

Кинетика сверхпроводящего состояния.

Критических ток узкого сверхпроводящего канала. Ток распаривания.



$$d; w \ll l_L; x \text{ } \rho = 0; |Y| = \text{const.}$$

Второе уравнение Гинзбурга–Ландау

$$j = (q/m)|Y|^2(\hbar \tilde{N}j - qA) = q|Y|^2 v_s = I/dw; Y = |Y| \exp(ij(r))$$

Первое уравнение Гинзбурга–Ландау

$$a(T)Y + b|Y|^3 Y + Y(\hbar \tilde{N}j - qA)^2/2m = (a(T) + mv_s^2/2)Y + b|Y|^3 Y = 0$$

$$|Y|^2 = -a/b(1 - mv_s^2/2|a|) = |Y|_{v=0}^2 [1 - (xmv_s/\hbar)^2]; x^2 = \hbar^2/2m|a|$$

$$j = q|Y|^2 v_s = q|Y|_{v=0}^2 [1 - (v_s x m/\hbar)^2] v_s$$

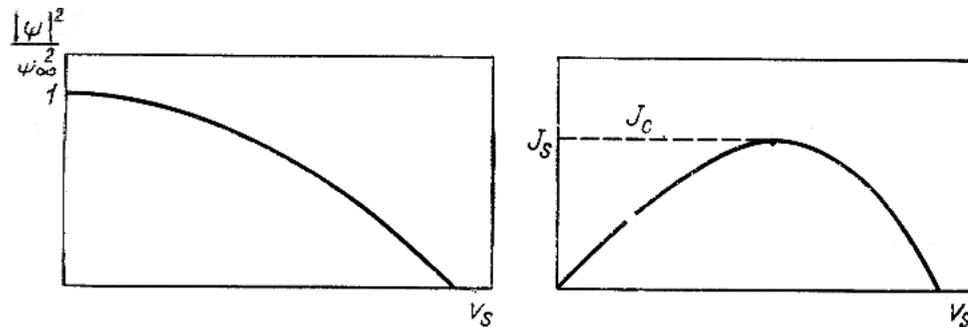


Рис. 4.3. Зависимость величин $|\psi|^2$ и J_s от скорости сверхтекучей компоненты v_s

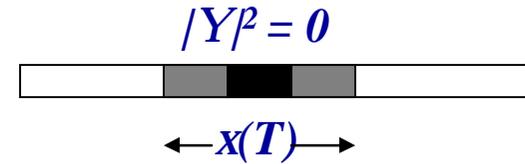
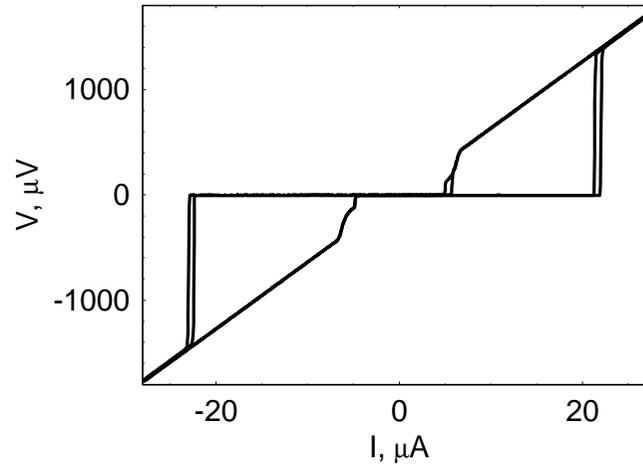
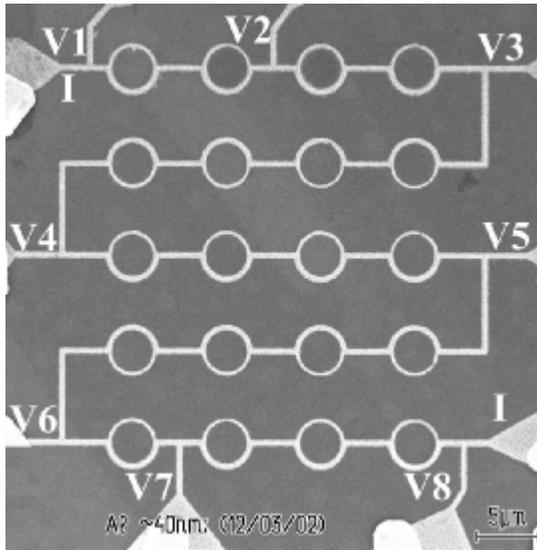
$$dj/dv_s = q|Y|_{v=0}^2 [1 - 3(v_s x m/\hbar)^2] = 0$$

$$\Rightarrow v_c = \hbar/\sqrt{3} m x(T) \mu (1 - T/T_c)^{1/2};$$

$$|Y|_{v=v_c}^2 = (2/3)|Y|_{v=0}^2 \mu (1 - T/T_c);$$

$$J_c = q(2/3)|Y|_{v=0}^2 (\hbar/\sqrt{3} m x) =$$

$$H_c/3\sqrt{6} \rho l_L \mu (1 - T/T_c)^{3/2}$$

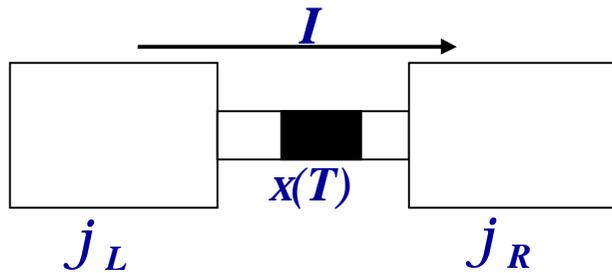


$$v_s = I/q|Y|^2 dw > v_c = \hbar/\sqrt{3}m x$$

$$f_{GL} = (a + mv_s^2/2)|Y|^2 + 0.5b|Y|^4$$

$$(a + mv_s^2/2)|Y|^2 = -|a||Y|^2 + mI^2/q^2s^2|Y|^2; s = dw$$

Центры проскальзывания фазы.



$$\hbar \tilde{N} j = mv + qA$$

$$\hbar d\tilde{N}j/dt = mdv/dt - qE$$

$$E = -dA/dt = -\tilde{N}V$$

$$I = I_s + I_n = I_s + s\Gamma_n E$$

$$Y_L = |Y| \exp(ij_L); Y_R = |Y| \exp(ij_R); Dj(t) = j_L - j_R$$

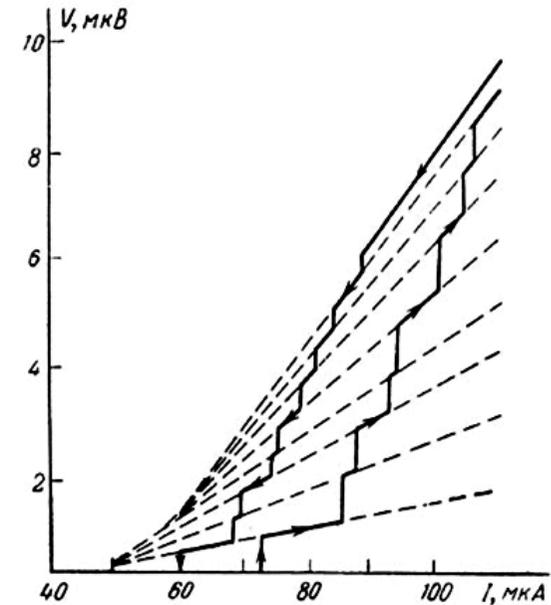
$$\tilde{N}(\hbar dj/dt - qV) = mdv/dt; Y = |Y| \exp(ij) = |Y| \exp(ij + i2pn)$$

$$\langle dv/dt \rangle_t = 0 \text{ P } \langle \tilde{N}(\hbar dj/dt - qV) \rangle = 0, \text{ но } \langle \tilde{N}V \rangle \neq 0$$

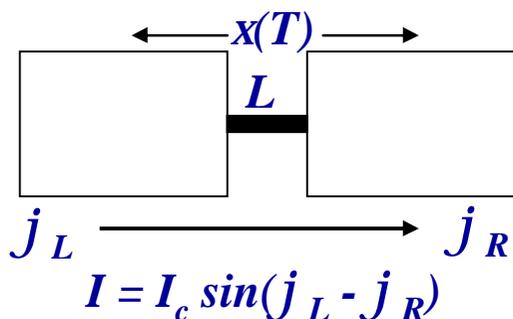
Р. Фейнман, Р. Лейтон, М. Сэндс, Фейнмановские лекции по физике. Изд. «Мир» М. 1977, том 6 Электродинамика, Глава 27, пар. 2.

Сохранение энергии и электромагнитное поле.

Пар. 5, «сумасшедшая» теория.



Эффекты Джозефсона



Л.Г. Асламазов, А.И. Ларкин, *ЖЭТФ* **48**, 976 (1965)

$$aY + b/Y^3 Y + (-i\hbar\tilde{N} - qA)^2 Y/2m = 0$$

$$Y = (|a|/b)^{1/2} y = n_s^{1/2} y; A = 0 \quad \tilde{P} \cdot y + y/|y|^2 \cdot x^2 \tilde{N}^2 y = 0$$

$$x^2 \tilde{N}^2 y \gg y x^2/L^2 \gg y \tilde{P} \tilde{N}^2 y \gg 0$$

$$y = \exp(ij_L)f(r) + \exp(ij_R)(1-f(r))$$

$$j = n_s(-iq\hbar/2m)(y^* \tilde{N} y - y \tilde{N} y^*) = n_s (q\hbar/2m) \text{Im}(y^* \tilde{N} y)$$

$$Y_L = n_{sL}^{1/2} \exp(ij_L) \quad Y_R = n_{sR}^{1/2} \exp(ij_R)$$

$$i\hbar \frac{d\Psi_L}{dt} = U_L \Psi_L + K\Psi_R \quad i\hbar \frac{d\Psi_R}{dt} = U_R \Psi_R + K\Psi_L \quad \begin{matrix} U_L = -qV/2; \\ U_R = qV/2 \end{matrix}$$

$$\frac{dn_{sL}}{dt} = \frac{2}{\hbar} K \sqrt{n_{sL} n_{sR}} \sin(j_L - j_R) \quad \frac{dn_{sR}}{dt} = -\frac{2}{\hbar} K \sqrt{n_{sL} n_{sR}} \sin(j_L - j_R) \quad I = dn_{sL}/dt = I_c \sin(j_L - j_R)$$

$$\frac{dj_L}{dt} = \frac{K}{\hbar} \sqrt{\frac{n_{sR}}{n_{sL}}} \cos(j_L - j_R) + \frac{qV}{2\hbar} \quad \frac{dj_R}{dt} = \frac{K}{\hbar} \sqrt{\frac{n_{sL}}{n_{sR}}} \cos(j_L - j_R) - \frac{qV}{2\hbar} \quad d(j_L - j_R)/dt = dDj/dt = qV/\hbar$$

$$I = I_c \sin(tqV/\hbar) \quad \langle I \rangle = 0$$

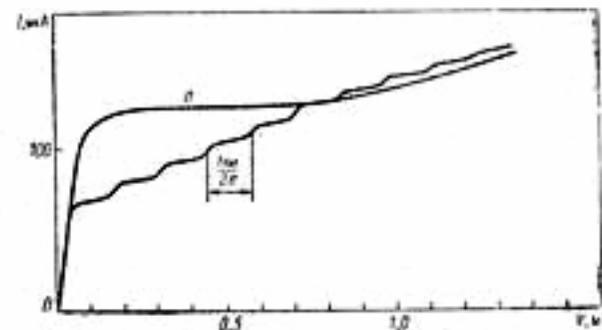
$$V = V_0 + v \cos(\omega t) \quad \tilde{P} \quad Dj(t) = tqV_0/\hbar + (qV_0/\hbar \omega) \sin(\omega t)$$

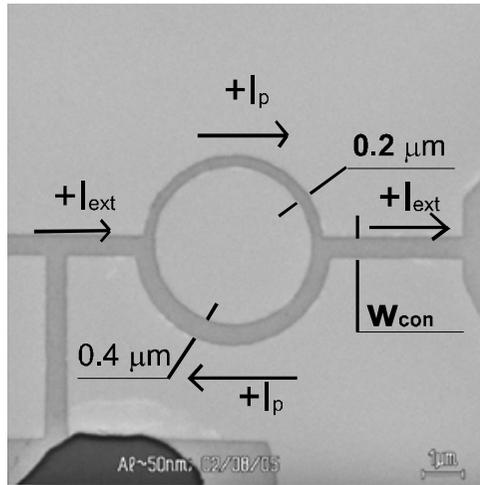
$$\sin Dj(t) \gg \sin(tqV_0/\hbar) + (qV_0/\hbar \omega) \sin(\omega t) \cos(tqV_0/\hbar)$$

$$I \gg I_c [\sin(tqV_0/\hbar) + (qV_0/\hbar \omega) \sin(\omega t) \cos(tqV_0/\hbar)]$$

$$\langle I \rangle \neq 0 \quad \text{при } \omega = qV_0/\hbar$$

S.Shapiro, *Phys.Rev.Lett.* **11**, 80 (1963)





$$\oint l dv = \frac{2ph}{m} \left(n - \frac{\Phi}{\Phi_0} \right)$$

$$l_n v_{sn} - l_w v_{sw} = l(v_{sn} - v_{sw})/2 = (2ph/m)(n - F/F_0)$$

$$I_{ext} = I_n + I_w = s_n j_n + s_w j_w = 2en_s(s_n v_{sn} + s_w v_{sw})$$

$$v_{sn} = I_{ext}/2en_s(s_n + s_w) + (2h/mr)s_w/(s_n + s_w) (n - F/F_0)$$

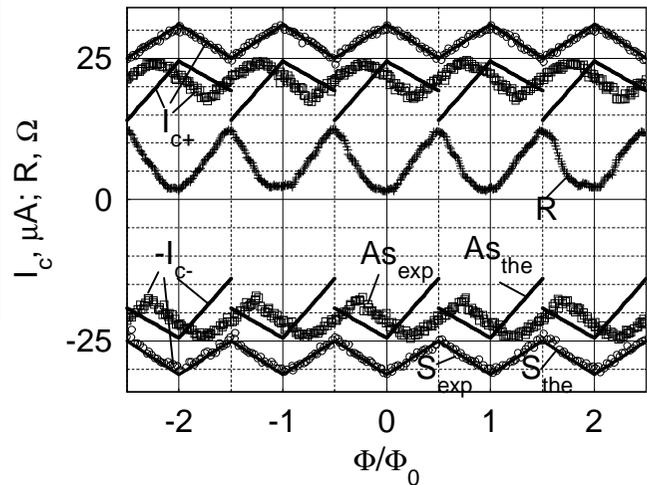
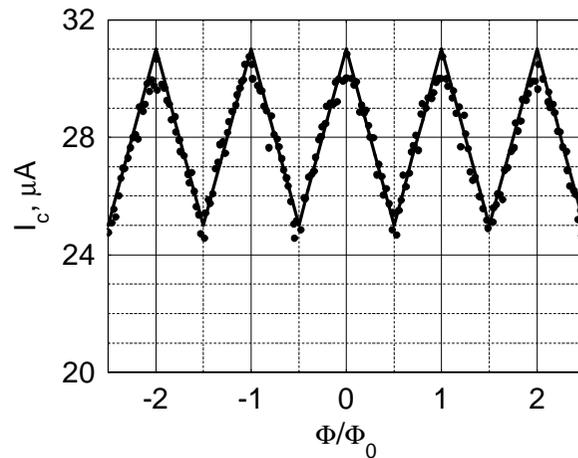
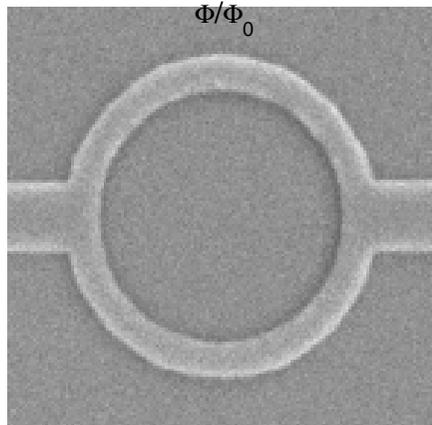
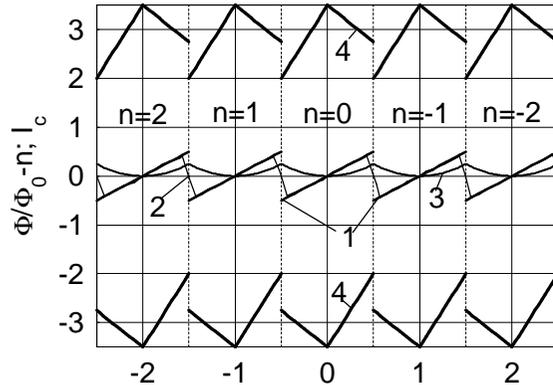
$$v_{sw} = I_{ext}/2en_s(s_n + s_w) - (2h/mr)s_n/(s_n + s_w)(n - F/F_0)$$

$$|v_{sn}| = v_{sc}$$

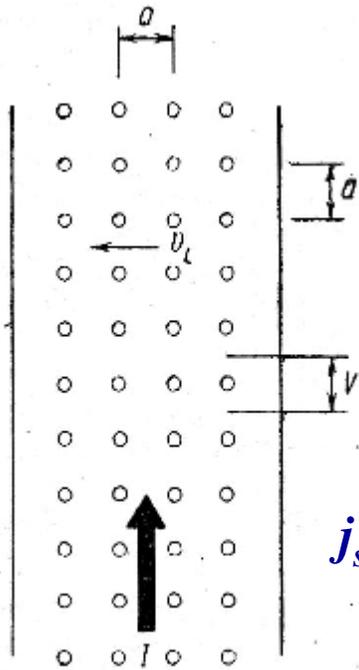
$$I_{c+}, I_{c-} = I_{c0} - 2I_{p,A} \left| n - \frac{\Phi}{\Phi_0} \right| \left(1 + \frac{s_w}{s_n} \right)$$

$$|v_{sw}| = v_{sc}$$

$$I_{c+}, I_{c-} = I_{c0} - 2I_{p,A} \left| n - \frac{\Phi}{\Phi_0} \right| \left(1 + \frac{s_n}{s_w} \right)$$



Сопротивление «течения потока» в состоянии Абрикосова.



$$F_L = j \times B$$

$$f_L = j \times F_0 = hv_L$$

$$E = B \times v_L$$

$$r_f = BF_0/h$$

$$E = jr_f$$

A

$$j = (H_{ext} - H_{in})/w$$

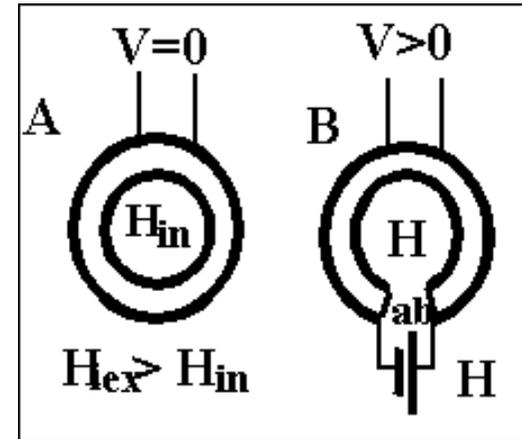
$$dH_{in}/dt = pr_{in}v_L F_0$$

$$V = 0$$

B

$$dH_{in}/dt = 0$$

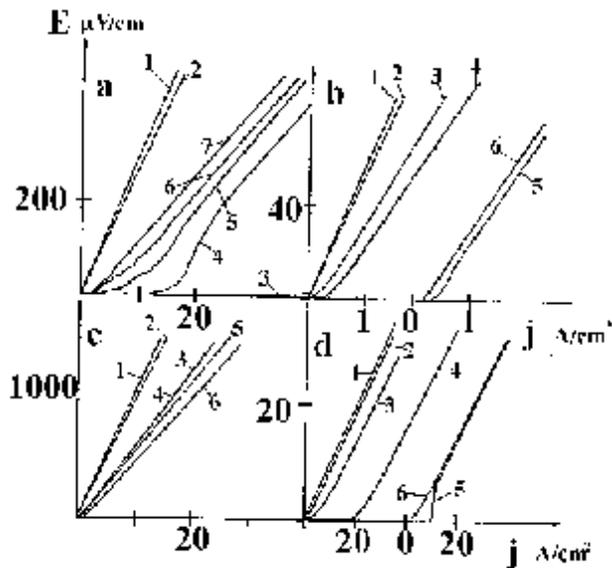
$$V \neq 0$$



$$j_s = (q/m)/Y^2 (\hbar \tilde{N} j - qA) \oint dl l^2 j_s = \frac{\Phi_0}{2p} \oint dl \nabla j - \Phi = \frac{\Phi_0}{2p} 2pn - \Phi = 0$$

A $\langle dj_s/dt \rangle = 0$ так как $d(nF_0 - F)/dt = 0$

B $\langle dj_s/dt \rangle = 0$ так как $(\hbar \langle dj/dt \rangle - qV) = 0$

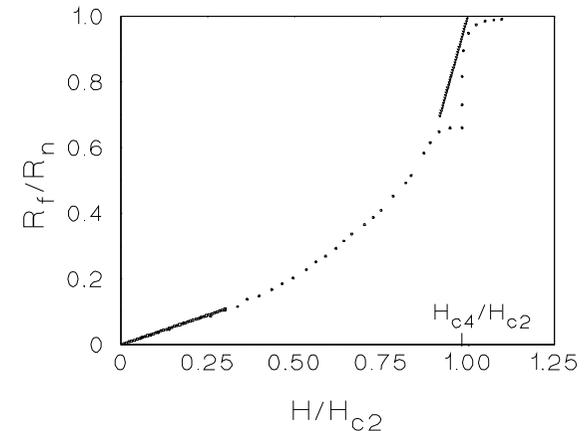


$$\frac{r_f}{r_n} = g \left(1 - \frac{H}{H_{c2}}\right)$$

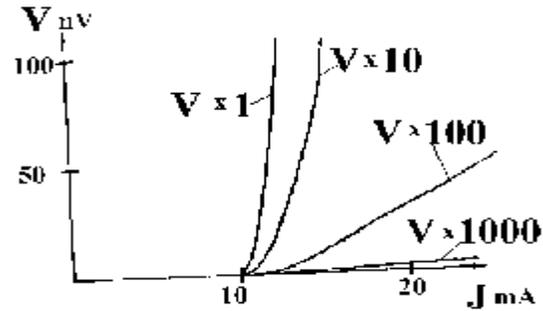
$$\frac{r_f}{r_n} = c \frac{H}{H_{c2}}$$

Л.П. Горьков, Н.Б. Копнин

УФН 116, 413 (1975)

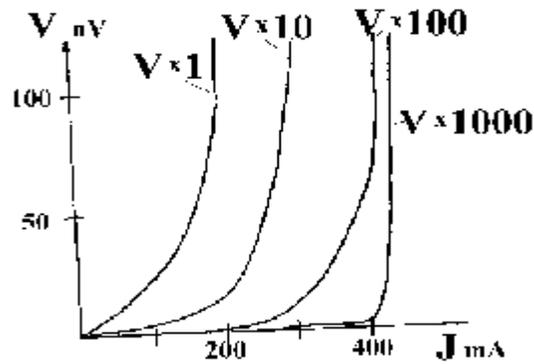
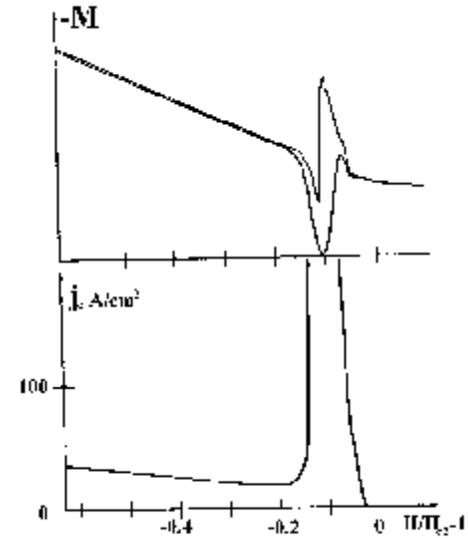


Пиннинг вихрей и крип вихрей.



$$f_L = j \cdot F_0 = f_p + hv_L$$

$$E = (j - j_c) r_f$$



$$E(j) = E_0 \sinh\left(\frac{j}{j_0}\right)$$

$$E_0 = r_p j_p \exp(-U/k_B T); j_0 = j_p k_B T / U$$

