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SMR/481 - 3

EXPERIMENTAL WORKSHOP ON
HIGH TEMPERATURE SUPERCONDUCTORS AND RELATED MATERIALS
(ADVANCED ACTIVITIES)

(26 November - 14 December 1990)

" Granularity Effects in the High-T_C Superconducting Oxides "

presented by:

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Granularity Effects in the High-Tc
Superconducting Oxides

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OUTLINE

1. Introduction
2. Weak versus strong intergranular coupling?
3. Intergranular (Josephson) penetration depth
4. Intergranular vortices
5. Intergranular critical currents and critical state
6. Thermal disruption of intergranular phase-locking
7. Intergranular reversibility line
8. Summary

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Granularity Effects in the High-Tc Superconducting Oxides

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Reference:

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"Granular and Superconducting Properties of the High-Temperature Superconductors"
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HIGH T_C UPDATE

VOL. 4, NO. 23
DEC. 1, 1990

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NOTA BENE: We wish to acknowledge two major contributions to *High-T_C Update:* \$5,000 from the Applied Superconductivity Conference, Inc., and \$15,000 from the Air Force Office of Scientific Research. There is still room on the masthead (directly above) for a donor who will give at least \$25,000 to support the newsletter. If you would rather pay for a subscription than make a donation, that also can be arranged. Please contact the editor.

Tl-Sr-V-O

Experimental attempts to confirm the possibility of superconductivity in the *V-Sr-Tl-O* system are reported in a preprint by LIU Zhiyi et al. (Beijing). Their results show some interesting anomalies but do not provide any convincing evidence for superconductivity. A mixture of V_2O_5, $SrCO_3$, and Tl_2O_3 was prepared with nominal atomic ratios $V:Sr:Tl = 1:1:0.2$, sintered at 850-900°C for 5-8 h in an H_2-Ar atmosphere, and cooled in the furnace. The product then was ground, pressed into pellets, and sintered at 900-940°C [illegible] 10-25 h in an H_2 atmosphere.

Three samples showed phenomena similar to those reported by S.-P. Matsuda et al. (Hitachi) (see the Oct. 1 and 15 *High-T_C Updates* for technical details). One of the samples, for example, had a resistivity at 165 K of about 9.7×10^{-4} Ωcm, which decreased sharply with decreasing temperature to 2×10^{-5} Ωcm at 135 K. Below 135 K the resistivity slowly decreased with decreasing temperature to a nearly constant value of 5×10^{-6} Ωcm at around 57 K.

Measurements of the ac susceptibility of this sample taken a day later showed the appearance of a diamagnetic response at 135 K as the temperature decreased. A small anomaly in both the real and the imaginary parts of the susceptibility also occurred around 165 K. Two days later, however, resistivity measurements no longer showed the sharp drop in resistance with decreasing temperature, and semiconducting behavior was observed. The diamagnetic signal also disappeared, and an antiferromagnetic transition was found at 85 K.

Vortex Chains

Experiments by C. A. Bolle (AT&T Bell Labs) et al. using magnetic decoration of the flux lattices in high-quality single crystals of $Bi_2Sr_2CaCu_2O_8$ have revealed parallel vortex chains when the magnetic field is applied at an angle relative to the c axis. The chains consist of single rows of vortices parallel to the plane containing the c axis and the applied magnetic field direction. The observation is consistent with the prediction by A. M. Grishin et al. [*Zh. Exp. Teor. Fiz.* 97, 1930 (1990)] that such chains should occur because of an attractive interaction between tilted vortices roughly a penetration depth apart.

Closely related theoretical work also has been done by A. Buzdin and A. Simonov, *JETP Lett.* 51, 191 (1990) and V. G. Kogan et al., *Phys. Rev. B* 42, 2631 (1990). The experiments, however455y, also observe something that is not predicted by the theory: a background of hexagonal vortex lattice filling the regions between the vortex chains.

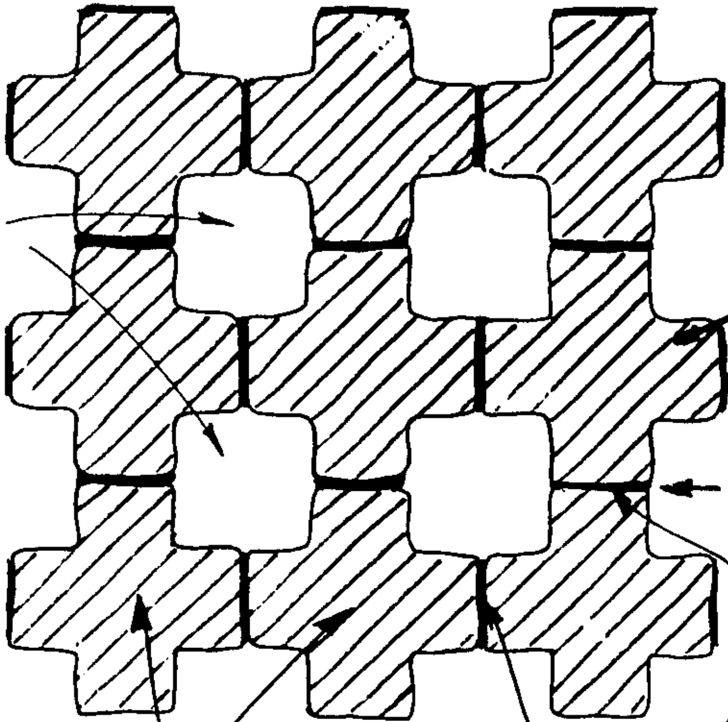
Phonons in $Nd_{1.85}Ce_{0.15}CuO_4$

Measurements of the generalized phonon density of states in superconducting $Nd_{1.85}Ce_{0.15}CuO_4$ by inelastic neutron scattering are reported in a preprint by J. W. Lynn et al. (Maryland and NIST). Maxima are found in the density of states at energies of 13, 51, and 65 meV. There is reasonable agreement at low energies between these experiments and the results of Q. Huang et al. [*Nature* 347, 369 (1990)] from point-contact tunneling measurements,

J. G. Bednorz and K. A. Müller, Z. Phys. 64, 189 (1986):

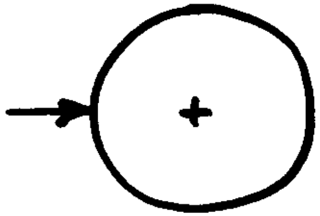
- THE HIGH-T_c SUPERCONDUCTORS ARE GRANULAR.
- TO UNDERSTAND THEIR ELECTROMAGNETIC BEHAVIOR, IT IS USEFUL TO THINK OF THEM AS ARRAYS OF JOSEPHSON-COUPLED SUPERCONDUCTING GRAINS.

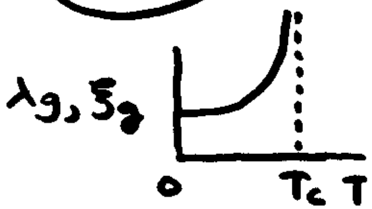
THEORIST'S MODEL FOR TYPICAL HIGH-T_c MATERIAL (~80% DENSE)



INTRAGRANULAR PROPERTIES (g)

	Representative Values
T_c	$T_c \sim 90\ \mathrm{K}$
R_g	$R_g \sim 1\,\mu m$
λ_g	$\lambda_g(0) \sim 0.2\,\mu m$
ξ_g	$\xi_g(0) \sim 20\,\mathring{A}$
	$\kappa = \dfrac{\lambda_g}{\xi_g} \sim 10^2$





Anisotropy ($\lambda_i = \lambda\sqrt{m_i}$, $\xi_i = \xi/\sqrt{m_i}$; $i = a, b, c$) is ignored here

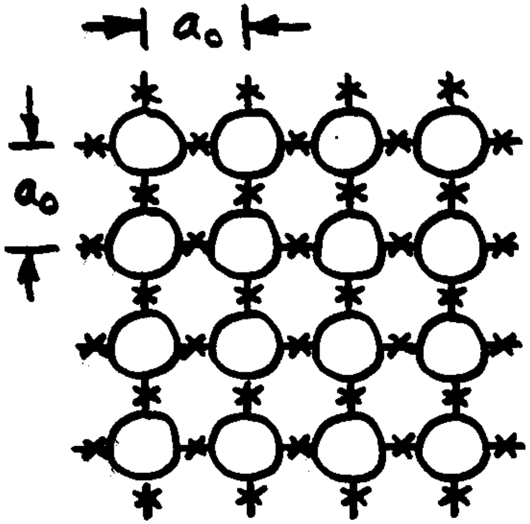
$$H_{c1g} \approx \frac{\phi_0}{4\pi\lambda_g^2}\left[\ln\left(\frac{\lambda_g}{\xi_g}\right) + 0.50\right] \qquad H_{c1g}(0) \sim 10^2\ \mathrm{Oe}$$

$$H_{cg} = \frac{\phi_0}{2\pi\sqrt{2}\,\lambda_g\xi_g} \qquad H_{cg}(0) \sim 10^4\ \mathrm{Oe}$$

$$H_{c2g} = \frac{\phi_0}{2\pi\xi_g^2} \qquad H_{c2g}(0) \sim 10^6\ \mathrm{Oe}$$

$J_{cg}(B,T)$ — $J_{cg}(0,0) \sim 10^7\ \mathrm{A/cm^2}$

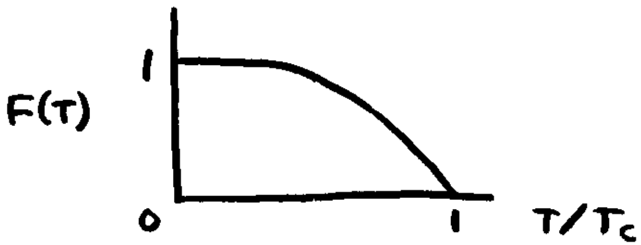
ARRAY OF JOSEPHSON-COUPLED SUPERCONDUCTING GRAINS



$$J_0 = \frac{I_0}{a_0^2}$$

$$I = I_0(T)\sin\phi \qquad I_0(0) = \frac{\pi\Delta(0)}{eR_n}$$

$$\frac{I_0(T)}{I_0(0)} = F(T) = \frac{\Delta(T)}{\Delta(0)}\tanh\left[\frac{\Delta(T)}{2k_BT}\right] \; *$$



* V. Ambegaokar and A. Baratoff, PRL 10, 486 (1963); E 11, 104 (1963)

GINZBURG-LANDAU THEORY FOR CRITICAL-CURRENT DENSITY OF THIN FILMS*†

For fixed current I, the Gibbs free energy per grain is:

$$\boxed{\Delta G = E_s(-2f^2 + f^4) + E_J f^2(1-\cos\phi) - \frac{\hbar}{2e} I\phi}$$

(tilted washboard potential)

$$\boxed{I = I_0 f^2 \sin\phi}$$

Minimize ΔG with respect to f^2 for fixed I and ϕ, then maximize I with respect to ϕ to obtain I_c or $J_c = I_c/a_0^2$.

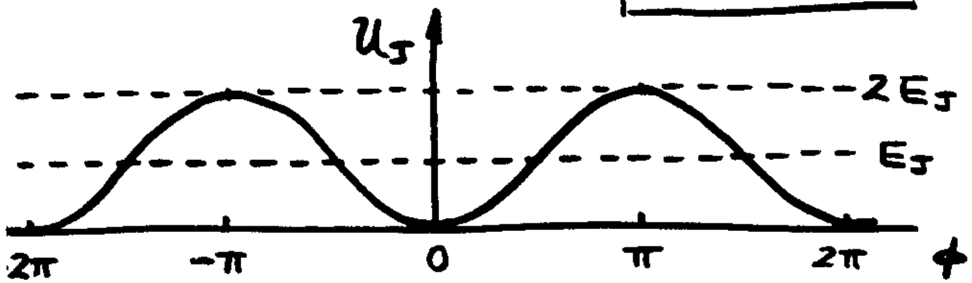
† G. Deutscher, Revue de Physique Appliquée 8, 127 (1973)

* J.R. Clem, B. Bumble, S.I. Raider, W.J. Gallagher, and Y. C. Shih, Phys. Rev. B 35, 6637 (1987)
[See also G. Deutscher, Y. Imry, and L. Gunther, Phys. Rev. B 10, 4598 (1974).]

JOSEPHSON COUPLING ENERGY

$$\mathcal{U}_J = E_J(1-\cos\phi)$$

$$\boxed{E_J = \frac{\hbar}{2e} I_0}$$



INTRAGRANULAR CONDENSATION ENERGY

$$\boxed{E_s = \frac{H_{cg}^2}{8\pi} V_g}$$

H_{cg} = intragranular bulk thermodynamic critical field

V_g = volume of a grain

THE IMPORTANT DIMENSIONLESS PARAMETER IS:

$$\boxed{\varepsilon = \frac{E_J}{2E_s}}$$

J. R. Clem et a
PRB 35, 6637
(1987)

$E_J = \frac{\hbar}{2e} I_0(T)$ = Josephson coupling energy of a junction

$E_s = \frac{H_{cg}^2(T)}{8\pi} V_g$ = Superconducting condensation energy of a grain

ε	Behavior
$\varepsilon \ll 1$	Like weakly Josephson-coupled superconducting grains: AB-like
$\varepsilon \gg 1$	Like a monolithic "dirty" superconductor with $\rho_n = R_n a_0$: GL-like

NbN $\varepsilon(0) = 0.16$, $\varepsilon(T_x) = 1$, $\varepsilon(T_c) = \infty$

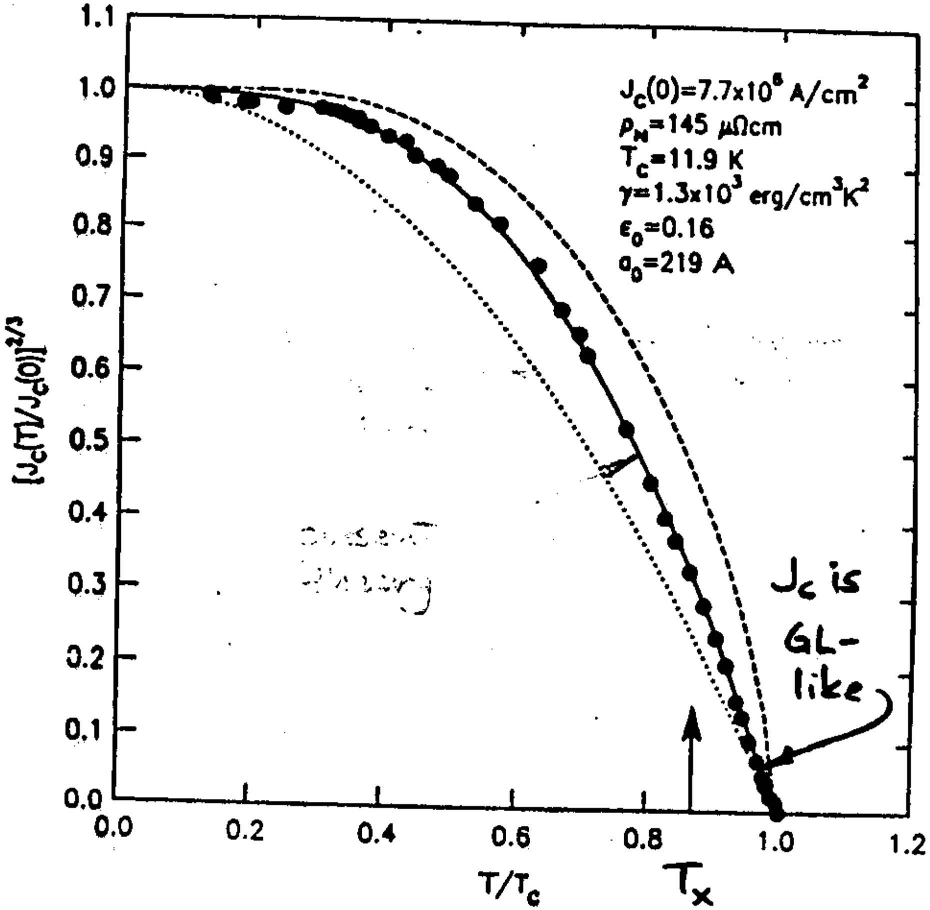


FIG. 3. $[J_c(T)/J_c(0)]^{2/3}$ versus T/T_c. Solid points: experimental data for a 225 Å NbN film; solid curve: theoretical curve calculated as described in the text; dashed curve: Ambegaokar-Baratoff critical current density [Ref. 14 and Eq. (1)]; dotted curve: Bardeen's [Ref. 36] expression, $[J_c(T)/J_c(0)]^{2/3} = 1 - (T/T_c)^2$, which approximates numerical calculations [Refs. 37-39] extending the Ginzburg-Landau theory to lower temperatures. The vertical arrow indicates the crossover temperature T_x.

VORTEX STATE FOR $T \approx T_c$ AND SMALL, STRONGLY-COUPLED GRAINS

$$\varepsilon = \frac{E_J}{2E_s} = \frac{2\xi_J^2(T)}{a_0^2} \gg 1$$

$$H_{c1J} \approx \frac{\phi_0}{4\pi\lambda_J^2}\left[\ln\left(\frac{\lambda_J}{\xi_J}\right) + 0.50\right]$$

$$H_{c2J} = \frac{\phi_0}{2\pi\xi_J^2}$$

A vortex has a core (of suppressed order parameter) of radius $\xi_J \gg a_0$.

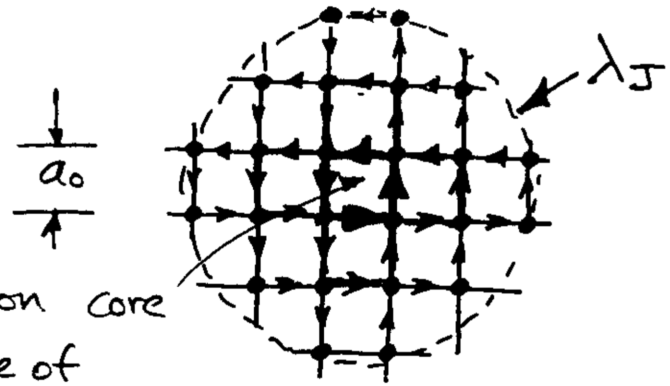
Good example: granular Al $(\varepsilon \sim 10^{3})$

- If the "grains" are aligned, or if their coupling is anisotropic, such an anisotropic Josephson-coupled-grain model can form the basis for an anisotropic Ginzburg-Landau theory, so long as $\xi_{Ji} \gg a_i$.

TYPICAL VALUES OF $\varepsilon(T=0)$ FOR VARIOUS GRANULAR SUPERCONDUCTORS

Material	$\varepsilon(T=0)$	
Al	10^2	GL-like
NbN	10^{-1}	Crossover at T
$YBa_2Cu_3O_7$	10^{-10}	AB-like

WEAKLY COUPLED GRAINS $\Rightarrow$ JOSEPHSON VORTEX



Josephson core

(No core of suppressed order parameter at center)

$$\varepsilon = \frac{E_J}{2E_S} = \frac{2\,\xi_J^2(T)}{a_0^2} \ll 1$$

$$H_{c1J} \approx \frac{\phi_0}{4\pi\lambda_J^2}\ln\left(\frac{\lambda_J}{a_0/2}\right) \sim 1\,\text{Oe} \,!$$

BUT

$$H_{c2} \neq \frac{\phi_0}{2\pi\xi_J^2} \quad \text{when } \xi_J < a_0 \,!$$

INSTEAD, THE UPPER CRITICAL FIELD IS THE H_{c2} OF AN INDIVIDUAL GRAIN.

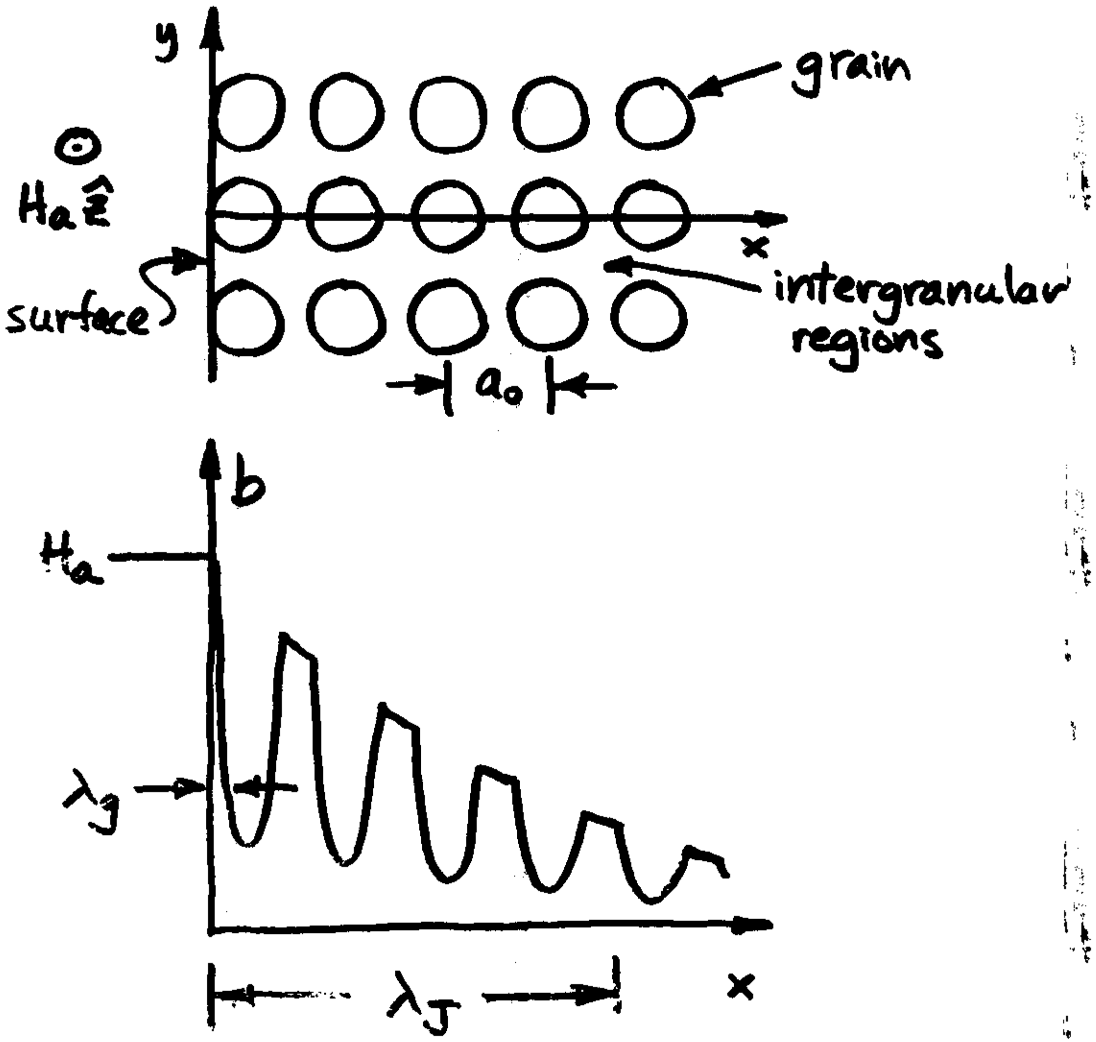
CONCLUSIONS

In the high-temperature superconductors, the intergranular Josephson coupling energy (E_J) is so weak, relative to the intragranular condensation energy (E_s) that intergranular supercurrents do not suppress the intragranular order parameter (Δ or Ψ):

1. The critical-current density J_c remains Ambegaokar-Baratoff-like.
2. Intergranular vortices have no core of suppressed order parameter.
3. Although λ_J remains meaningful, ξ_J is irrelevant.

INTERGRANULAR PENETRATION DEPTH λ_J

Assume phase-locking, $T < T_{cJ}$



INTERGRANULAR PENETRATION DEPTH λ_J

$$\boxed{\lambda_J(T) = \left[\frac{c\phi_0}{8\pi^2 a_0 J_0(T)\mu_{eff}(T)}\right]^{\frac{1}{2}}}$$

when $\lambda_J(T) > a_0$. $(B = \mu_{eff} H)$

Representative values for high-temperature superconductors:

If $\quad f_n \approx \mu_{eff} \approx 0.3$

$\qquad I_0 \approx 100\ \mu A$

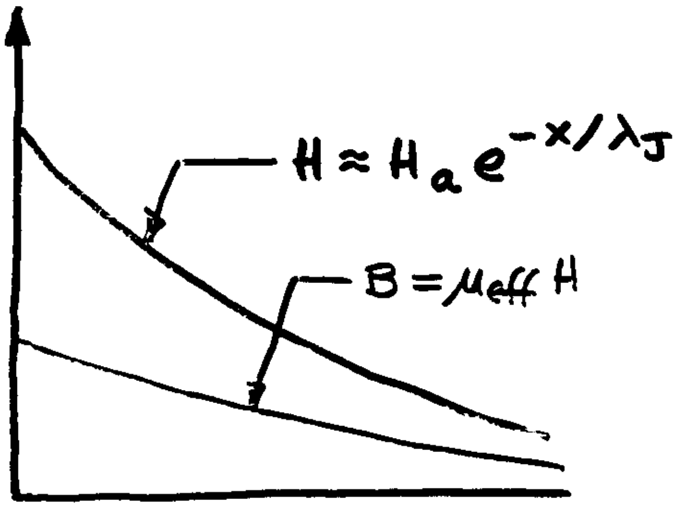
$\qquad a_0 \approx 1\ \mu m$

$\qquad J_c \approx 10^4\ A/cm^2$

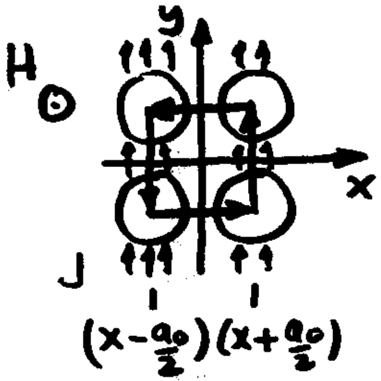
then

$\qquad \lambda_J \approx 3\ \mu m$

[J. R. Clem, Physica C 153-155, 50 (1988)]



DERIVATION OF INTERGRANULAR PENETRATION DEPTH λ_J



As in a SQUID,

$$\oint_C \vec{a}\cdot d\vec{l} = \mu_{eff} H a_0^2$$

$$\approx \frac{\phi_0}{2\pi}\left[\Delta\gamma(x+\tfrac{a_0}{2}) - \Delta\gamma(x-\tfrac{a_0}{2})\right]$$

$$J_y(x\pm\tfrac{a_0}{2}) = J_0 \sin\Delta\gamma(x\pm\tfrac{a_0}{2}) \approx J_0\Delta\gamma(x\pm\tfrac{a_0}{2})$$

$$\Rightarrow \quad \frac{dJ_y}{dx} = -\frac{2\pi a_0 J_0 \mu_{eff}}{\phi_0} H$$

$$+ \text{ Ampere's law}, \quad \frac{dH}{dx} = -\frac{4\pi}{c} J$$

$$\Rightarrow \boxed{\frac{d^2H}{dx^2} = \frac{H}{\lambda_J^2}} \quad \boxed{\lambda_J = \left(\frac{c\phi_0}{8\pi^2 a_0 J_0 \mu_{eff}}\right)^{1/2}}$$

Representative values:

$f_n \approx \mu_{eff} \approx 0.3$, $I_c \approx 100\,\mu A$, $a_0 \approx 1\,\mu m$,
$J_0 \approx 10^4\,A/cm^2 \Rightarrow \lambda_J \approx 3.0\,\mu m$

H = INTERGRANULAR MAGNETIC FIELD

B = LOCALLY-AVERAGED MAGNETIC FLUX DENSITY

$$= \Phi(\text{inter})/a_0^2 + \Phi(\text{intra})/a_0^2$$

$$= \mu_{eff} H$$

$$\mu_{eff} = f_n + f_s\left[1 - P(R_g/\lambda_g)\right]$$

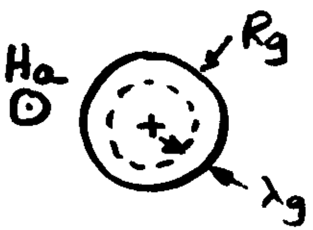
= effective temperature-dependent permeability

$P(R_g/\lambda_g)$ = factor by which penetration-depth effects suppress a grain's magnetization below that for complete Meissner flux exclusion

$P \approx 1, \quad \lambda_g \ll R_g \quad \Rightarrow \mu_{eff} \approx f_n$
$\approx 0.5, \quad \lambda_g \sim R_g/5$
$\ll 1, \quad \lambda_g \gtrsim R_g \quad \Rightarrow \mu_{eff} \approx 1$

MODELS FOR P

CYLINDRICAL GRAINS



$x = R_g/\lambda_g$

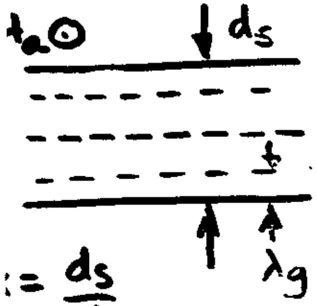
$$P_{cyl}(x) = 1 - \frac{2I_1(x)}{x I_0(x)}$$

$$\approx 1 - 2/x \quad , \quad x \gg 1$$

$$\approx 0.107 \quad , \quad x = 1$$

$$\approx x^2/8 \quad , \quad x \ll 1$$

SLAB-LIKE GRAINS



$x = \dfrac{d_s}{2\lambda_g}$

$$P_{slab} = 1 - \frac{\tanh x}{x}$$

$$\approx 1 - 1/x \quad , \quad x \gg 1$$

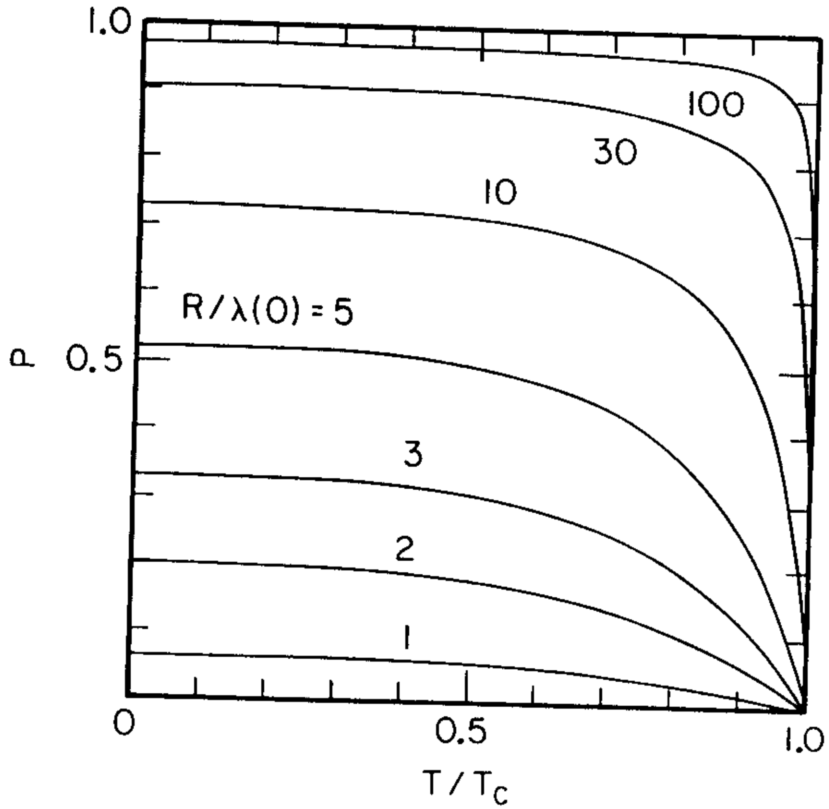
$$\approx 0.238 \quad , \quad x = 1$$

$$\approx x^2/3 \quad , \quad x \ll 1$$

DIRTY LIMIT:

$$\left[\frac{\lambda_g(0)}{\lambda_g(T)}\right]^2 = F(T) = \frac{\Delta(T)}{\Delta(0)} \tanh\left[\frac{\Delta(T)}{2k_BT}\right]$$

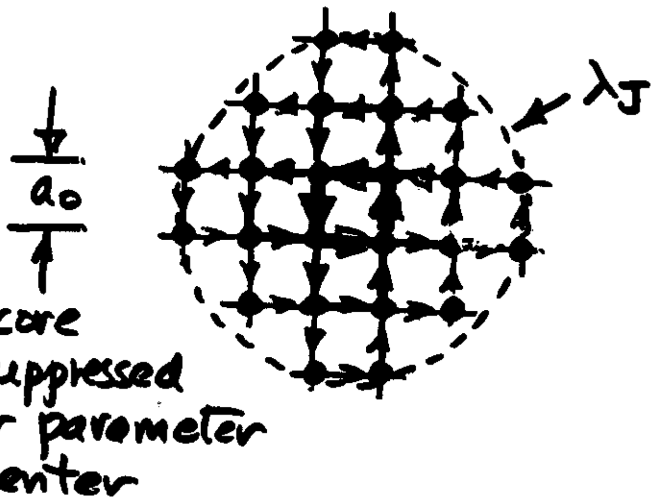
TEMPERATURE DEPENDENCE OF PENETRATION-DEPTH-EFFECT FACTOR P



SAMPLES OF DIMENSIONS $< \lambda(T)$ BECOME MAGNETICALLY INVISIBLE.

INTERGRANULAR VORTEX ENERGETICALLY FAVORED WHEN $H_a > H_{c1J}$

Intergranular vortex:



INTERGRANULAR LOWER CRITICAL FIELD

$$\boxed{H_{c1J} \approx \frac{\phi_0}{4\pi\lambda_J^2\mu_{eff}} \ln\left(\frac{2\lambda_J}{a_0}\right)}$$

$$\approx \frac{2\pi a_0 J_0}{c} \ln\left(\frac{2\lambda_J}{a_0}\right)$$

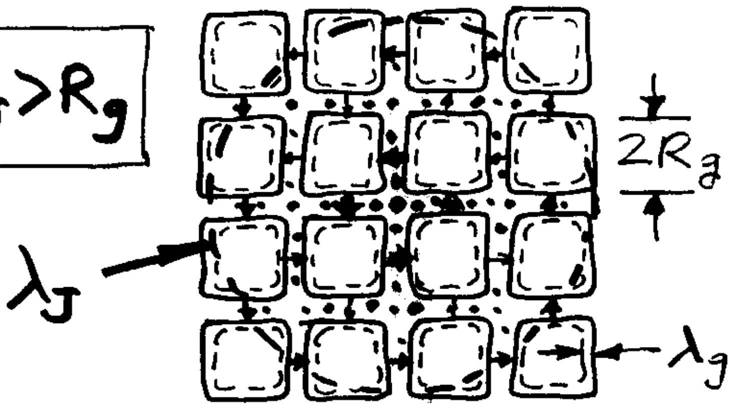
Representative values:

when $f_n \approx \mu_{eff} \approx 0.3$, $I_0 \approx 100\,\mu A$, $a_0 \approx 1\,\mu m$, $J_0 \approx 10^4\, A/cm^2$, $\lambda_J \approx 3.0\,\mu m$, $H_{c1J} \approx 1.1\,Oe$

INTERGRANULAR JOSEPHSON VORTICES

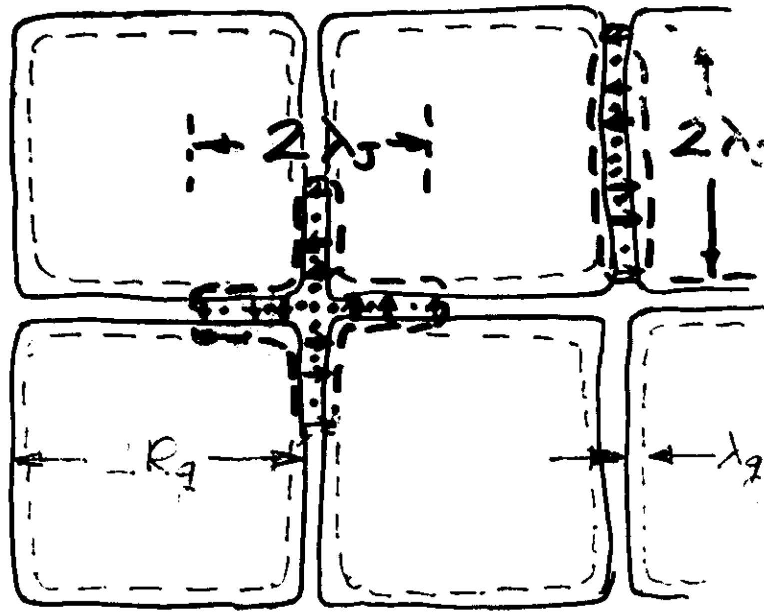
LOW-DENSITY SAMPLES, WEAK JOSEPHSON COUPLIN

$\boxed{\lambda_J > R_g}$



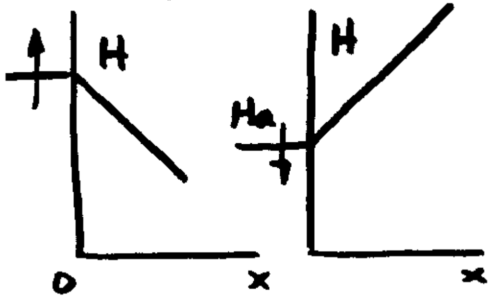
HIGH-DENSITY SAMPLES, STRONGER JOSEPHSON COUPLI

$\boxed{\lambda_J < R_g}$



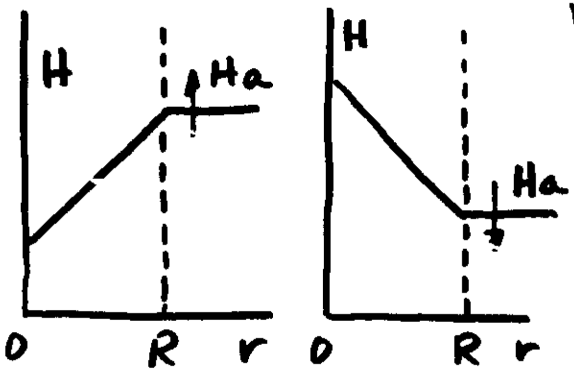
NTERGRANULAR CRITICAL STATE HEN $H_a > H_{cJ}$ AND $T < T_{cJ}(H)$

lanar geometry



$$\boxed{\frac{dH}{dx} = \pm \frac{4\pi}{c} J_{cJ}(H,T)}$$

ylindrical geometry



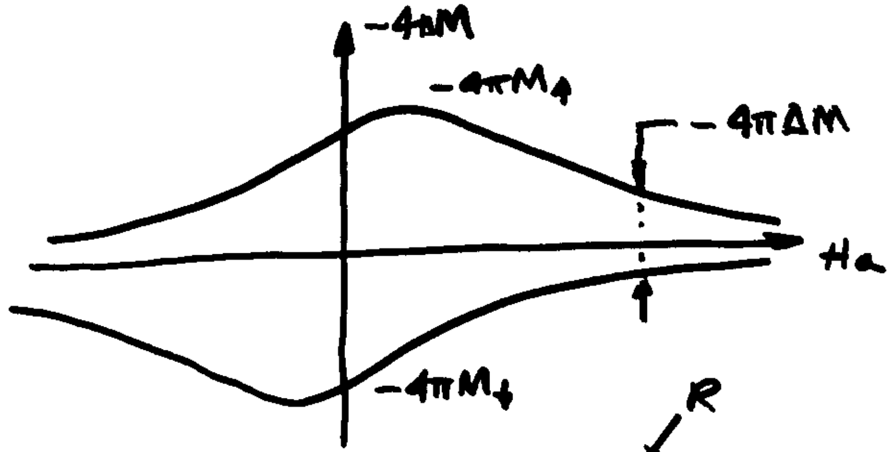
$$\boxed{\frac{dH}{dr} = \pm \frac{4\pi}{c} J_{cJ}(H,T)}$$

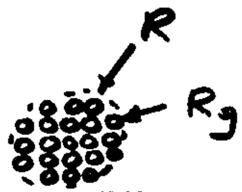
NTERGRANULAR (TRANSPORT) CRITICAL-URRENT DENSITY

$$J_{cJ}(H,T) < J_0(H,T) = J_0(T) \left\langle \left| \frac{\sin(\pi\Phi/\Phi_0)}{(\pi\Phi/\Phi_0)} \right| \right\rangle, \quad \Phi = HA$$

INTRAGRANULAR CRITICAL STATE WHEN $H > H_{c1g}$ GOVERNED BY $J_{cg}(B^{intra},T)$

Magnetization hysteresis loop for fixed T:



Cylindrical grain model 

gives

$$-4\pi\Delta M = \frac{8\pi J_{cJ} R}{3c} + f_s \frac{8\pi J_{cg} R_g}{3c}$$

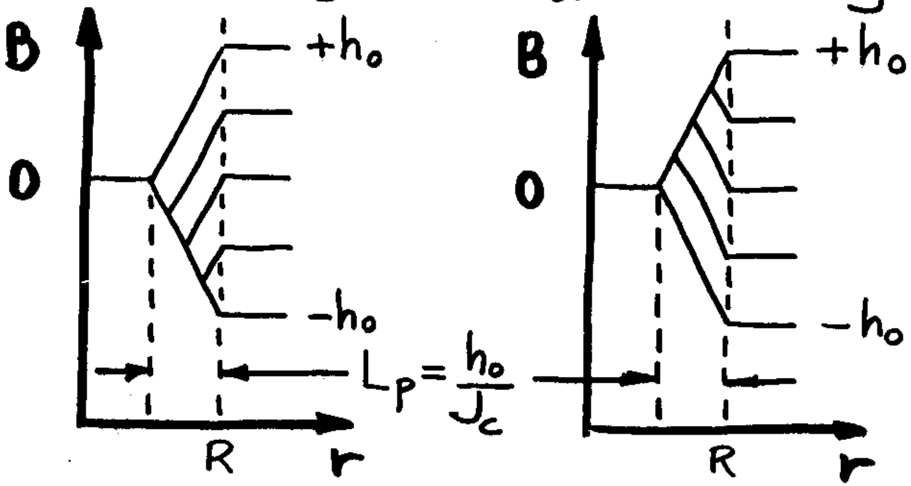
Usually, $J_{cg}R_g \gg J_{cJ}R$!

CONCLUSIONS:

1. ΔM measurements alone yield only an upper limit for J_{cJ}.
2. ΔM can be non-zero even when $J_{cJ} = 0$.

HYSTERETIC AC LOSSES

H_a increasing $\qquad$ H_a decreasing



Hysteretic loss per cycle per unit area $= W' \propto \oint B\, dH_a$

$W' \sim (\mu_0 h_0 L_p)\cdot h_0 \sim \mu_0 h_0^3/J_c$

CONVENTIONAL SUPERCONDUCTORS

$W' = 2\mu_0 h_0^3 / 3J_c$

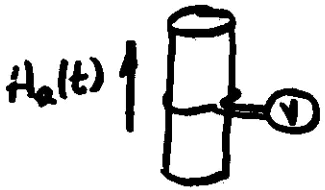
HIGH-T_c SUPERCONDUCTORS (small h_0)

$W' = 2\mu_0 h_0^3 \underline{f_n} / 3 J_{\underline{cJ}}$

Nonsuperconducting fraction f_n

Intergranular critical current density

AC PERMEABILITY (SUSCEPTIBILITY) PEAKS CAN GIVE J_{cg} AND J_{cJ} VERSUS H_0 AND T



$h(t) = h_0 e^{-i\omega t}$

$b_{ac} = \tilde{\mu}\, h(t)$

$\boxed{\tilde{\mu} = \mu' + i\mu''}$

$H_a(t) = H_0 + h(t)$

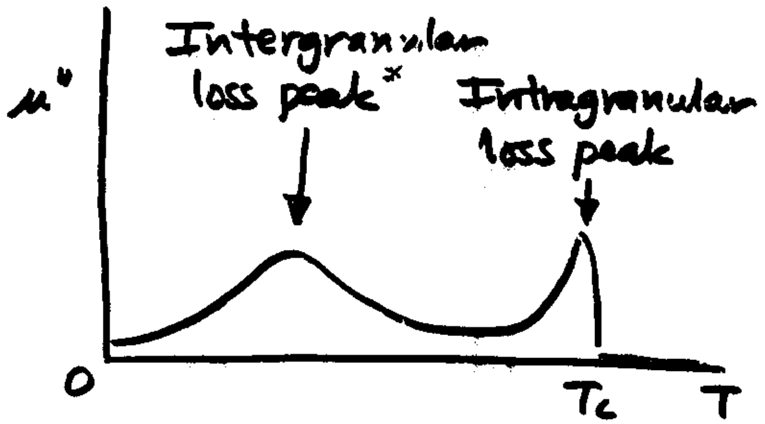
$(\mu' = 1 + 4\pi\chi', \ \mu'' = 4\pi\chi'')$

Poynting's theorem gives

$\boxed{\mu'' = 4W_v / b_0^2}$

W_v = loss per cycle per unit volume

Maximum in loss versus H_0 or $T \Leftrightarrow \mu''$ peak



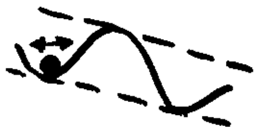
* B. Renker et al Z. Phys. B 67, 1 (1987)

* K.-H. Müller et al. Physica C 158, 69 (1989); 366 (1989)

DIMENSIONLESS RATIOS MEASURING RELATIVE DEPTH OF AC FIELD PENETRATION

$x_g = ch_0 / 4\pi J_{cg} R_g$ intragranular

$x_J = ch_0 / 4\pi J_{cJ} R$ intergranular



INTRAGRANULAR LOSS PEAK

Near T_c, $J_{cJ} \approx 0$, $x_J \gg 1$

$\mu''_{max} = 0.212 f_s$ occurs when $x_g = 1$

$J_{cg}(H_0, T_{peak}) = ch_0 / 4\pi R_g$

INTERGRANULAR LOSS PEAK

Well below T_c, J_{cg} is very large and $x_g \ll 1$

$\mu''_{max} = 0.212 f_n$ occurs when $x_J = 1$

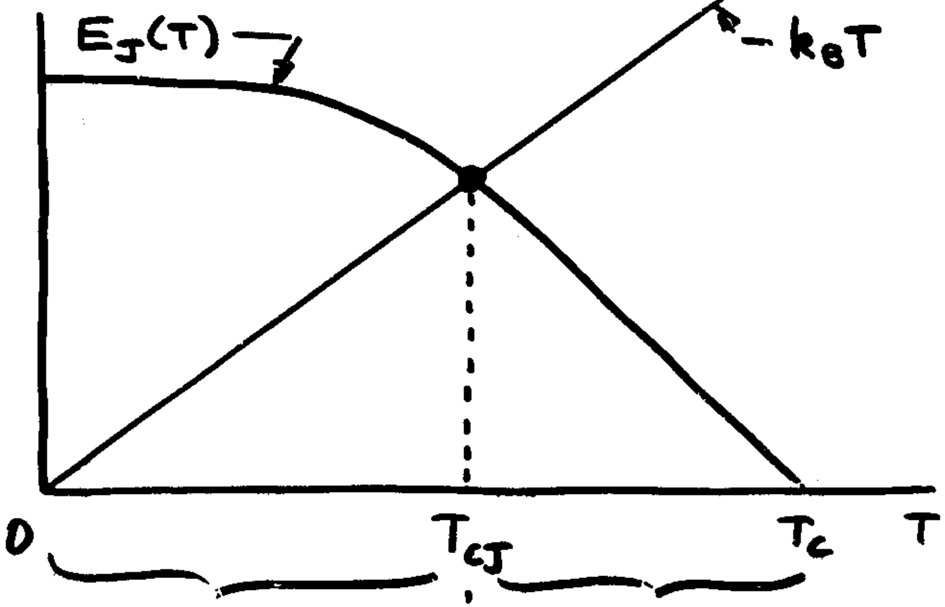
$J_{cJ}(H_0, T_{peak}) = ch_0 / 4\pi R$

CONCLUSION:

Two-peak structure in μ'' can be used to obtain both J_{cg} and J_{cJ} versus H_0 and T.

JOSEPHSON PHASE-LOCKING TEMPERATURE T_{cJ} $(I_{th} = I_0)$

$$\boxed{E_J(T_{cJ}) \approx k_B T_{cJ}}$$



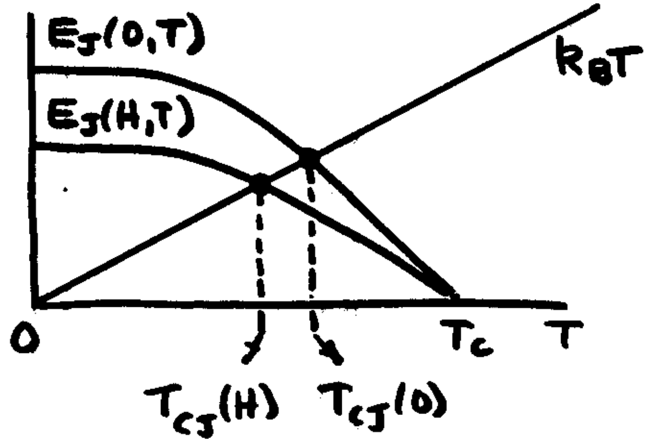
The array is:

phase-locked, superconductive, and magnetically irreversible | phase-decoupled, resistive, and magnetically reversible

in its intergranular properties.

FIELD DEPENDENCE OF JOSEPHSON PHASE-LOCKING TEMPERATURE $T_{cJ}(H)$

$$\boxed{E_J(H, T_{cJ}) \approx k_B T_{cJ}(H)}$$



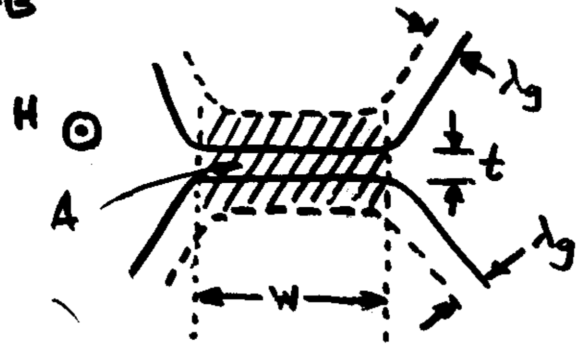
$$\boxed{E_J(H,T) = \frac{\hbar}{2e} \underset{\uparrow \text{A-B}}{I_0(T)} \left\langle \left| \frac{\sin(\pi \Phi/\phi_0)}{(\pi \Phi/\phi_0)} \right| \right\rangle}$$

$\Phi = HA$

$A \approx w(t + 2\lambda_g)$

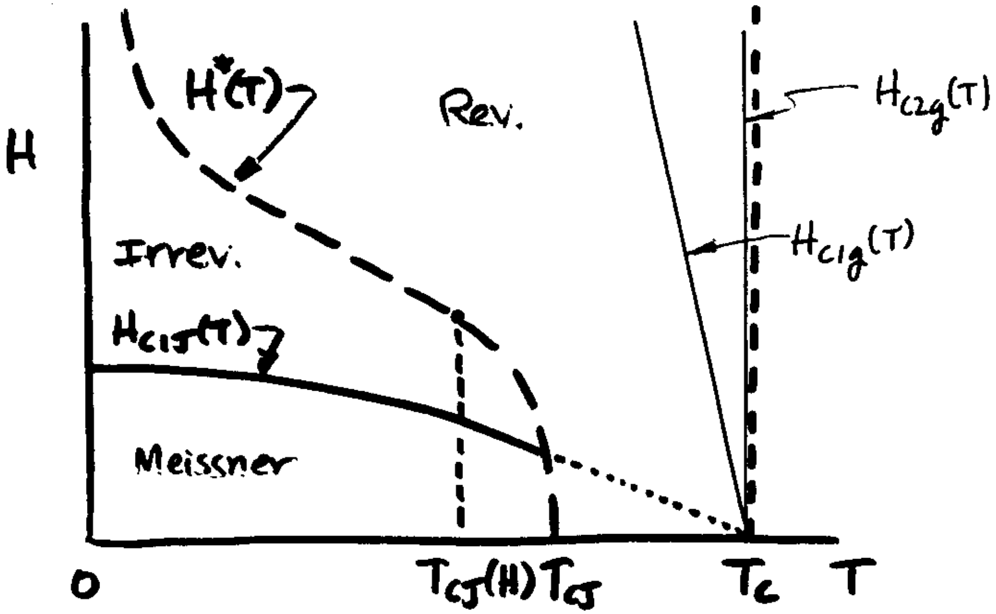
= effective junction area

($\pi\Phi/\phi_0 = H/H_c$, where $H_c \approx$ 11 Oe if $w \approx 1\mu m$, $\lambda_g \approx 0.2\mu m$)



λ_g = intragranular penetration depth

INTERGRANULAR FIELD DISTRIBUTIONS



$H^*(T)$ = INTERGRANULAR PHASE-DECOUPLING FIELD: $E_J(H^*,T) \approx k_B T$

Irrev.

- $H < H^*(T)$, $T < T_{cJ}(H)$
- phase-locked (pinned) vortex state
- superconductive
- H has critical state slopes ($J_{cJ} \neq 0$)
- magnetically irreversible

Rev.

- $H > H^*(T)$, $T > T_{cJ}(H)$
- phase decoupled (thermally depinned) vortex state
- resistive
- H is uniform ("$J_{cJ} = 0$")
- magnetically reversible

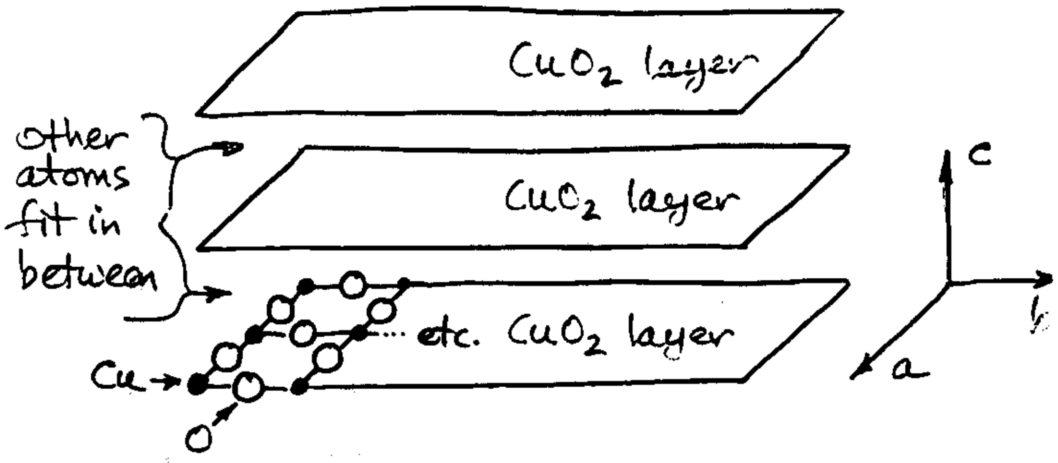
SUMMARY (THIS PART)

- Typical samples of bulk high-temperature superconductors are *granular*, with
  - ◊ *strongly superconducting grains*, which are
  - ◊ *weakly Josephson coupled* via insulating, normal, or weakly superconducting barriers.
- Sound theoretical understanding of the *electromagnetic properties* requires careful distinction between
  - ◊ *intragranular* and
  - ◊ *intergranular*

  properties.

ANISOTROPY

AT THE ATOMIC LEVEL, CuO_2 LAYERS SEEM TO BE THE ESSENTIAL BUILDING BLOCKS OF THE HIGH-T_c OXIDES:

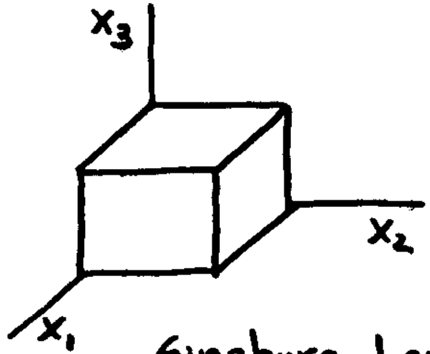


Current-carrying properties depend upon the direction of $\vec{J}$ relative to the CuO_2 planes.

The magnetic properties and J_c depend upon the direction of $\vec{H}$ relative to the CuO_2 planes.

ANISOTROPY

Principal axes:



Normalized effective masses: m_1, m_2, m_3

$$m_1 m_2 m_3 = 1$$

Ginzburg-Landau theory:

Spatial variation of order parameter along $\hat{x}_i$:

$$\xi_i = \xi / \sqrt{m_i} \qquad (\xi_1 \xi_2 \xi_3)^{1/3} = \xi$$

Penetration depth of screening currents along $\hat{x}_i$:

$$\lambda_i = \lambda \sqrt{m_i} \qquad (\lambda_1 \lambda_2 \lambda_3)^{1/3} = \lambda$$

Bulk thermodynamic critical field:

$$H_c = \frac{\phi_0}{\sqrt{2}\, 2\pi \xi \lambda}$$

$YBa_2Cu_3O_{7-\delta}$

* G.J. Dolan, F. Holtzberg, C. Feild, and T. R. Dinger, PRL 62, 2184 (1989)

$$\lambda_a : \lambda_b : \lambda_c \;=\; 1.15 : 1 : 5.5 \quad *$$

$$\lambda_i = \lambda \sqrt{m_i}$$

$$m_a : m_b : m_c \;=\; 1.32 : 1 : 30$$

$\Rightarrow \quad m_a = 0.39$ (∥ CuO_2 layers, ⊥ CuO chains)

$m_b = 0.29$ (∥ CuO_2 layers, ∥ CuO chains)

$m_c = 8.78$ (⊥ CuO_2 layers)

$m_a m_b m_c = 1$

see also:

R.A. Klemm and J. R. Clem, Phys. Rev. B21, 1868 (1980),

V.G. Kogan, Phys. Rev. B24, 1572 (1981),

V.G. Kogan and J. R. Clem, Phys. Rev. B24, 2497 (1981).

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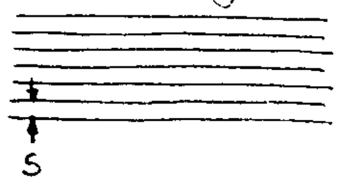
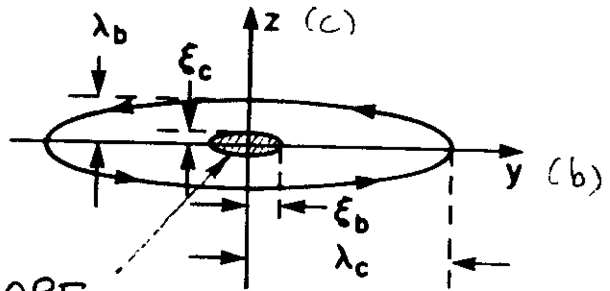
* L.Ya. Vinnikov et al., Fisma Zh. Eksp. Teor. Fiz. 49, 83 (1989).

$YBa_2Cu_3O_7$

CROSS SECTION OF A VORTEX POINTING IN THE a-DIRECTION

CuO_2 layers:





ABRIKOSOV CORE (suppressed order parameter) WHEN $\xi_c(T) \gg s$

LONDON MODEL VORTEX

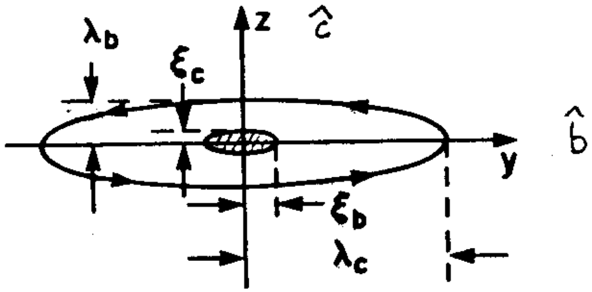
Axis along $\hat{x}$ (a axis):

$$\boxed{b_x = \frac{\phi_0}{2\pi\lambda_b\lambda_c} K_0\left(\sqrt{\left(\frac{y}{\lambda_c}\right)^2 + \left(\frac{z}{\lambda_b}\right)^2}\right)}$$

Elliptical contours of constant b_x

$$\left(\frac{y}{\lambda_c}\right)^2 + \left(\frac{z}{\lambda_b}\right)^2 = \text{const.}$$

Elliptical streamlines of $\vec{J}$



Elliptical core

$$\left(\frac{y}{\lambda_c}\right)^2 + \left(\frac{z}{\lambda_b}\right)^2 = \left(\frac{\xi_b}{\lambda_c}\right)^2 = \left(\frac{\xi_c}{\lambda_b}\right)^2 = \tilde{\kappa}_a^{-2}$$

Effective κ: $\tilde{\kappa}_a = \kappa/\sqrt{m_a}$

$\kappa = \lambda/\xi$ $\qquad\qquad$ $\sqrt{m_a} = 1/\sqrt{m_b m_c}$

ACCURATE EXPRESSION FOR H_{c1}

Vortex along the a axis:

$$H_{c1}(\parallel \hat{a}) = \frac{\phi_0}{4\pi\lambda_b\lambda_c}\left[\ln\left(\sqrt{\frac{\lambda_b\lambda_c}{\xi_c\xi_b}}\right) + 0.50 + O(1/\kappa)\right]$$

$$\approx \sqrt{m_a}\,\frac{\phi_0}{4\pi\lambda^2}\left[\ln\left(\frac{\kappa}{\sqrt{m_a}}\right) + 0.50\right]$$

Vortex along the principal axis i:

$$H_{c1}(\parallel \hat{x}_i) \approx \sqrt{m_i}\,\frac{\phi_0}{4\pi\lambda^2}\left[\ln\left(\frac{\kappa}{\sqrt{m_i}}\right) + 0.50\right]$$

UPPER CRITICAL FIELD H_{c2}

long the $\hat{a}$ axis

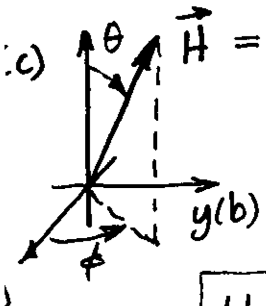
$$H_{c2}(\parallel \hat{a}) = \frac{\phi_0}{2\pi \xi_b \xi_c} = \frac{\phi_0}{2 \cdot \text{core area}}$$

r

$$H_{c2}(\parallel \hat{a}) = \frac{\phi_0 \sqrt{m_b m_c}}{2\pi \xi^2} = \frac{\phi_0}{2\pi \xi^2} \frac{1}{\sqrt{m_a}} = \sqrt{2}\,\tilde{\kappa}_a H_c$$

$$\tilde{\kappa}_a = \kappa / \sqrt{m_a}$$

Along (θ, ϕ)

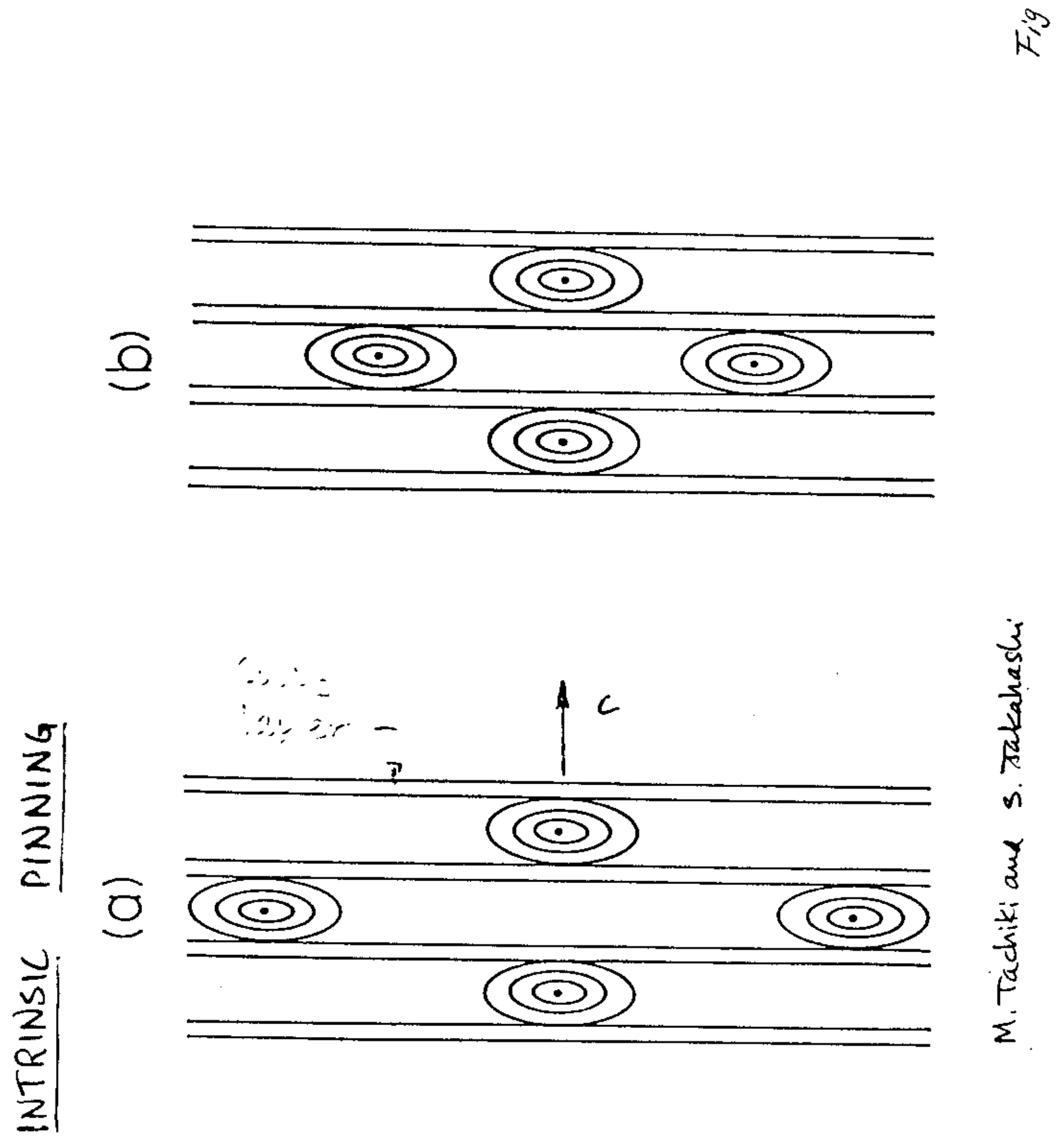


$$\vec{H} = H(\hat{x}\sin\theta\cos\phi + \hat{y}\sin\theta\sin\phi + \hat{z}\cos\theta)$$

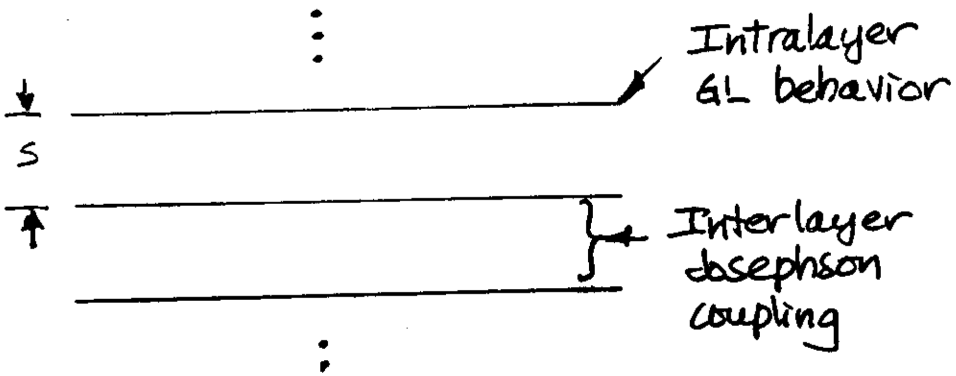
$$\boxed{H_{c2}(\theta, \phi) = \sqrt{2}\,\kappa_{eff}(\theta, \phi)\, H_c}$$

where $\kappa_{eff}(\theta,\phi) = \kappa / \sqrt{m_{eff}(\theta,\phi)}$,

$$m_{eff}(\theta,\phi) = m_a \sin^2\theta \cos^2\phi + m_b \sin^2\theta \sin^2\phi + m_c \cos^2\theta$$



LAWRENCE - DONIACH MODEL[1]



When $T \to T_c$ and $\xi_\perp(T) \gg s$, the equations can be linearized. They reduce to those of GL theory with an effective mass tensor.[1] (For $\vec{H} \parallel$ layers, elliptical vortices with cores with suppressed order parameter.)

When T is low and $\xi_\perp < s/2$, the cores "fit between the layers." (Still get elliptical vortices, but the cores are Josephson cores.[2] The order parameters on the layers are not significantly suppressed.)

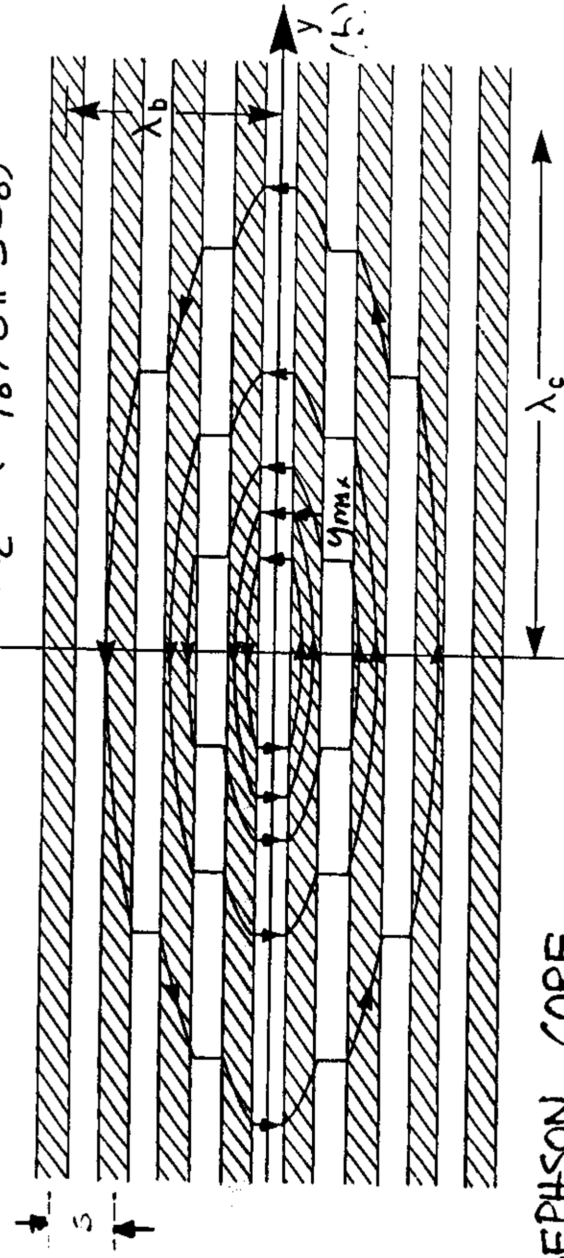
1. W.E. Lawrence and S. Doniach, LT 12, p. 361.
2. L.N. Bulaevskii, Sov. Phys. Usp. 18, 514 (1976).

JOSEPHSON VORTEX ALONG X (a) DIRECTION

$\xi_c(T) < s/2$

Two length scales for y variation:

$\lambda_c = (c\phi_0 / 8\pi^2 s J_0)^{1/2}$



$y_{max} = \left(\frac{s}{2\lambda_b}\right)\lambda_c \ll \lambda_c$

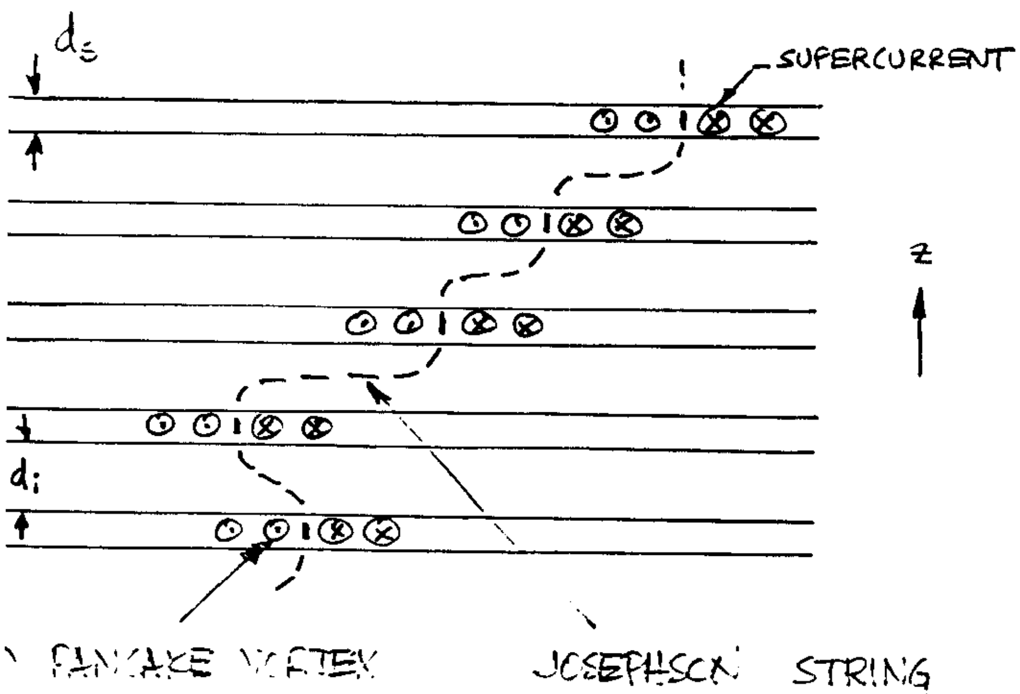
JOSEPHSON CORE

$J_z(y,z) = J_0 \sin \Delta\gamma(y,z)$

- $\Delta\gamma(0,0) = \pi \Rightarrow J_z(0,0) = 0$
- $\Delta\gamma(y_{max},0) = \pi/2$

Figure 5

ORTEX LINE REPRESENTED AS A
TACK OF 2D PANCAKE VORTICES
ONNECTED BY JOSEPHSON STRINGS



$\lambda_c \approx (c\Phi_0/8\pi^2 s J_c)^{1/2}$

= axis of vortex line

$|J_z| \ll |\vec{J}\,(\text{in-plane})|$ when $\lambda_J \gg \lambda_\parallel$

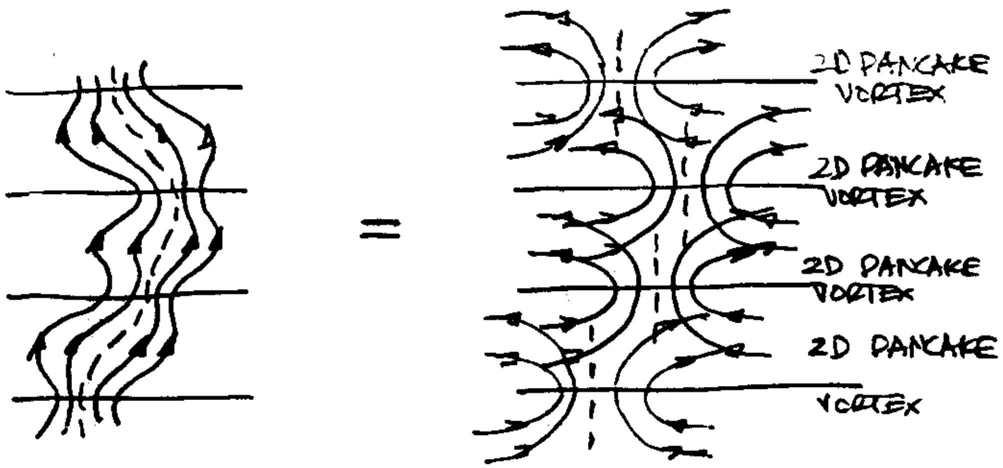
$(\lambda_c \gg \lambda_a, \lambda_b)$

GOALS:

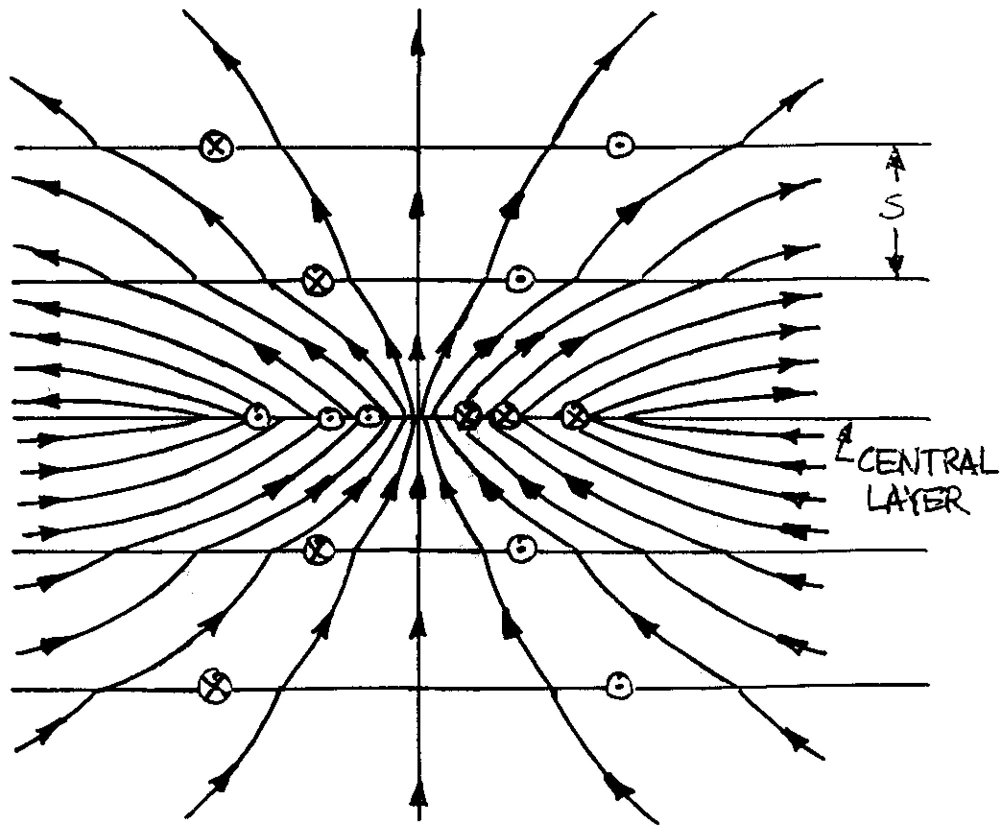
- **To calculate the vortex structure in a layered superconductor *so anisotropic* that interlayer Josephson coupling can be ignored.**
- **To describe wiggly vortex lines as stacks of *2D pancake vortices.***
- **To calculate the *interaction energy* between 2D pancake vortices in the same layers and in different layers.**
- **To estimate the *effects of thermal agitation* upon the displacements of the 2D pancake vortices.**

RESULTS WHEN JOSEPHSON COUPLING IS TURNED OFF ($\lambda_J = \lambda_c \to \infty$): 2D PANCAKE VORTICES COUPLE ONLY MAGNETICALLY

SOLUTION BY SUPERPOSITION



EFFECT OF SCREENING BY SUPERCONDUCTING LAYERS ABOVE AND BELOW THE LAYER CONTAINING THE 2D PANCAKE VORTEX

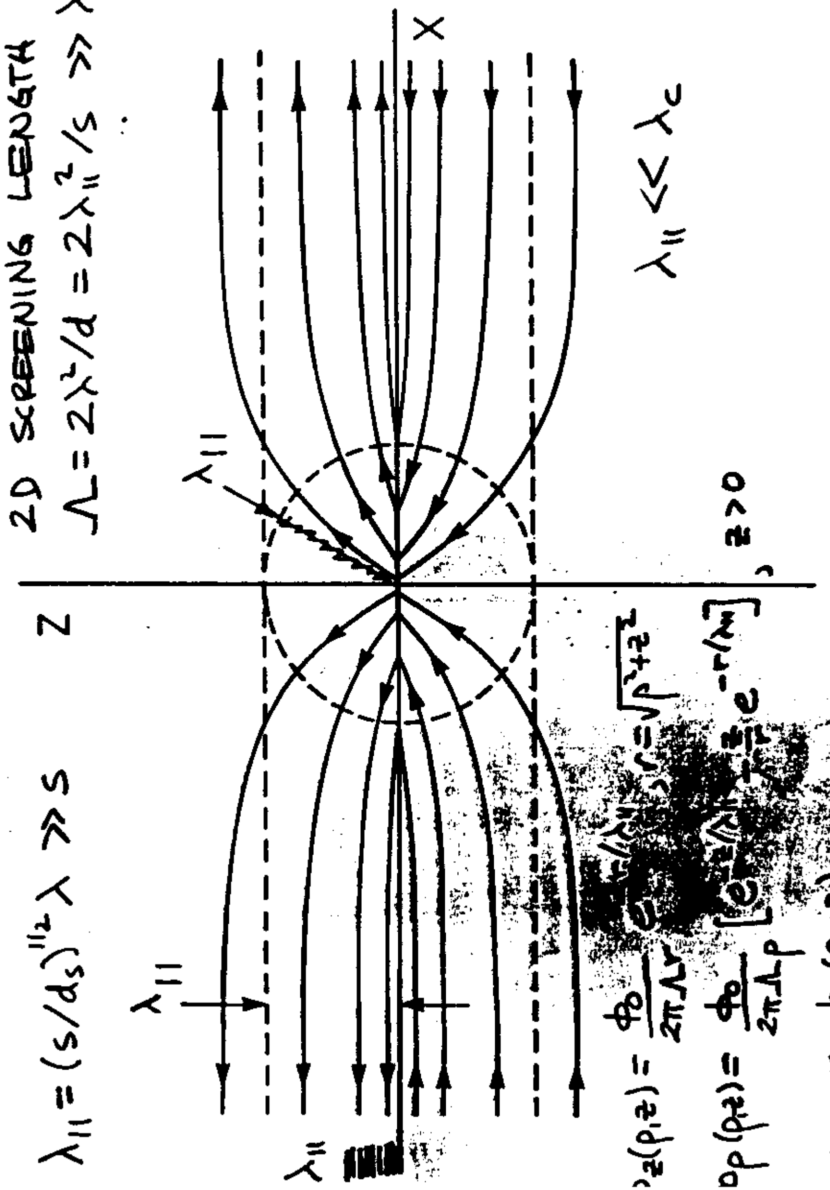


OF AN INFINITE STACK OF LAYERS

$\lambda_{\parallel} = (s/d_s)^{1/2}\lambda \gg s$

2D SCREENING LENGTH

$\Lambda = 2\lambda^2/d = 2\lambda_{\parallel}^2/s \gg \lambda_{\parallel}$



$\lambda_{\parallel} \ll \lambda_c$

$$b_z(\rho,z) = \frac{\phi_0}{2\pi\Lambda r} e^{-r/\lambda_{\parallel}}, \quad r = \sqrt{\rho^2+z^2}$$

$$b_\rho(\rho,z) = \frac{\phi_0}{2\pi\Lambda\rho}\left[e^{-|z|/\lambda_{\parallel}} - \frac{|z|}{r} e^{-r/\lambda_{\parallel}}\right], \quad z>0$$

$$= -b_\rho(\rho,-z)$$

REPULSIVE INTERACTION BETWEEN 2D PANCAKE VORTICES IN THE SAME LAYER

$\odot \quad \odot \rightarrow \vec{F}$

$$F_\rho = \frac{\phi_0^2}{4\pi^2\Lambda\rho}\left[1 - \underbrace{\frac{\lambda_{\parallel}}{\Lambda}}_{\sim 10^{-3}}\left(1 - e^{-\rho/\lambda_{\parallel}}\right)\right]$$

$$U(\rho) \approx -\frac{\phi_0^2}{4\pi^2\Lambda}\ln\rho$$

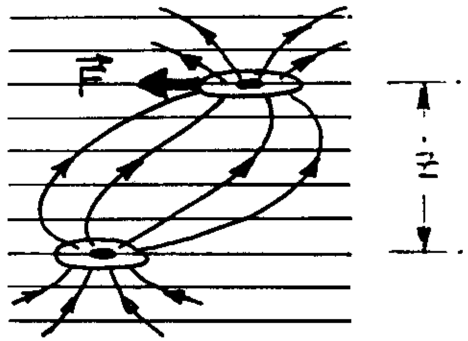
ATTRACTIVE INTERACTION BETWEEN 2D PANCAKE VORTICES AND ANTIVORTICES IN THE SAME LAYER

$\odot \xleftarrow{\vec{F}} \otimes$

$$F_\rho = -\frac{\phi_0^2}{4\pi^2\Lambda\rho}\left[1 - \frac{\lambda_{\parallel}}{\Lambda}\left(1 - e^{-\rho/\lambda_{\parallel}}\right)\right]$$

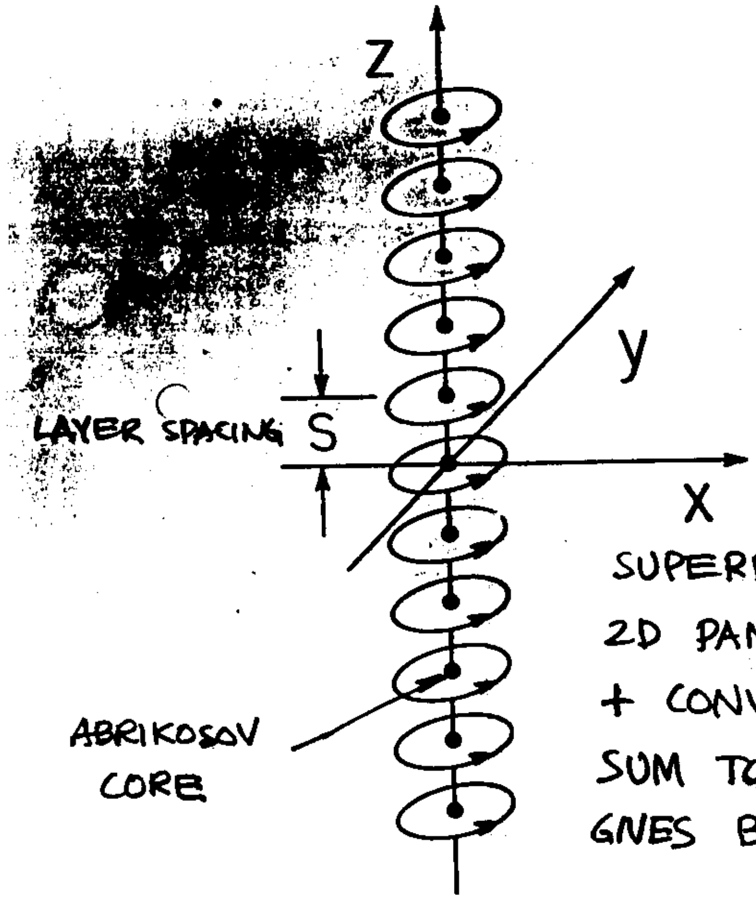
$$U(\rho) \approx \frac{\phi_0^2}{4\pi^2\Lambda}\ln\rho$$

ATTRACTIVE INTERACTION BETWEEN 2D PANCAKE VORTICES IN DIFFERENT LAYERS



$$F_\rho = -\frac{\phi_0^2 \lambda_{\parallel}}{4\pi^2 \Lambda^2 \rho}\left(e^{-|z|/\lambda_{\parallel}} - e^{-\sqrt{\rho^2+z^2}/\lambda_{\parallel}}\right)$$

LINE VORTEX REGARDED AS A STACK OF 2D PANCAKE VORTICES



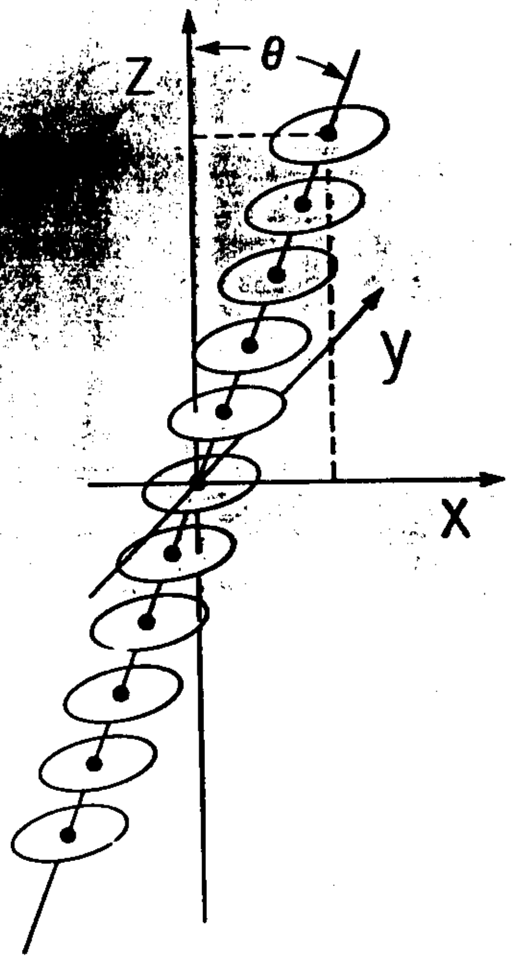
SUPERPOSITION OF 2D PANCAKE FIELDS + CONVERTING THE SUM TO AN INTEGRAL GIVES BACK:

$$\vec{b}(\rho,z) = \hat{z}\,\frac{\phi_0}{2\pi\lambda_{\parallel}^2}\,K_0(\rho/\lambda_{\parallel})$$

(the familiar London-model result)

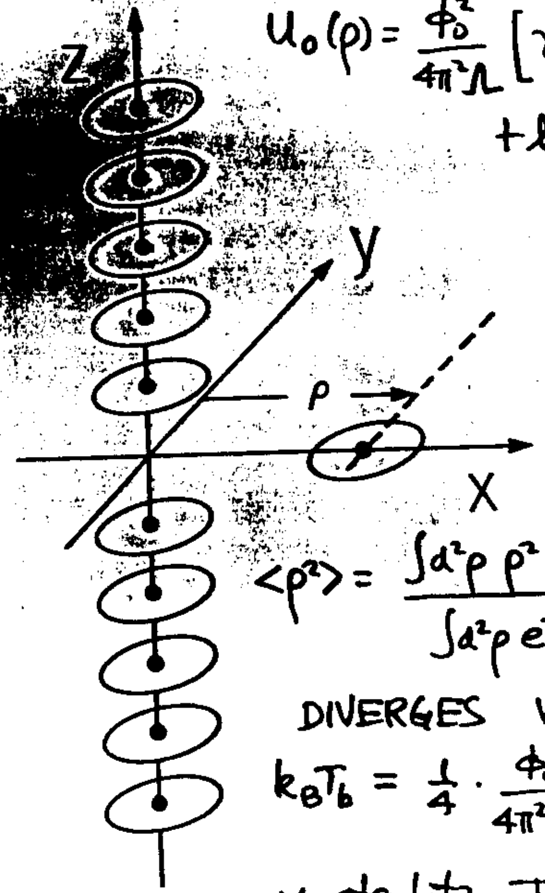
ϵ_1: $H_{c1} \approx \frac{\phi_0}{4\pi\lambda_{\parallel}^2}\ln\left(\frac{\lambda_{\parallel}}{\xi_{\parallel}}\right)$, $\xi_{\parallel} \ll \lambda_{\parallel}$

TILTED INFINITE STACK OF 2D PANCAKE VORTICES



(θ): $H_{c1 B}(\theta) = \frac{\phi_0}{4\pi\lambda_{\parallel}^2} \cos\theta \, \ln\left[\frac{\lambda_{\parallel}}{\xi_{\parallel}} \; \frac{(1+\cos\theta)}{2\cos\theta}\right]$

THERMALLY INDUCED BREAKUP OF A STACK OF 2D PANCAKE VORTICES



$$U_0(\rho) = \frac{\phi_0^2}{4\pi^2\Lambda}\left[\gamma + K_0(\rho/\lambda_{\parallel}) + \ln\left(\frac{\rho}{2\lambda_{\parallel}}\right)\right]$$

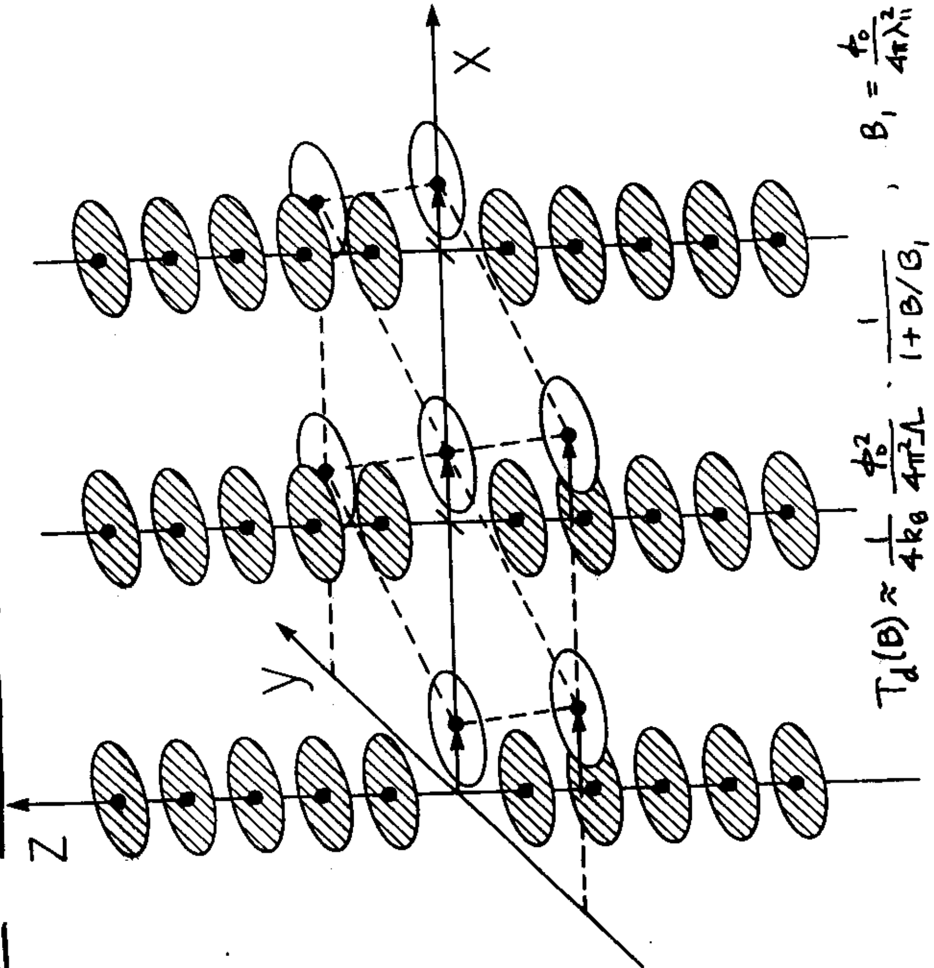
$$\langle \rho^2 \rangle = \frac{\int d^2\rho \, \rho^2 e^{-U_0(\rho)/k_BT}}{\int d^2\rho \, e^{-U_0(\rho)/k_BT}}$$

DIVERGES WHEN

$$k_B T_b = \frac{1}{4} \cdot \frac{\phi_0^2}{4\pi^2\Lambda}$$

Kosterlitz–Thouless condition

THERMAL DECOUPLING OF VORTEX LATTICES IN DIFFERENT LAYERS



$$T_d(B) \approx \frac{1}{4k_B}\,\frac{\phi_0^2}{4\pi^2\Lambda}\cdot\frac{1}{1+B/B_1}\,, \quad B_1 = \frac{\phi_0}{4\pi\lambda_\parallel^2}\left(\frac{\sqrt{3}}{2\pi}\right) \sim B_{c1}$$

"YBCO" $\Rightarrow$ $T_d(B) \sim (0.5K\text{-}T)/B$ for large $B \gg B_{c1}$

WHEN TO NEGLECT JOSEPHSON COUPLING ENERGY

$\odot \qquad \otimes$

$\longleftarrow \rho \longrightarrow$

Magnetic coupling energy at $\rho \approx \lambda_\parallel$ is:

$$U_M(\lambda_\parallel) \approx \left(\frac{\phi_0}{2\pi}\right)^2 \frac{1}{\Lambda}$$

where

$$\Lambda = 2\lambda_\parallel^2/s$$

Josephson coupling energy at $\rho \approx \lambda_\parallel$ is:

$$U_J(\lambda_\parallel) \sim \left(\frac{\phi_0}{2\pi}\right)^2 \frac{1}{\lambda_c}$$

where

$$\lambda_c = [c\phi_0/8\pi^2 s J_0]^{1/2}$$

THUS

$$U_J(\lambda_\parallel) \ll U_M(\lambda_\parallel) \text{ when } \lambda_c \gg \Lambda$$

INTRAGRANULAR

- COMPACT VORTICES
- STRONGLY PINNED
- HIGH INTRAGRANULAR CRITICAL CURRENT DENSITY, WEAKLY SUPPRESSED BY MAGNETIC FIELDS

INTERGRANULAR

LARGE EXTENDED VORTICES (several μm)

WEAKLY PINNED

LOW INTERGRANULAR CRITICAL CURRENT DENSITY, HIGHLY SENSITIVE TO MAGNETIC FIELDS (at the 10 G level; 1 mT level)