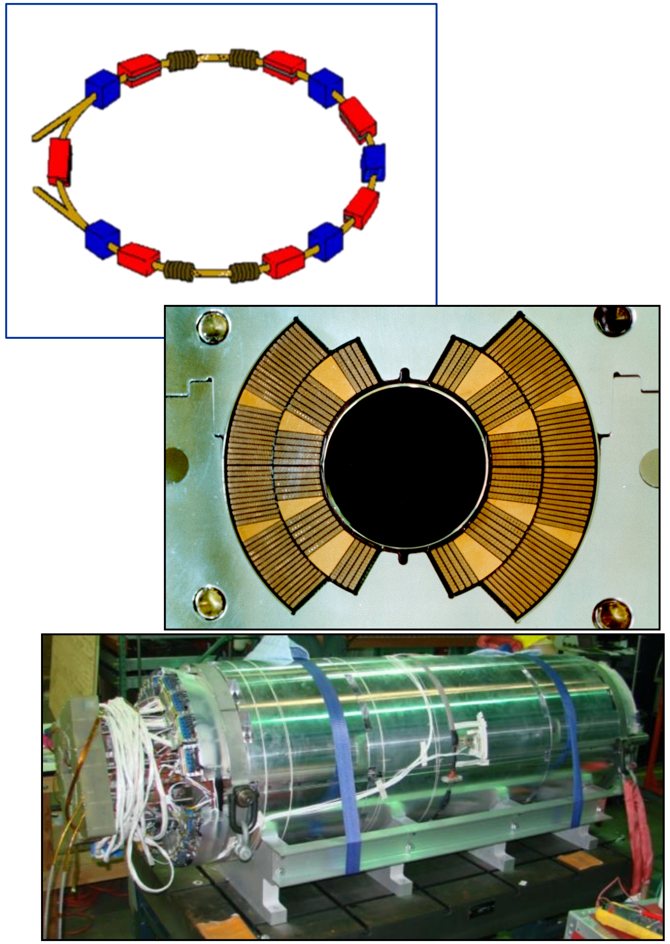
Accelerator Technology Challenges Magnets and Superconductivity
PART I

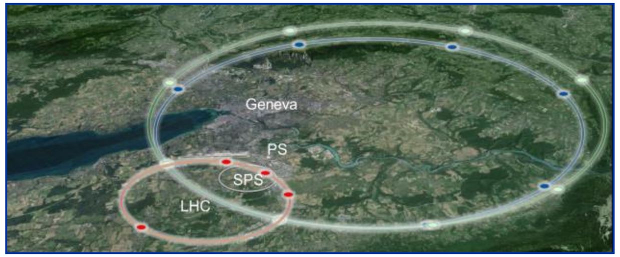
Hélène Felice with material borrowed from P. Ferracin, E. Todesco, L.Bottura , A Devred

18/07/2022

Context and Goals of the lecture

- Why do we need magnets in accelerators?
- Why do we need Superconducting Magnets and what is superconductivity?
- How do we design and build magnets? From the conductor to the full magnet using well known Low Temperature Superconductors
- Which magnets for HL-LHC?
- Beyond HL-LHC? Many challenges ahead…

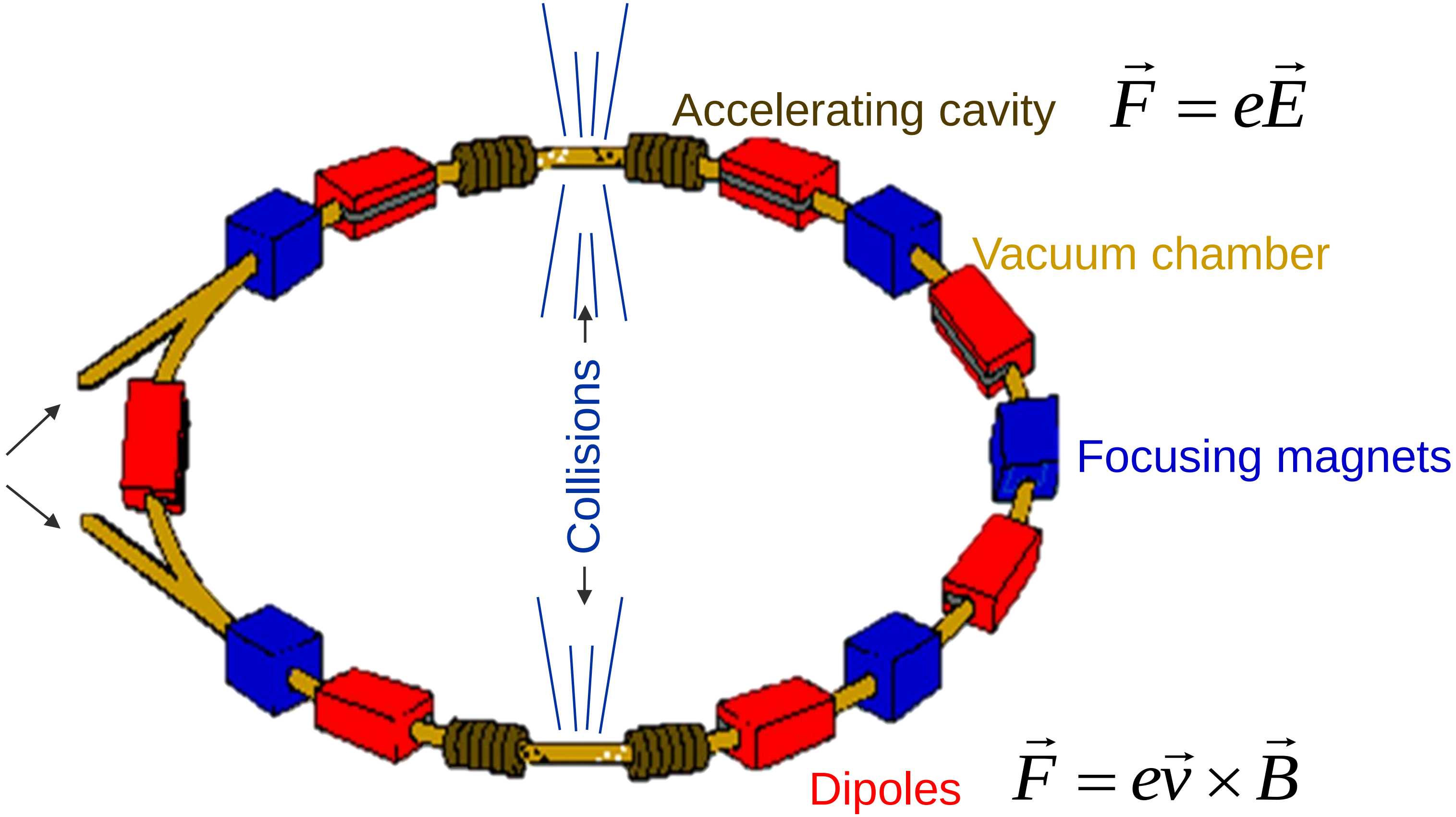




Why do we need magnets in accelerators?

- Electrical field accelerates particles

- Magnetic field steers the particles in a closed (circular) orbit to drive particles through the same accelerating structure several times



Dipole role and relation to beam energy

$$p = eBr$$

$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

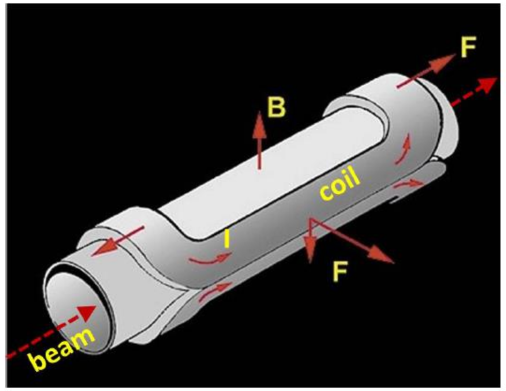
- Relation between *magnetic induction (commonly called Field in our business) B*, curvature radius ρ and momentum *p*

- Particle accelerated → energy increased → magnetic field increased ("synchro") to keep the particles on the same orbit of curvature

LHC example: curvature radius is 2800 m, field is 8.3 T, energy is 7000 GeV (i.e. 7 TeV)

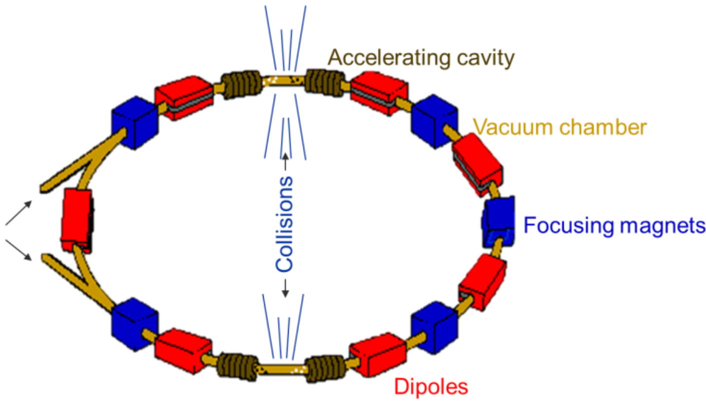
$$E[GeV] = 0.3\text{´}\ 8.3\text{´}\ 2800 = 7000$$

Dipoles in a nutshell

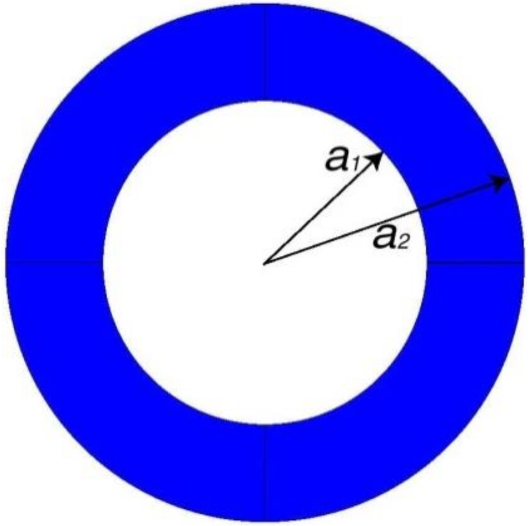


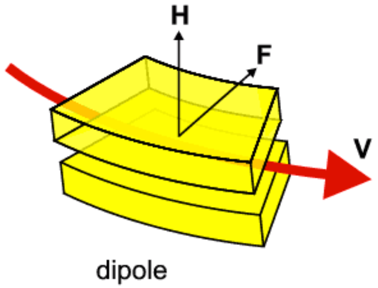
Vertical magnetic induction B_y in T produced by a current Density $J_0 \cos\theta$ (A/mm2) with a1/a2 inner/outer radius

$$B_y = -\frac{\mu_0 J_0}{2}(a_2 - a_1)$$



$$p = eBr$$





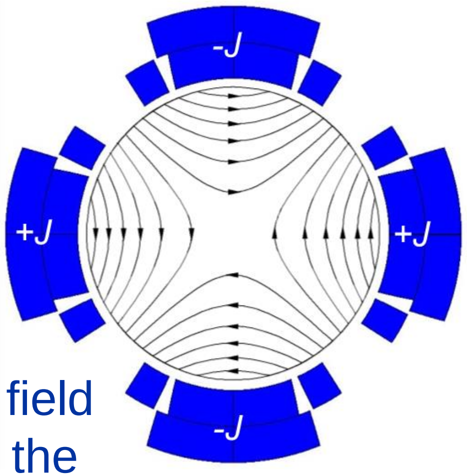
In dipoles, the larger B, the larger the steering strength

Quadrupoles in a nutshell

The quadrupoles focus the beam

They provide a field equal to zero in the center increasing linearly with the radius – Gradient G

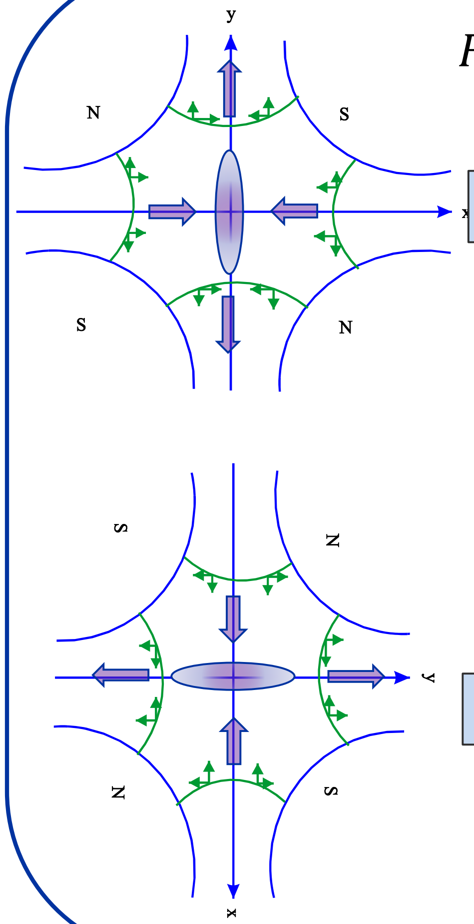
$$\boxed{G = \frac{B_y}{r} = -\frac{\mu_0 J_0}{2} \ln \frac{r_{out}}{r_{in}}}$$



$$\begin{cases} B_y = Gx \\ B_x = Gy \end{cases}$$

Quadrupoles provide a field which is proportional to the transverse deviation from the orbit, acting like a spring

$$F_x = e\left[\vec{v} \times \vec{B}\right]_x \approx -ecB_y$$



Focusing Quadrupole

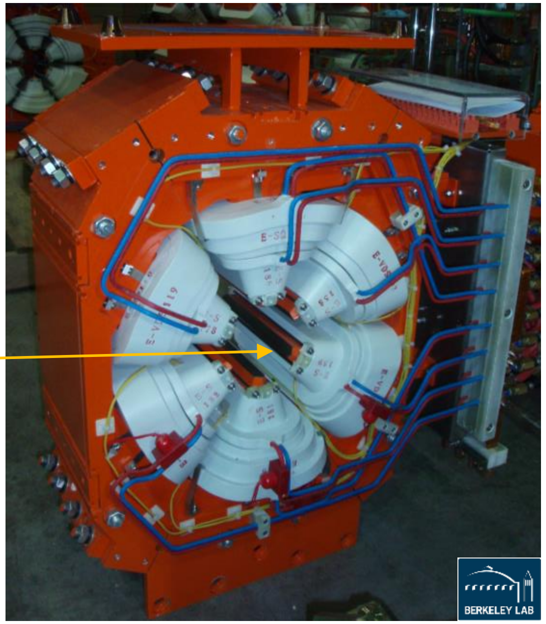
Rotated by 90º

De-focusing Quadrupole

In quads, the larger B, the larger the focusing strength

What about copper conductor?

- The greater the current density J, the greater the magnetic field
- Copper can typically transport 5 to 15 A/mm^2 when properly cooled
- Normal conducting magnets for accelerators are made with a copper winding around a ferromagnetic core that greatly enhances the field
    - The shape of the pole gives the field homogeneity
    - field limited to the iron saturation around 2T



- A large number of accelerators in the world are made with normal conducting magnets (Cu conductor) also called warm magnets
- A few examples of light sources

SESAME

SOLEIL SYNCHROTRON

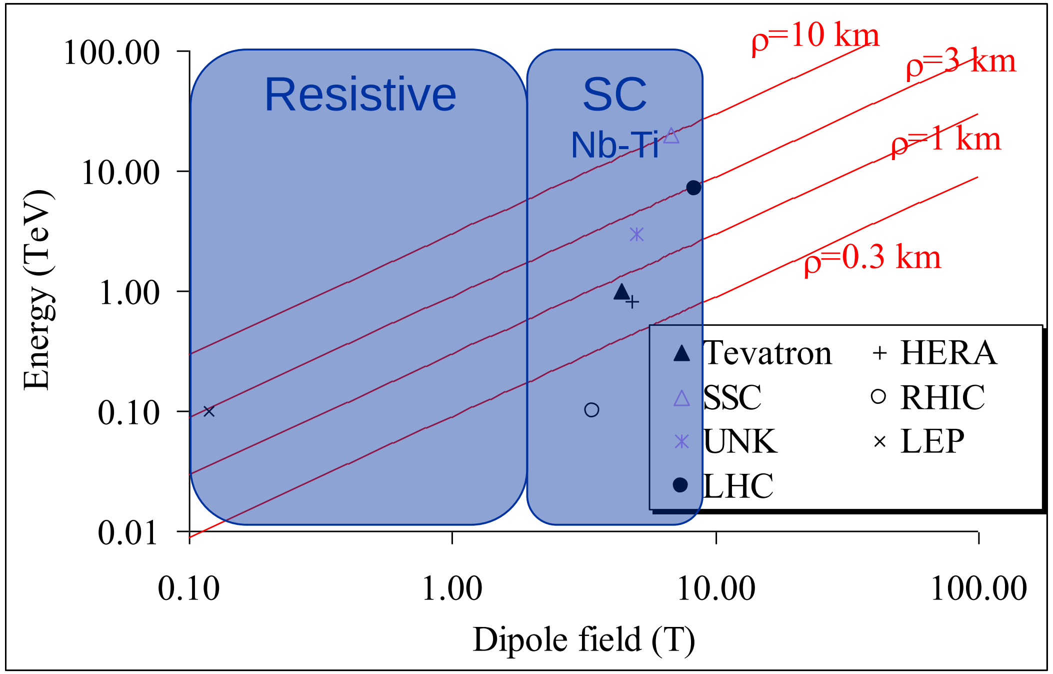
ALS ADVANCED LIGHT SOURCE

Beyond Copper conductor ➡ Superconductors

- LHC with 2 T would be 100 km long…
- Having 8 T magnets, we need 3 Km curvature radius to have 7 TeV
- If we had 800 T magnets, 30 m would be enough …

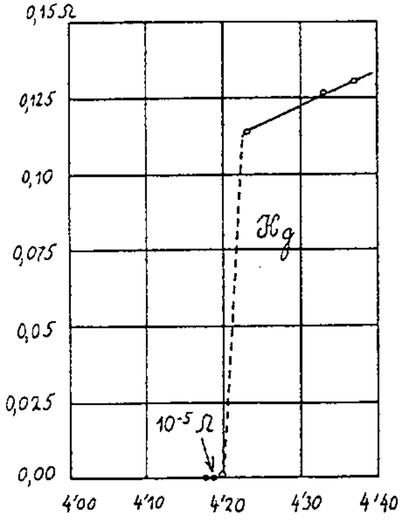
Ezio Todesco

$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$



In 1911, Kamerlingh Onnes discovered the superconductivity of mercury

- Below 4.2 K, mercury has a non measurable electric resistance => potential to transport very high current and to produce very high field
- Discovery thanks his success in liquifying Helium in 1908



4.2 K is called the critical temperature Tc:

For T< Tc
the material is superconducting

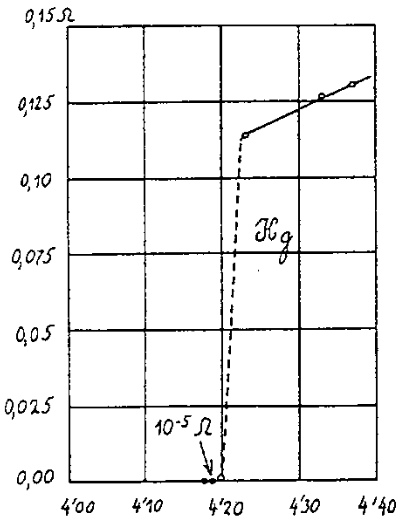
Superconductivity in a nutshell: discovery

1911

40’s – 80’s

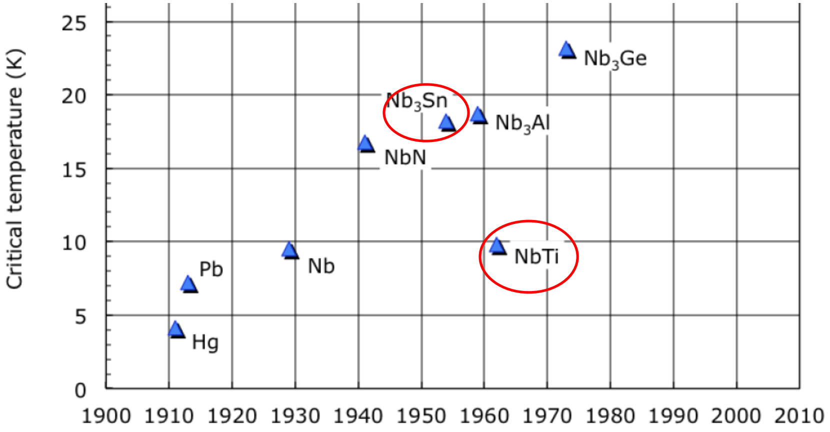
1986

LTS Low Temperature superconductors



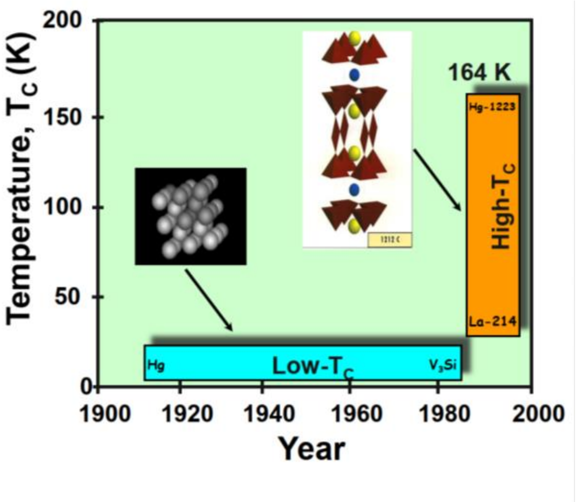
… thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*…

H. Kamerlingh-Onnes (1911)



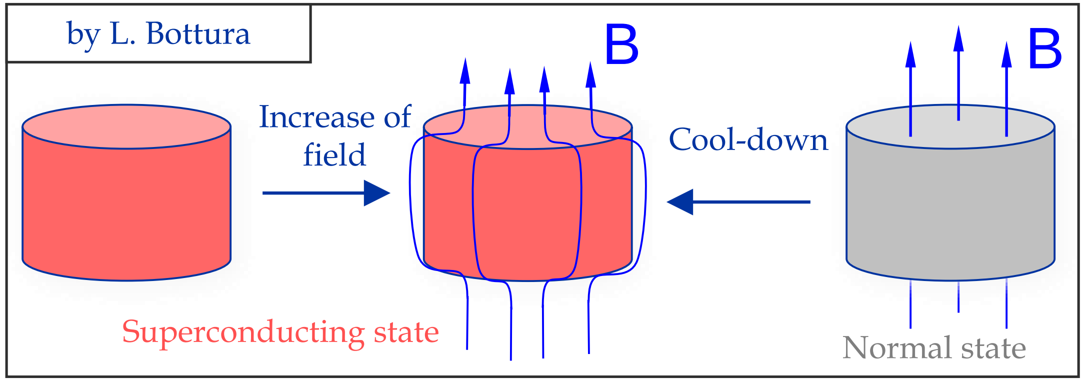
Theoretical limit around 30 K

HTS High Temperature superconductors



1987 – Nobel Prize to Bernorz and Mueller for the discovery of superconductivity in ceramic material

Type I superconductors

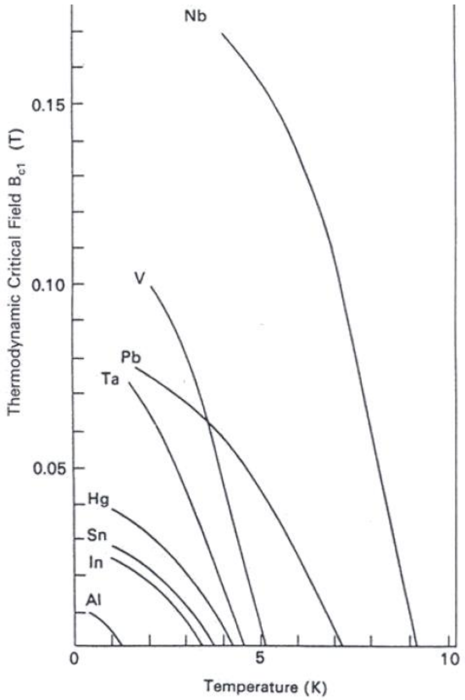


The first superconductor material demonstrate a complete field exclusion called Meissner-Ochsenfeld effect (1933)

It behaves as a perfect diamagnetic material

- for T< T_c
- B must be < B_c called critical field

- If we look closely, the field penetrates over a tiny depth (~10 nm) called London penetration depth λ_L

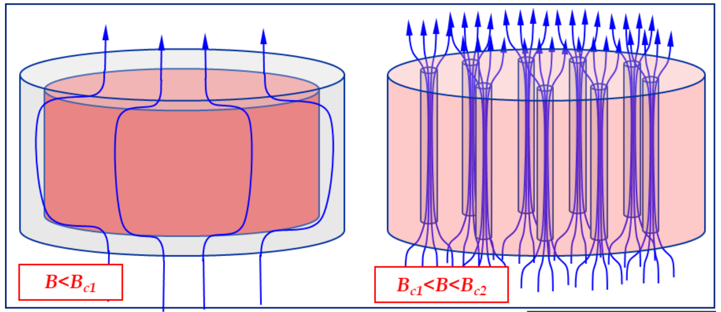


B_c is very small a few mT to barely above 100 mT

Not useful for Magnet engineers

Type II superconductors

In the 50's, discovery of a new type of superconductor
For B < B_{c1} => behaves like a type I superconductor
For B_{c1} < B < B_{c2} => Mixed state



by L. Bottura

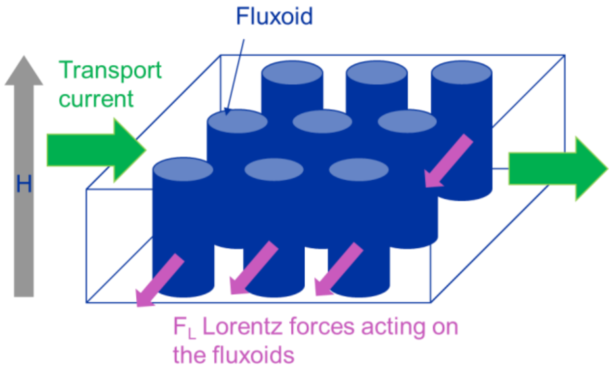
For B_{c1} < B < B_{c2} Penetration of the field as quantum of flux Φ_0 called fluxoids

$$\Phi_0 = h/2e = 2.07 \text{ x } 10^{-15} \text{ Wb}$$

The core of the vortex is normal conducting and is of radius ξ
Super current are developing aroung each core over the London depth λ_L
For Type II superconductor $\xi < \lambda_L$

A Lorentz force is acting on the fluxoid when a transport current flows in the SC: $F_L = JxB$

If the fluxoids are not anchored: flux flow regime => energy dissipation (dB/dt) => loss of superconductivity

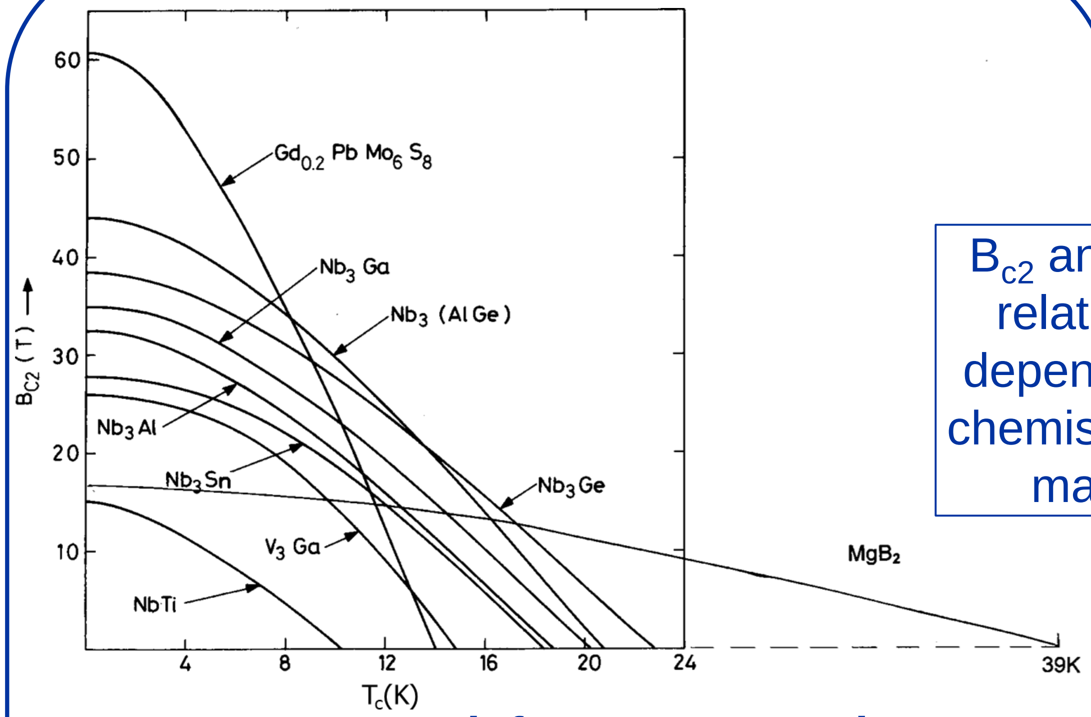


Necessity to pin the fluxoids using defect and imperfections of the material => pinning centers exerting a pinning force F_p

As long as $\mathbf{F_L \leq F_p}$ the superconductor can carry transport current

$\mathbf{J_c}$ is the critical current density at which, for a given **B** and at a given **T** we have $\mathbf{F_p \leq F_L}$

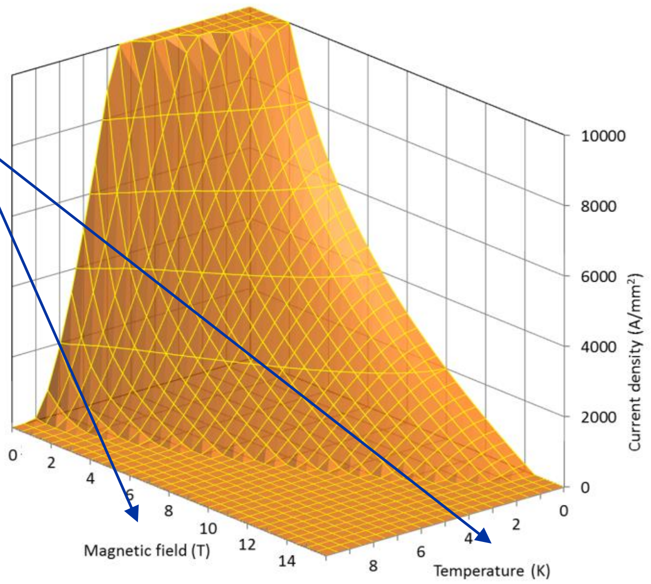
Concept of critical surface



Important remark for magnet engineers:
Of all the metallic superconductors, only NbTi which is an alloy is ductile.
All other are brittle inter-metallic compounds

B_{c2} and T_c are related and depend on the chemistry of the material

We have now 3 parameters: J_c, B_{c2} and T_c allowing to define the **critical surface** of practical superconductors - beyond: resistive state

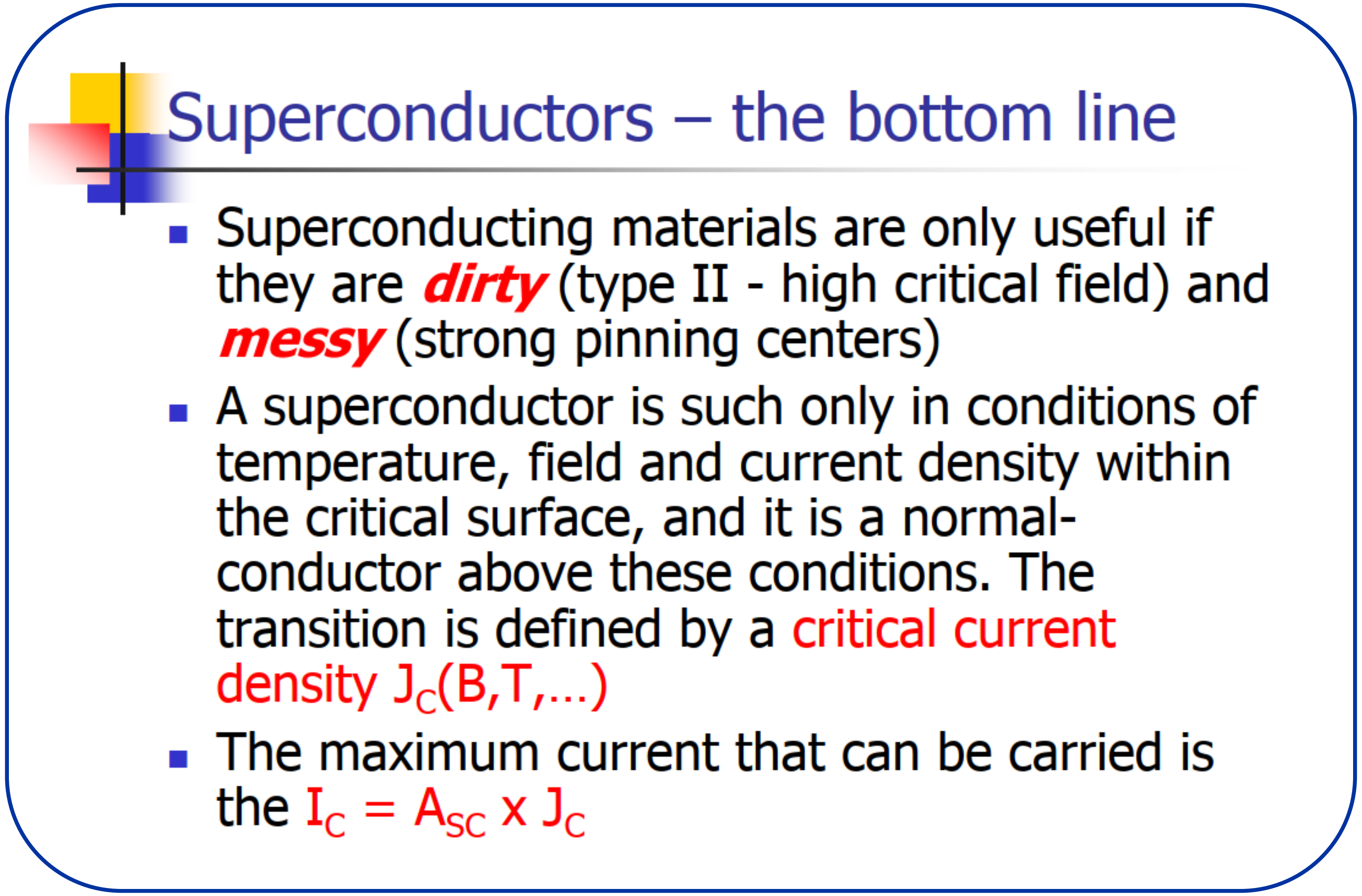


High J_c obtained with the optimization of the conductor layout by the manufacturer

This is a dedicated field of R&D

When we talk about J_c we always specify at which field and which temperature (same for other parameters)

In summary – from Luca Bottura



Superconductors – the bottom line

- Superconducting materials are only useful if they are ***dirty*** (type II - high critical field) and ***messy*** (strong pinning centers)
- A superconductor is such only in conditions of temperature, field and current density within the critical surface, and it is a normal-conductor above these conditions. The transition is defined by a critical current density $J_C(B,T,\ldots)$
- The maximum current that can be carried is the $I_C = A_{SC} \times J_C$

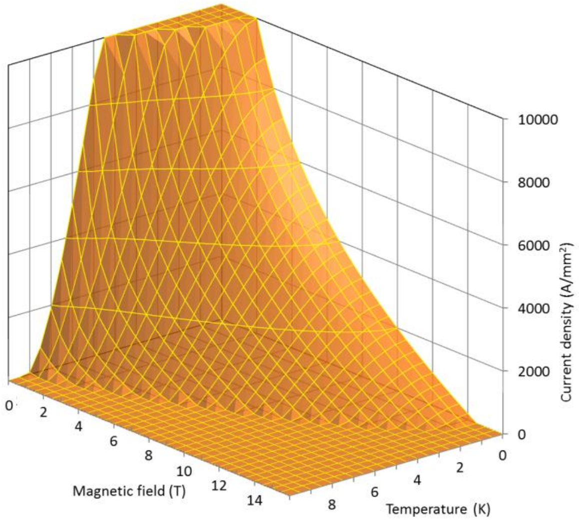
Practical superconductors: NbTi and Nb$_3$Sn

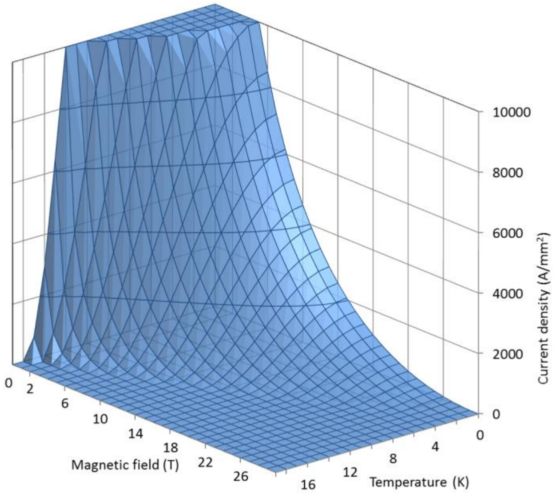
Nb and Ti → NbTi ductile alloy

  - Obtained by Extrusion + drawing

- **T_c** is ~ **9.2 K** at 0 T
- **B_{C2}** is ~**14.5 T** at 0 K

- Firstly used in **Tevatron** (80s), then in all the other
- 1 euro per m





Nb and Sn →Nb$_3$Sn intermetallic compound

  - Brittle, strain sensitive, formed at ~650°C

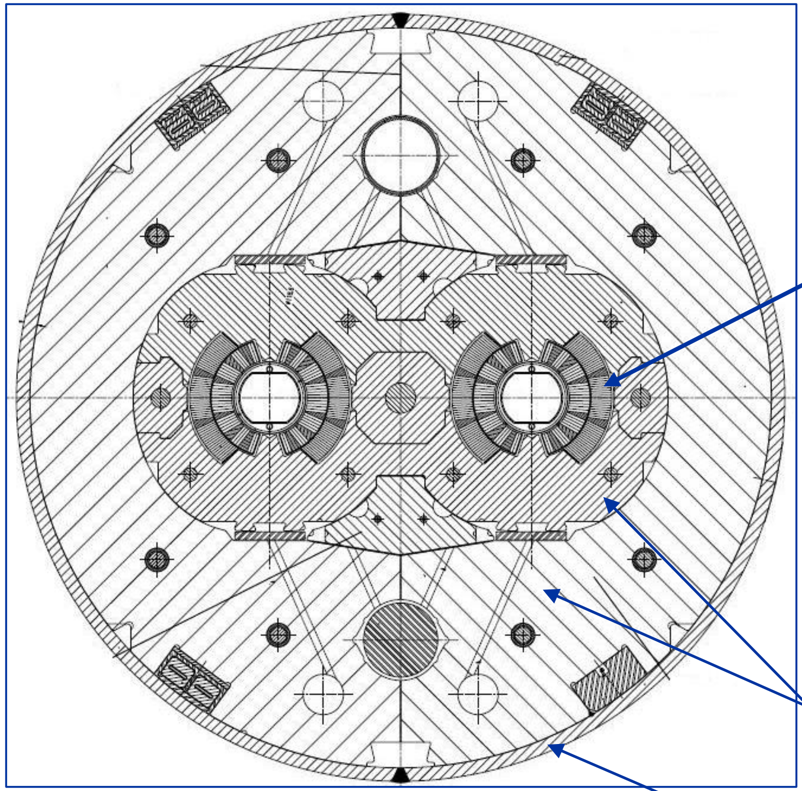
- **T_C** is ~**18 K** at 0 T
- **B_{C2}** is ~**28 T** at 0 K

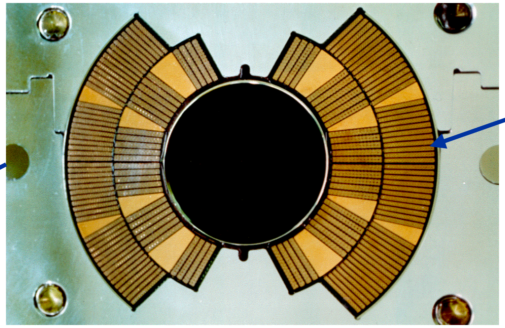
- Used in **ITER**
- 5 euro per m

P. Ferracin

Practically, what are we talking about when we talk about accelerator magnets? A few key components

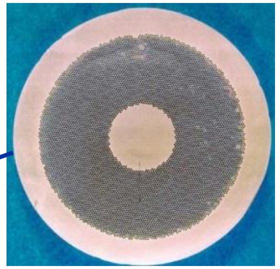
LHC Dipole

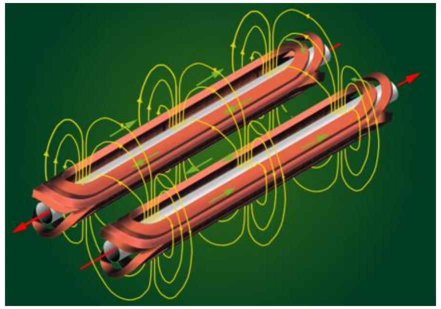




Coil cross-section

SC strand/wire





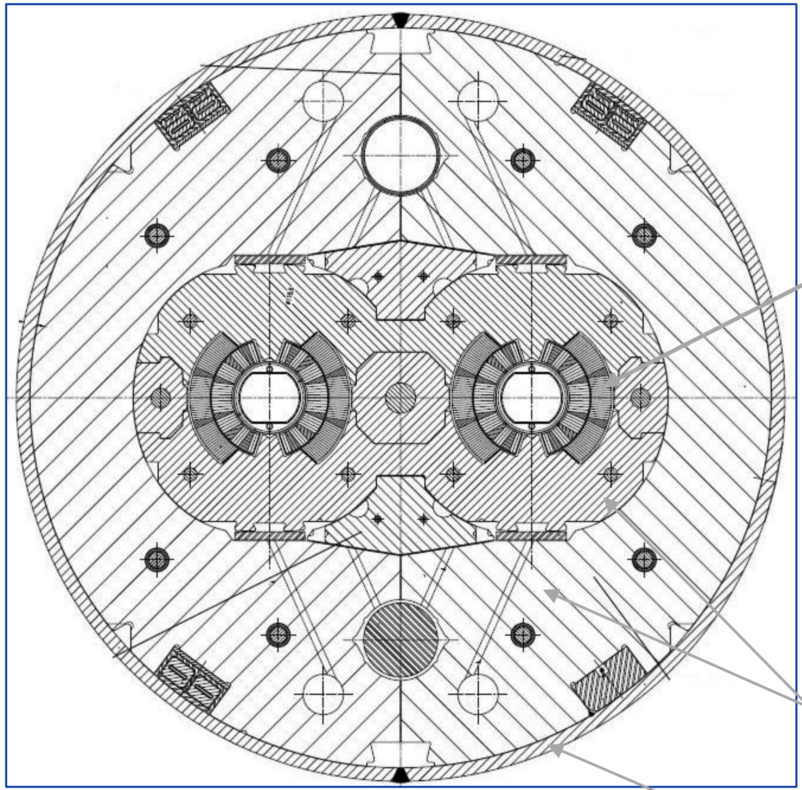
Coils

Mechanical Support structure

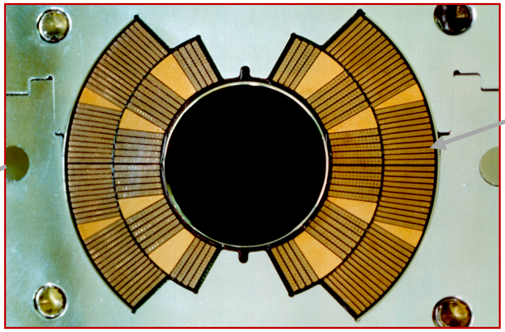
Helium Vessel

Practically, what are we talking about when we talk about accelerator magnets? A few key components

LHC Dipole

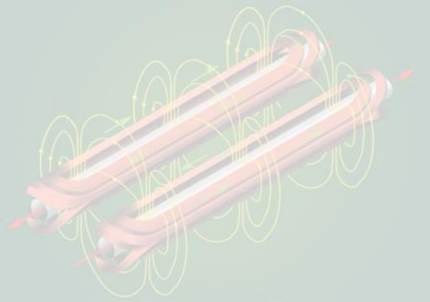


Let's start with the heart of the magnet: the coil



Coil cross-section

SC strand



Coils

Mechanical Support structure

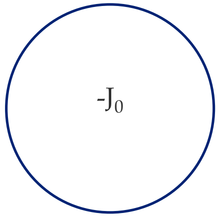
Helium Vessel

How and why do we get this strange cross-section?

Ideal dipole Field # 1: Intersecting Ellipses/Circles

Within a cylinder carrying **j_0** , perpendicular to the plane of the slide, the field is perpendicular to the radial direction and proportional to the distance to the centre ***r***

$$B = -\frac{\mu_0 j_0 r}{2}$$

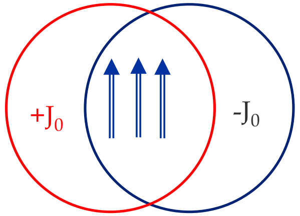


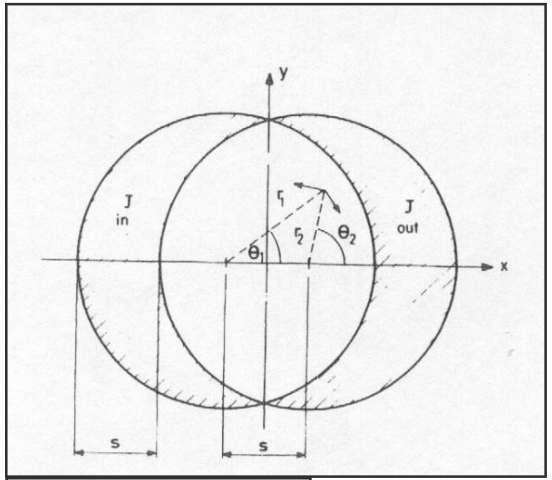
Combining the effect of two intersecting cylinders

$$B_x = \frac{\mu_0 j_0 r}{2}\left\{-r_1 \sin\theta_1 + r_2 \sin\theta_2\right\} = 0$$

$$B_y = \frac{\mu_0 j_0 r}{2}\left\{-r_1 \cos\theta_1 + r_2 \cos\theta_2\right\} = -\frac{\mu_0 j_0}{2} s$$

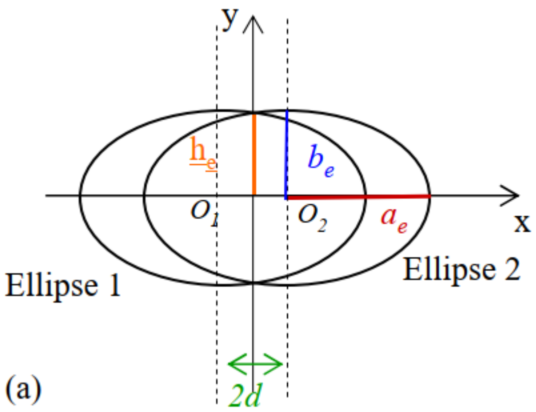
A uniform current density in the area of two **intersecting circles** produces a pure dipole





by M. Wilson

A little harder work to demonstrate similar conclusion for **intersecting ellipses**



$$\boxed{\overline{B_{ellipse}} = \mu_0 J \frac{2 b_e d}{a_e + b_e}}$$

docnum.univ-lorraine.fr/public/INPL/2006_FELICE_H.pdf

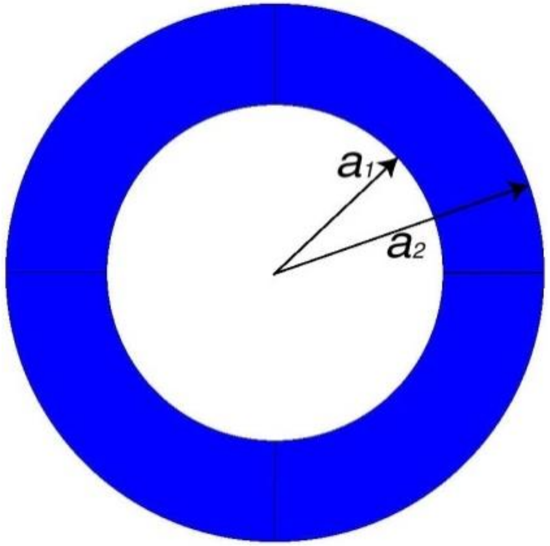
Ideal dipole Field #2: Current density distribution in Cosθ

If we assume

- $J = J_0 \cos\theta$ where J_0 [A/m^2] is ⊥ to the cross-section plane
- Inner (outer) radius of the coils = *a1 (a2)*

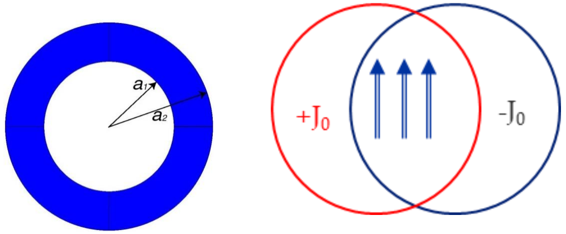
The generated field is a **pure dipole**

$$B_y = -\frac{\mu_0 J_0}{2}(a_2 - a_1)$$



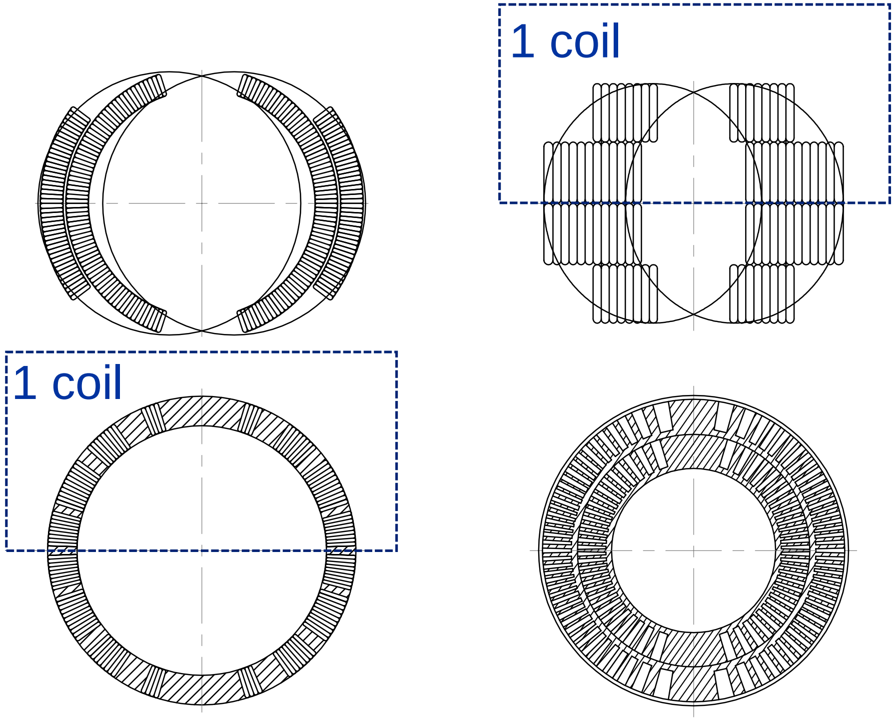
B ∝ current density
B ∝ coil width *w=a2-a1*
B is independent of the aperture *r* (not so obvious)

From ideal dipole to practical magnetic configuration



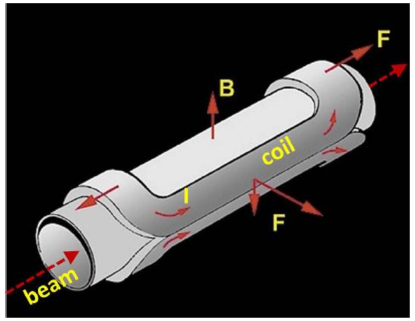
Approximation of ideal shapes

- Sector stacking of conductor
- Block approach
- Sector with wedges



Consequence: the dipole field has some imperfections
How do we assess them and how we deal with them?

Let’s start with the 2D field representation: complex formalism



x and y perpendicular to the beam (transverse coordinates), z along the beam

Flux conservation – Maxwell Gauss

$$\nabla \cdot B = \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0$$

In presence of a constant axial field (here = 0)

$$\frac{\partial B_z}{\partial z} = 0$$

$$\boxed{\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} = 0}$$

Maxwell Ampere’s law

$$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$$

In absence of current and varying electrical field

$$\nabla \times B = \left(\frac{\partial B_y}{\partial z} - \frac{\partial B_z}{\partial y}, \frac{\partial B_z}{\partial x} - \frac{\partial B_x}{\partial z}, \frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial x} \right) = 0$$

$$\boxed{\frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial x} = 0}$$

Cauchy Riemann conditions

$$\begin{cases} \dfrac{\partial f_x}{\partial x} - \dfrac{\partial f_y}{\partial y} = 0 \\ \dfrac{\partial f_x}{\partial y} + \dfrac{\partial f_y}{\partial x} = 0 \end{cases}$$

B can be written as an analytic function

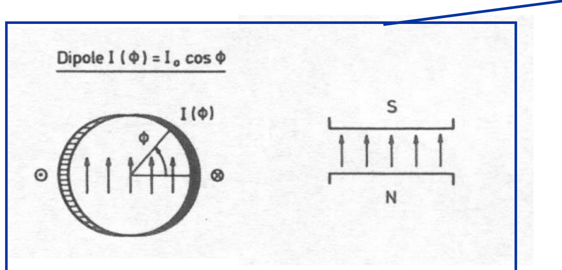
$$\boxed{B_y(x,y) + iB_x(x,y)}$$

Definition of field harmonics in 2D

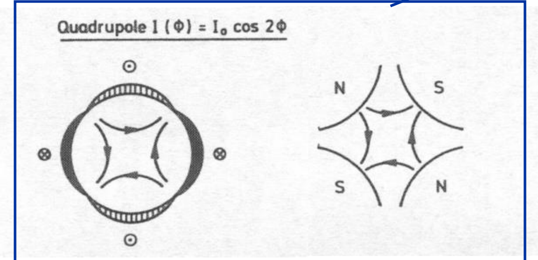
B as an analytic function can be expressed as a series expansion with (x,y) in domain D (aperture of the magnet)

$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty} C_n (x+iy)^{n-1} = \sum_{n=1}^{\infty} (B_n + iA_n)(x+iy)^{n-1}$$

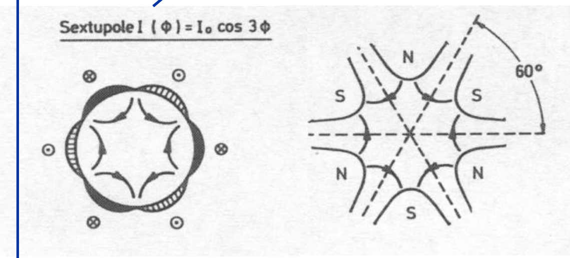
$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty} C_n (x+iy)^{n-1} = C_1 + C_2(x+iy) + \ldots$$



A dipole



A quadrupole



A sextupole

from P. Schmuser et al, pg. 50

Each coefficient corresponds to a “pure” multipolar field

Definition of field harmonics in 2D

$$B_y(x,y)+iB_x(x,y)=\sum_{n=1}^{\infty}C_n\left(x+iy\right)^{n-1}=\sum_{n=1}^{\infty}\left(B_n+iA_n\right)\left(x+iy\right)^{n-1}$$

The field harmonics are rewritten as (EU notation)

$$B_y+iB_x=10^{-4}B_1\sum_{n=1}^{\infty}(b_n+ia_n)\left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$

We factorize 10^{-4} since the deviations from ideal field are ~0.01%

Factorization of the main component (B_1 for dipoles, B_2 for quadrupoles)

Reference radius R_{ref} to have dimensionless coefficients

The coefficients b_n, a_n are called normalized multipoles: b_n are the <u>normal</u>, a_n are the <u>skew</u> (adimensional)

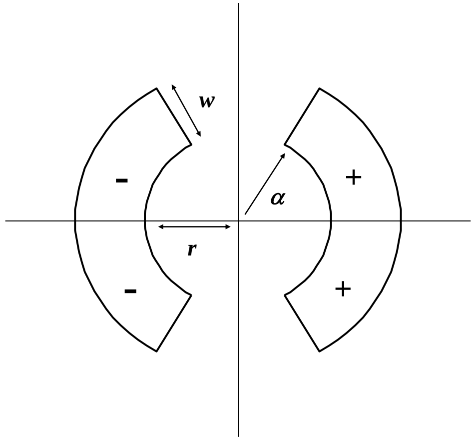
!! US notation is different from EU notation $b_2^{US}=b_3^{EU}$

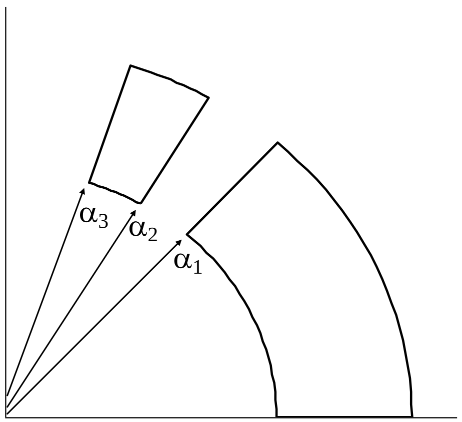
Now that we have the tools: how do we go from ideal to practical coil cross sections?

For symmetry reasons only certain harmonics are «allowed»
In a dipole B_{2n+1} are allowed: B3, B5…

Multipoles for a sector coil can be expressed for n > 2

$$B_n = -\frac{j\mu_0 R_{ref}^{n-1}}{\pi}\frac{2\sin(\alpha n)}{n}\frac{(r+w)^{2-n}-r^{2-n}}{2-n}$$





Multipoles can be made equal to zero

$$B_3 = \frac{\mu_0 jR_{ref}^2}{\pi}\frac{\sin 3\alpha_3 - \sin 3\alpha_2 + \sin 3\alpha_1}{3}\left(\frac{1}{r}-\frac{1}{r+w}\right)$$

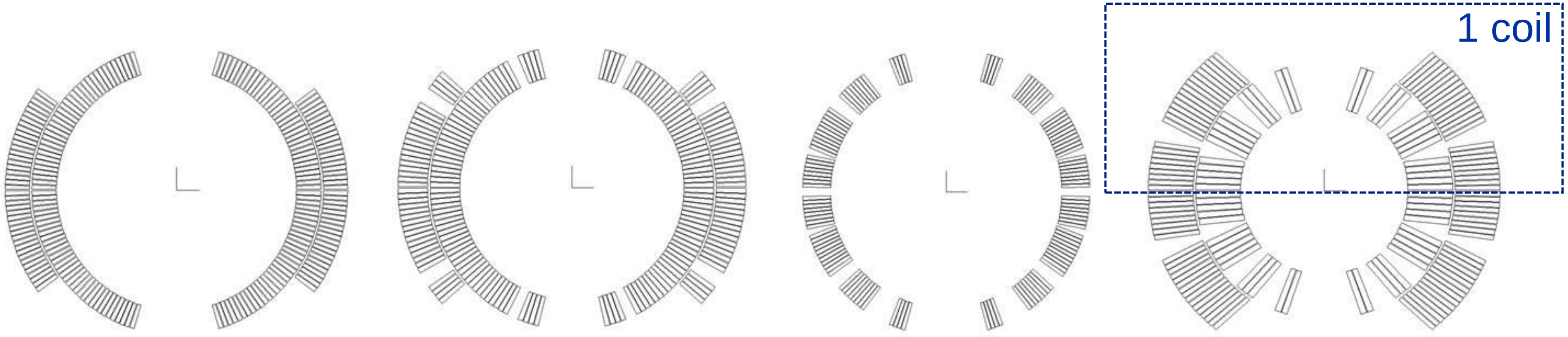
$$B_5 = \frac{\mu_0 jR_{ref}^4}{\pi}\frac{\sin 5\alpha_3 - \sin 5\alpha_2 + \sin 5\alpha_1}{5}\left(\frac{1}{r^3}-\frac{1}{(r+w)^3}\right)$$

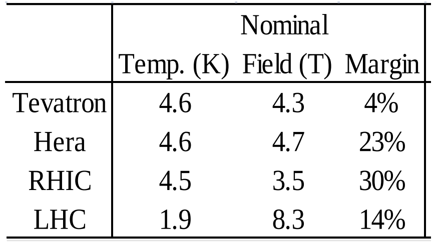
Equations to set to zero B_3 and B_5

$$\begin{cases}\sin(3\alpha_3)-\sin(3\alpha_2)+\sin(3\alpha_1)=0\\ \sin(5\alpha_3)-\sin(5\alpha_2)+\sin(5\alpha_1)=0\end{cases}$$

(48°,60°,72°) or (36°,44°,64°) are solutions

Coil cross sections (to scale) of the four superconducting colliders

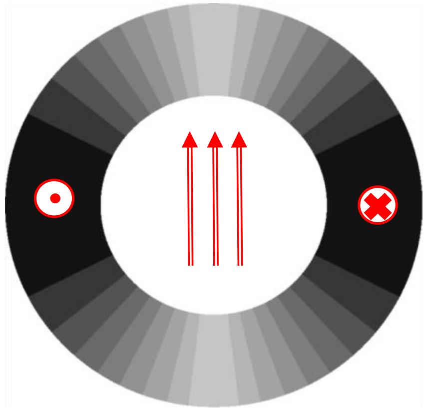


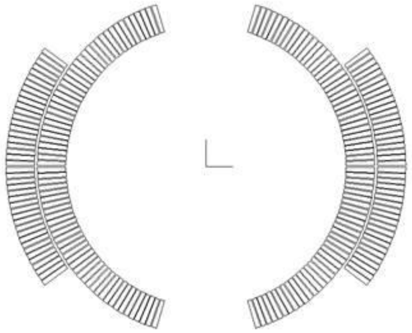


	Nominal		
	Temp. (K)	Field (T)	Margin
Tevatron	4.6	4.3	4%
Hera	4.6	4.7	23%
RHIC	4.5	3.5	30%
LHC	1.9	8.3	14%

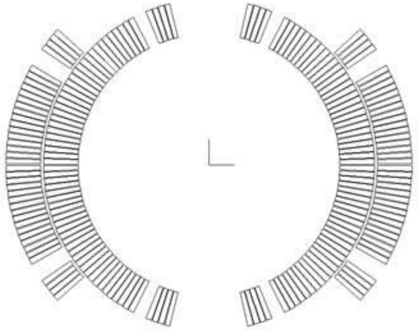
Increased coil complexity (nested layers, wedges and coil blocks) to achieve higher efficiency and improved field homogeneity

Coil cross sections (to scale) of the four superconducting colliders

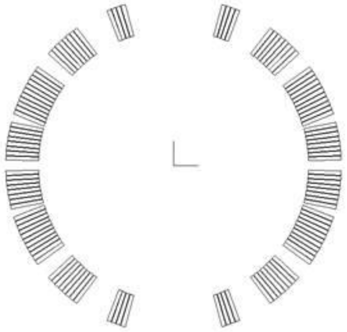




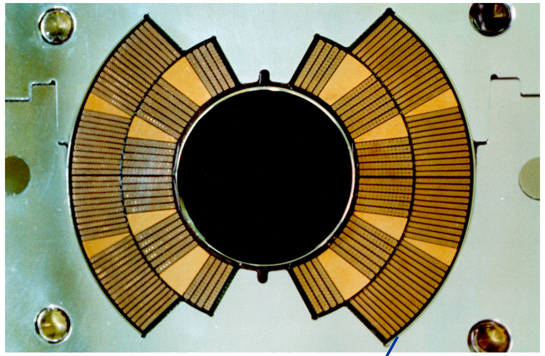
Tevatron



HERA

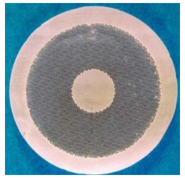


RHIC



LHC

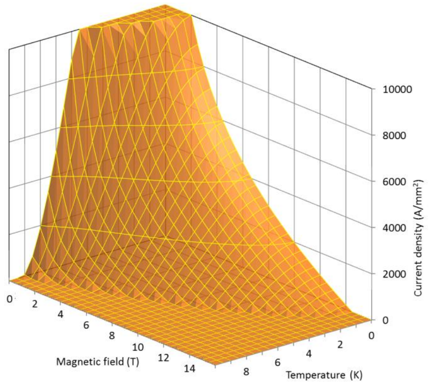
Now that we know how to design magnetically a cross-section, let’s take a look at the conductor itself



strand

cable

Practical superconductors: strand

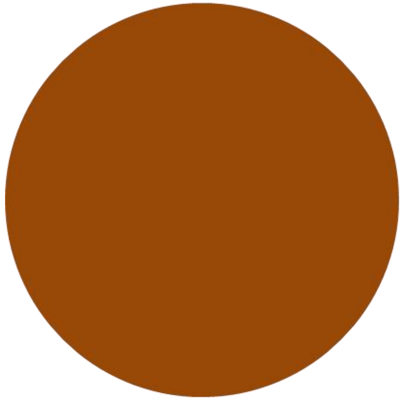


Focus on LTS since all existing accelerator magnets are made of LTS so far

A word on HTS tomorrow

LTS STRANDS

Cu

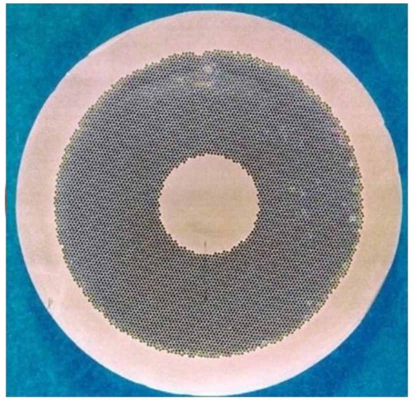


J_e ~ 5 A/mm^2

I ~ 3 A

B = 2 T

Nb-Ti

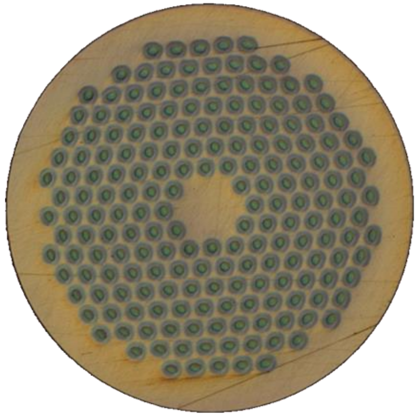


J_e ~ 600-700 A/mm^2

I ~ 300-400 A

B = 8-9 T

Nb_3Sn



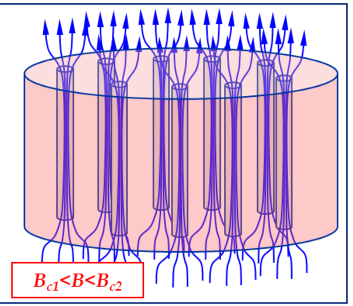
J_e ~ 600-700 A/mm^2

I ~ 300-400 A

B = 12-16 T

- Multifilamentary structure: Why?
- Presence of Cu: Why?
- Any other detail?

Multi-filamentary wire: fighting flux jumps



by L. Bottura

Let’s remember than in a Type II superconductor submitted to an external magnetic field, the flux penetrates by quantum of flux called fluxoids

If the superconductor is subjected to a thermal disturbance, J_c will change

Thermal disturbance => $\underbrace{dJ_c/dt \Rightarrow dB/dt}$ => E electrical field => E . J_c power dissipation

Reorganization of fluxoids called flux jump

Some criteria exist to evaluate the critical size of the superconductor
In the case of a slab of superconductor of thickness 2a, according to the adiabatic criteria, the half size of the slab should be

$$a \le \sqrt{\frac{3\gamma C(\theta_c - \theta_0)}{\mu_0 j_c^2}}$$

where j_c is the critical current density [A m^{-2}], γ is the density [kg m^{-3}], C is the specific heat [J kg^{-1}], and θ_c is the critical temperature.

$\Rightarrow$ **The higher Jc, the higher risk of flux jump (low field)**
$\Rightarrow$ **Incentive to reduce the SC filament size < 50 μm**

Multi-filamentary wire: dealing with magnetization

The current distribution in a Type II superconductor is given by the **Bean Critical state** (1962)

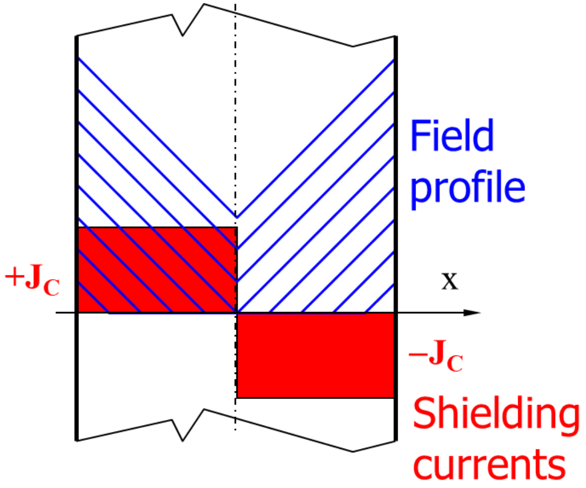
The local current density is either null or equal to Jc

When a filament is in a varying B_{ext}, shielding currents are developing starting from the outer surface of the filament.

Based on Bean's model, the current density is J_c

They **do not decay** when B_{ex} is held constant

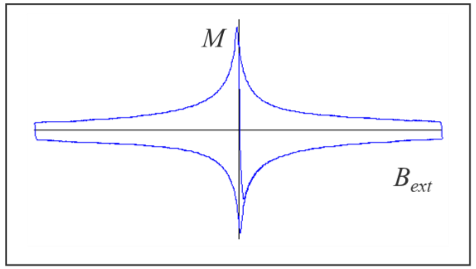
→ Shielding / **persistent currents**



The shielding current are producing a magnetic moment

A magnetization can be defined and causes:

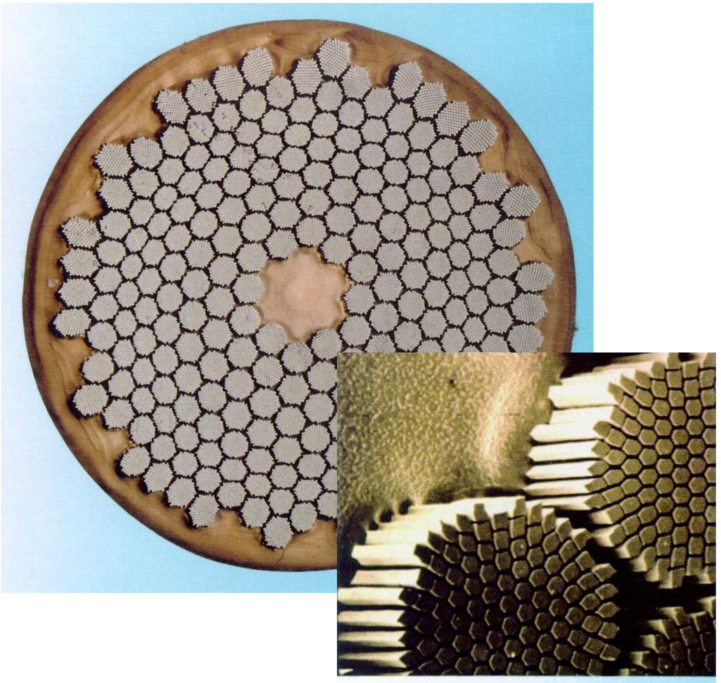
- Field distorsion
- losses



This magnetization is proportional to J_c and to the filament size

⇒ **Incentive to reduce the SC filament size as much as possible (6-7 μm in LHC)**

Multifilament wire: inter-filament coupling



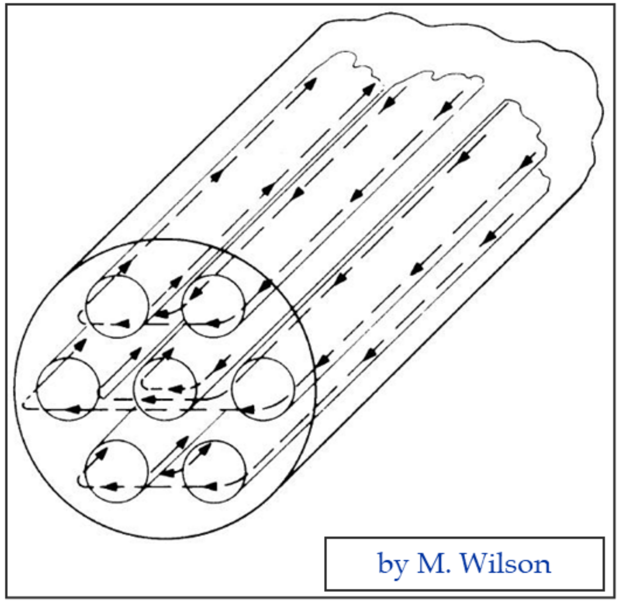
Wire composed of very small filaments

When a multi-filamentary wire is subjected to a time varying magnetic field,
current loops are generated between filaments => inter-filament coupling

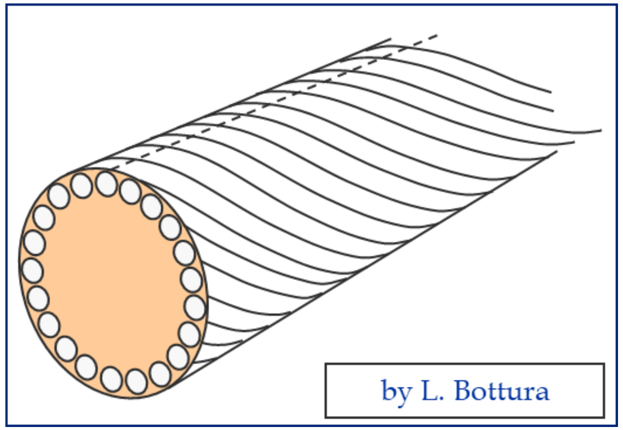
- If filaments are straight, large loops with large currents → **ac losses**
- If the strands are magnetically coupled the effective filament size is larger → **flux jumps**

To reduce these effects, filaments are **twisted**

- twist pitch of the order of 20-30 times of the wire diameter.

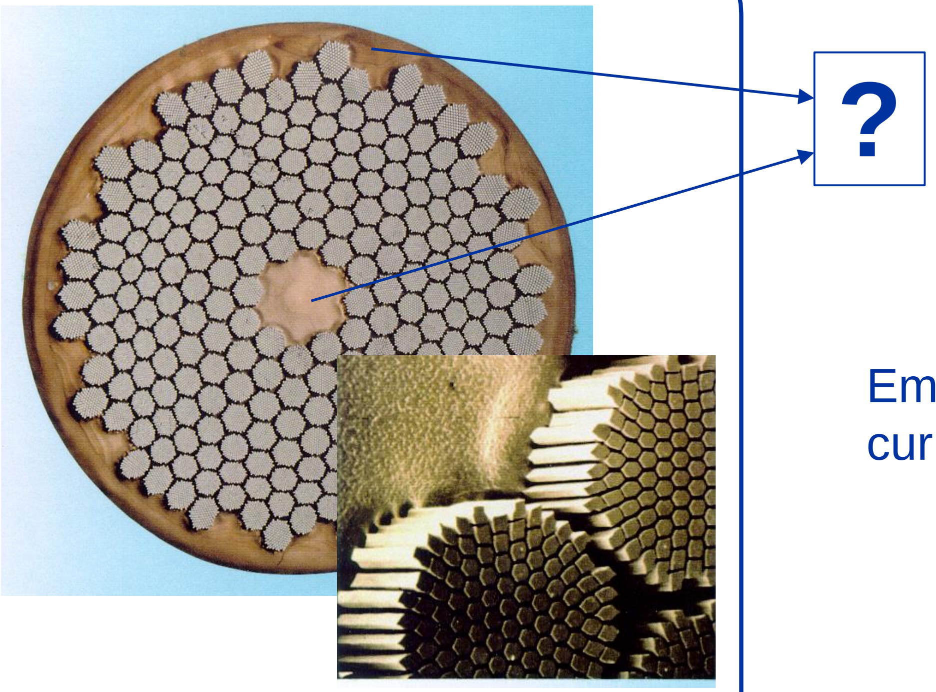


by M. Wilson



by L. Bottura

Multifilament wire: presence of a stabilizer (Cu)



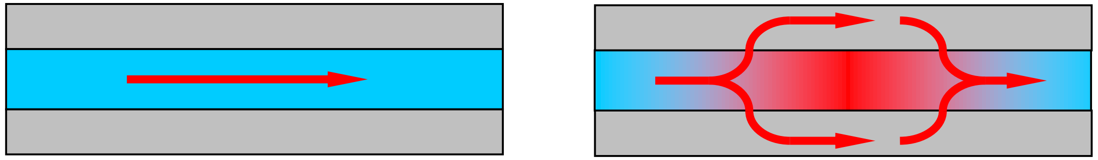
Wire composed of very small filaments

When T > Tc, the resistivity of superconducting materials (in normal state) is very high

$\rho_{\text{Nbti,n}} \sim 5\ 10^{-7}\ \Omega.\text{m}$ whereas $\rho_{\text{Cu}} \sim 1.7\ 10^{-8}\ \Omega.\text{m}$

If the SC becomes normal, its temperature will rise very quickly (ms) by Joule heating

Embedding the SC in a low resistivity matrix such as copper, allows the current to flow in the matrix in case of quench (transition to normal state)

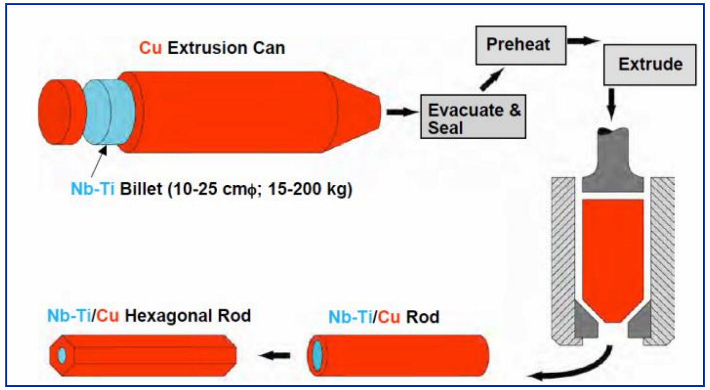


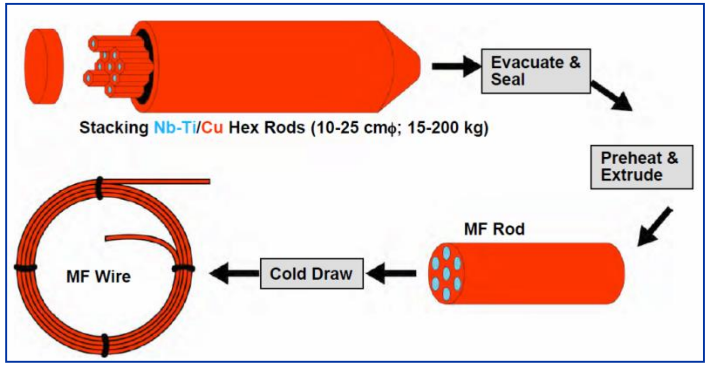
by L. Bottura

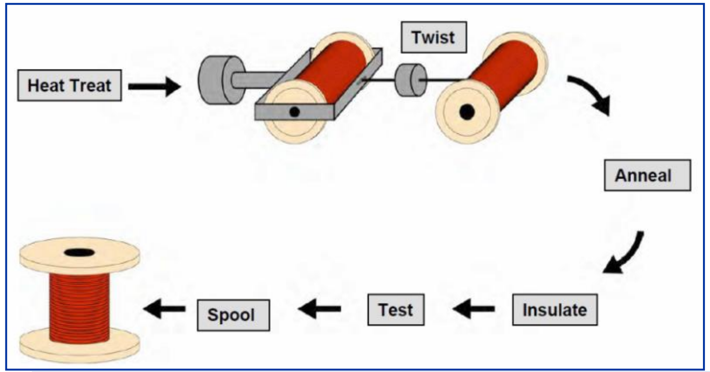
Depending on the perturbation inducing the quench:

- Either the SC can recover
- Or the current flow through the matrix will allow gaining time to protect the magnet system (see later)

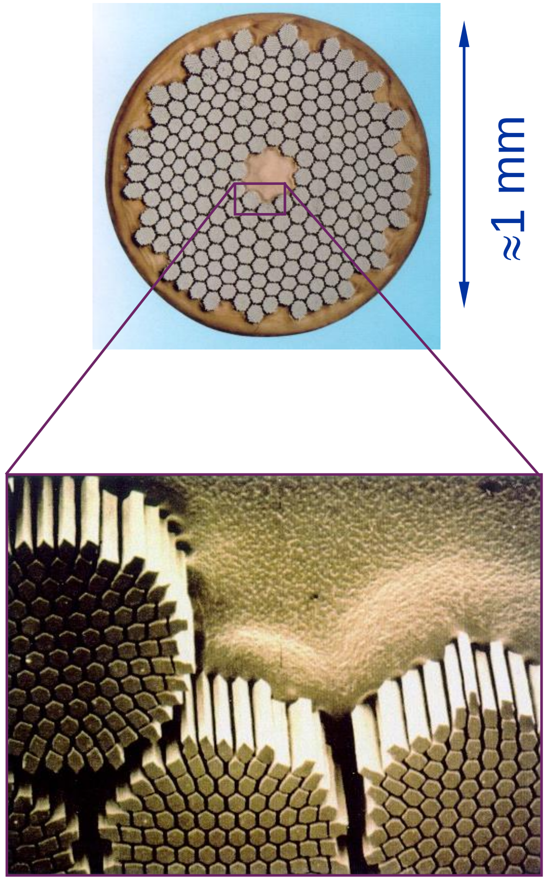
Fabrication of NbTi wire

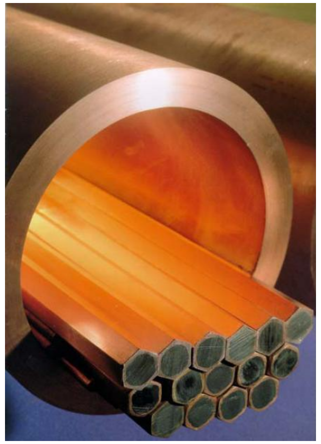






- Nb-Ti ingots in Cu can
  - 200 mm Ø, 750 mm long
- Becomes Monofilament rods are stacked to form a multifilament billet
  - then extruded and drawn down
- Heat treatments are applied to produce pinning centers (precipitates).
- When the number of filaments is very large, multifilament rods can be re-stacked (double stacking process)

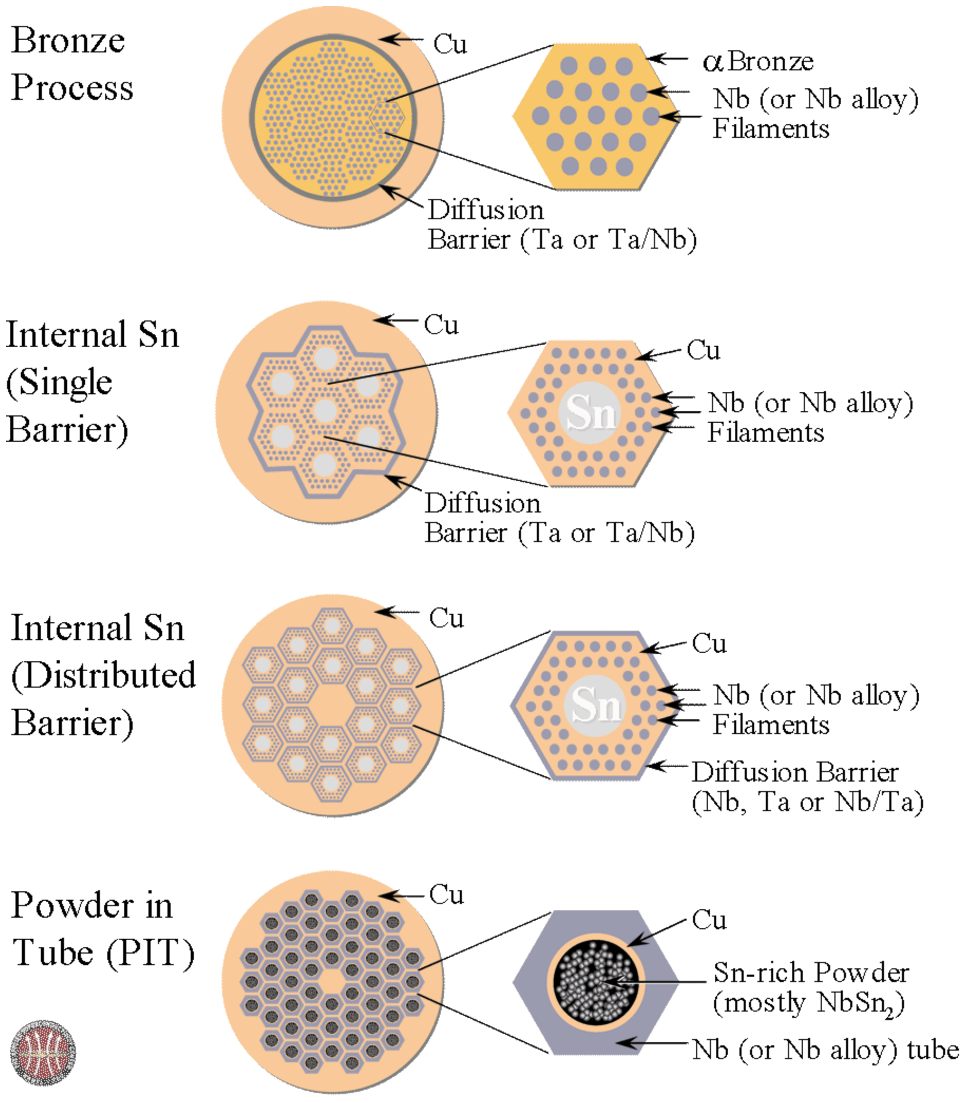




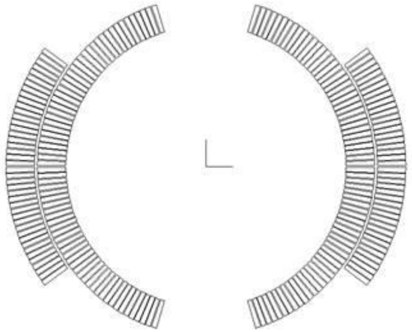
Fabrication of Nb_3Sn wire

- Nb_3Sn is brittle and cannot be drawn in final form.
- The precursors of Nb and Sn are drawn
- The wire must heat-treated to ≈650 C for several hours, to form the Nb_3Sn phase

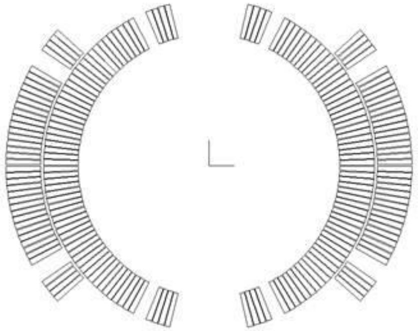
We will see later that the heat treatment occurs after the full coil fabrication



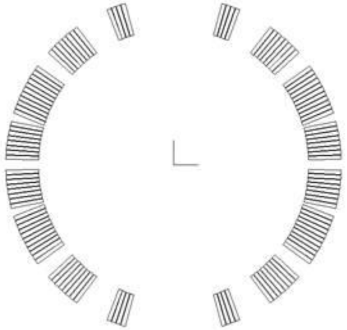
Coil cross sections (to scale) of the four superconducting colliders



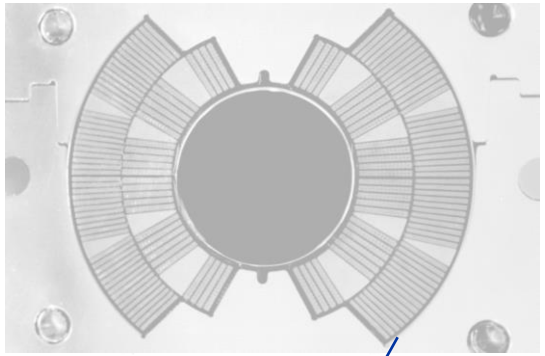
Tevatron



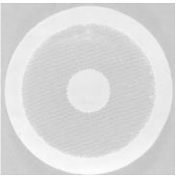
HERA



RHIC



LHC



strand

cable

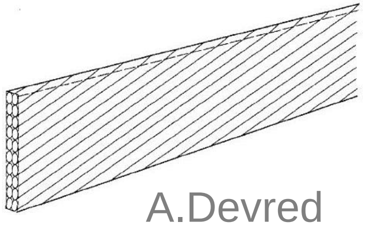
Now that we know how to design magnetically a cross-section, let’s take a look at the conductor itself

From the strand to the cable

Link to seminar

Why a cable?:

- To lower the inductance
- To ease coil wind- ability
- Allow current redistribution


A.Devred

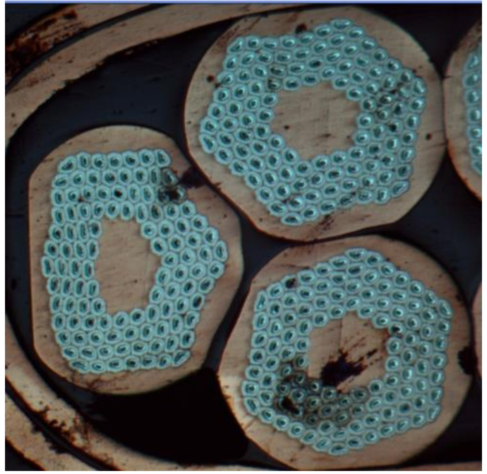
Rutherford cable made of two layers of multifilamentary strands: rectangular or trapezoidal

J. Fleiter – cabling machine Bldg 163 - CERN

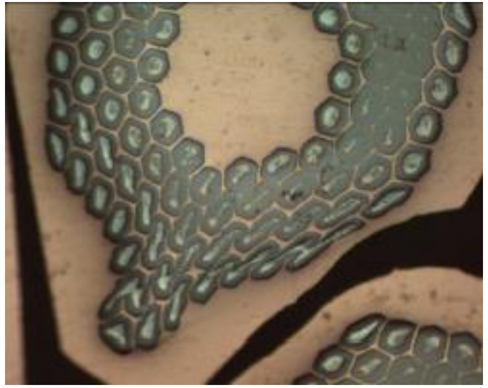
Cable must be compacted enough to insure enough mechanical stability for winding

But too much compaction can lead to edges deformation:

- reduction of the filament cross-sectional area (Nb-Ti)
- breakage of reaction barrier with incomplete tin reaction (Nb_3Sn)



Could affect magnet performance



Characterization of the critical surface

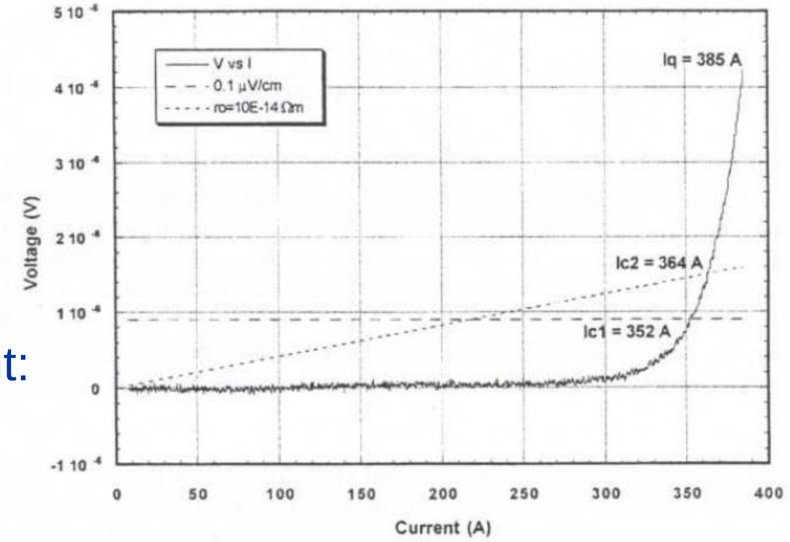
36093021.pdf (iaea.org)

Electrical characterization of a SC strand looking at its Voltage vs current curve

“Self standing” strand

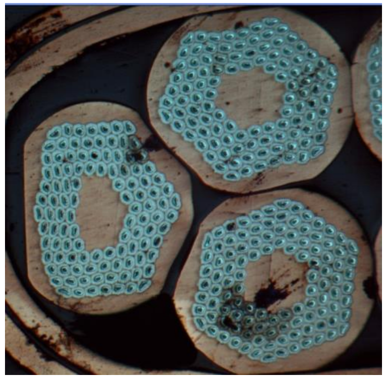
Versailles project on Advanced MAterials and Standards (VAMAS)

Standardized procedure and mandrel material to mount the wire sample (called Short Sample)



Criteria to define the critical current: I_c is defined as the current where $\rho_{sc} = 10^{-14}\ \Omega$m or $E = 0.1\ \mu$V/cm.

Definition of I_c (B,T) for a virgin strand



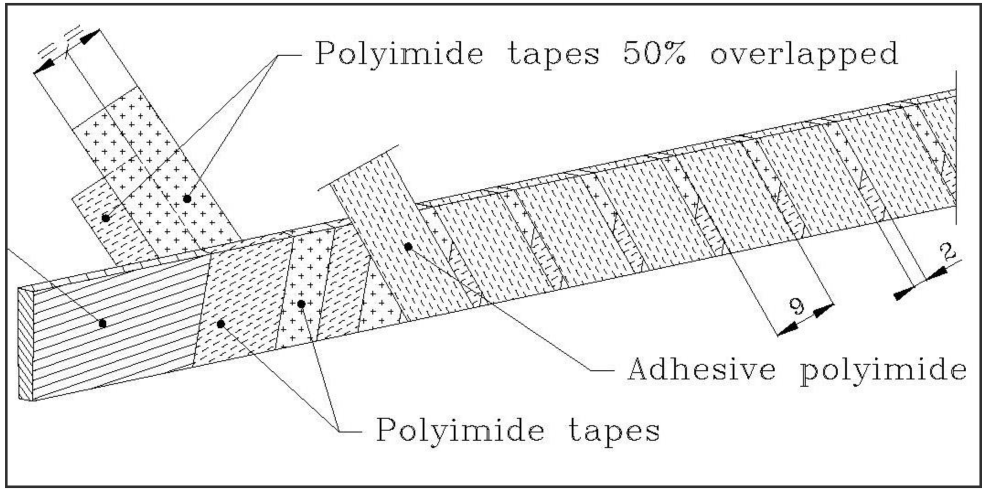
Cable Ic

Cabling can induce I_c degradation due to high compaction during cabling => Extracted strands (XS) from cables are also measured to quantify the possible degradation (typically a few %)

$$I_{c\text{-cable}} = n_{strand} \times I_{c\ XS}$$

Cable Insulation

- Good **dielectric properties** to withstand turn-to-turn *V* after a quench
- Good **mechanical properties** to withstand high stress conditions
- **Porosity** to allow penetration of helium (or epoxy)
- **Radiation hardness**
- In Nb-Ti magnets overlapped layers of **polyimide**
- In Nb_3Sn magnets, **fiber-glass** braided or as tape/sleeve.
- Typically the insulation thickness: 100 and 200 µm.

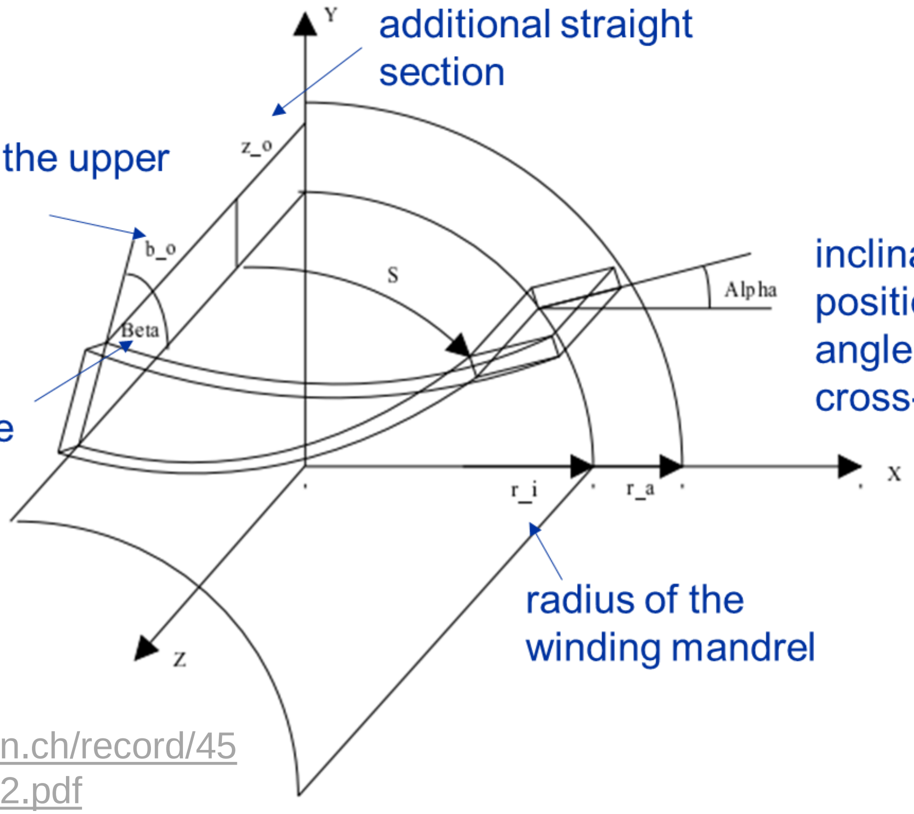


Mastering the thickness of the insulation within a few microns is key due to the large number of turns

3D coil end design

So far, we have only discussed 2D design but we need to address the 3D. End design is important as the particle sees the integrated field over the magnet length!

Coordinate system of the coil end



additional straight section

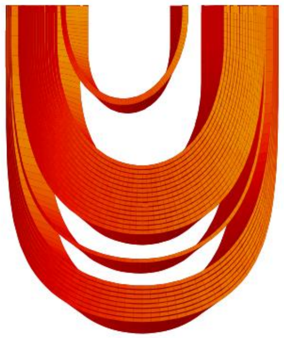
ellipticity of the upper edge of the conductor

inclination angle in the YZ plane

inclination and positioning angle in the 2d cross-section

radius of the winding mandrel

https://cds.cern.ch/record/451091/files/p192.pdf



End design optimization

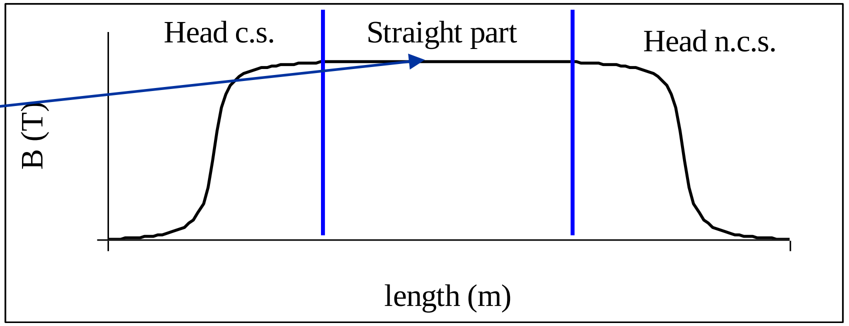
- Minimizing peak field in the ends
- Field quality

CAD design of the end parts: physical parts around which the ends are wound

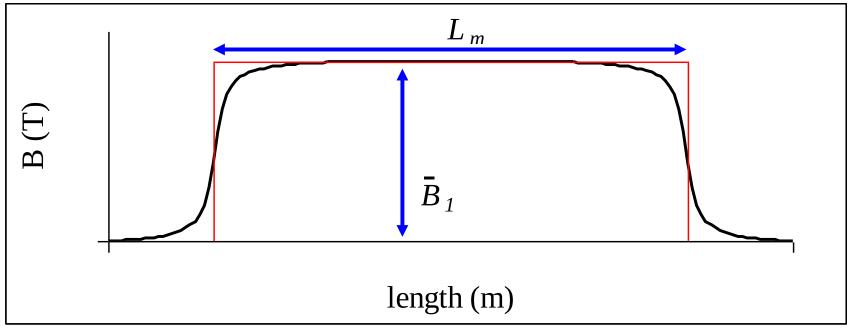
Field quality in 3D

The particle sees the integrated field over the magnet length
Concept of integrated main component value

$$\bar{B}_1 \equiv \frac{\int_{sp} B_1(s)ds}{\int_{sp} ds}$$



$$L_m \equiv \frac{\int B_1(s)ds}{\bar{B}_1}$$

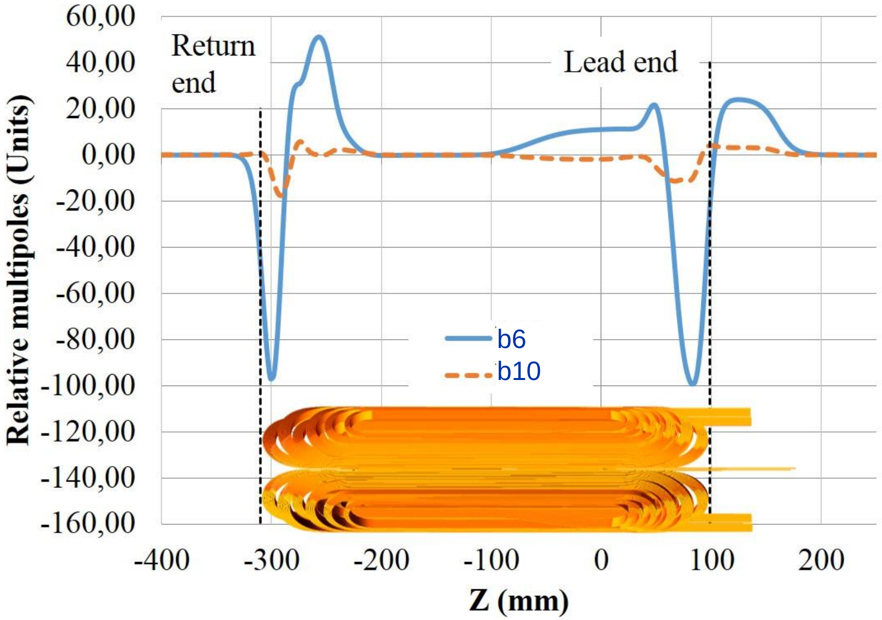


$$\bar{a}_n \equiv \frac{\int B_1(s)a_n(s)ds}{\int B_1(s)ds}$$

$$\bar{b}_n \equiv \frac{\int B_1(s)b_n(s)ds}{\int B_1(s)ds}$$

Concept of integrated multipoles

Example of the MQYYM quadrupole
Coil ends have been designed so that b6 and b10 integrate to zero

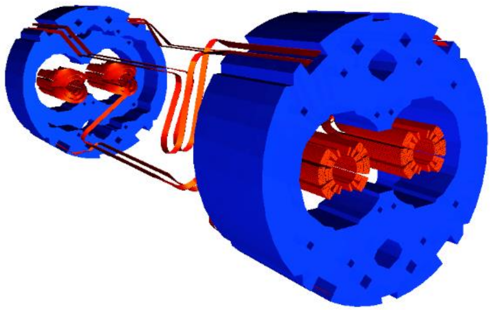


M. Segreti

Simulation and magnetic field computation

ROXIE: Routine for the Optimization of Magnet X-sections, Inverse Field Computation and Coil End Design

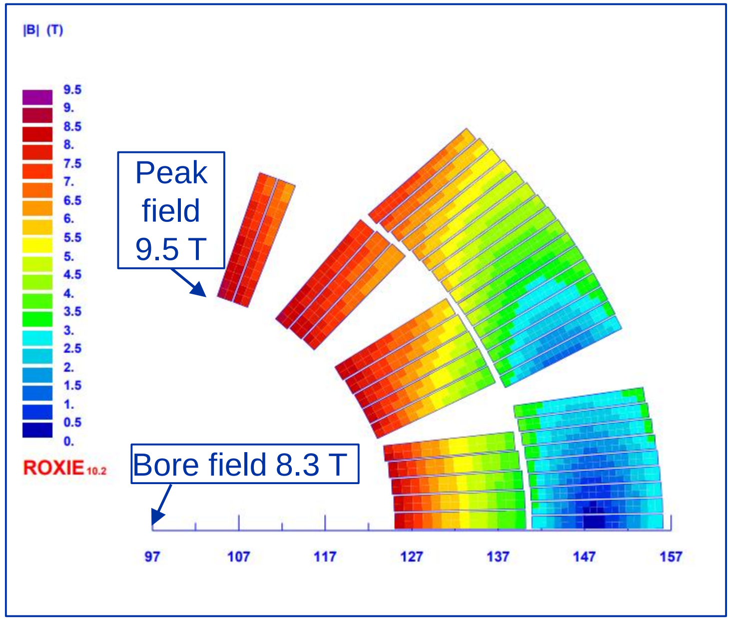
- Developped by S. Russenschuck at CERN
- Specific to superconducting accelerator magnet design
- coil geometry, iron geometry, and coil ends
- Several routines for optimization
- Evaluation of field quality, including iron saturation (BEM-FEM methods) and persistent currents



Roxie CERN webpage

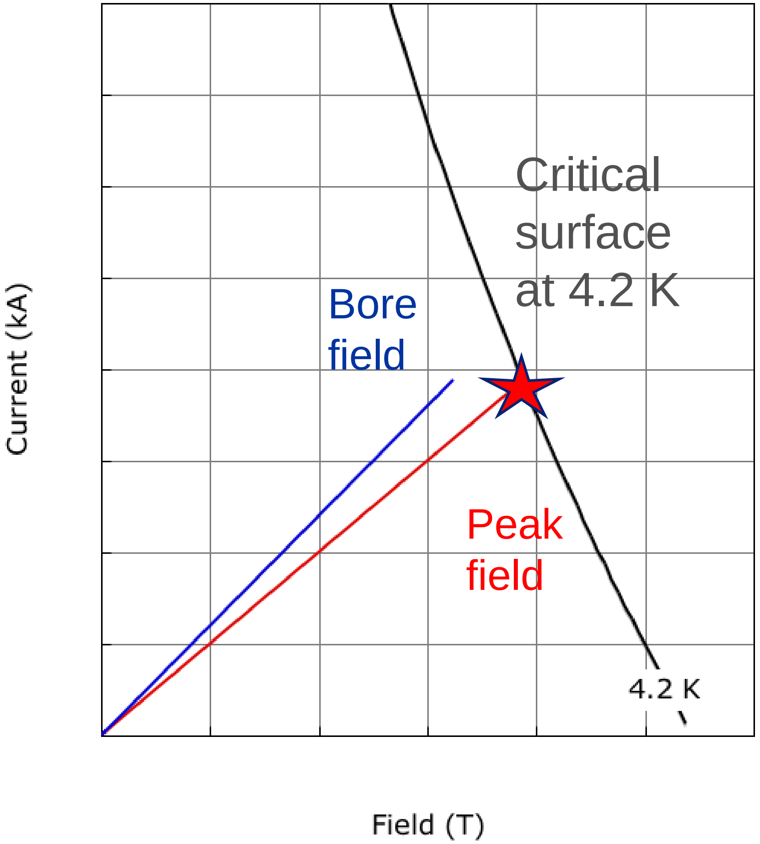
ROXIE Cross section of LHC dipole

- Peak field : maximum field in the coil
- Bore field : field at the center of the aperture



LHC Design Report - CERN Document Server

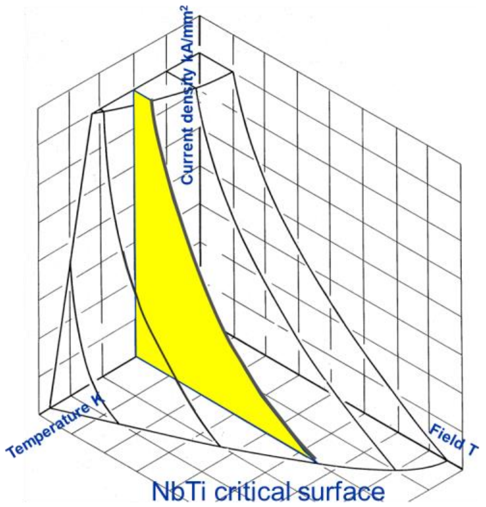
Concept of load line and quench



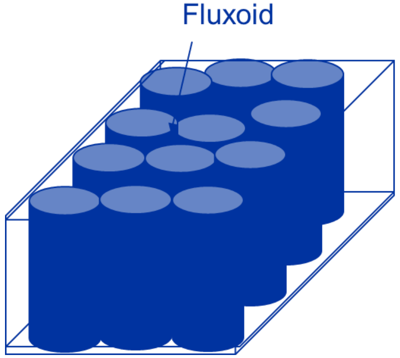
- The peak field as the function of the field defines the magnet load line
- The maximum magnet performance is obtained when the load line reaches the critical surface. Beyond that point the supercoductor becomes resistive

⇒ this the quench :transition from SC to normal material

- A similar bore field load line can be plotted



NbTi critical surface



SC fully penetrated and the normal cores of the fluxoids are covering the material => fully resistive

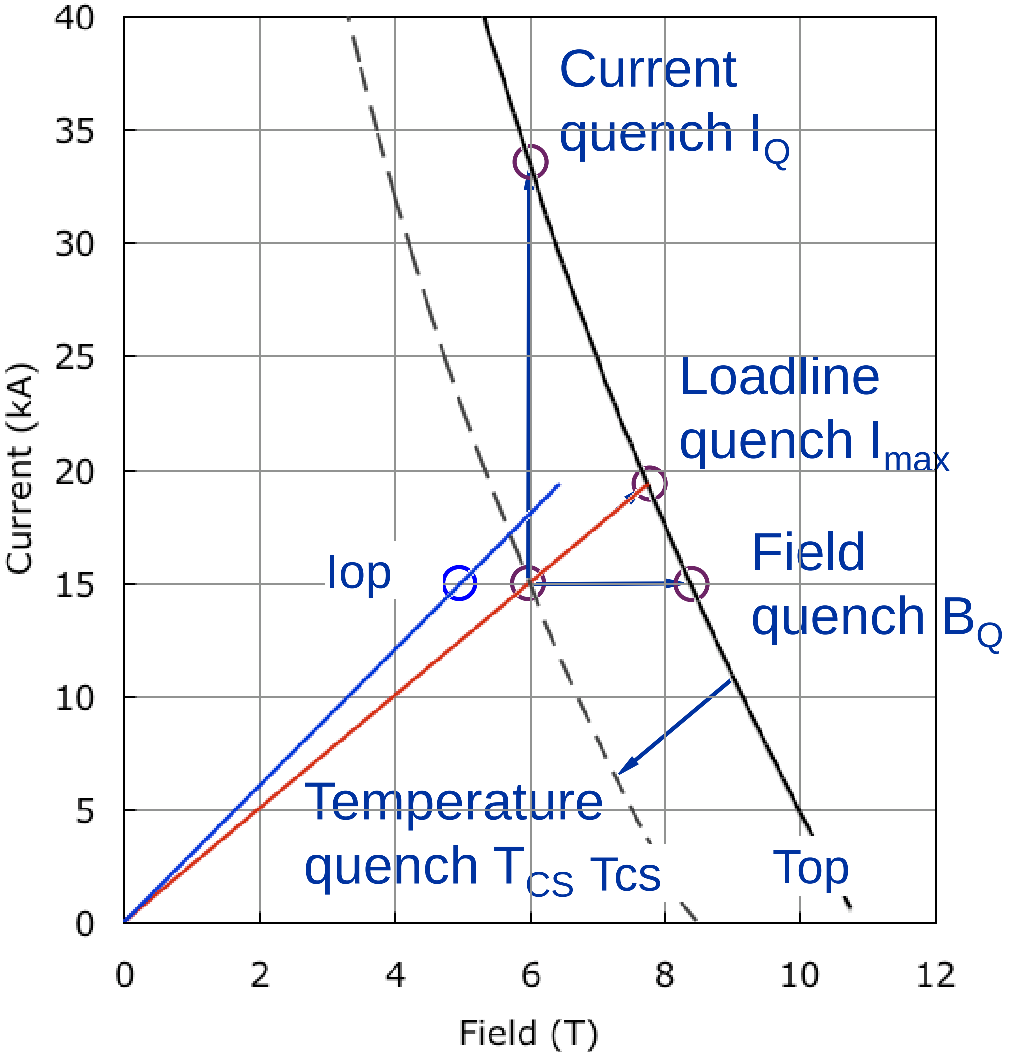
Margins in SC magnets

- Among magnet engineers, a commonly used concept is the loadline margin
- The concept is always criticized (not physical) but never replaced: the success of a magnet judged on its ability of reaching the max performance

$$LL\,margin = 1 - \frac{I_{op}}{I_{max}}$$

E. Todesco

- A more physical margin is the temperature margin: T_{CS}-T_{op}
- How much can we heat locally to reach the critical surface (at the operational current density and field)?



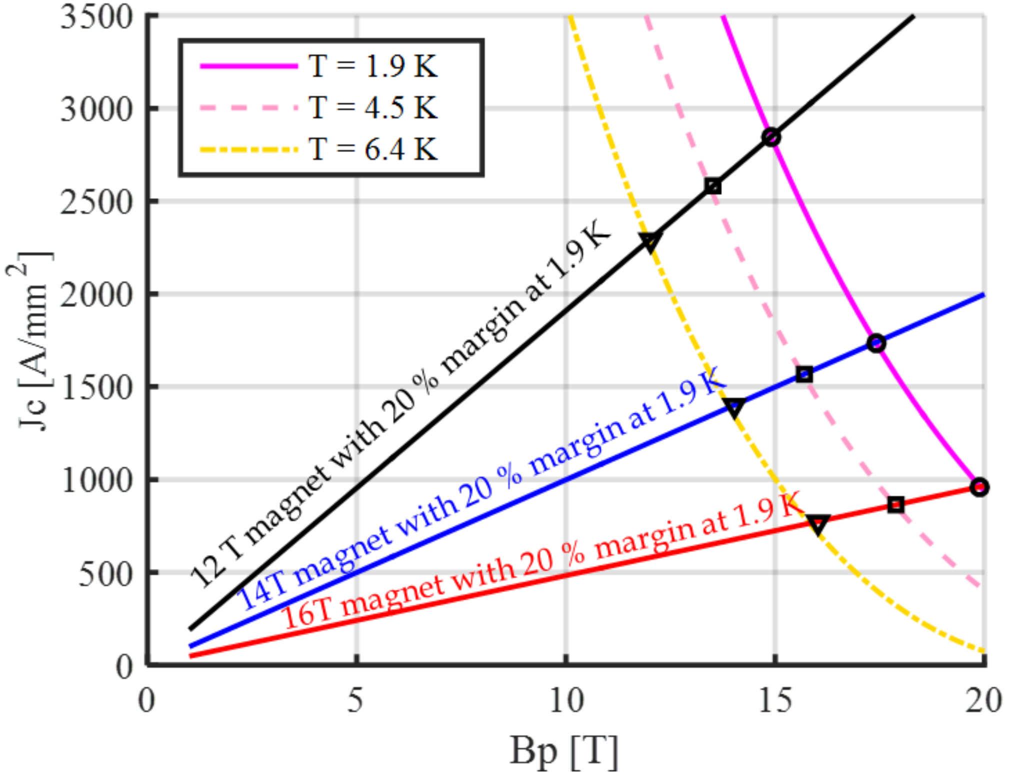
Consideration on margins for NbTi and Nb_3Sn

For Nb_3Sn and Nb-Ti the temperature margin depends only on the loadline margin and very weakly on the field.

For a given a material and an operational temperature, load line margin and temperature margin are equivalent

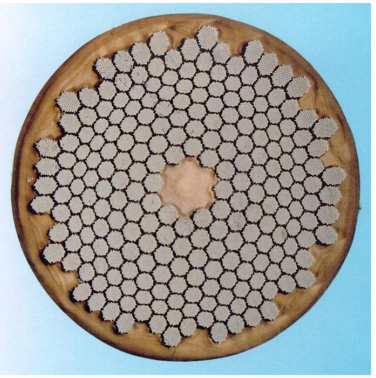
For a given LL margin, Nb_3Sn T margin is about 2.5 times greater than NbTi T margin

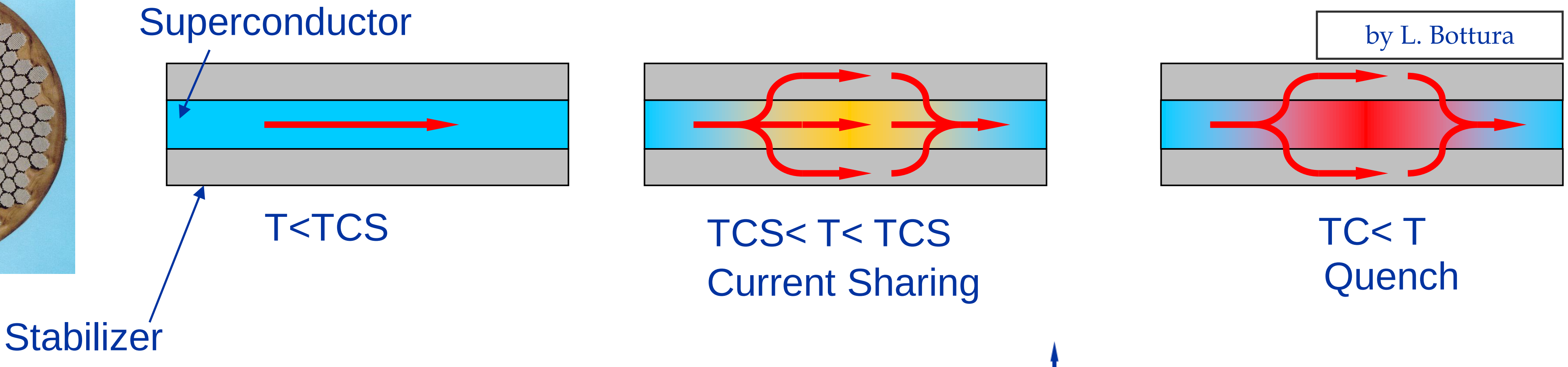
Temperature margins at 20% on loadline		
Operational temperature	1.9 K	4.2 K
Nb-Ti	2.1 K	1.2 K
Nb_3Sn	4.5 K	3.0 K



E. Todesco, S. Izquierdo Bermudez

Quench phenomenon : a few more details





by L. Bottura

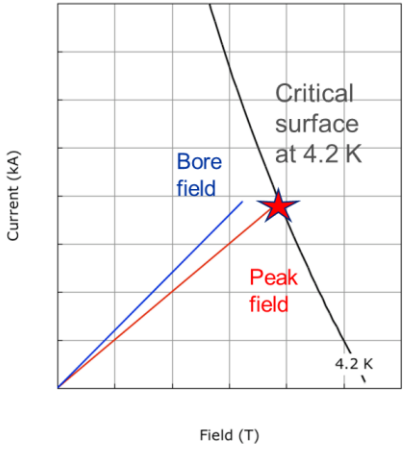
Superconductor

Stabilizer

T<TCS

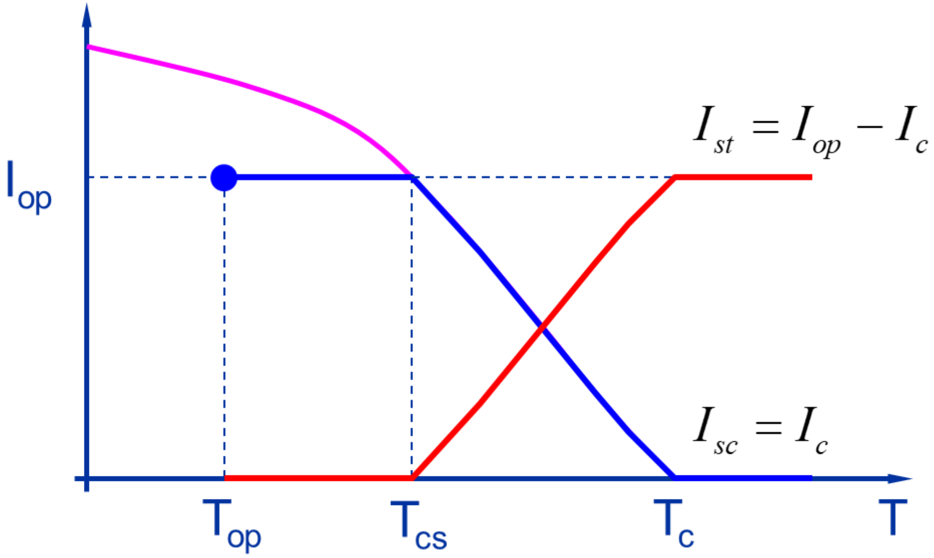
TCS< T< TCS
Current Sharing

TC< T
Quench

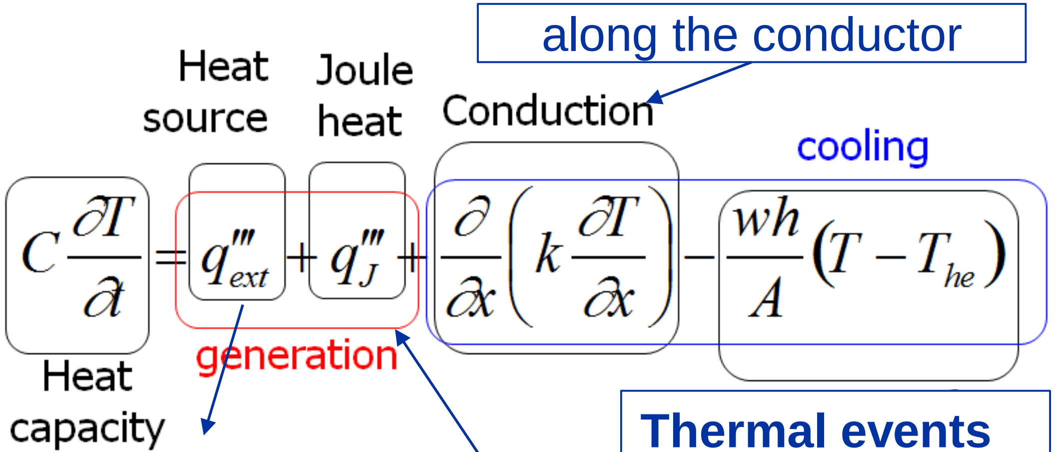


When any margin of the magnet is «eaten»

- the current starts to flow in the stabilizer
- If the temperature keeps rising, the current will ONLY flow in the stabilizer – without sufficient cooling, the transition is irreversible: it is a quench



Quench phenomenon and concept of protection



$$C\frac{\partial T}{\partial t} = q'''_{ext} + q'''_{J} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \frac{wh}{A}\left(T - T_{he}\right)$$

CAUSES

Mechanical events
- Frictional motion
- Epoxy cracking

Electromagnetic events
- Flux-jumps ,AC loss

Nuclear events
- Particle showers

Thermal events such as Degraded cooling

When the current starts to flow in the stabilizer

by L. Bottura

But in fact: what is the problem?

Stored energy in the magnet

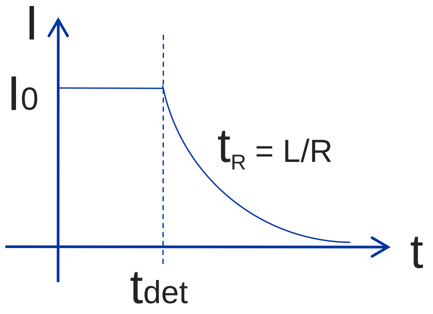
$$E_m = \int_V \frac{B^2}{2\mu_0}\,dv = \frac{1}{2}LI^2$$

LHC dipole : 7 MJ
A 20 ton truck at 100 km/h: 7.7 MJ

This energy has to be removed and/or dissipated in the magnet :
- To minimize the rise of temperature
- To minimize gradient of temperature inside the coil (homogeneous distribution)

=> Concept of quench Protection

How to protect a magnet against quench?



1) When the quench starts, a resistive voltage starts to grow
2) Detection of that voltage (threshold at about 100 mV)
3) Triggering of the protection

$$\gamma C_p(T)dT = \rho J(t)^2 dt$$

4) Current decay in L/R, the quicker the decay the lower the temperature in the coil (0.1 to 0.5 s)

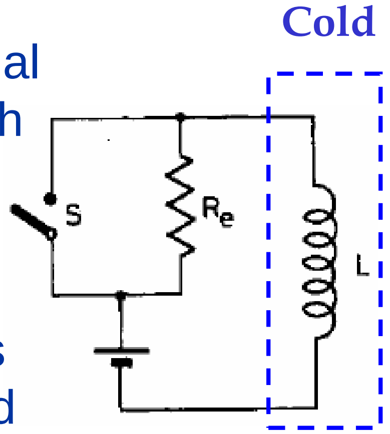
$$\int_0^\infty I(t)^2 dt = A_{tot} A_{Cu} \int_{T_0}^{T_{max}} \frac{\sum_k \gamma_k v_k C_{p,k}}{\rho_{Cu}(T,B)} dT$$

Increase the R

Cut the power supply

By adding an external resistor in series with the magnet: dump resistor

Part of the energy is extracted, dissipated outside the magnet

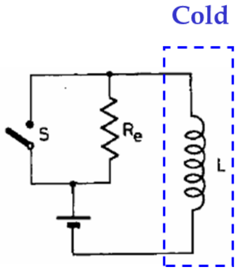


M.K. Wilson, Superconducting Magnets

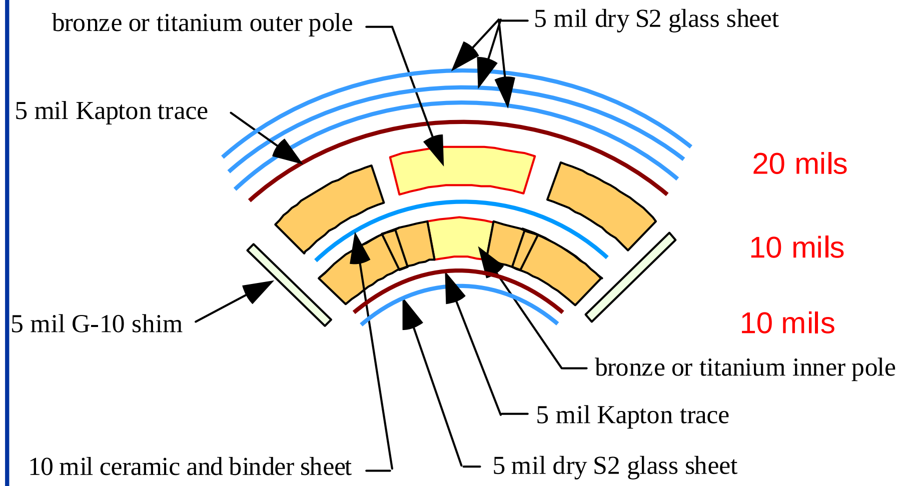
By heating up the coil, using heating elements on top of the coils called quench heater or protection heaters

Protection: always watch the dielectric strength

- The energy extraction triggers high voltage at the magnet terminals – usual limit set to 1 kV
- Internal voltages are developping due to the magnet inductance



Importance of the design of a proper dielectric insulation in the coil



Rodger Bossert, FNAL

Importance of the electrical QA tests

Hipot

- Look for leakage current between coil and magnet components under high DC voltage
- Verify that the coil sustains the required voltage limits without breakout

Impulse test

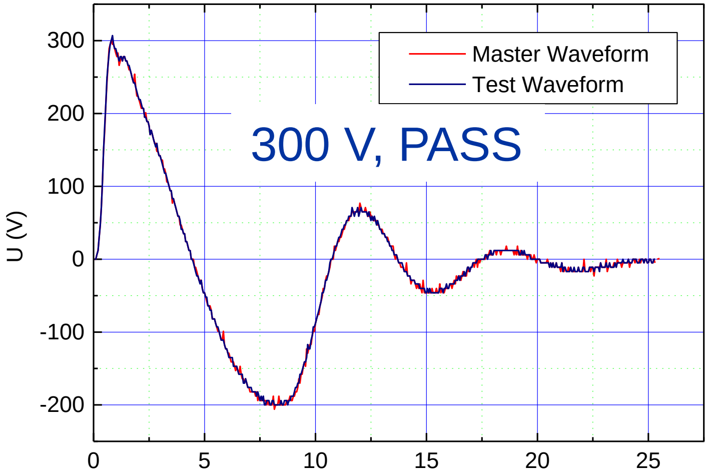
- Look for turn-to turn shorts and insulation breakdown and coil to coil parts

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

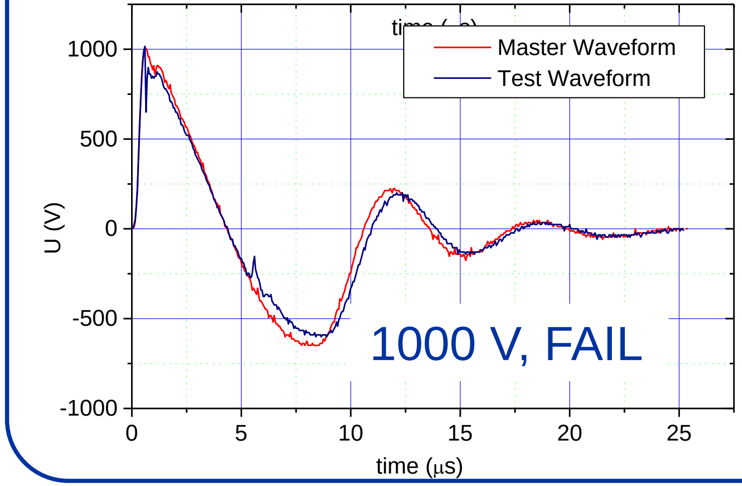
Examples of dielectric failure

Diagnosed before test

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$



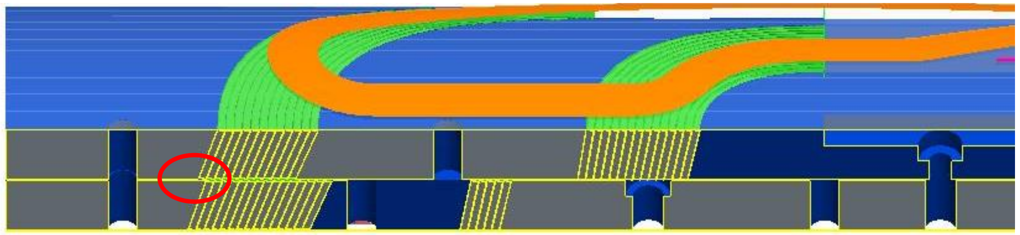
300 V, PASS



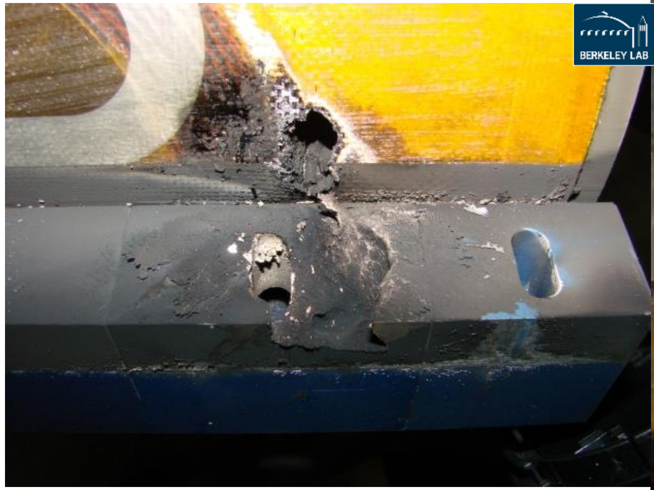
1000 V, FAIL

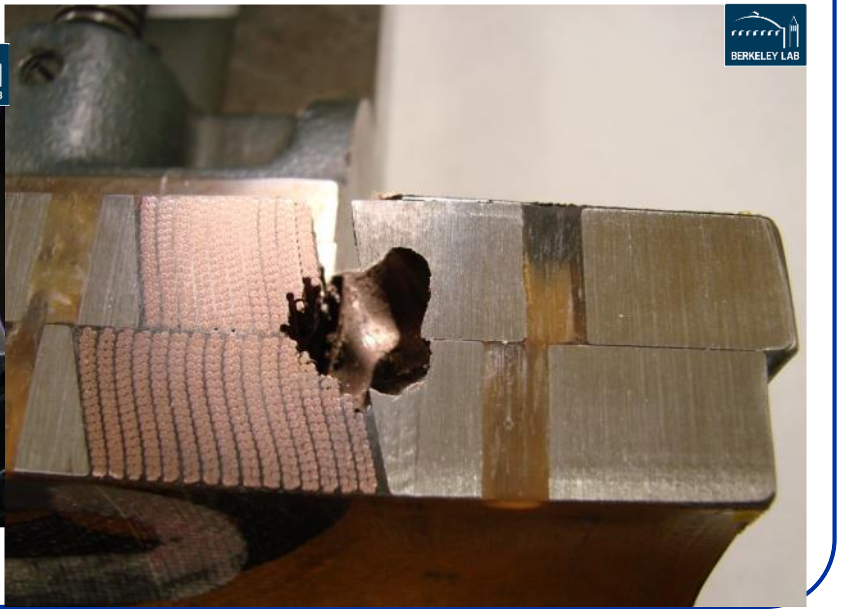
Coil not used in a magnet

Not diagnosed (occured during test) with tragic consequence

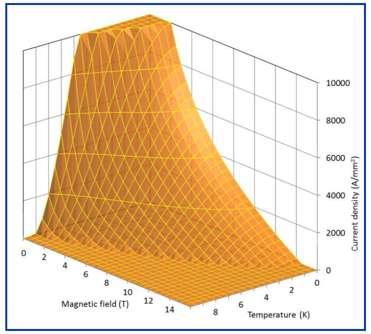


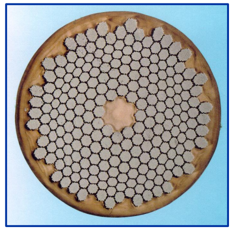
S. Caspi, R. Hafalia





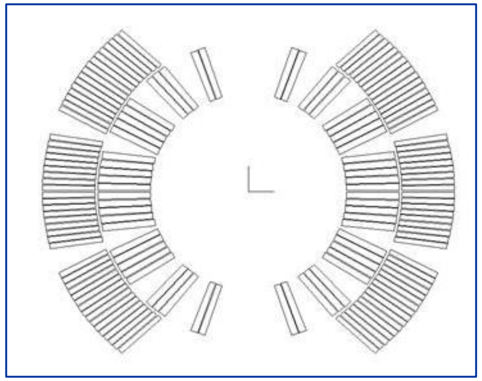
Summary of Part I





- We need superconding magnets to bend high energy particle beams

- We need complex conductor: stabilizer, subdivision, twisting, cabling… => practical superconductors

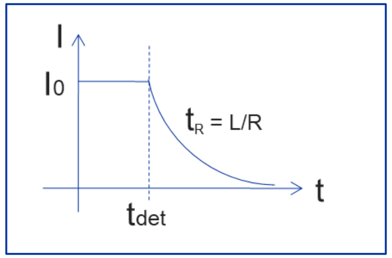


- Superconductor operation is limited by a critical surface (B, I and T) beyond which the superconductor quenches = becomes highly resistive

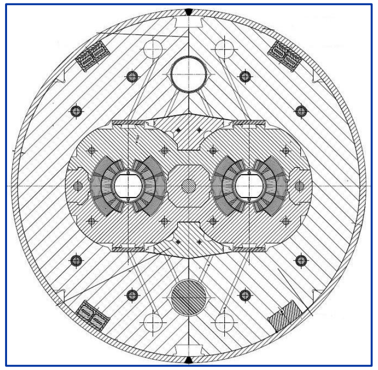
- We have Ideal field distributions which we approximate
    - 2D and 3D design tools
    - Field homogenity
    - Margins

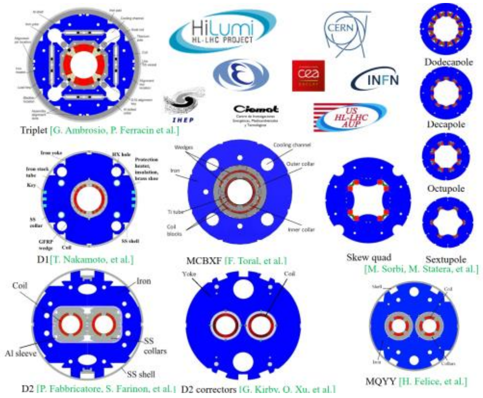
$$E_m = \int_V \frac{B^2}{2\mu_0} dv = \frac{1}{2} L I^2$$

- Large magnetic stored energy in the magnets: we need to protect them in case of quench



Teaser of part II





We will take a look at:

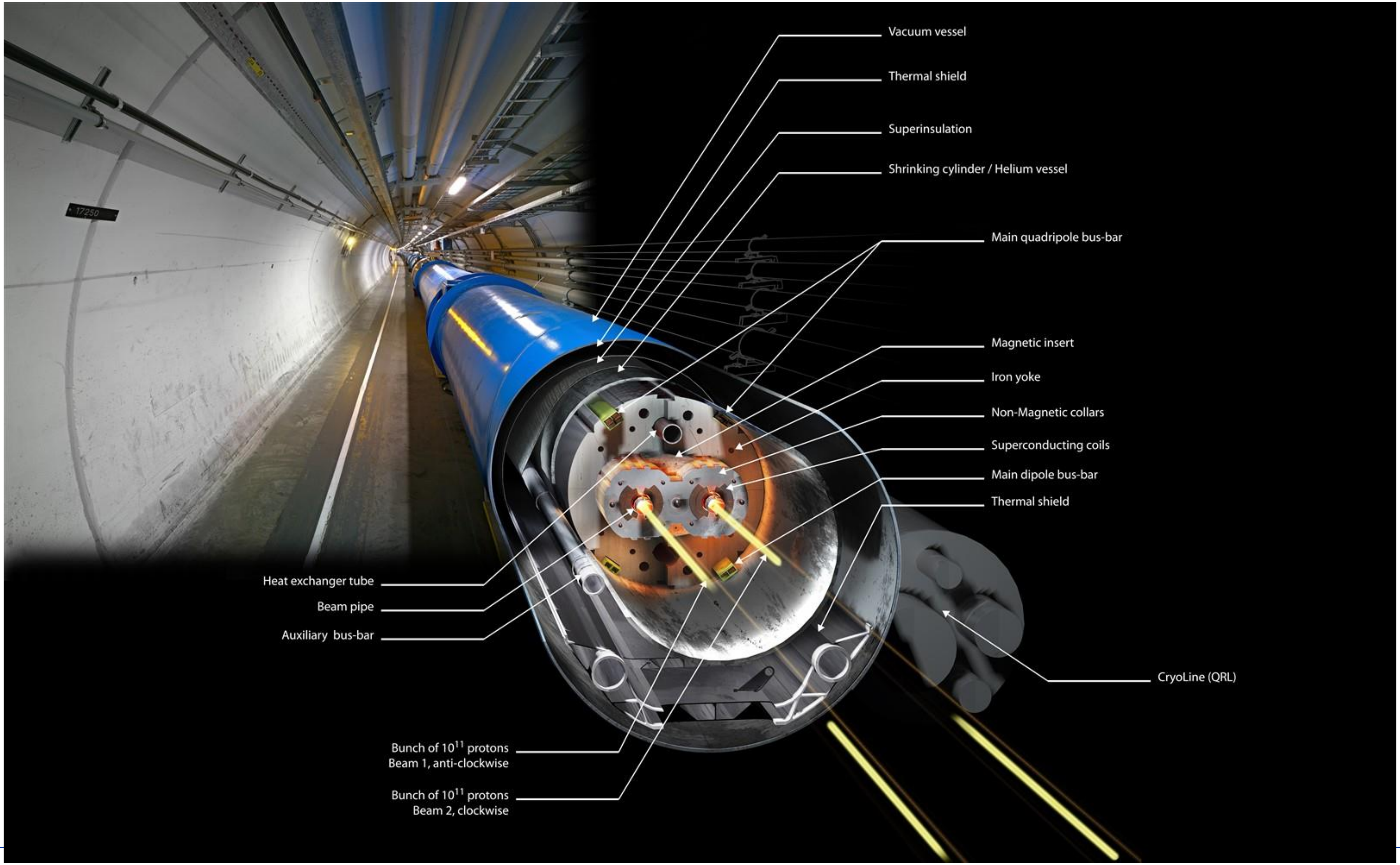
- The **coil manufacturing**
- **the support structure** in which the coils are assembled
- The cold test and the concept of **training**

This should complete the overview of the magnet technology main concepts.

Then:

- HL-LHC at a glance with its zoo of magnets and associated challenges
- Beyond HL-LHC… what's next?

CERN


Vacuum vessel
Thermal shield
Superinsulation
Shrinking cylinder / Helium vessel
Main quadripole bus-bar
Magnetic insert
Iron yoke
Non-Magnetic collars
Superconducting coils
Main dipole bus-bar
Thermal shield
CryoLine (QRL)
Heat exchanger tube
Beam pipe
Auxiliary bus-bar
Bunch of 10^11 protons Beam 1, anti-clockwise
Bunch of 10^11 protons Beam 2, clockwise
17250