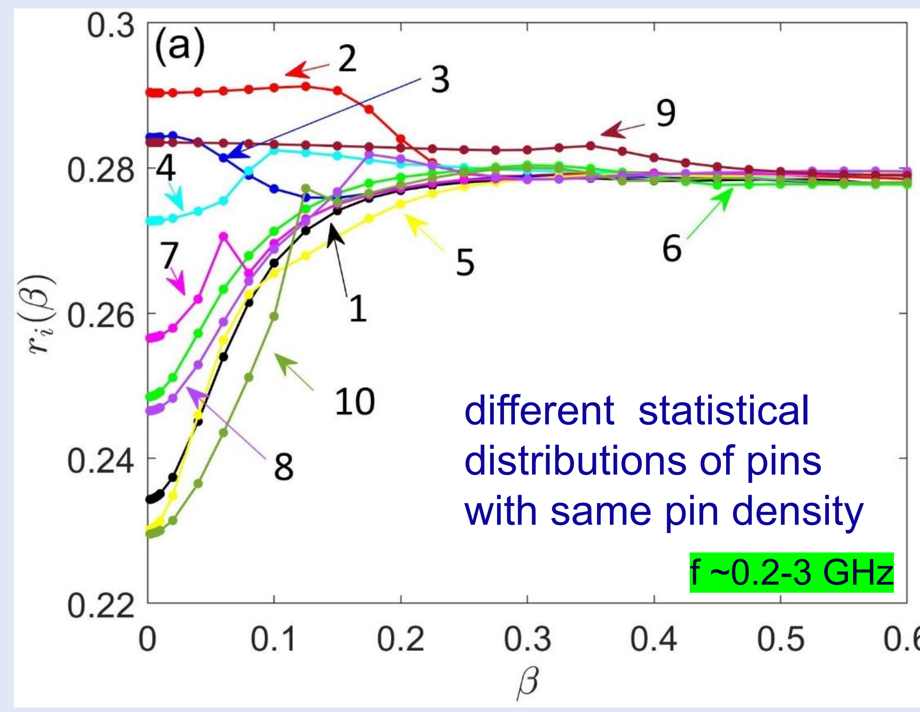
$$r_i(\beta) = \frac{\gamma_0}{g_0\Gamma N_v\beta^2}\sum_{k=1}^{N_v}\int_0^1 dt\int_0^l \beta_t e^{-x}\dot{y}_k(x,t)dx$$

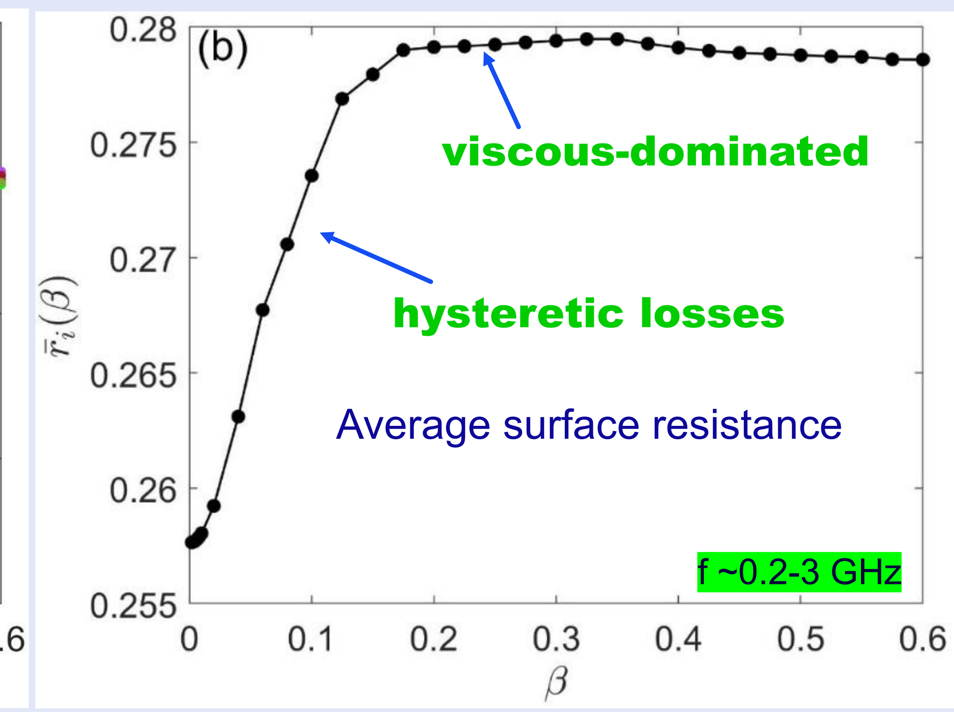
$$R_i(H) = \frac{\rho_{n0}B_0}{\lambda_0 B_{c20}}r_i(\beta)$$

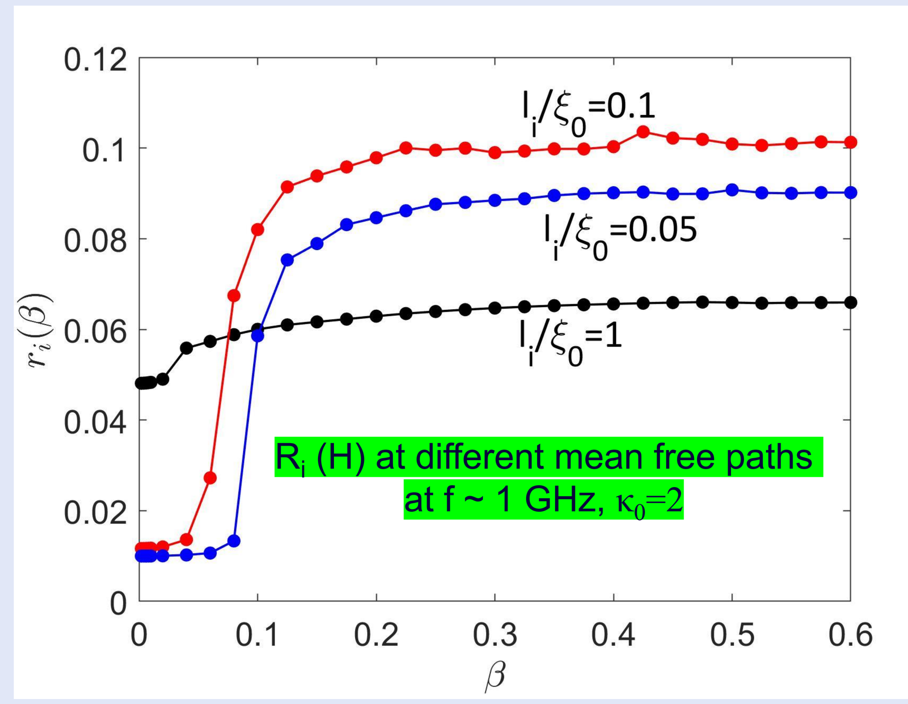
B_0-Field due to trapped flux

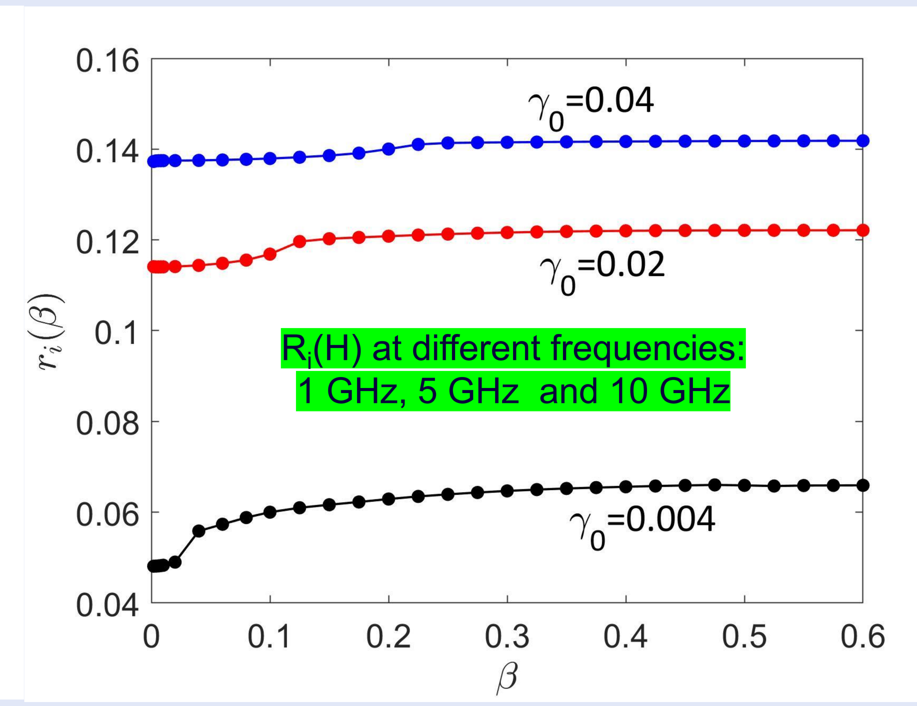
NUMERICAL RESULTS

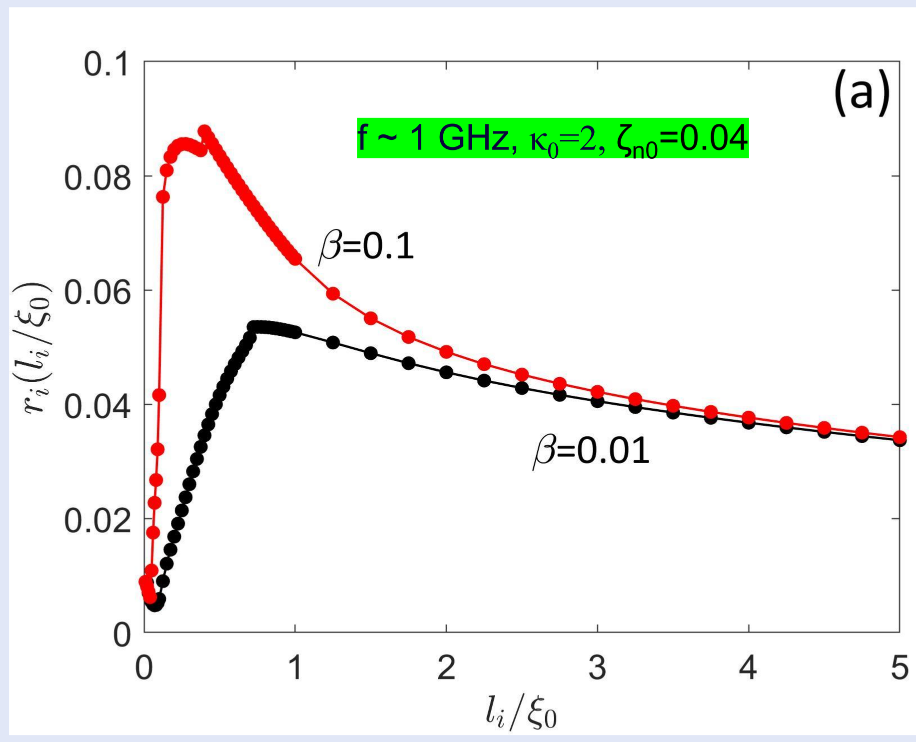
- Taking $\lambda_0/\xi_0=1$, λ=40 nm, $\rho_n=10^{-9}$ Ωm, U_n=1.4 meV/nm [2,3] for a clean Nb at f=1 GHz, we obtain $\gamma_0=g_0f/f_0 \approx 0.004$ and ζ_{n0}=0.04.

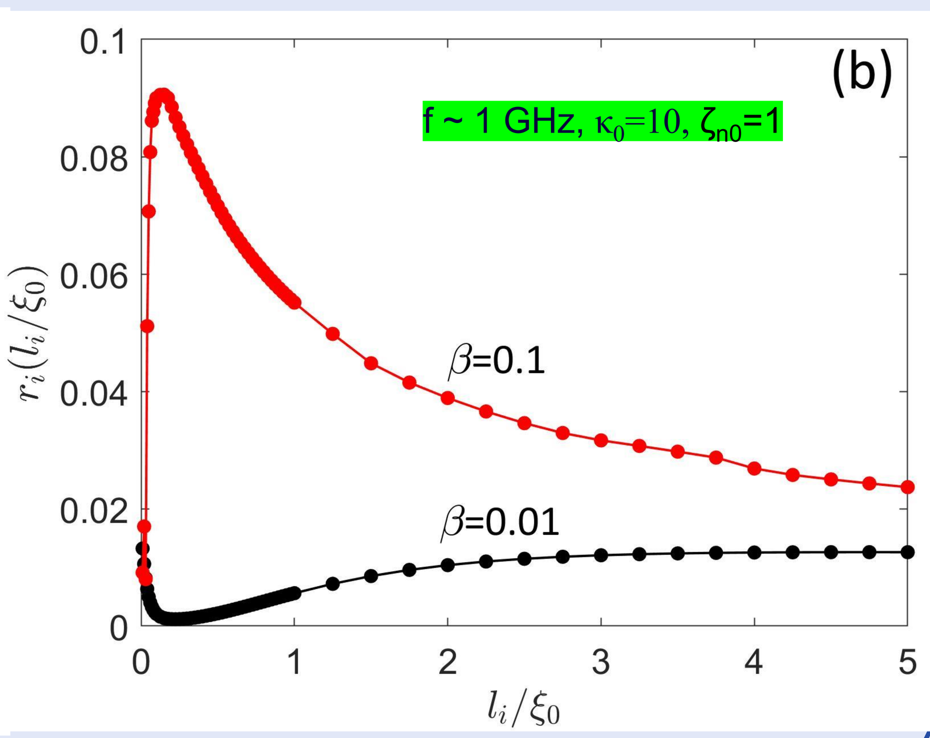












Dependencies of the surface resistance on the mean free path

SUMMARY

- Field dependent $R_i(H)$ strongly depends on the mean free path, pinning density, strength, and their statistical distributions at small fields.
- Low-field global surface resistance averaged over statistical realizations of random pinning potential increases nearly linearly with H and levels off at higher fields.
- $R_i(H)$ at strong RF field becomes a nonmonotonic function of H which decreases with H at higher frequencies if we consider the Larkin-Ovchinnikov decrease of η(v) [1,2]. This can contribute to the negative Q(H) slope in SRF cavities.
- Overheating can mask the descending field dependence of $R_i(H)$ as frequency increases.
- More details can be found in our previous work in [1] and [2].

[1] W.P.M.R. Pathirana and A. Gurevich, Nonlinear dynamics and dissipation of a curvilinear vortex driven by a strong time-dependent Meissner current. Phys. Rev. B, 101, 064504 (2020).
[2] W.P.M.R. Pathirana and A. Gurevich, Effect of random pinning on nonlinear dynamics and dissipation of a vortex driven by a strong microwave current. Phys. Rev. B, 103, 184518 (2021).
[3] Checchin, M, Martinello, M, Grassellino, A, Romanenko, A, Zasadzinski J F. Electron mean free path dependence of the vortex surface impedance, Supercond. Sci. Technol. 30, 034003 (2017).

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