A one week course on

Superconducting Accelerator Magnets

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Contents

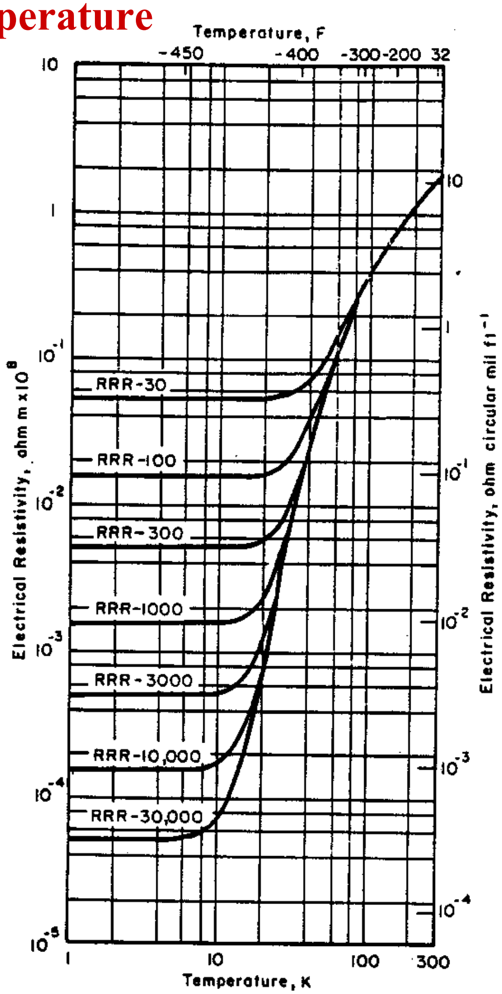
Note: This is not intended to be a complete and balanced course on magnet design.
It is more focused on the magnetic design and field quality.

The Superconductivity

Resistivity of Cu as a function of Temperature

RRR=ρ(273K)/ρ(~4K)

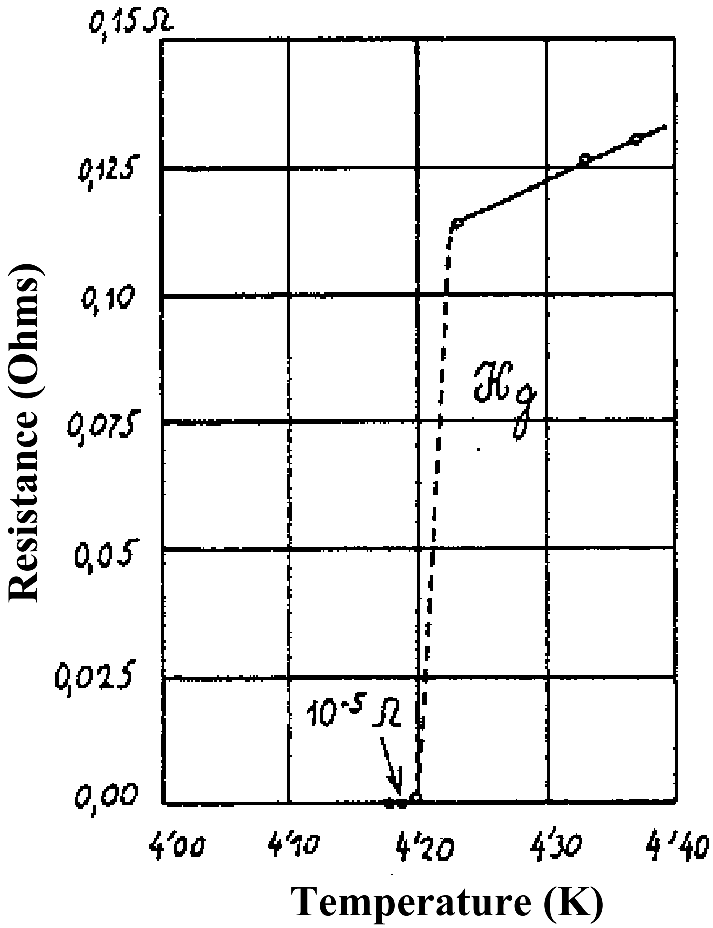
High purity copper has larger RRR



ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR COPPER

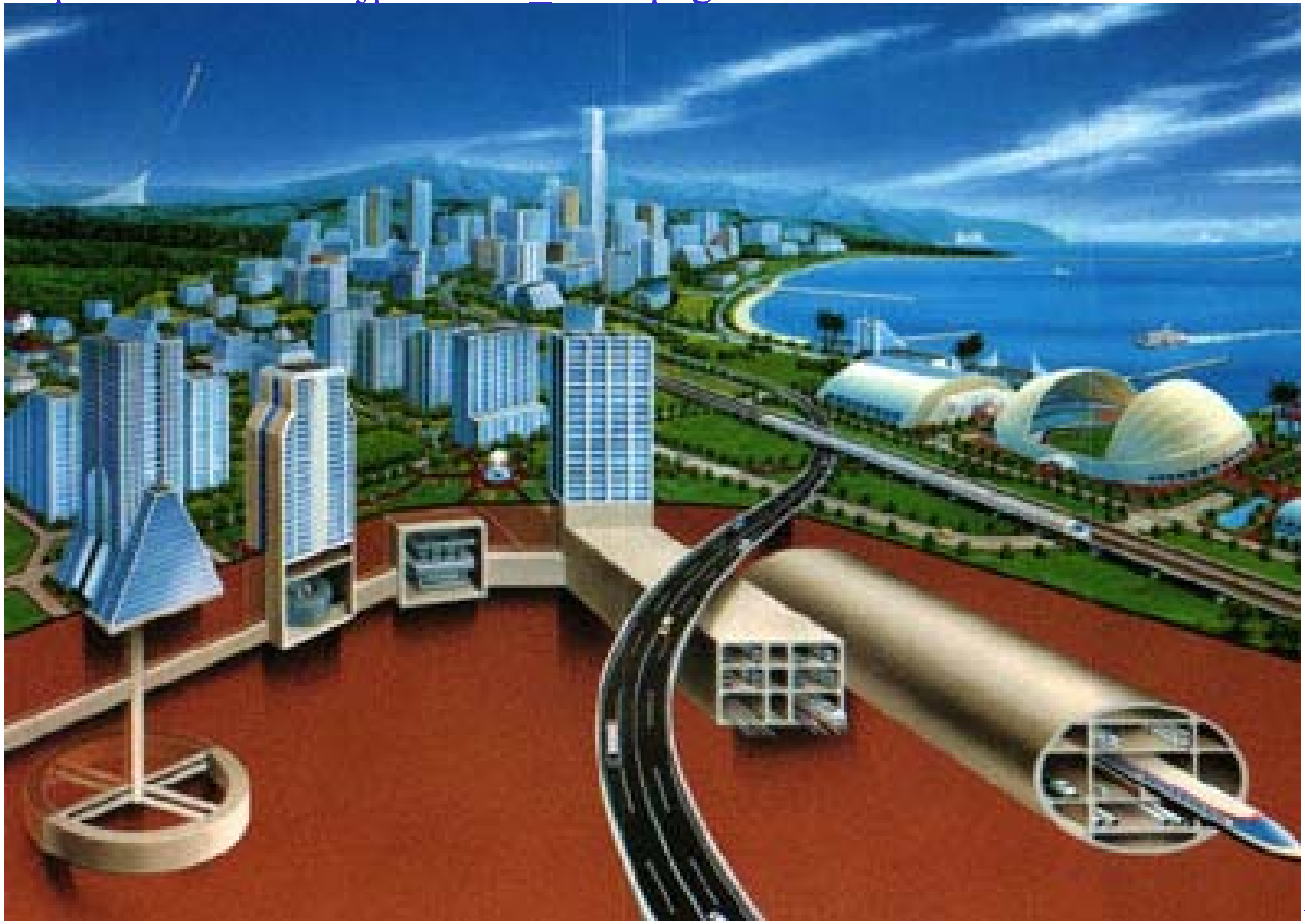
First observation of "Superconductivity" by Onnes (1911)

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



A Future Vision of Mass Use of SC
An Environment Friendly High Tech Village

From: International Superconductivity Technology Center, Japan
http://www.istec.or.jp/ISTEC_homepage/index-E.html

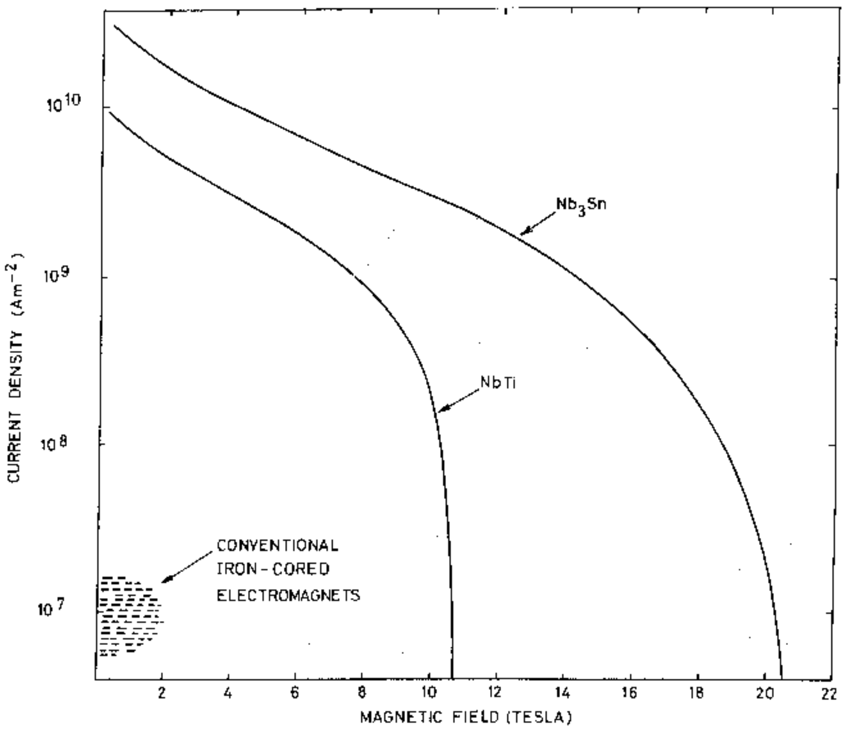


Assignment #1:
What is missing (or hidden) in this picture?

Answer:
A circular collider that uses superconducting magnets and RF Cavities.

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.

A Typical High Energy Collider Chain

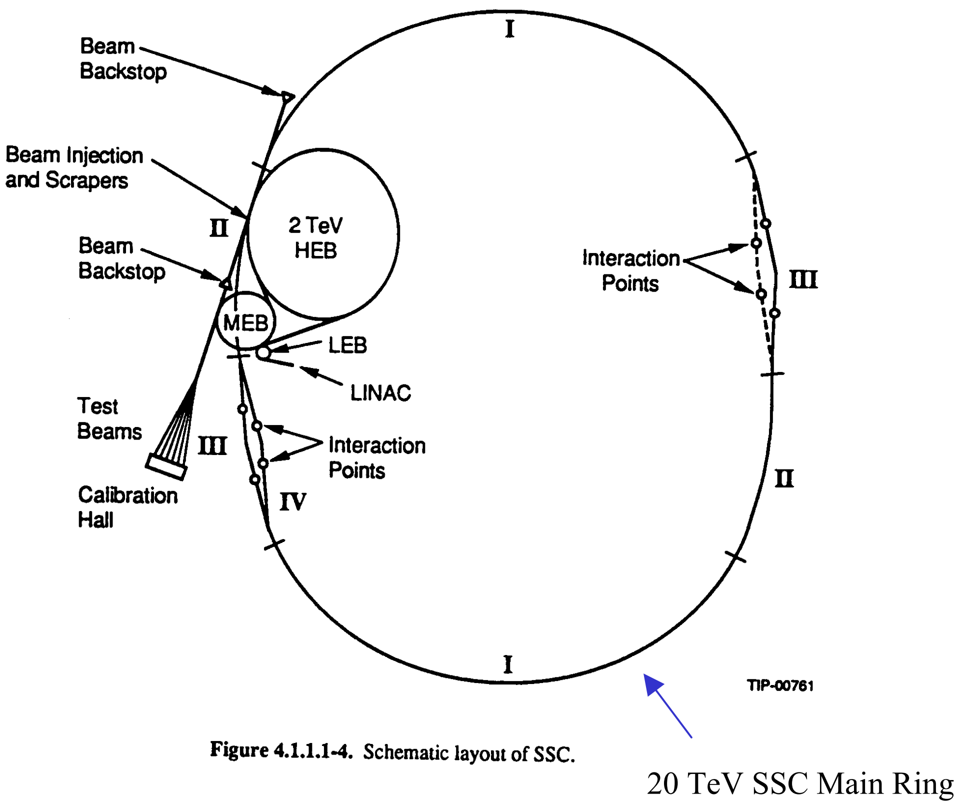
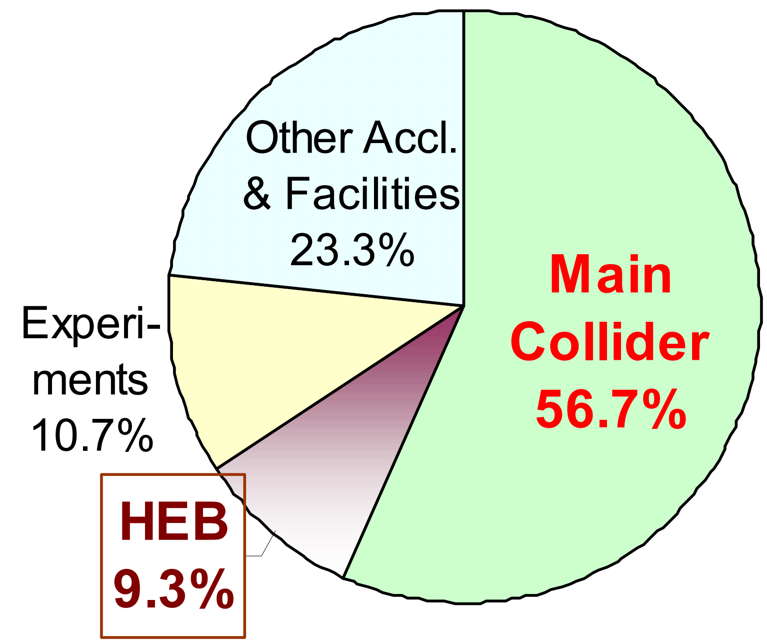


Figure 4.1.1.1-4. Schematic layout of SSC.

Cost Distribution of Major Systems

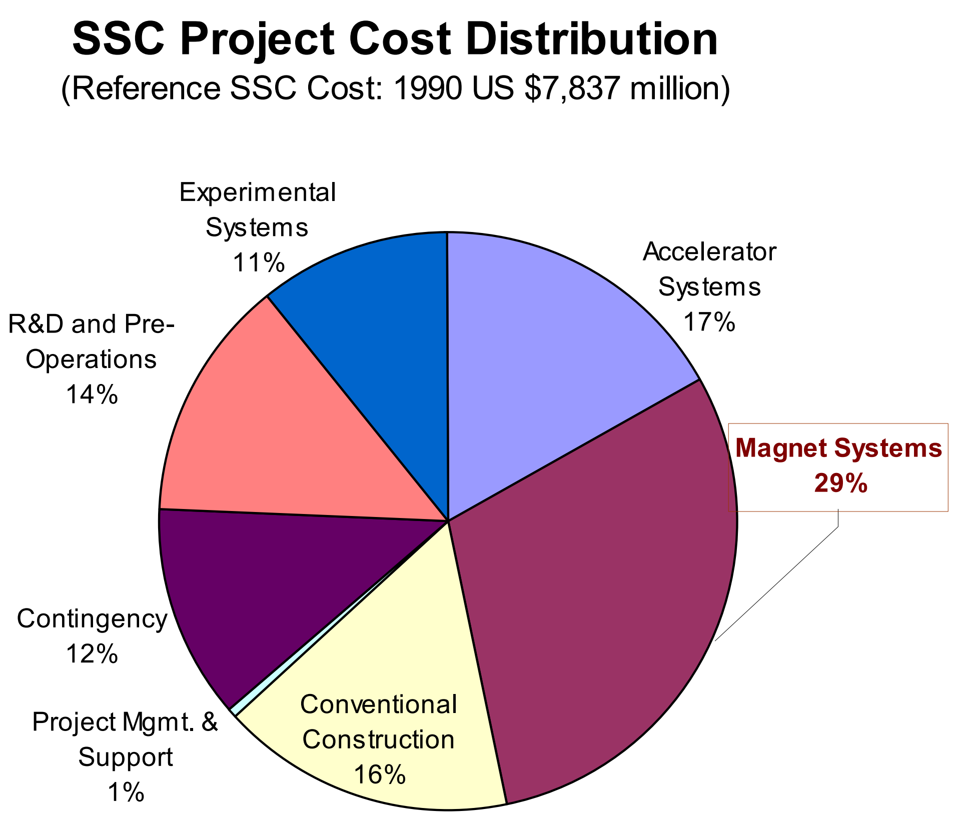
(Reference SSC Cost: 1990 US $7,837 million)

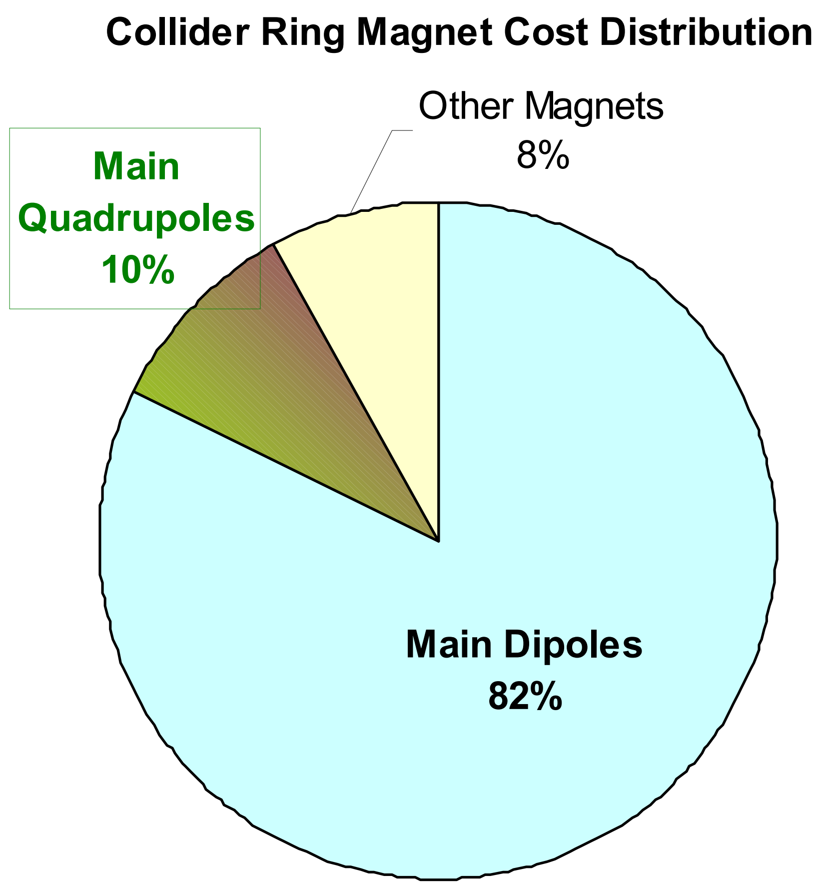


Schematic Layout of SSC

(Derived based on certain assumptions)

Cost of the Main Components in Modern High Energy Hadron Collider





The dipole magnet system of the main ring is the cost driver.

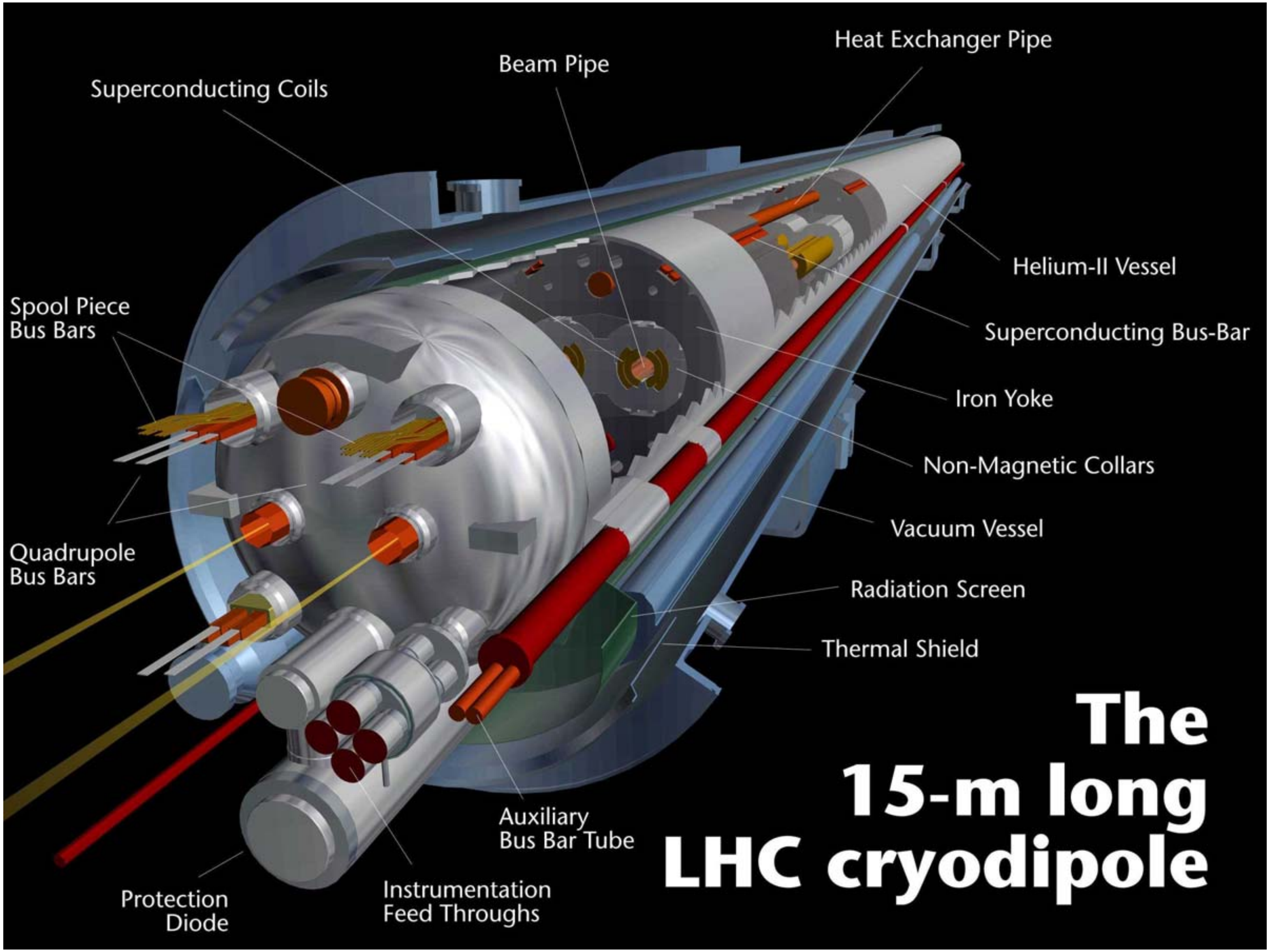
But the cost of other magnets and systems is also important!

Major Accelerator Projects with Superconducting Magnets

Machine	Location	Energy	Circumference	Status
Tevatron	Fermilab, USA	900 GeV (p) X 900 GeV (p-)	6.3 km	Commisioned: 1983
HERA	DESY, Germany	820 GeV (p) X 30 GeV (e)	6.4 km	Commisioned: 1990
SSC	SSCL, USA	20 TeV (p) X 20 TeV (p)	87 km	Cancelled: 1993
UNK	IHEP, Russia	3 TeV	21 km	Suspended
RHIC	BNL, USA	100 GeV/amu X 100 GeV/amu (proton: 250GeV X 250 GeV)	3.8 km	Commisioned: 2000
LHC	CERN, Europe	7 TeV (p) X 7 TeV (p)	27 km	Expected: 2005

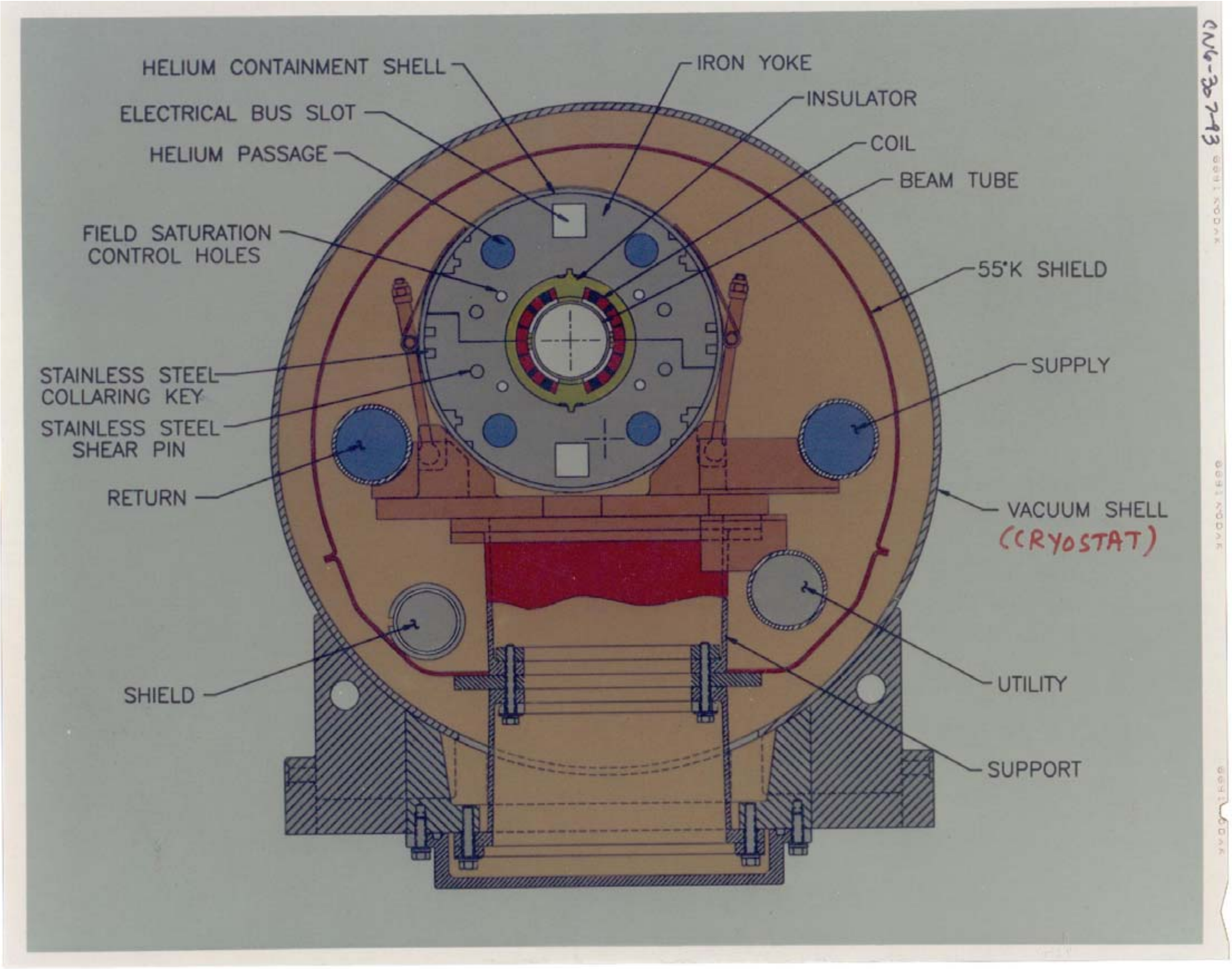
	Dipoles				Quadrupoles			
Machine	B(T)	Aper(mm)	Length(m)	Number	Grad(T/m)	Aper(mm)	Length(m)	Number
Tevatron	4	76.2	6.1	774	76	88.9	1.7	216
HERA	4.68	75	8.8	416	91.2	75	1.9	256
SSC	6.7	50	15	7944	194	40	5.7	1696
UNK	5	70	5.8	2168	70	70	3	322
RHIC	3.5	80	9.7	264	71	80	1.1	276
LHC	8.3	56	14.3	1232	223	56	3.1	386

Schematic of Twin Aperture LHC Dipole in Cryostat

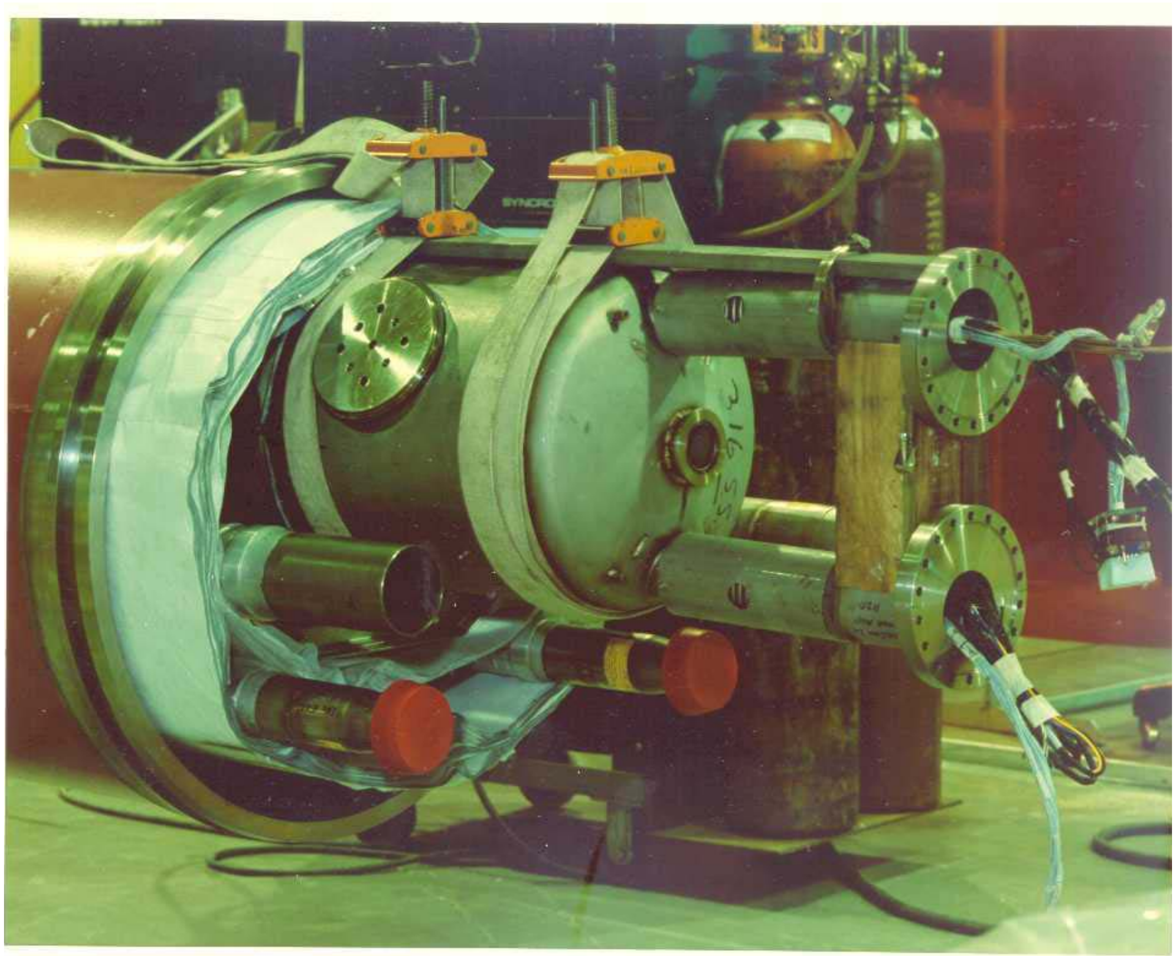


SSC Magnets in Cryostat

RHIC Dipole in Cryostat (schematic)



Dipole Coldmass Being Assembled in Cryostat

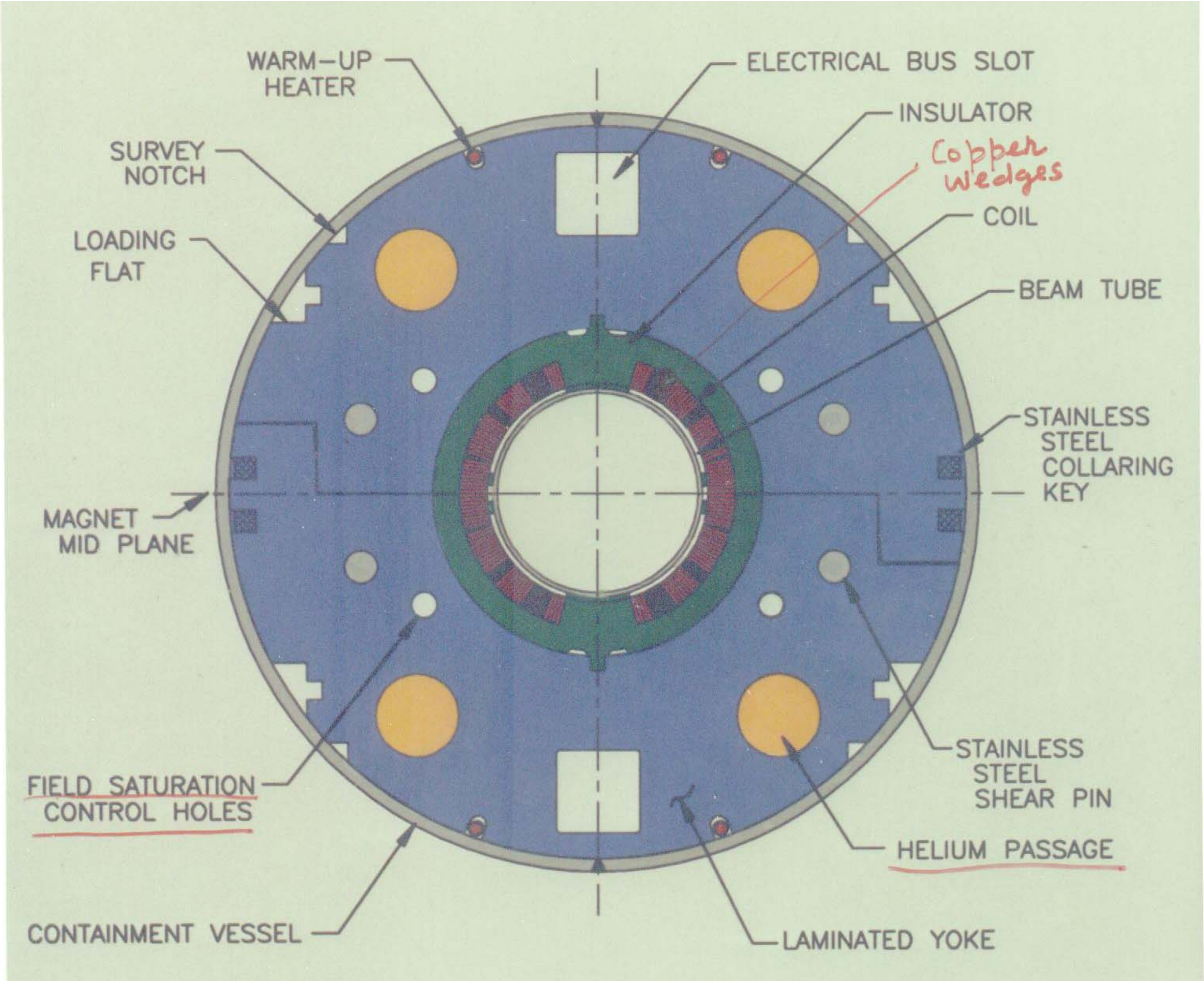


RHIC Magnet Coldmass During Assembly

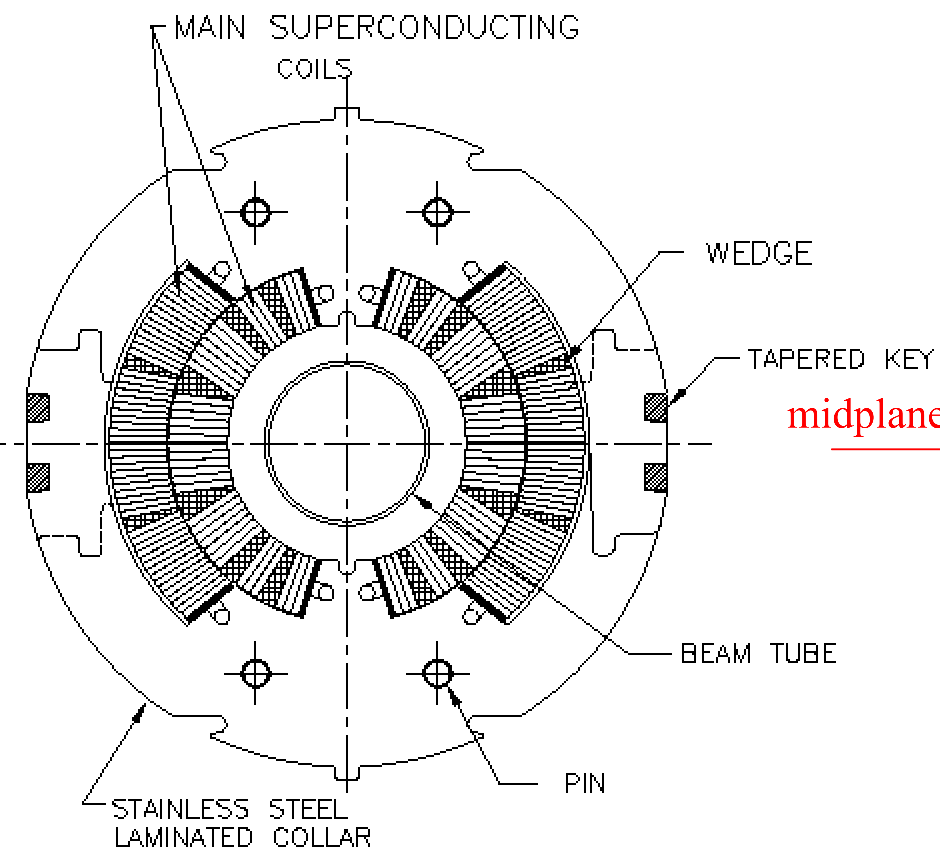
RHIC dipole coldmass during assembly

RHIC insertion quad coldmass during assembly

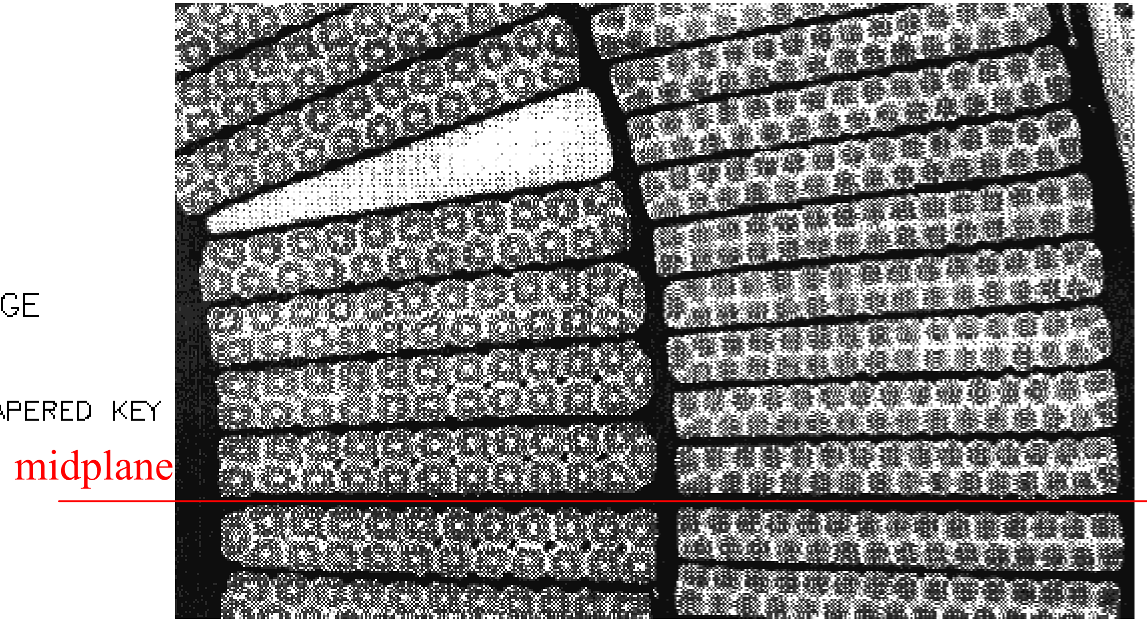
RHIC Dipole Coldmass



Collared Coil Cross-section



SSC 50 mm dipole collared coil cross-section



Scanned and photo-enhanced image of a dissected SSC 40 Coil (still in collar). Inner and outer stands, wedge and insulation (dark) can be seen. One can determine the actual position of cable in a collared coil (warm).

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

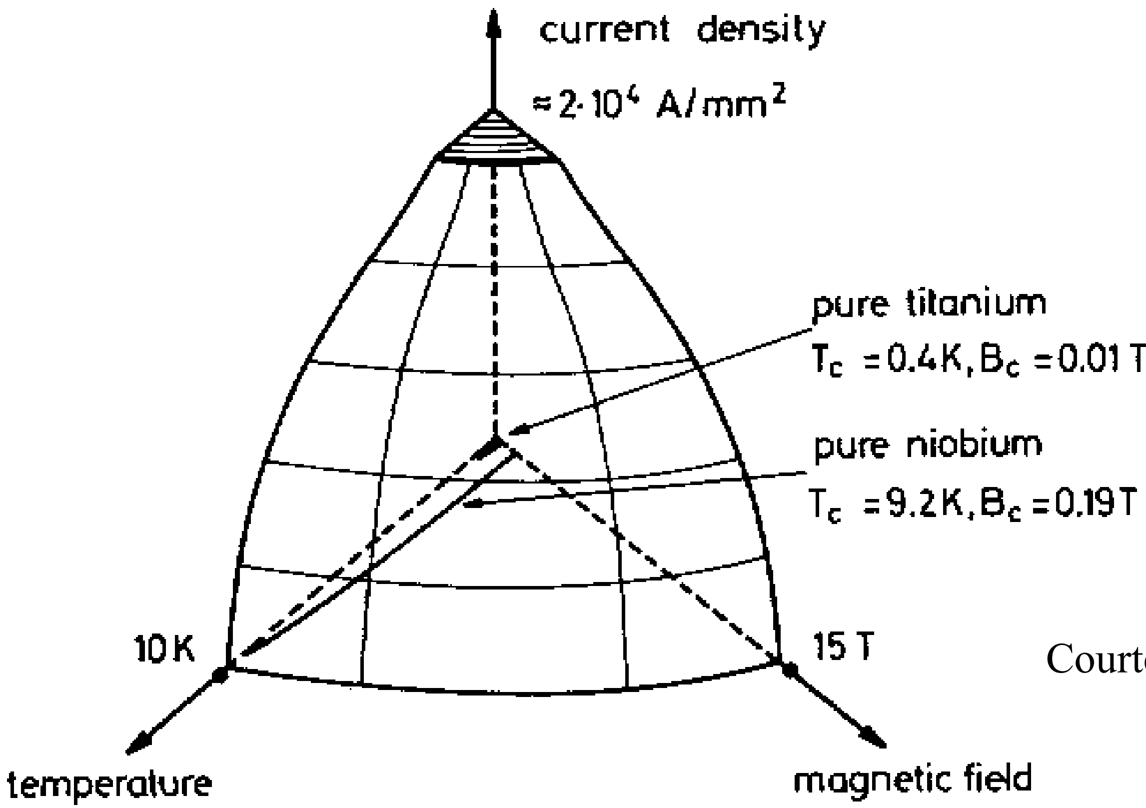
1980 Tevatron: The first accelerator using superconducting magnets

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 find a place here? Have patience!

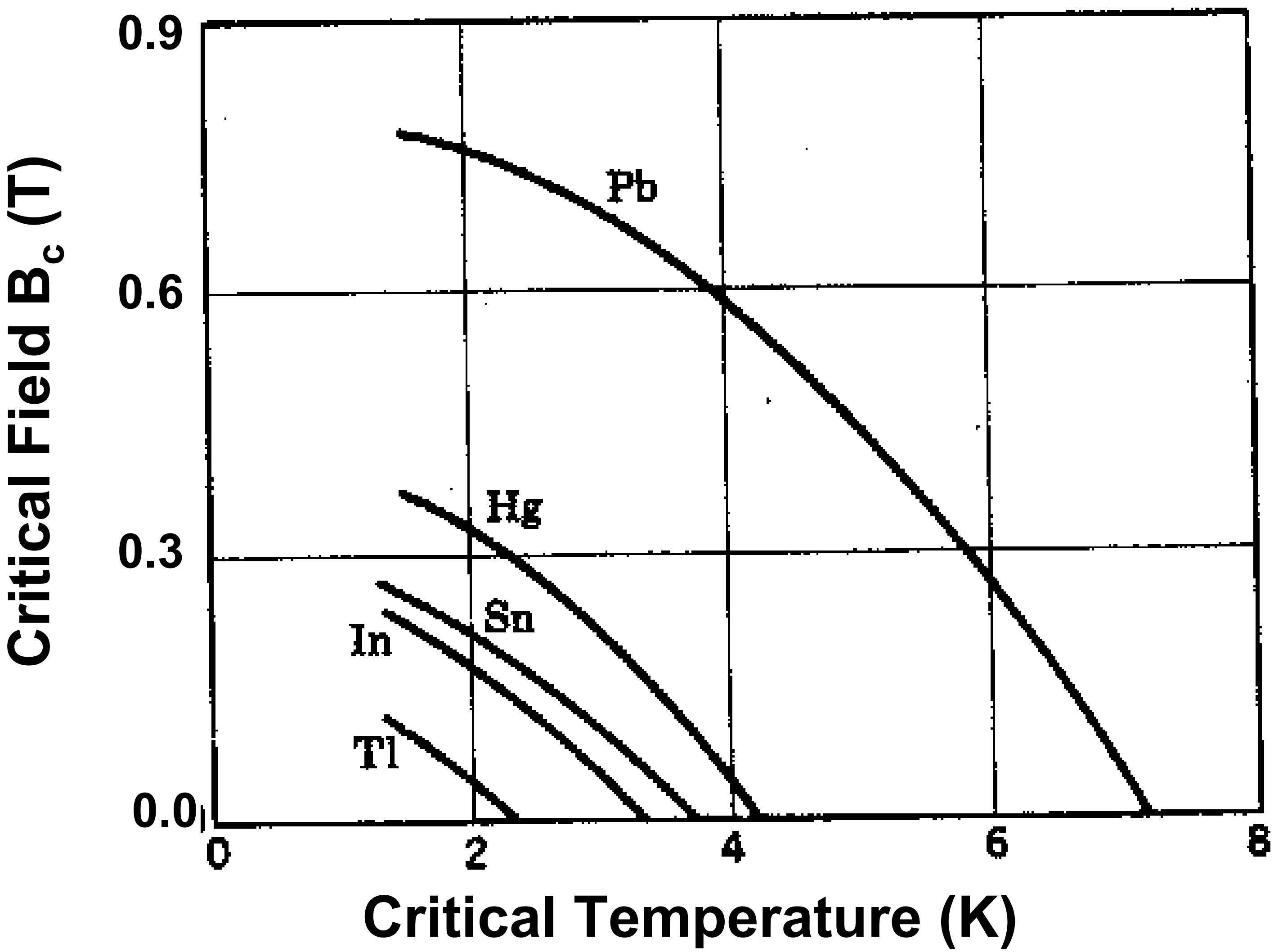
Critical Surface of Nb-Ti



Courtesy: P. Schmuser

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.

Critical Surface of Type I Superconductors



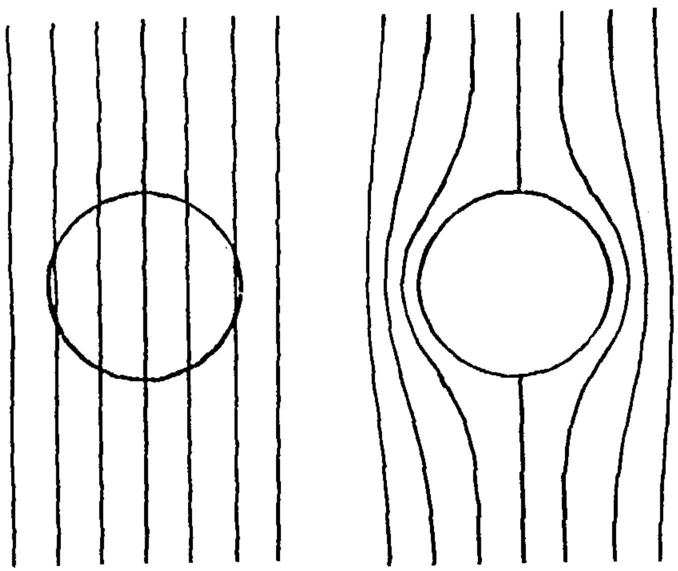
Type I superconductors are obviously NOT suitable for high field magnet applications.

Meissner Effect

Another remarkable characteristic of superconductor:

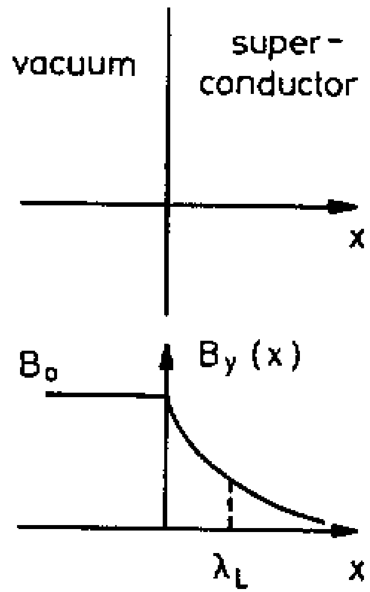
They exclude the field from going through inside.

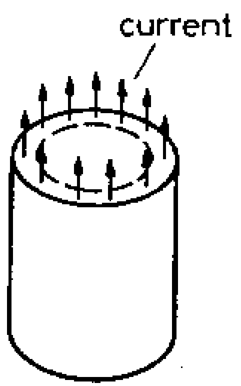
Meissner and Ochsenfeld (1933)



Normal Conductor   Superconductor

Courtesy: Wilson





Courtesy: Schmuser

Attenuation of magnetic field and shielding currents in Type I superconductors

Type I and Type II Superconductors

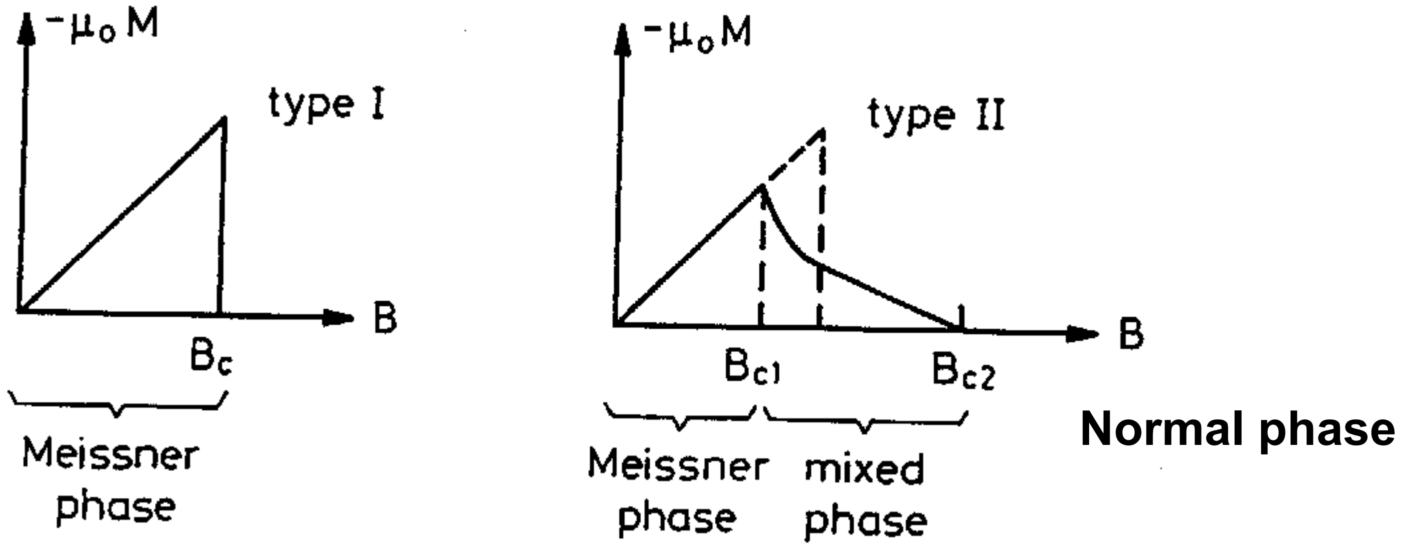


Figure 10: Magnetisation of type I and type II superconductors as a function of field.

Type I:

Also known as the soft Superconductors.

Completely exclude the flux lines.

Allow only small field (< 0.1 T).

Not suitable.

Type II:

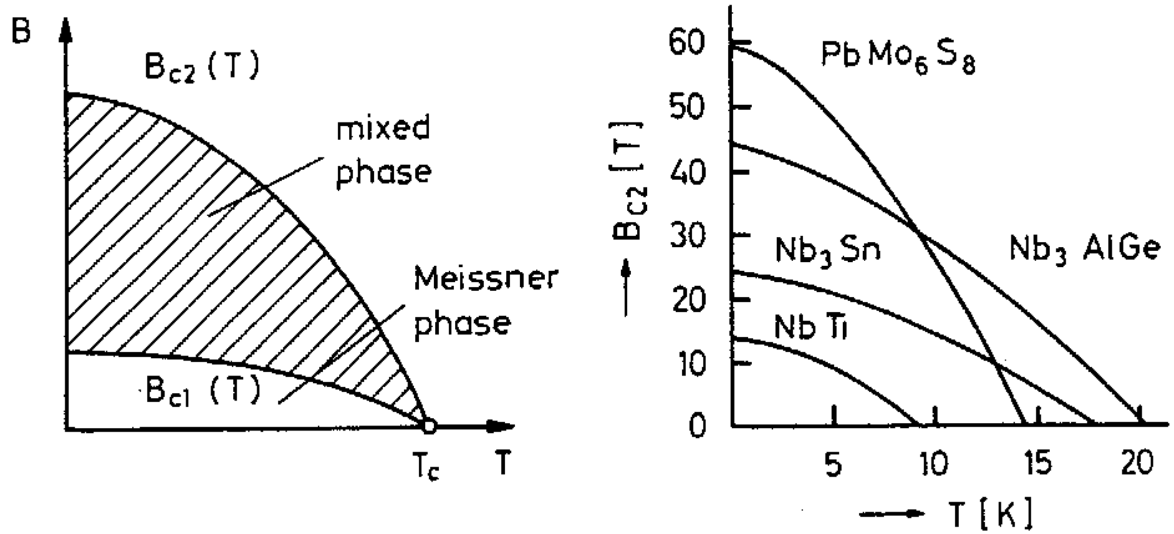
Also known as the hard Superconductors

Completely exclude flux lines up to Bc1 but then part of the flux enters till Bc2

Allow much higher fields.

Examples: NbTi, Nb_3Sn

Type II Superconductors



Courtesy: Schmuser

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

Conductors that are used in building magnets are Type II superconductors.

Nb-Ti is ductile and has been used in all accelerator magnets used in the machine so far.

Nb_3Sn (allows field > 10 T) is brittle and requires extra design and magnet construction consideration.

London Penetration Depth and Coherence Length

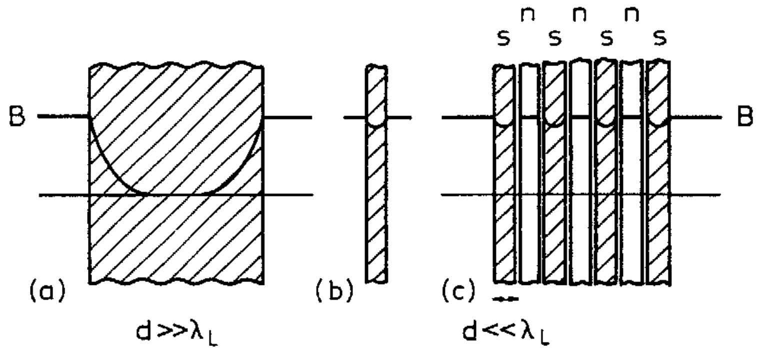


Figure 14: Attenuation of field (a) in a thick slab and (b) in thin sheet. (c) Subdivision of a thick slab into alternating layers of normal and superconducting slices.

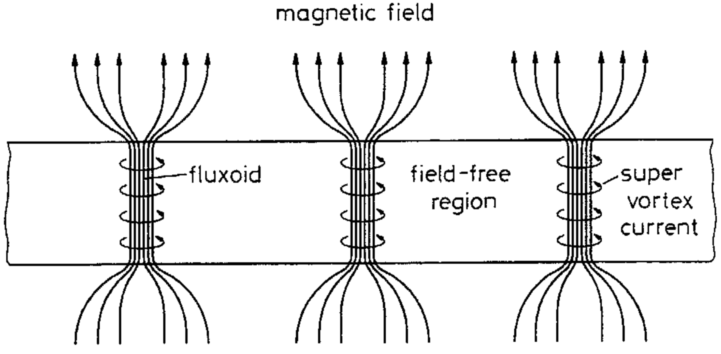
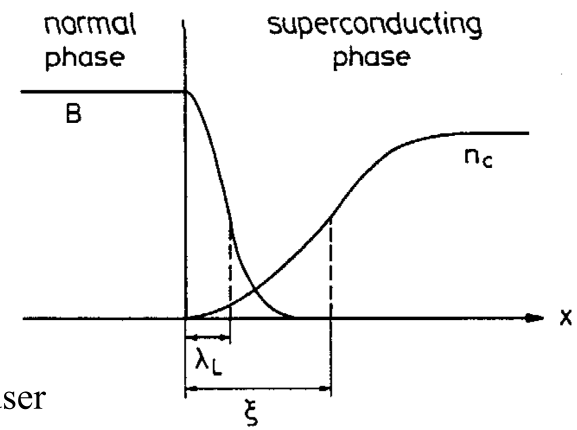


Figure 13: Flux tubes in a type II superconductor.



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 cooper pairs rise

Nb is type II

Current Transport in Bulk Superconductors

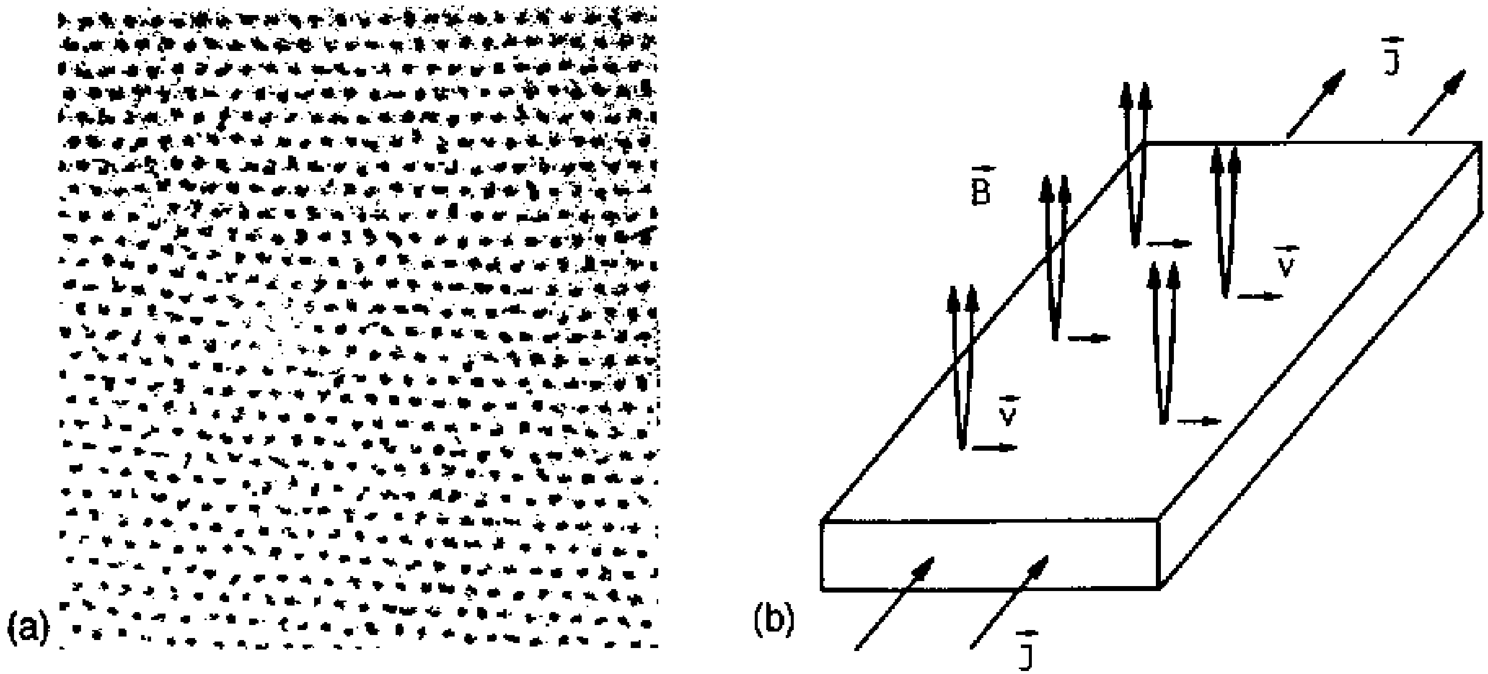


Figure 2.7: (a) Fluxoid pattern in niobium (courtesy U. Essmann). The distance between adjacent flux tubes is 0.2 μm. (b) Scheme of fluxoid motion in a current-carrying type II superconductor.

Courtesy: Schmuser

Flux Jumping

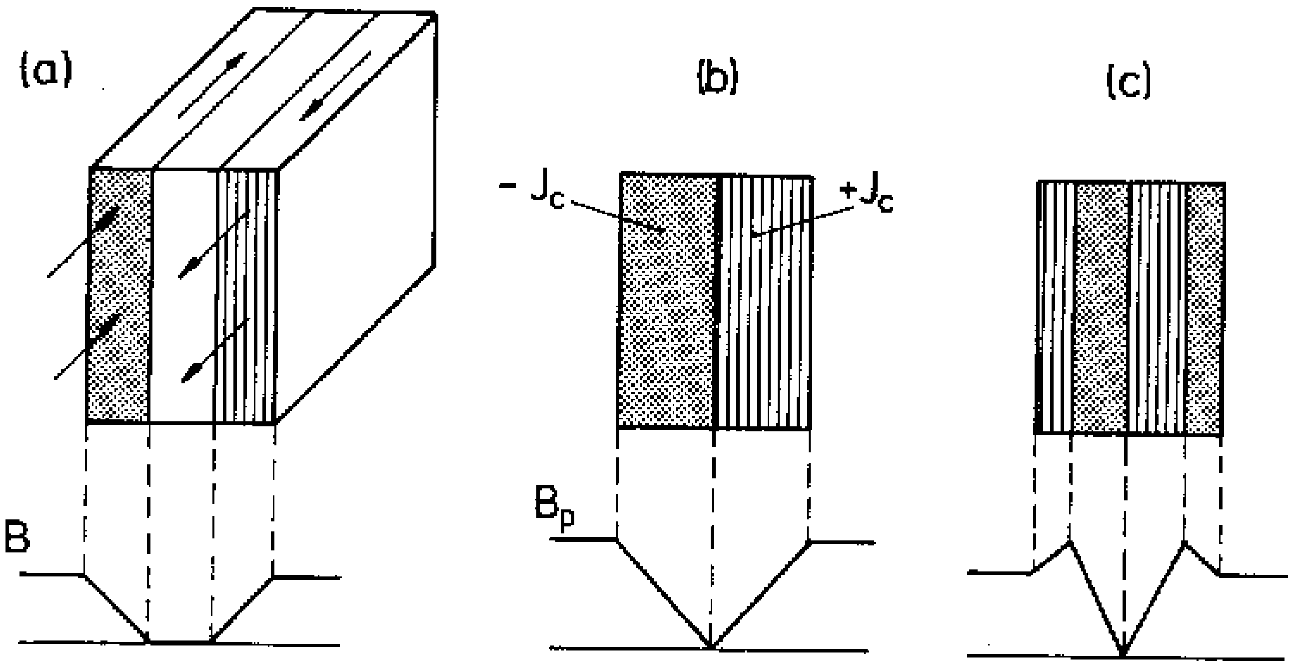
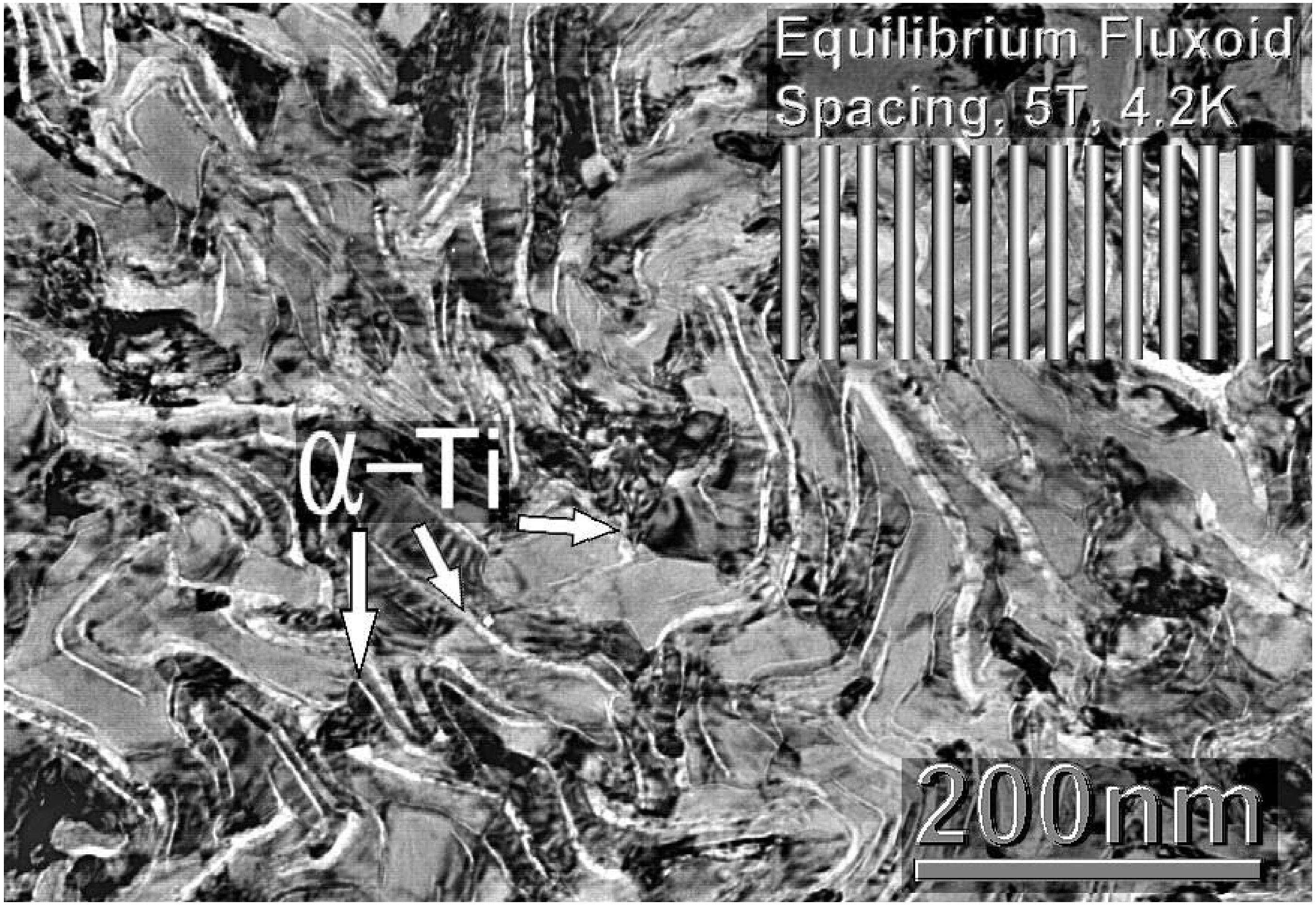


Figure 2.12: Current and field distribution in a slab of hard superconductor according to the critical-state model. The external field is parallel to the surface. (a) Initial exposition to a small external field. (b) The penetrating field B_p. (c) External field first raised above B_p and then lowered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

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)

Instability from Flux Jumping

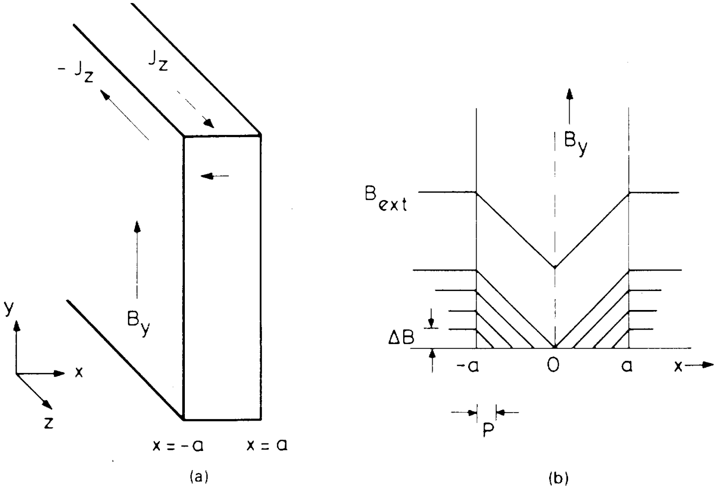
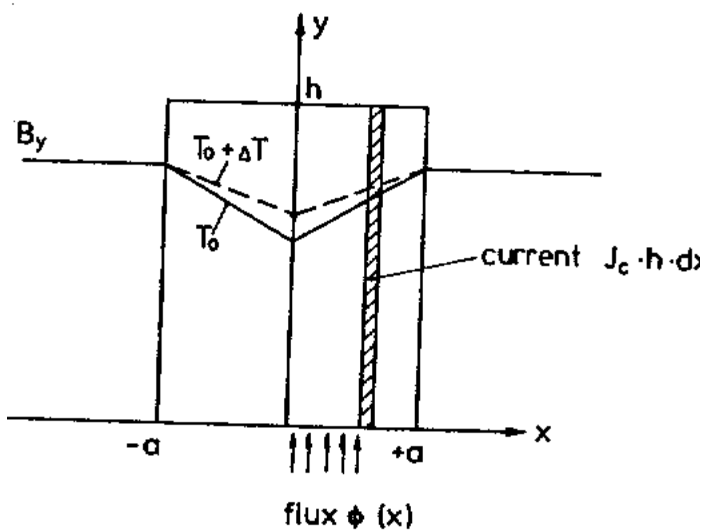


Fig. 7.1. (a) Screening currents induced to flow in a slab by a magnetic field parallel to the slab surface; (b) Magnetic field pattern across the slab showing the reduction of internal field by screening currents.



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

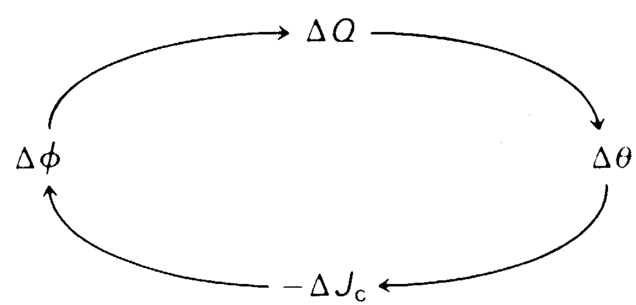
b) change in screening currents allows flux to move into the superconductor

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 value for NbTi is < 40 μ; for safety reasons use ~ 20 μ.

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

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

Magnetization Effects in SC Filaments

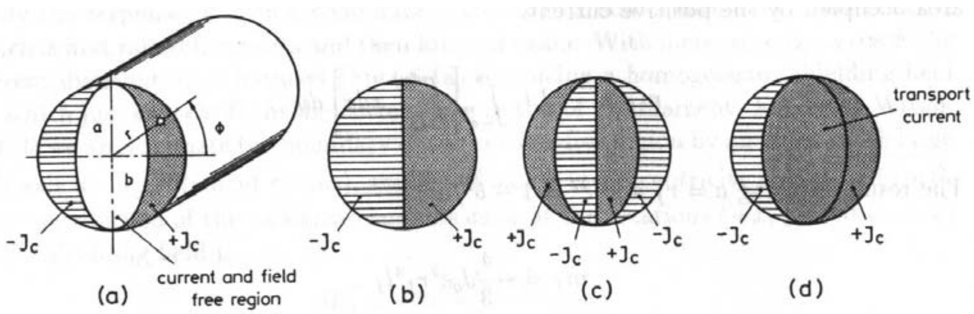


Figure 6.1: Schematic view of the persistent currents which are induced in a superconducting filament by a varying external field. (a) The external field is raised from zero to a value B_e less than the penetrating field B_p. (b) A 'fully-penetrated' filament, i.e. $B_e \geq B_p$. (c) Current distribution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

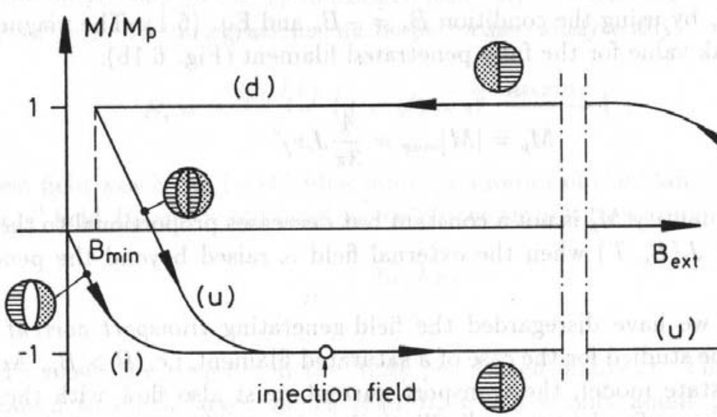


Figure 6.2: The normalized magnetization M/M_p of a NbTi filament as a function of the external field. (i): initial curve, (u): up-ramp branch, (d): down-ramp branch. Also shown are the current distributions in the filament. The field dependence of J_c has been neglected.

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

Persistent current induced magnetization:

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

J_c , CRITICAL CURRENT DENSITY

d , FILAMENT DIAMETER

ν , VOL. FRACTION OF NbTi

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

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

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

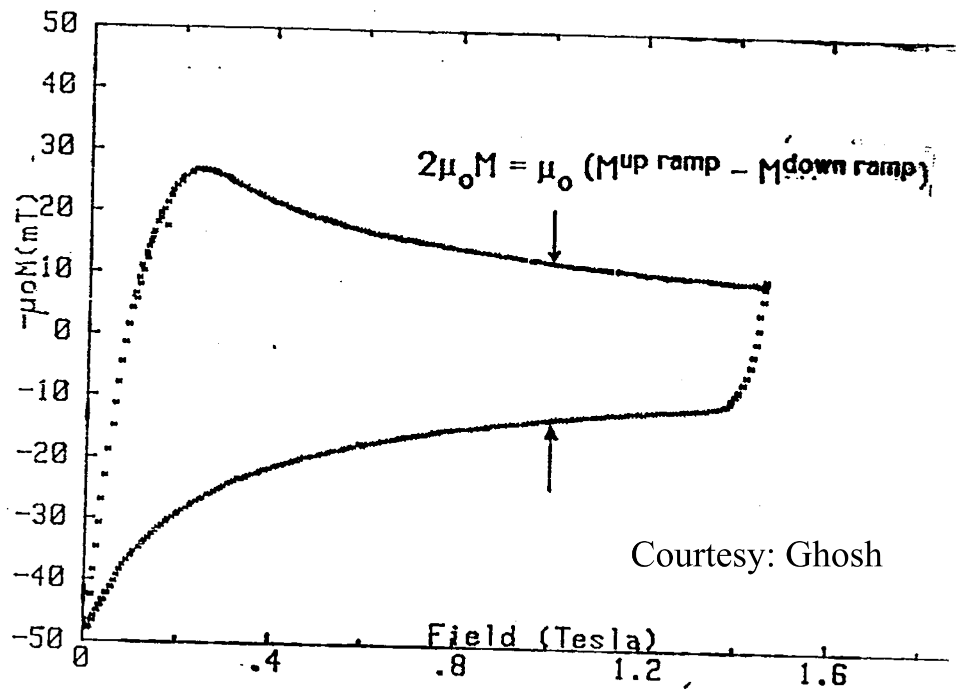
Problem in Nb_3Sn Magnets because

(a) Jc is higher by several times

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

In Nb3Sn case, the effective filament diameter is larger than NbTi by about an order of magnitude.

Measured magnetization (NbTi)

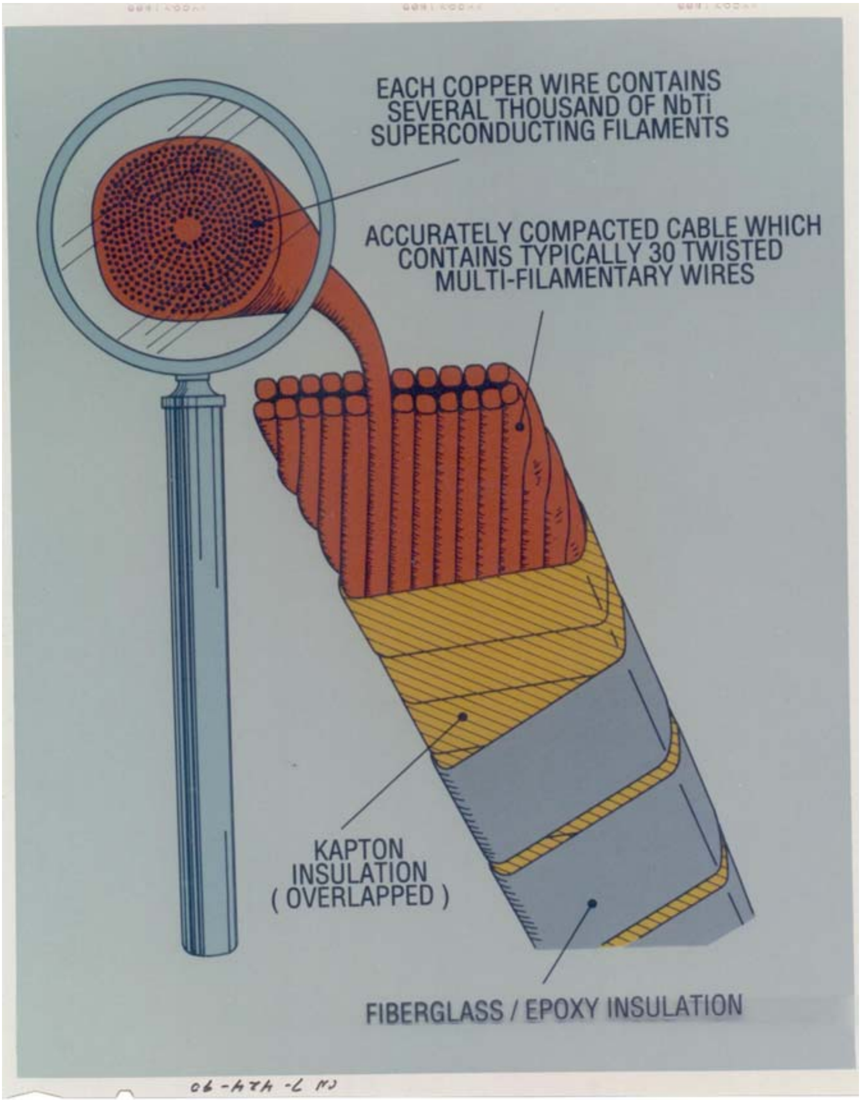


Courtesy: Ghosh

Fig. of a typical magnetization loop.

Either reduce the effective filament diameter or come up with a design that minimizes the effect of magnetization in the magnets.

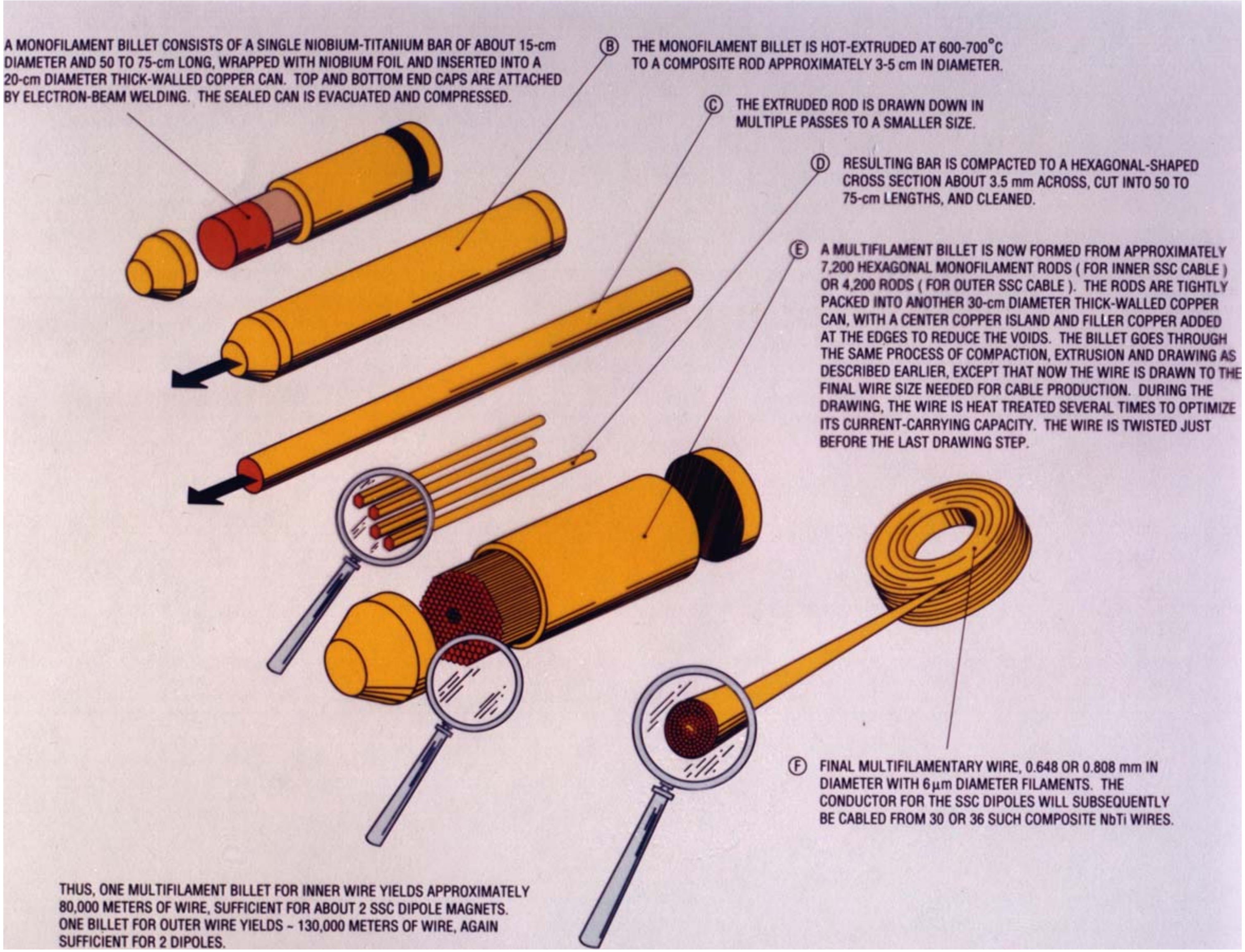
A Typical Superconducting Cable



Filaments in an actual cable

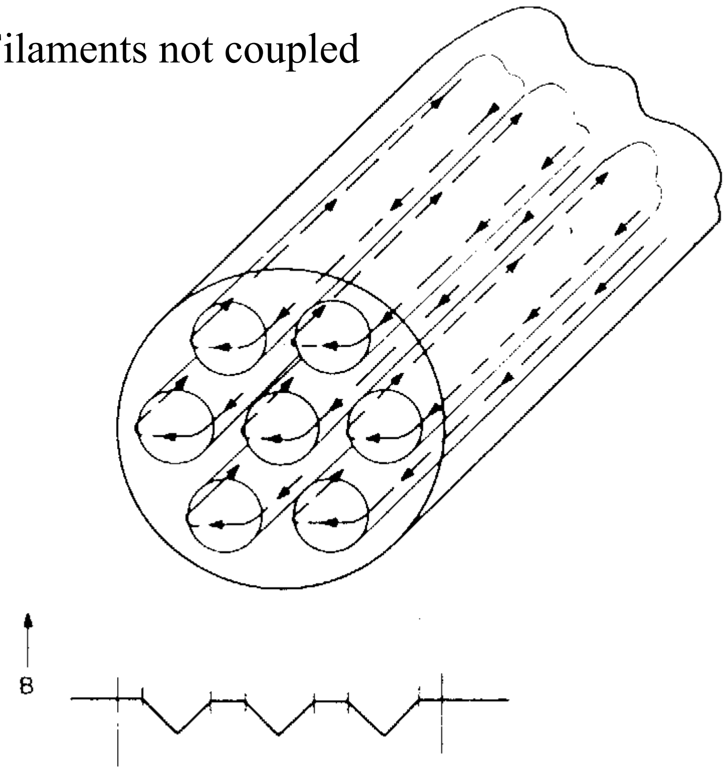
(Filament size in SSC/RHIC magnets: 6 micron)

Manufacturing of Nb-Ti Wires

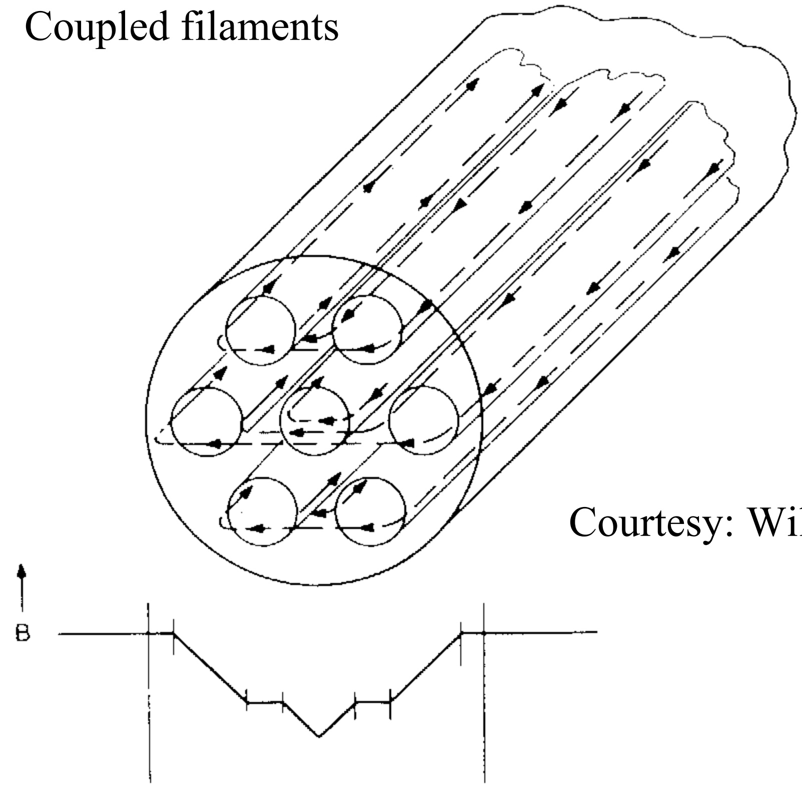


Stability of Superconducting Wire Made of Many Filaments

Filaments not coupled



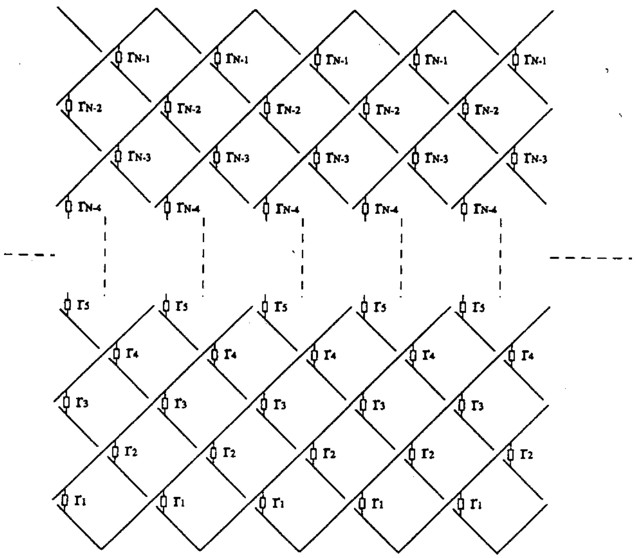
Coupled filaments



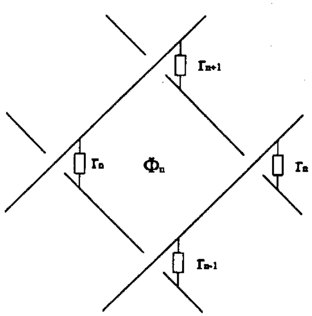
Courtesy: Wilson

A wire composed of twisted filaments

Interstrand Coupling



a) Overall Circuit



b) Single Loop

Figure 3-9 Equivalent Circuit for Rutherford-type Cable

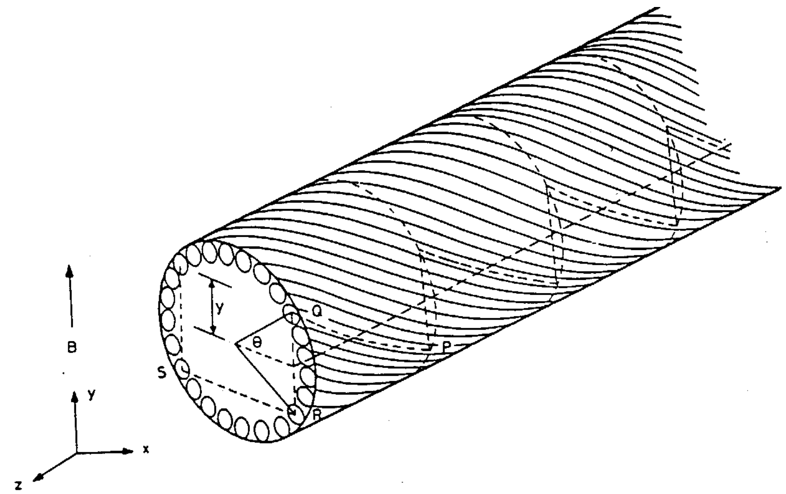


Figure 3-7 Multifilamentary Composite [28]

Courtesy: Devred

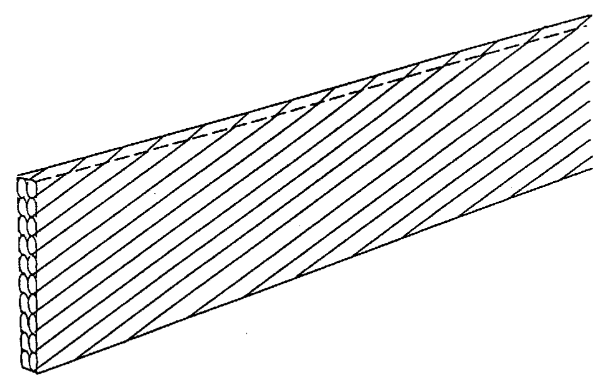
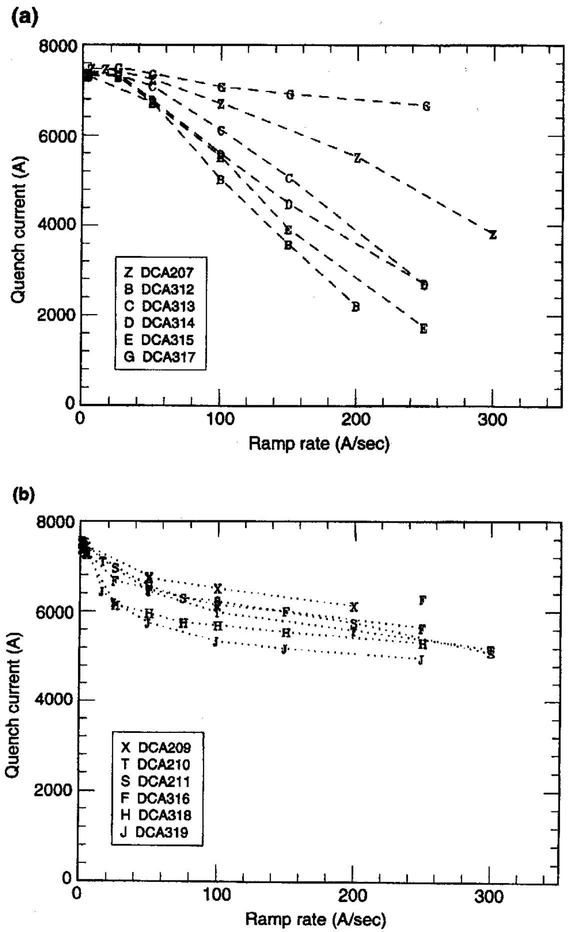


Figure 3-8 Rutherford-type Cable

Influence of Interstrand Coupling



Courtesy: Devred

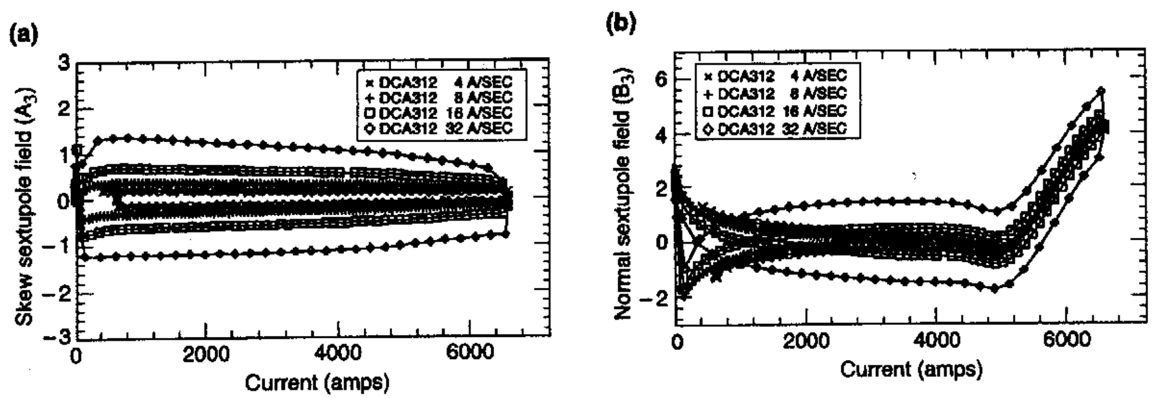
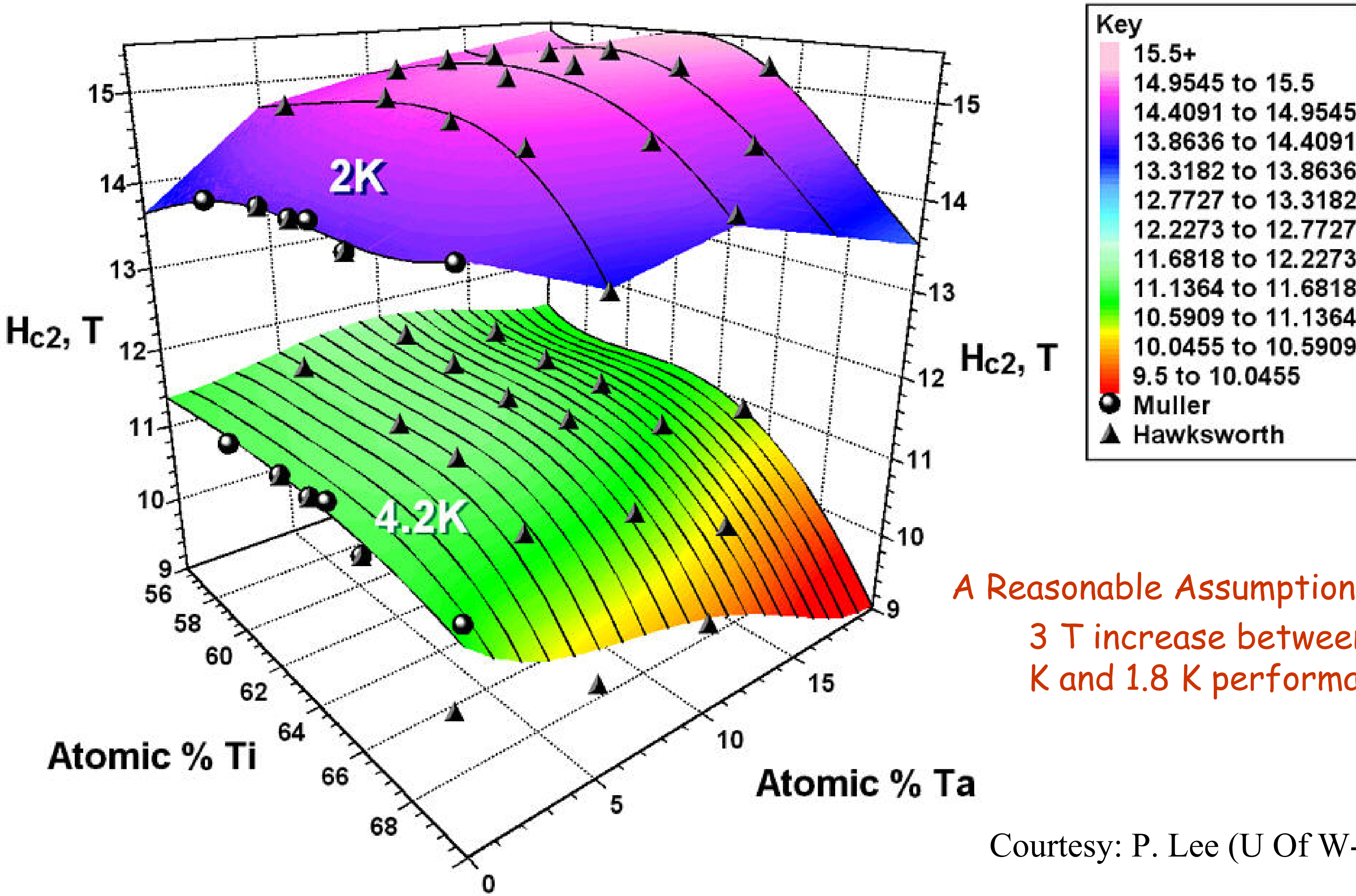


Figure 52. Effects of interstrand coupling currents on multipole field coefficients measured as a function of ramp rate in the central part of a SSC dipole magnet [160]: (a) skew sextupole field coefficient (A_3) and (b) normal sextupole field coefficient (B_3). The transport-current contribution has been subtracted from the data.

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.)

Nb-Ti Alloys at 4.2 K and 1.8 K

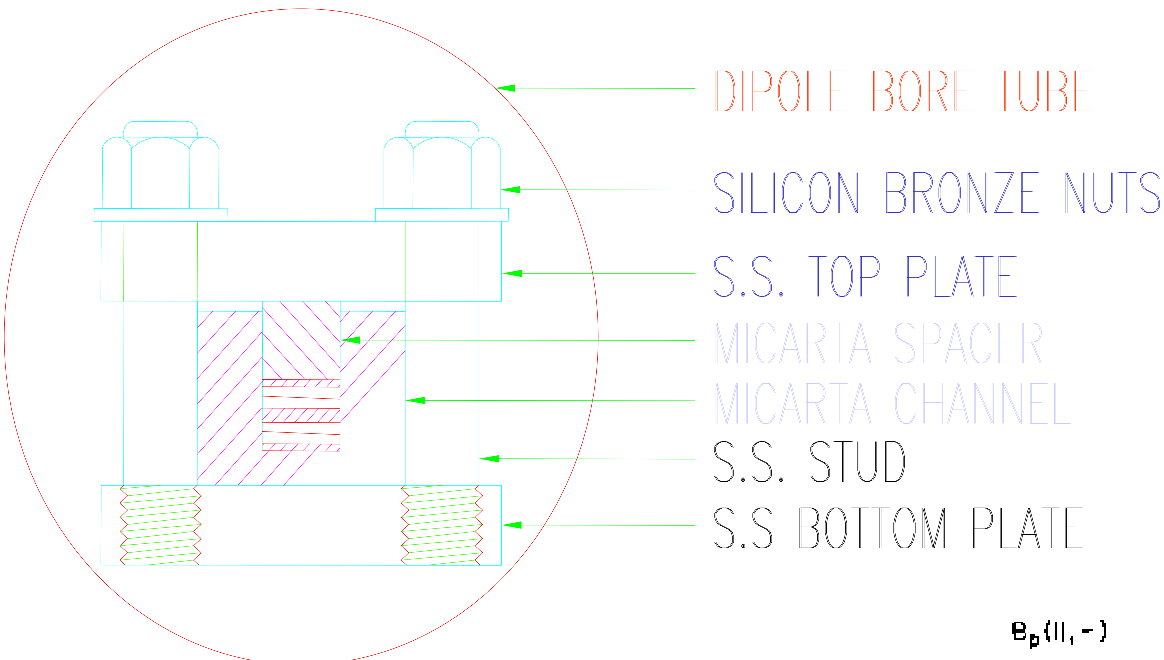


A Reasonable Assumption:

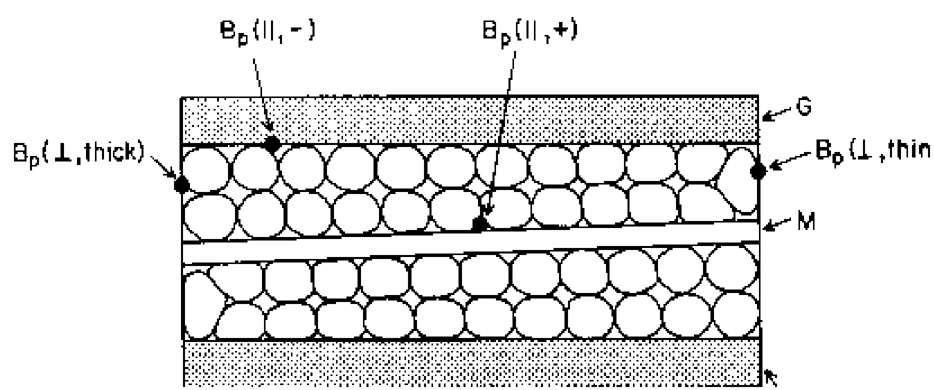
3 T increase between 4.2 K and 1.8 K performance

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

Cable Measurement Set-up



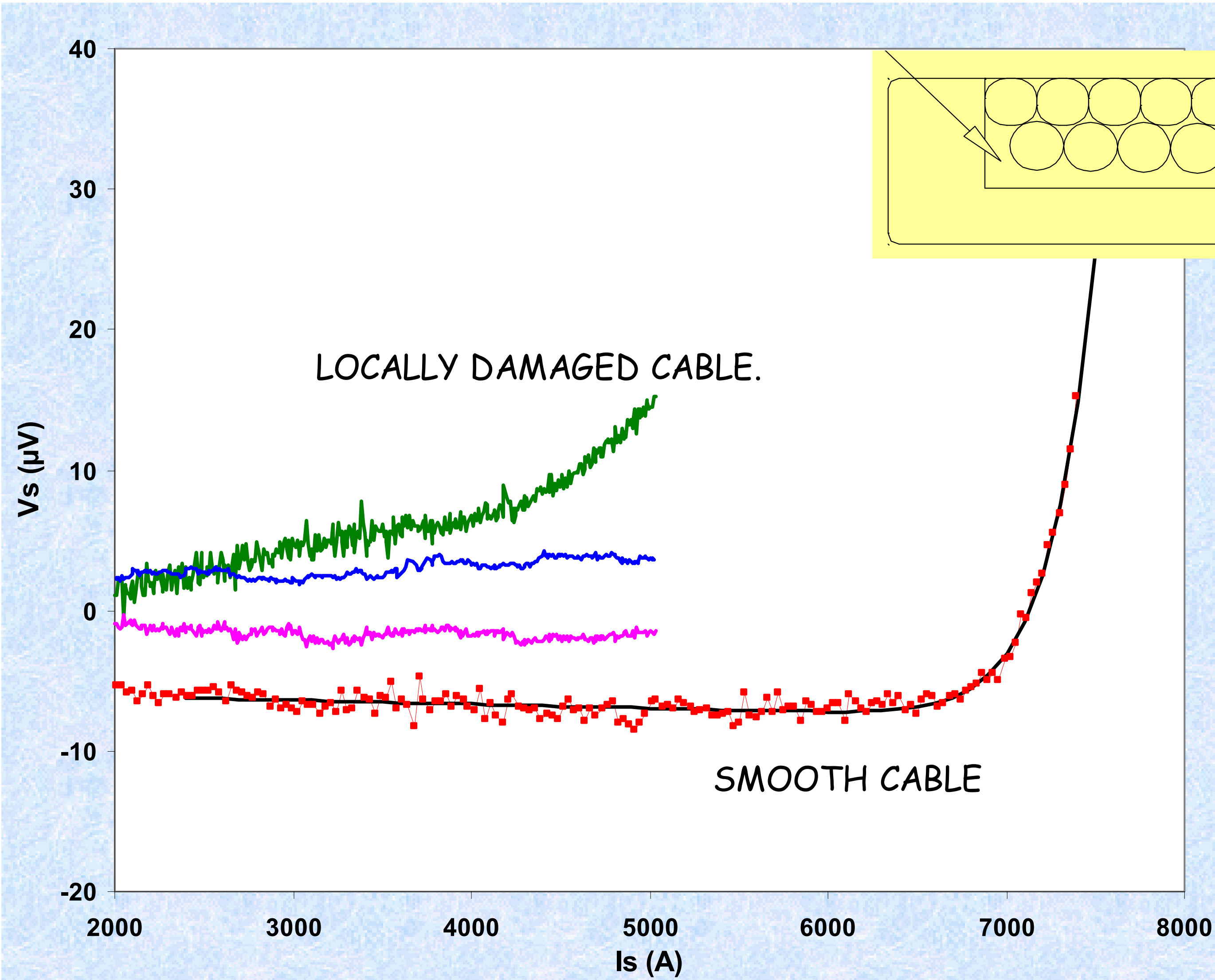
Courtesy: Ghosh

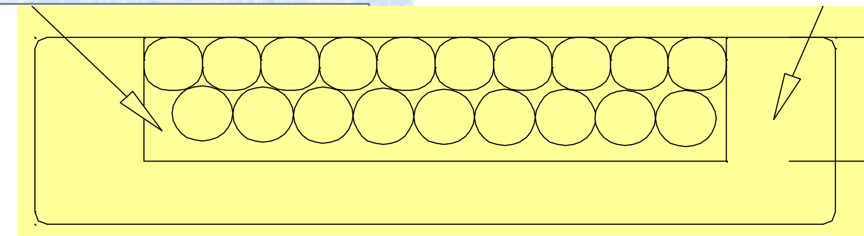


BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Nb3Sn Cable in Cu- Channel





n-value:

A good indicator of the quality of cable

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

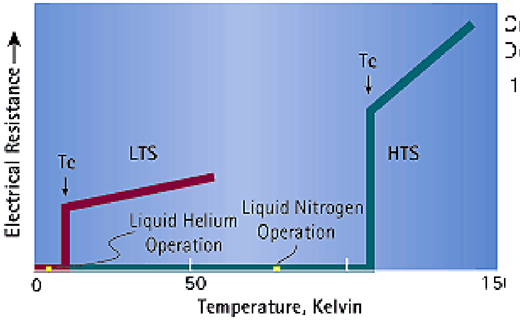
Courtesy: Ghosh

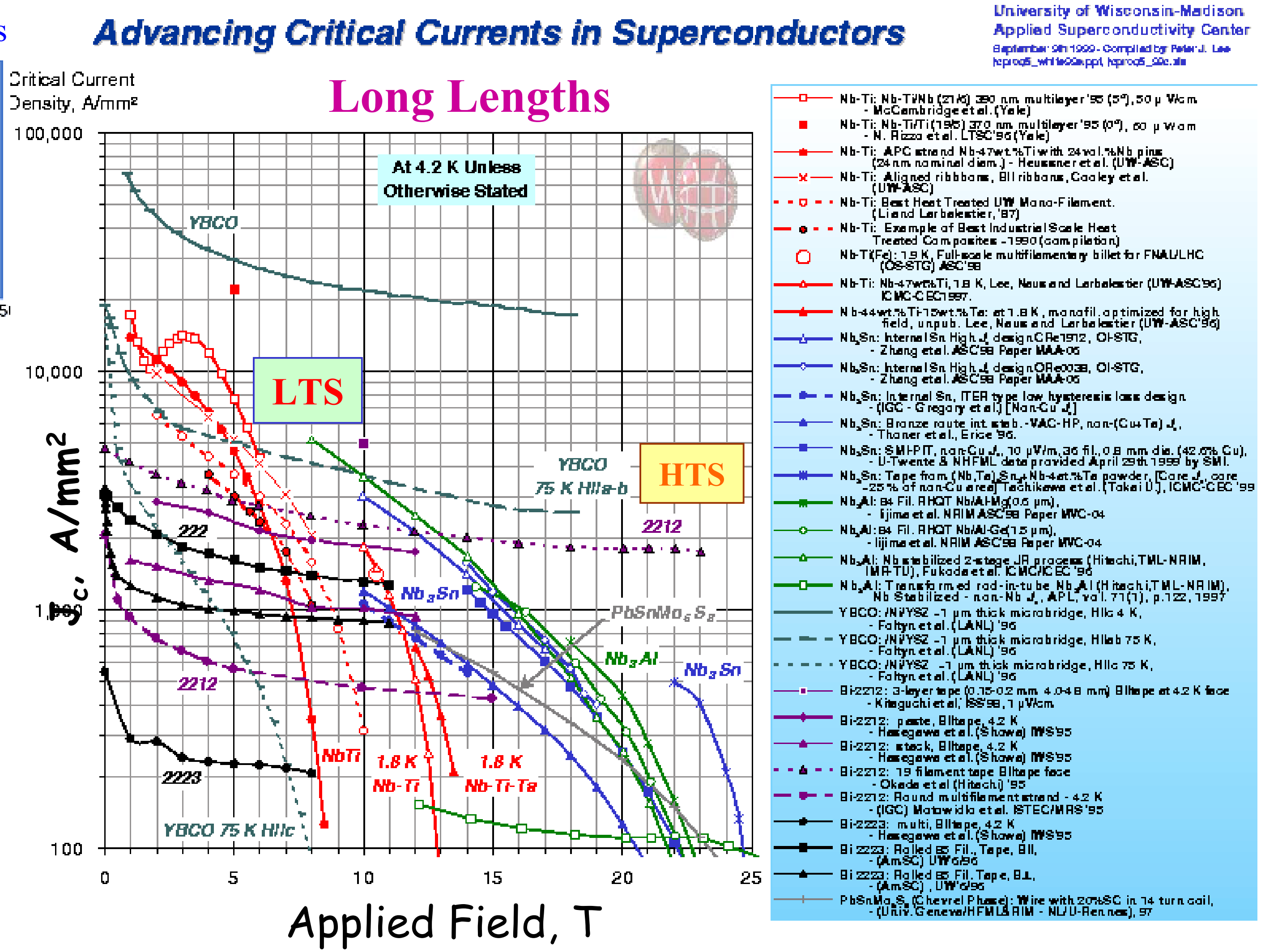
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

High Field Magnets and High Temperature Superconductors (HTS)

From: American Supercondctors





For high field magnets, we are interested in the "Low Temperature", performance of "High Temperature Superconductors".

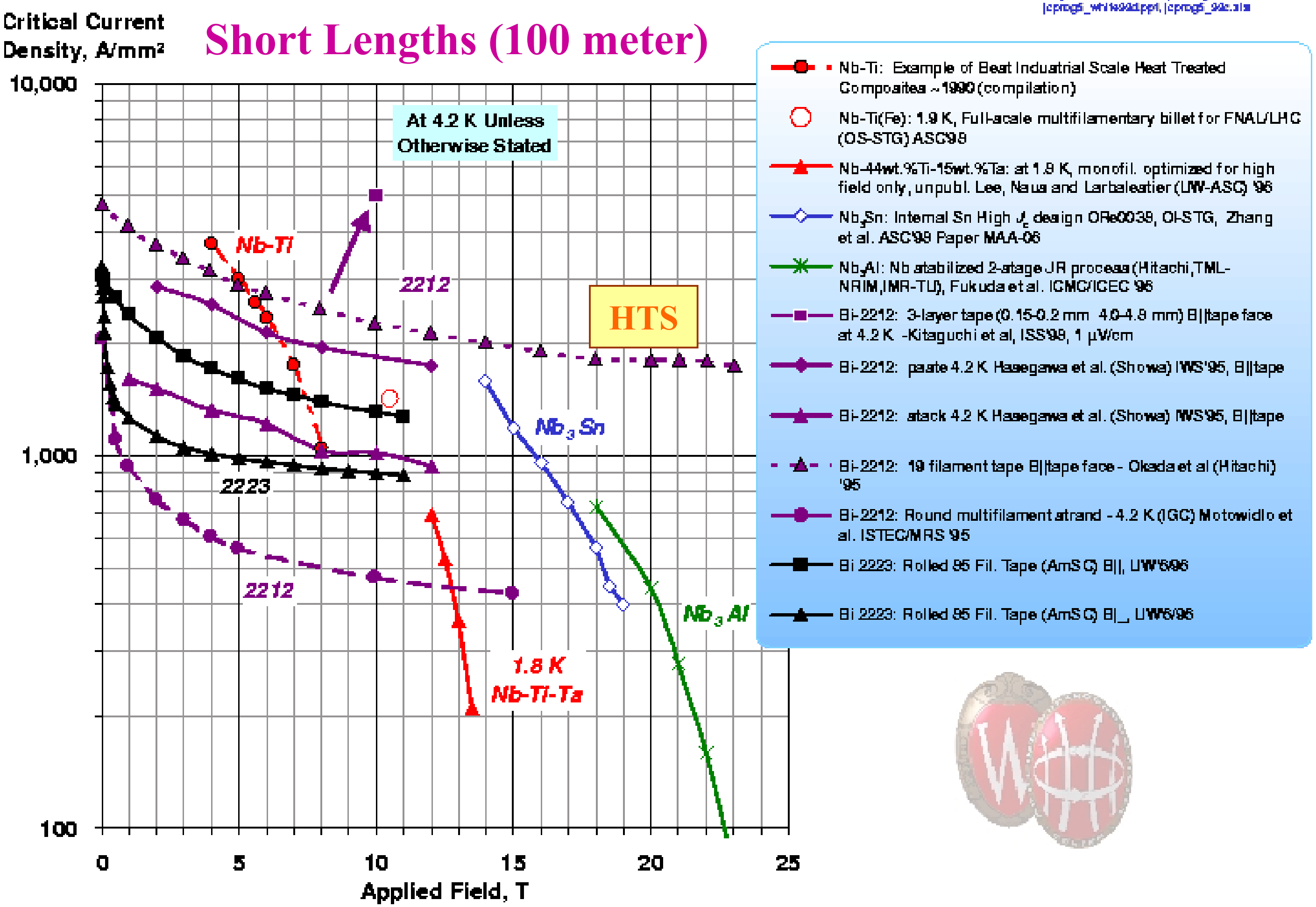
At very high fields, HTS have a better performance.

But what really matters is the engineering (overall) current density.

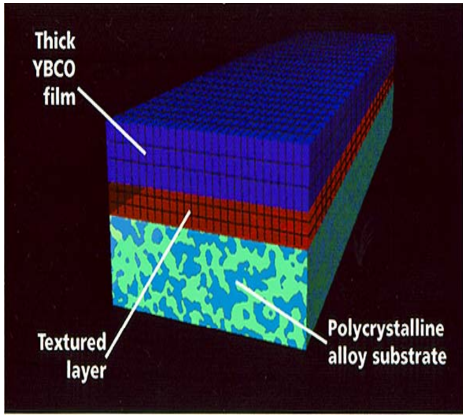
High Field Magnets and High Temperature Superconductors (HTS)

Advancing Critical Currents in Superconductors

University of Wisconsin-Madison
Applied Superconductivity Center
August 2nd 1999 - Compiled by Peter J. Lee
Jcprog5_white99d.ppt, Jcprog5_99c.xls



For high field magnets, we are interested in the "Low Temperature", characteristic of "High Temperature Superconductors".



But what really matters is the engineering current density (J_e)!

Superconducting Magnets in Accelerators
The Cost Issue

•In circular machines, the size of the machine is determined by the field in the magnet (Circumference ∝ 1/R).

•High field magnets may reduce the overall accelerator system cost (tunnel, facilities, vacuum system, etc.). Superconducting magnets may also reduce the operating cost as there is no Joule heating.

•But the superconducting magnets themselves are much more expansive than the conventional warm magnets. In addition, one must also consider the additional cryogenic costs (both installation and operational).

•Use superconducting magnets only if there is a substantial savings because they also bring the complexities (magnet protection, cryogenic system, etc.). In high energy colliders (specially in hadron colliders), the superconducting magnets tend to minimize the cost of building and operating the machine.

•However, even when the superconducting magnets are used, the highest attainable field is often NOT the most cost effective solution.

•Moreover, in very high energy collider and storage ring, one must also consider the synchrotron radiations. For example, using superconducting magnets is not an option for the proposed Next Linear collider (NLC). Even in the next generation hadron collider, it is becoming an issue.

In short, for arc magnet, the cost is the driver.

Superconducting Magnets in Accelerators
The Cost Issue

Bulk Magnet Cost:

- Material cost (superconductor, iron, stainless steel, etc.)
- Labor cost
- Associated component cost (quench protection, etc.)

First Magnet Cost:

- R&D cost for developing a new design

In small production, the R&D cost may exceed the material and labor cost.

Example: Specialty magnets for large machines.

Use or adapt existing design to meet requirements.

If a new design is needed, the cost optimization strategy should be different in case of a few magnets as compared to the cost optimization of a large scale production.

- For example don't worry about minimizing the amount of conductor to save money.

Why Use Superconducting Magnets in Accelerators?

Show resistivity of Copper

Arnaud 2-16

Show resistivity of LTS and HTS

May be from American Superconductor

Wilson's J,B chart showing
Conventional magnet and NbTi
and Nb3Sn curve

Major Accelerator Projects with Superconducting Magnets

Tevatron (year):

Energy:

Main Dipole Field

HERA

RHIC

LHC

Also SSC (canceled but R&D produced significant development in superconductor and magnet R&D)

What is involved in the magnetic design of superconducting (SC) magnets?

Everywhere in the magnet, the conductor must remain below critical surface while the field is maximized in the magnet aperture

Field must be uniform in magnet aperture

Very uniform

Relative errors (typical): $dB/B \sim 10^{-4}$

Maximizing Field in the Magnet Aperture

Field on the conductor in single layer RHIC dipole

B-J-T Curve

Most of the conductor stays well below critical surface

Grading for higher field:

Put higher current density in conductor that is towards outer radius and towards midplane

Maximizing Field in the Magnet Aperture: Conductor Grading

Field on the conductor in two layer SSC dipole

Most of the conductor stays well below critical surface

Grading for higher field

2-d B-J Curve

Show LHC main dipole
and LHC IR Quad for inter-layer grading

Magnetic Design & Analysis of Actual Magnets

A concise tour of the magnetic design process

- First come up with an overall design
- Then develop a detailed design

Remember : Magnet design is an iterative process

Field harmonics in superconducting magnets

- What to expect?
- How to minimize them?
- What is the state of the art?

Analysis of measured field harmonics

- What do they tell us about the magnet construction?

A tool to monitor magnet production

Most examples in this course comes from RHIC magnet

A matter of convenience as I work there

Also the latest and most documented completed (recently) project

The major project of the day: LHC

Overall Magnetic Design (First cut - 0th order process)

Coil Aperture

- Usually comes from accelerator physicists
- But also depends on the expected field errors in the magnet
- A feedback between accelerator physicists and magnet scientists may reduce safety factors in aperture requirements

Design Field

- Higher field magnets make machine smaller

  Reduce tunnel and infrastructure cost

  But increase magnet cost, complexity and reduce reliability
- Determines the choice of conductor and operating temperature

Find a cost minimum with acceptable reliability.

Coil Design: Starting Parameters

Coil width (first cut) : $w \sim 2B_0/(\mu_0 J_0)$

J_0 is the operating current density and not the current density in conductor (J_c)

Check B-J-T curve of superconductor

Coil cross section optimization (More details)

Use computer codes

ROXIE at CERN, etc. (the most modern code)
PAR2DOPT (similar codes at LBL) used in designing RHIC and SSC magnets

Minimize peak (maximum) field on the conductor

Typical value
single layer : 110% of Bo
double layer :
105% in inner
85% in outer (put higher current density)

Minimize field harmonics

First 2-d (cross section) and then 3-d (ends)

Yoke cross section optimization (More details)

Use computer codes

POISSON, etc. (public domain)
OPERA (commercial)
ROXIE (now require licensing?)

Setup basic model with proper boundary conditions

Usually a quadrant for dipoles with

- field perpendicular on x-axis
- field parallel on y-axis
- infinite boundary condition is desired on the other two sides or extent model sufficiently far away

Note: A significant portion of this talk was given in non-electronic format

Incomplete Talk

Sorry Plastic Slides Not-included