Lecture II

Superconductivity

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Basic Superconductivity

An Introduction to Superconductivity

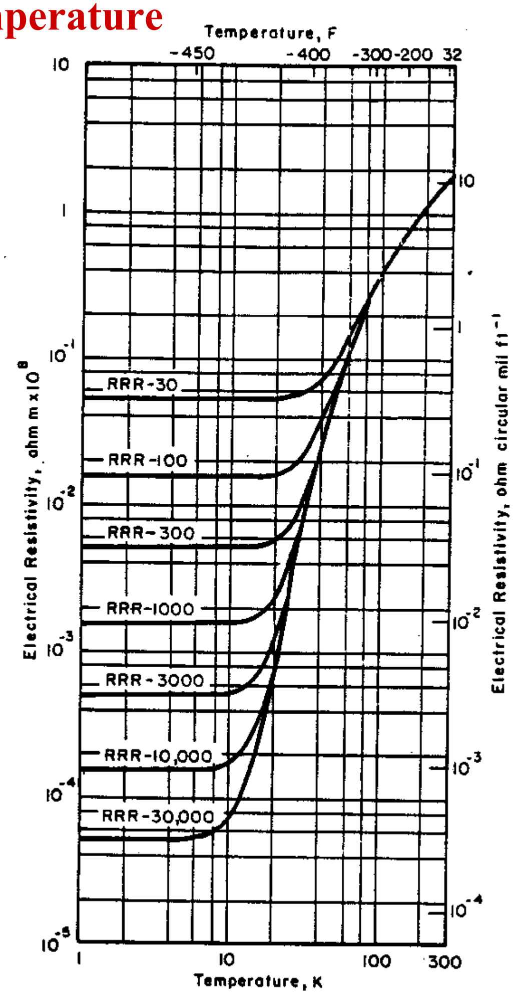
• It will not be a general course on superconductivity

•The purpose of this lecture is to give you a brief introduction to the parts that are relevant to designing superconducting accelerator magnets

The Superconductivity

Resistivity of Cu as a function of Temperature

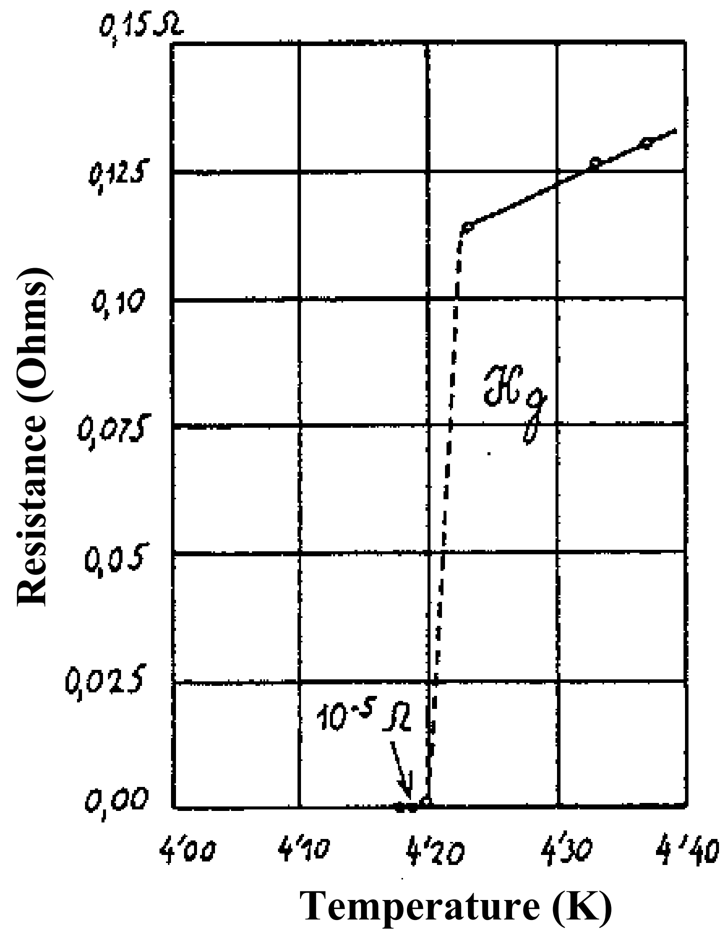
RRR=ρ(273K)/ρ(~4K)
High purity copper has larger RRR



ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR COPPER

First observation of "Superconductivity" by Onnes (1911)

Resistance of Mercury falls suddenly below measurement accuracy at very low temperature



Superconducting Accelerator Magnets
A Brief History

1908 Heinke Kemerlingh Onnes achieves very low temperature (<4.2 K)

1911 Onnes and Holst observe sudden drop in resistivity to essentially zero

Superconductivity is born !

1914 Persistent current experiments

1933 Meissner-Ochsenfeld effect observed

1935 Fritz and London theory

1950 Ginsburg - Landau theory

1957 BCS Theory

1967 Observation of Flux Tubes in Type II superconductors

1980 Tevatron: The first accelerator using superconducting magnets

1986 First observation of High Temperature Superconductors

It took ~70 years to get first accelerator from conventional superconductors.

How long will it take for HTS to get to accelerator magnets? Have patience!

Critical Surface of Nb-Ti

Critical Surface

The surface on 3-d (J,T,B) volume within which the material remain superconducting.

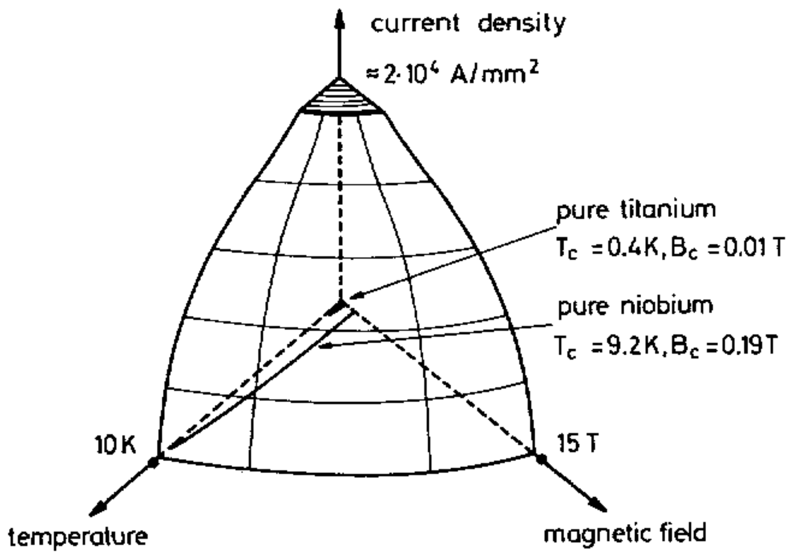


Figure 2.11: Sketch of the critical surface of NbTi. Also indicated are the regions where pure niobium and pure titanium are superconducting. The critical surface has been truncated in the regime of very low temperatures and fields where only sparse data are available.

Operating point of the magnet must stay within this volume with a suitable margin.

What a magnet designer always dreams for ?:

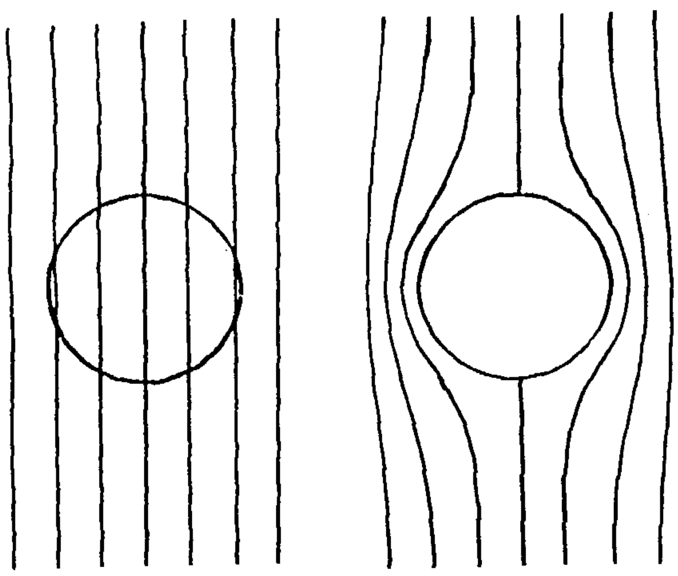
A material that remains superconducting at higher temperatures and at higher fields.

Meissner Effect

A remarkable observation in superconductors:

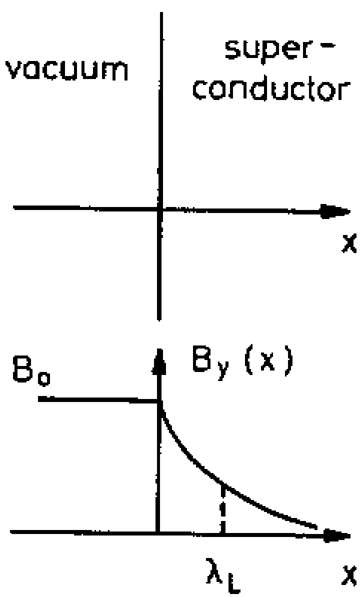
They exclude the magnet flux lines from going through it.

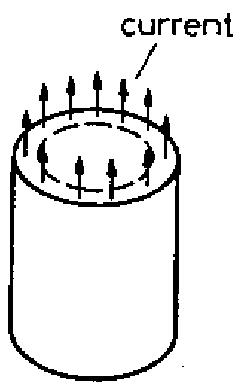
Meissner and Ochsenfeld (1933)



Normal Conductor Superconductor

Courtesy: Wilson





Courtesy: Schmuser

Attenuation of magnetic field and shielding currents in Type I superconductors

Type I and Type II Superconductors

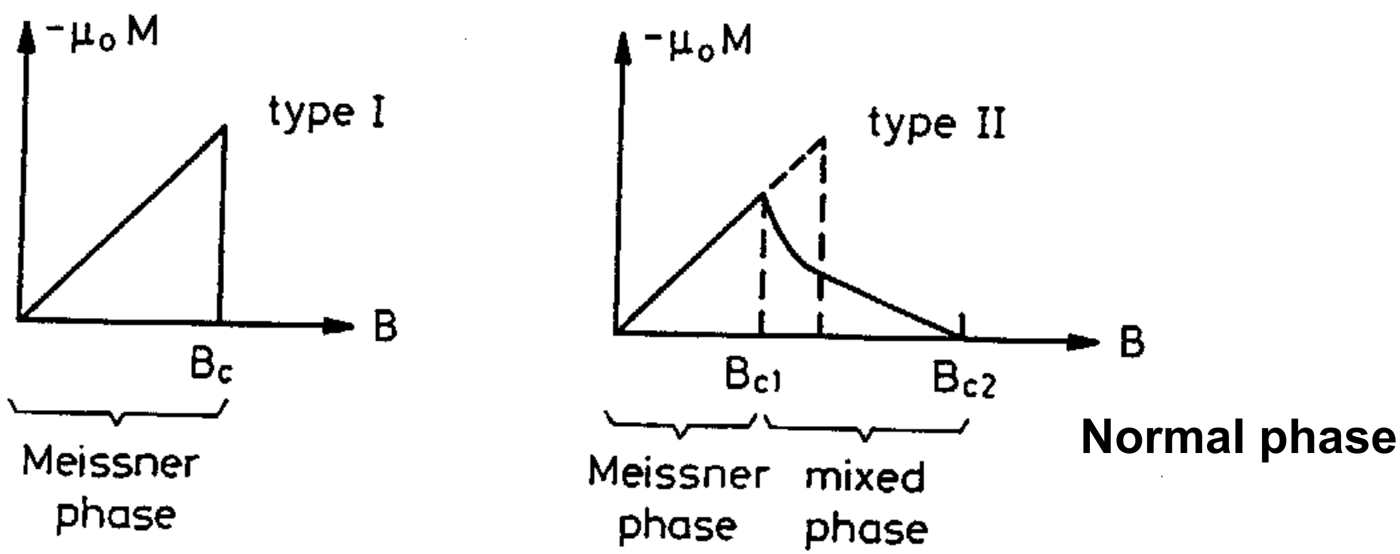


Figure 10: Magnetisation of type I and type II superconductors as a function of field.

Type I:

Also known as the "soft superconductors".

Completely exclude the flux lines.

Allow only small field (< 0.1 T).

Not good for accelerator magnets.

Type II:

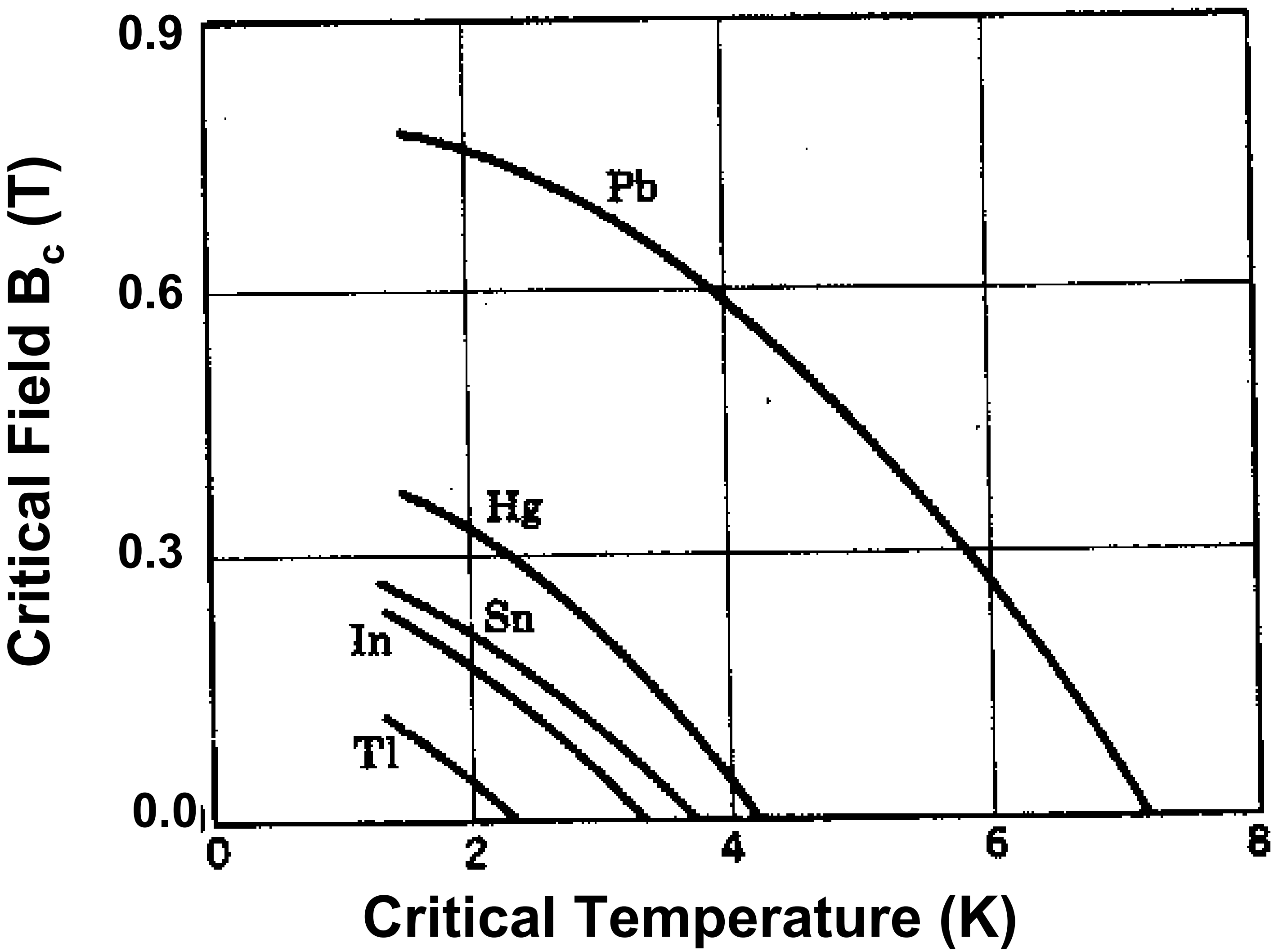
Also known as the "hard superconductors".

Completely exclude flux lines up to Bc_1 but then part of the flux enters till Bc_2

Important plus: Allow much higher fields.

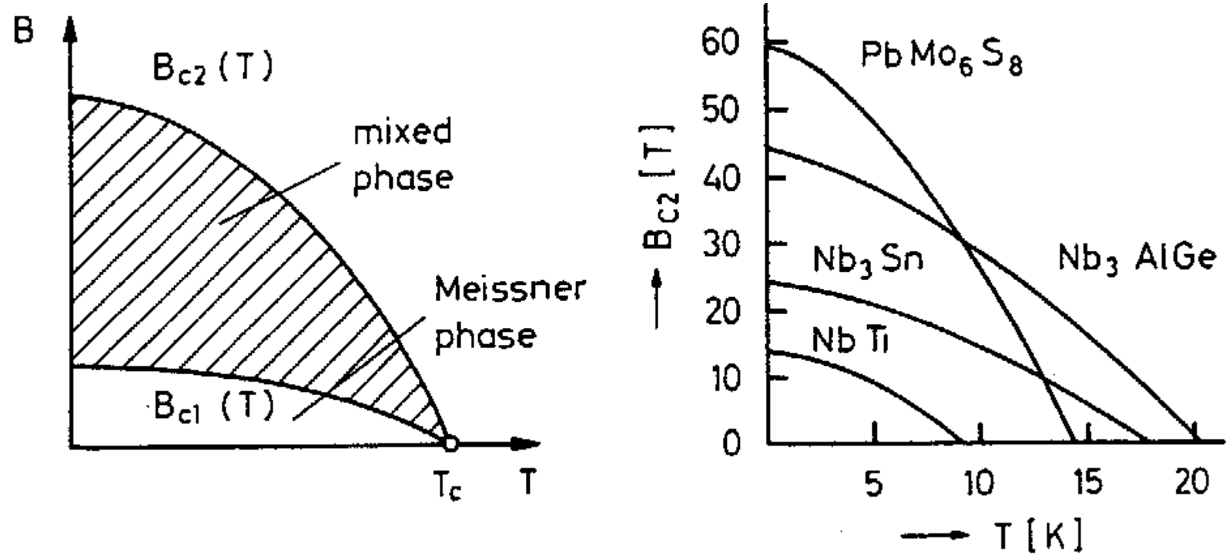
Examples: NbTi, Nb_3Sn

Critical Surface of Type I Superconductors



Type I superconductors are obviously NOT suitable for high field magnet applications.

Critical Surface of Type II Low Temperature Superconductors (LTS)



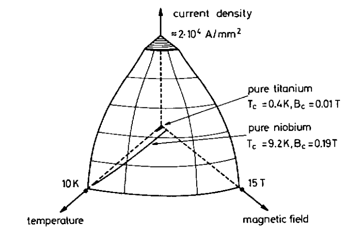


Figure 2.11: Sketch of the critical surface of NbTi. Also indicated are the regions where pure niobium and pure titanium are superconducting. The critical surface has been truncated in the regime of very low temperatures and fields where only sparse data are available.

Not shown here: MgB_2 (39 K)

Figure 12: (a) The phase diagram of a type II superconductor. (b) The upper cr several high-field alloys as a function of temperature.

- Conductors that are currently being used in building accelerator magnets are Type II Low Temperature Superconductors.
- NbTi, a ductile material, has been the conductor of choice so far. All accelerator machine magnets have been and are being built with this superconductor.
- For future high field magnet applications one must turn to Nb_3Sn, etc.(higher Bc_2). However, Nb_3Sn is brittle nature, and presents many challenge in building magnets.

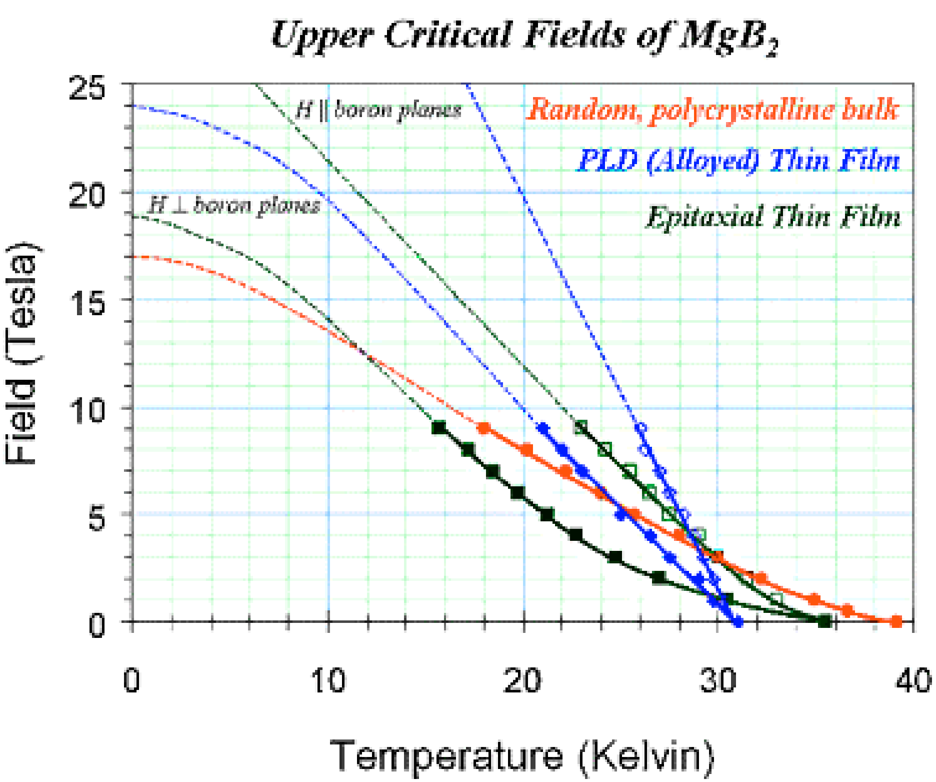
Magnesium Diboride (MgB_2)

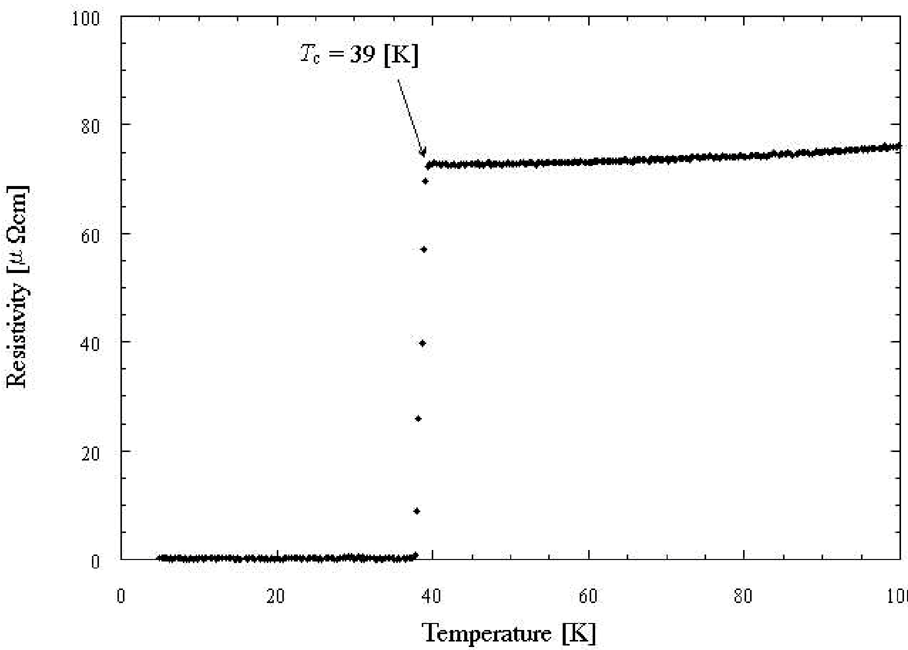
Magnesium Diboride (MgB_2)

Discovered in January 2001 (Akimitsu)

LTS with Tc: ~39 K

A low temperature superconductor with high T_c





The basic powder is very cheap, and abundantly available. The champion performance is continuously improving in terms of J_c and B_c. However, it is still not available in sufficient lengths for making little test coils.

London Penetration Depth and Coherence Length

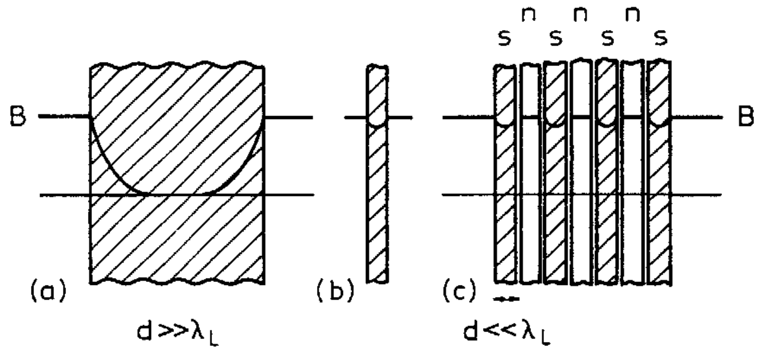


Figure 14: Attenuation of field (a) in a thick slab and (b) in thin sheet. (c) Subdivision of a thick slab into alternating layers of normal and superconducting slices.

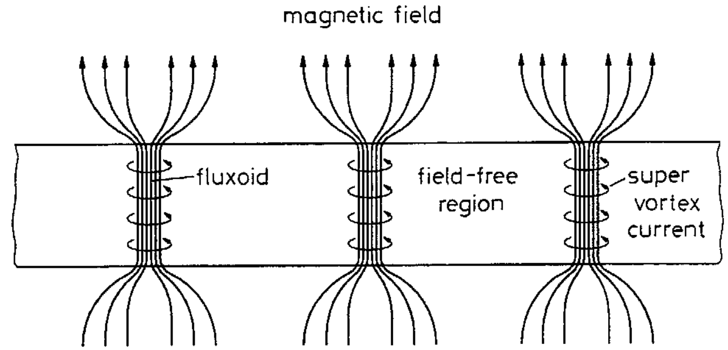
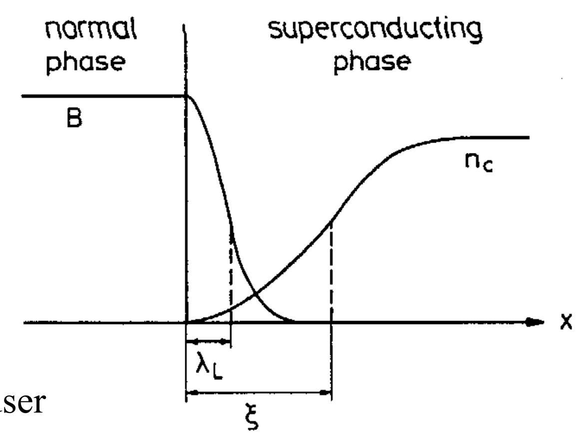


Figure 13: Flux tubes in a type II superconductor.



Courtesy: Schmuser

Figure 15: The decay of the magnetic field and the rise of the Cooper pair density at a normal-superconductor interface.

material	In	Pb	Sn	Nb
λ_L [nm]	24	32	≈ 30	32
ξ [nm]	360	510	≈ 170	39

Ginzburg-Landau Parameter

$$\kappa = \lambda_L / \xi$$

$$\text{type I:} \quad \kappa < 1/\sqrt{2}$$

$$\text{type II:} \quad \kappa > 1/\sqrt{2}.$$

- "London Penetration Depth" tells how field falls
- "Coherence Length" tells how does cooper pair density increases

Nb is type II superconductor

Current Transport in Bulk Superconductors

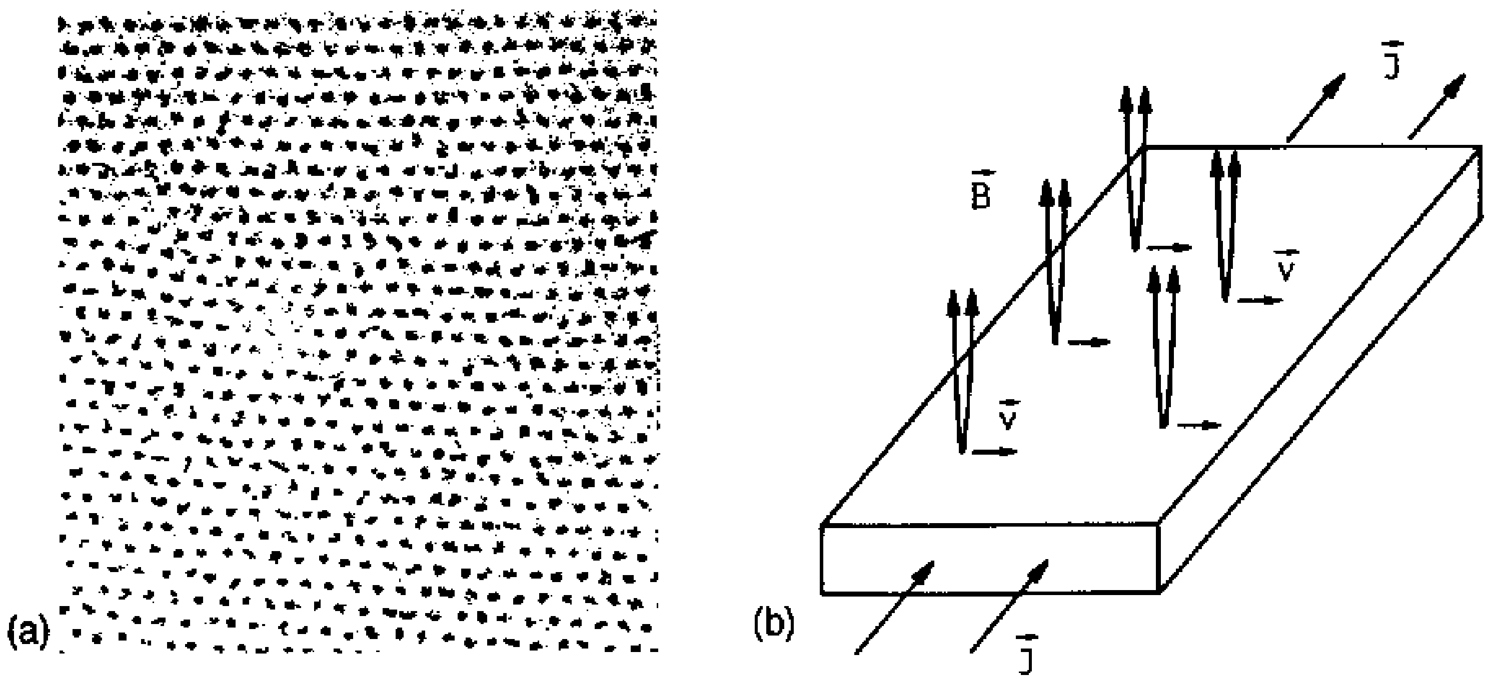
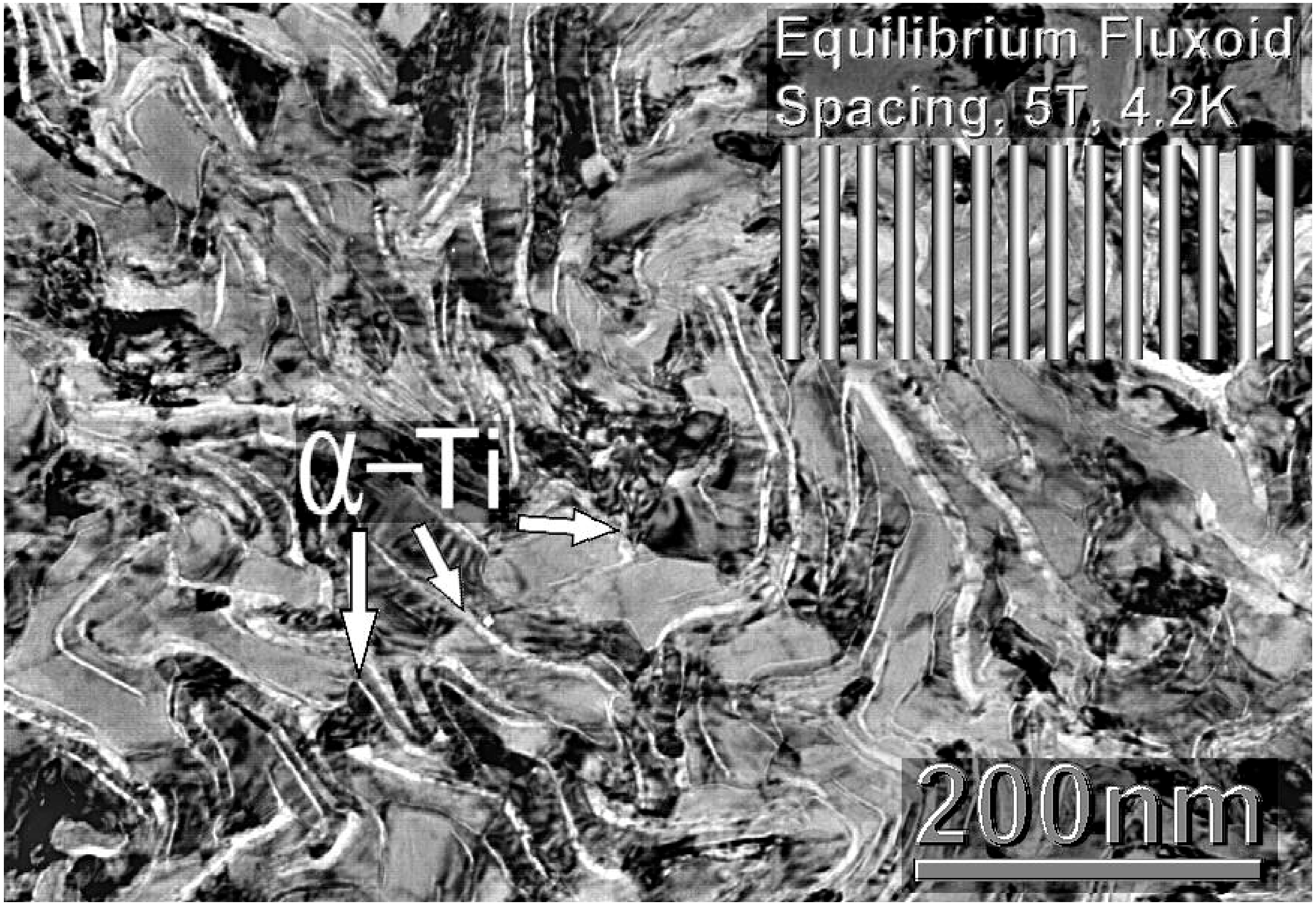


Figure 2.7: (a) Fluxoid pattern in niobium (courtesy U. Essmann). The distance between adjacent flux tubes is 0.2 μm. (b) Scheme of fluxoid motion in a current-carrying type II superconductor.

Courtesy: Schmuser

Motion of these fluxoids generates heat.

Nb-Ti Microstructure



A high critical current density microstructure in a conventionally processed Nb-Ti microstructure (UW strand).
Courtesy: P.J. Lee (University of Wisconsin-Madison)

Difference Between the Superconductor Requirements for Superconducting RF Cavities and Superconducting Magnets for Particle Accelerators

- **For superconducting RF cavities, one needs very high purity materials, with no defects.**

- **For superconducting magnets, the presence of certain defects is essential, as without those defects, it can not stand those high fields.**

Flux Jumping

Initially, when the field is raised, large screening current are generated to oppose the changes. These current densities may be much larger than J_c which will create Joule heating. However, these large currents soon die and attenuate to J_c, which persist.

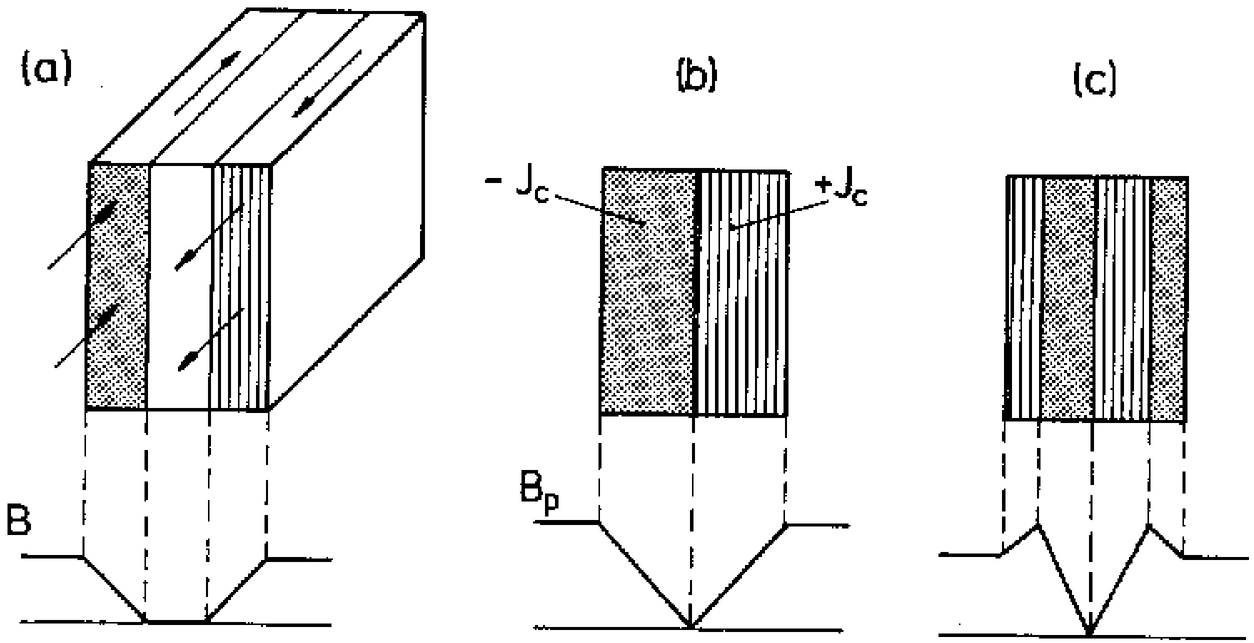


Figure 2.12: Current and field distribution in a slab of hard superconductor according to the critical-state model. The external field is parallel to the surface. (a) Initial exposition to a small external field. (b) The penetrating field B_p. (c) External field first raised above B_p and then lowered again.

Instability from Flux Jumping

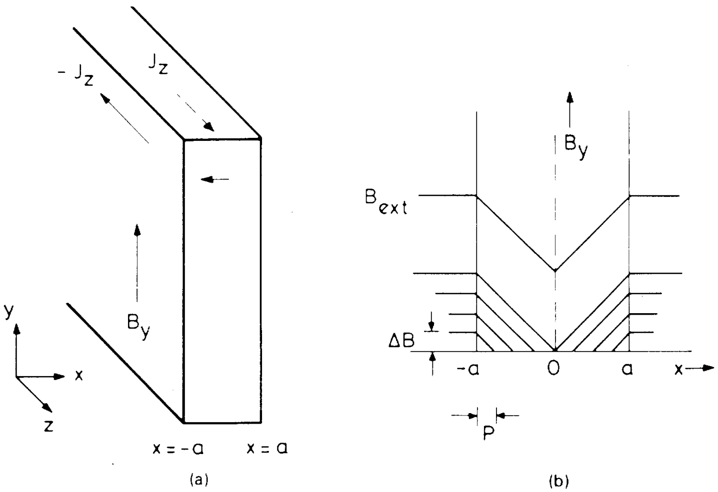
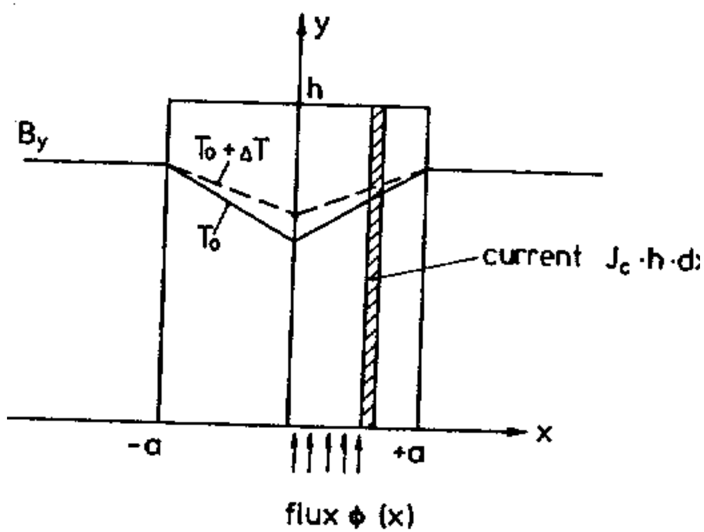


Fig. 7.1. (a) Screening currents induced to flow in a slab by a magnetic field parallel to the slab surface; (b) Magnetic field pattern across the slab showing the reduction of internal field by screening currents.



Flux Jumping

Unstable behaviour shown by all type 2 superconductors when subjected to a magnetic field

It arises because.

a) magnetic field induces screening currents, flowing at critical density

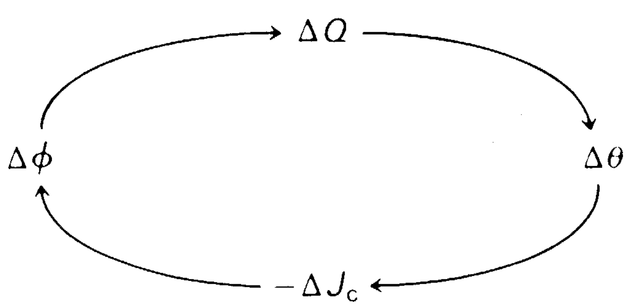
b) change in screening currents allows flux to move into the superconductor

c) flux motion dissipates energy

d) thermal diffusivity is low, so energy dissipation causes local temperature rise

e) critical current density falls with increasing temperature

f) go to b)



Courtesy: Wilson

Stability Criteria Against Flux Jumping

ΔQ heat increases temperature ΔT and reduces J_c by ΔJ_c

Calculate if this creates an unstable (runaway) situation?

$B(x) = B_o - \mu_o J_c (a-x) h$

$\phi(x) = Bo\, x - \mu_o J_c (ax - x^2/2) h$

Change in flux due to change in J_c: $\Delta\phi(x) = \mu_o \Delta J (ax - x^2/2) h$

Additional heat due to flux motion: $\Delta q = \int_0^x \Delta\phi(x) J_c\, dx = \mu o\; J_c\; \Delta J_c\; a^2/3$

To first order $\Delta J_c = J_c \Delta T / (T_c - T_o)$, thus $\Delta q = \mu_o J^2{}_c\, a^2 / [3(T_c - T_o)]\, \Delta T$

Total heat to raise the temperature: $\Delta Q + \Delta q = C\, \Delta T$

where C is specific heat per unit volume

$\Delta Q = C\, \Delta T - \Delta q = \{C - \mu_o J^2{}_c\, a^2 / [3(T_c - T_o)]\}\Delta T = C'\, \Delta T$

where $C' = \{C - \mu_o J^2{}_c\, a^2 / [3(T_c - T_o)]\}$ is the effective specific heat.

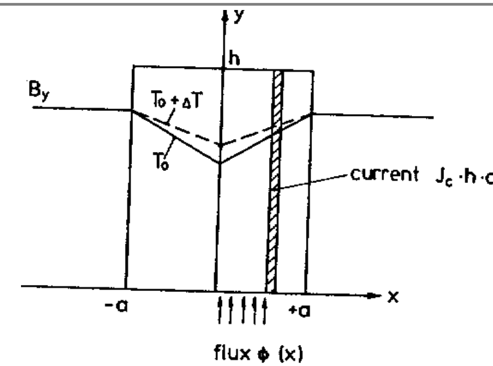
For stability condition, the effective specific heat must be positive.

This determines the maximum slab thickness "a" for stability

Similarly determine condition for filament of diameter r.

The computed filament diameter for flux stability in NbTi is < 40 μ;

for safety margin use ~ 20 μ.



Assignment:

Go through the expressions.

$$a < \sqrt{\frac{3C(T_c - T_o)}{\mu_o J_c^2}}$$

$$r < \frac{\pi}{4}\sqrt{\frac{3C(T_c - T_o)}{\mu_o J_c^2}}$$

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Superconducting
Magnet Division

Magnetization Effects in Superconducting Filaments

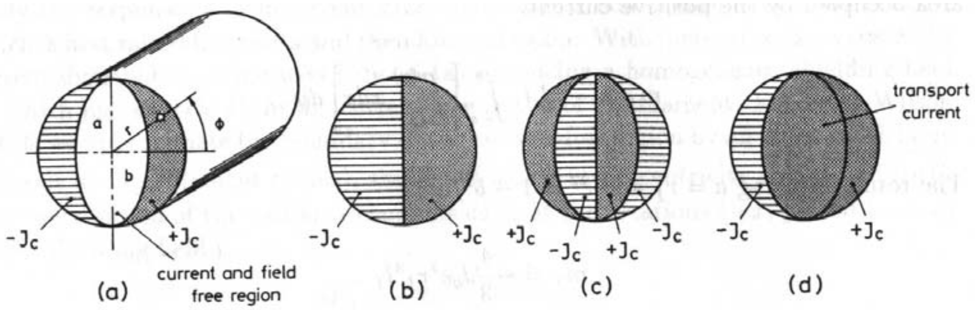


Figure 6.1: Schematic view of the persistent currents which are induced in a superconducting filament by a varying external field. (a) The external field is raised from zero to a value B_e less than the penetrating field B_p. (b) A 'fully-penetrated' filament, i.e. $B_e \geq B_p$. (c) Current distribution which results when the external field is first increased from zero to a value above B_p and then decreased again. (d) Same as (b) but with a large transport current.

Courtesy: Schmuser

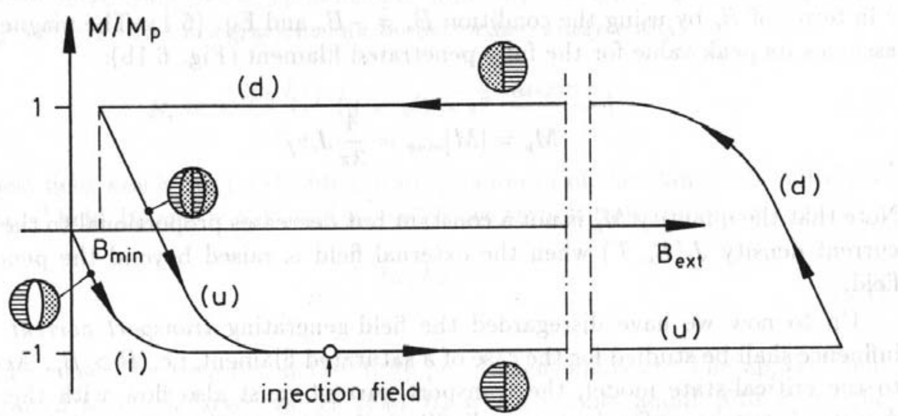


Figure 6.2: The normalized magnetization M/M_p of a NbTi filament as a function of the external field. (i): initial curve, (u): up-ramp branch, (d): down-ramp branch. Also shown are the current distributions in the filament. The field dependence of J_c has been neglected.

The above magnetization creates persistent current, a major issue in SC magnets.

Persistent current induced magnetization:

$$2\mu_0 M = 2\mu_0 \frac{2}{3\pi} \nu J_c d \qquad (1)$$

J_c , CRITICAL CURRENT DENSITY

d , FILAMENT DIAMETER

ν , VOL. FRACTION OF NbTi

$$M_s = M/\nu \qquad (2)$$

Persistent Current-induced Harmonics in High Field (Nb_3Sn Magnets)

Persistent current induced magnetization :

$$2\mu_0 M = 2\mu_0 \frac{2}{3\pi} \nu J_c d \quad (1)$$

J_c , CRITICAL CURRENT DENSITY

d , FILAMENT DIAMETER

ν , VOL. FRACTION OF NbTi

$$M_s = M/\nu \quad (2)$$

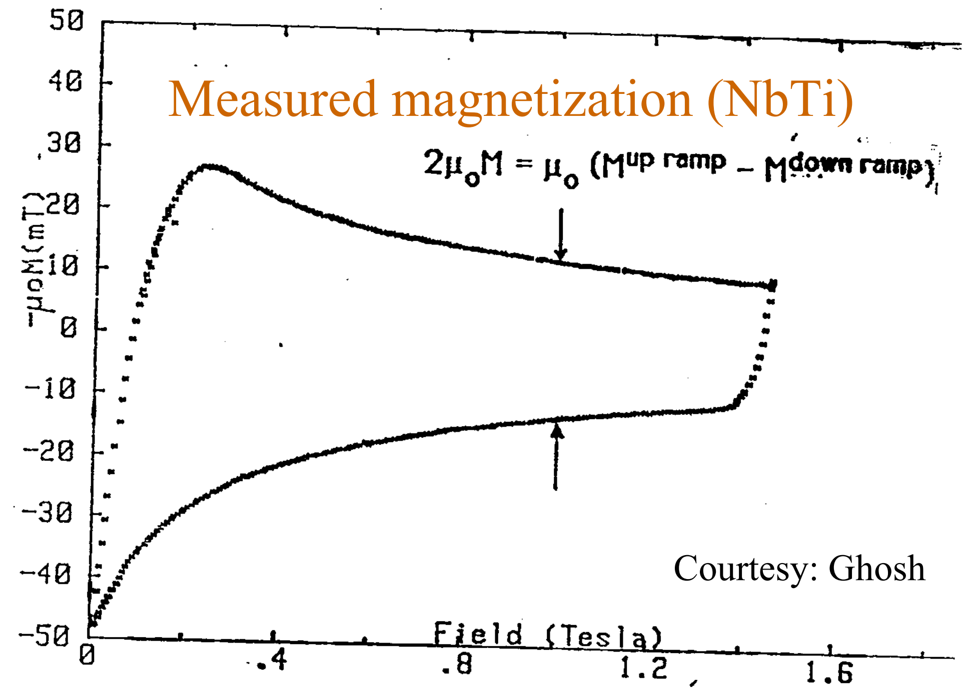


Fig. of a typical magnetization loop.

Problem in Nb_3Sn Magnets because

(a) Jc is higher by several times

(b) Filament size is big and gets bigger after reaction due to sintering

In most Nb_3Sn available today, the effective filament diameter is an order of magnitude larger than that in NbTi. The obvious solution is to reduce filament diameter; however, in some cases it also reduces J_c.

A small filament diameter is important for :

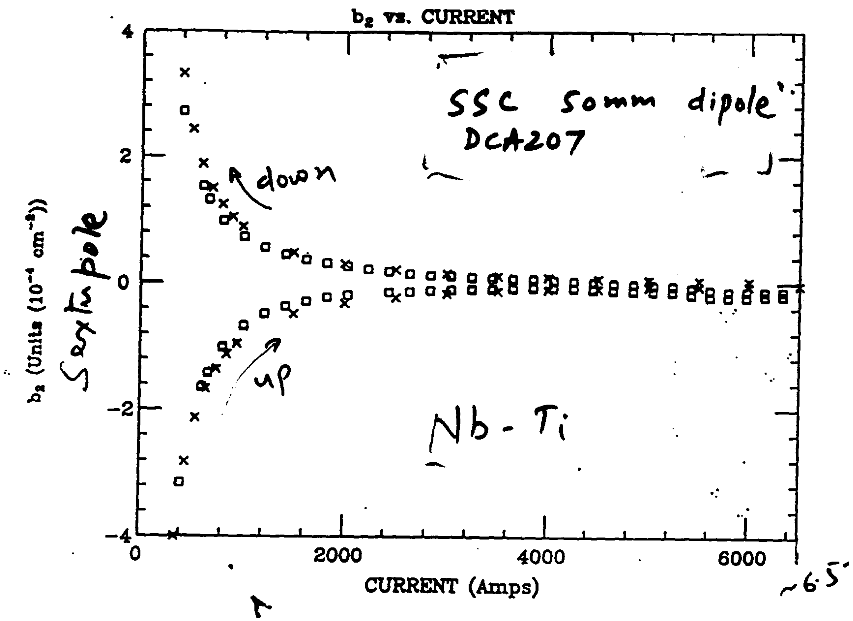
- **increasing stability**
- **reducing persistent currents**

Persistent Current-induced Harmonics
(may be a problem in Nb_3Sn magnets, if done nothing)

Nb_3Sn superconductor, with the technology under use now, is expected to generate persistent current-induced harmonics which are **a factor of 10-100 worse** than those measured in Nb-Ti magnets.

In addition, a snap-back problem is observed when the acceleration starts (ramp-up) after injection at steady state (constant field).

Measured sextupole harmonic in a Nb-Ti magnet



Measured sextupole harmonic in a Nb_3Sn magnet

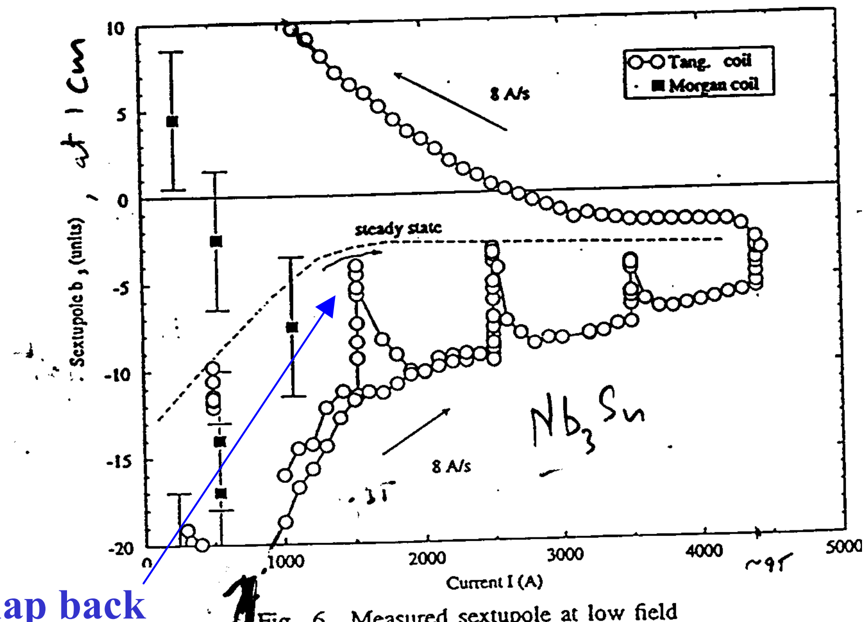
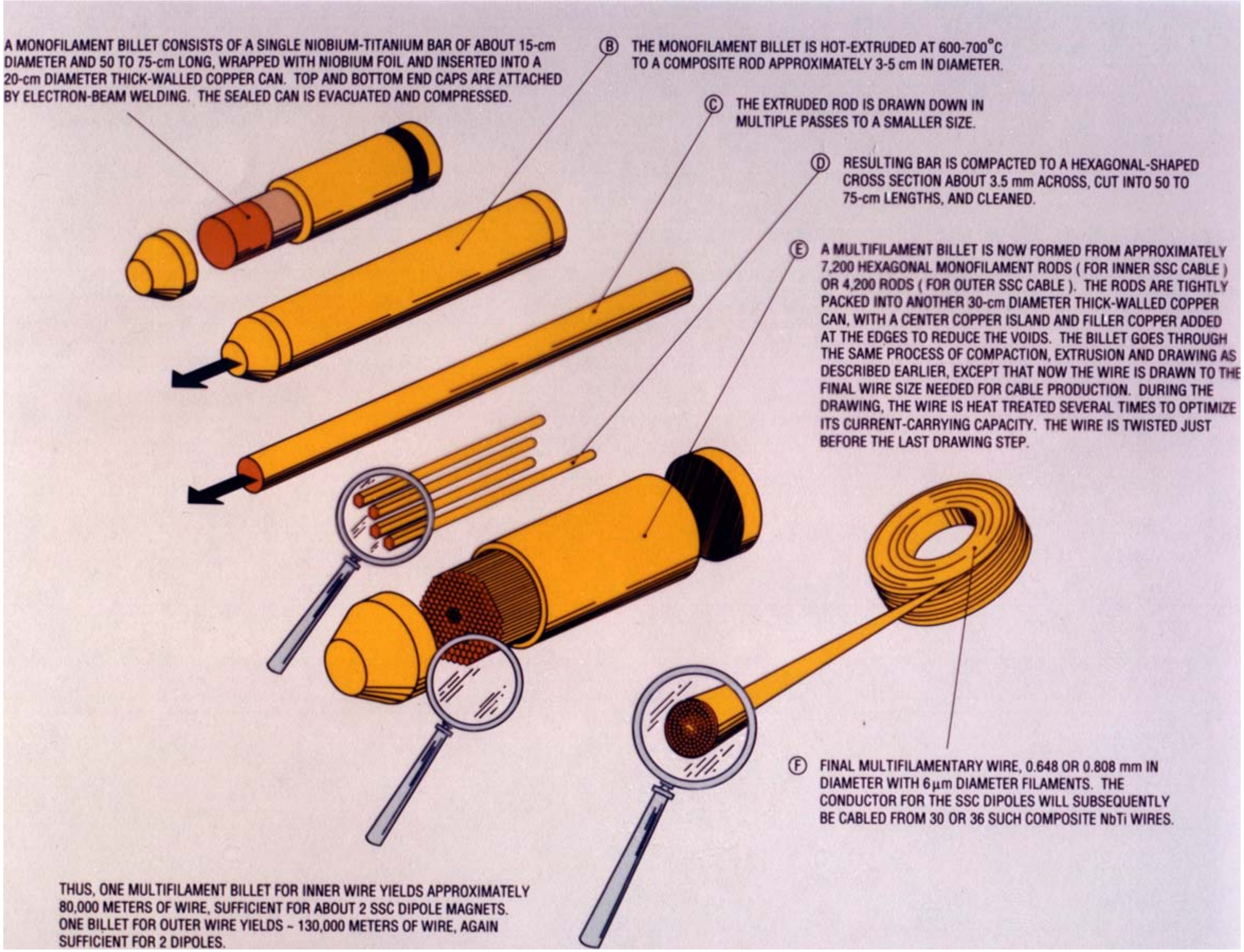


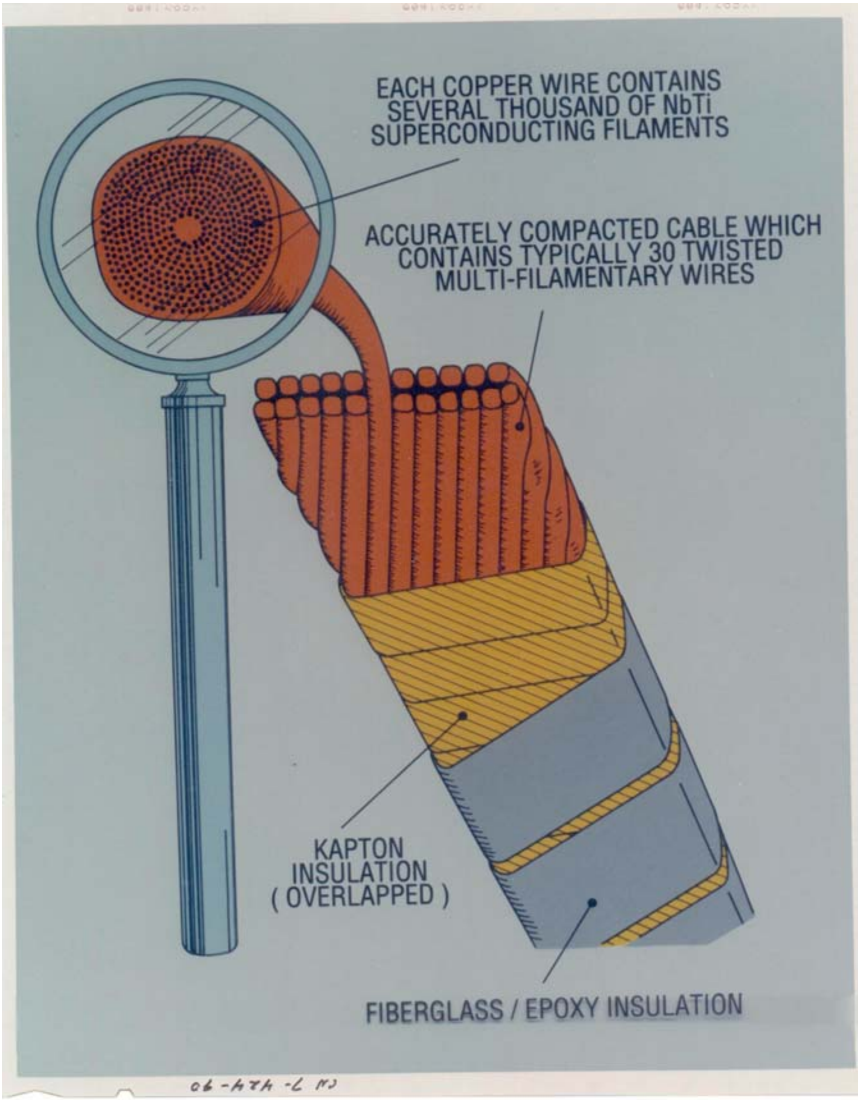
Fig. 6. Measured sextupole at low field (direction of arrow indicates up or down current).

Either reduce the effective filament diameter or come up with a magnetic design that minimizes the effect of magnetization in the magnets (LBL, FNAL, TAMU).

Manufacturing of Nb-Ti Wires



A Typical Superconducting Cable

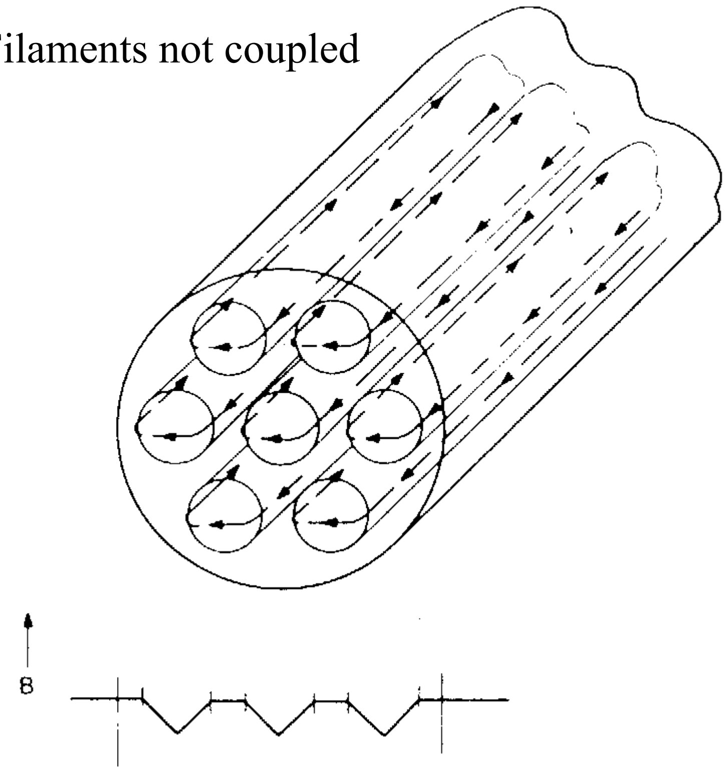


Filaments in an actual cable

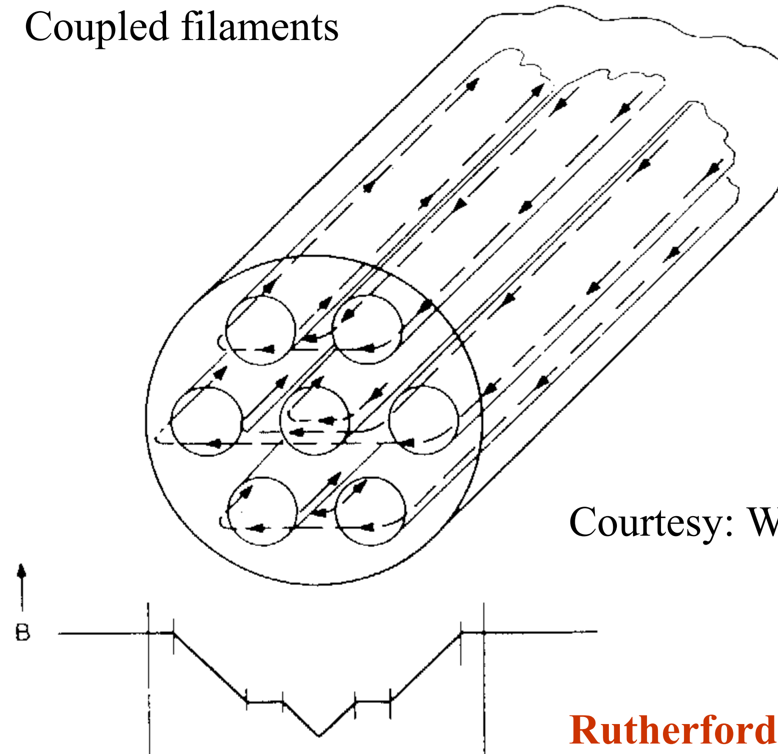
(Filament size in SSC/RHIC magnets: 6 micron)

Stability of Superconducting Wire (Wire is Made of Many Filaments)

Filaments not coupled



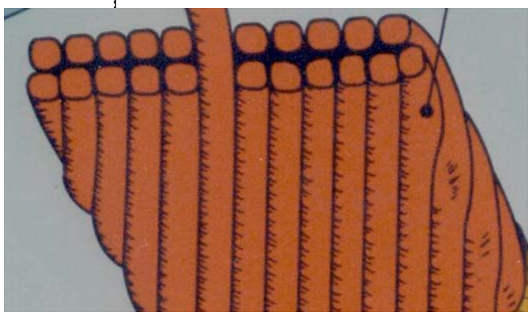
Coupled filaments



Courtesy: Wilson

A wire composed of twisted filaments

Rutherford cable



Interstrand Coupling

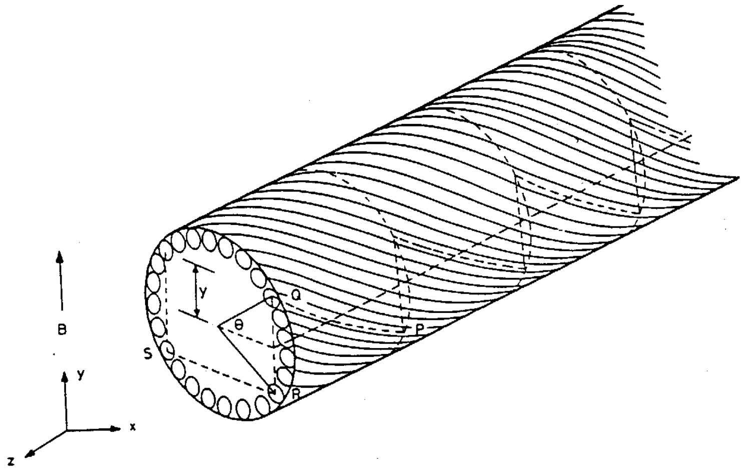
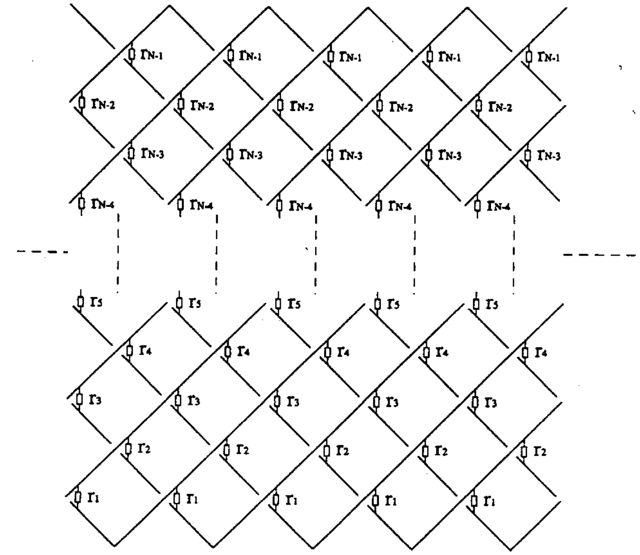


Figure 3-7 Multifilamentary Composite [28]



a) Overall Circuit

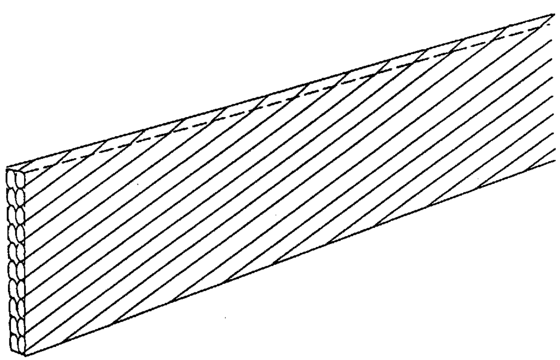
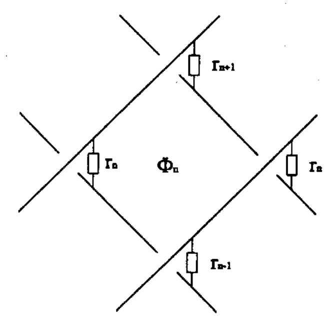


Figure 3-8 Rutherford-type Cable



b) Single Loop

Figure 3-9 Equivalent Circuit for Rutherford-type Cable

Courtesy: Devred

Influence of Interstrand Coupling

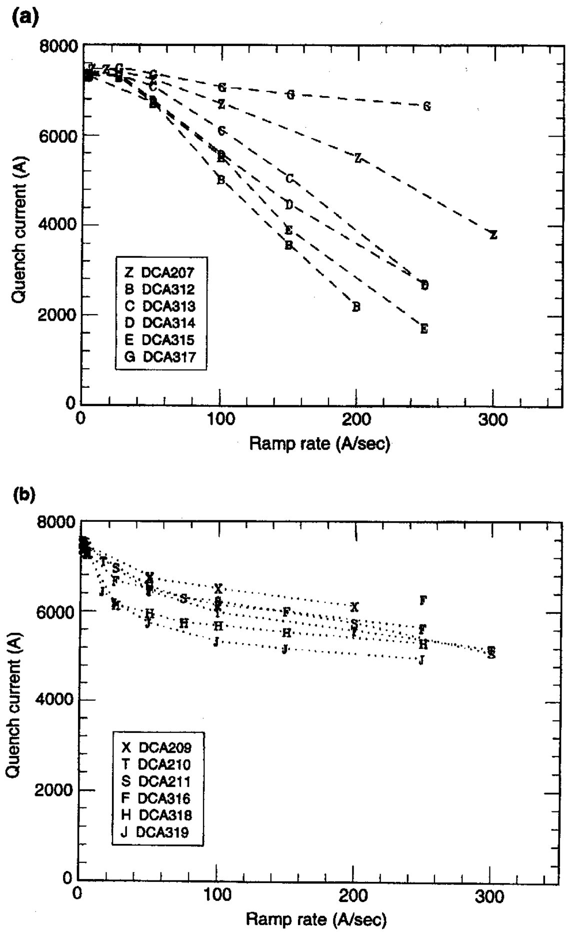
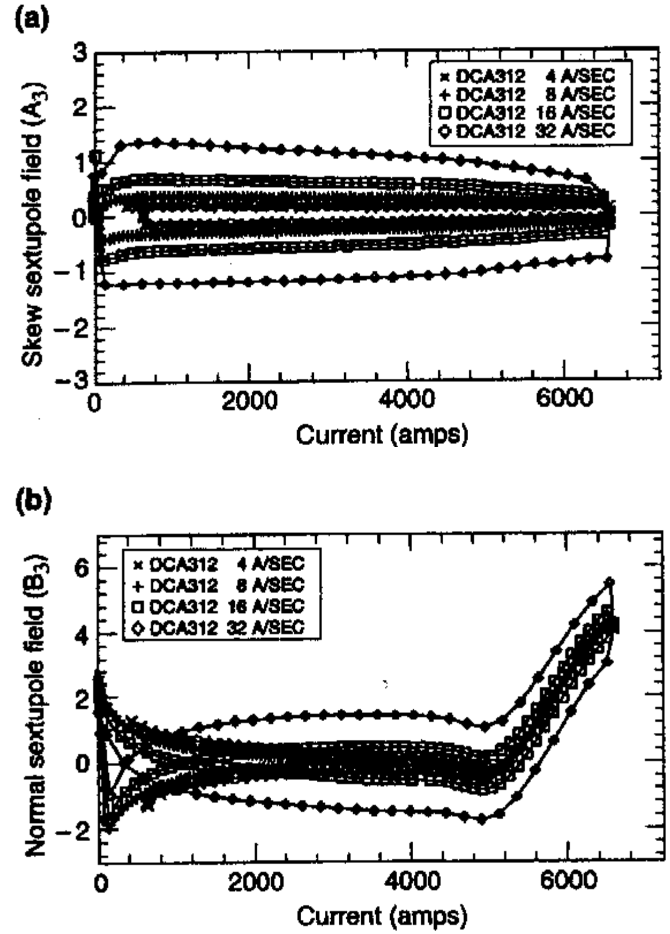


Figure 58. Ramp rate sensitivity of selected 5-cm-aperture, 15-m-long SSC dipole magnet prototypes: (a) Type A and (b) Type (b). (The magnets are grouped according to the manufacturer and the production batch of their inner cable strands.)

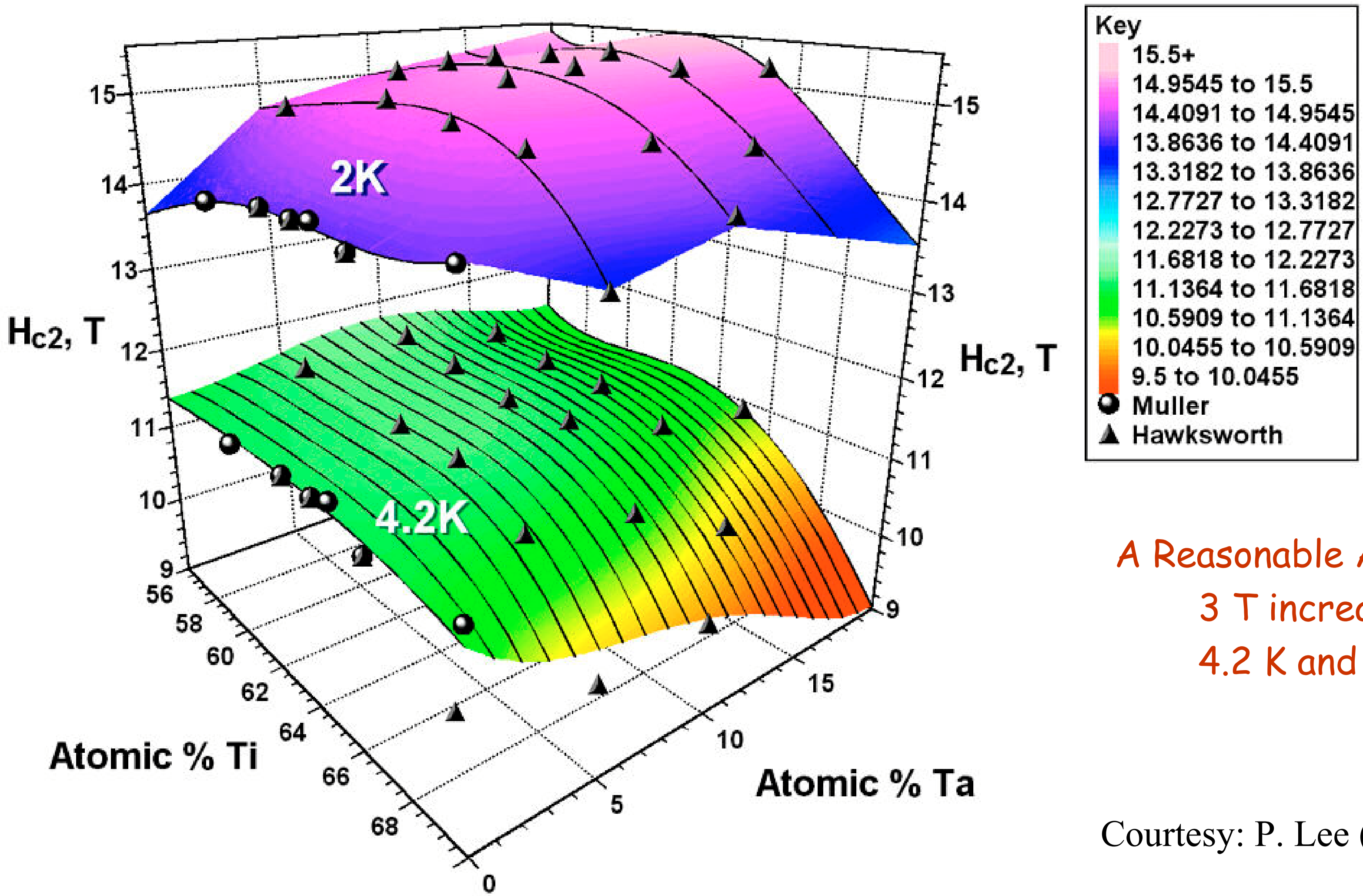


Effects of interstrand coupling currents on multipole field coefficients measured as a function of ramp rate in the central part of a SSC dipole magnet [160]: (a) skew sextupole field coefficient (A_3) and (b) normal sextupole field coefficient (B_3). The transport-current contribution has been subtracted from the data.

Courtesy: Devred

Nb-Ti Alloys at 4.2 K and 1.8 K

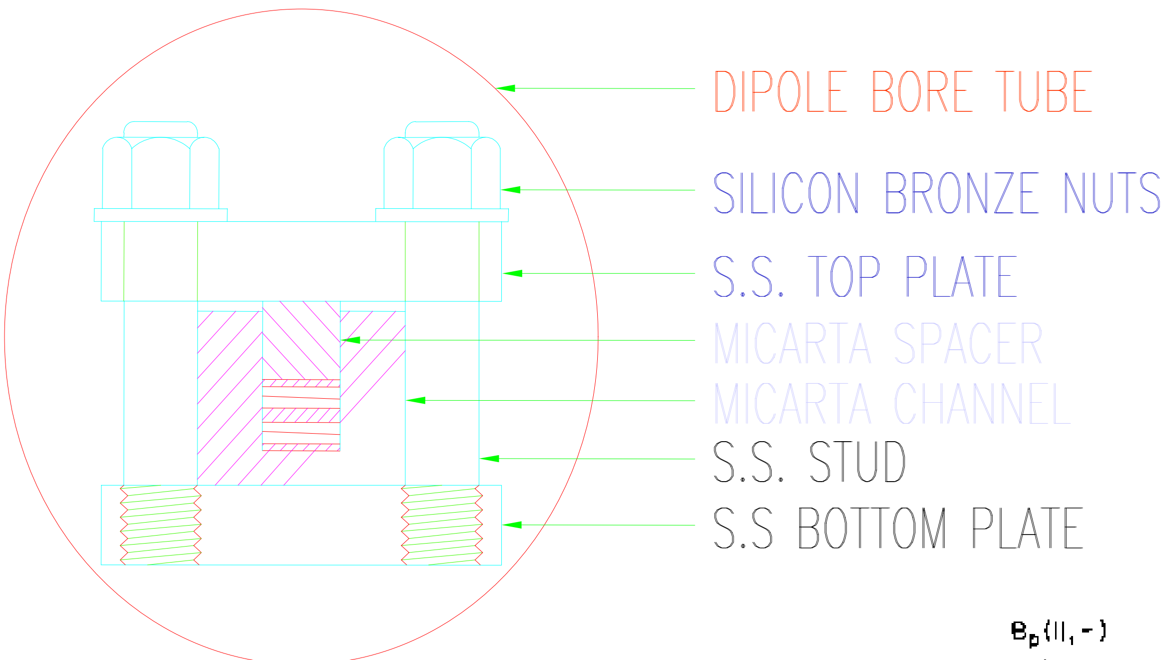
LHC will operate at 1.8 K; all current accelerators operate at ~4.5 K. All use Nb-Ti.

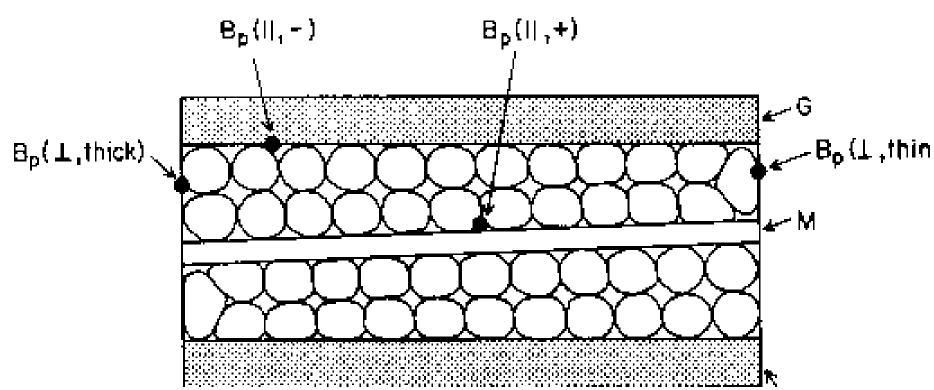


A Reasonable Assumption:
3 T increase between
4.2 K and 1.8 K

Courtesy: P. Lee (U Of W-M)

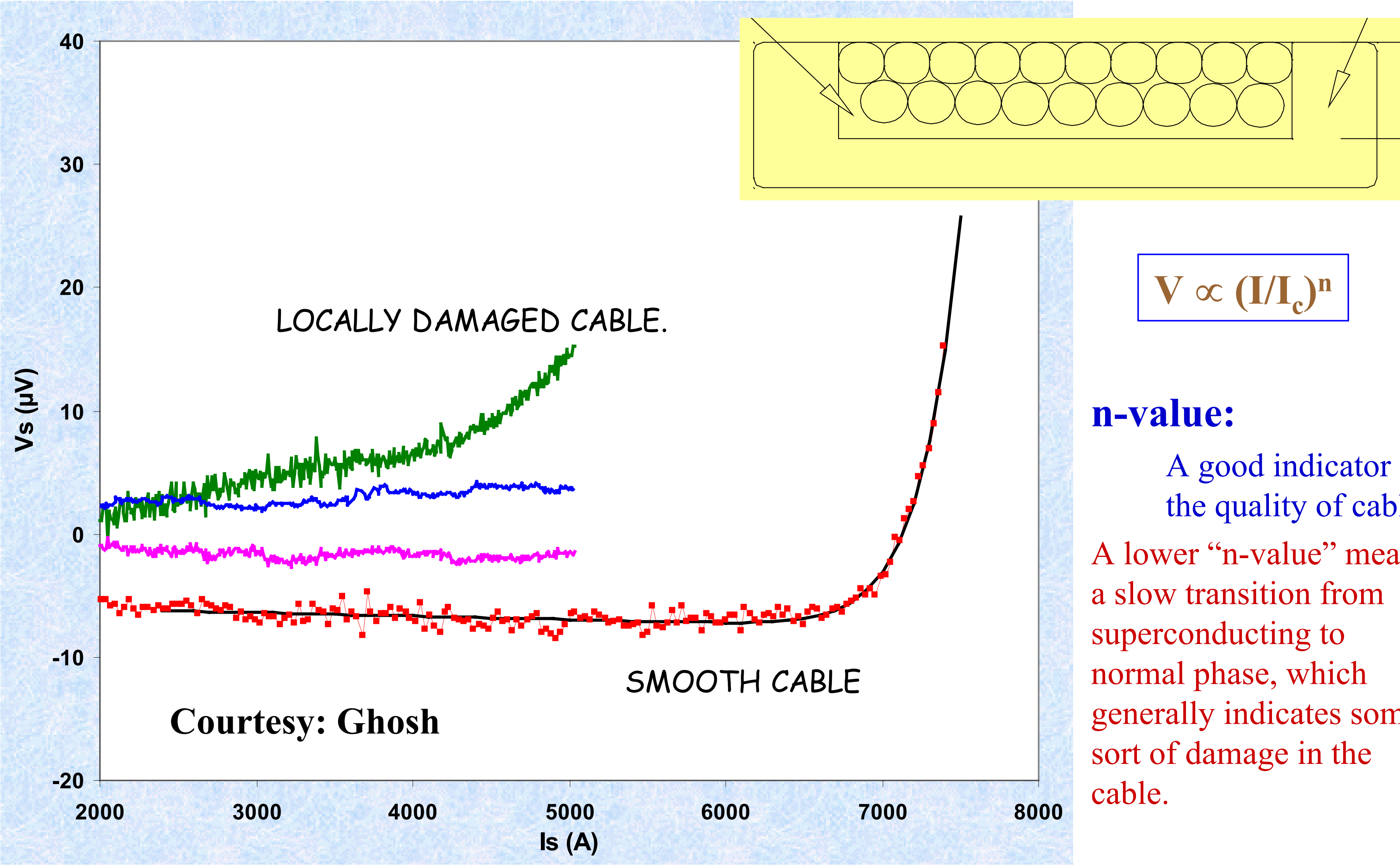
Cable Measurement Set-up





Courtesy: Ghosh

Nb3Sn Cable in Cu- Channel



$V \propto (I/I_c)^n$

n-value:

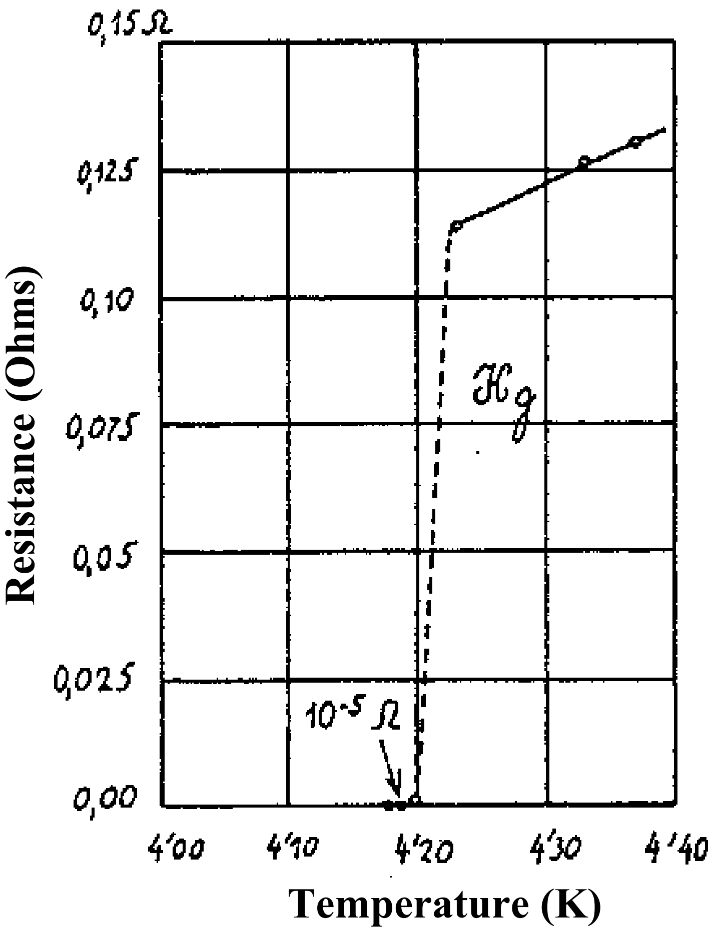
A good indicator of the quality of cable.

A lower "n-value" means a slow transition from superconducting to normal phase, which generally indicates some sort of damage in the cable.

The Conventional Low Temperature Superconductors (LTS) and the New High Temperature Superconductors (HTS)

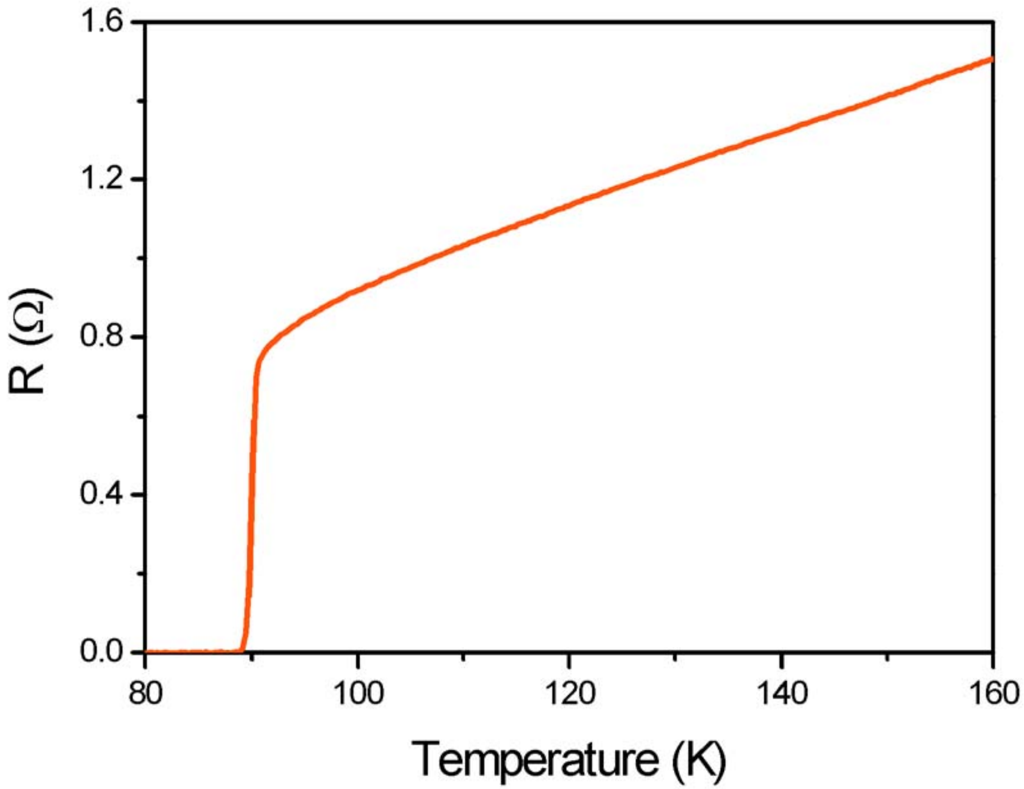
Low Temperature Superconductor Onnes (1911)

Resistance of Mercury falls suddenly below meas. accuracy at very low (4.2) temperature



New materials (ceramics) loose their resistance at NOT so low temperature (Liquid Nitrogen)!

High Temperature Superconductors (HTS)



Critical Surface of High Temperature Superconductors (HTS)

HTS (this example, BSCCO2212) can operate at a temperature much higher than ~4 K required for conventional LTS; say 20K (or even more).

Field perpendicular

C.M. Friend et al. / Physica C 258 (1996) 213–221 215

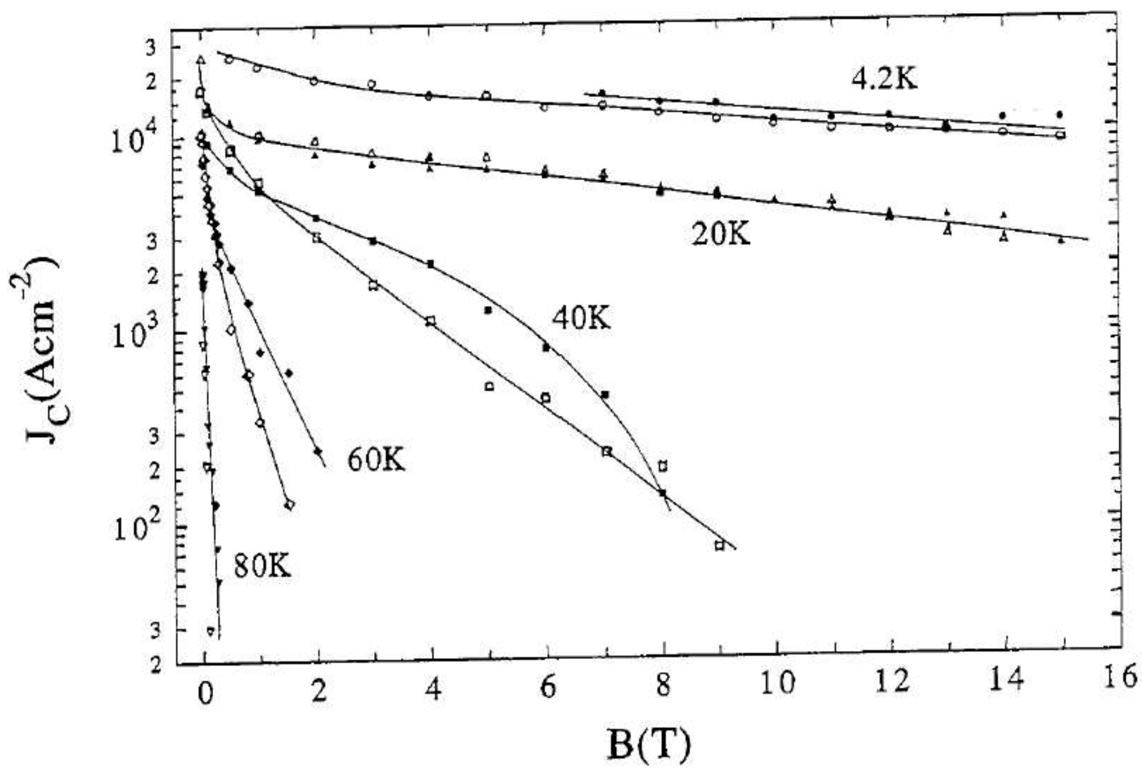


Fig. 2. $J_c(B, T)$ for the 19 filament wire (open symbols) and 37 filament wire (closed symbols) for the perpendicular field orientation.

Critical Surface of High Temperature Superconductors (HTS)

HTS (this example, BSCCO2212) can operate at a temperature much higher than ~4 K required for conventional LTS; say 20K (or even more).

Field parallel case is better (lower drop in Jc)
C.M. Friend et al., Physica C (1996)

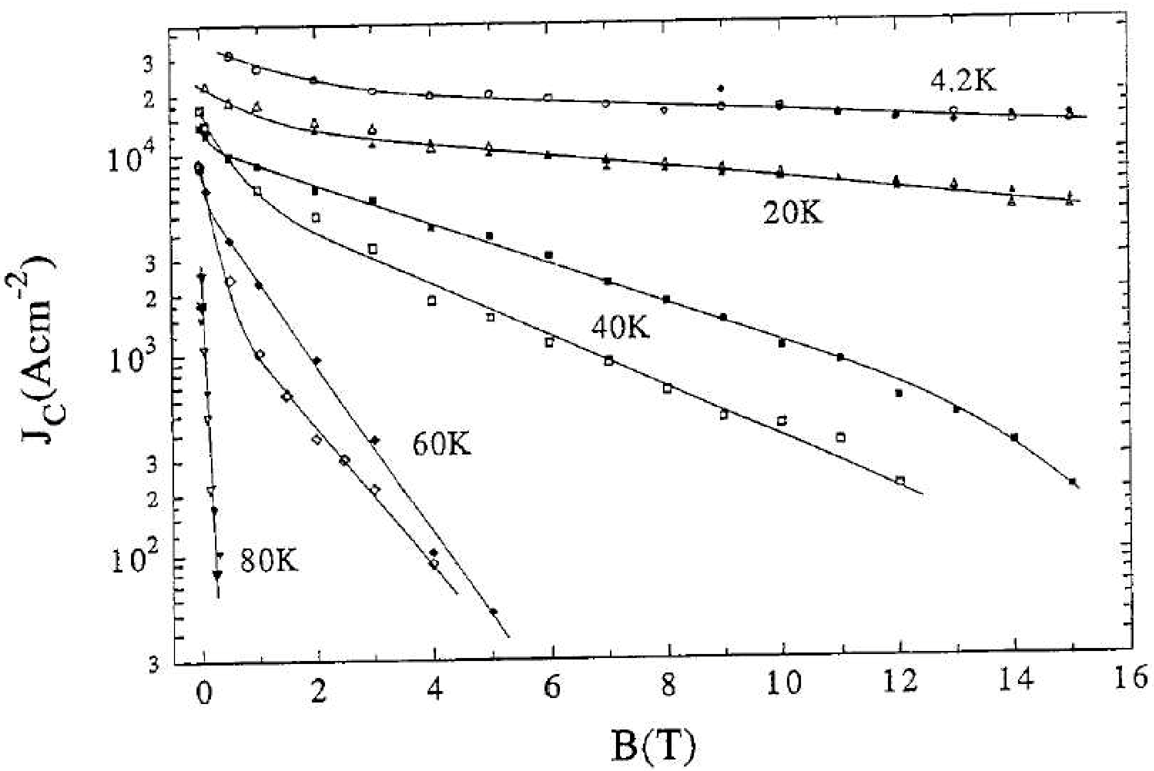


Fig. 3. $J_c(B, T)$ for the 19 filament wire (open symbols) and 37 filament wire (closed symbols) for the parallel field orientation.

Popular HTS Materials of Today

- BSCCO 2223 $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$
- BSCCO 2212
- YBCCO

- MgB_2 is technically a low temperature superconductor (LTS) with critical temperature ~39 K.

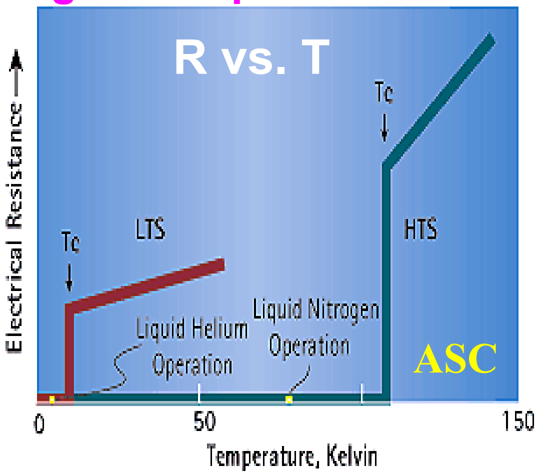
Of these only BSCCO2212 and BSCCO2223 are now available in sufficient quantity to make accelerator magnets.

BROOKHAVEN NATIONAL LABORATORY

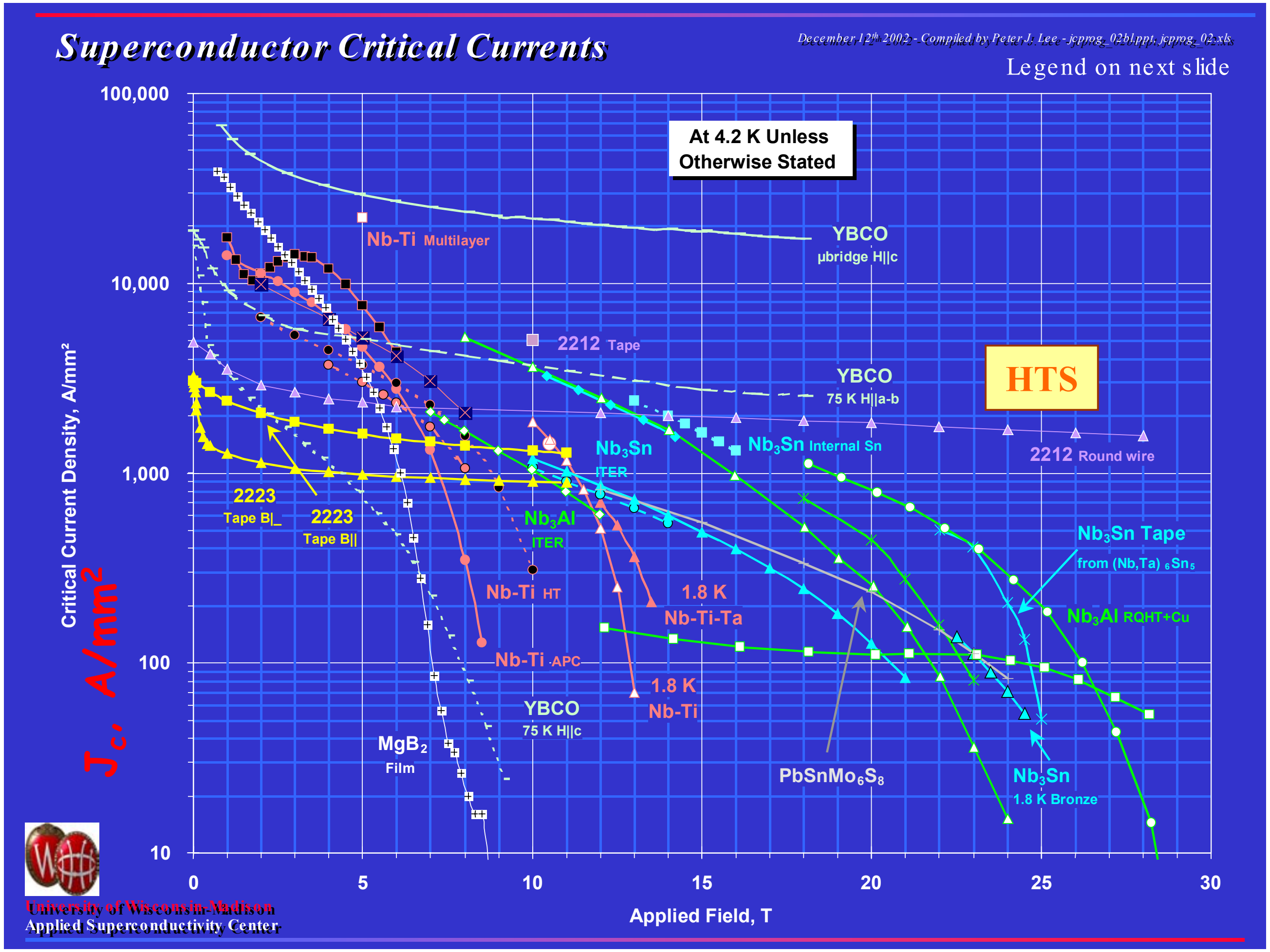
Superconducting Magnet Division

Some Remarkable Properties of HTS (High Temperature Superconductors)

HTS retain superconductivity to higher temperature



Also compare the high field performance of "High Temperature Superconductors (HTS)" as compared to that of "Low Temperature Superconductors (LTS)".



Applied Field, T

High Field Superconductors

Differences between Low field and high field superconductors:

Low field superconductors (NbTi) are ductile.

The coils can be wound without significantly damaging the conductors.

High field superconductors (Nb_3Sn and HTS) are brittle!

One has to be very careful in winding coil with these brittle material or use alternate design to minimize the damage on conductors.

One can also wind the coil before they become brittle (& superconducting) and react the material after winding to make them superconductor.

This is referred to as "*Wind and React*" technique and it requires everything in the coil to go through the high temperature (650 C or more) reaction process. One has to be careful in choosing material, etc.

Usable Current Densities in Coils

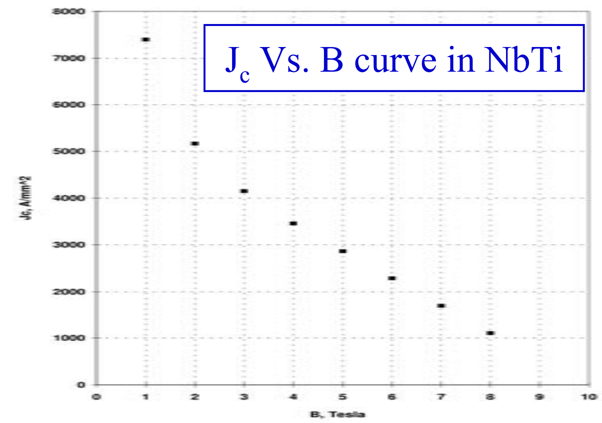
Even though the superconductor may be capable of carrying a current density of 3000 A/mm^2 or so, only a fraction of that is available to power the magnet.

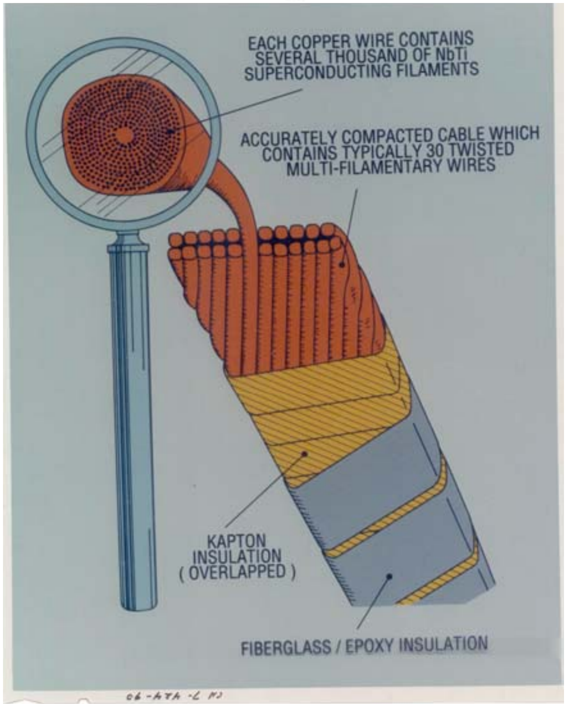
Here is why?

• There should be enough copper within the wire to provide stability against transient heat loads and to carry the current in the event superconductor turns normal. Usually copper content is more than superconductor. In most NbTi medium field production magnets, the maximum current density in copper is 1000 A/mm^2 or less at the design field. In high field Nb_3Sn R&D magnets, we are allowing it to be twice that.

• The trapezoidal "Rutherford cable" is made of several round wire. The fill factor may be 90% or so.

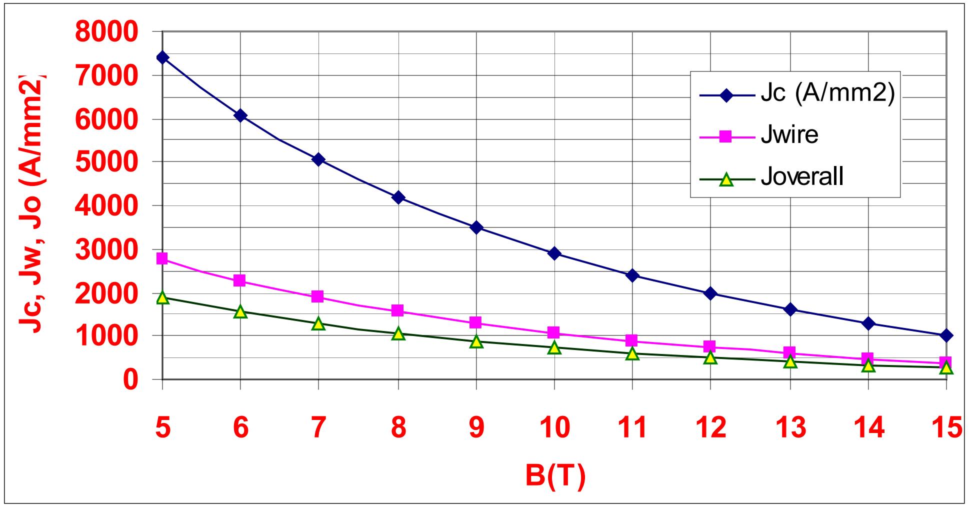
• The coil is consisted of many turns. There must be a turn-to-turn insulation taking ~15% of the volume.



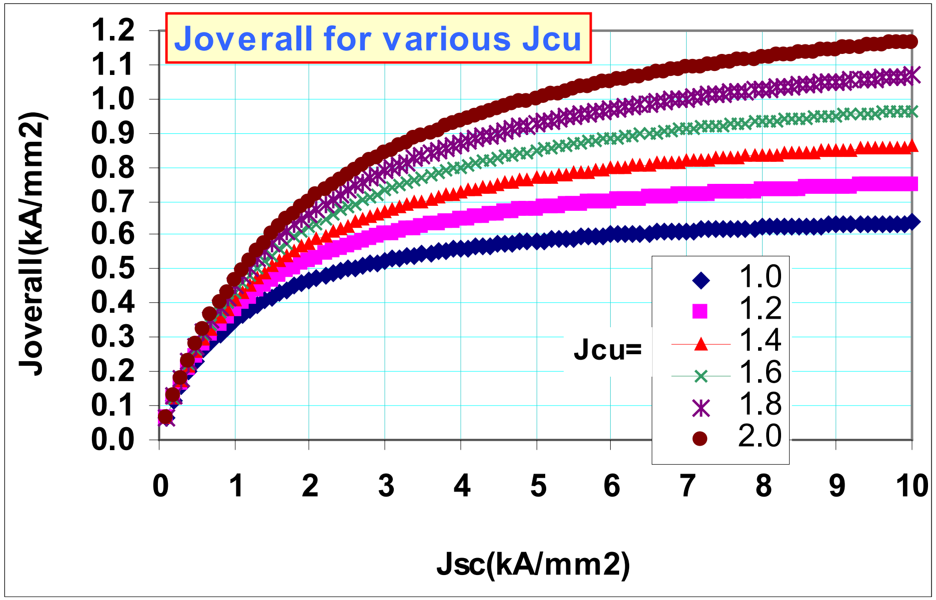


Usable Current Densities in Coils

The example on the right is for a Nb_3Sn superconducting cable with Cu/Sc ratio fixed at 1.7. Note that overall current density in the coil is only ¼ of the superconductor current density.



In the example on the right, the overall current density is computed to keep current density in copper at a given value.



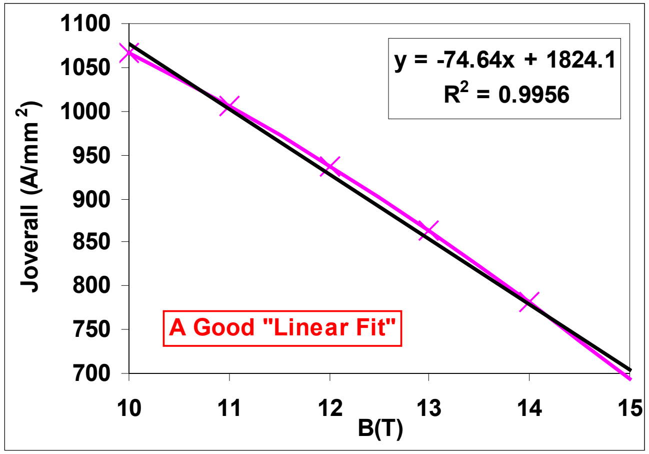
BROOKHAVEN NATIONAL LABORATORY

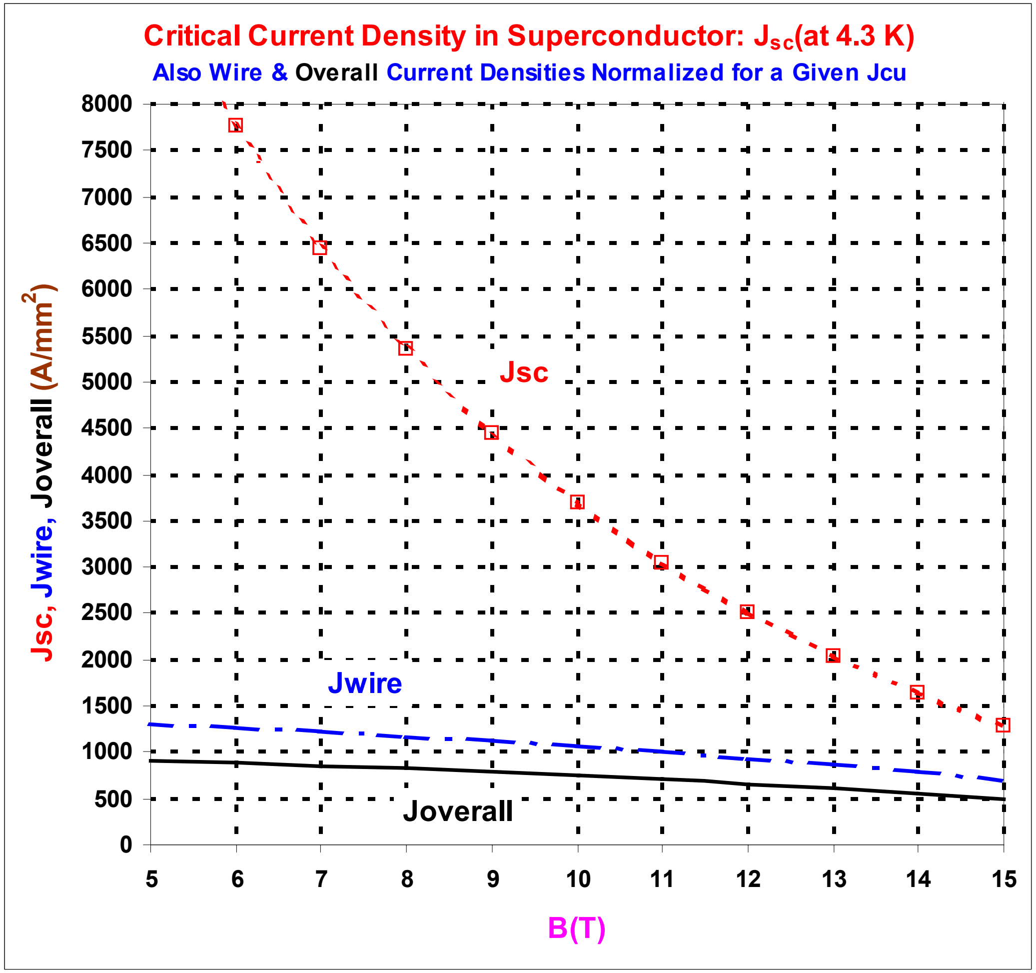
Superconducting Magnet Division

Usable Current Density in Magnet Design (A case study of Nb_3Sn for fix J_{cu} at quench)

J_{sc}(12T,4.3K)	J_{cu}(A/mm^2)
2500	1500

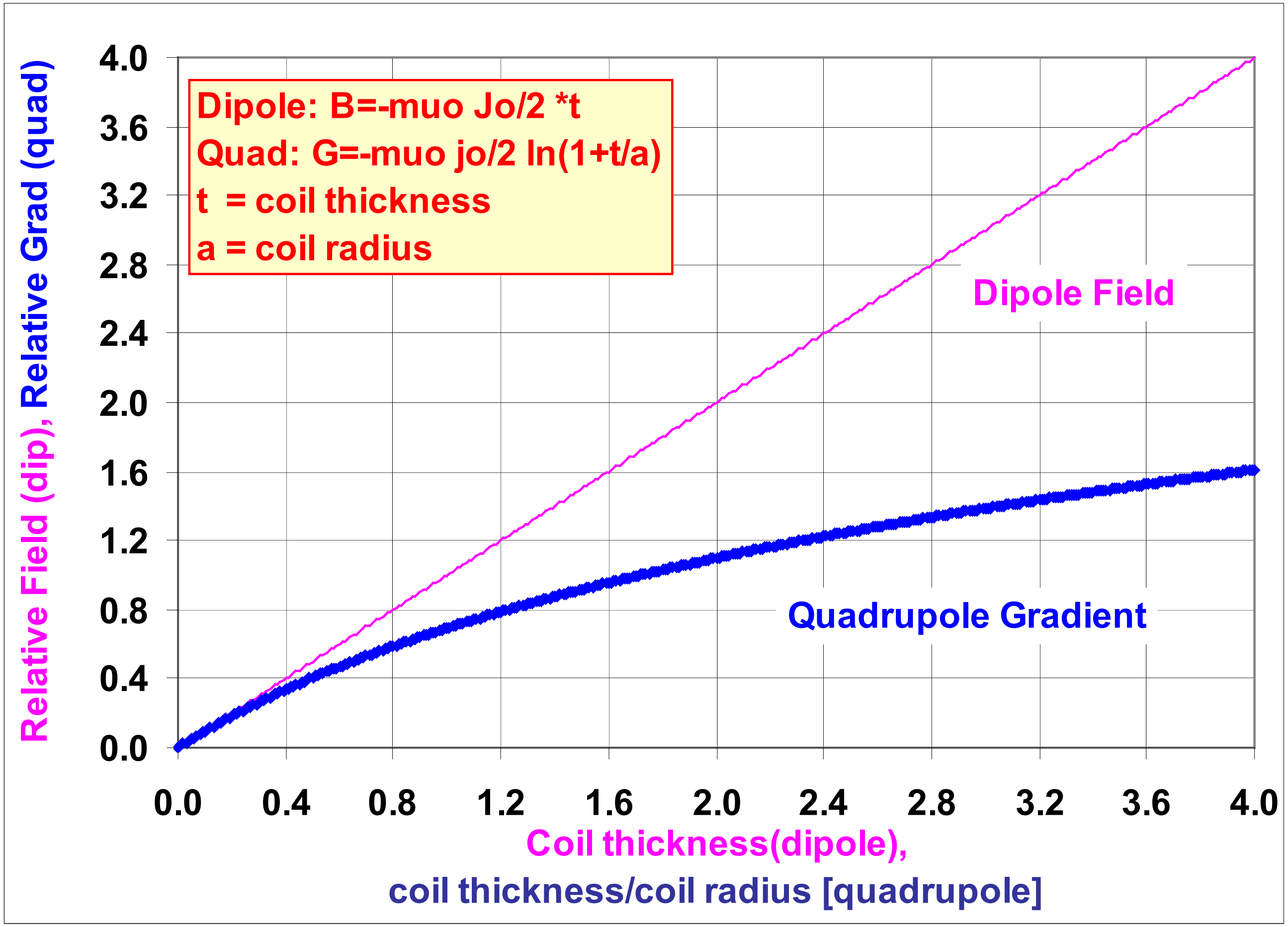
Cu/Sc Ratio	B(T)	J_c(A/mm^2)	J_{wire}(A/mm^2)	Joverall
6.30	5	9454	1295	911
5.18	6	7766	1257	885
4.29	7	6431	1216	856
3.56	8	5347	1171	825
2.96	9	4446	1122	790
2.46	10	3689	1066	751
2.03	11	3048	1005	708
1.67	12	2500	938	660
1.35	13	2031	863	607
1.09	14	1631	781	550
0.86	15	1289	693	488
	Scaled from TWCA			Insulated





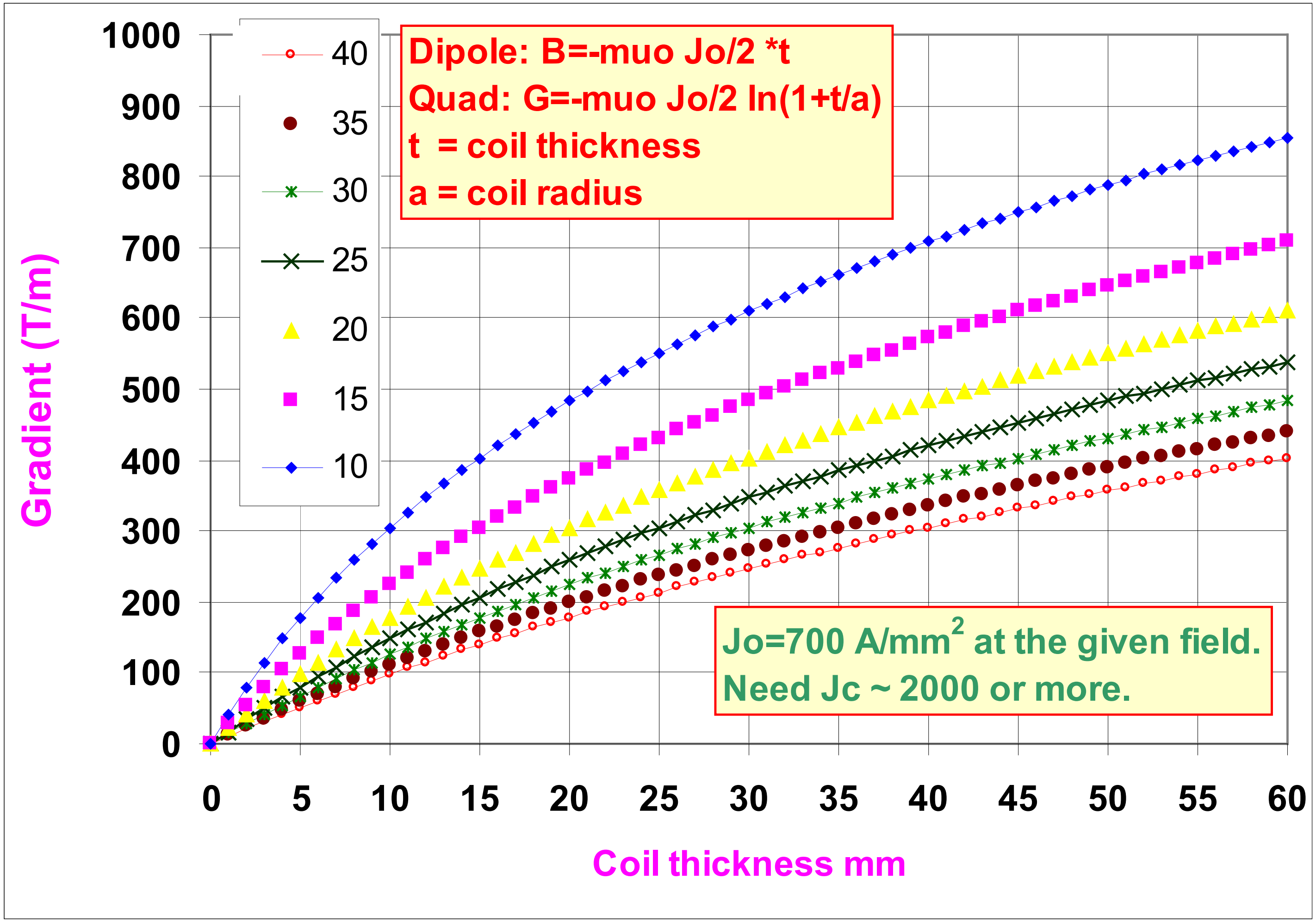
Assignment: Obtain J_{wire} and $J_{overall}$ curves for magnet designs at various short sample fields. Assume the (B_c,J_c) relationship above and J_{cu} to be 1500 A/mm2 at quench.

A Guide to Choosing the Maximum Field in Superconducting Magnets



To get maximum field keep increasing coil thickness (within practical limit) till you reach the maximum field in the coil where magnet quenches

Quadrupole Gradient for various coil radius



Note: Legends are coil radius, not aperture

The plot scale linearly with Jo (current density in coil).

A reasonable range of Jc is 400-1000 A/mm^2

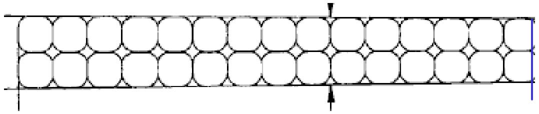
Important number is pole-tip field = Gradient * coil radius

In large aperture magnets, forces become large.

Assignment

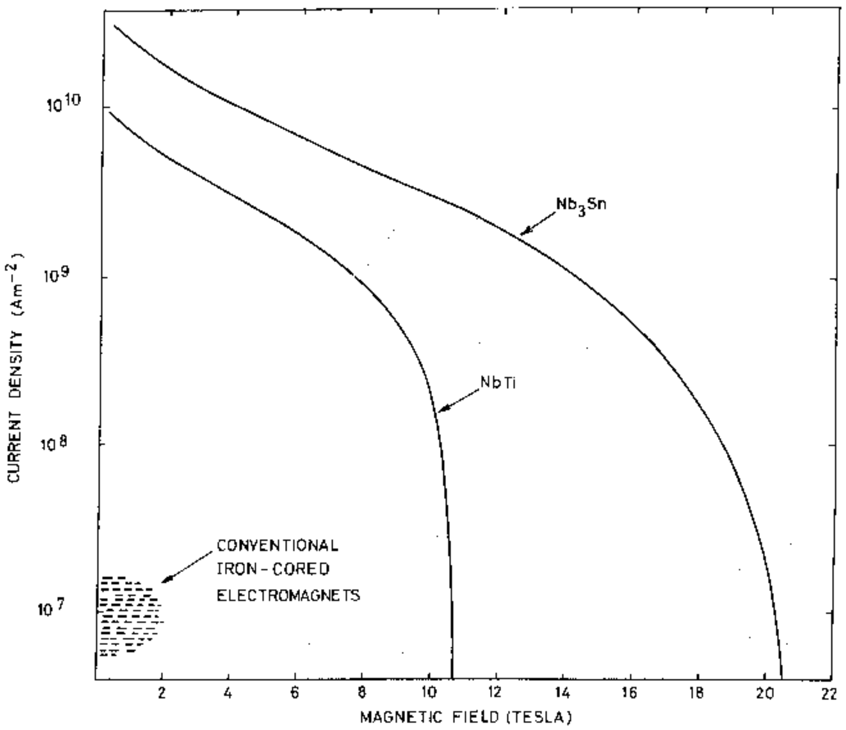
Assume that a rectangular cable (Non-Keystone, Rutherford cable) is made of 30 wires (strands). The diameter of each wire is 1 mm. The width of the insulated cable is 17 mm and thickness is 2 mm. The insulation on each side of the cable is 0.2 mm. The critical current density of superconductor at 12 T is 2500 A/mm^2. The wire has 40 % superconductor and you can assume that the rest is copper.

The magnet made with this cable operates at 12 T. Compute the current density in wire, in insulated cable and bare cable (cable without insulation) at 12 T. What will be the current density in copper if the magnet quenches (looses its superconductivity) at 12 T?



Why Use Superconducting Magnets in Accelerators?

Use of superconductors in accelerator magnets generate field much higher than what can be achieved from the normal conductors.



Courtesy: Martin Wilson

Two major reasons for using superconducting magnets in the accelerators:

Cost advantage

In high energy circular hadron colliders, the superconducting magnets reduce the size of a machine. This usually translate in to a reduction in the overall machine cost. Superconducting magnets also lower the power consumption and hence the cost of operating a high energy machine.

Performance advantage

In interaction regions, a few high field and high field quality magnets may significantly enhance the luminosity of the machine. In this case magnet costs may be large but the overall returns to experimentalists are high.