Lecture II

Superconductivity
(A brief and limited overview)

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Basic Superconductivity

The purpose of this lecture is to give you a brief overview of superconductivity.

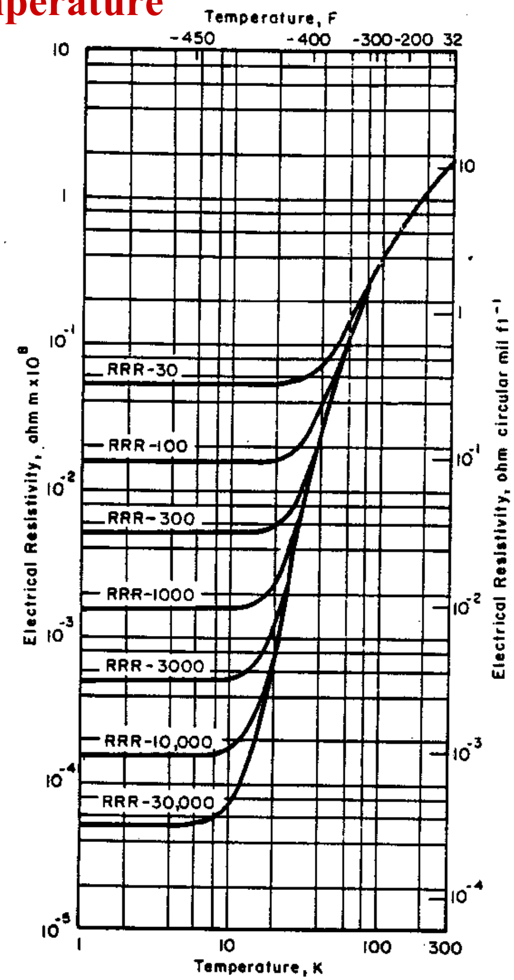
This introduction will cover some history, basic principles and a few aspects of superconductivity that are relevant to designing accelerator magnets.

Superconductivity

Resistivity of Cu as a function of Temperature

RRR=ρ(273K)/ρ(~4K)

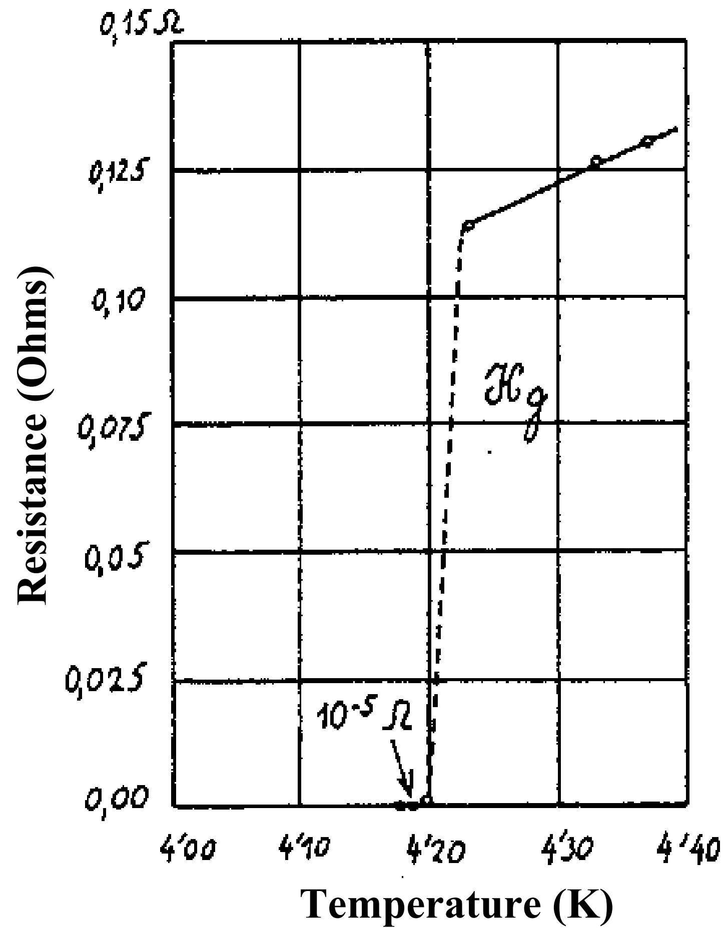
High purity copper has larger RRR



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 the first accelerator with 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 remains superconducting.

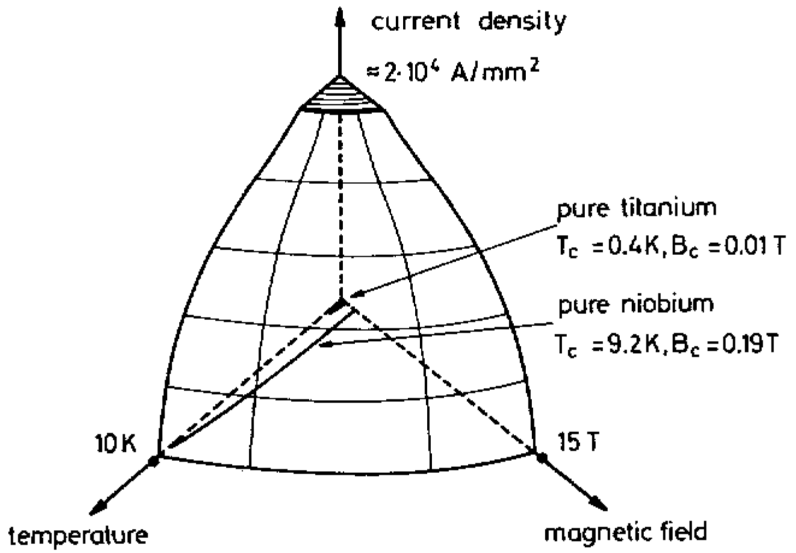


Figure 2.11: Sketch of the critical surface of NbTi. Also indicated are the regions where pure niobium and pure titanium are superconducting. The critical surface has been truncated in the regime of very low temperatures and fields where only sparse data are available.

In a magnet, the operating point must stay within this volume with a suitable safety margin!

Magnet designers dreams material:

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

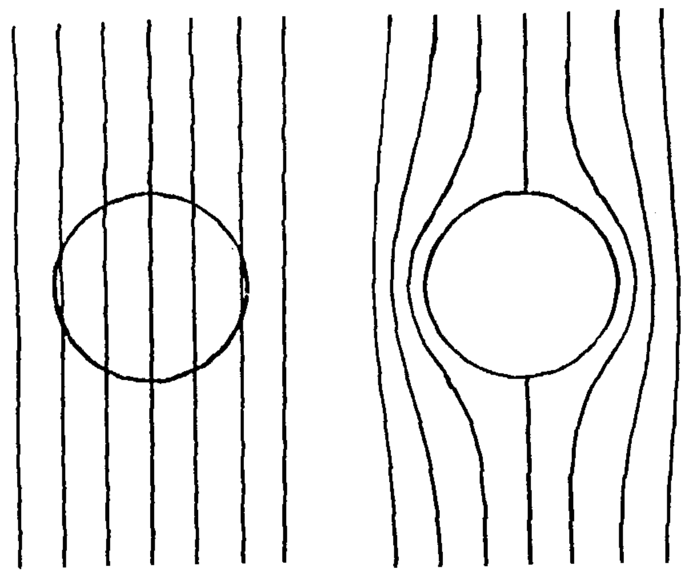
But it must also have good material properties!!!

Meissner Effect

A remarkable observation in superconductors:

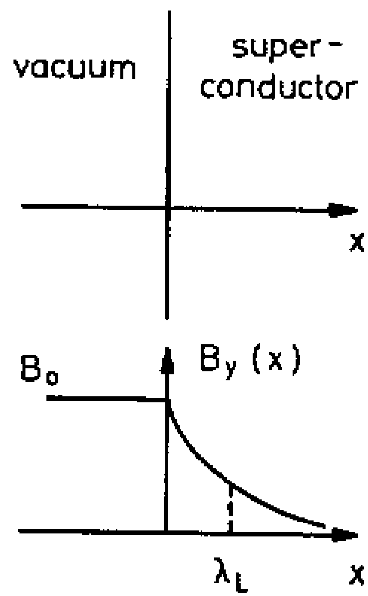
They exclude magnet flux lines from going through them.

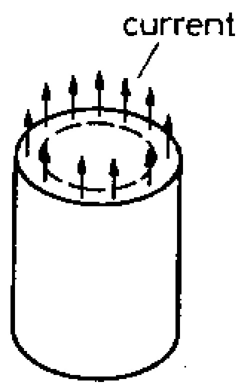
Meissner and Ochsenfeld (1933)



Normal Conductor Superconductor

Courtesy: Wilson





Courtesy: Schmuser

Attenuation of magnetic field and shielding currents in Type I superconductors

Type I and Type II Superconductors

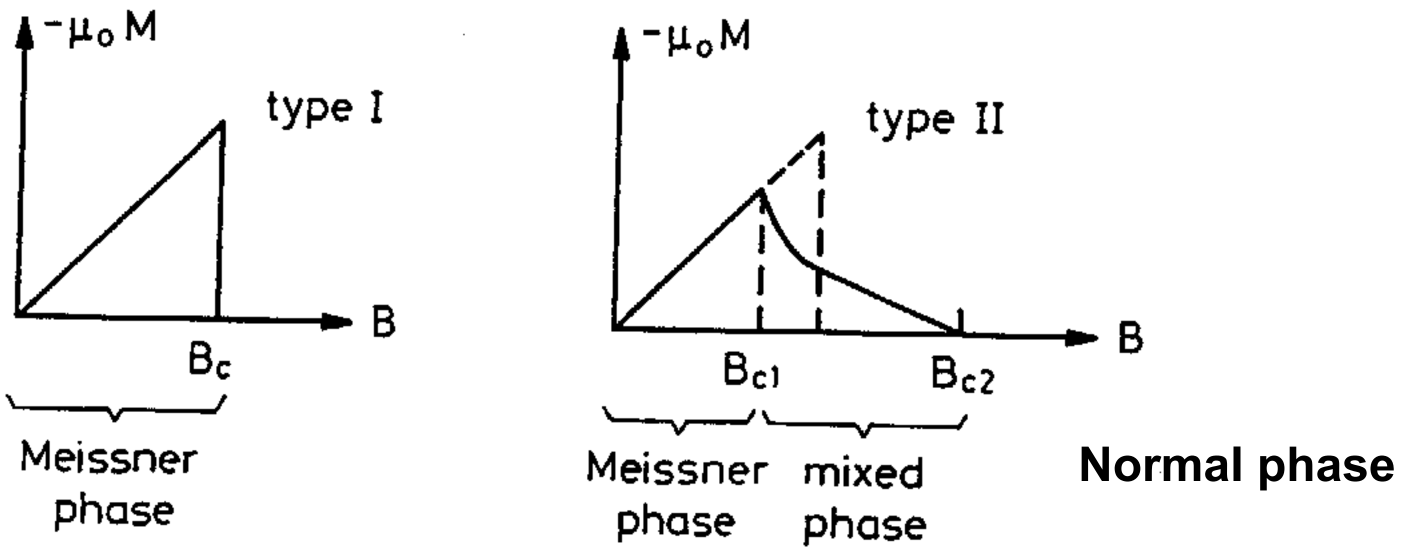


Figure 10: Magnetisation of type I and type II superconductors as a function of field.

Type I:

Also known as "soft superconductors".

Completely exclude flux lines (Meissner Effect).

Allow only small field (<< 1 T).

Not good for accelerator magnets.

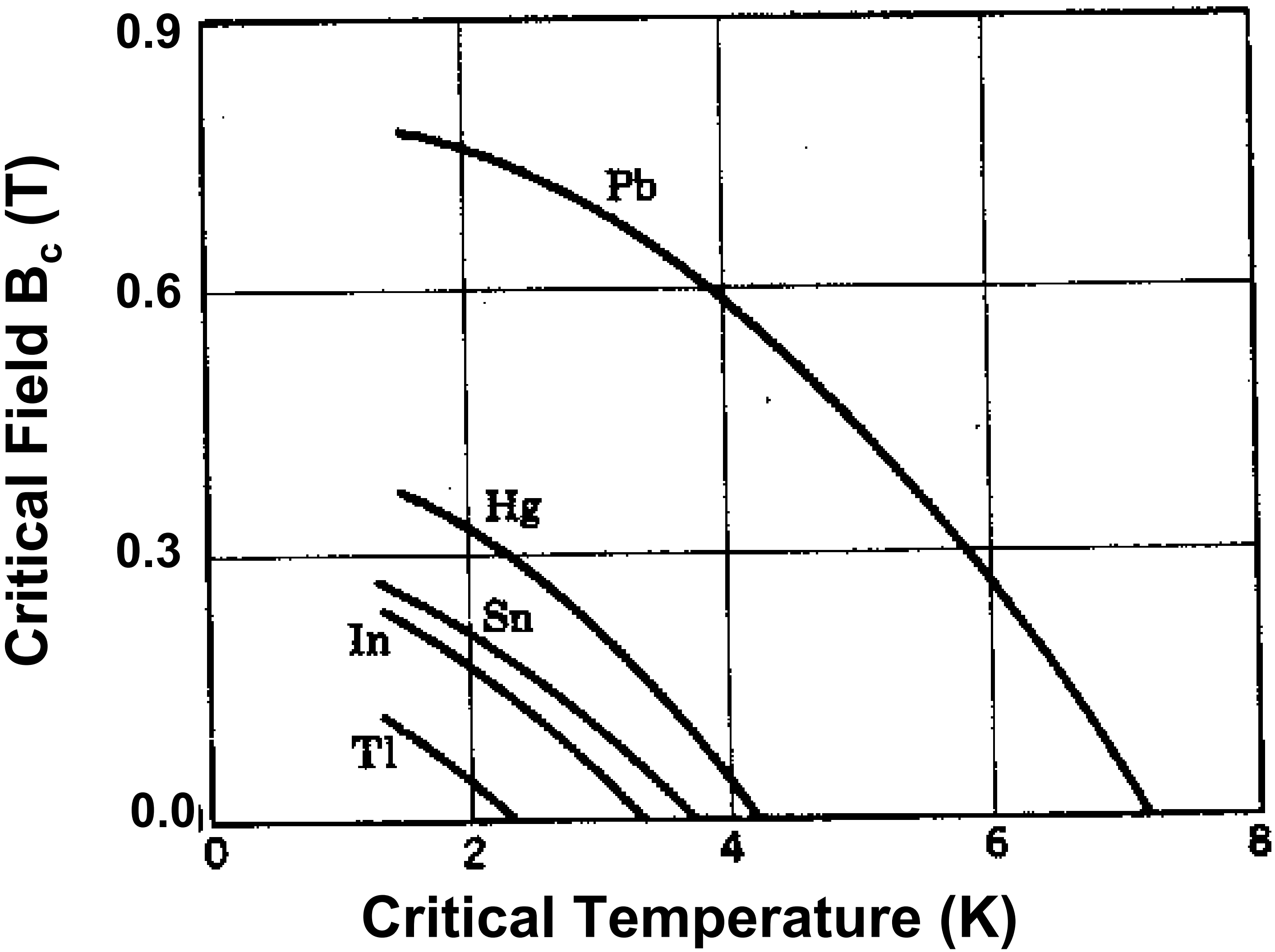
Type II:

Also known as "hard superconductors".

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

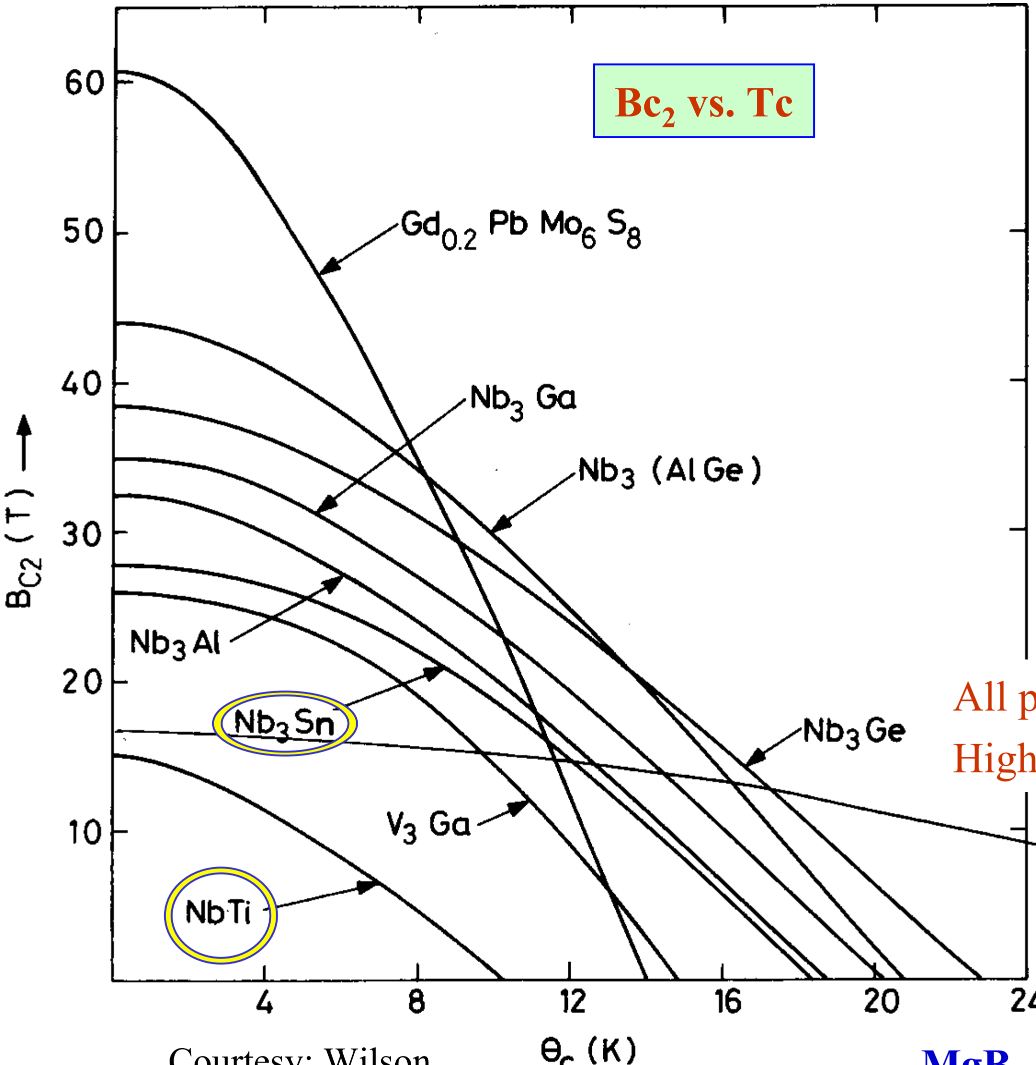
- Important plus: Allow much higher fields.
- These are the one that are used in building accelerator magnets.

Critical Surface of Type I Superconductors



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

Magnesium Diboride (MgB_2)



Courtesy: Wilson

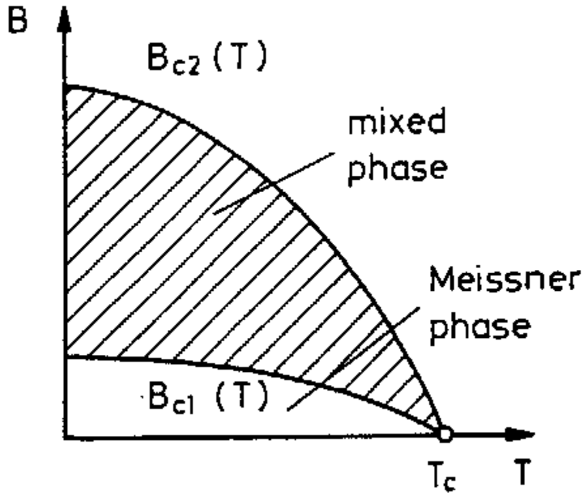


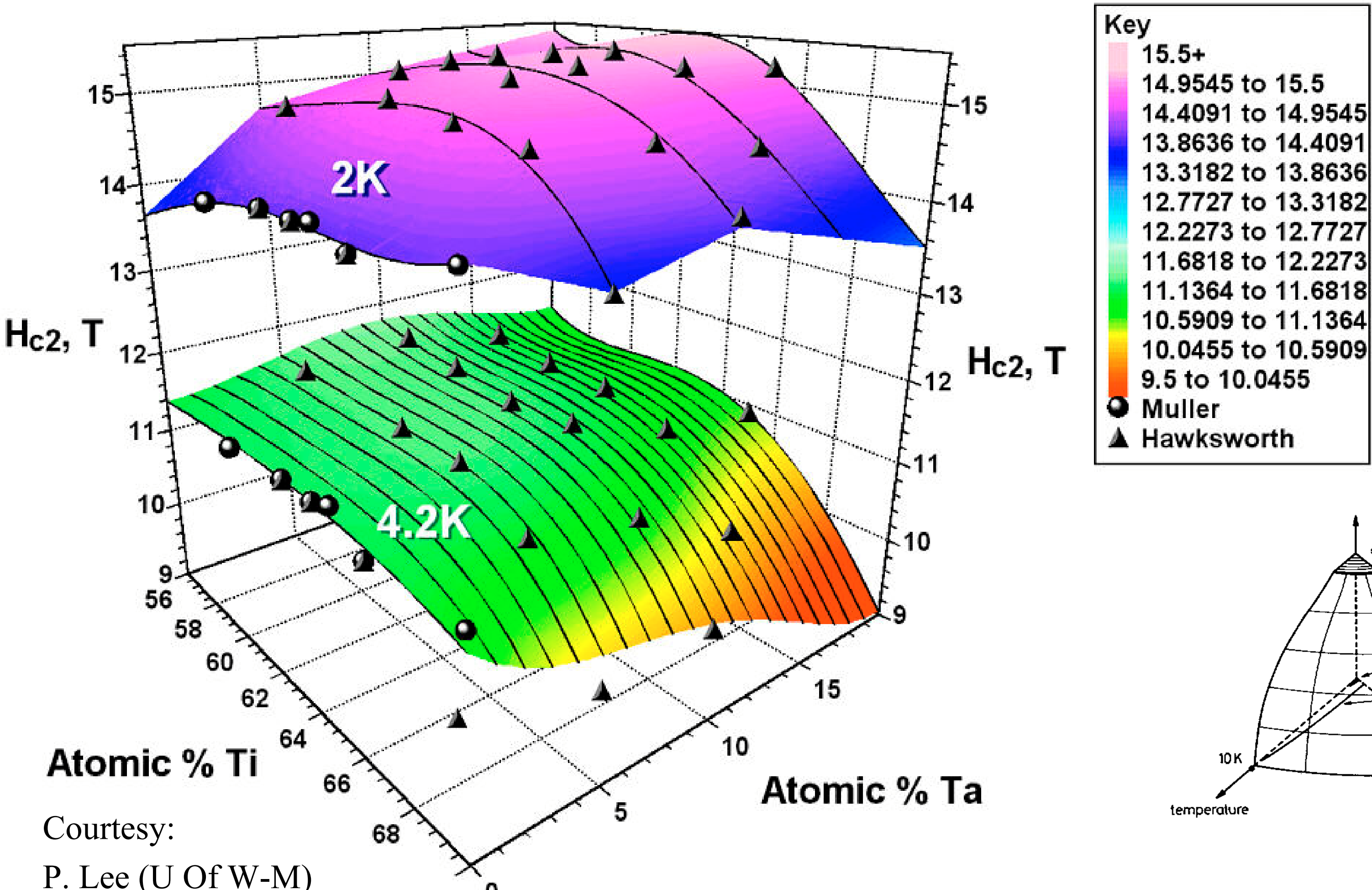
Figure 12: (a) The phase diagram of a type II

All present accelerator magnets are made with NbTi

High field R&D magnets are being built with Nb_3Sn

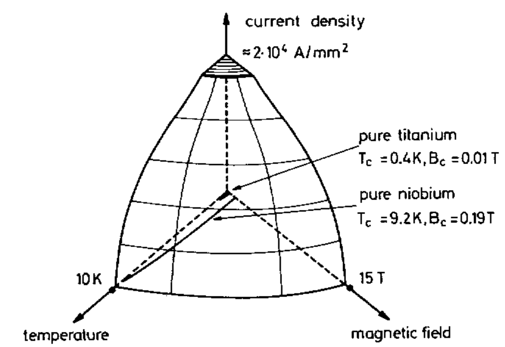
MgB_2 is LTS with high Tc (perhaps highest possible)

Nb-Ti Alloys at 4.2 K and 1.8 K



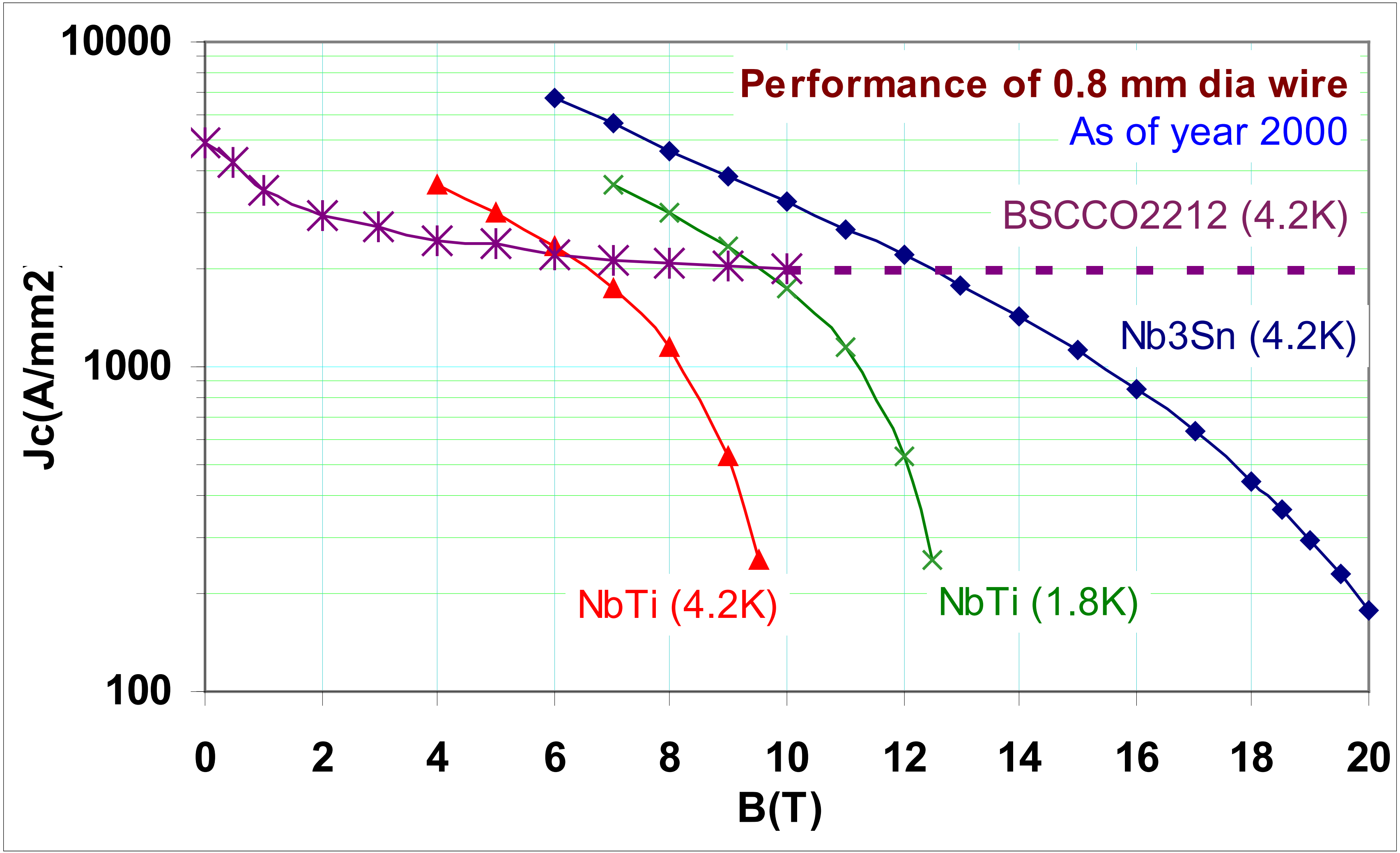
Courtesy:
P. Lee (U Of W-M)

A Reasonable Assumption for Nb-Ti:
3 T increase in B_c between 4.2 K and 1.8 K



All present superconducting accelerators operate at ~4.5 K and use Nb-Ti.
LHC magnets will operate at ~1.8 K, to generate higher fields, while still using Nb-Ti.

Critical Current Density as a Function of Field



Low Temperature Superconductors (LTS) for Accelerator Magnets

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

Type I and Type II Superconductors

London Penetration Depth and Coherence Length

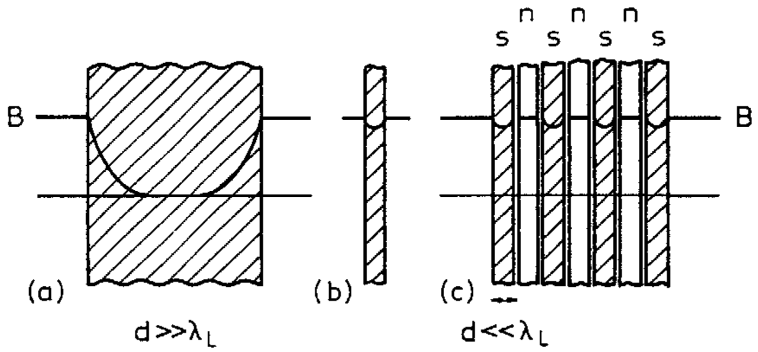


Figure 14: Attenuation of field (a) in a thick slab and (b) in thin sheet. (c) Subdivision of a thick slab into alternating layers of normal and superconducting slices.

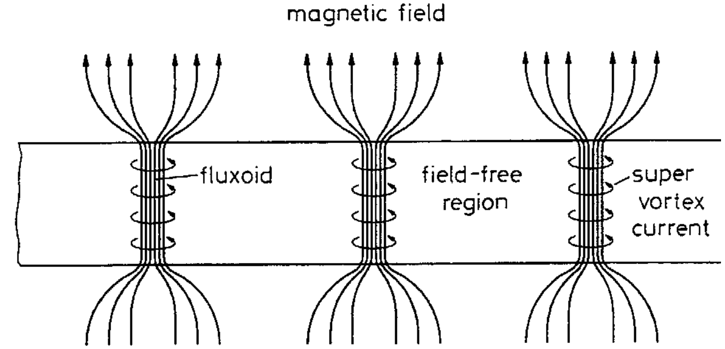
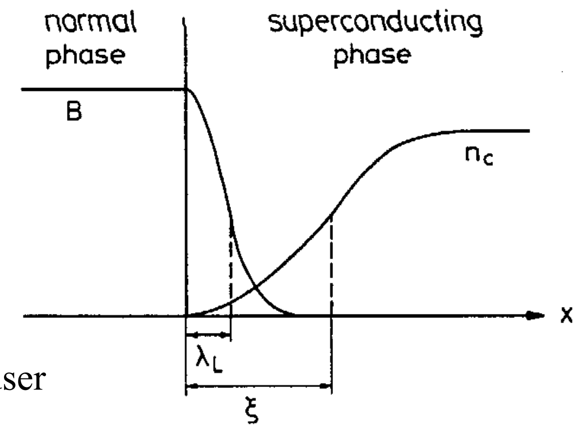


Figure 13: Flux tubes in a type II superconductor.



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 or the depth to which field may penetrate
- "Coherence Length" tells how Cooper pair density increases (indicates the range of interaction between Cooper pairs)

Note: Pure Niobium (Nb) is type II superconductor

Current Transport in Bulk Superconductors

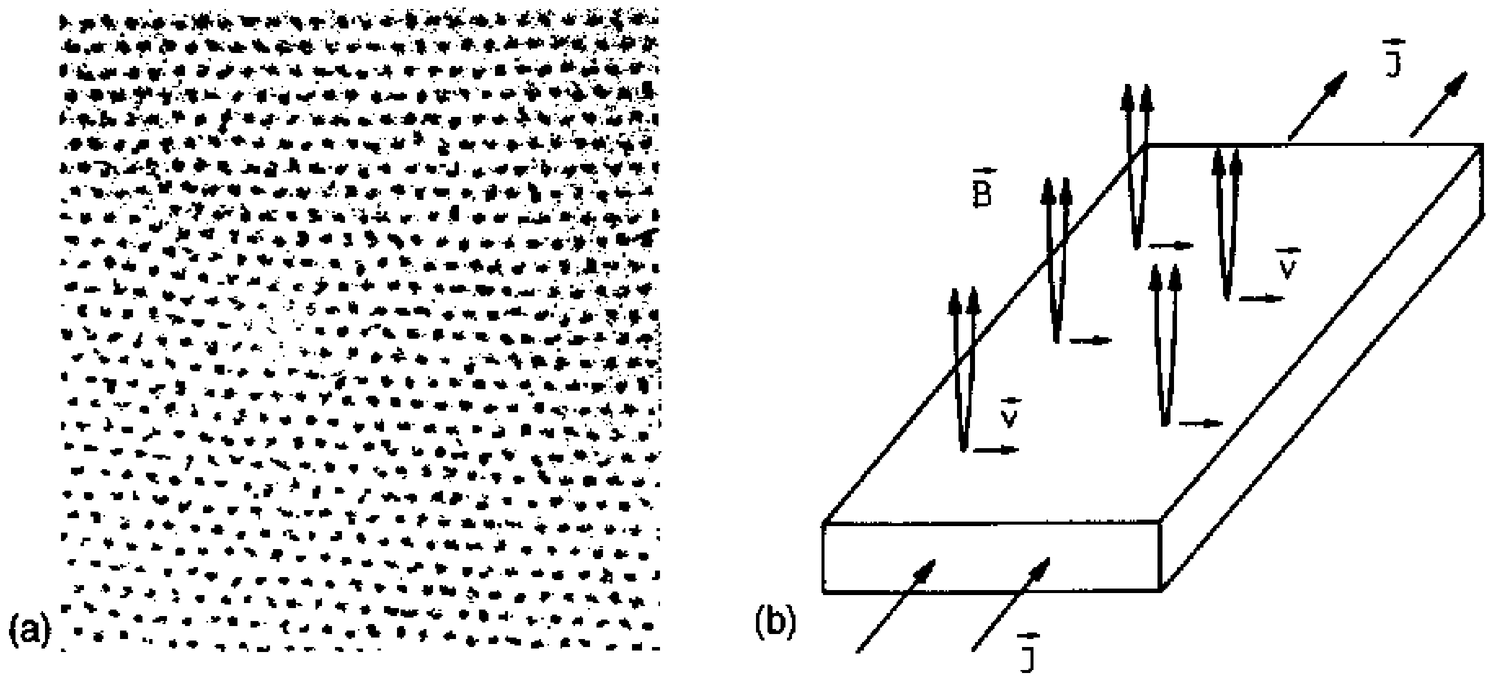
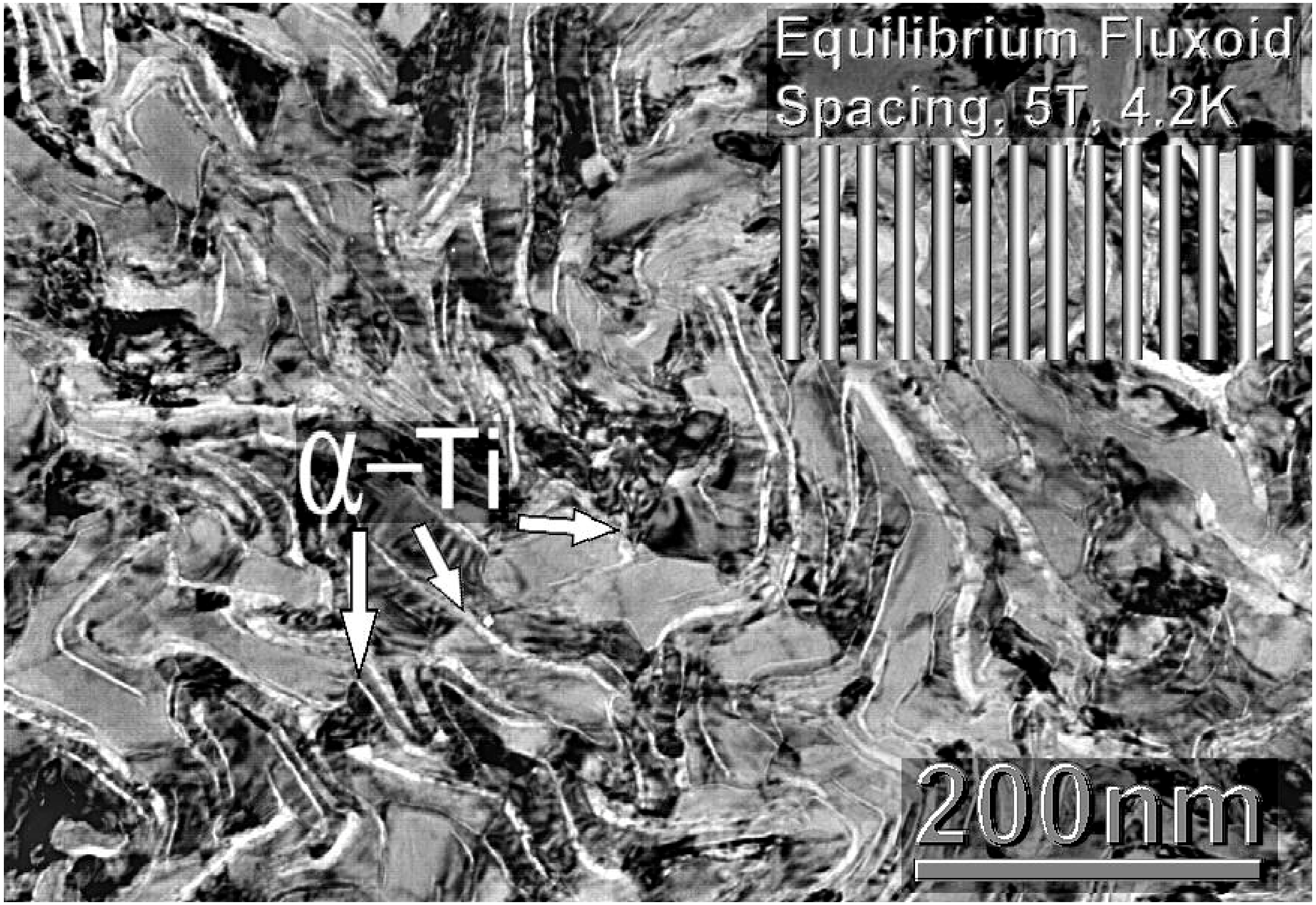


Figure 2.7: (a) Fluxoid pattern in niobium (courtesy U. Essmann). The distance between adjacent flux tubes is 0.2 μm. (b) Scheme of fluxoid motion in a current-carrying type II superconductor.

Courtesy: Schmuser

Motion of these fluxoids generates heat.

Nb-Ti Microstructure



These defects are crucial for a superconductor to become usable for magnetic field application. These are the one that allow fields.

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

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

- For superconducting magnet applications, the presence of certain defects is essential.
- For superconducting RF cavities, one needs very high purity materials, with no defects.
- RF cavities are made with high purity Niobium

  Note: Niobium (Nb) is only one of three metals that is Type II superconductor (others are vanadium and technetium).

  Hc_1 of Niobium ~ kG.

  Note that high purity bulk Niobium (RRR >150) is Type I superconductor.

Flux Jumping

Initially, when the field is raised, large screening currents are generated to oppose the changes. These current densities may be much larger than J_c (critical current density till which material remains superconducting) A current higher than J_c will create Joule heating. However, these large currents soon die and attenuate to J_c, which persists.

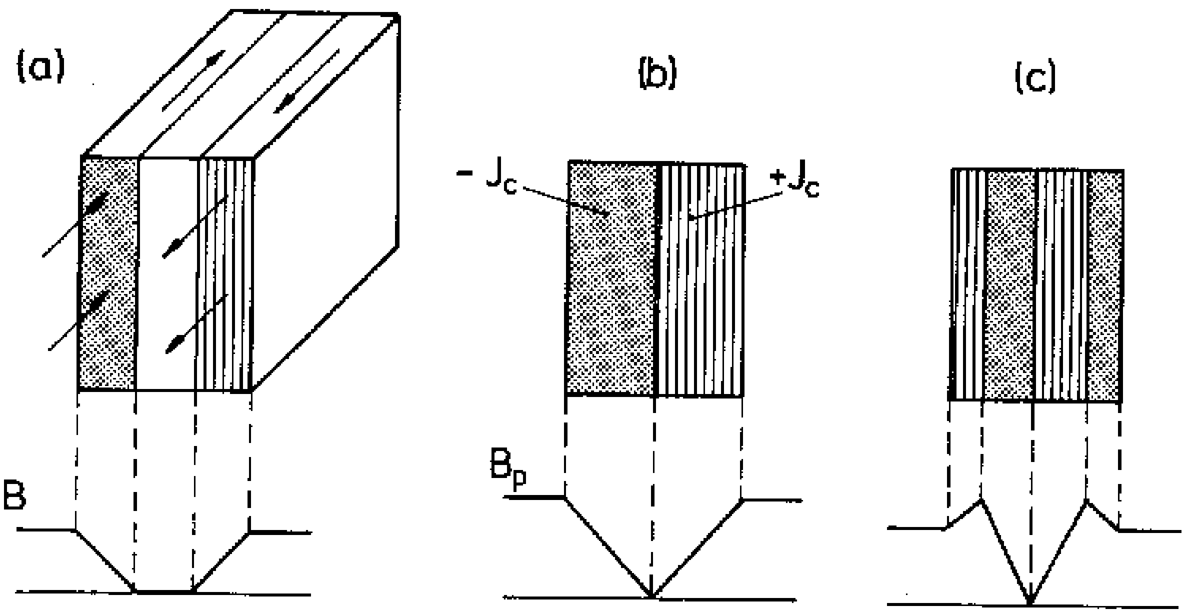


Figure 2.12: Current and field distribution in a slab of hard superconductor according to the critical-state model. The external field is parallel to the surface. (a) Initial exposition to a small external field. (b) The penetrating field B_p. (c) External field first raised above B_p and then lowered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

Instability from Flux Jumping

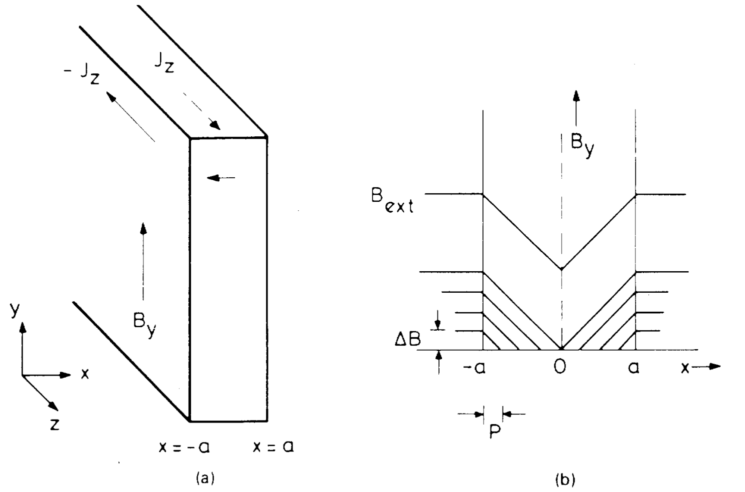
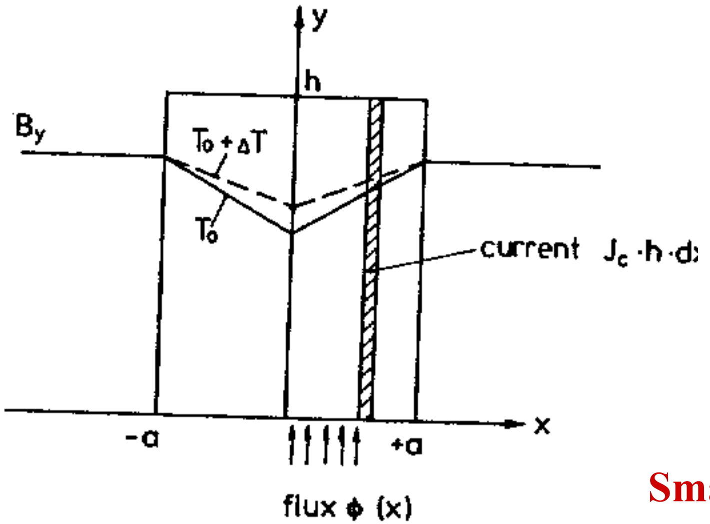


Fig. 7.1. (a) Screening currents induced to flow in a slab by a magnetic field parallel to the slab surface; (b) Magnetic field pattern across the slab showing the reduction of internal field by screening currents.



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

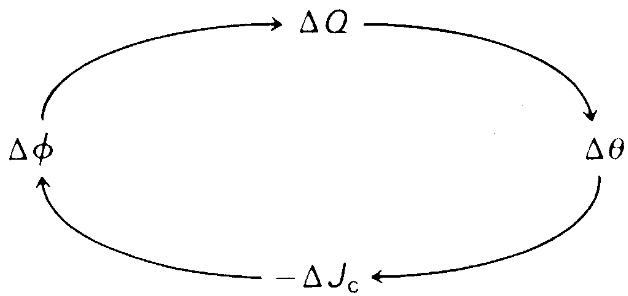
c) flux motion dissipates energy

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



Small filament diameter is required to reduce flux jumping.

Magnetization Effects in Superconducting Filaments

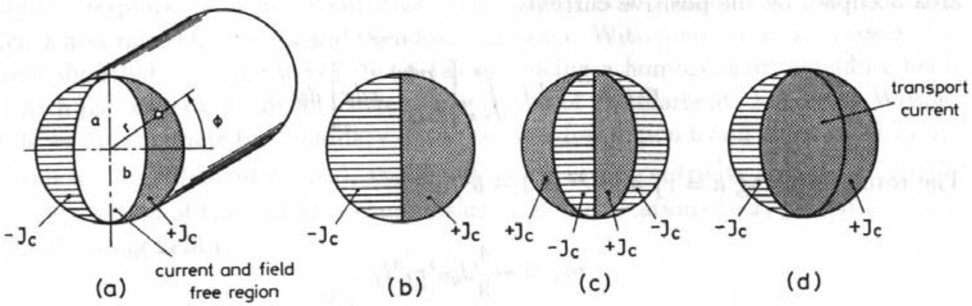


Figure 6.1: Schematic view of the persistent currents which are induced in a superconducting filament by a varying external field. (a) The external field is raised from zero to a value B_e less than the penetrating field B_p. (b) A 'fully-penetrated' filament, i.e. $B_e \geq B_p$. (c) Current distribution 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

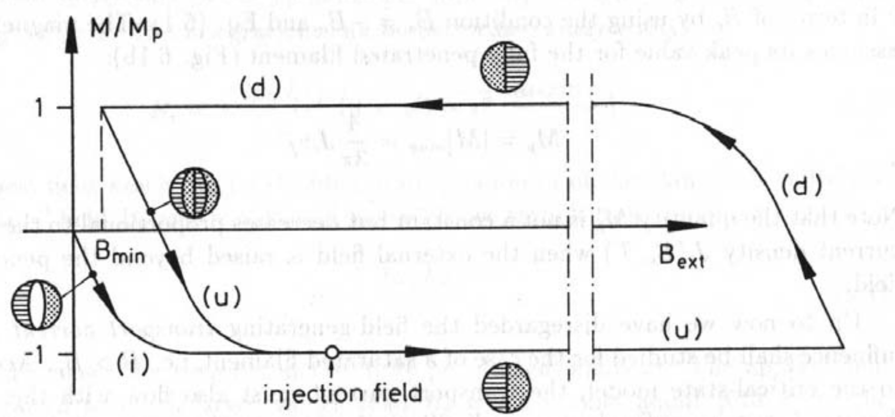


Figure 6.2: The normalized magnetization M/M_p of a NbTi filament as a function of the external field. (i): initial curve, (u): up-ramp branch, (d): down-ramp branch. Also shown are the current distributions in the filament. The field dependence of J_c has been neglected.

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

Animesh Jain to discuss persistent currents in significant details.

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

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

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

Persistent current induced magnetization :

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

J_c , CRITICAL CURRENT DENSITY

d , FILAMENT DIAMETER

ν , VOL. FRACTION OF NbTi

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

Problem in Nb_3Sn Magnets because

(a) Jc is several times higher

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

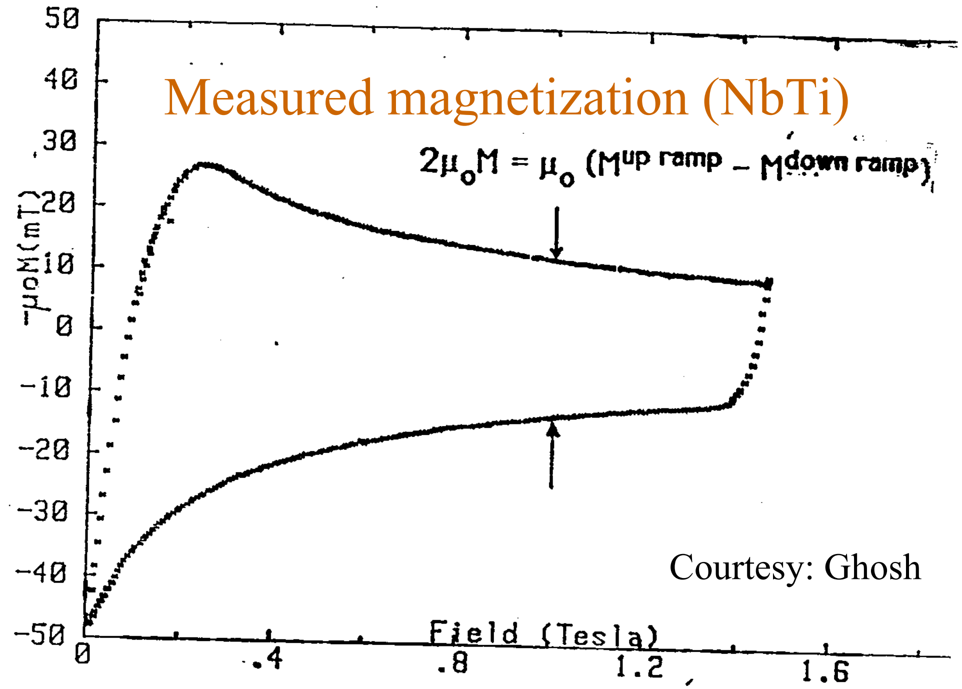


Fig. of a typical magnetization loop.

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 nothing done)

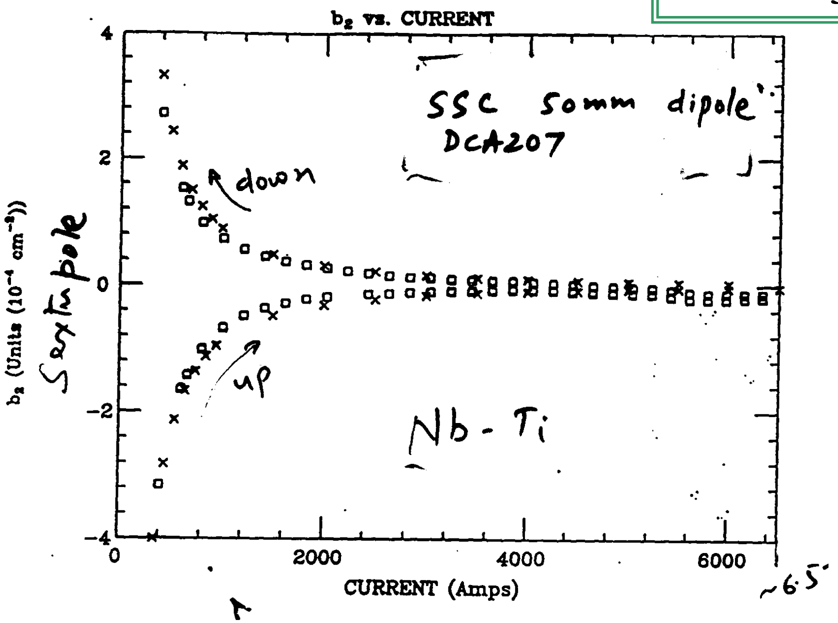
Nb_3Sn superconductor, with the technology now in use, is expected to generate persistent current-induced harmonics which are **a factor of 10-100 worse** than those measured in Nb-Ti magnets.

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

Magnetization :

$$M = \frac{4}{3\pi} J_c\, a$$

Measured sextupole harmonic in a Nb-Ti magnet



Measured sextupole harmonic in a Nb_3Sn magnet

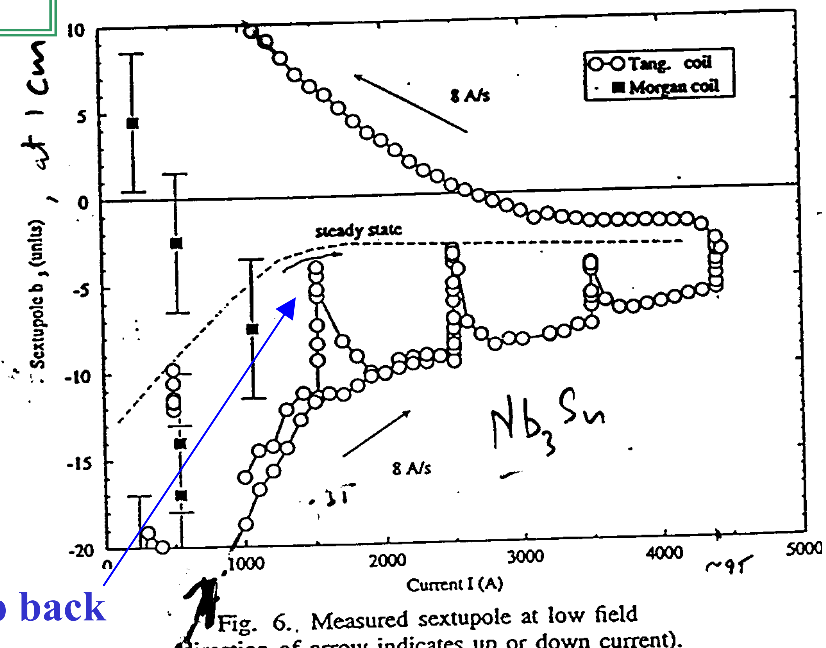
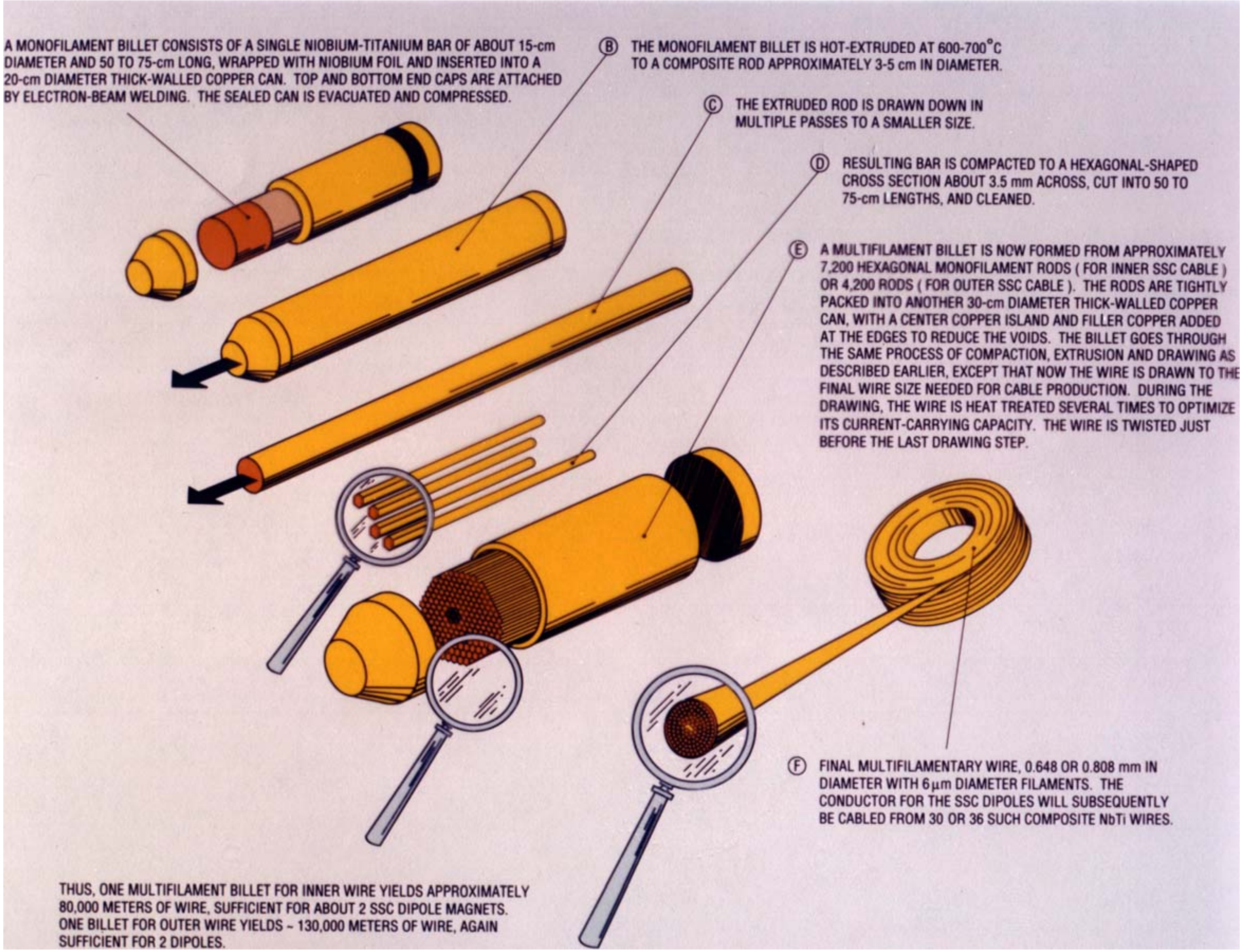


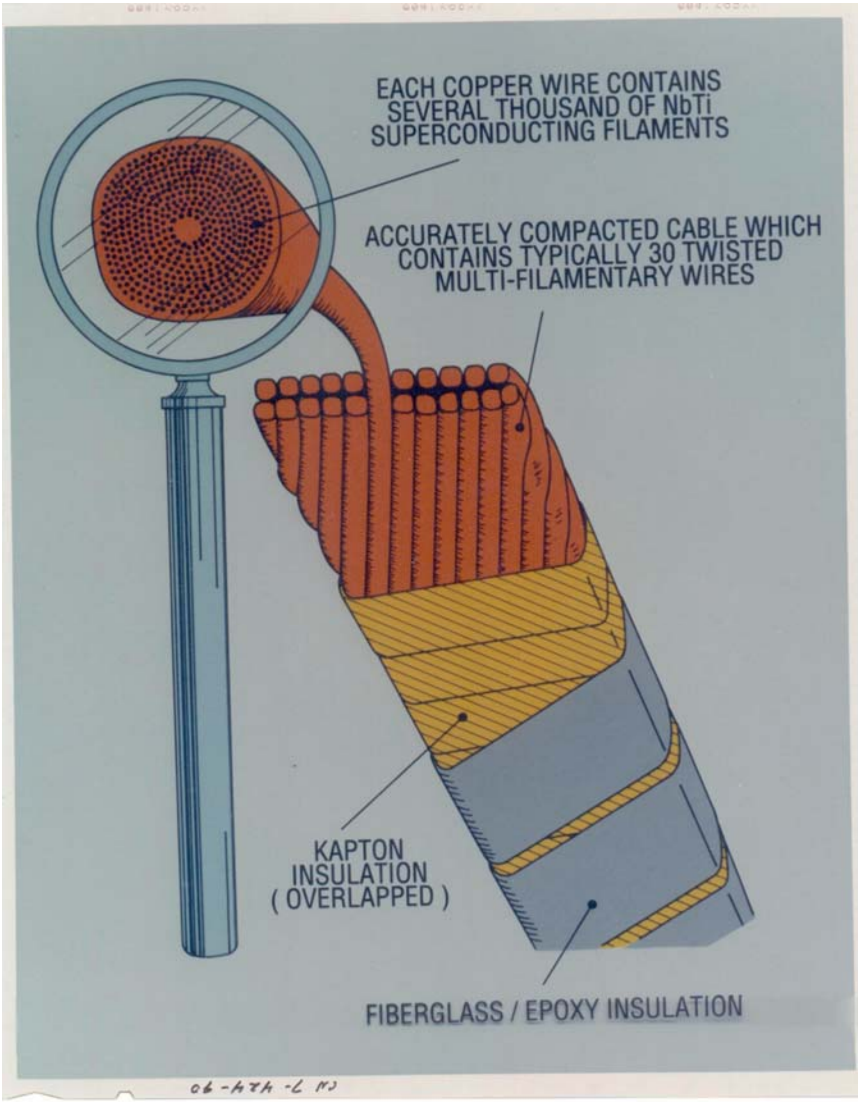
Fig. 6. Measured sextupole at low field (direction of arrow indicates up or down current).

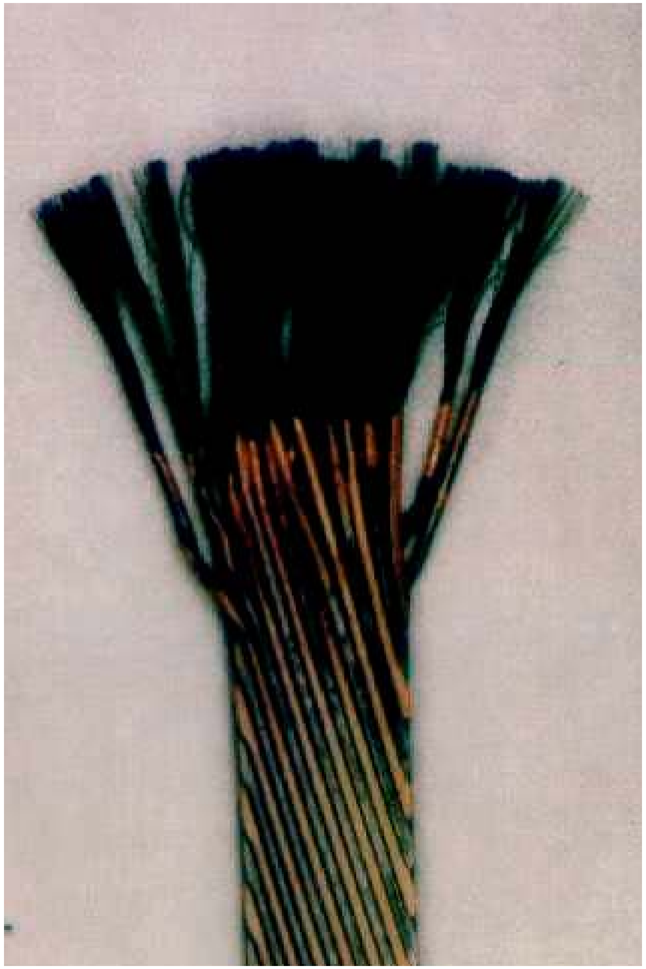
Either reduce the effective filament diameter or come up with a magnetic design that minimizes the effect of magnetization in the magnets (LBL, FNAL, TAMU).

Manufacturing of Nb-Ti Wires



A Typical Superconducting Cable



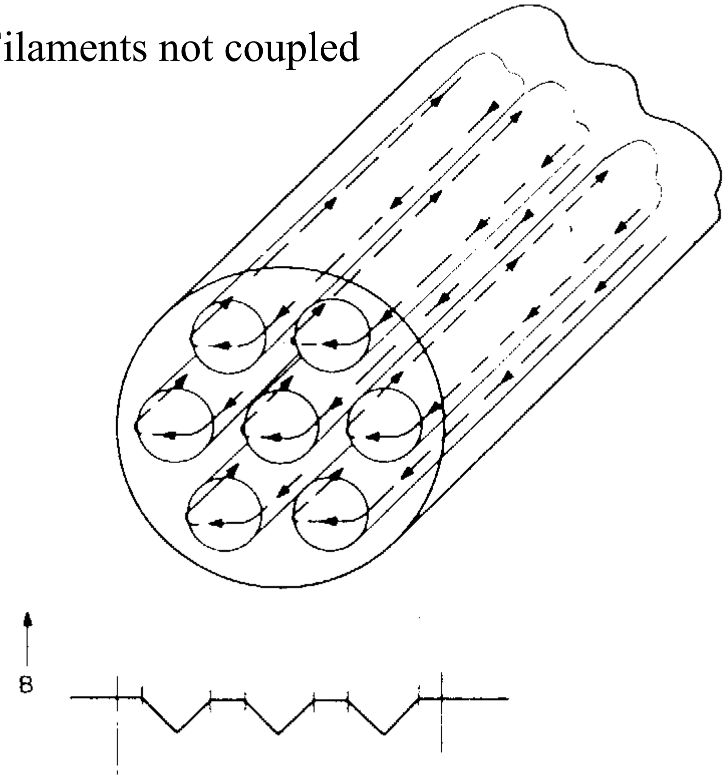


Filaments in an actual cable

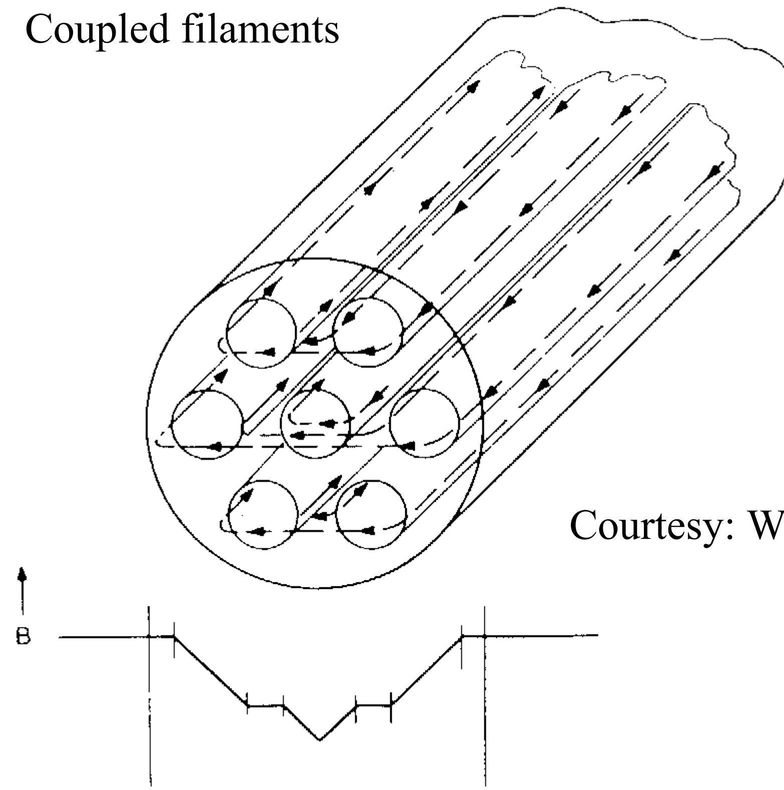
(Filament size in SSC/RHIC magnets: 6 micron)

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

Filaments not coupled



Coupled filaments



Courtesy: Wilson

Magnetization :

$$M = \frac{4}{3\pi} J_c \, a$$

Coupling of filaments (in changing field) is undesirable because it increases effective radius.

This brings back flux jump instability and magnetization.

Twisting: The Key to Stability

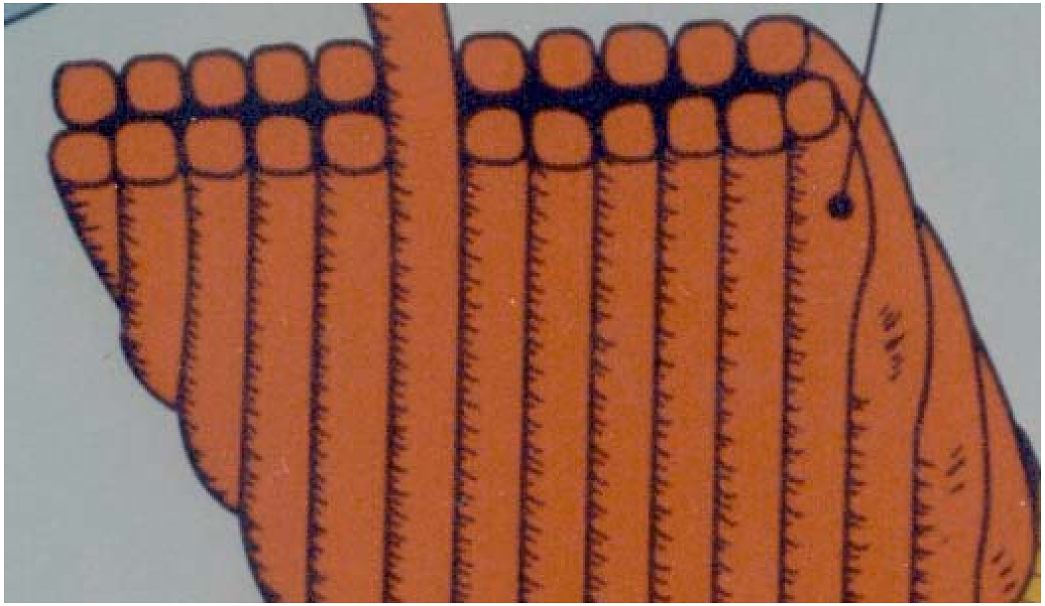
A wire composed of twisted filaments

Courtesy: Wilson

Twisting significantly reduces the influence coupling.

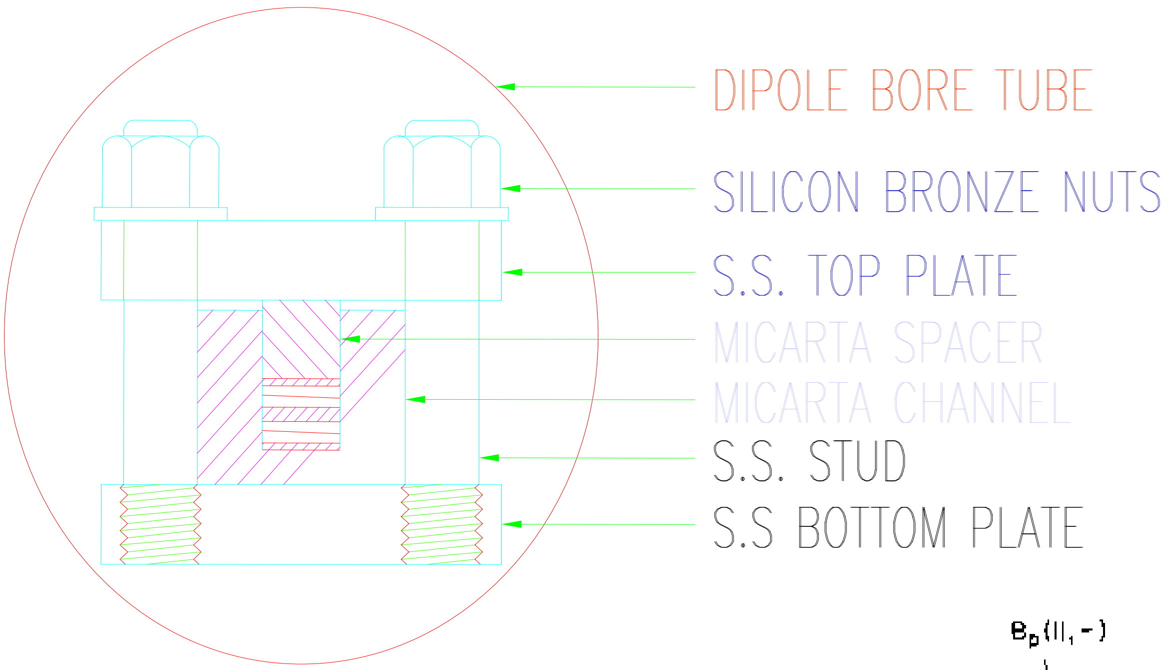
The sign of dB/dt reverses every half pitch.

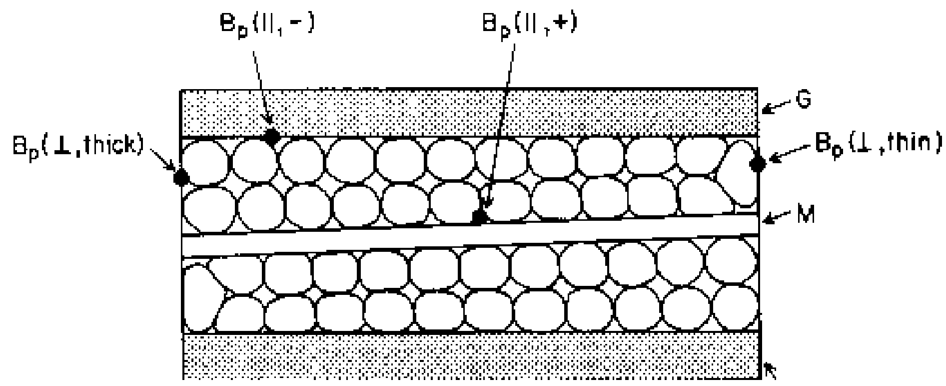
Rutherford cable



Wires are twisted in cable for the same reason, i.e., to reduce the coupling.

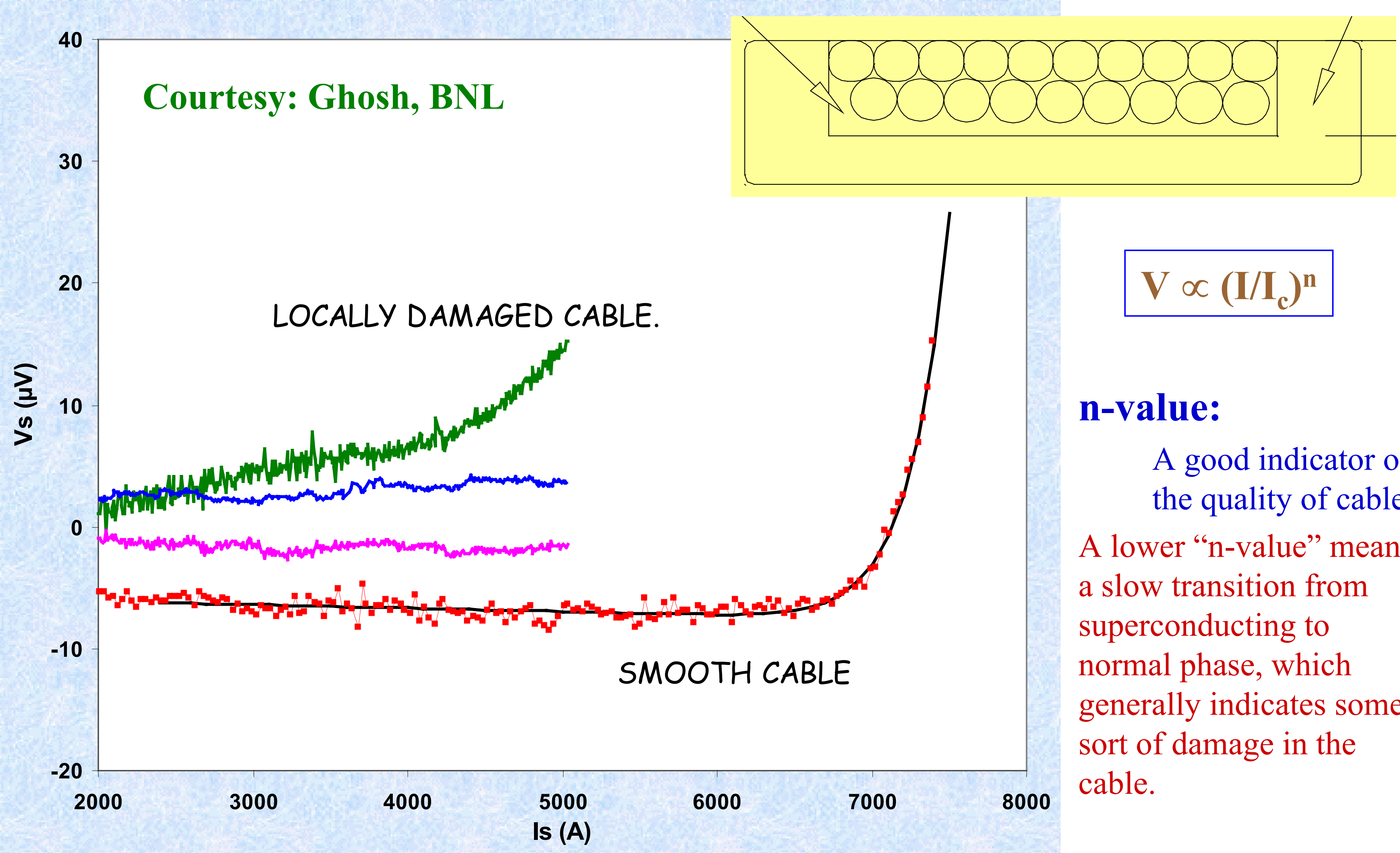
Cable Measurement Set-up at BNL





Courtesy: Ghosh, BNL

Nb_3Sn Cable in Cu- Channel



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

n-value:

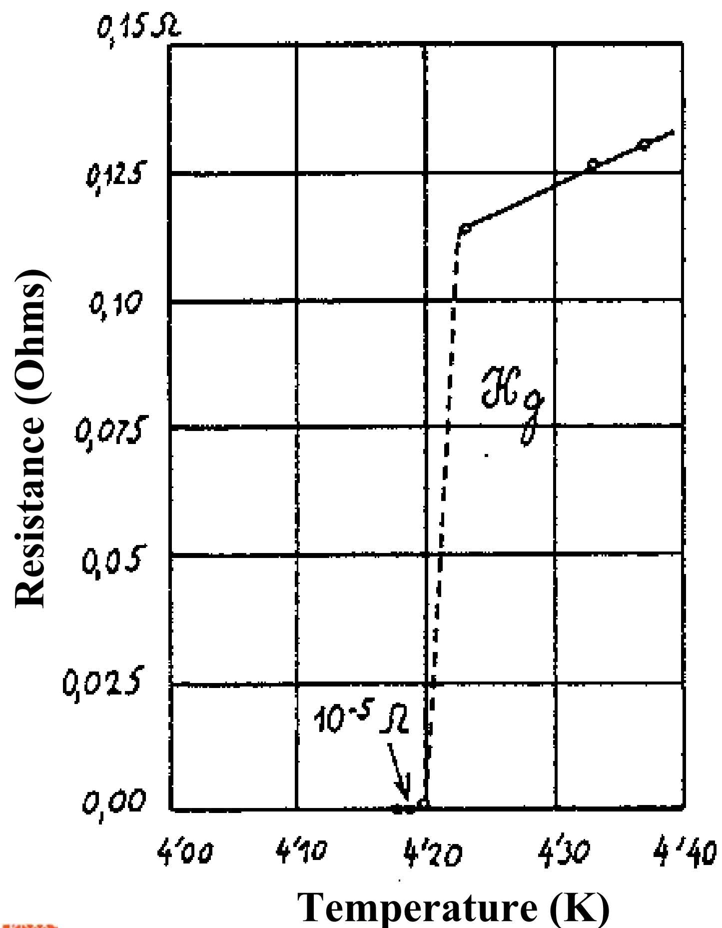
A good indicator of the quality of cable.

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

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

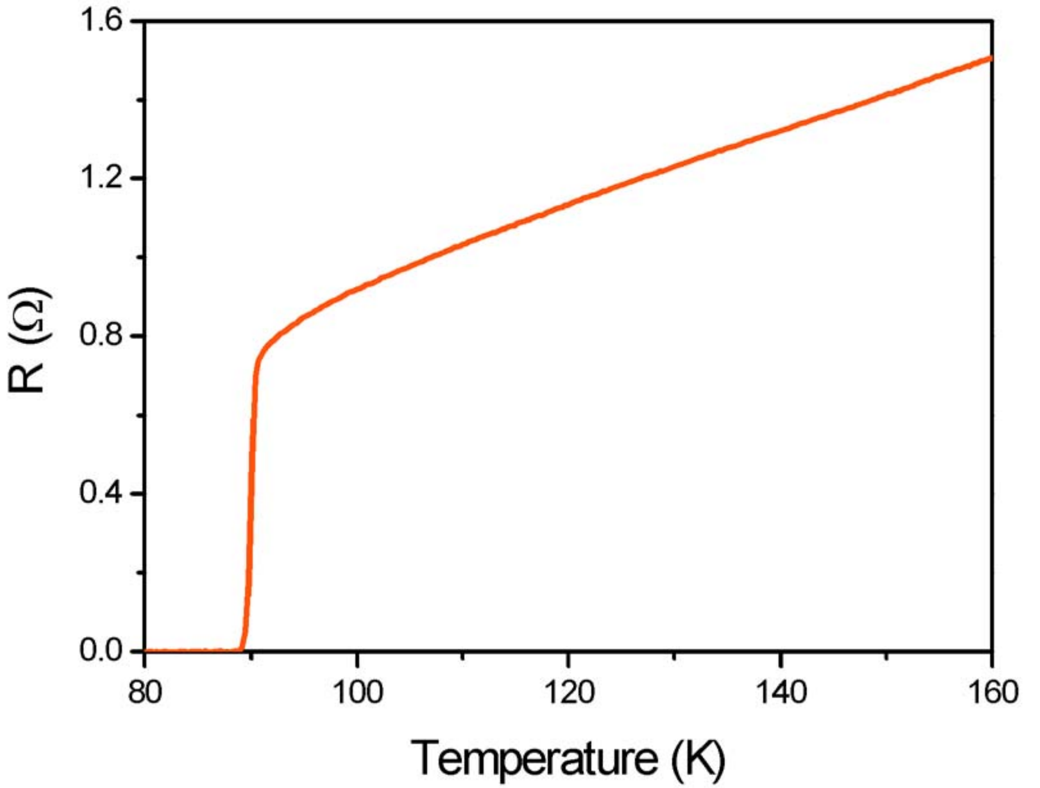
Low Temperature Superconductor Onnes (1911)

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)



Popular HTS Materials of Today

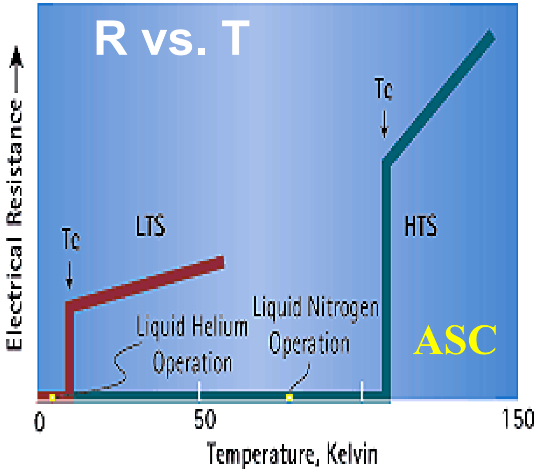
- BSCCO 2223 (T_c ~ 110 K)
- BSCCO 2212 (T_c ~ 85 K)
- YBCO (T_c ~ 90 K)

- MgB_2 is a low temperature superconductor (LTS) with critical temperature ~39 K (almost highest possible by current theories).

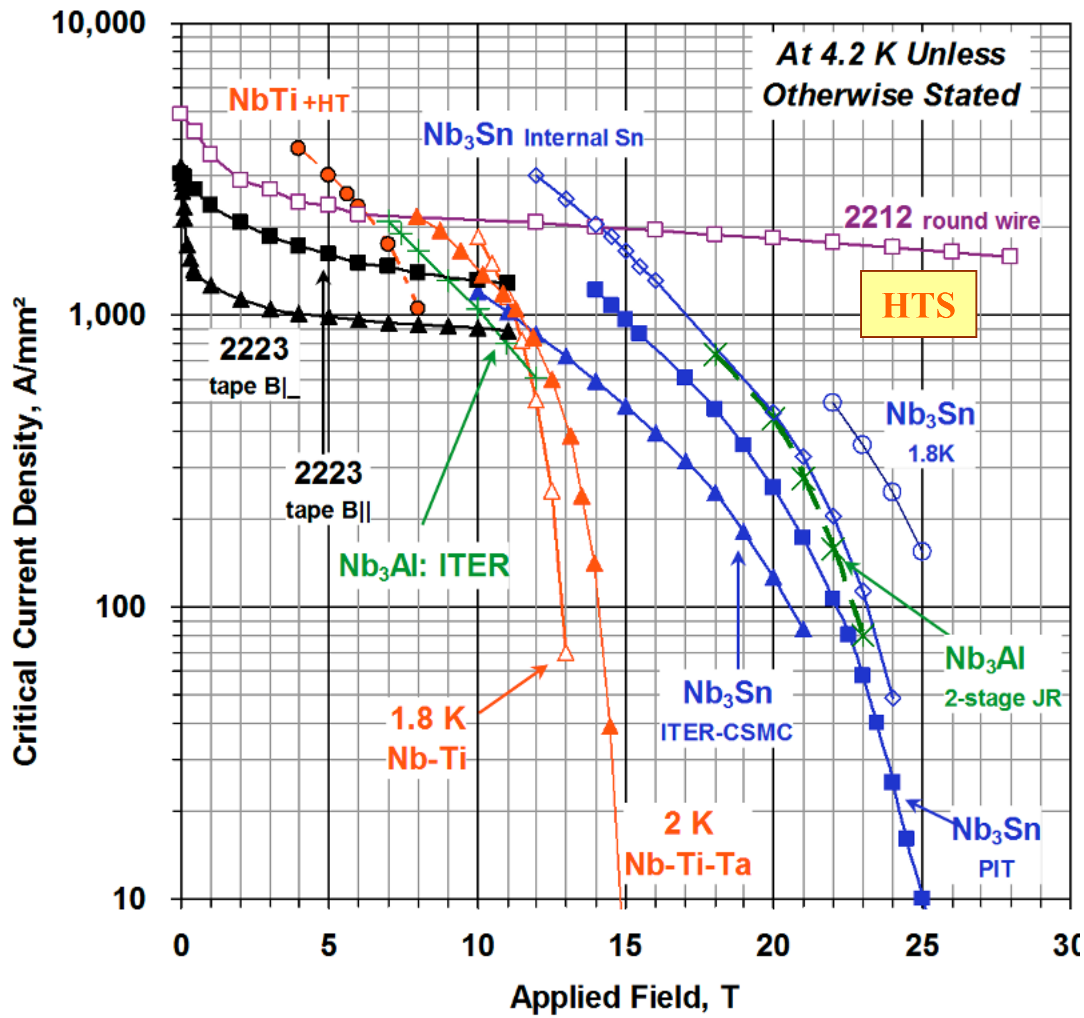
Of these only BSCCO2212 and BSCCO2223 (first generation) are now available in sufficient quantity to make accelerator magnets. YBCO (second generation) HTS is expected to be available soon (couple of years) in sufficient lengths to make magnets. Second generation superconductor is expected to have a much lower cost.

Some Remarkable Properties of HTS (High Temperature Superconductors)

HTS retains their superconductivity to a much higher temperature

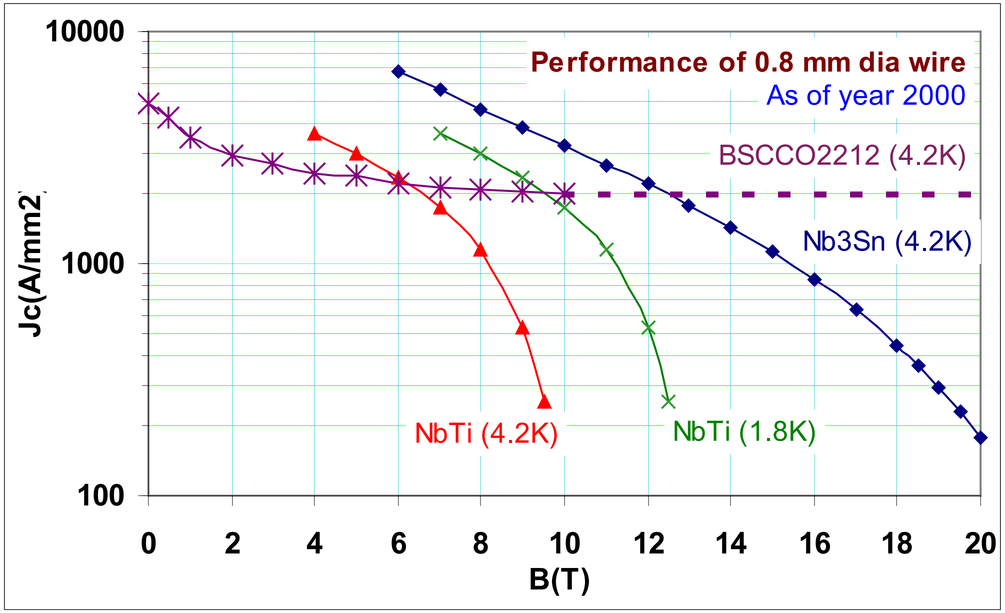


Also compare the high field performance of "High Temperature Superconductors (HTS)" to that of "Low Temperature Superconductors (LTS)".

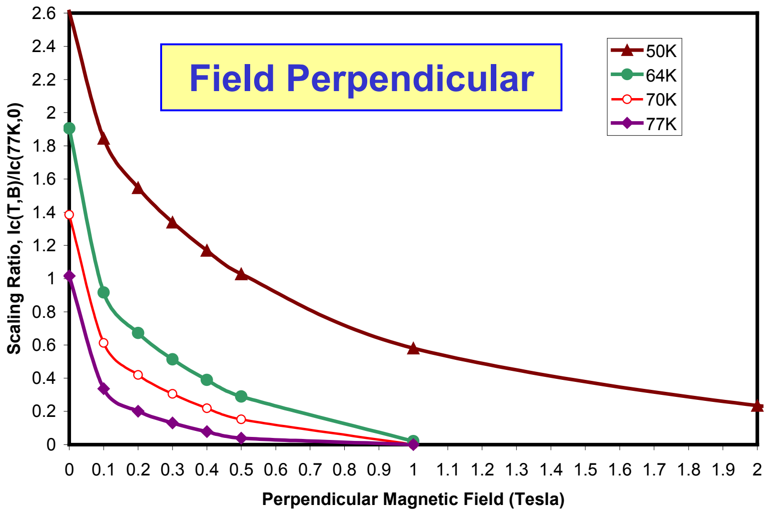


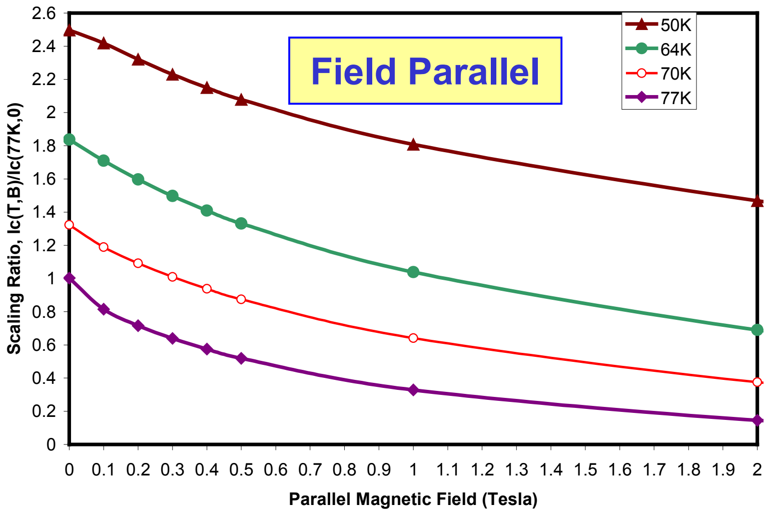
High Temperature Superconductors

High Temperature Superconductors (HTS) now carry significantly higher current over Low Temperature Superconductors (LTS), at low temperature high fields (see below) or at high temperature low fields (see right).



Critical current scaling Ratio over 77K, self field





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.

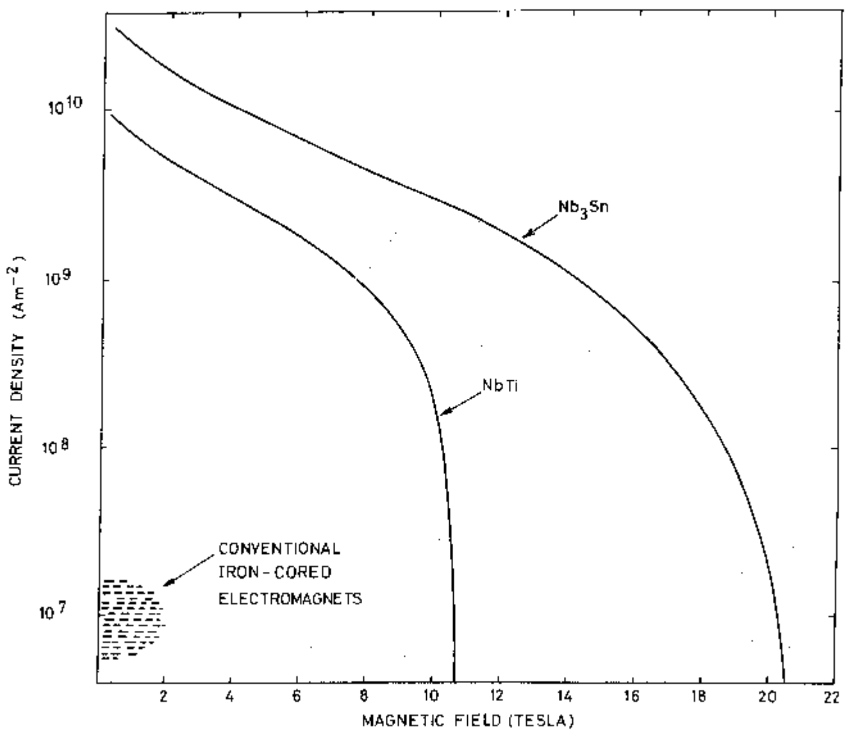
High field superconductors (Nb_3Sn and HTS) are brittle!

One has to be very careful in winding coils with these brittle material or use an 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.

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, 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.