Dissipation in thin narrow superconducting films

L.N. Bulaevskii, LANL
V.G. Kogan, Ames Iowa.

1. Dark counts in photon detectors (dissipation in thin films).
2. Dissipation in superconducting wires, ALMH theory.
3. Dissipation due to vortex motion in thin films.

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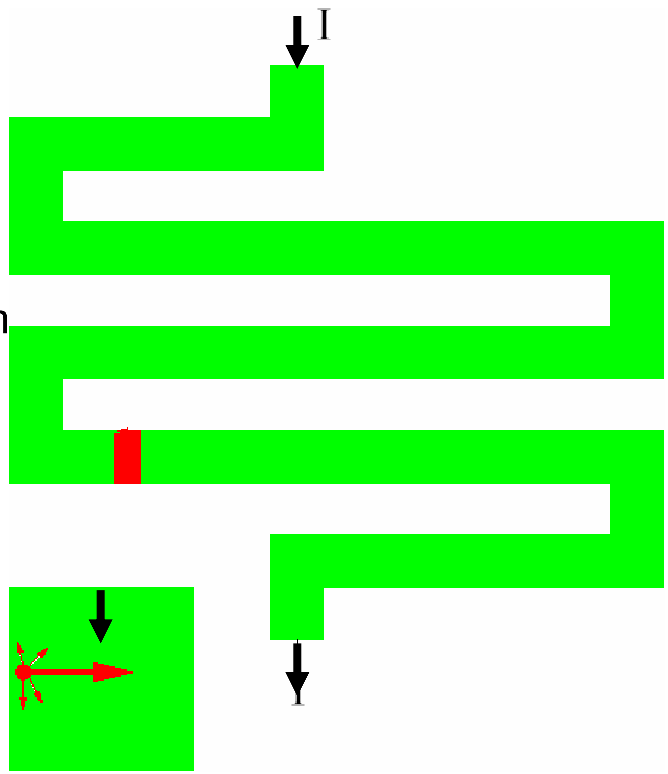
Motivation: dark counts in photon superconducting detectors

d=5 nm

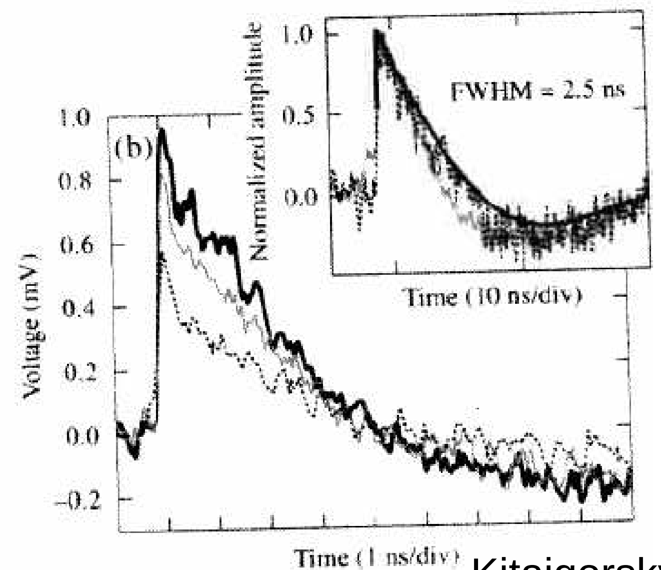
W=120 nm

ξ =4 nm



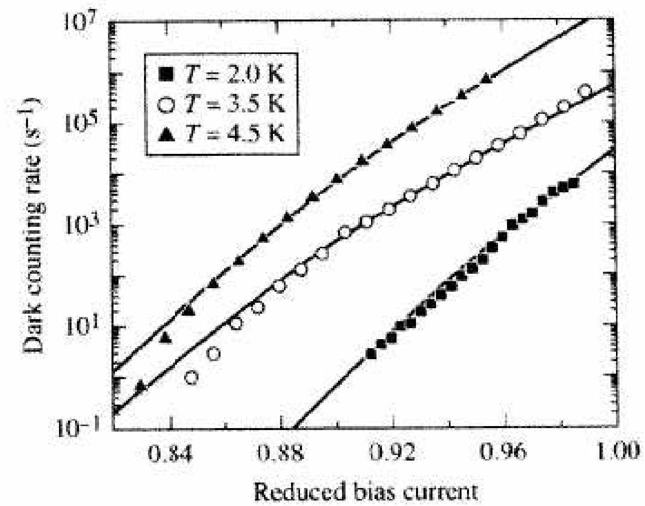
NbN

T_c =15 K



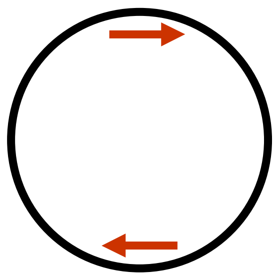
Kitaigorsky

Sobolevsky



- Bias current close to I_c for sensitivity.
- Counts without photons (dark counts), $V_{dc} > 0$.
- Origin: vortex motion across strip

Dissipation in thin wire, length L, ALMH theory.



I

$$\Psi_n(x) = \Psi_0 e^{i\kappa_n x + \phi}, \qquad \kappa_n = \frac{2\pi n}{L},$$

$$I = I_0 \kappa_n (1 - \kappa_n^2), \qquad \kappa_{\max} = \frac{1}{\sqrt{3}}.$$

- Change of current: $\kappa_n \to \kappa_{n-1}$.
- Phase changes locally inside normal region by 2π.
- Saddle point solution:

$$\Psi_{s,n\to n-1} = [\alpha \tanh(\alpha x / \xi\sqrt{2}) - i\kappa\sqrt{2}] e^{i\kappa x + \phi}, \qquad \alpha = (1 - 3\kappa^2)^{1/2}.$$

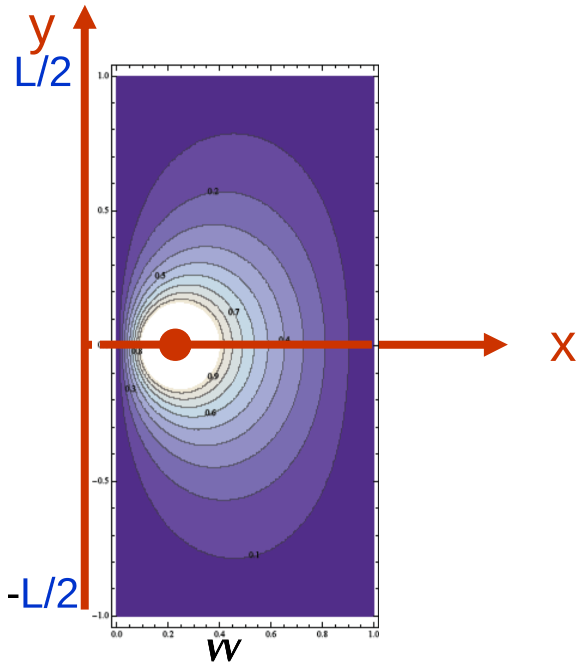
- Barrier $\Delta F_{n\to n-1} = \dfrac{\sigma H_c^2 \xi}{8\pi} f(\kappa) \tan^{-1}(\alpha / \kappa\sqrt{2}), \qquad R = \Omega e^{-\Delta F / T},$

$$\Omega = \frac{L}{\tau_{TDGL}\xi}\left(\frac{\sqrt{2}\sigma H_c^2 \xi \alpha^{3/2}}{24\pi^4 T}\right)^{1/2} \sqrt{|\varepsilon_{1S}|}\left[\varepsilon_{n1}\varepsilon_{n2}\prod_{m=4}\frac{\varepsilon_{nm}}{\varepsilon_{sm}}\right]^{1/2} \approx \frac{1}{\tau_{TDGL}}\left[\frac{\Delta F_{n\to n-1}}{T}\right]^{1/2}.$$

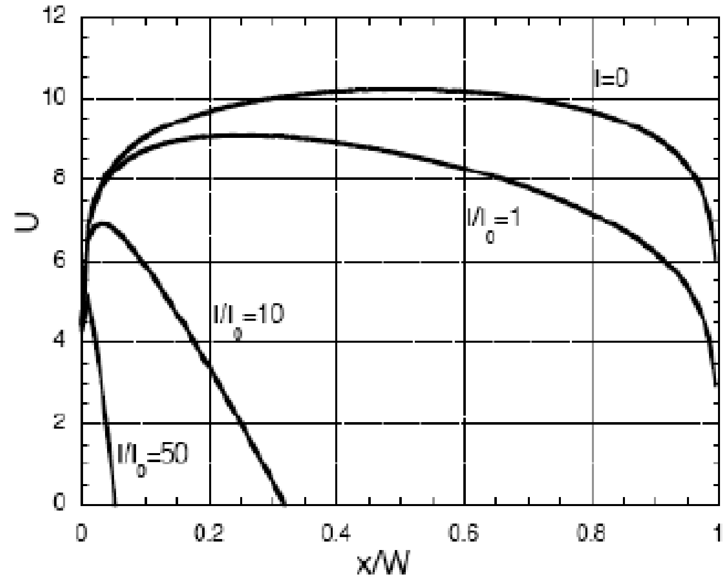
[Fluctuation factor]

Thin film, length L, width w, $\xi \quad w \quad \Lambda = 2\lambda_L^2 / d$

- Pearl vortex energy inside strip (kinetic energy of currents), $A \propto 1/\Lambda \to 0.$



V. Kogan



$$I_0 = \frac{c\Phi_0}{8\pi\Lambda}$$

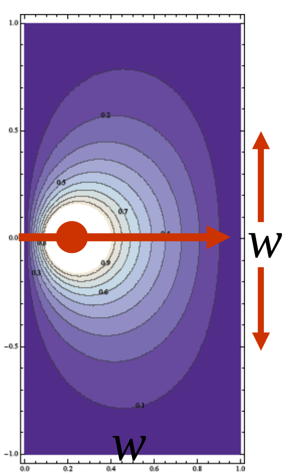
U in units

$$\varepsilon_0 = \frac{\Phi_0^2}{8\pi^2\Lambda}$$

- Phase difference between y-edges for L>>w $\varphi(L/2) - \varphi(-L/2) = 2\pi x.$
- Vortex moving x=0 and x=w changes phase difference by $2\pi.$
- Saddle point solution: vortex at maximum of the potential at given current.
- Barrier: $\Delta F_{n\to n+1} = \varepsilon_0 \ln \frac{2wI_0}{e\pi\xi I}, \quad I \quad I_0, \quad I_c = I_0 \frac{2w}{e\pi\xi}.$

Attempt frequency and fluctuation factor

- Rate of vortex crossings: $R_{n\to n-1} = \Omega e^{-\Delta F/T}$,
- DC voltage given by Josephson relation: $V = (\hbar/2e_{el})R_{n\to n-1}$.
- Attempt frequency: $\Omega \approx \dfrac{L}{\tau_{TDGL}\xi}\left[\varepsilon_{n2}\varepsilon_{n3}\prod_{m=4}\dfrac{\varepsilon_{nm}}{\varepsilon_{sm}}\right]^{1/2}$. $\varepsilon_{sm} > \varepsilon_{nm} > 0.$
- Exponential factor: $e^{-\Delta F/T} = (2\nu/\pi)^{1/2}(I/I_c)^{\nu}$, $\nu = \varepsilon_0/T$,
- Near critical current exponential dependence: $(I/I_c)^{\nu} \approx \exp[\nu(I/I_c - 1)]$.
- Estimate for fluctuation factor (numerical calculations are in progress):



$$\left[\varepsilon_{n2}\varepsilon_{n3}\prod_{m=4}\frac{\varepsilon_{nm}}{\varepsilon_{sm}}\right]^{1/2} \propto \exp\left(-\frac{rw^2}{\xi^2}\right), \quad r(I) = \ ?$$

- 1D: fluctuation factor is of order unity $w \approx \xi$.
- Strip: fluctuation factor diminishes strongly dissipation rate.