Summer Student Lecture

Superconductivity and superconducting magnets for the LHC Upgrade

Paolo Ferracin

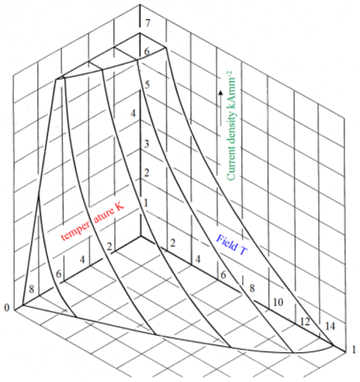
(paolo.ferracin@cern.ch)

European Organization for Nuclear Research (CERN)

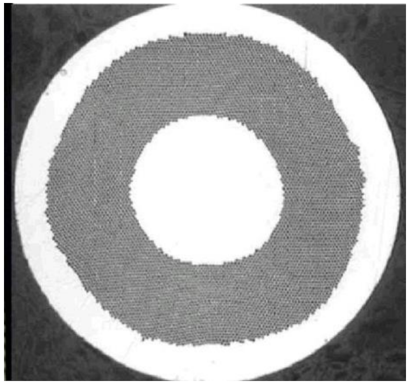
Introduction
Goal of the lecture

- Overview of **superconducting magnets** for particle accelerators (dipoles and quadrupoles)
  - Description of the components and their function
  - **…past, present, and future**: HiLumi LHC and FCC
- From the superconducting material to the full magnet

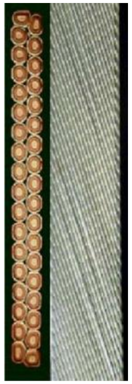
Superconducting material



Superconducting strand

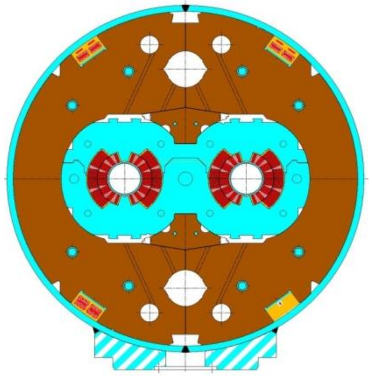


Superconducting cable



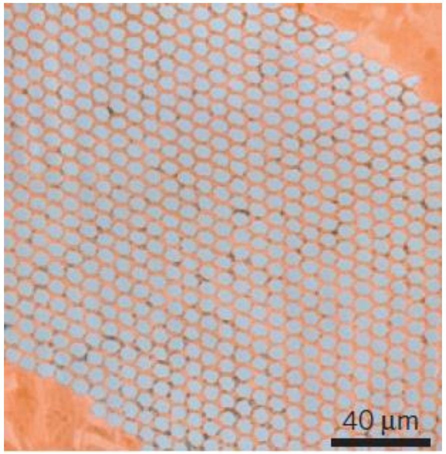
Superconducting coil

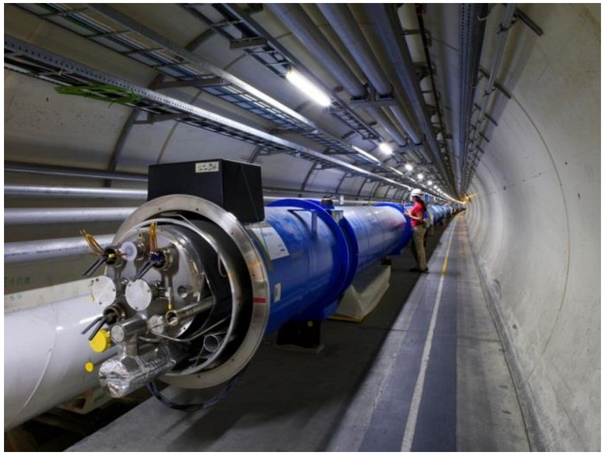
Superconducting magnet



Introduction
Superconducting magnet technology

- Multidisciplinary field: mixture of
  - Chemistry and material science: **superconducting materials**
  - Quantum physics: the key mechanisms of **superconductivity**
  - Classical electrodynamics: **magnet design**
  - Mechanical engineering: **support structures**
  - Electrical engineering: powering of the magnets
  - Cryogenics: keep them **cool** …
- Very different order of magnitudes





Outline

- **Particle accelerators and superconductors**
- **Magnetic design and coils**
- **Mechanics of superconducting magnets**
- **Quench and protection**
- **HiLumi LHC and FCC**

References

- **Particle accelerators and superconductors**

  - K.-H. Mess, P. Schmuser, S. Wolff, "*Superconducting accelerator magnets*", Singapore: World Scientific, 1996.
  - Martin N. Wilson, "*Superconducting Magnets*", 1983.
  - Fred M. Asner, "*High Field Superconducting Magnets*", 1999.

  - P. Ferracin, E. Todesco, S. Prestemon, "*Superconducting accelerator magnets*", US Particle Accelerator School, www.uspas.fnal.gov.
    - **Units 2 by E. Todesco**

  - A. Devred, "*Practical low-temperature superconductors for electromagnets*", CERN-2004-006, 2006.

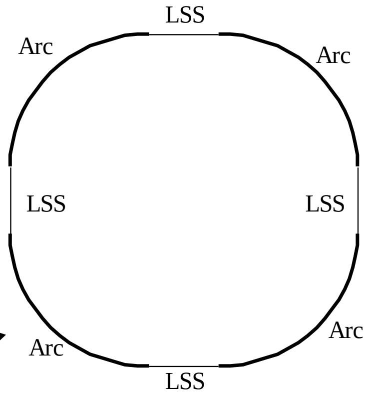
  - Presentations from Luca Bottura and Martin Wilson

Particle accelerators and magnets

by E. Todesco

- Principle of synchrotrons
  - Driving particles in the same accelerating structure several times
- Electro-magnetic field accelerates particles

$$\vec{F} = e\vec{E}$$



- Magnetic field steers the particles in a ~circular orbit

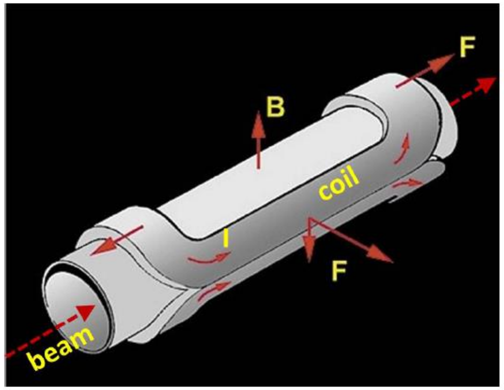
$$\vec{F} = e\vec{v} \times \vec{B}$$

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

$$\underset{\uparrow}{p} = e\underset{\uparrow}{B}\rho$$

Constant

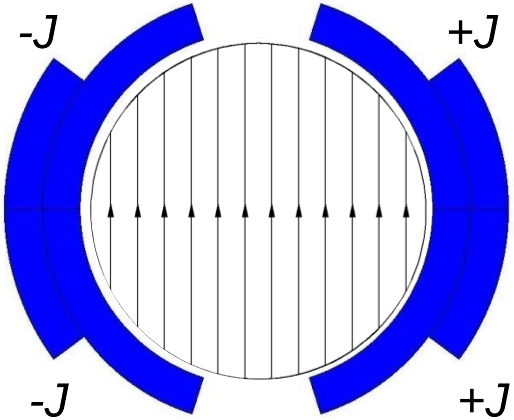
Particle accelerators and magnets
Dipoles

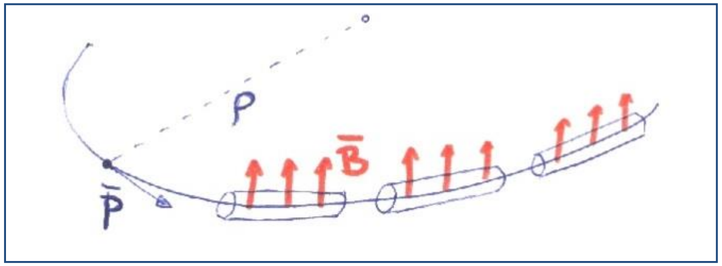


- Main field components is B_y
  - Perpendicular to the magnet axis z
- Electro-magnets: field produced by a current (or current density)

$$\boxed{B_y = -\frac{\mu_0 J_0}{2}(r_{out} - r_{in})}$$

- Magnetic field steers (bends) the particles in a ~circular orbit



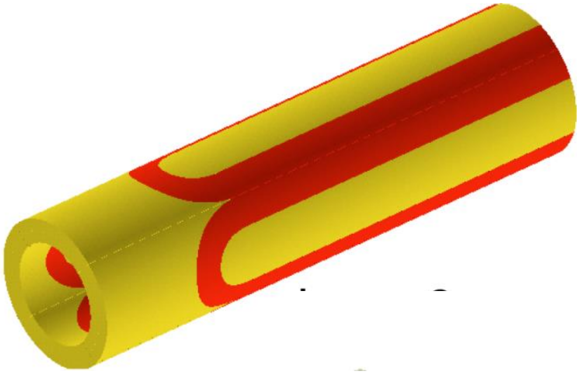


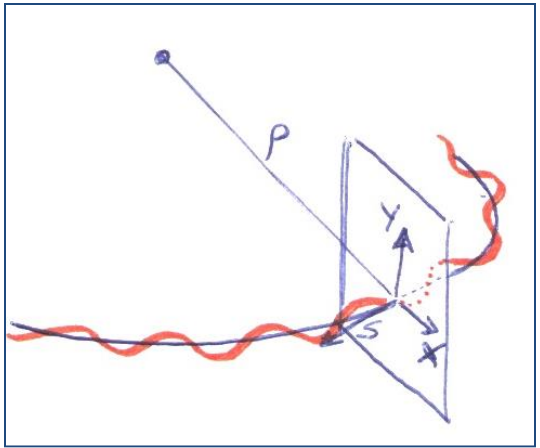
$$\boxed{p = eB\rho}$$

by E. Todesco

Particle accelerators and magnets
Quadrupoles

- The force necessary to stabilize linear motion is provided by the quadrupoles
- They provide a field equal to zero in the center
  - increasing linearly with the radius
- They act as a spring: focus the beam
- Prevent protons from falling to the bottom of the aperture due to the **gravitational force**
  - it would happen in less than 60 ms





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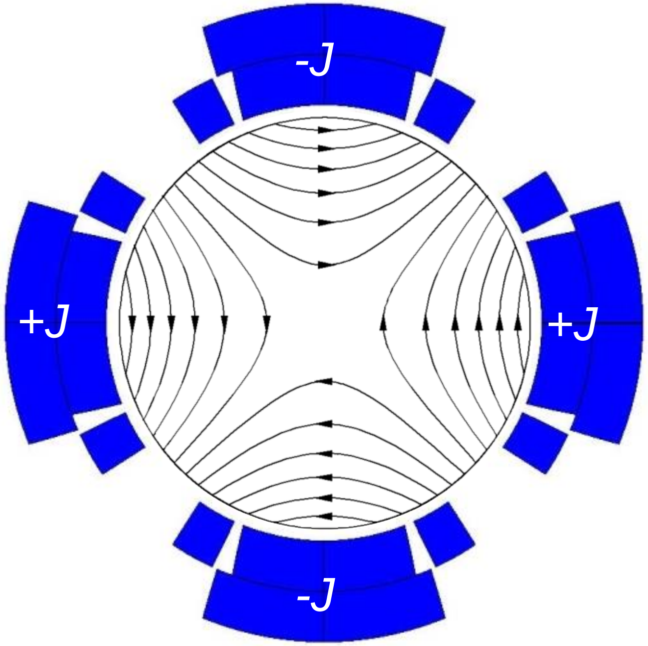
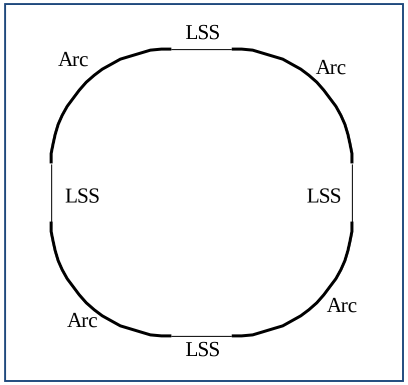
$$G=\frac{B_y}{r}=-\frac{\mu_0 J_0}{2}\ln\frac{r_{out}}{r_{in}}$$

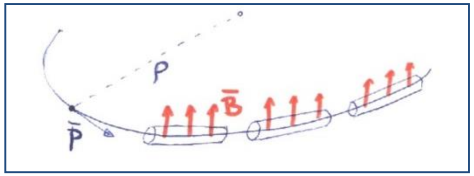


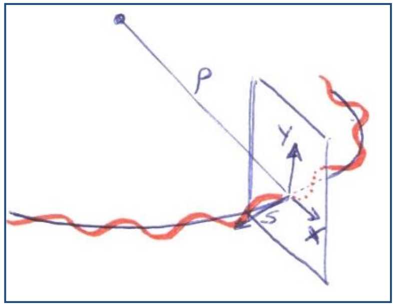
Particle accelerators and magnets

- Dipoles: the larger B, the larger the energy
- Quadrupoles: the larger B, the larger the focusing strength
- For an electro-magnet, the larger B, the larger must be J



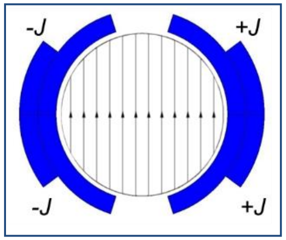
$$p = eB\rho$$

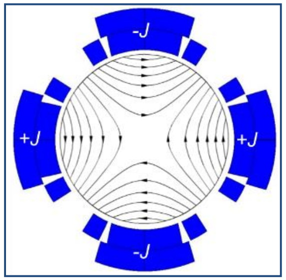




$$B_y = -\frac{\mu_0 J_0}{2}(r_{out} - r_{in})$$

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

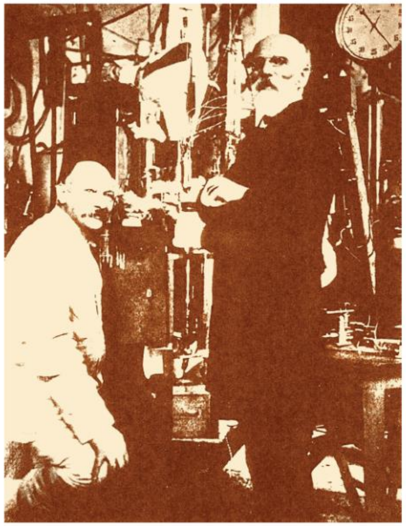


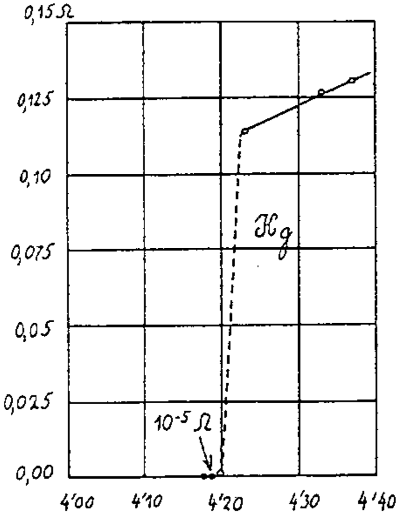


- In normal conducting magnets, J ~ 5 A/mm^2
- In superconducting magnets, Je ~ 600-700 A/mm^2

Superconductivity
The discovery

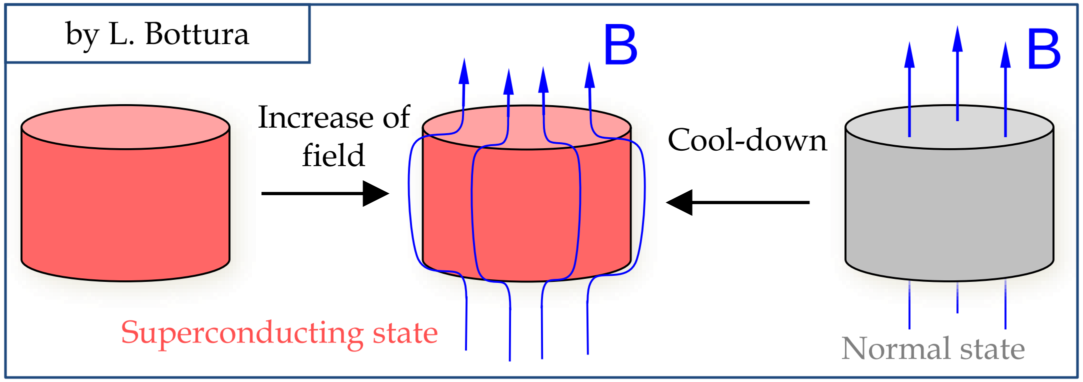
- Superconductivity discovered in 1911 by Kammerling-Onnes
  - **ZERO resistance** of mercury wire at 4.2 K
- Temperature at which the transition takes place: **critical temperature T_c**
- Observed in many materials
  - but not in the typical best conductors (Cu, Ag, Au)
- At $T > T_c$, superconductor very poor conductor
- 2 kinds of superconductors
  - **Type I and Type II**
    - Different behaviour with magnetic field



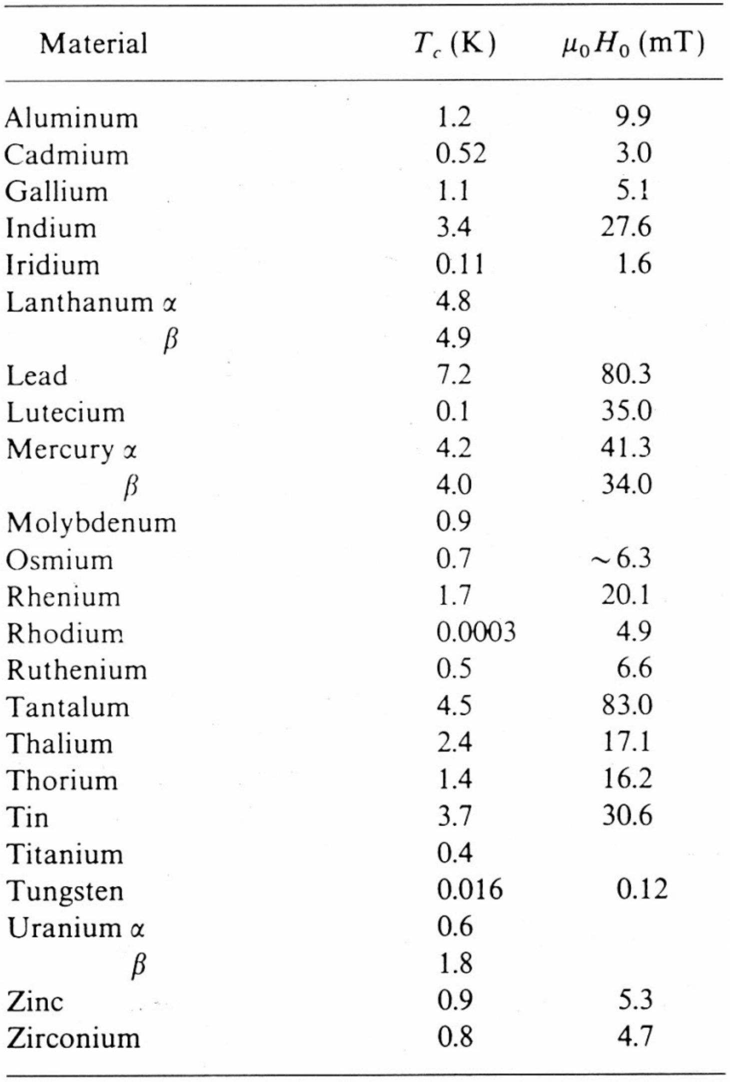


Superconductivity
Type I superconductors

- Meissner-Ochsenfeld effect (1933)
- Perfect diamagnetism
  - With $T<T_c$ magnetic field is expelled
- But, the B must be < **critical field B_c**
  - Otherwise superconductivity is lost


by L. Bottura

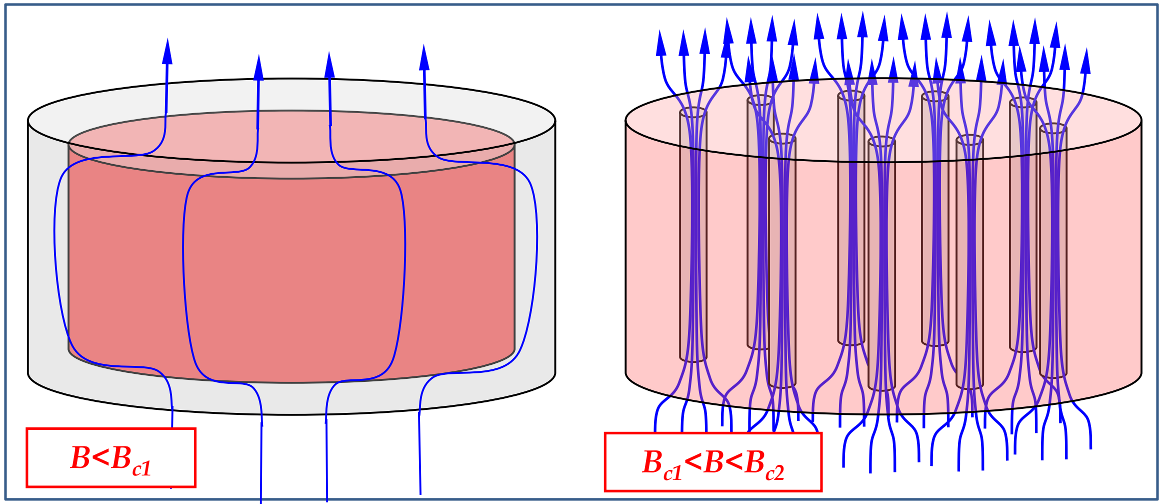
- Unfortunately, first discovered superconductors (**Type I**) with **very low B_c** ($\leq$ 0.1 T)
  - not practical for electro-magnets



Material	T_c (K)	$\mu_0 H_0$ (mT)
Aluminum	1.2	9.9
Cadmium	0.52	3.0
Gallium	1.1	5.1
Indium	3.4	27.6
Iridium	0.11	1.6
Lanthanum α	4.8	
β	4.9	
Lead	7.2	80.3
Lutecium	0.1	35.0
Mercury α	4.2	41.3
β	4.0	34.0
Molybdenum	0.9	
Osmium	0.7	~6.3
Rhenium	1.7	20.1
Rhodium	0.0003	4.9
Ruthenium	0.5	6.6
Tantalum	4.5	83.0
Thalium	2.4	17.1
Thorium	1.4	16.2
Tin	3.7	30.6
Titanium	0.4	
Tungsten	0.016	0.12
Uranium α	0.6	
β	1.8	
Zinc	0.9	5.3
Zirconium	0.8	4.7

Superconductivity
Type II superconductors

- So, for 40-50 years, superconductivity was a research activity
- Then, in the 50's, **type II superconductors**
  - Between B_{c1} and B_{c2} : mixed phase
    - B penetrates as flux tubes: *fluxoids*
      - with a flux of $\phi_o = h/2e = 2 \cdot 10^{-15}$ *Wb*
- Much higher fields and link between T_c and B_{c2}



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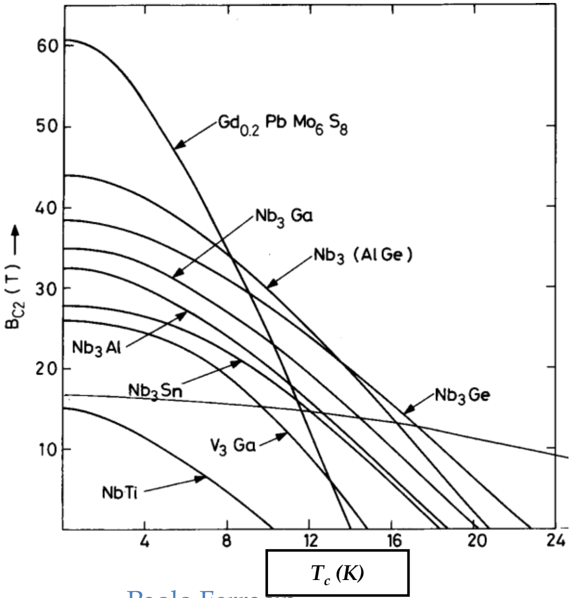
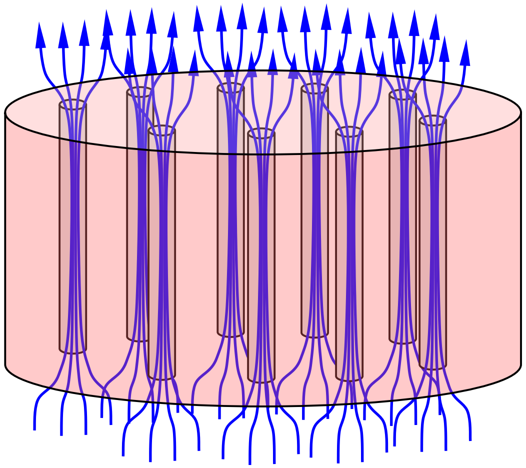


Superconductivity
Hard superconductors

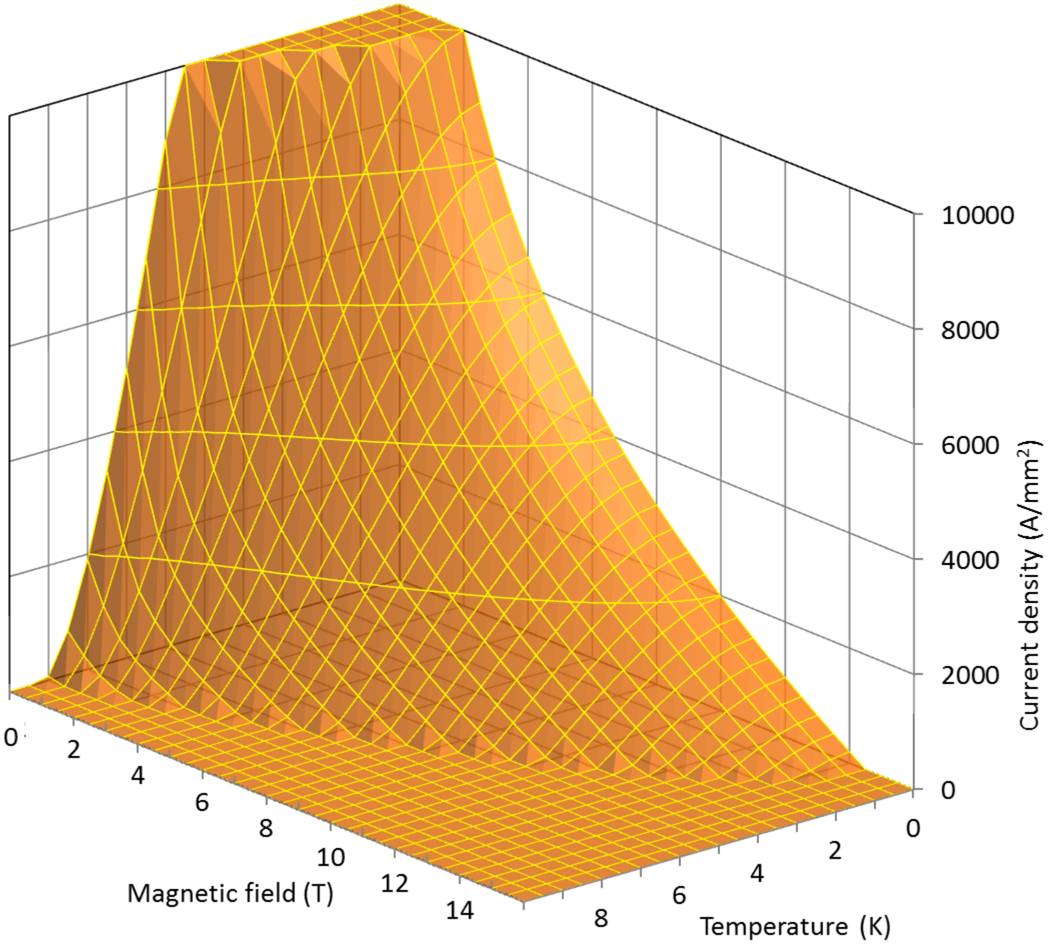
- …but, if a current passes through the tubes
    - Lorentz force on the fluxoids: $\boldsymbol{F_L = J \times B}$
- The force causes a **motion** of tubes
    - Flux motion (dB/dt) → (V) → **dissipation** (VI)
- Fluxoids must be locked by **pinning centers**
    - Defects or impurities in the structure



- The pinning centres exert a pinning force $\boldsymbol{F_p}$
- As long as $\boldsymbol{F_p \leq J \times B}$
    - No flux motions → no dissipation
- J_c is the current density at which, for a given $\boldsymbol{B}$ and at a given T the pinning force is exceeded by the Lorentz force

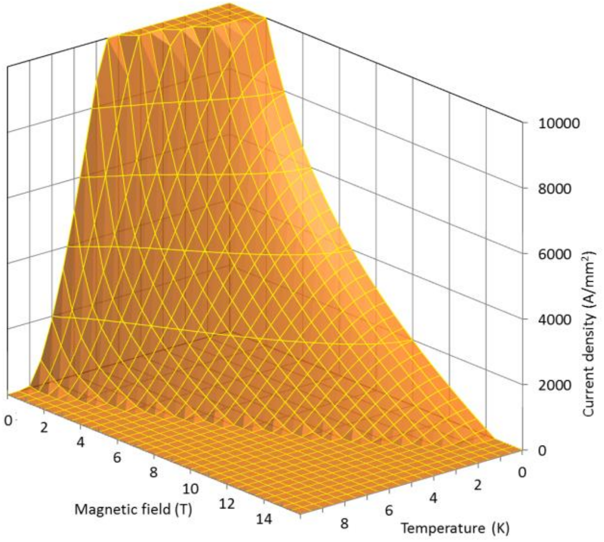
Superconductivity
Critical surface

- A type II material is supercond. below the **critical surface** defined by
  - Critical temperature ***Tc***
    - Property of the material
  - Upper critical field B_{c2}
    - Property of the material
  - Critical current density J_c
    - Hard work by the producer

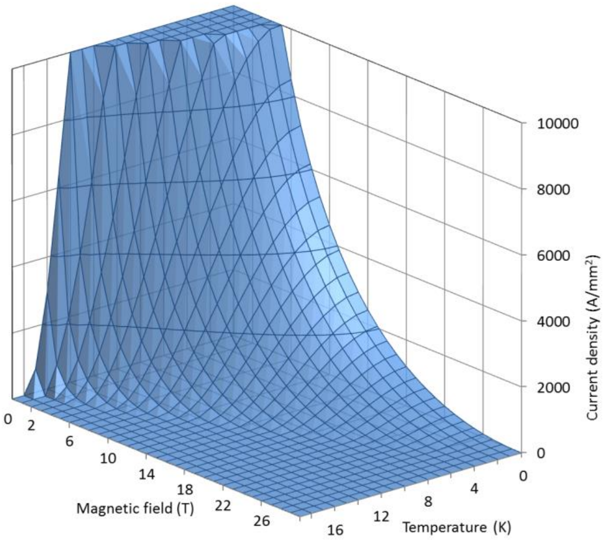


Superconductivity
Nb-Ti (1961) and Nb$_3$Sn (1954)

- Nb and Ti → ductile alloy
  - Extrusion + drawing
- T_c is ~**9.2 K** at 0 T
- B_{C2} is ~**14.5 T** at 0 K
- Firstly in **Tevatron** (80s), then all the other
- ~50-200 US$ per kg of wire (1 euro per m)

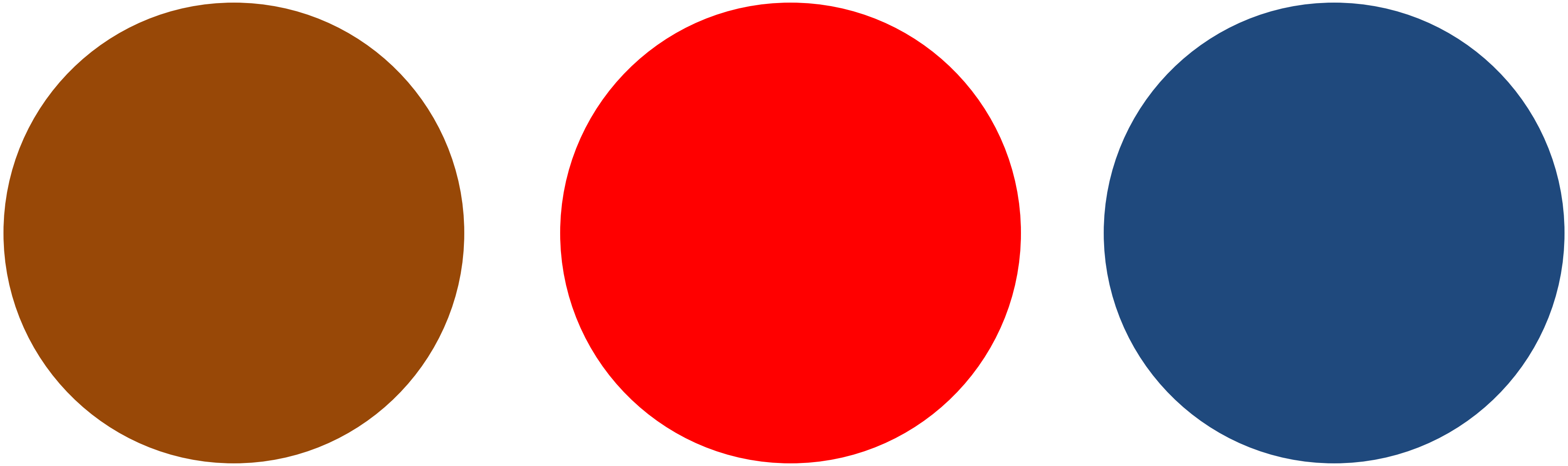


- Nb and Sn → intermetallic compound
  - Brittle, strain sensitive, formed at ~650-700°C
- T_C is ~**18 K** at 0 T
- B_{C2} is ~**28 T** at 0 K
- Used in **NMR**, **ITER**
- ~700-1500 US$ per kg of wire (5 euro per m)



Superconductivity from Cu to Nb_3Sn

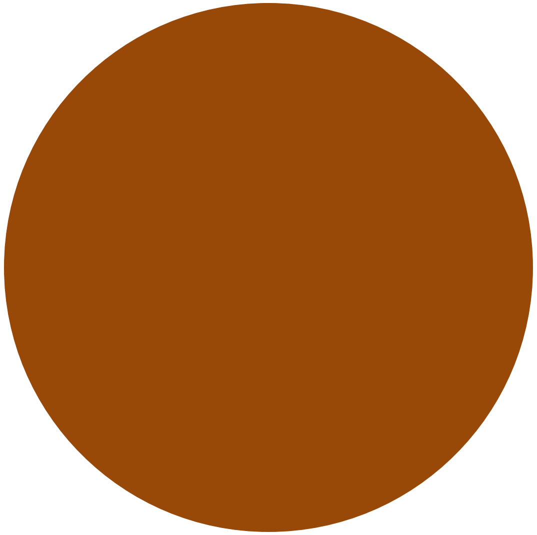
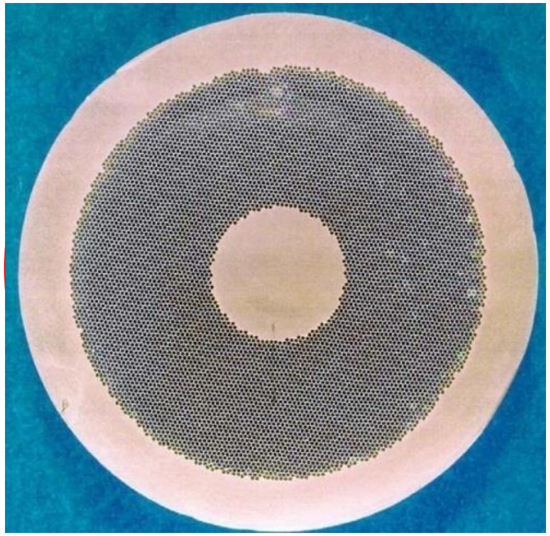
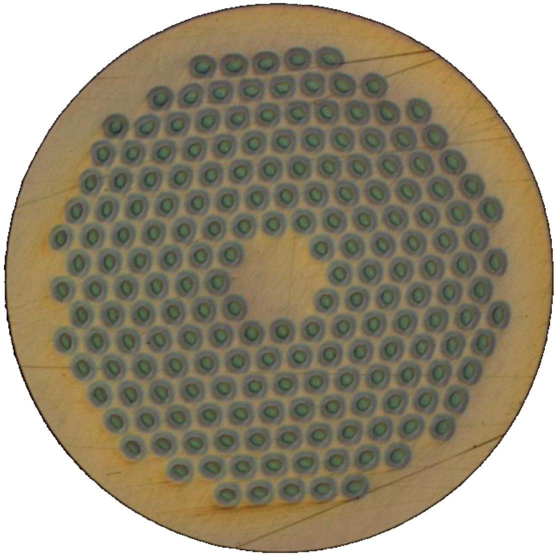
- Typical operational conditions (0.85 mm diameter strand)



Cu	Nb-Ti	Nb_3Sn
J_e ~ 5 A/mm^2	**J_e ~ 600-700 A/mm^2**	**J_e ~ 600-700 A/mm^2**
I ~ 3 A	**I ~ 300-400 A**	**I ~ 300-400 A**
B = 2 T	**B = 8-9 T**	**B = 12-13 T**

Practical superconductors

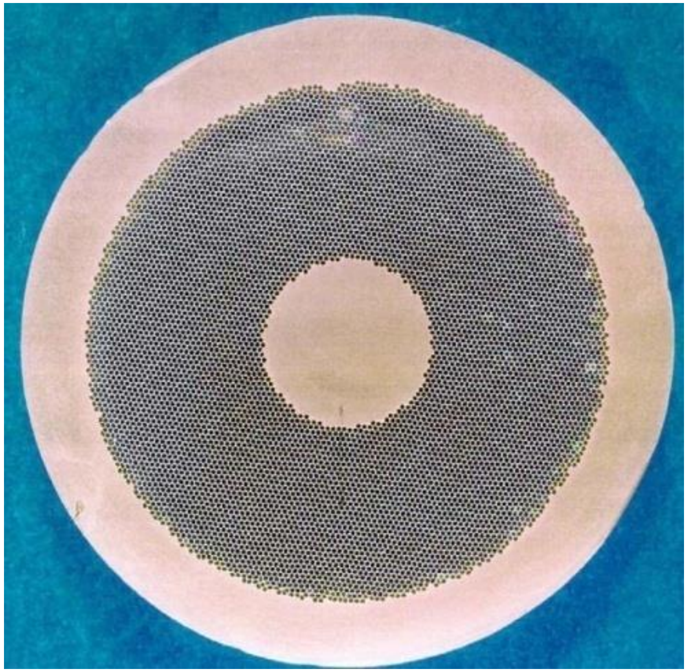
- Typical operational conditions (0.85 mm diameter strand)

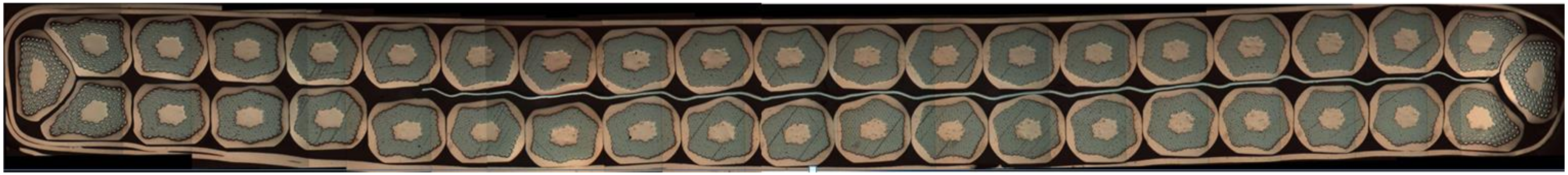
Cu	Nb-Ti	Nb_3Sn
		
$J_e \sim 5$ A/mm^2	$J_e \sim 600$-700 A/mm^2	$J_e \sim 600$-700 A/mm^2
$I \sim 3$ A	$I \sim 300$-400 A	$I \sim 300$-400 A
$B = 2$ T	$B = 8$-9 T	$B = 12$-13 T

Practical superconductors
Introduction

- Superconducting materials are produced in small filaments and surrounded by a stabilizer (typically copper) to form a *multi-filament wire* or *strand*.

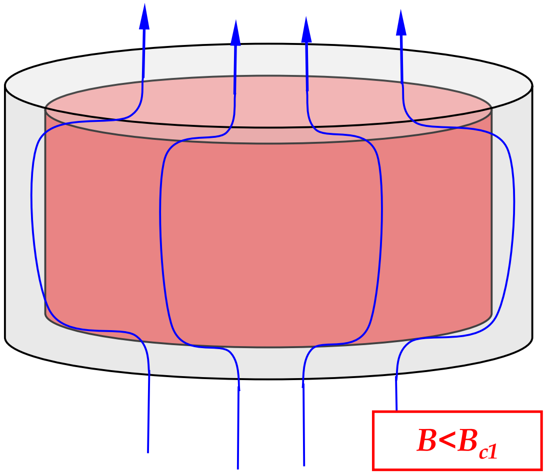
- A superconducting cable is composed by several wires: *multi-strand cable*.





Practical superconductors
Multi-filament wires motivations

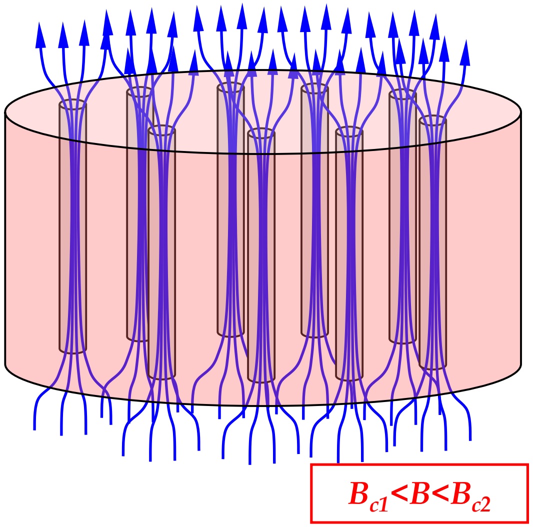
- Fluxoid distribution depends on **B** and J_c
- Thermal disturbance → the local change in J_c → motion or "**flux jump**" → power dissipation



- Stability criteria for a slab (adiabatic condition)

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

  - a is the half-thickness of the slab
  - 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}]
  - θ_c is the critical temperature.



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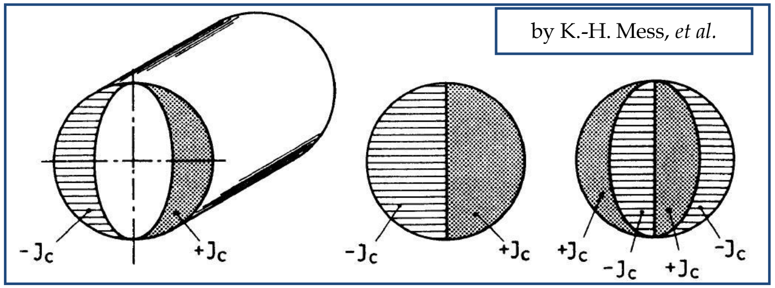
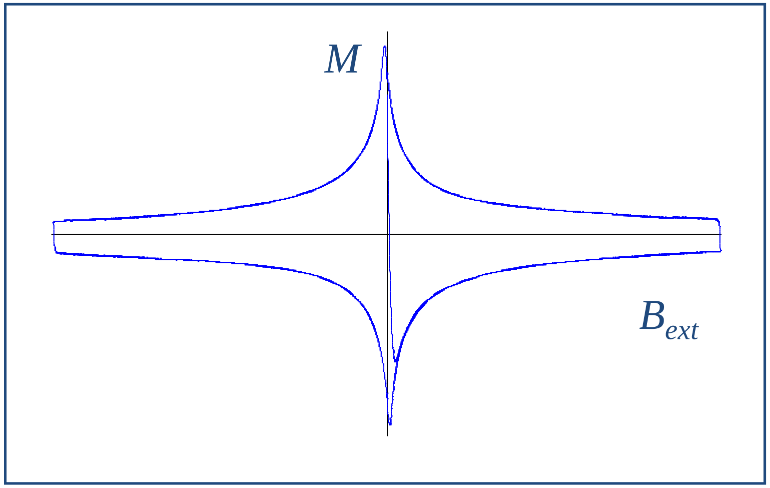
- Filament diameters usually < 50 μm

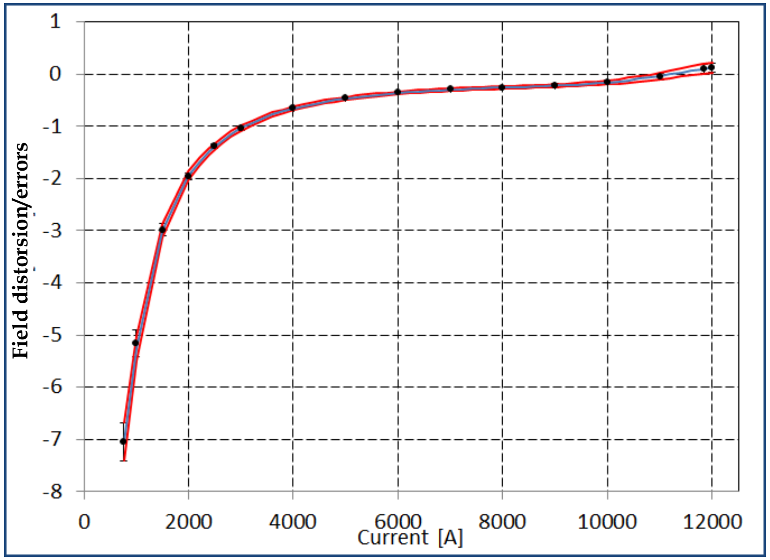
Practical superconductors
Multi-filament wires motivations

- **Superconductor magnetization**
  - When a filament is in a varying B_{ext}, its inner part is shielded by currents distribution in the filament periphery
    - They **do not decay** when B_{ex} is held constant → **persistent currents**



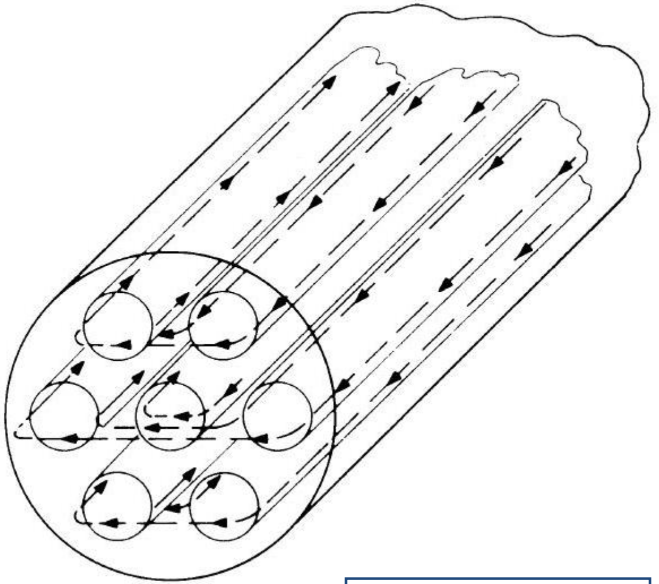


  - These currents produce **field errors** and **ac losses** proportional to $J_c r_f$
    - LHC filament diameter 6-7 μm.
    - HERA filament diameter 14 μm.

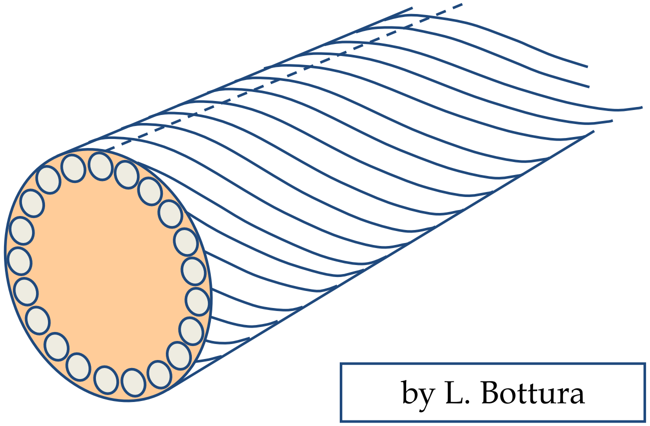


Practical superconductors
Multi-filament wires motivations

- **Inter-filament coupling**
  - When a multi-filamentary wire is subjected to a time varying magnetic field, **current loops** are generated between filaments.
  - 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.



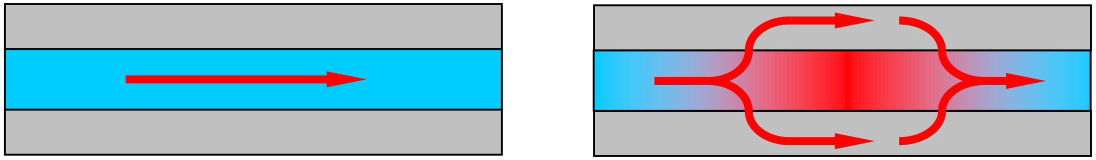
by M. Wilson



by L. Bottura

Practical superconductors
Multi-filament wires motivations

- **Quench protection**
  - Superconductors have a very high normal state resistivity
    - If quenched, could reach very high temperatures in few ms.
  - If embedded in a **copper matrix**, when a quench occurs, current redistributes in the low-resisitivity matrix → **lower peak temperature**

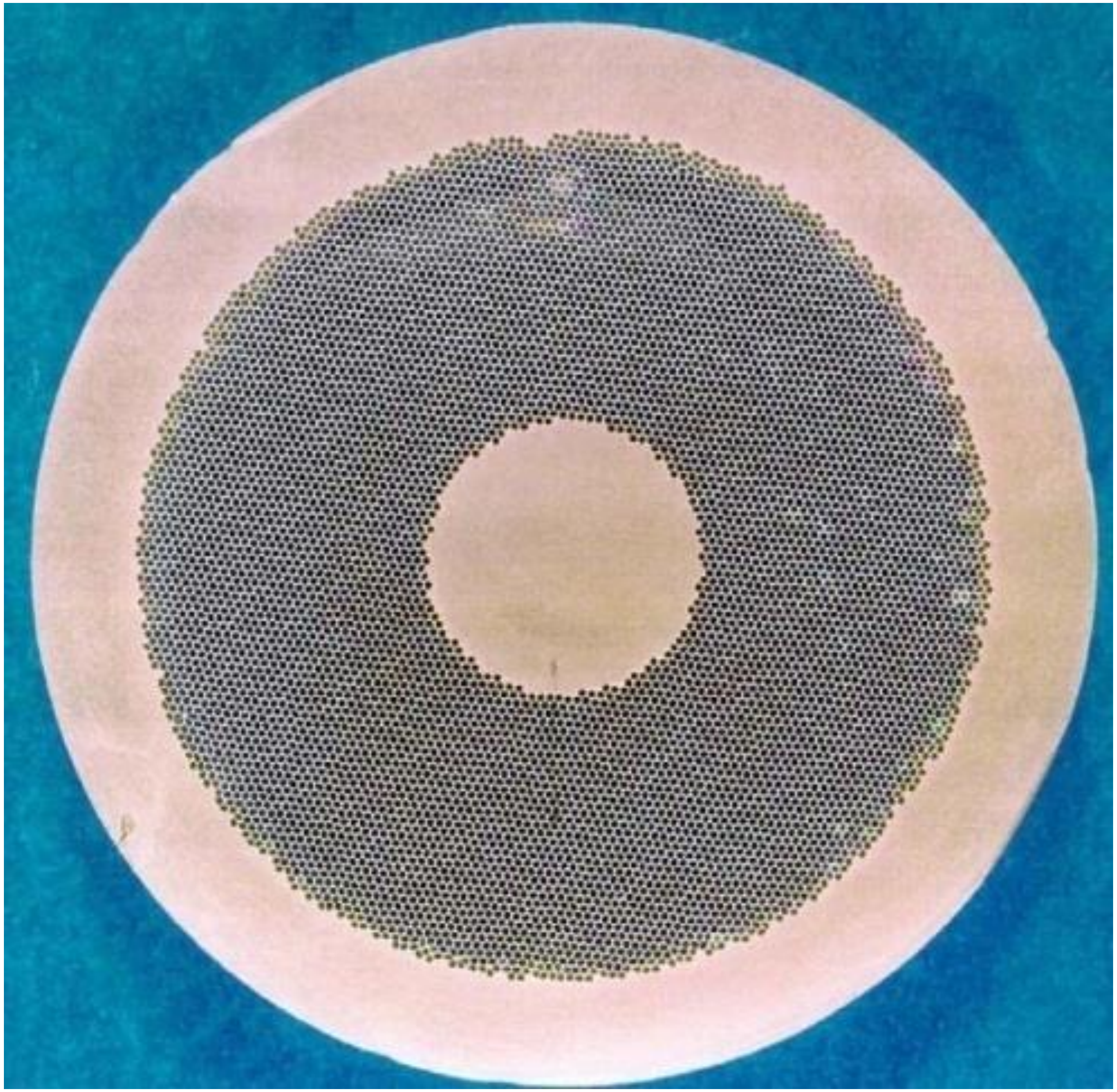


by L. Bottura

  - The copper matrix provides **time to act** on the power circuit
  - In the case of a small volume of superconductor heated beyond the critical temperature the current can flow in the copper for a short moment, allowing the filament to **cool-down and recover** supercond.
  - The matrix also helps stabilizing the conductor against **flux jumps**

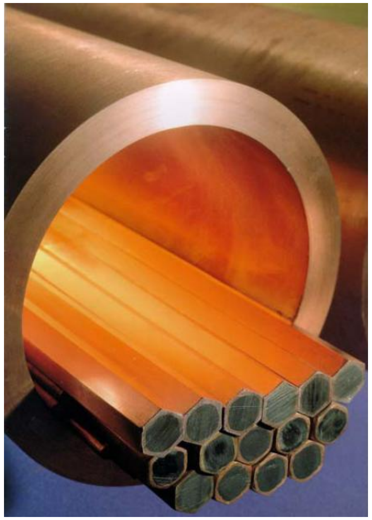
Practical superconductors
Multi-filament wires motivations

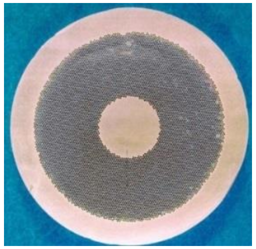
- **Flux jumps**
- **Persistent currents**
- **AC losses**
- **Quench protection**

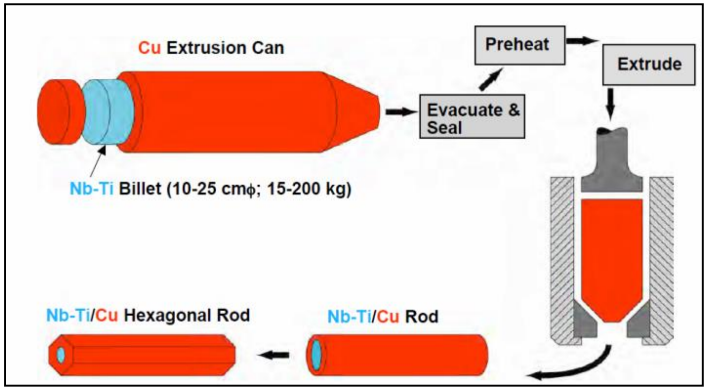


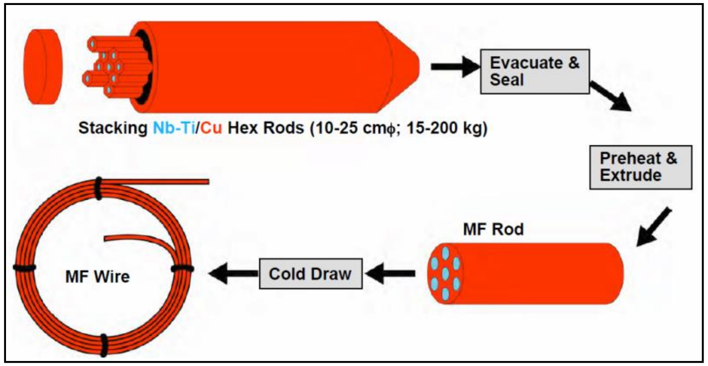
Practical superconductors
Fabrication of Nb-Ti multifilament wires

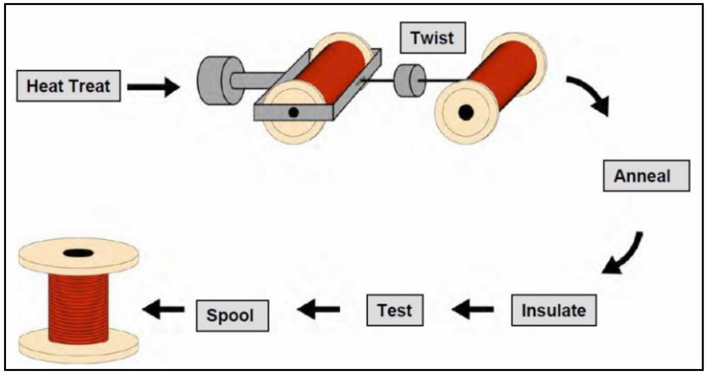
- Nb-Ti **ingots**
  - 200 mm Ø ¬ 750 mm long
- **Monofilament rods** are stacked to form a **multifilament billet**
  - then extruded and drawn down
  - can be re-stacked: double-stacking process





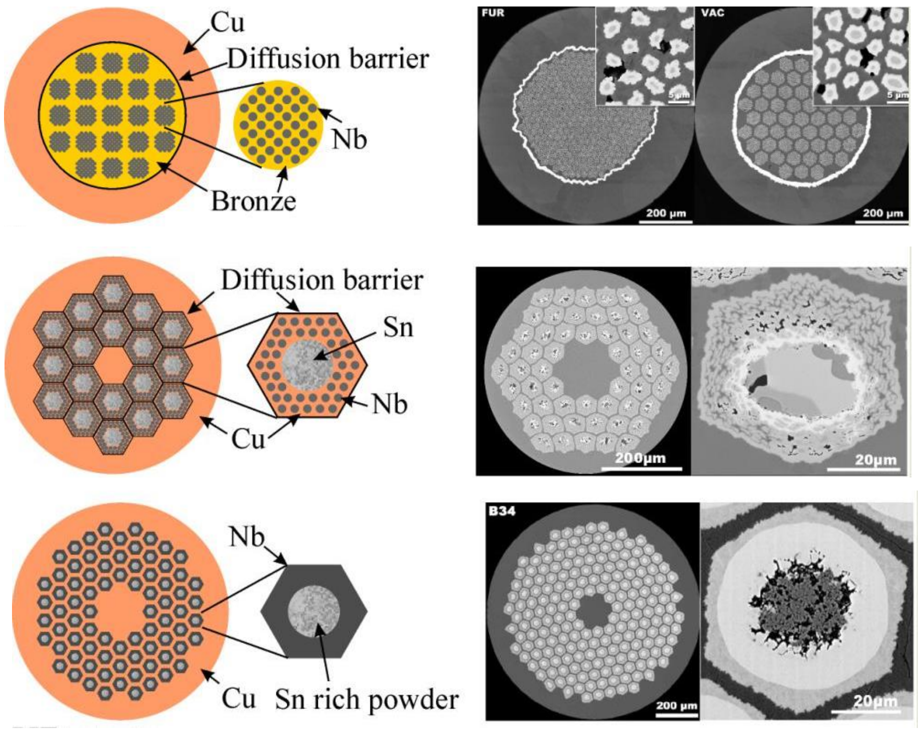






Multifilament wires
Fabrication of Nb_3Sn multifilament wires

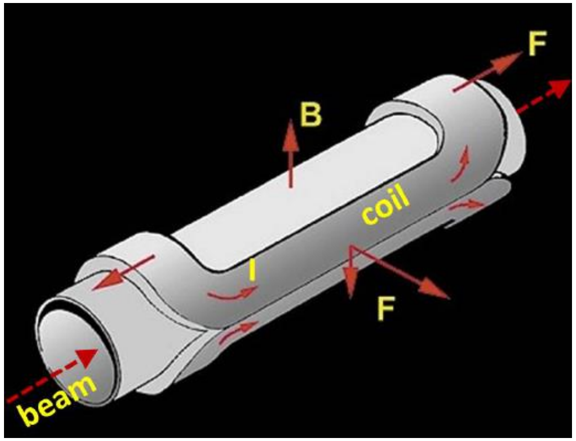
- Since Nb_3Sn is brittle
  - it cannot be extruded and drawn like Nb-Ti.
- Process in several steps
  - Assembly multifilament billets from with **Nb and Sn separated**
  - Fabrication of the wire through extrusion-drawing
    - Fabrication of the cable
    - Fabrication of the coil
  - “**Reaction**”
    - Sn and Nb are heated to 600-700 C
    - Sn diffuses in Nb and reacts to form Nb_3Sn

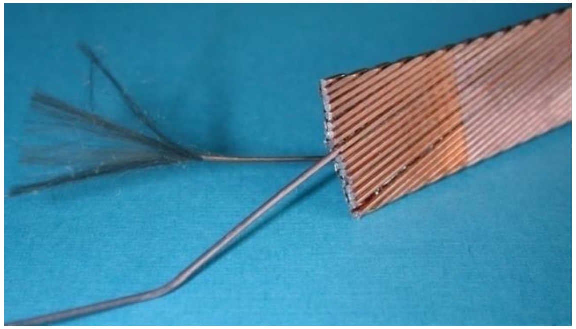


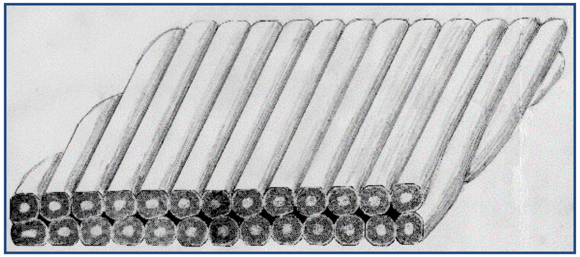
by A. Godeke

Practical superconductors
Multi-strand cables motivations

- Most of the superconducting coils for particle accelerators wound from a multi-strand cable (**Rutherford cable**)
  - Reduction of strand **piece length**
  - reduction of **number of turns**
    - easy winding
    - smaller coil inductance
      - less V for power supply during ramp-up;
      - after a quench, faster discharge and V
  - **current redistribution** in case of a defect or a quench in one strand
- The strands are **twisted** to
  - Reduce **inter-strand coupling currents**
    - Losses and field distortions
  - Provide more **mechanical stability**

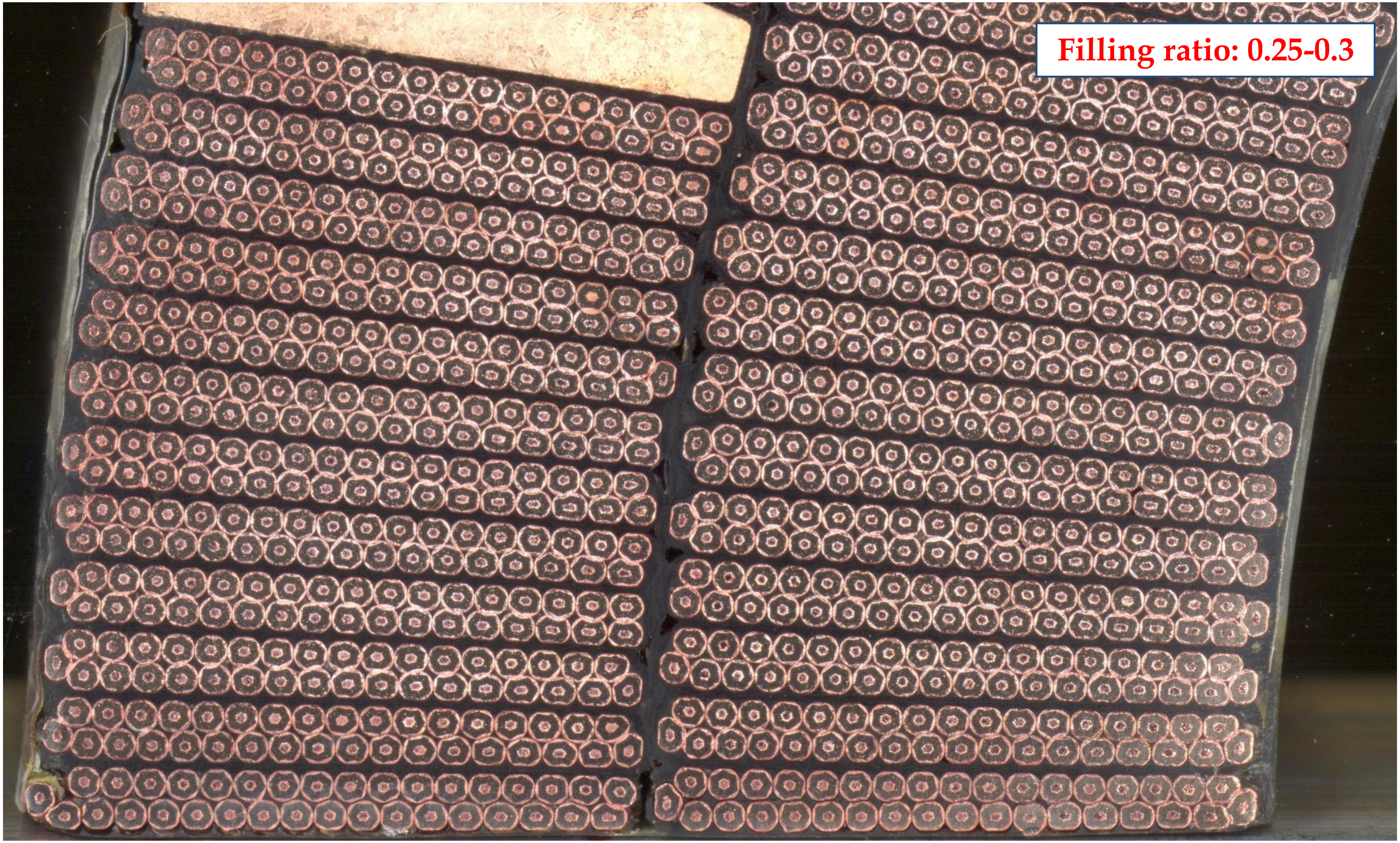






by M. Wilson

Practical superconductors
Superconducting cables



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Outline

- Particle accelerators and superconductors
- Magnetic design and coils
- Mechanics of superconducting magnets
- Quench and protection
- HiLumi LHC and FCC

References

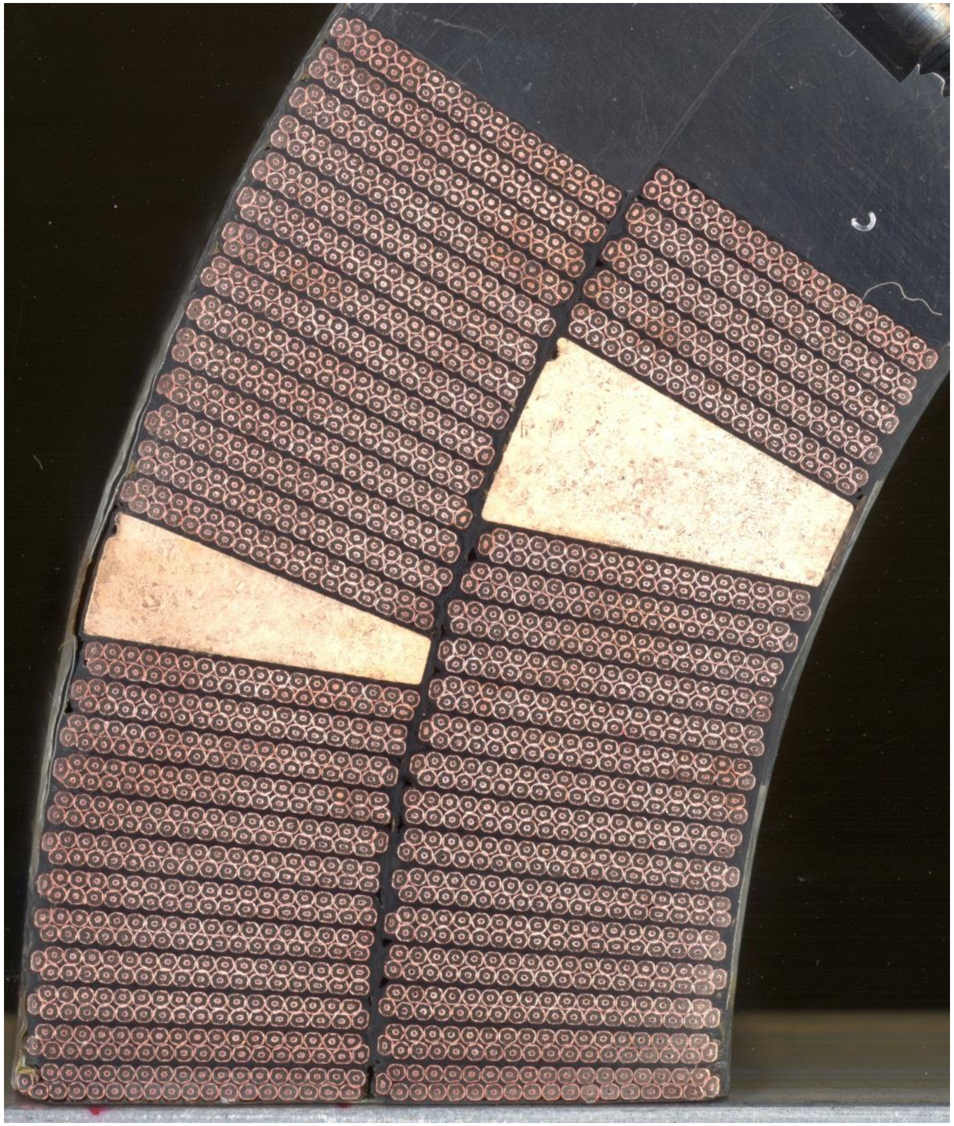
- **Magnetic design and coils**
  - K.-H. Mess, P. Schmuser, S. Wolff, “*Superconducting accelerator magnets*”, Singapore: World Scientific, 1996.
  - Martin N. Wilson, "*Superconducting Magnets*", 1983.
  - Fred M. Asner, "*High Field Superconducting Magnets*", 1999.
  - S. Russenschuck, “*Field computation for accelerator magnets*”, J. Wiley & Sons (2010).

  - P. Ferracin, E. Todesco, S. Prestemon, “*Superconducting accelerator magnets*”, US Particle Accelerator School, www.uspas.fnal.gov.
    - **Units 5, 8, 9 by E. Todesco**
  - A. Jain, “*Basic theory of magnets*”, CERN 98-05 (1998) 1-26

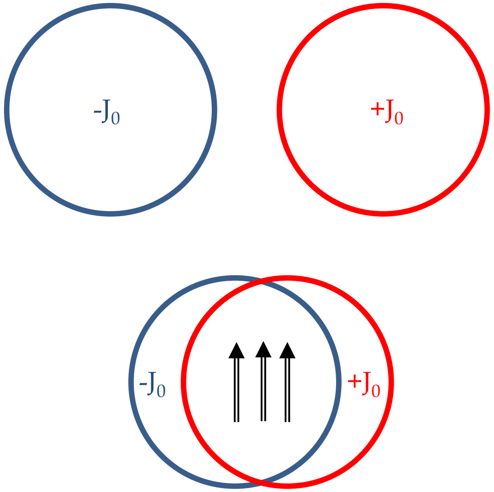
  - L. Rossi, E. Todesco, “*Electromagnetic design of superconducting quadrupoles*”, Phys. Rev. ST Accel. Beams 10 (2007) 112401.
  - L. Rossi and Ezio Todesco, “*Electromagnetic design of superconducting dipoles based on sector coils*”, Phys. Rev. ST Accel. Beams 9 (2006) 102401.

Magnetic design and coils

- How do we create a **perfect field**?
- How do we **express** field and its "**imperfections**"?
- How do we design a coil to **minimize field errors**?
- How do we **fabricate** a coil?



Perfect dipole field
Intercepting circles (or ellipses)



- Within a cylinder carrying j_0, the field is perpendicular to the radial direction and proportional to the distance to the centre r:

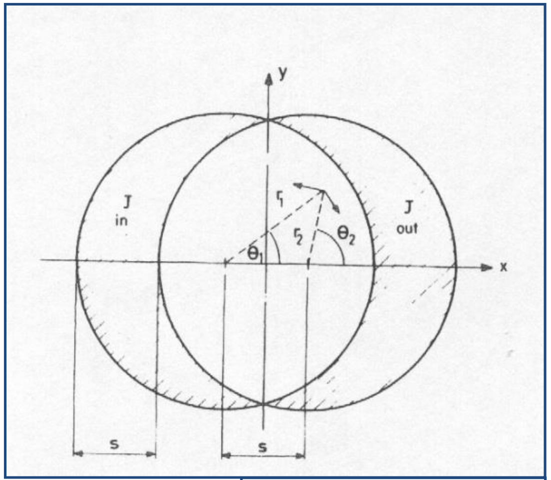
$$B = -\frac{\mu_0 j_0 r}{2}$$

  - Combining the effect of two intersecting cylinders

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

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

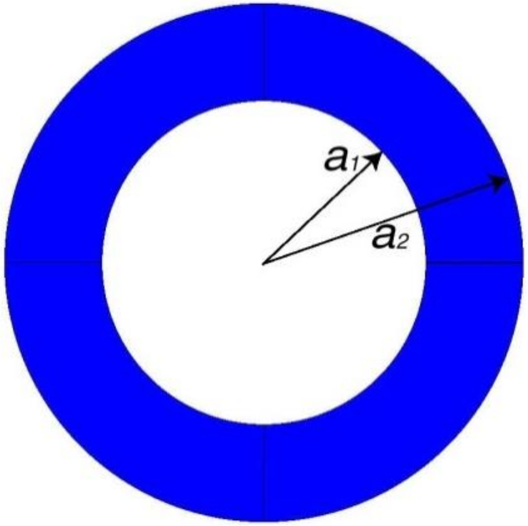
- A uniform current density in the area of two **intersecting circles** produces a pure dipole
  - The aperture is not circular
  - Not easy to simulate with a flat cable
- Similar proof for **intersecting ellipses**



by M. Wilson

Perfect dipole field
Thick shell with $cos\theta$ current distribution

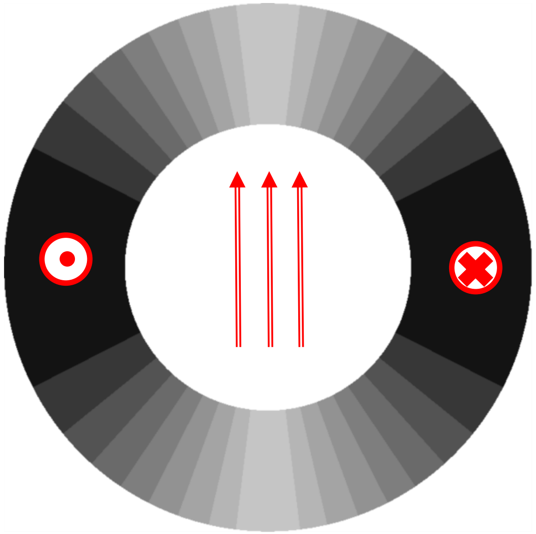
- If we assume
  - $J = J_0 \cos\theta$ where J_0 [A/m^2] is ⊥ to the cross-section plane
  - Inner (outer) radius of the coils = *a1 (a2)*



- The generated field is a **pure dipole**

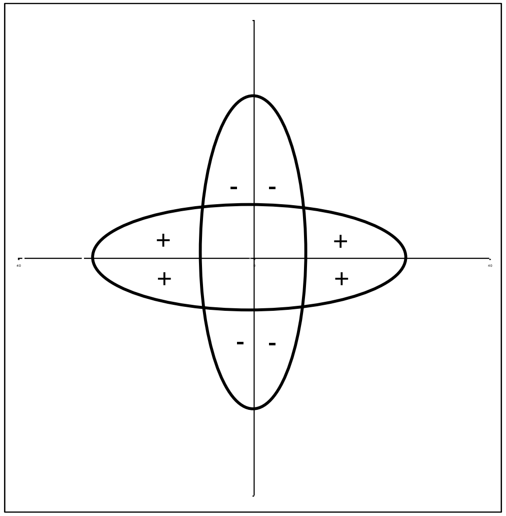
$$B_y = -\frac{\mu_0 J_0}{2}(a_2 - a_1)$$

- Linear dependence on **coil width**



- **Easier** to achieve with a Rutherford cable

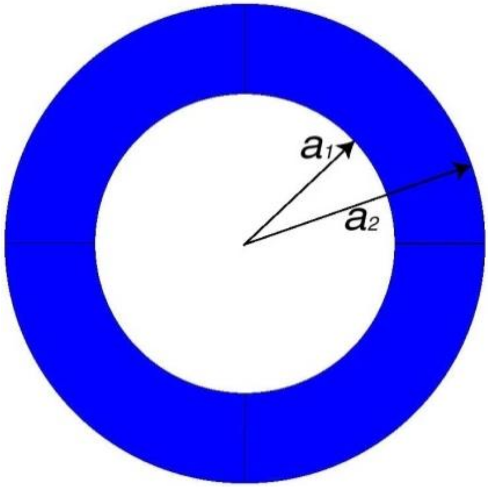
Perfect quadrupole field



- **Intercepting ellipses** or **circles**

- Thick shell with ***cos2θ* current distribution**
- If we assume
  - $J = J_0 \cos 2\theta$ where J_0 [A/m^2] is ⊥ to the cross-section plane
  - Inner (outer) radius of the coils = *a1 (a2)*

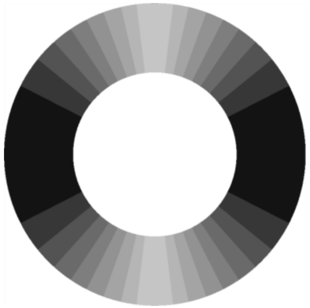
$$G = \frac{B_y}{r} = -\frac{\mu_0 J_0}{2} \ln \frac{a_2}{a_1}$$



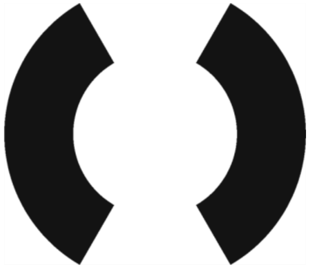
- And so on…
  - Perfect sextupoles: **cos3*θ*** or **3** intersect. ellipses
  - Perfect 2*n*-poles: **cos*nθ*** or ***n*** intersecting ellipses

From ideal to practical configuration

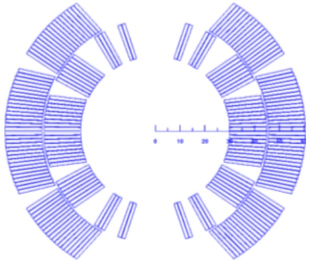
- How can I reproduce **thick shell with a** ***cosθ*** distribution with a cable?
  - Rectangular cross-section and constant *J*



- First “rough” approximation
  - **Sector dipole**



- Better ones
  - More **layers** and **wedges** to reduce *J* towards 90°



- As a result, the field is **not perfect** anymore
  - How can I express in improve the “imperfect” field inside the aperture?

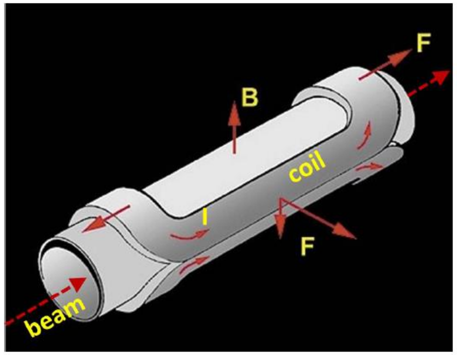
Field representation
Maxwell equations

- **Maxwell equations** for magnetic field

$$\nabla \cdot B = \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0 \qquad \nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$$

- In absence of charge and magnetized material

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



- If $\frac{\partial B_z}{\partial z} = 0$ (constant longitudinal field), then

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

Field representation
Analytic functions

- If $\dfrac{\partial B_z}{\partial z} = 0$

  Maxwell gives

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

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

Cauchy-Riemann conditions

and therefore the function $\boldsymbol{B_y + iB_x}$ is analytic

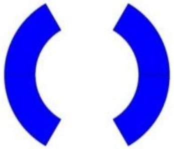
$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty} C_n (x+iy)^{n-1}$$

where C_n are **complex coefficients**

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

- Advantage: we reduce the description of the field to a (simple) series of complex coefficients

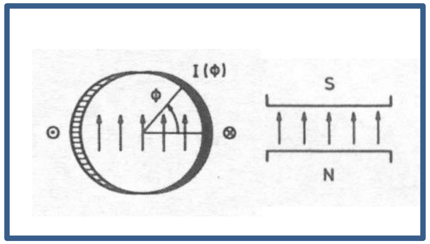
Magnetic design
Harmonics



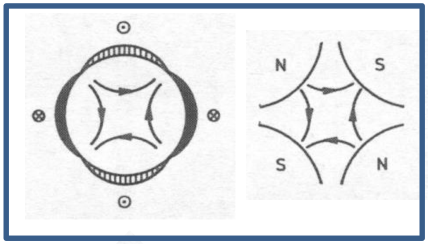
- The field can be expressed as (simple) series of coefficients
- So, each coefficient corresponds to a "pure" multipolar field

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

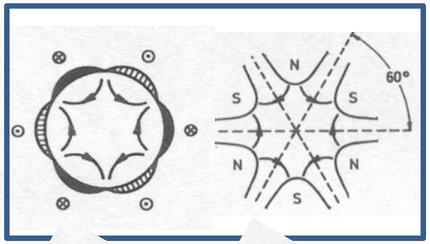
B_1



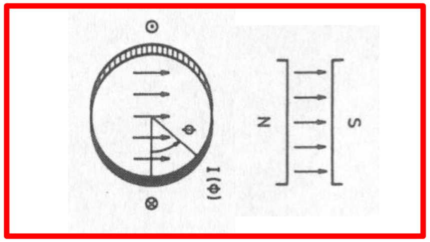
B_2



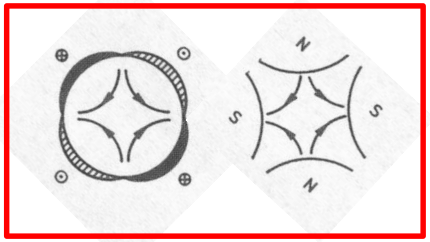
B_3



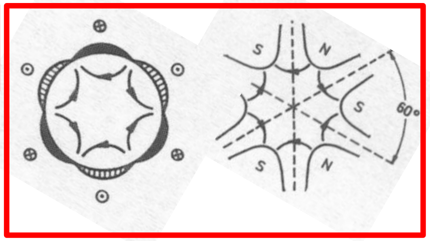
A_1



A_2



A_3



by K.-H. Mess, *et al.*

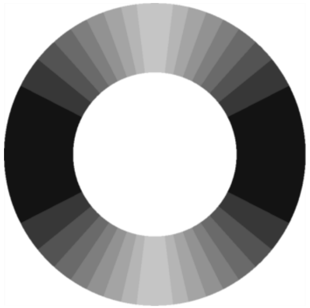
- The field harmonics are rewritten as

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

- The coefficients b_n, a_n are called normalized multipoles
  - b_n are the normal, a_n are the skew (adimensional)

Back to the original issue:
From ideal to practical configuration

- How can I reproduce **thick shell with a** $\cos\theta$ distribution with a cable?
  - Rectangular cross-section and constant *J*



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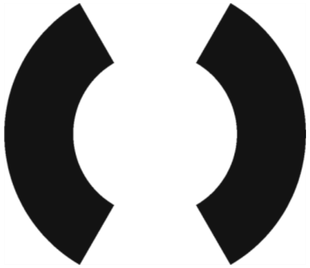
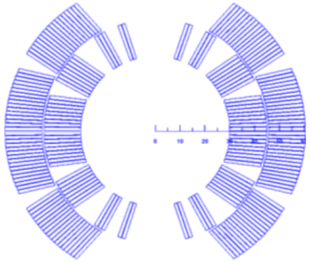
  - **Sector dipole**



- Better ones
  - More **layers** and **wedges** to reduce *J* towards 90°



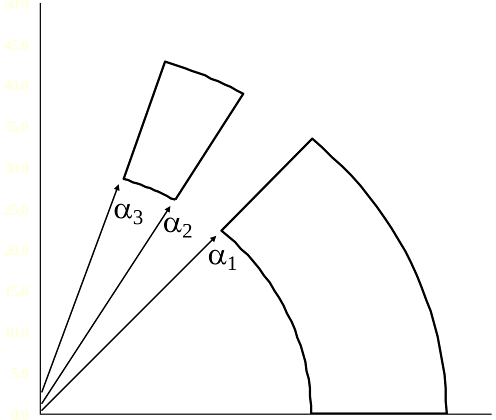
- Now, I can use the multipolar expansion to **optimize** my “practical” **cross-section**

A “good” field quality dipole
Sector dipole

by E. Todesco

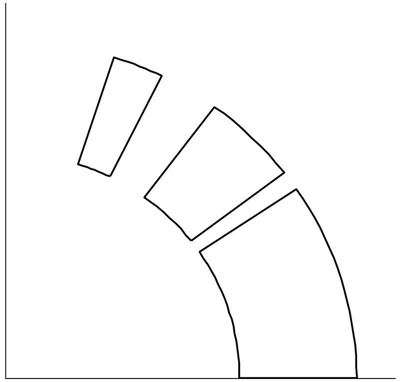
- We compute the central field given by a **sector dipole with 2 blocks**
  - Equations to set to zero ***B_3, B_5 and B_7***

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



- And the one given by a **3 blocks**
  - Equations to set to zero ***B_3, B_5, B_7, B_9 and B_{11}***

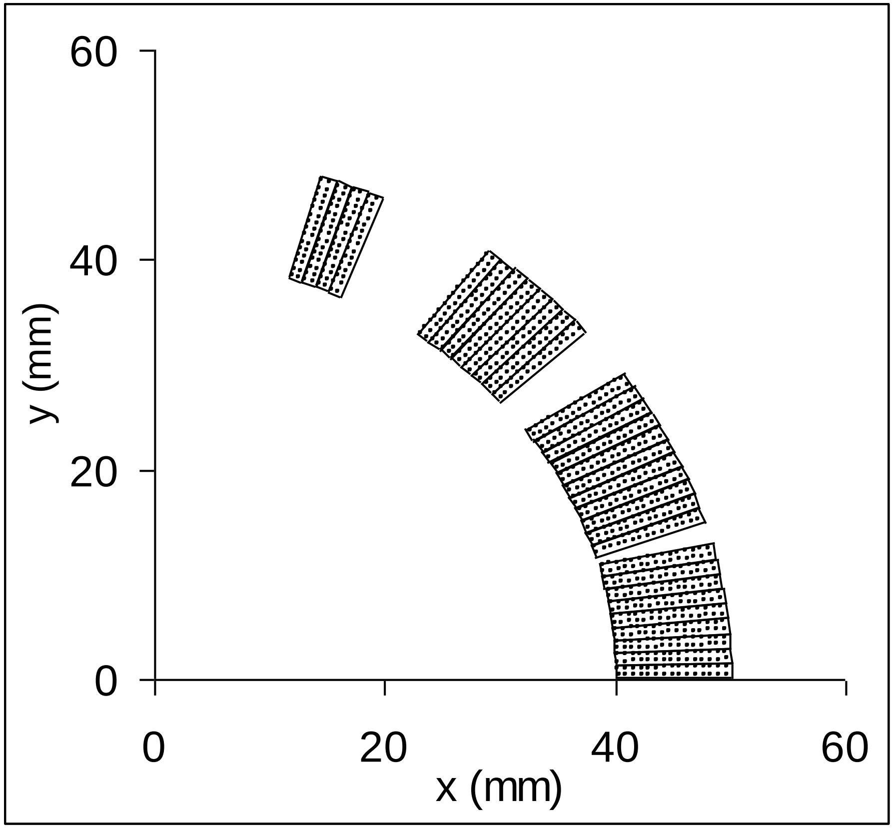
$$\begin{aligned}\sin(3\alpha_5)-\sin(3\alpha_4)+\sin(3\alpha_3)-\sin(3\alpha_2)+\sin(3\alpha_1)=0\\ \sin(5\alpha_5)-\sin(5\alpha_4)+\sin(5\alpha_3)-\sin(5\alpha_2)+\sin(5\alpha_1)=0\\ \sin(7\alpha_5)-\sin(7\alpha_4)+\sin(7\alpha_3)-\sin(7\alpha_2)+\sin(7\alpha_1)=0\\ \sin(9\alpha_5)-\sin(9\alpha_4)+\sin(9\alpha_3)-\sin(9\alpha_2)+\sin(9\alpha_1)=0\\ \sin(11\alpha_5)-\sin(11\alpha_4)+\sin(11\alpha_3)-\sin(11\alpha_2)+\sin(11\alpha_1)=0\end{aligned}$$

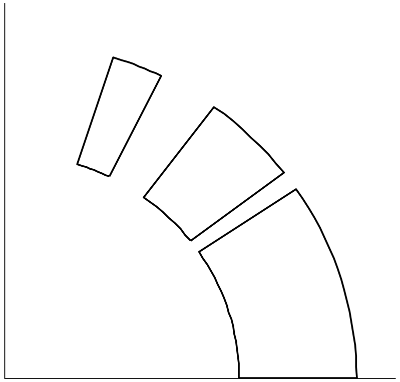


Two wedges, $b_3=b_5=b_7=b_9=b_{11}=0$
[0°-33.3°,37.1°-53.1°,63.4°- 71.8°]

A "good" field quality dipole
Sector dipole

- Let us see two coil lay-outs of real magnets
  - The **RHIC dipole** has **four blocks**

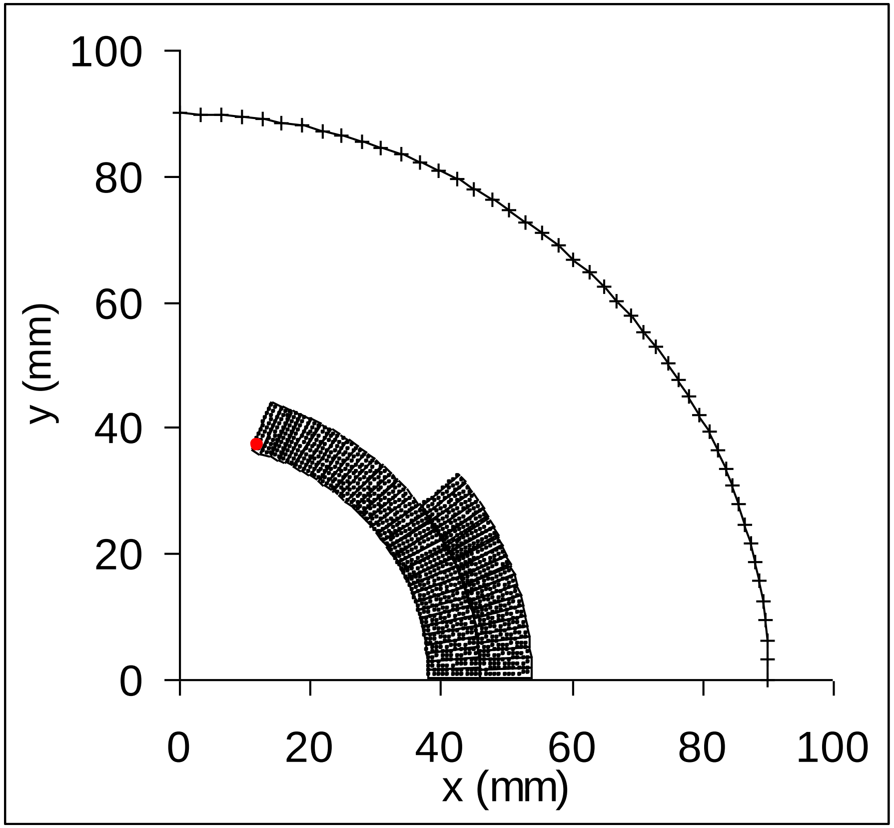




Two wedges, $b_3=b_5=b_7=b_9=b_{11}=0$
[0°-33.3°,37.1°-53.1°,63.4°- 71.8°]

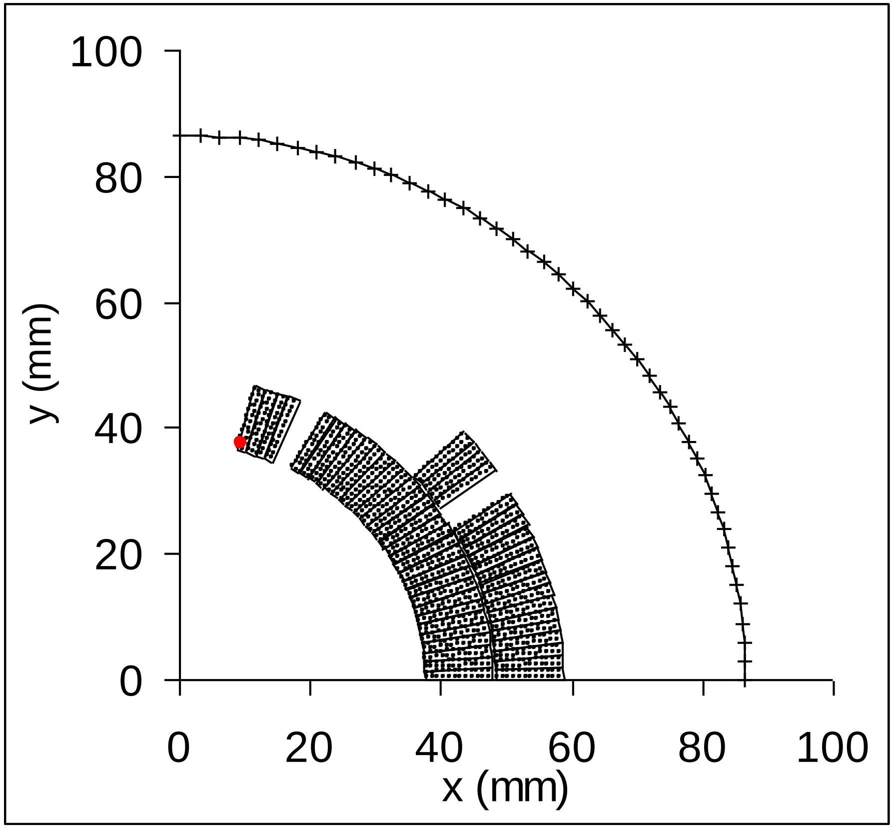
A review of dipole lay-outs

- Tevatron MB



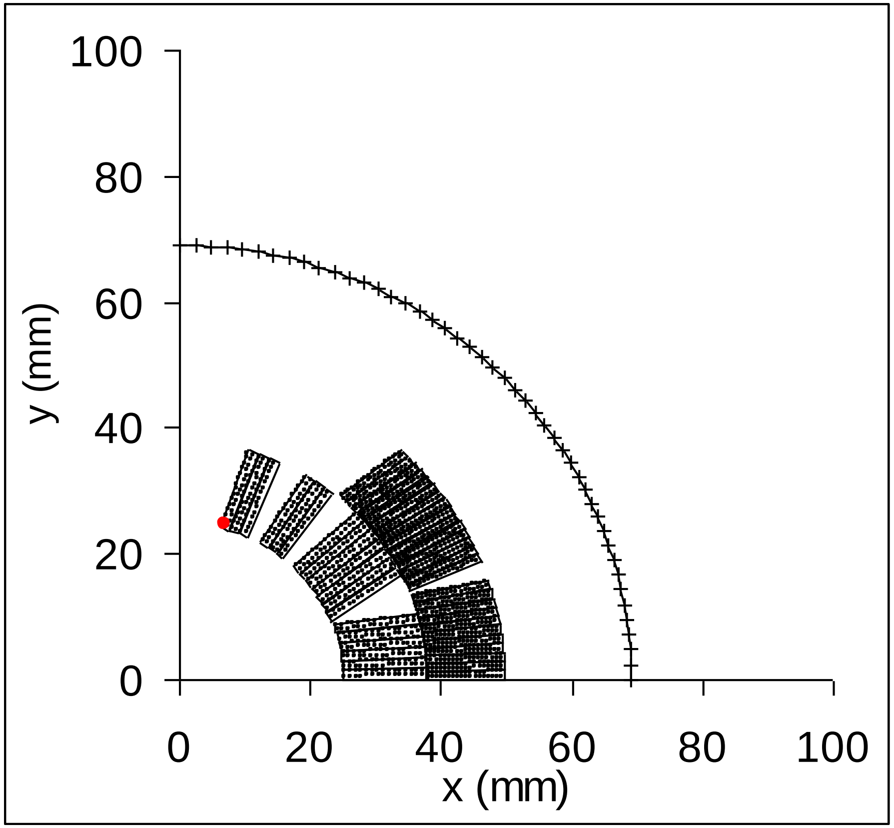
A review of dipole lay-outs

- HERA MB



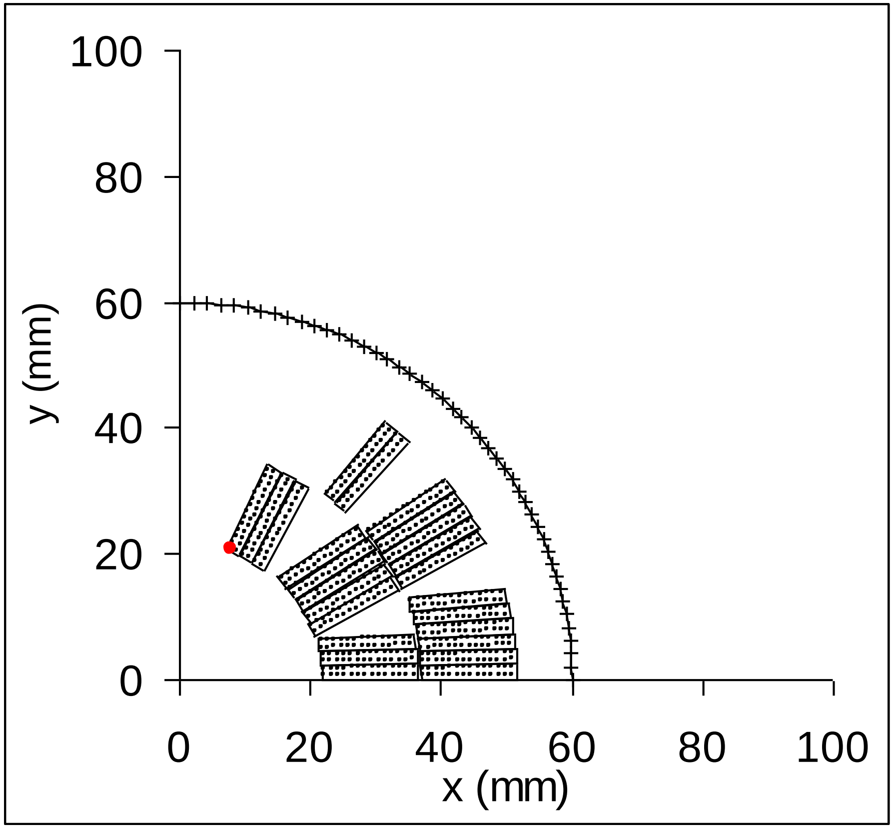
A review of dipole lay-outs

- SSC MB



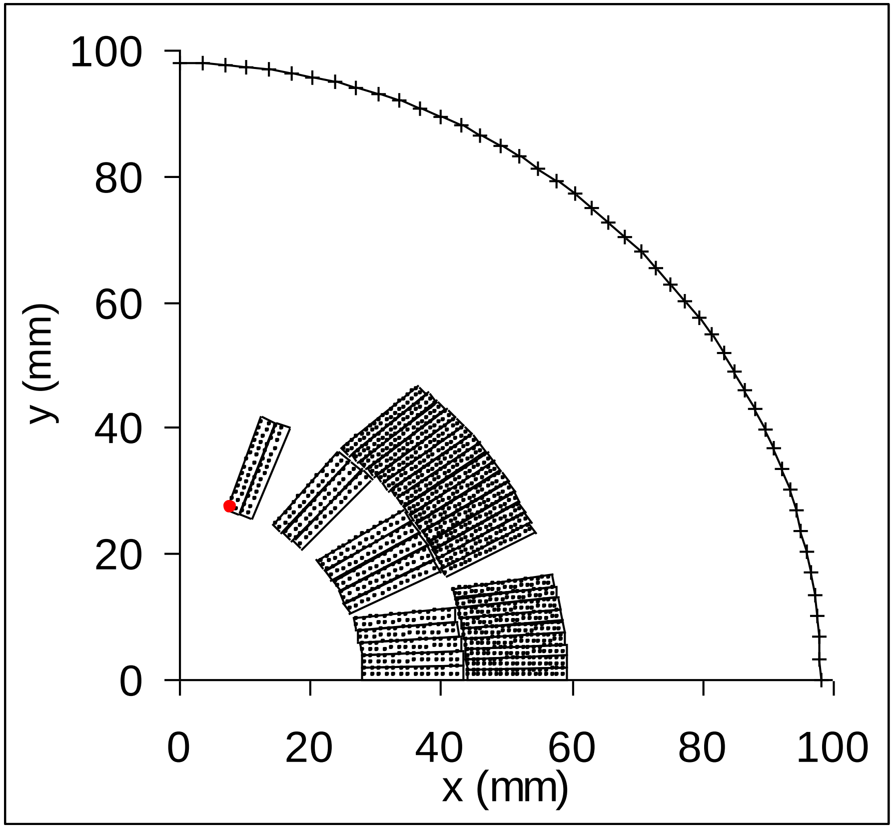
A review of dipole lay-outs

- HFDA dipole



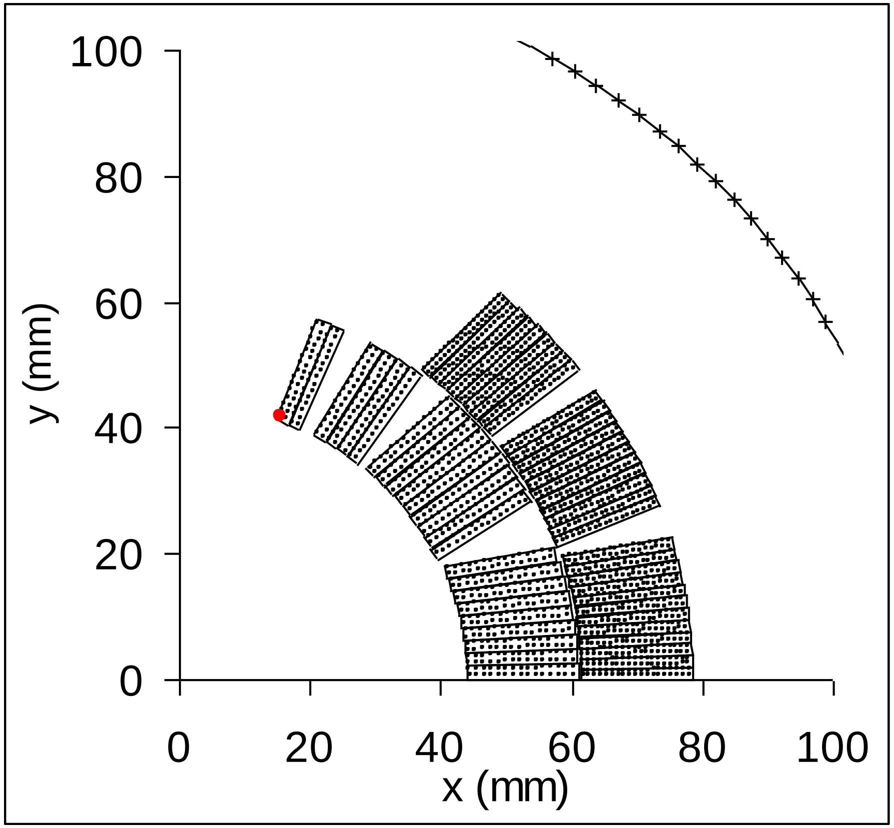
A review of dipole lay-outs

- LHC MB



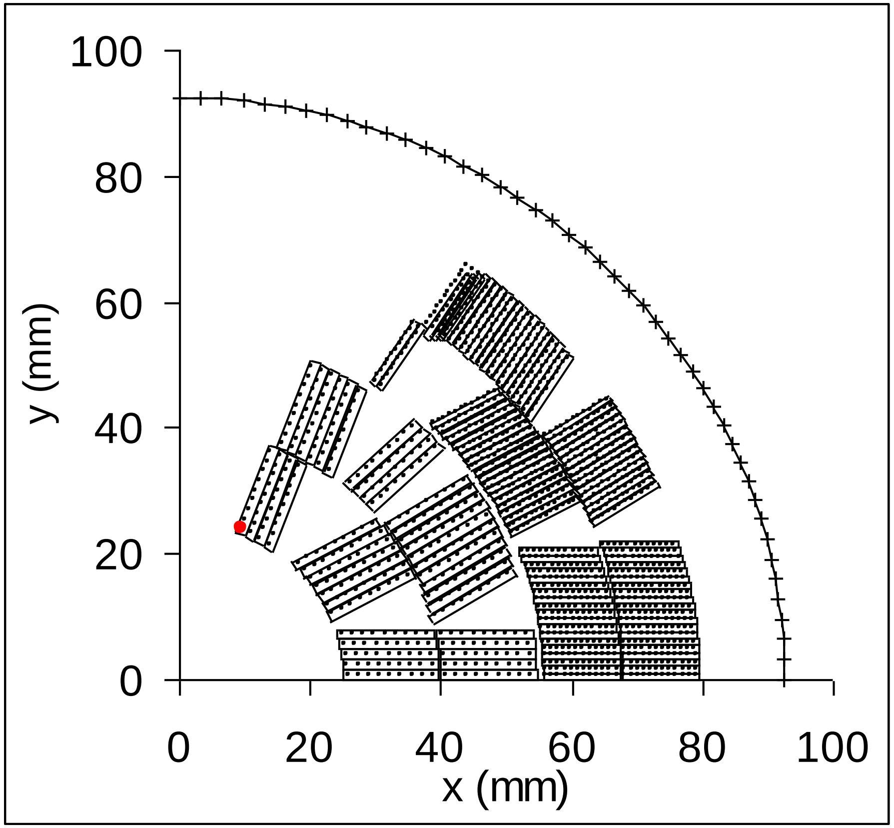
A review of dipole lay-outs

- FRESCA



A review of dipole lay-outs

- D20



Magnetic design and coils

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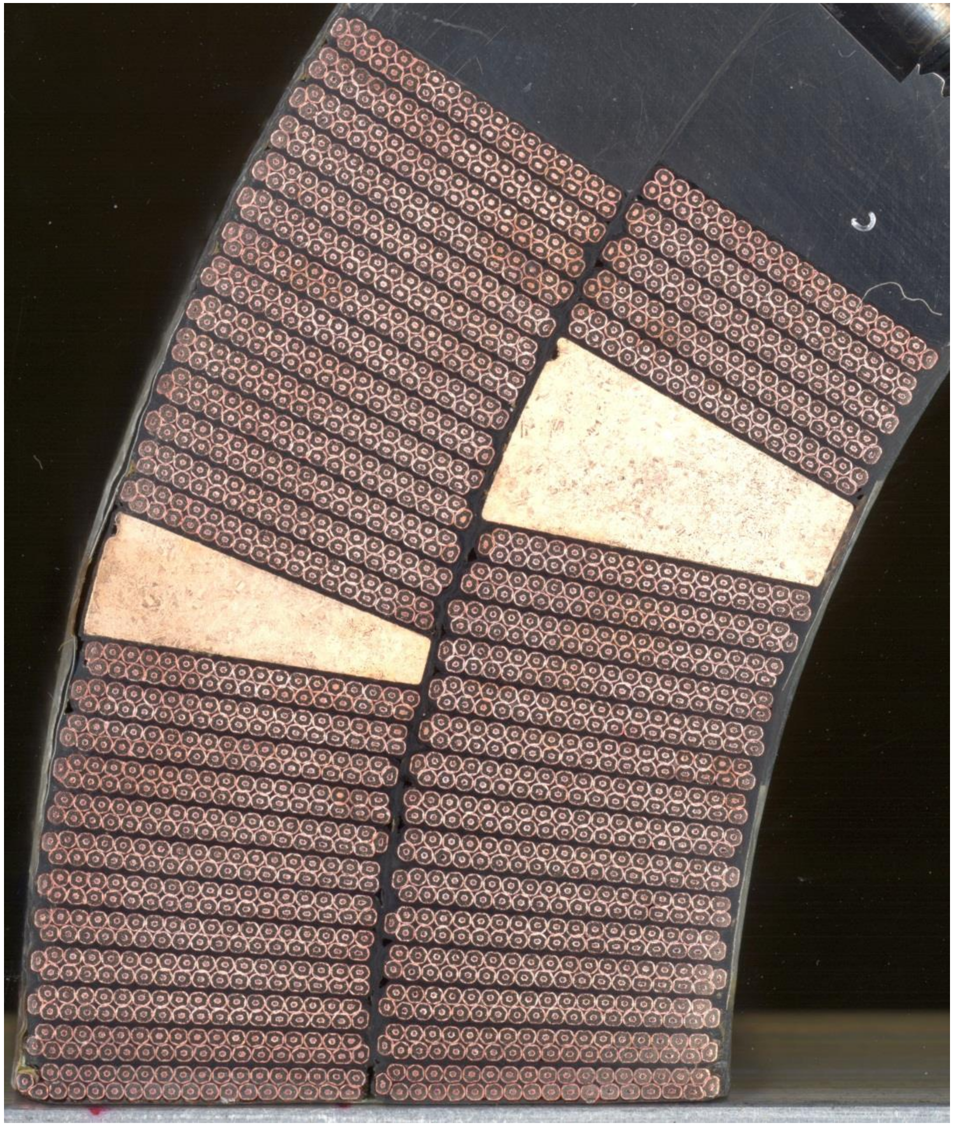
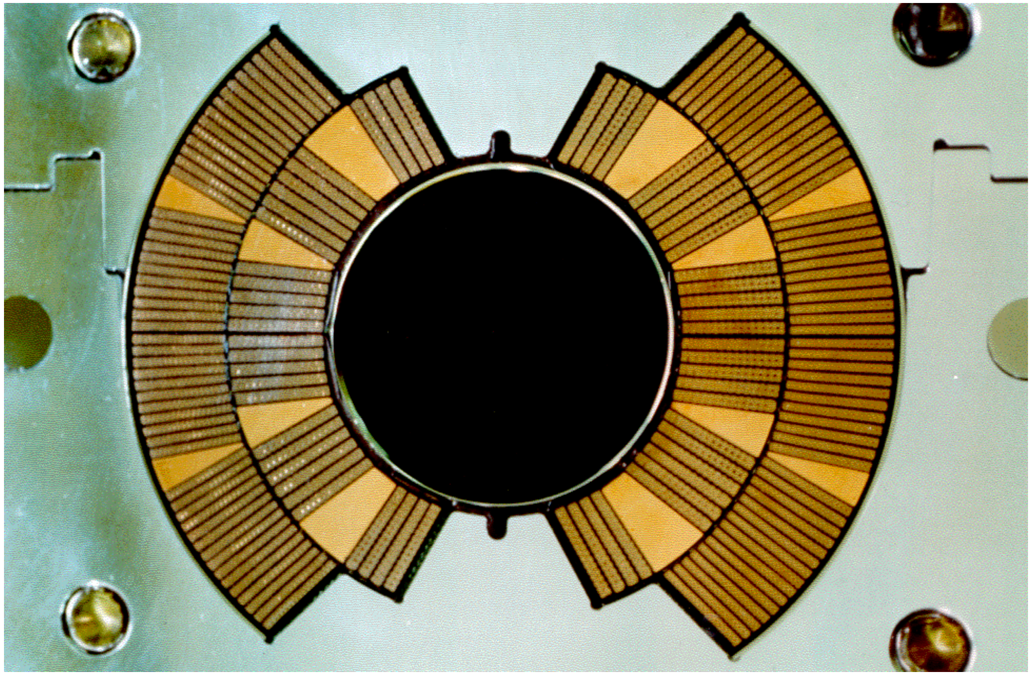
- How do we **express** field and its “**imperfections**”?
- How do we design a coil to **minimize field errors**?
- How do we **fabricate** a coil?



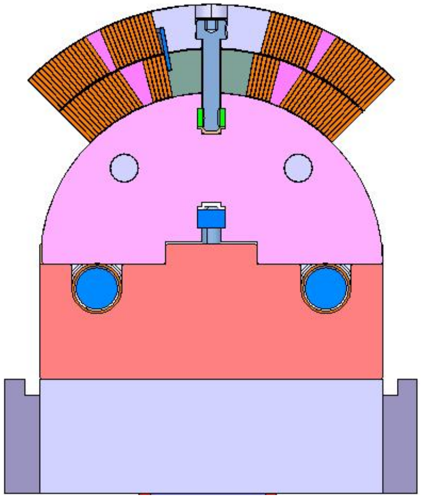
Coil fabrication
Winding

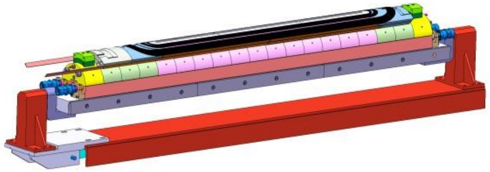
- The coil: most **critical component** of a superconducting magnet
- **Cross-sectional accuracy** of few hundredths of millimeters over ~15 m
- **Laminated tooling**

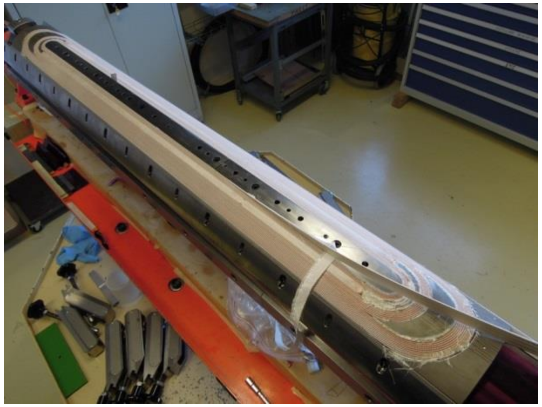


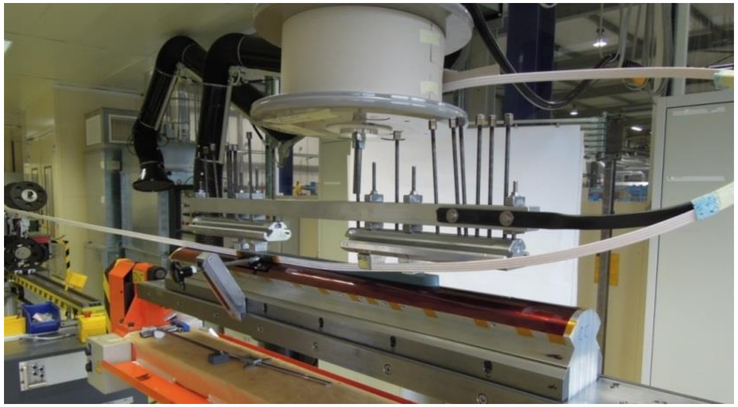
Coil fabrication
Winding

- The cable is wound around a **pole** on a mandrel.
    - The mandrel is made of laminations
- Winding starts from **pole turn** of the inner layer
- Cable maintained in **tension** (200 N)
- For large production→ **automated winding machines**

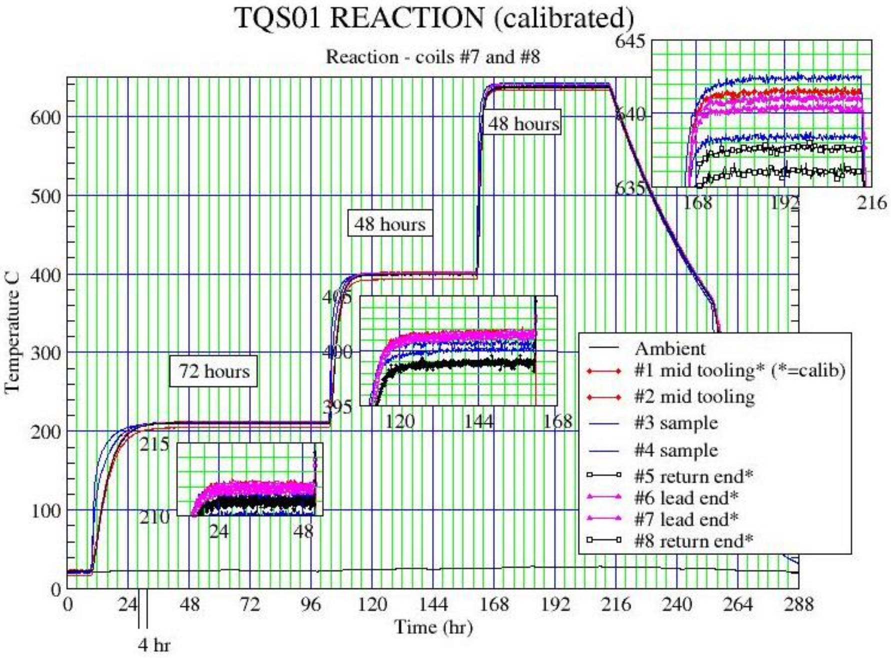








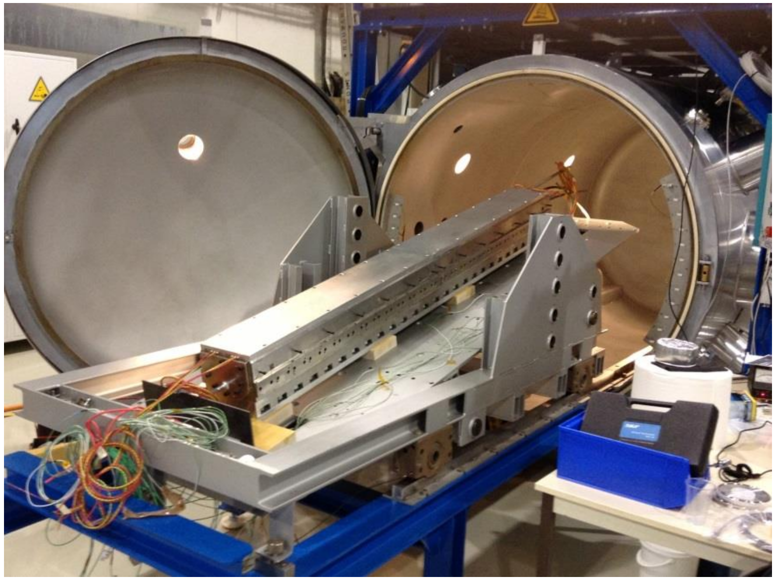
Coil fabrication
Reaction of Nb_3Sn coils



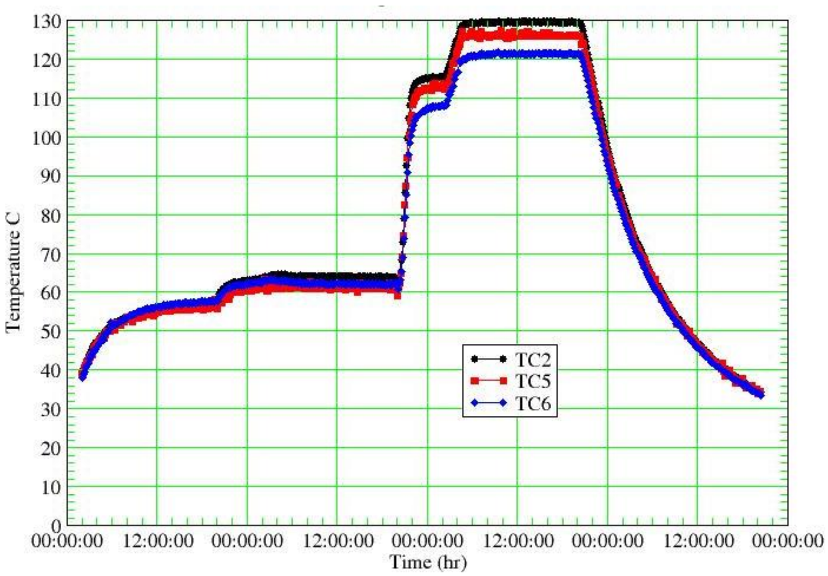
- **Heat treatment**
  - Sn and Nb are heated to 650-700 C in vacuum or inert gas (argon)
    - They reacts to form Nb_3Sn
- The cable becomes **brittle**
- The reaction is characterized by **three temperature steps**
  - Homogeneity is of about ± 3 °C

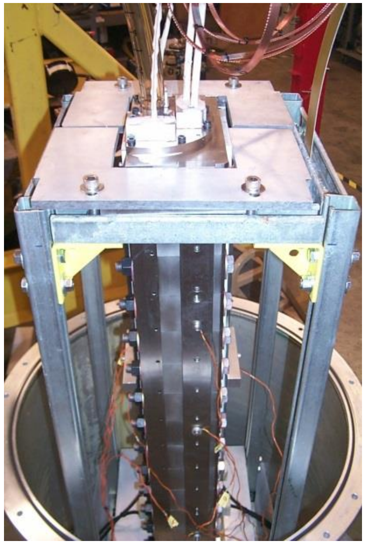
- Reaction oven with argon gas flow
  - **Minimize O_2 content** and Cu oxydation

Coil fabrication
Vacuum impregnation of Nb_3Sn coils

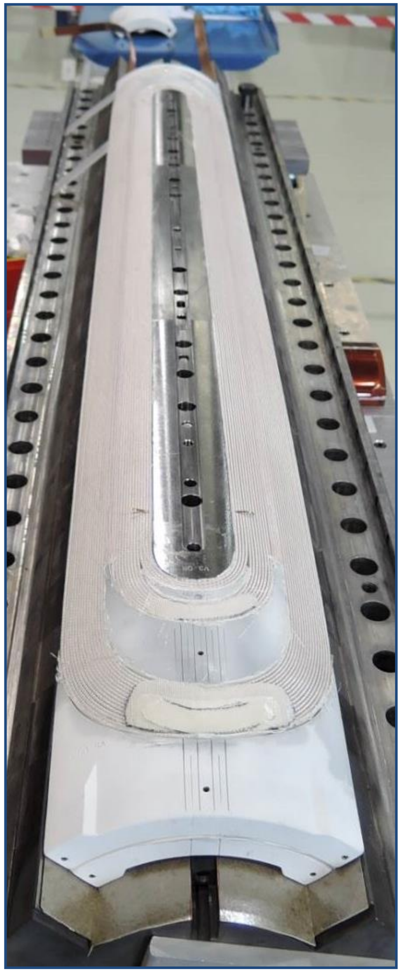


- After reaction, coil placed in a **impregnation fixture**
    - The fixture is inserted in a vacuum tank, evacuated → **epoxy injected**
    - high viscosity at room temperature,
    - low viscosity at ~60 °C
    - Then, **curing** at ~150 °C → solid block





Overview of coil fabrication stages



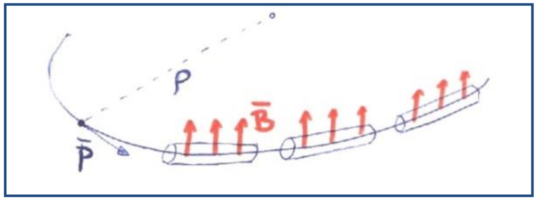
After winding/curing

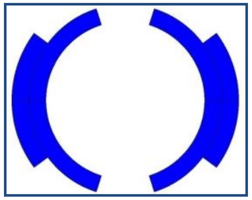
After reaction

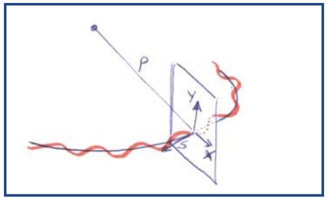
After impregnation

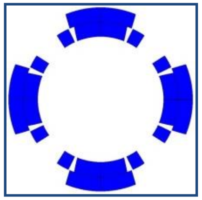
Summary

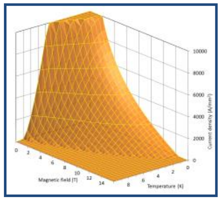
- **Particle accelerators and superconductors**

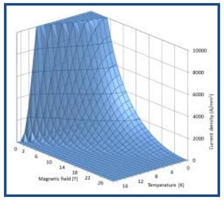


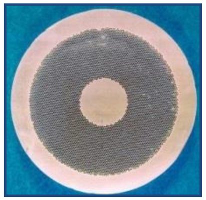


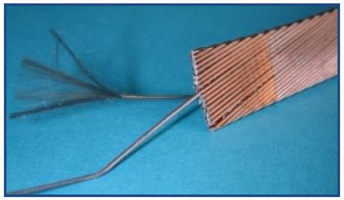




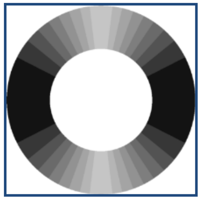


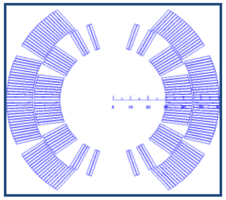


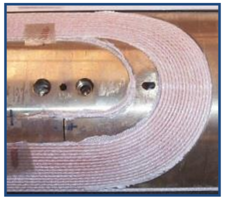


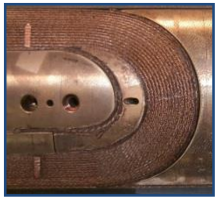


- **Magnetic design and coils**









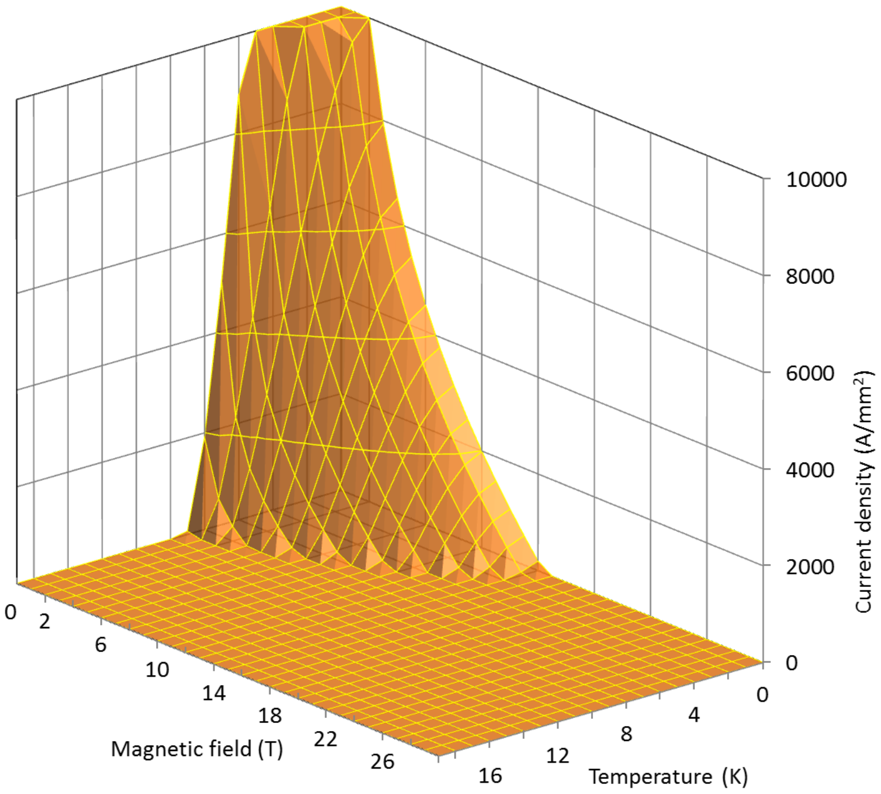
Next lecture

- **Mechanics of superconducting magnets**
- **Quench and protection**
- **HiLumi LHC and FCC**

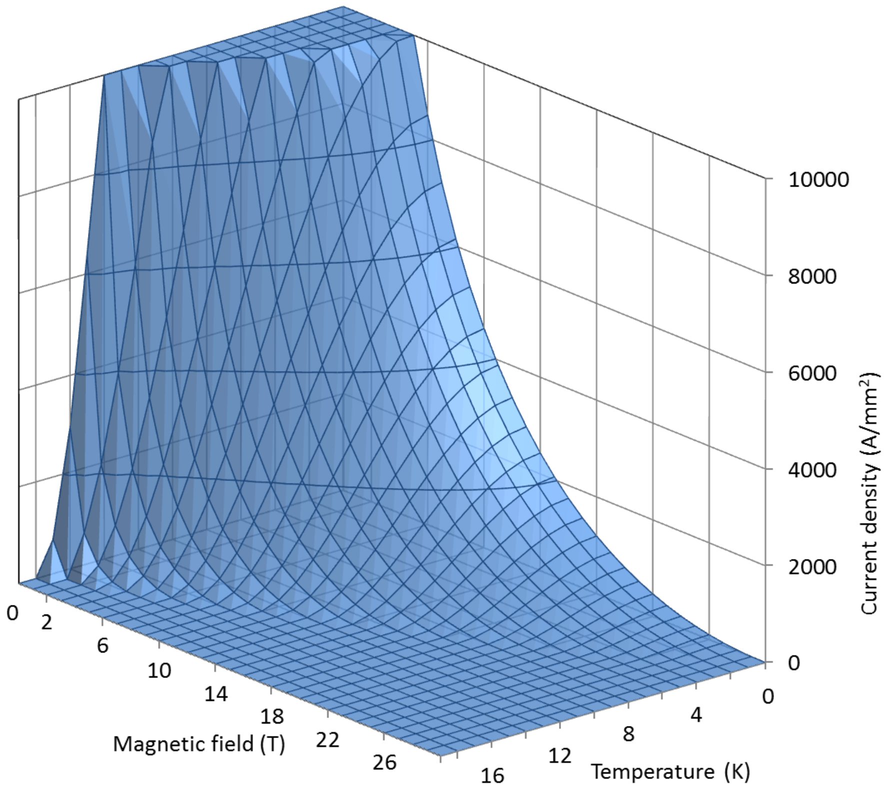
Appendix

Superconductivity
Nb-Ti vs. Nb_3Sn

Nb-Ti

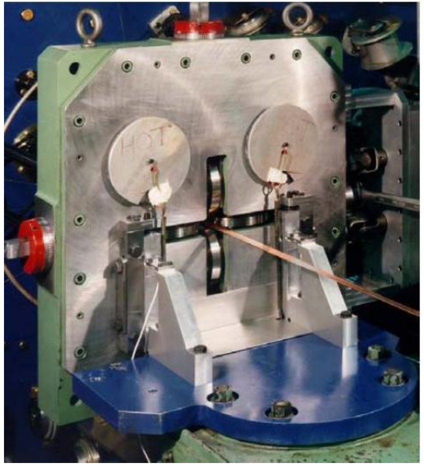


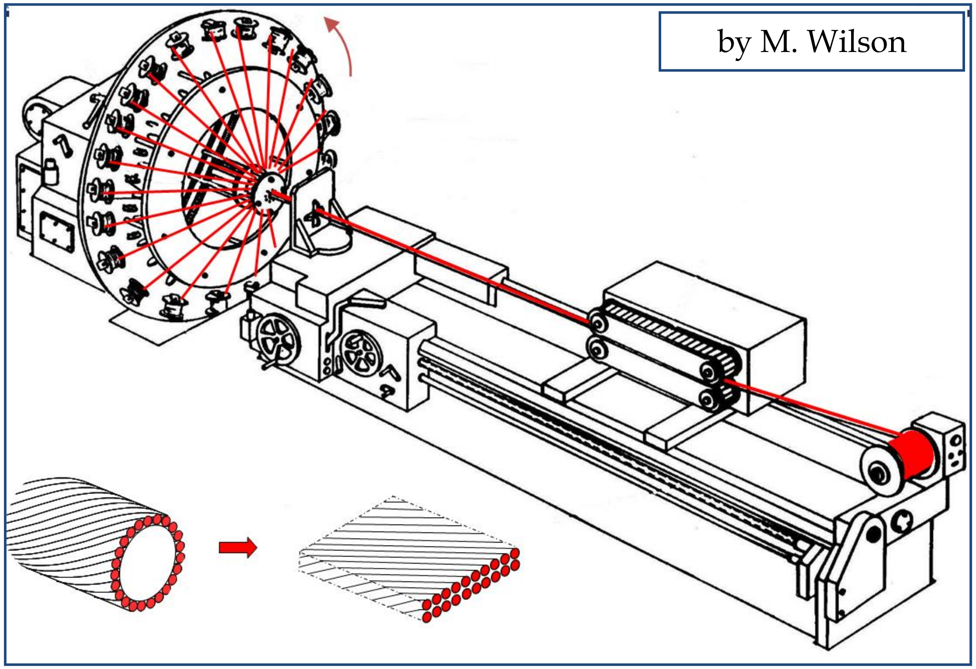
Nb_3Sn

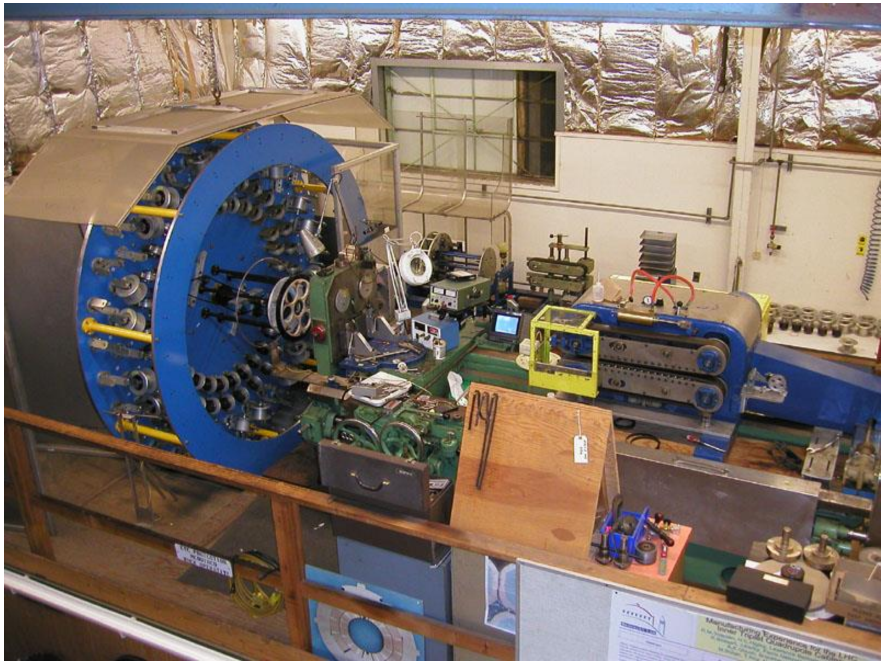


Practical superconductors
Multi-strand cables motivations

- Rutherford cables fabricated by **cabling machine**
  - Strands wound on spools mounted on a rotating drum
  - Strands twisted around a conical mandrel into rolls (Turk's head)
  - The rolls compact the cable and provide the final shape

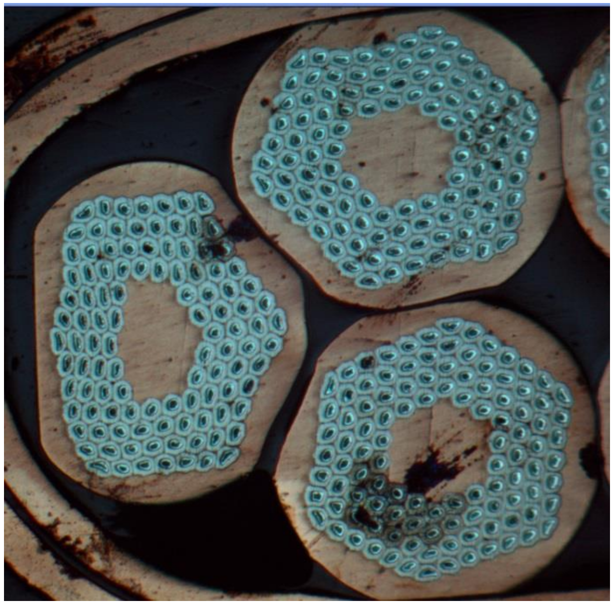


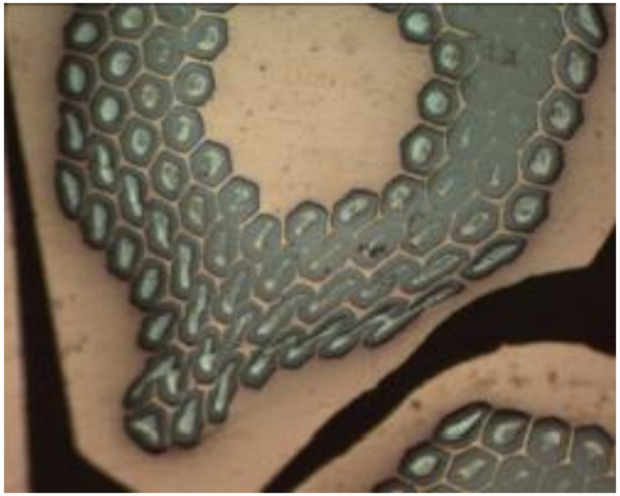

by M. Wilson

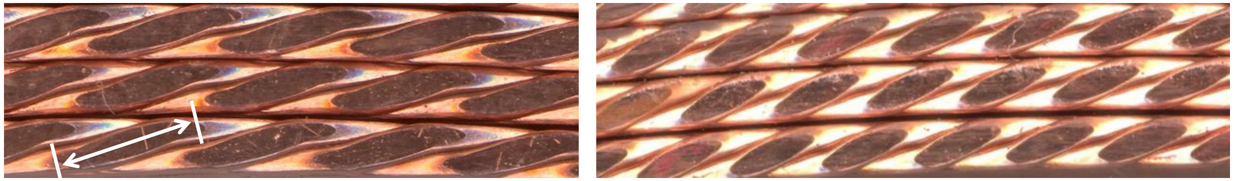


Practical superconductors
Multi-strand cables

- **Edge deformation** may cause
  - reduction of the filament cross-sectional area (Nb-Ti)
  - breakage of reaction barrier with incomplete tin reaction (Nb_3Sn)
- In order to avoid degradation
  - strand cross-section investigated
  - Edge facets are measured
    - General rule: no overlapping of facets



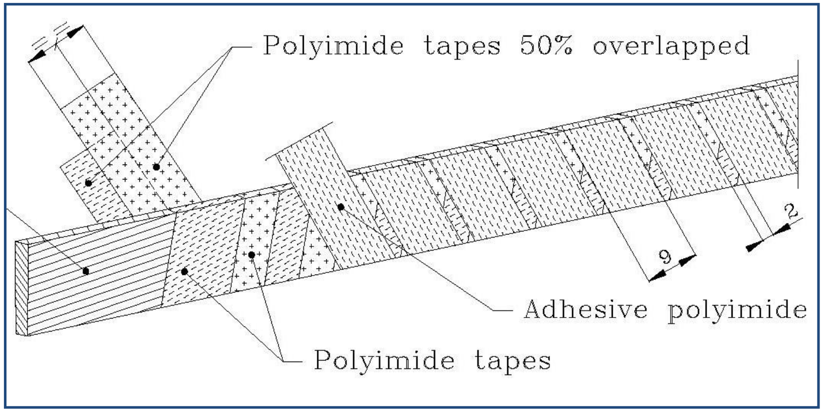




- **Keystone angle** is usually of ~ 1° to 2°

Practical superconductors
Cable insulation

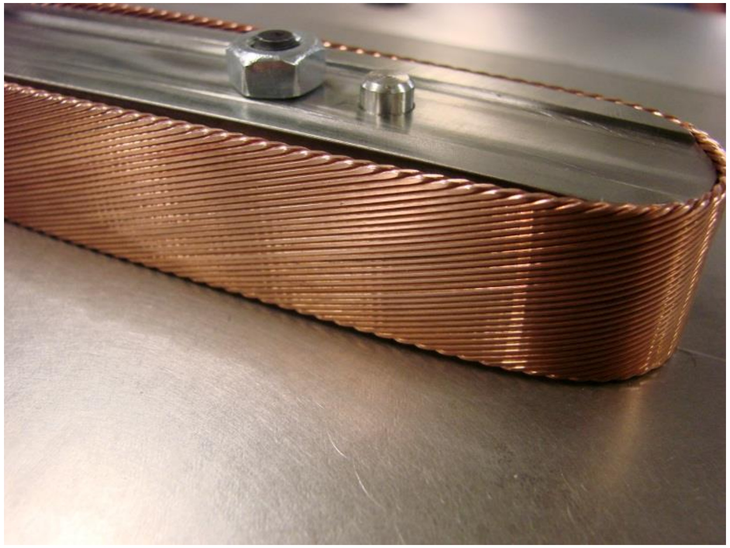
- The cable insulation must feature
  - Good **electrical properties** to withstand turn-to-turn *V* after a quench
  - Good **mechanical properties** to withstand high pressure conditions
  - **Porosity** to allow penetration of helium (or epoxy)
  - **Radiation hardness**
- In Nb-Ti magnets overlapped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

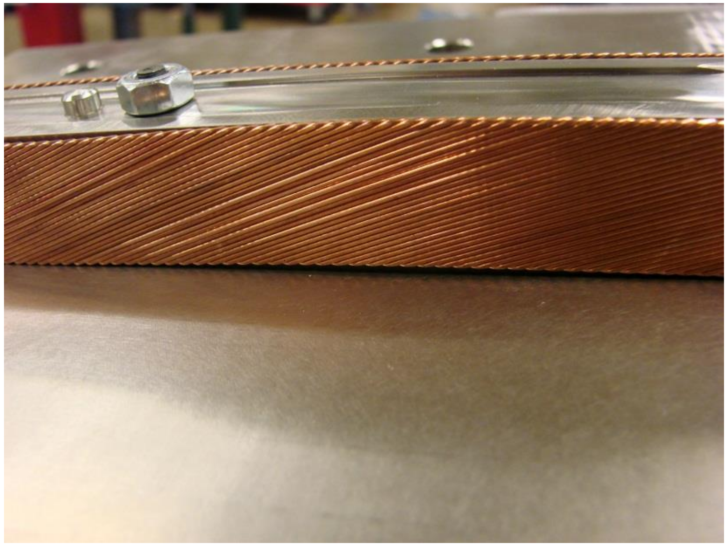


Coil fabrication
Winding and curing

- There is a **minimum bending radius**, which depends on the cable dimensions.
  - Is there a general rule?
    - No, but usually the bending radius is 10-15 times the cable thickness.
  - The cable must be constantly monitored during winding.

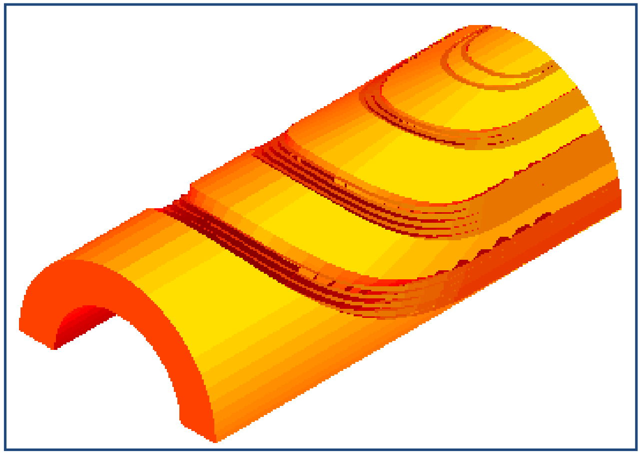
- If the bending radius is too small
  - **De-cabling** during winding;
  - Strands "**pop-out**".

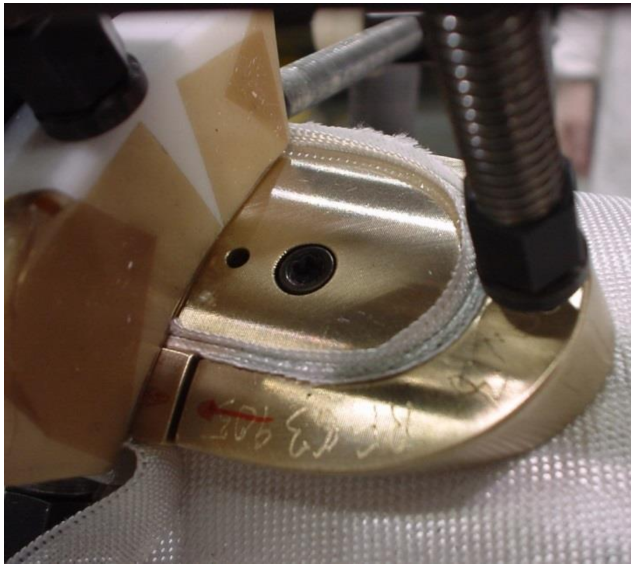




Coil fabrication
Winding and curing

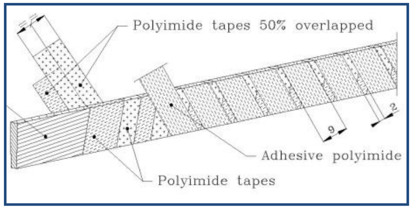
- In the **end region**, more difficult to constrain the turns
  - bent over the narrow edge
- To improve the mechanical stability and to reduce the peak field → **end spacers**
  - **constant perimeter** approach
    - The two narrow edges of the turn in the ends follow curves of equal lengths.
- In Nb-Ti magnets, end spacers are produced by 5-axis machining of epoxy impregnated fiberglass
  - Remaining voids are then filled by resins
- In Nb_3Sn magnets, end spacers are made of aluminum bronze or stainless steel.



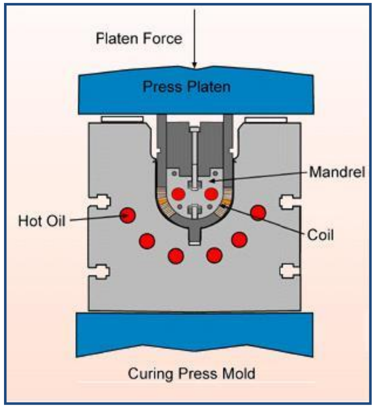


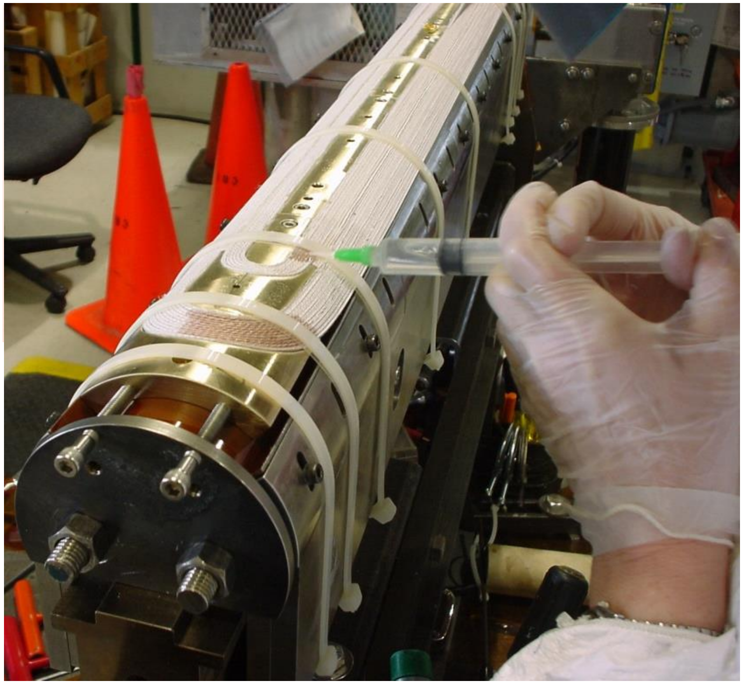
Coil fabrication
Winding and curing

- The goal of curing
    - Glue turns facilitating **handling**
- Coils are placed in the **curing mould** equipped with a **heating** system, and **compressed** in press
- Nb-Ti coils cured up to 190±3 °C at 80-90 MPa (LHC) to **activate resin**



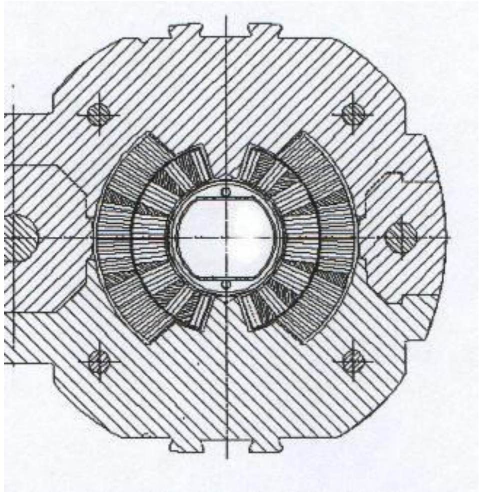
- In Nb_3Sn coils, cable insulation is injected with **ceramic binder**
    - Cured at 150° C and at ~10-30 MPa



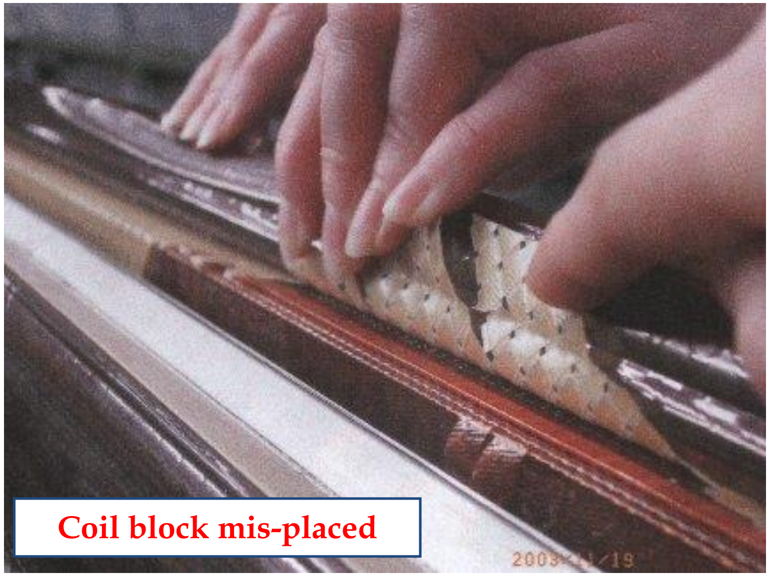


….more on field harmonics

- As we said, we **minimize** harmonics during **design** phase
- After fabrication we can **measure** them
  - Reproducibility of coil positioning is ~20-50 mm (1 σ)
- If an anomaly is observed-→ **inverse problem**
  - Which coil **defect** could cause such an **anomaly**?



Missing shim



Coil block mis-placed