I. Essential Materials Properties for Useful Conductors
II. Development of High Jc in Conductor Forms

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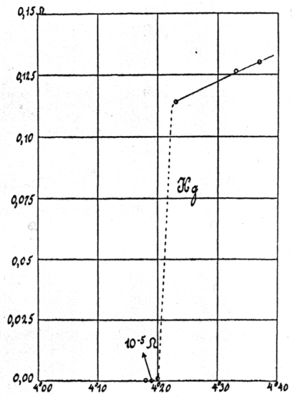
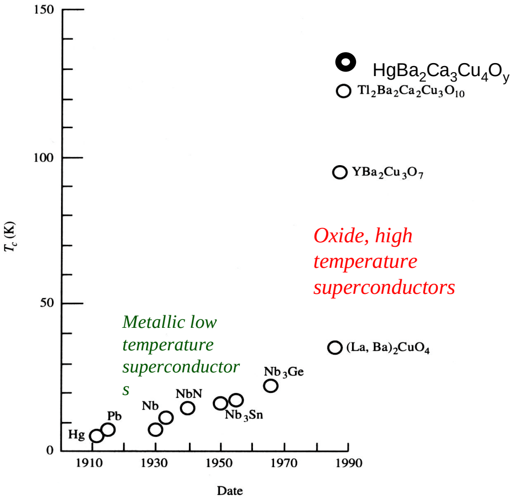
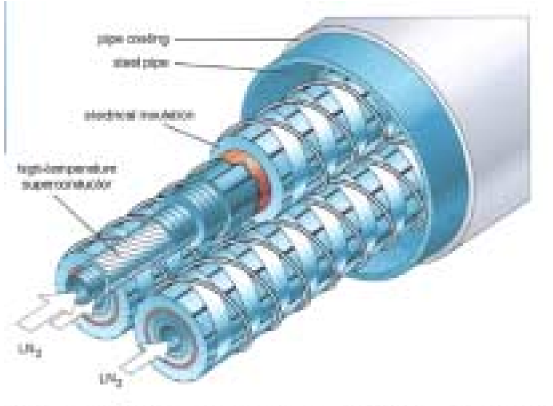
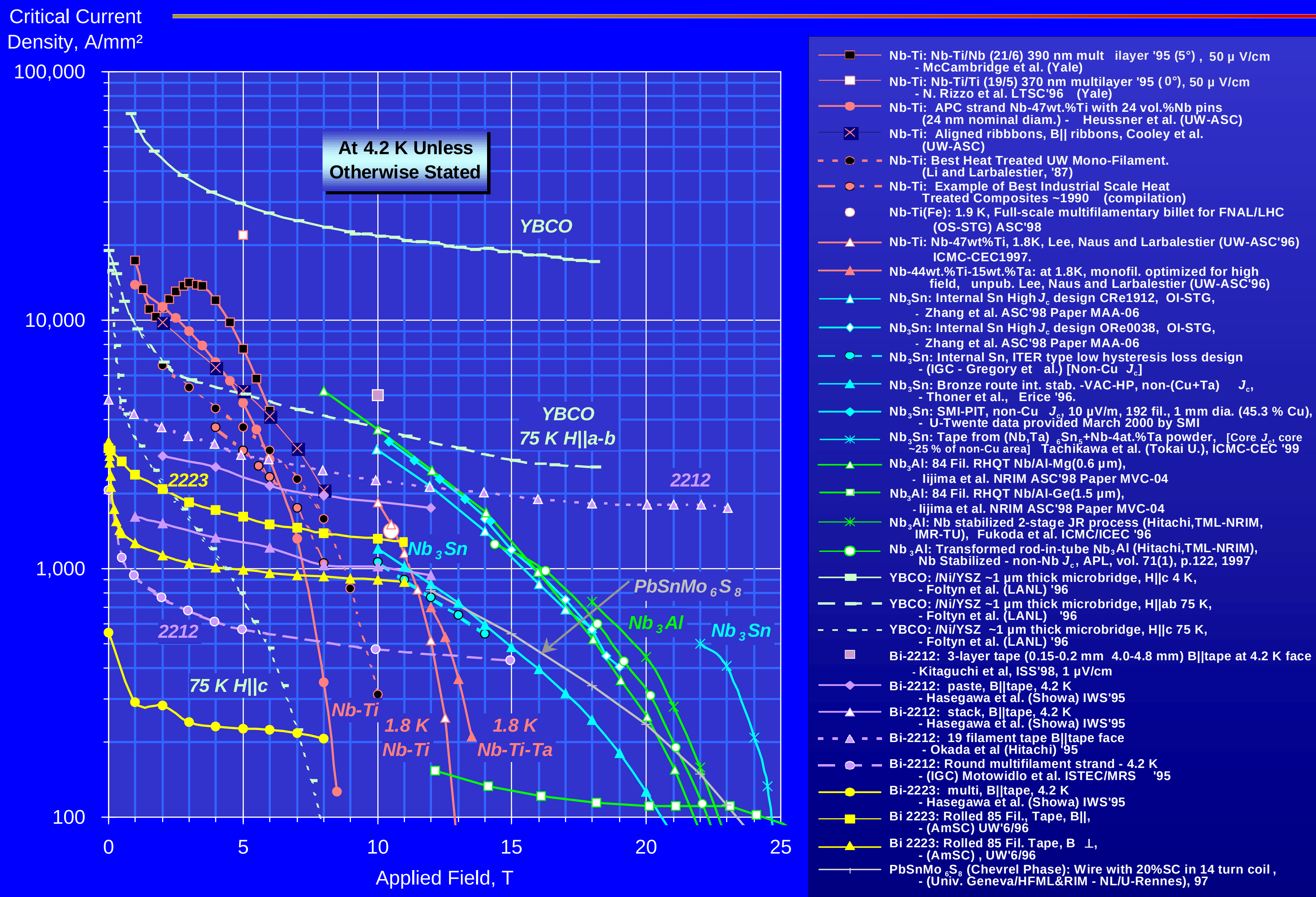






The cross-section of a three-core HTS cable showing the liquid-nitrogen (LN$_2$) ducts along the core of each cable, and the spirally wound high-temperature superconductor tapes.



At 4.2 K Unless Otherwise Stated

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Outline of Lectures

- I. Basics of the Critical Current Density
- II. Basic Materials Issues
- III. Niobium Titanium
- IV. Niobium Tin
- V. BSCCO
- VI. YBCO
- VII. Summary Issues

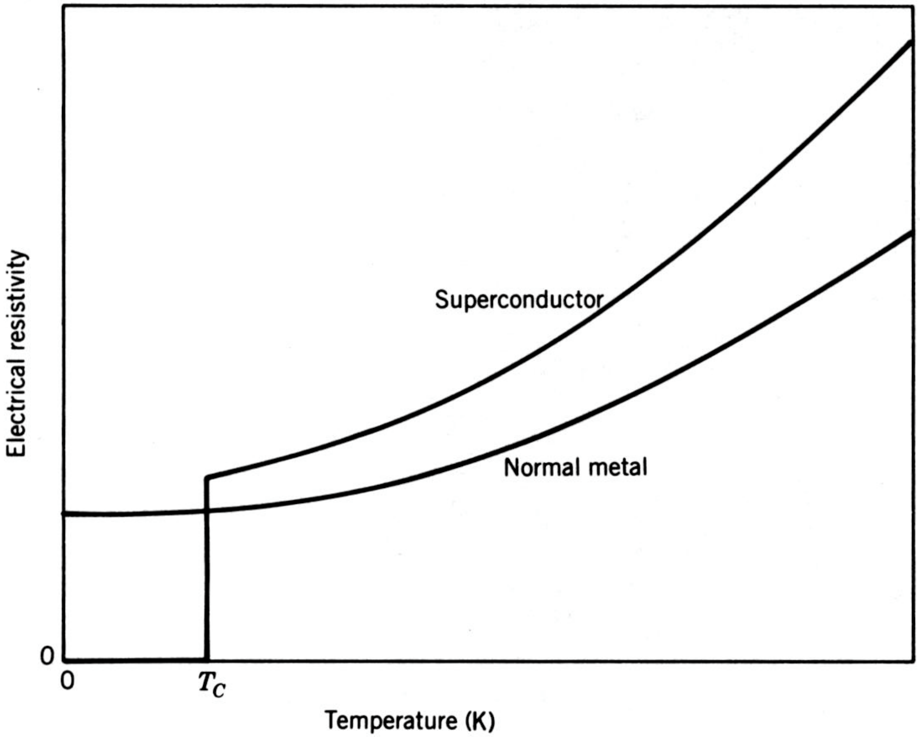
Ia. “Zero Resistivity”

- Non-Superconducting Metals
  - $\rho = \rho_o + aT$ for $T > 0$ K*
  - $\rho = \rho_o$ Near $T = 0$ K

  *Recall that $\rho(T)$ deviates from linearity near $T = 0$ K

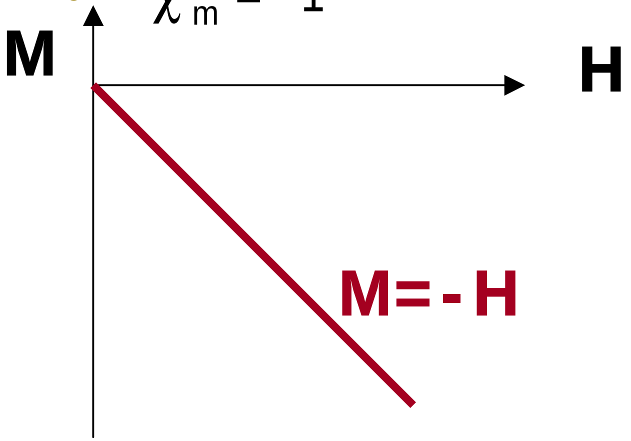
- Superconducting Metals
  - $\rho = \rho_o + aT$ for $T > T_c$
  - $\rho = 0$ for $T < T_c$

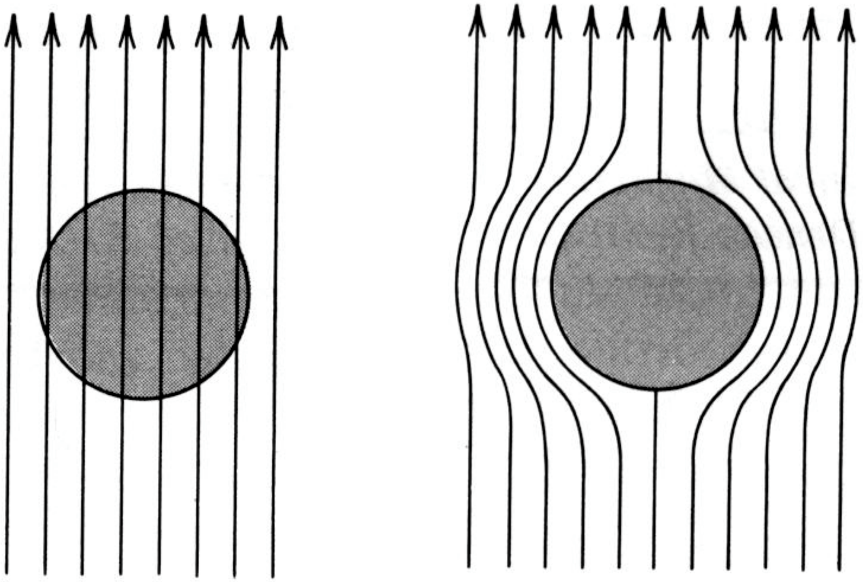
- Superconductors are more resistive in the normal state than good conductors such as Cu



Ib. Perfect Diamagnetism

- $\chi_m = -1$





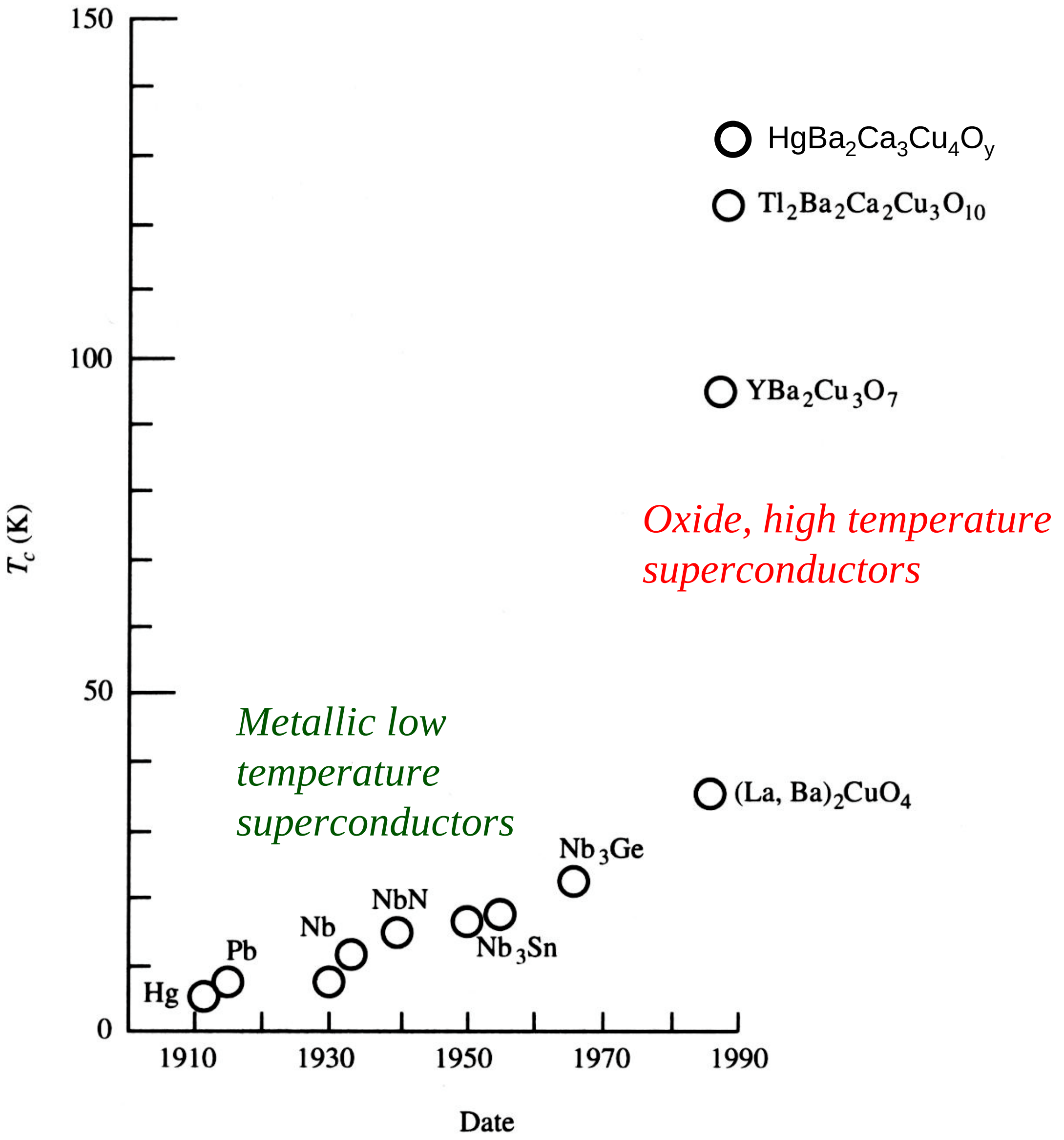
Normal Metal **Superconductor**

- Means:

$$B = \mu_o(H + M)$$
$$B = \mu_o(H + \chi_m H)$$
$$B = 0$$

Flux is excluded from the bulk by supercurrents flowing at the surface to a penetration depth (λ) ~ 200-500 nm

Ic. T_c History



Id. Low Temperature Superconductors

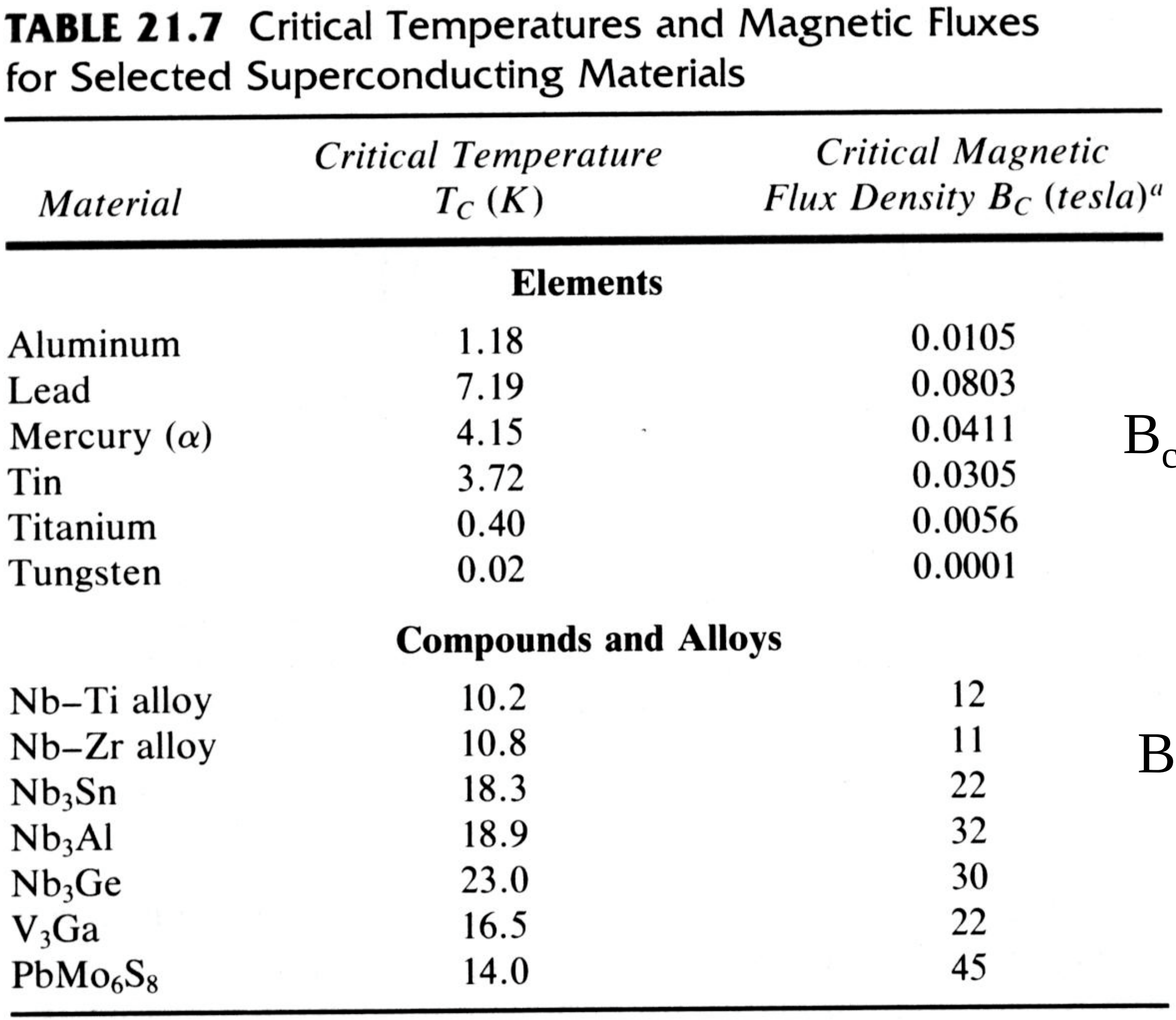


TABLE 21.7 Critical Temperatures and Magnetic Fluxes for Selected Superconducting Materials

Material	*Critical Temperature* T_C *(K)*	*Critical Magnetic Flux Density* B_C *(tesla)*[a]
	Elements	
Aluminum	1.18	0.0105
Lead	7.19	0.0803
Mercury (α)	4.15	0.0411
Tin	3.72	0.0305
Titanium	0.40	0.0056
Tungsten	0.02	0.0001
	Compounds and Alloys	
Nb–Ti alloy	10.2	12
Nb–Zr alloy	10.8	11
Nb_3Sn	18.3	22
Nb_3Al	18.9	32
Nb_3Ge	23.0	30
V_3Ga	16.5	22
$PbMo_6S_8$	14.0	45

Type I

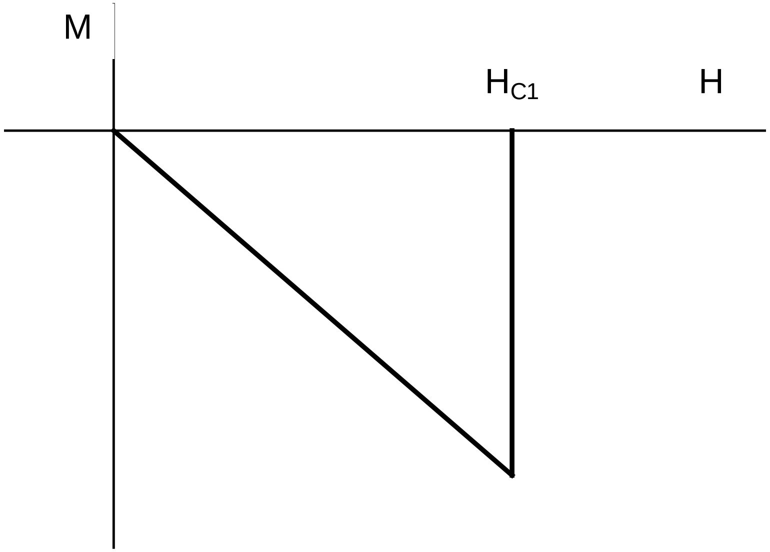
B_c

Type II

B_{c2}

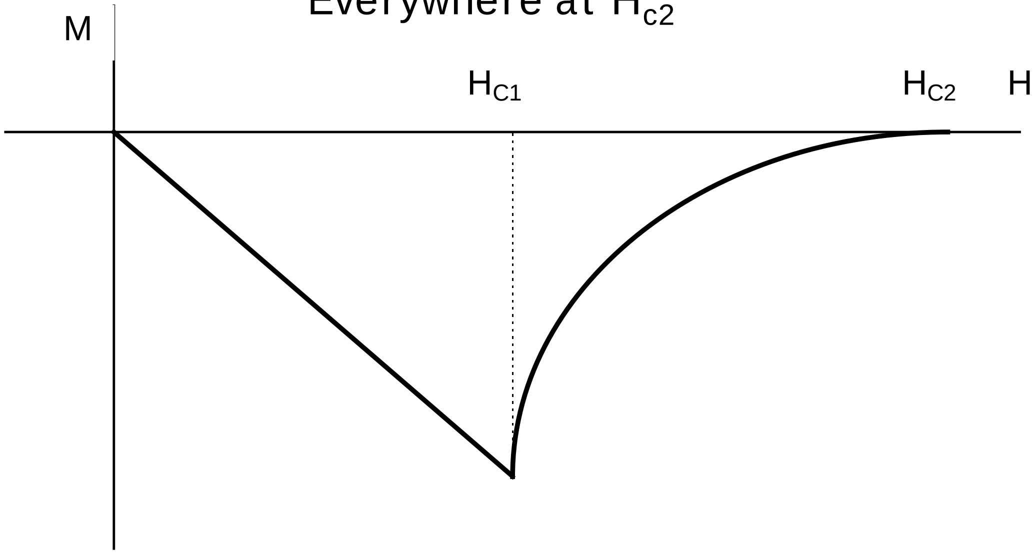
Ie. Type I and Type II

- Type I
  - Material Goes Normal Everywhere at H_c



Complete flux exclusion up to H_c, then destruction of superconductivity by the field

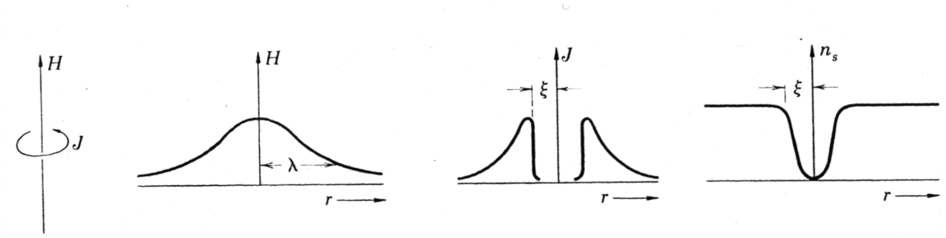
- Type II
  - Material Goes Normal Locally at H_{c1}, Everywhere at H_{c2}



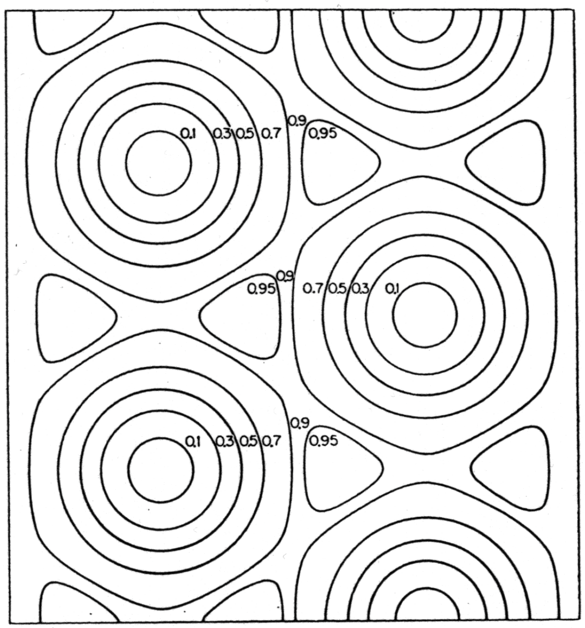
Complete flux exclusion up to H_{c1}, then partial flux penetration as vortices

Current can now flow in bulk, not just surface

If. Vortex properties



- Two characteristic lengths
  - coherence length ξ, the pairing length of the superconducting pair
  - penetration depth λ, the length over which the screening currents for the vortex flow
- Vortices have defined properties in superconductors
  - normal core dia, ~2ξ
  - each vortex contains a flux quantum ϕ_0 currents flow at J_d over dia of 2λ
  - vortex separation $a_0 = 1.08(\phi_0/B)^{0.5}$



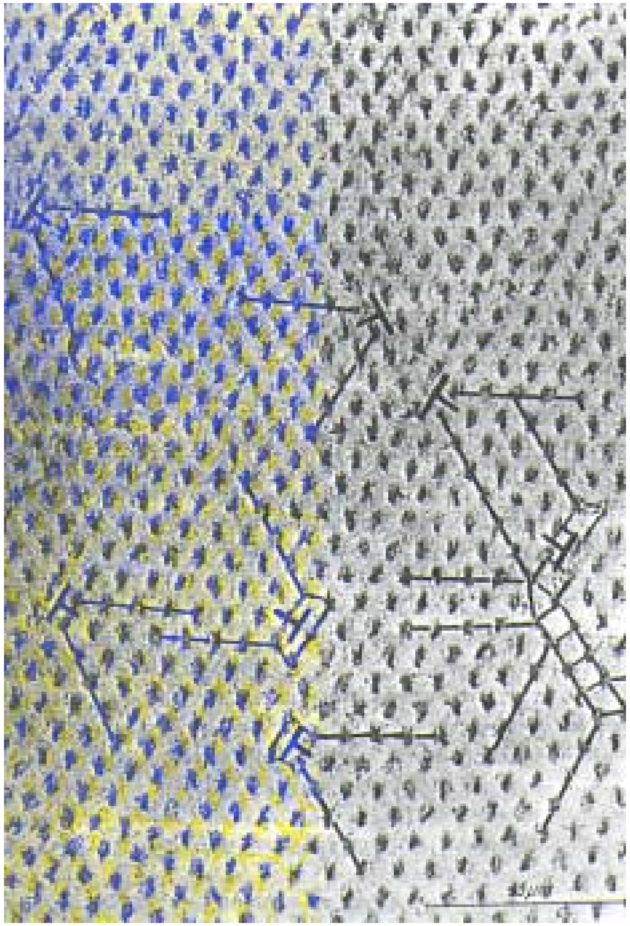
$H_{c2} = \phi/2\pi\xi^2$

$\phi_0 = h/2e = 2.07 \times 10^{-15}$ Wb

B/B_{c2} (=b) ~ 0.2

Ig. Vortex Imaging by Decoration

- Vortex state can be imaged in several ways
  - Magnetic decoration
  - Small angle neutron scattering
  - Hall probes
  - Scanning probe emthods
- First was by sputtering magnetic smoke on to a magnetized superconductor in the remanent state
  - Lattice structure confirmed *and* defects in lattice seen



Trauble and Essmann 1967

Ih. Bean Model

- Bean (1962) and London (1963) introduced the concept of the critical state in which the bulk currents of a type II superconductor flow either at $+J_c$, $-J_c$ or zero.
  - *Critical State is a static force balance between the magnetic driving force* JxB and the pinning force exerted on vortices by the microstructure F_P
    - $|(B \times (\nabla \times H))| = BJ_c(B)$
  - *Solutions define the macroscopic current patterns and enable the J_c to be determined from magnetization measurements*

Ii. Macroscopic Current Flow and Flux Patterns

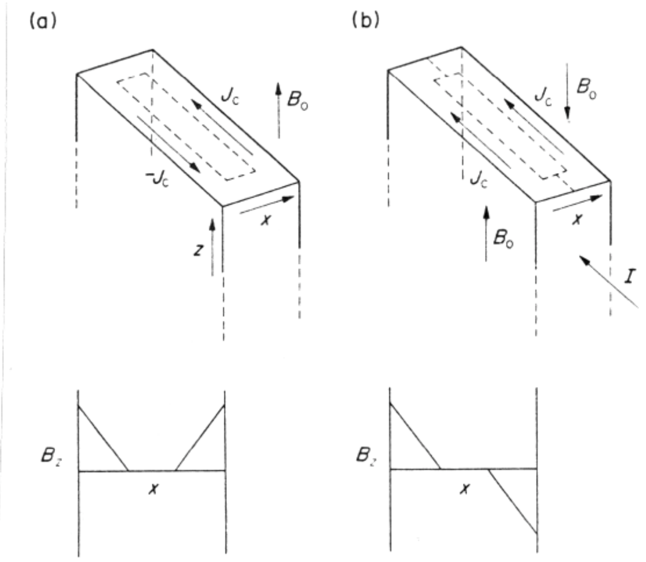


Figure 1
Schematic of the flux profile and current flow for (a) a slab in an applied field B_0 and (b) a sample with similar dimensions carrying a total current I sufficient to generate a field B_0 at the surface of the sample

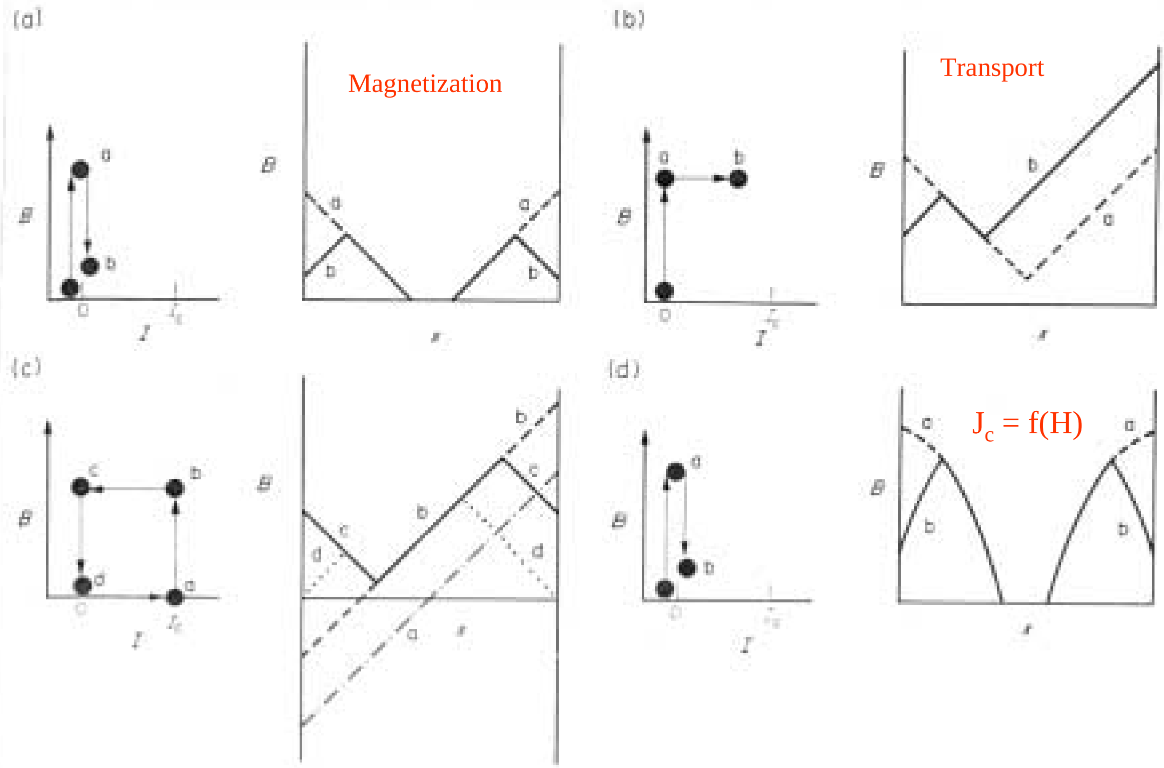


Figure 2
Schematic of the critical state flux profile; the different current–applied field trajectories are indicated in the IB diagrams: (a-c) Bean model with J_c constant; (d) as (a) but $J_c(B)$ decreasing strongly with increasing B

After Peter Kes in Concise Encyclopedia on Magnetic and Superconducting Materials, Ed J. Evetts Pergamon 1991

Ij. Magnetization and the Bean Model

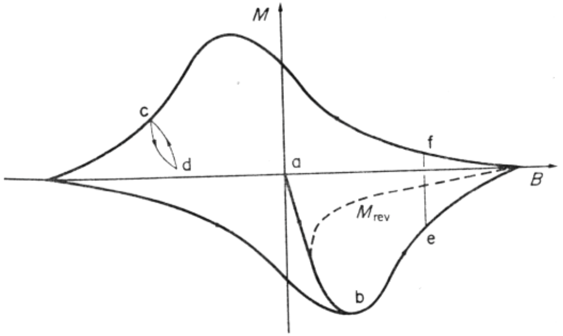
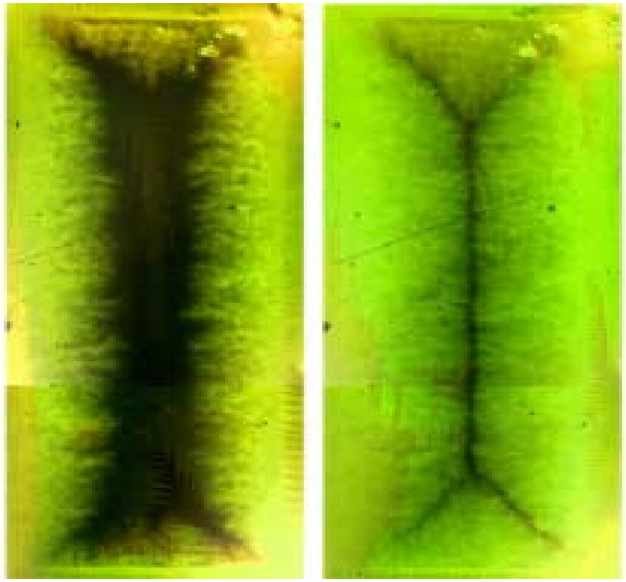


Figure 4
A typical hysteretic magnetization loop including the reversible magnetization M_{rev}. The figure also indicates the initial curve from zero induction (ab), a minor loop excursion typically experienced by a superconductor under low amplitude ac conditions (cdc) and a pair of magnetization values used to extract $J_c(B)$ information as described in the text (ef)

Table 1
The magnetization for a full critical state established in the samples indicated for different applied field directions

Sample shape and field orientation	M (A m^{-1})
Cylinder diameter $2a$	
$B \parallel$ axis	$J_c a/3$
$B \perp$ axis	$4 J_c a/3\pi$
Infinite slab, thickness d	
$B \parallel$ face	$J_c d/2$
Square section bar ($d \times d$)	
$B \parallel$ axis	$J_c d/6$
$B \perp$ face	$J_c d/4$
Sphere radius a	$3\pi J_c a/32$
Disk, $2a$, thickness d	
$B \perp$ face	$J_c a/3$
Rectangular section bar ($b \times d$ with $b > d$)	
$B \parallel$ axis	$\frac{3b-d}{12b} J_c d$

- m=MV=0.5 $\int$(rxj)dV
  - where $j=(1/m_0)\nabla xB$ or $m=MV=\sum I_i x S_i$
- Slab geometry is very simple
  - $dB/dx = \pm J_c(B)$



Magneto optical image of current flow pattern in a BSCCO tape. The “roof” pattern defines the lines along which the current turns.

Ik. Flux Pinning Theory

- Defects cause variation in ΔG of FLL
  - up to 10^7A/cm^2 at >30T
- Vortex separation few ξ for b>0.5
- Dense interaction of FLL with defect array
  - unperturbed vortex array is a FLL
  - defects perturb the FLL
  - defects seldom form a lattice
- Experiment measures global summed pinning force $F_p=J_c x B$, often >20GN/m^3
- Elementary interaction is $f_{p,}$ generally small, e.g.~ 10^{-14}N for binding to a point defect
- Predictive, quantitative theory of flux pinning is mostly lacking
- 3 step process
  - compute f_p
  - compute elastic/plastic interactions of defect(s) and FLL
  - Sum interactions over all pins and vortices
- 2 main cases:
  - weak pinning, statistical summation (Labusch, Larkin and Ovchinnikov)
  - strong pinning with full summation
- Useful materials try to fall into the second category

II. Defect-FL Interactions

- Magnetic interactions on $\sim\lambda$
- Perturbations to currents by interfaces and surfaces
  - no normal component of J
- Strong in low–κ materials

- Vortex core interactions on $\sim\xi$
- Possibility for point defects, precipitates, dislocations to pin
- Perturb local $|\Psi|^2$ through Δ_{density}, $\Delta_{\text{elasticity}}$ or $\Delta_{\text{electron-phonon}}$
- Can also perturb electron mean free path and hence ξ

$$F= \int d^3r(A|\Delta|^2 +(B/2)|\Delta|^4 + C|\partial\Delta|^2 + (h^2/2\mu_0)) ,$$

$$A=N(0)(1-t),\ B= 0.1N(0)/(k_BT_c)^{2,}\ C=0.55\xi^2N(0)\chi(\alpha)$$

Core interactions dominate in useful materials

Im. Summation and Scaling

- Strong pinning materials (Nb-Ti wires, irradiated HTS) often exhibit full summation
  - $F_p = n_{defects} f_{pdefect}$
- Weak pinning requires statistical summation as already noted
  - many adjustable, often non-verifiable parameters

Scaling of the global pinning force with H, T can often be seen:

$F_p(B,T) = b^p(1-b)^q$ Nb-Ti often $b(1-b)$, Nb_3Sn $b^{0.5}(1-b)^2$

HTS scaling functions complicated by thermal activation effects

In. The Irreversibility Field

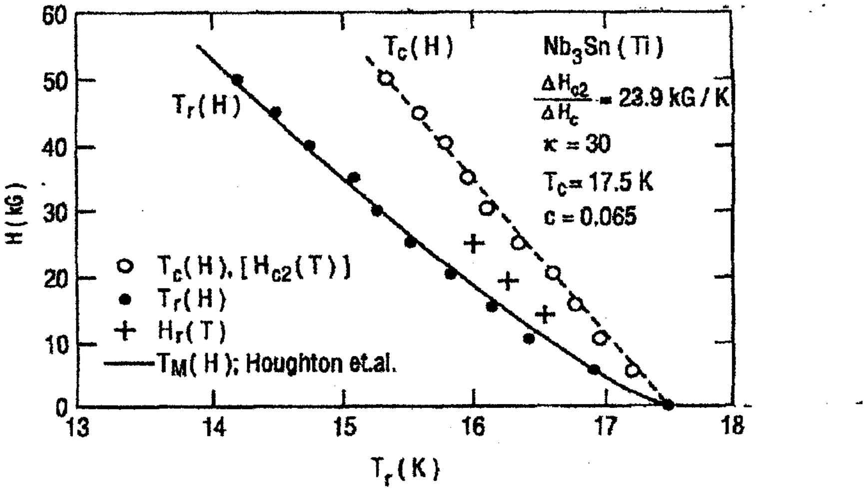


FIG. 3. $T_r(H)$ and $T_c(H)$ [$H_{c2}(T)$] for Nb_3Sn (∼3.5 μm) and the melting temperature $T_M(H)$ from Eqs. (1) and (2). The crosses are the irreversibility fields $H_r(T)$ as determined from hysteresis measurements at constant temperature.

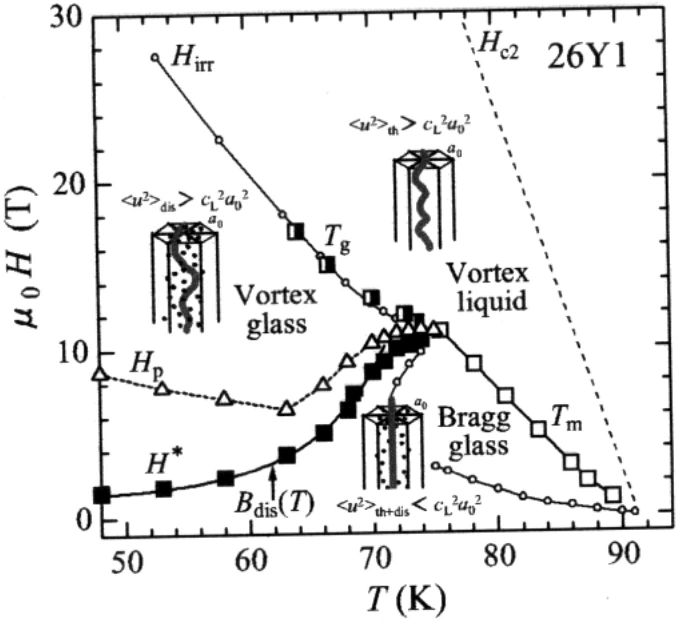


Figure 7. The vortex-matter phase diagram in untwinned $YBa_2Cu_3O_y$. The transition lines $T_m(H)$, $T_g(H)$, and $H^*(T)$ terminate at the critical point and divide into three different phases of the vortex liquid, the vortex glass, and the Bragg glass. The full curve is a fit to the field-driven transition line $B_{dis}(T)$.

Simple H-T diagram for LTS:

Suenaga, Ghosh, Xu, Welch PRL **66**, 1777 (1991)

Complex H-T diagram for HTS

Nishizaki and Kabayashi SuST 13, 1 (2000)

Io. Summary of Current Density Issues

- Enormous J_c can be obtained in some systems
  - ~10% of depairing current density (~H_c/λ) in Nb-Ti and for many HTS at low temperatures
  - HTS suffer from thermal activation and lack of knowledge about what are the pins
- Practical materials want full summation to get maximum J_c
- To compute F_p a priori in arbitrary limit is so far beyond us
- Useful materials tend to be made first and optimized slowly as control of nanostructure at scale of 0.5-2 nm is not trivial