2017 Joint Universities Accelerator School

Superconducting Magnets

Section I

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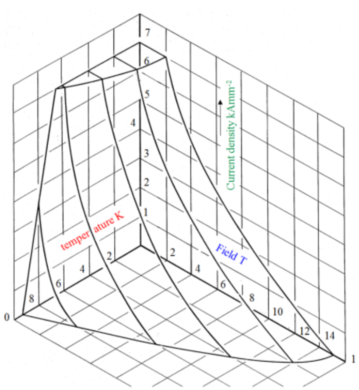
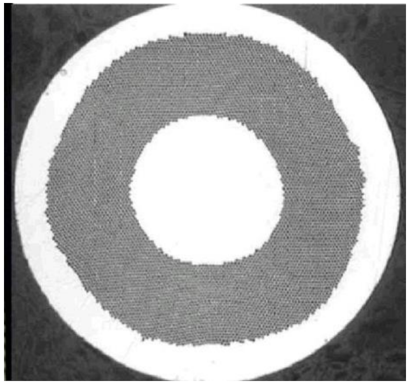
Introduction
Goal of the course

- Overview of **superconducting magnets** for particle accelerators (dipoles and quadrupoles)
  - Description of the components and their function
- From the superconducting material to the full magnet

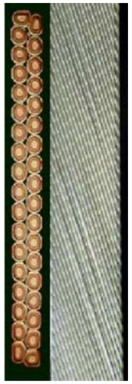
Superconducting material



Superconducting strand

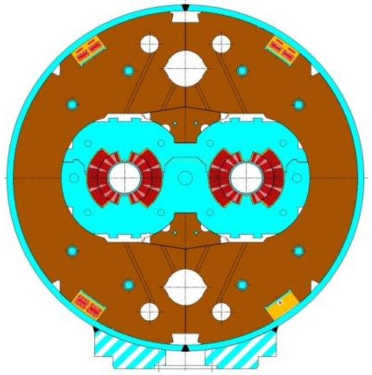


Superconducting cable



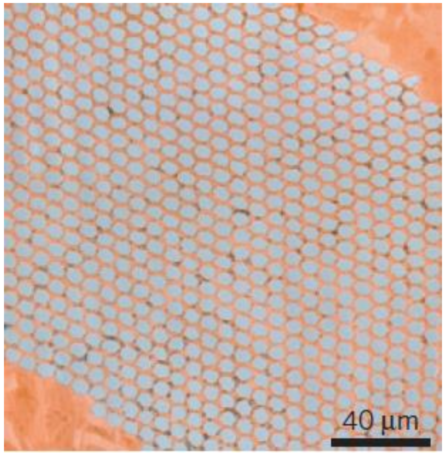
Superconducting coil

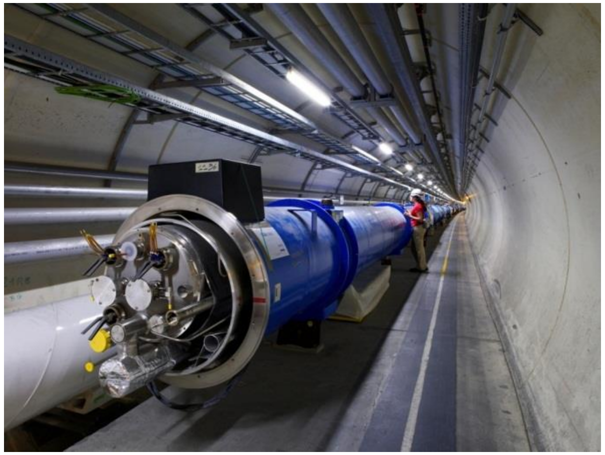
Superconducting magnet



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

- **Section I**
  - Particle accelerators and magnets
  - Superconductivity and practical superconductors
  - Magnetic design
- **Section II**
  - Coil fabrication
  - Forces, stress, pre-stress
  - Support structures
- **Section III**
  - Quench, training, protection

References

- Particle accelerators and magnets
- Superconductivity and practical 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

References

- Magnetic design
  - 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

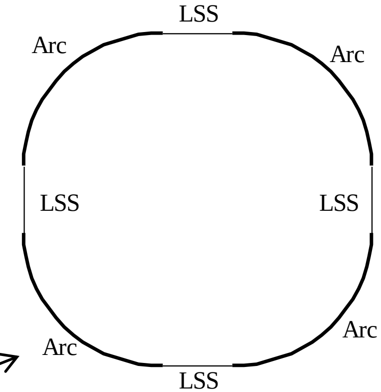
  - L. Rossi, E. Todesco, *"Electromagnetic design of superconducting quadrupoles"*, Phys. Rev. ST Accel. Beams 10 (2007) 112401.
  - L. Rossi and Ezio Todesco, *"Electromagnetic design of superconducting dipoles based on sector coils"*, Phys. Rev. ST Accel. Beams 9 (2006) 102401.

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

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

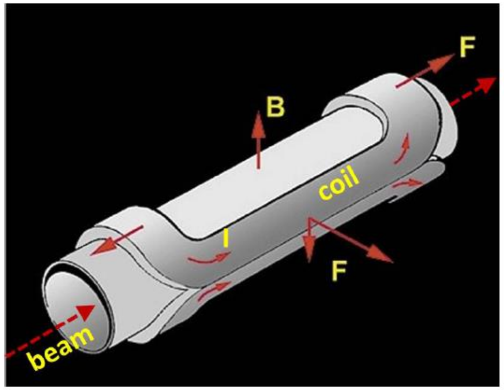
- Particle accelerated → energy increased → magnetic field increased ("synchro") to keep the particles on the same orbit of curvature ρ

$$p = eB\rho$$

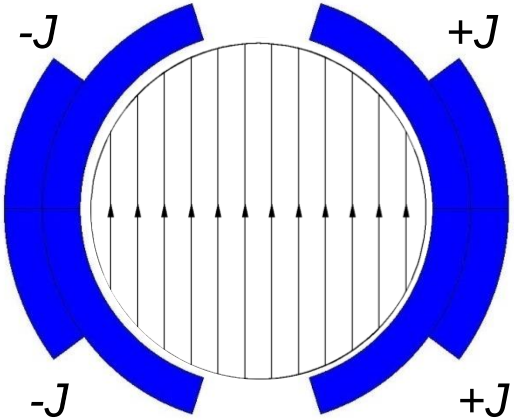
Constant

Particle accelerators and magnets
Dipoles

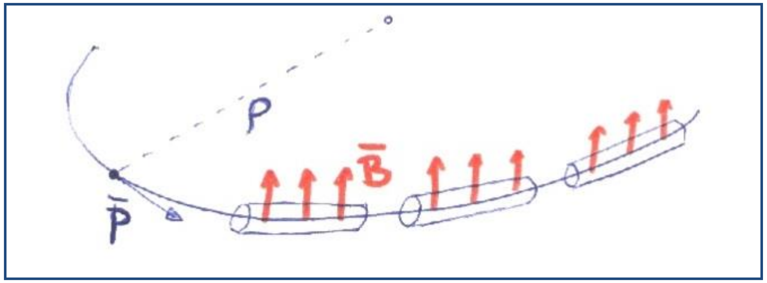
- Main field components is B_y
  - Perpendicular to the axis of the magnet z
- Electro-magnets: field produced by a current (or current density)



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



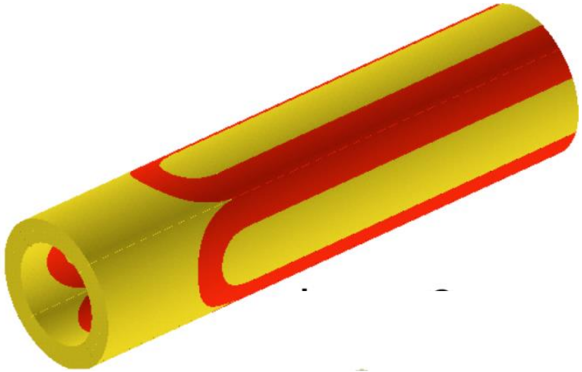
- **Magnetic field steers (bends) the particles in a ~circular orbit**

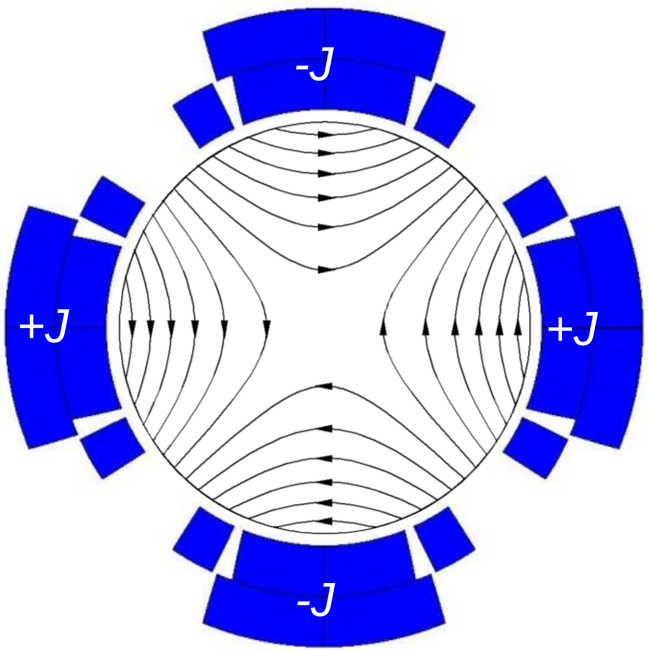


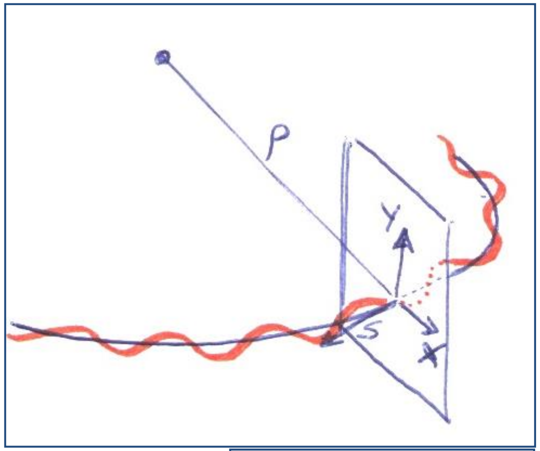
by E. Todesco

$$p = eB\rho$$

- 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





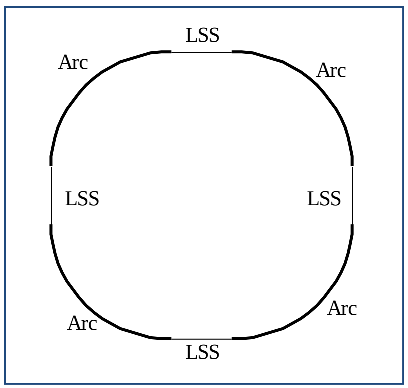


by E. Todesco

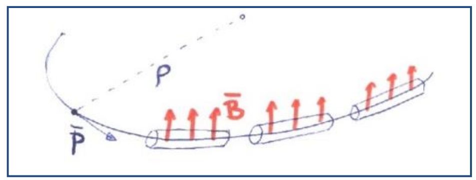
$$G = \frac{B_y}{r} = -\frac{\mu_0 J_0}{2} \ln \frac{r_{out}}{r_{in}}$$

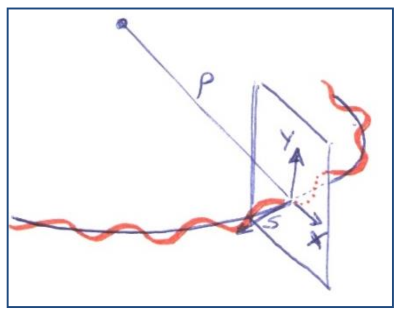
Particle accelerators and magnets

- 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

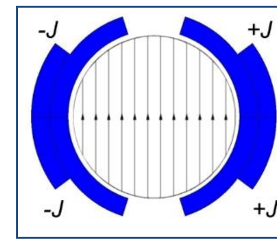


$$p = eB\rho$$

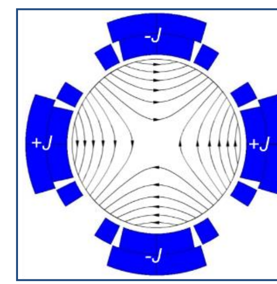




$$B_y = -\frac{\mu_0 J_0}{2}(r_{out} - r_{in})$$



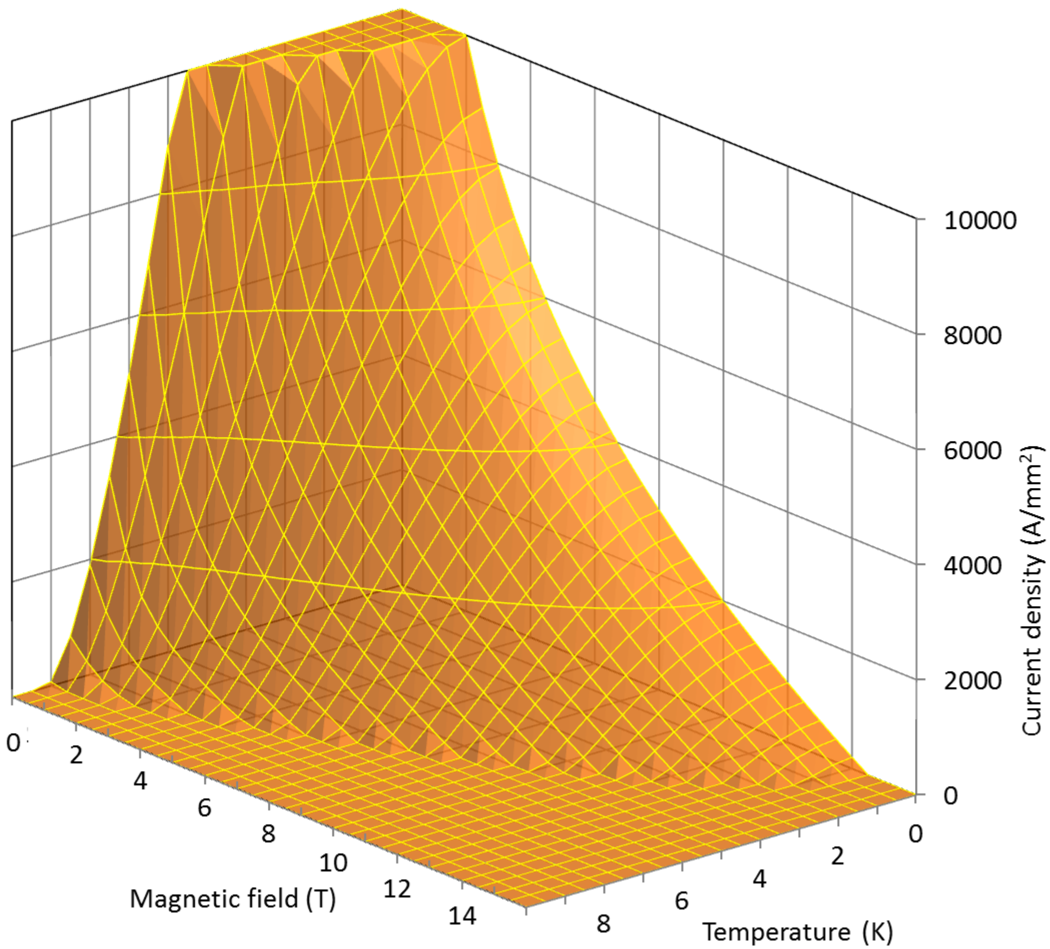
$$G = \frac{B_y}{r} = -\frac{\mu_0 J_0}{2} \ln \frac{r_{out}}{r_{in}}$$



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

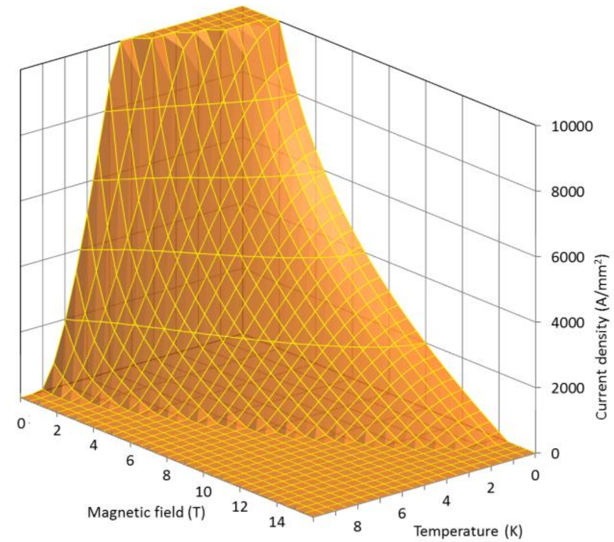
Superconductivity
Critical surface

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

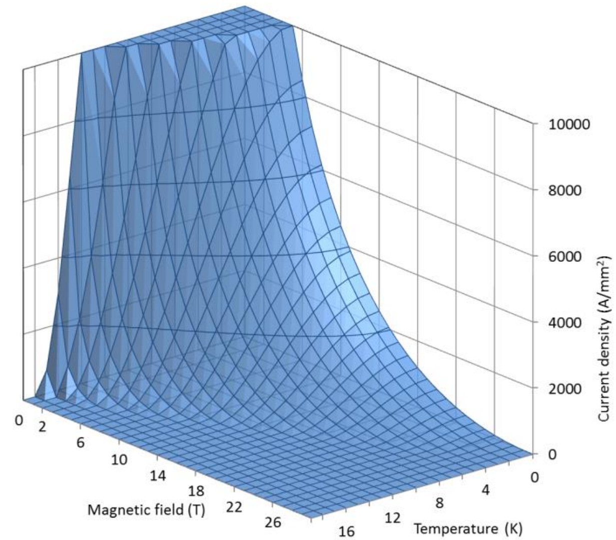


Superconductivity
Nb-Ti (1961) and Nb_3Sn (1954)

- 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)

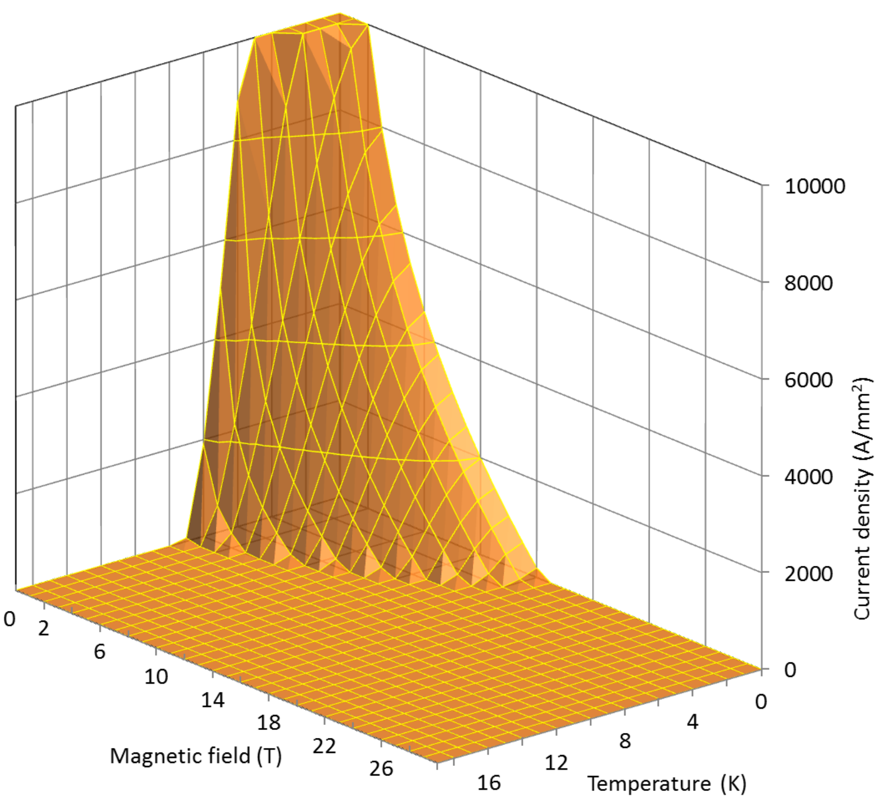


- Nb and Sn → intermetallic compound
  - Brittle, strain sensitive, formed at ~650-700°C
- T_C is ~**18 K** at 0 T
- B_{C2} is ~**28 T** at 0 K
- Used in **NMR**, **ITER**
- ~700-1500 US$ per kg of wire (5 euro per m)

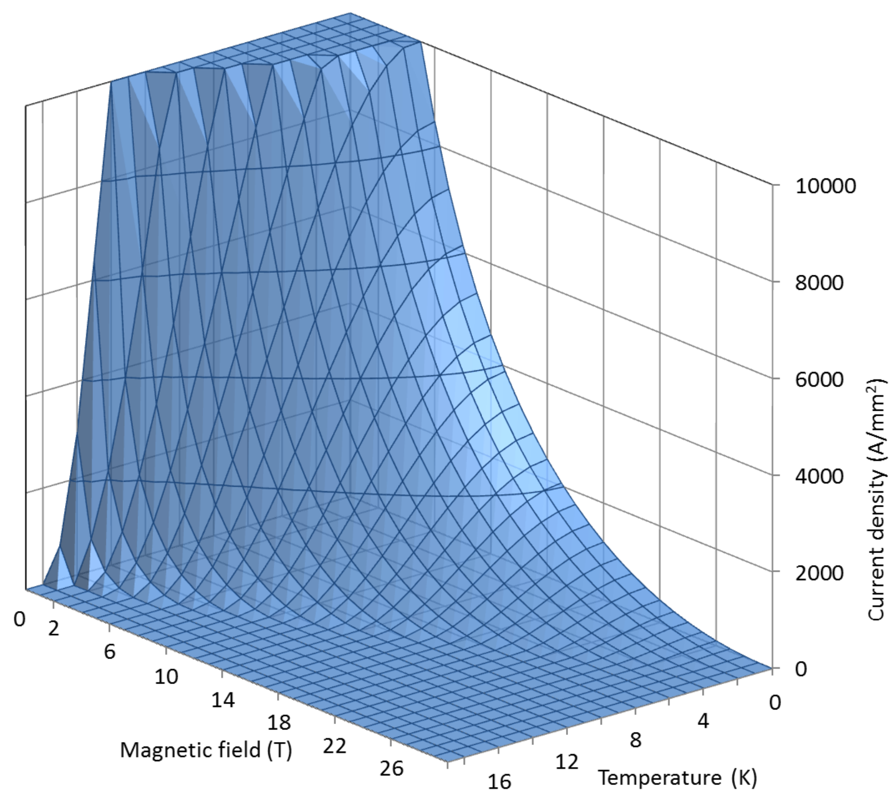


Superconductivity
Nb-Ti vs. Nb_3Sn

Nb-Ti



Nb_3Sn



Superconductivity from Cu to Nb_3Sn

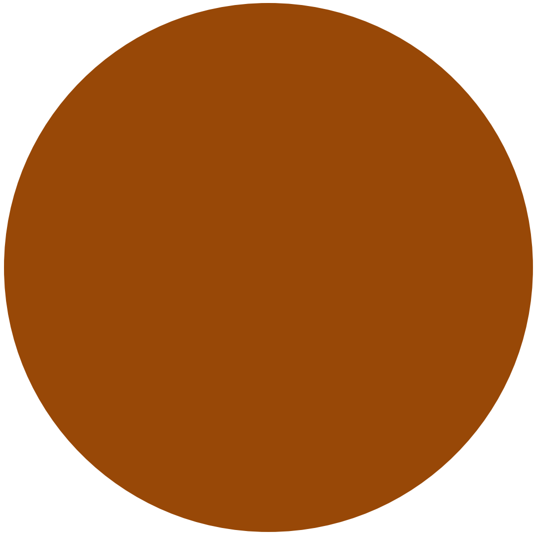
- Typical operational conditions (0.85 mm diameter strand)

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

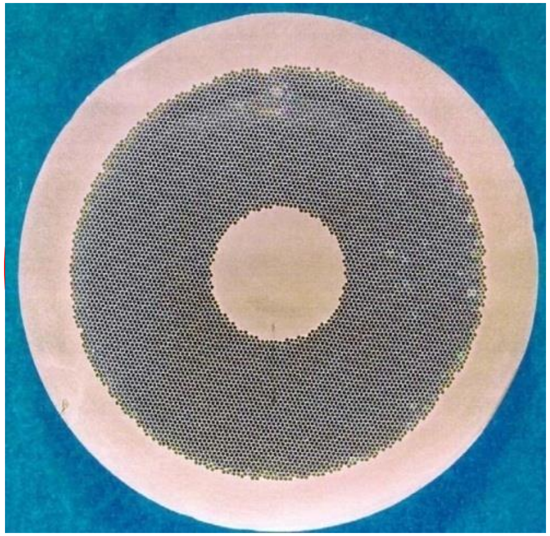


$J_e \sim 5$ A/mm^2

$I \sim 3$ A

$B = 2$ T

Nb-Ti

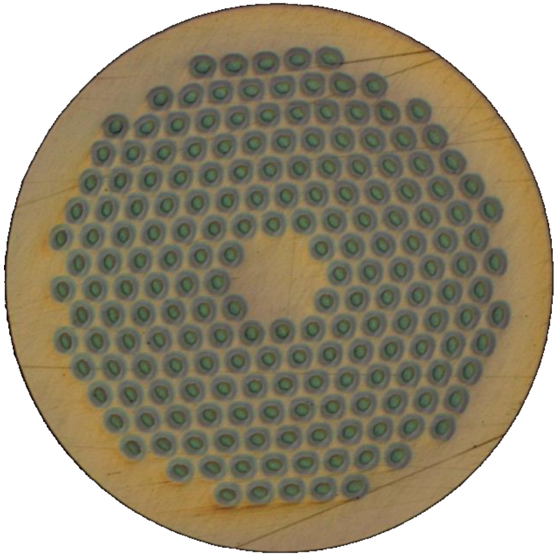


$J_e \sim 600\text{-}700$ A/mm^2

$I \sim 300\text{-}400$ A

$B = 8\text{-}9$ T

Nb_3Sn



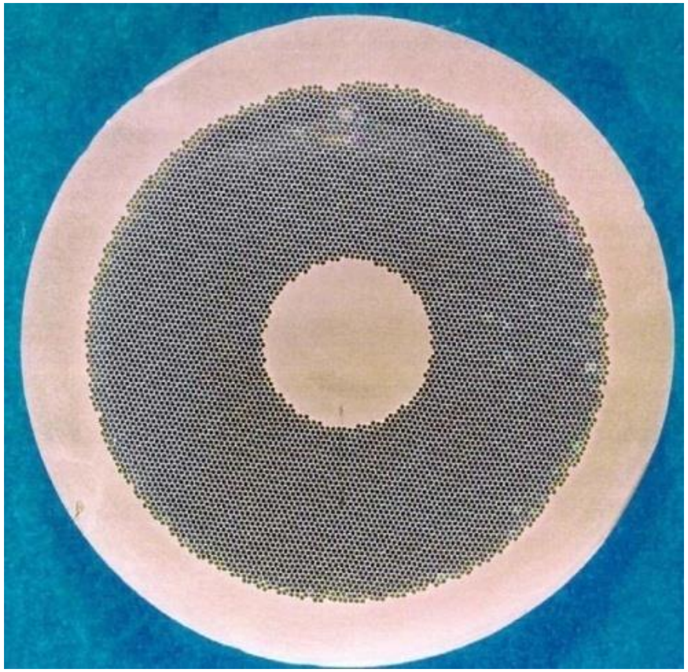
$J_e \sim 600\text{-}700$ A/mm^2

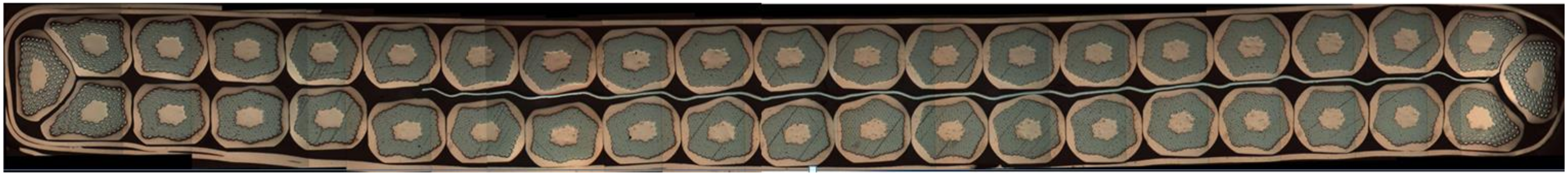
$I \sim 300\text{-}400$ A

$B = 12\text{-}13$ T

Practical superconductors
Introduction

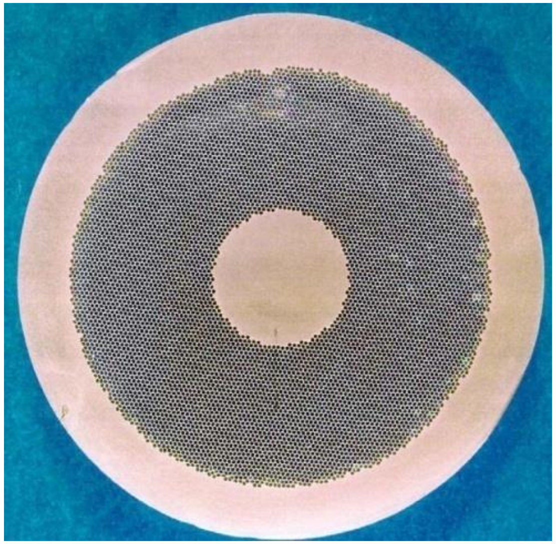
- Superconducting materials are produced in small filaments and surrounded by a stabilizer (typically copper) to form a *multi-filament wire* or *strand*.
- A superconducting cable is composed by several wires: *multi-strand cable*.

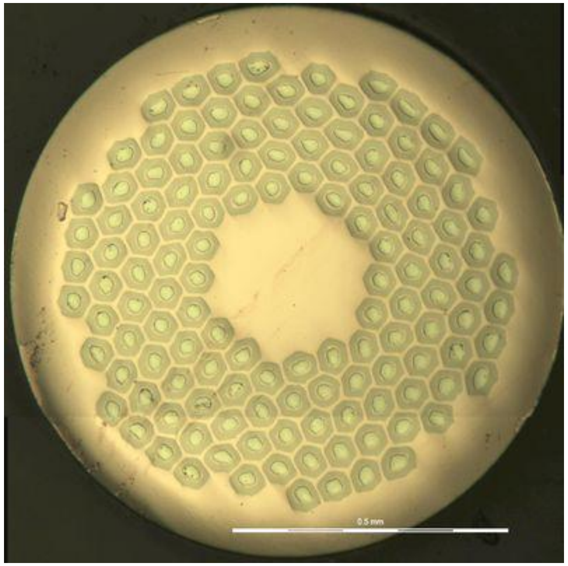




Practical superconductors
Multi-filament wires motivations

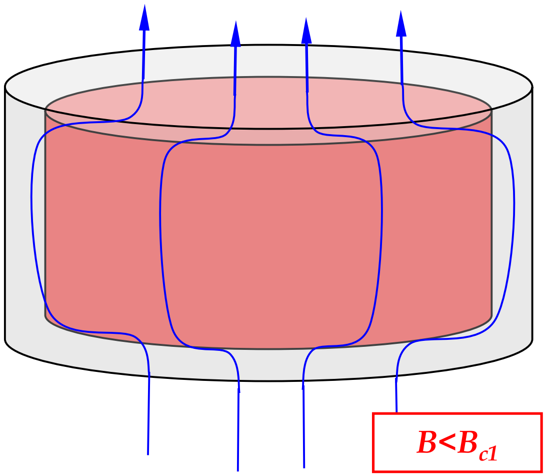
- The superconducting materials used in accelerator magnets are
  - subdivided in filaments of small diameters
    - to reduce magnetic instabilities called **flux jumps**
    - to minimize field distortions due to superconductor **magnetization**
  - twisted together
    - to reduce interfilament coupling and **AC losses**
  - embedded in a copper matrix
    - to **protect** the superconductor **after a quench**
    - to reduce magnetic instabilities called flux jumps





Practical superconductors
Multi-filament wires motivations

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

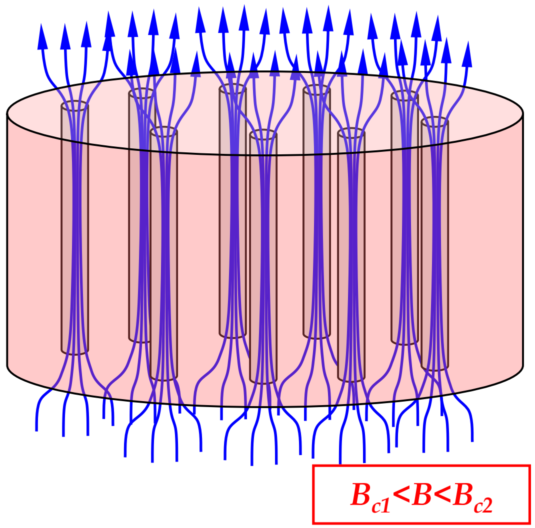


- Stability criteria for a slab (adiabatic condition)

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

  - 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.

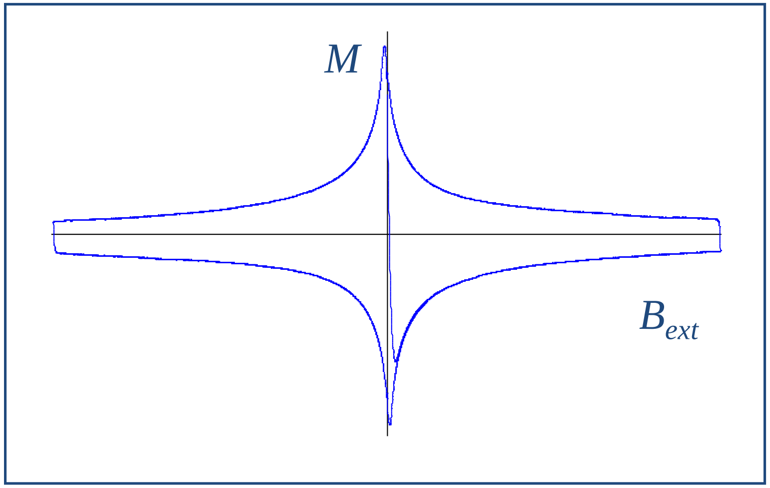
- Nb-Ti filament diameters usually < 50 μm

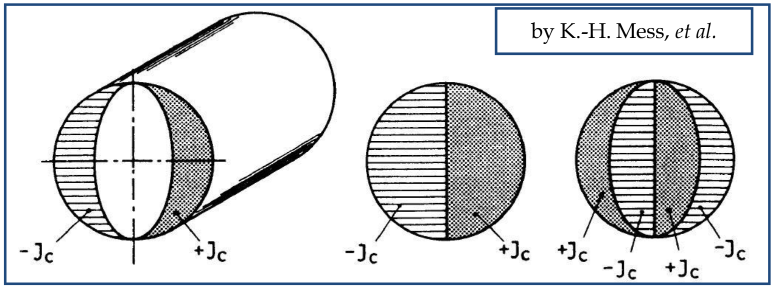


by L. Bottura

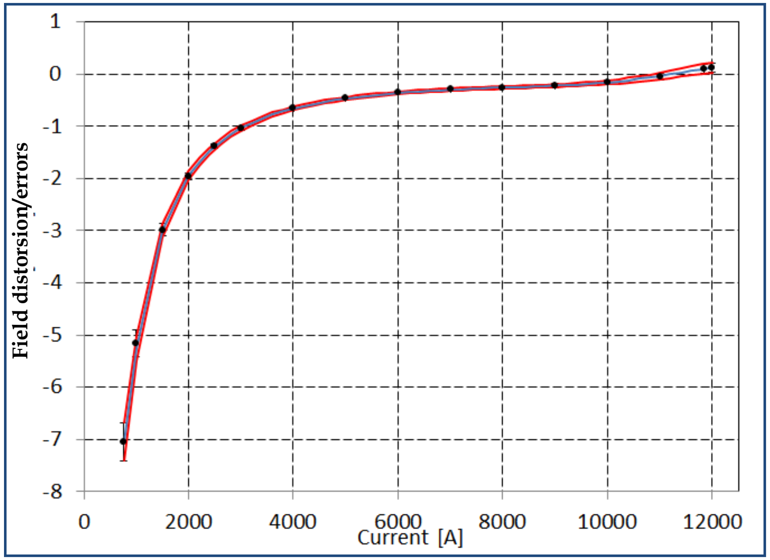
Practical superconductors
Multi-filament wires motivations

- **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**



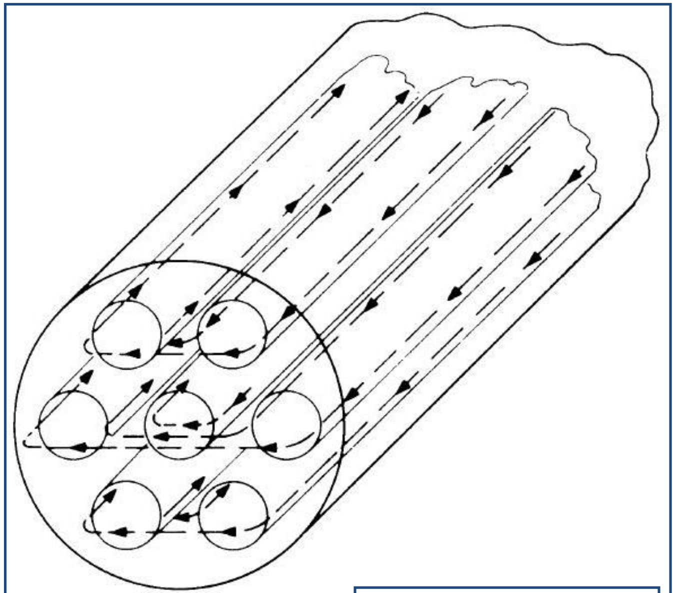


  - These currents produce **field errors** and **ac losses** proportional to $J_c r_f$
    - LHC filament diameter 6-7 μm.
    - HERA filament diameter 14 μm.



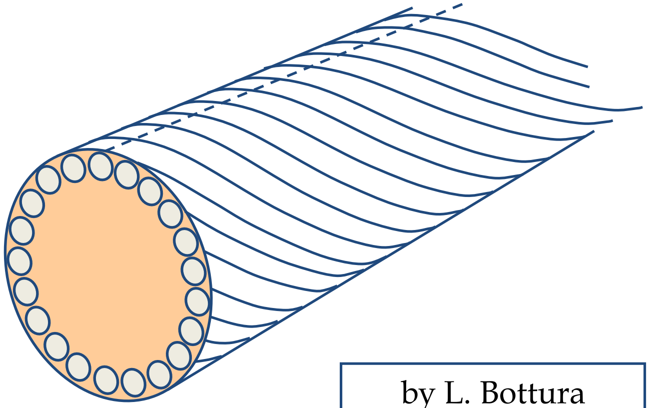
Practical superconductors
Multi-filament wires motivations

- **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**



by M. Wilson

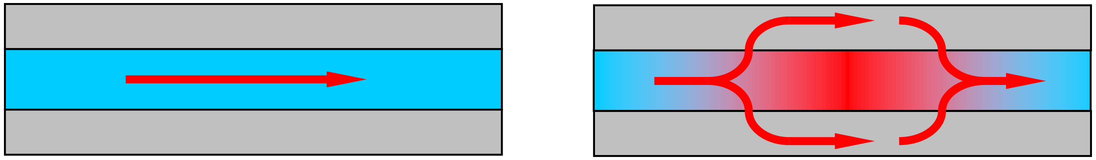
- To reduce these effects, filaments are **twisted**
  - twist pitch of the order of 20-30 times of the wire diameter.



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**

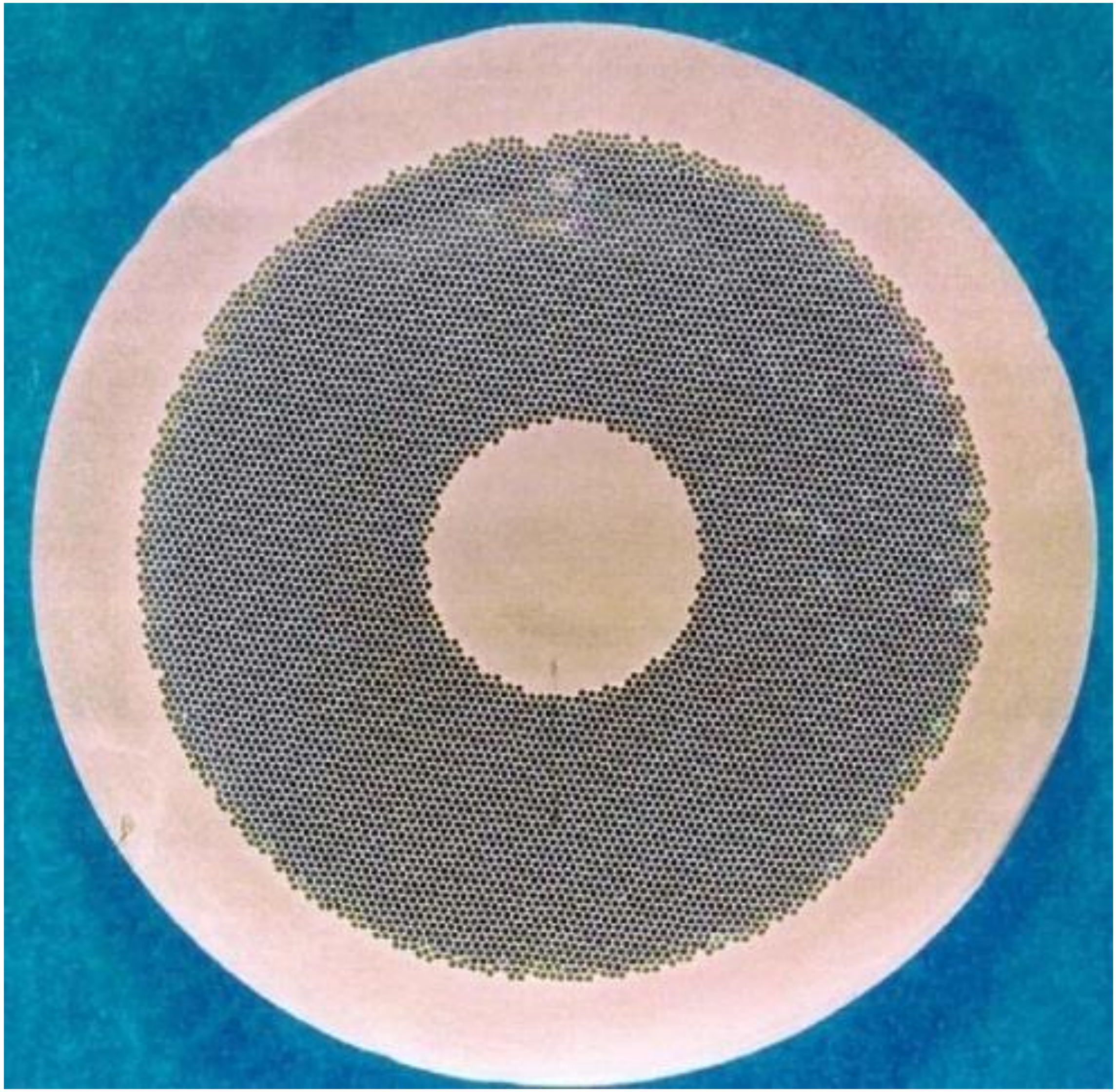


by L. Bottura

  - 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**

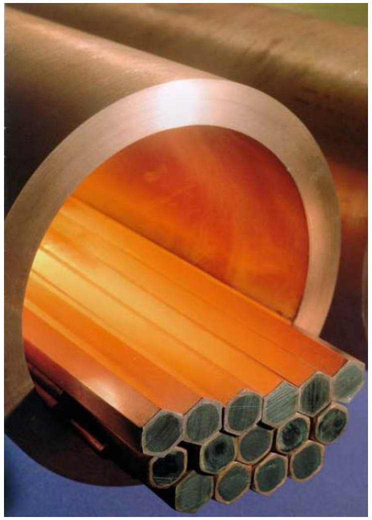
Practical superconductors
Multi-filament wires motivations

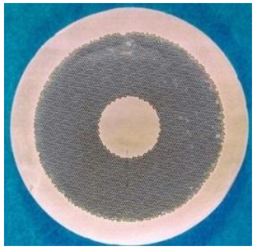
- **Flux jumps**
- **Persistent currents**
- **AC losses**
- **Quench protection**

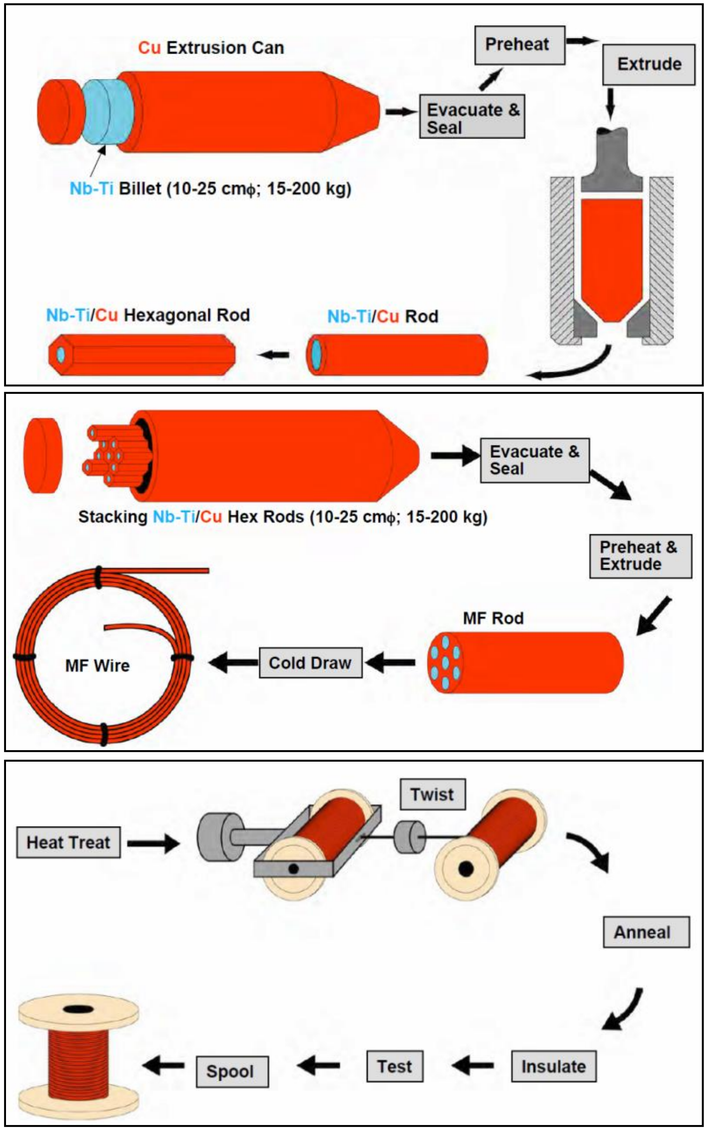


Practical superconductors
Fabrication of Nb-Ti multifilament wires

- 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

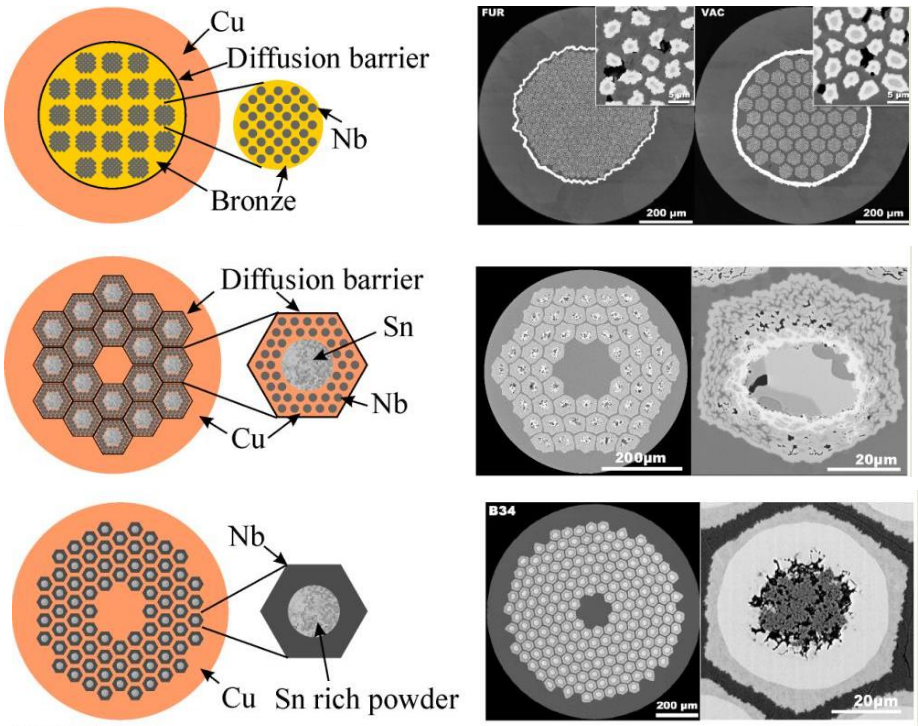






Multifilament wires
Fabrication of Nb_3Sn multifilament wires

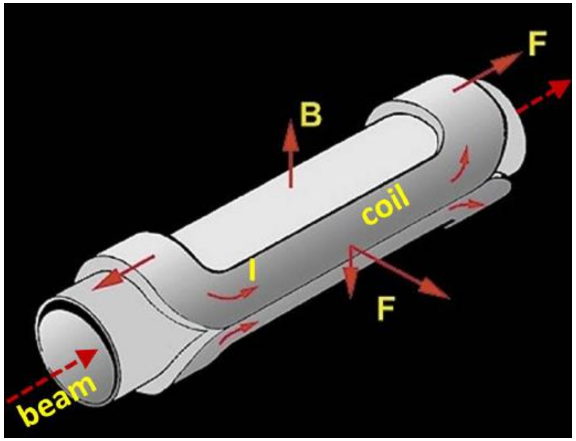
- Since Nb_3Sn is brittle
  - it cannot be extruded and drawn like Nb-Ti.
- Process in several steps
  - Assembly multifilament billets from with **Nb and Sn separated**
  - Fabrication of the wire through extrusion-drawing
    - Fabrication of the cable
    - Fabrication of the coil
  - "**Reaction**"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

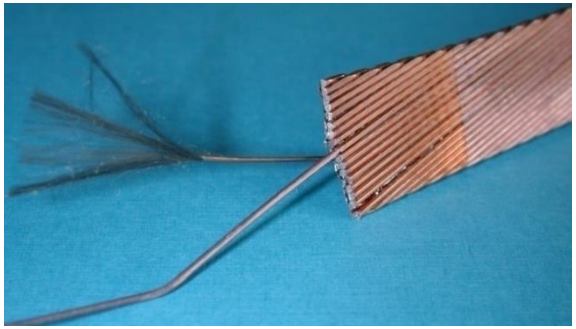


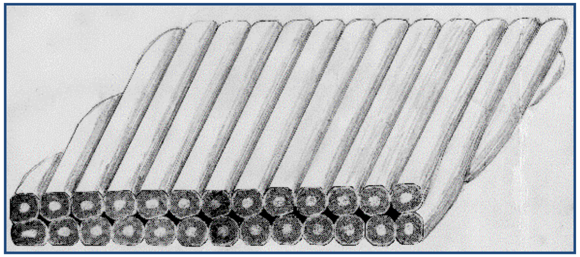
by A. Godeke

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**



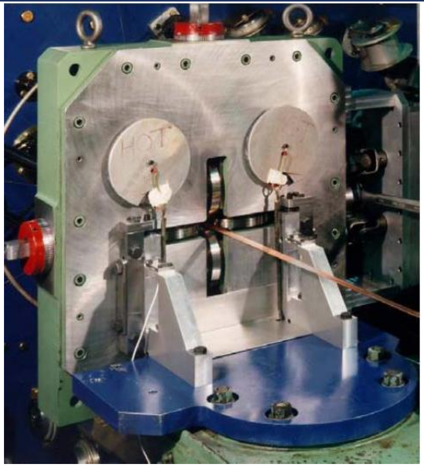


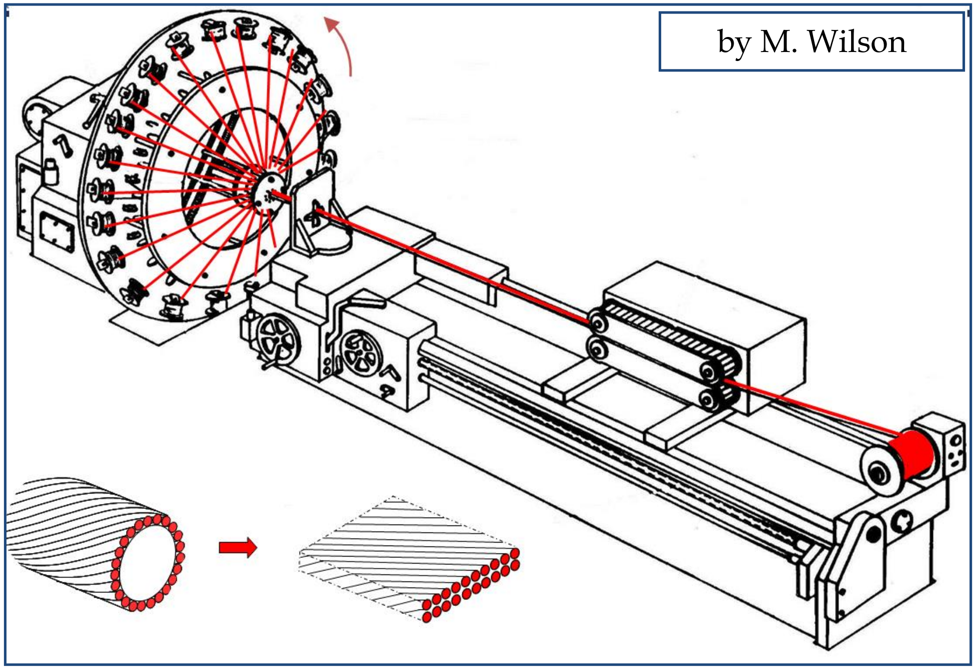


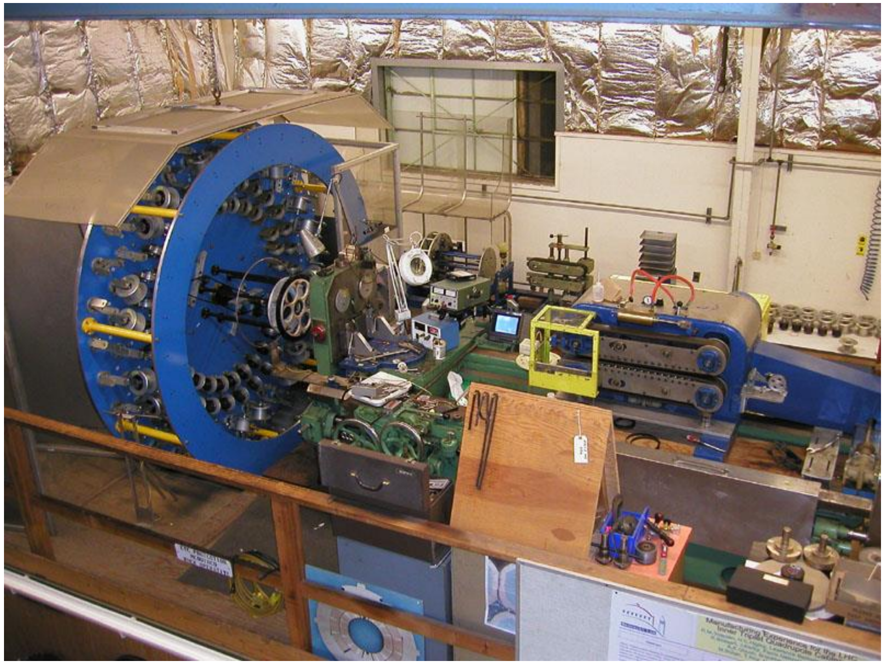
by M. Wilson

Practical superconductors
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

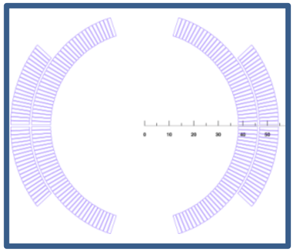




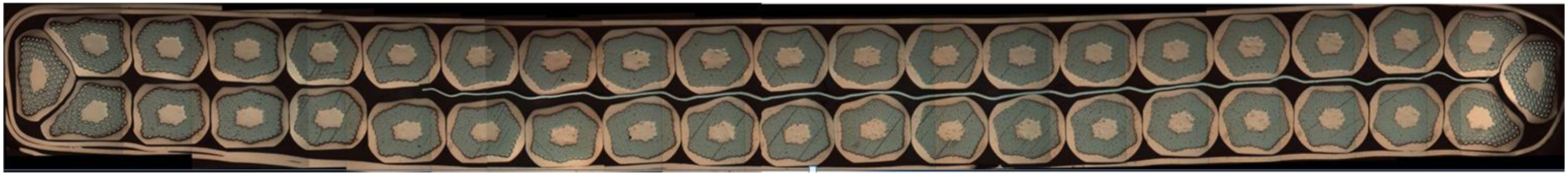


Practical superconductors
Multi-strand cables

- A Rutherford cable can be **rectangular** or **trapezoidal**
  - To stacking cables in an arc-shaped coil around the beam pipe

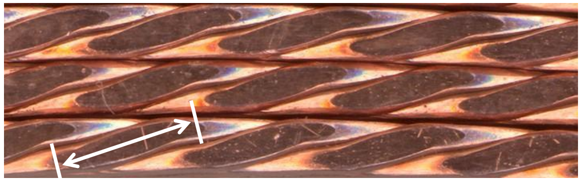
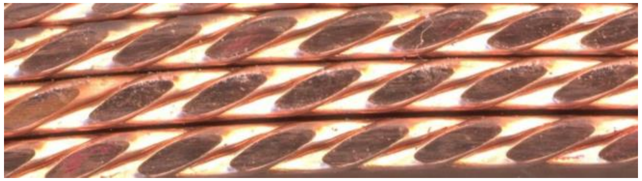


- **Cable compaction**
  - Ratio of the sum of the cross-sectional area of the strands (direction parallel to the cable axis) to the cross-sectional area of the cable
    - 88% (Tevatron) to 92.3% (HERA).
  - Chosen to provide good mechanical stability + high current capability + enough space for helium cooling or epoxy impregnation.
- **Cables degradation**
  - Critical current density of a virgin wire before cabling is higher then the one of a wire after cabling

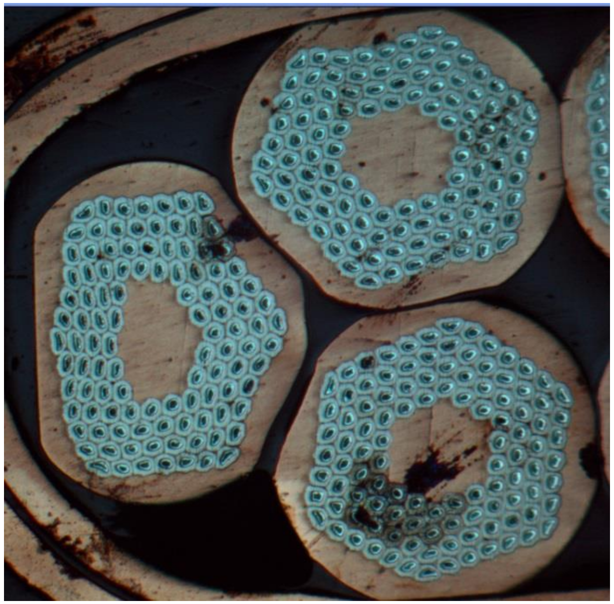
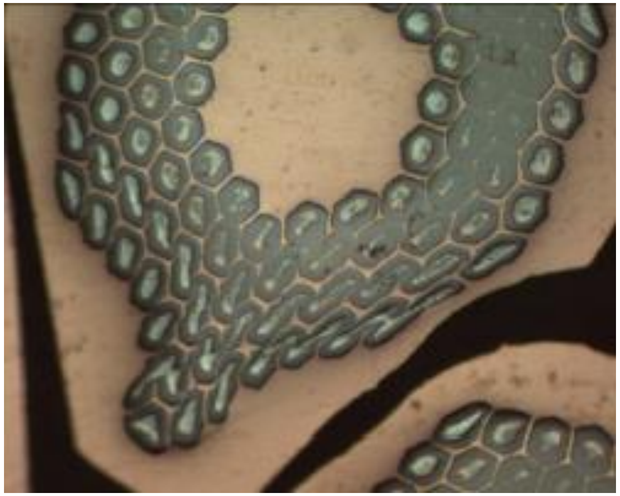


Practical superconductors
Multi-strand cables

- **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

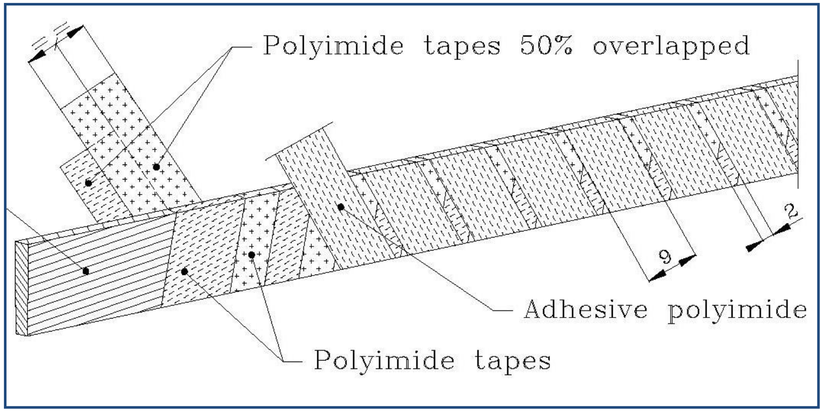



- **Keystone angle** is usually of ~ 1° to 2°

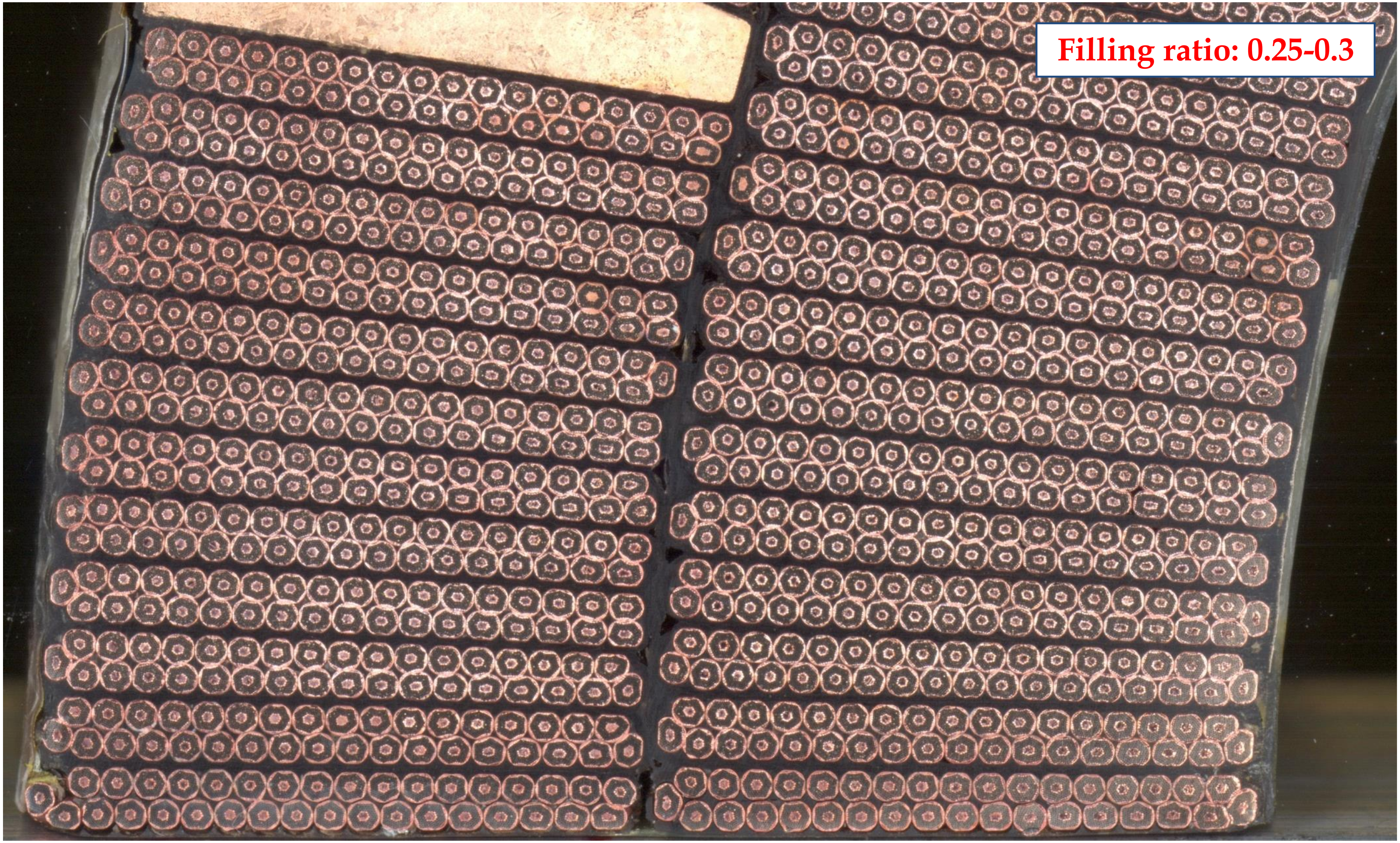



Practical superconductors
Cable insulation

- 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.



Practical superconductors
Superconducting cables



Outline

- **Section I**
  - Particle accelerators and magnets
  - Superconductivity and practical superconductors
  - Magnetic design
- **Section II**
  - Coil fabrication
  - Forces, stress, pre-stress
  - Support structures
- **Section III**
  - Quench, training, protection

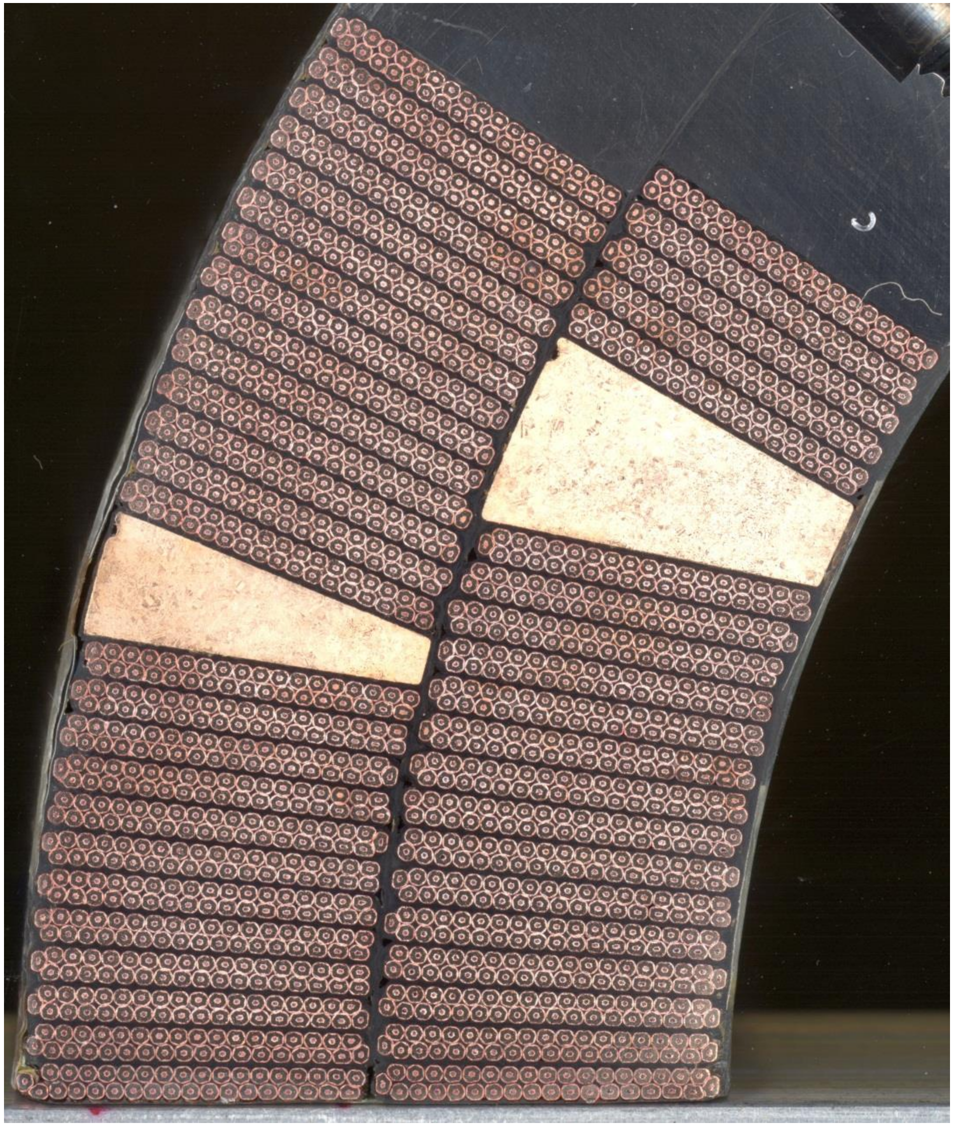
Magnetic design
Introduction

- The magnetic design is one of the first steps in the a superconducting magnet development
- It starts from the **requirements** (from accelerator physicists, researchers, medical doctors…others)
  - A field "**shape**"
    - Dipole, quadrupole, etc
  - A field **magnitude**
    - Usually with low T superconductors from 5 to 20 T
  - A field **homogeneity**
    - Uniformity inside a solenoid, harmonics in a accelerator magnet
  - A given **aperture** (and **volume**)
    - Some cm diameter for accelerator magnets, much more for detectors and fusion magnets

Magnetic design

- **How much** conductor do we need to meet the requirements?
- And in **which configuration**?

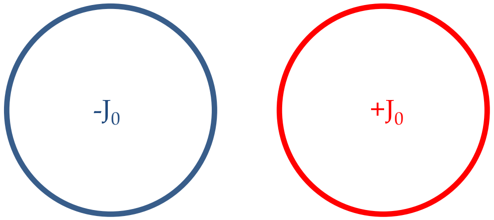
- **Outline**
  - How do we create a **perfect field**?
  - How do we express the field and its "**imperfections**"?
  - How do we **design a coil** to minimize field errors?
  - **Overview** of different designs



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***:

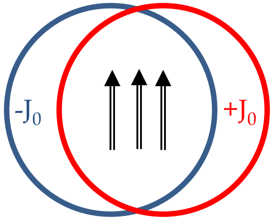
$$B = -\frac{\mu_0 j_0 r}{2}$$



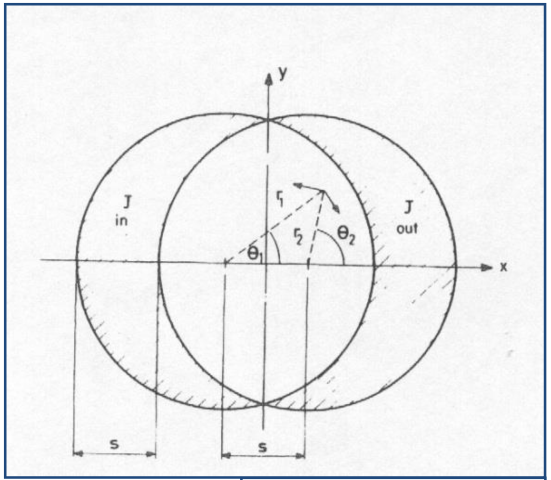
  - Combining the effect of two intersecting cylinders

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

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



- 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**



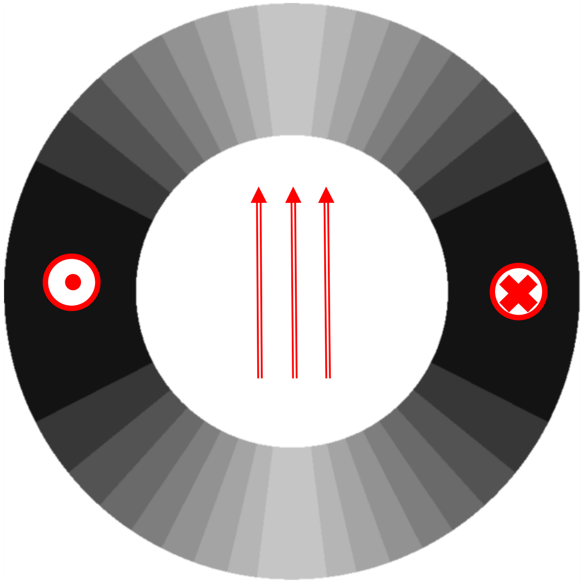
by M. Wilson

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

- Thick shell
  - Current density $J = J_0 \cos\theta$ on a shell with a finite thickness

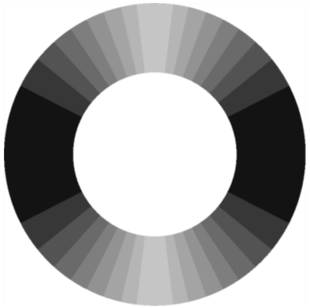
$$B_{\mathrm{bore}} = -\frac{J_0 \mu_0}{2} w$$

  - Where, B_{bore} is the bore field, J_0 is overall current density and w is the coil width
  - Ideal case
    - ***Conductor peak field $B_{peak} = B_{bore}$***
    - Perfect field quality
- Comparison:
  - For solenoid
    - $B_1 = -J_0 \mu_0 w$
    - Twice more efficient than a dipole

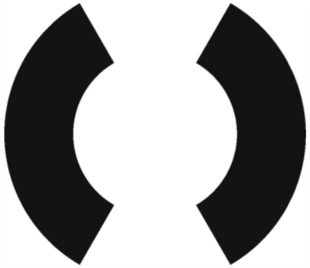


From ideal to practical configuration

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



- First "rough" approximation
  - **Sector dipole**

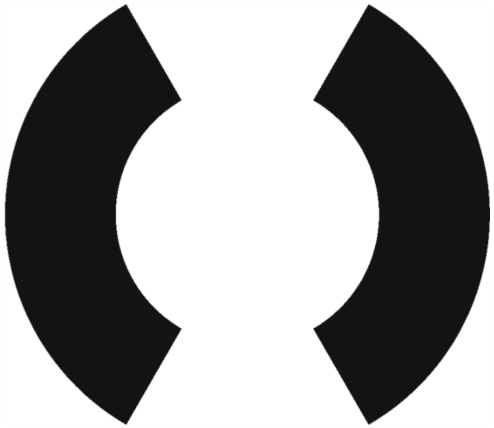


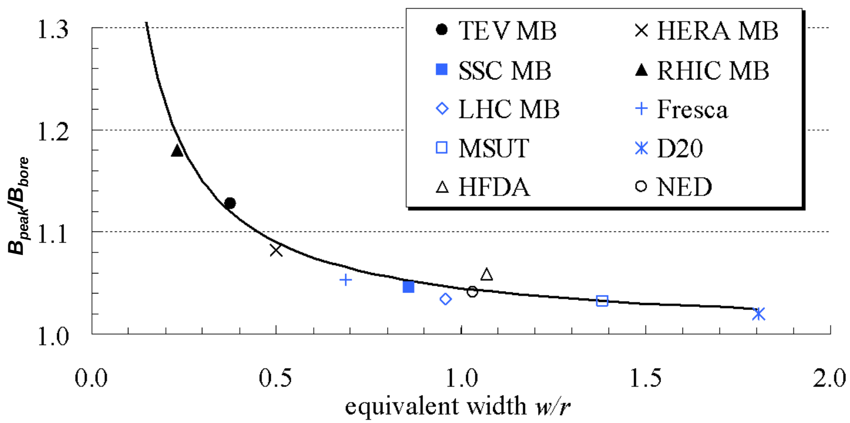
Computation of the load line
Approximations of practical winding cross-sections

- Sector coil
  - Current density $J = J_0$ (A per unit area) on a sector with a maximum angle α

$$B_{\text{bore}} = -\frac{2J_0\mu_0}{\pi} w\sin(\alpha)$$

  - Where, B_{bore} is the bore field, J_0 is overall current density and w is the coil width
  - "Less ideal" case
    - "Not so perfect" field quality
      - Best with α = 60 degrees
    - $B_{peak} = B_{bore} \cdot \sim 1.04$



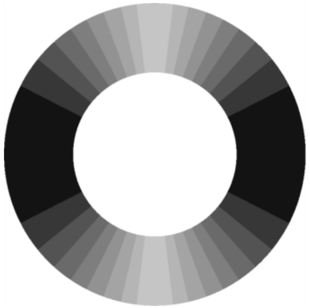


L. Rossi, E. Todesco, "Electromagnetic design of superconducting quadrupoles", Phys. Rev. ST Accel. Beams 9 (2006) 102401.

- With a w/r of 30/30 = 1 → 1.04

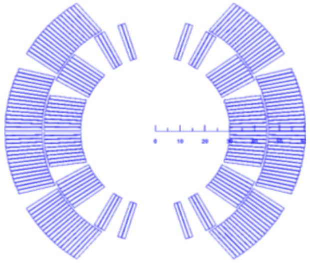
From ideal to practical configuration

- 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?

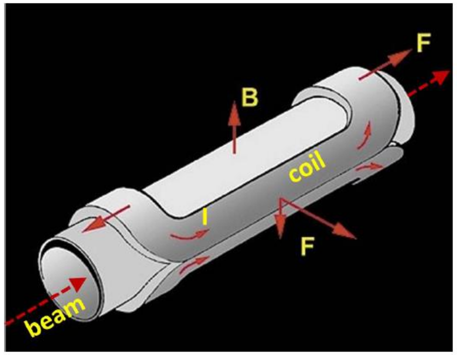
Field representation
Maxwell equations

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

  Maxwell gives

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

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

Cauchy-Riemann conditions

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

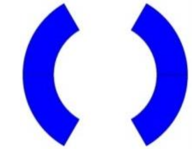
$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty} C_n (x+iy)^{n-1}$$

where C_n are **complex coefficients**

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

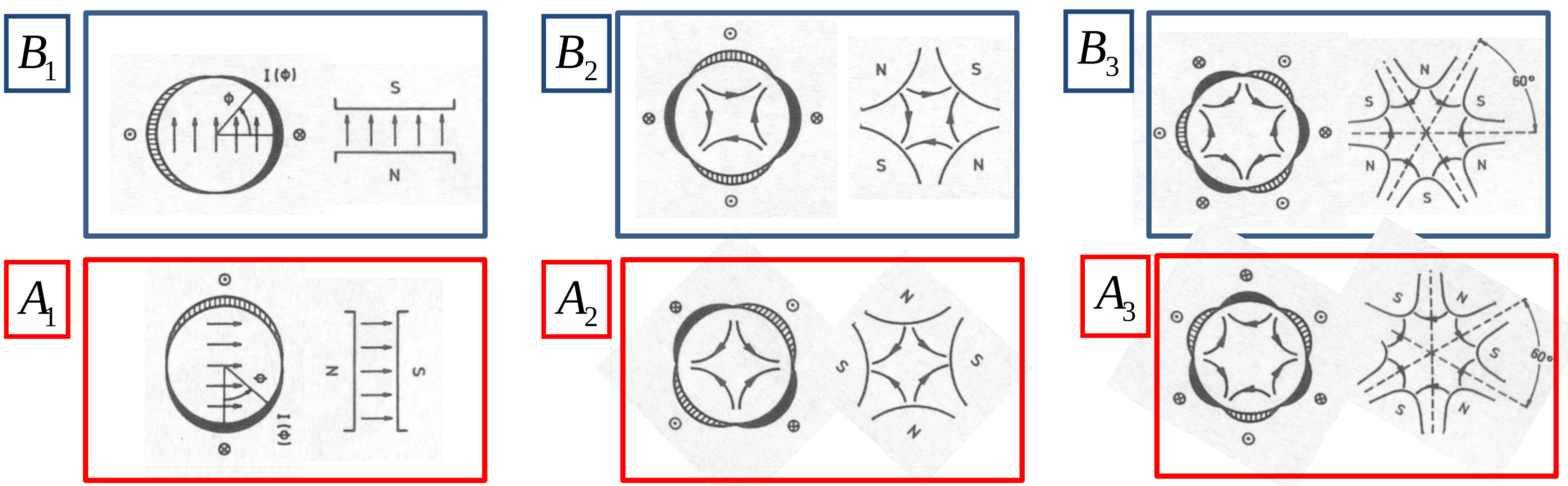
- Advantage: we reduce the description of the field to a (simple) series of complex coefficients

Magnetic design
Harmonics



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

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



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

- The field harmonics are rewritten as

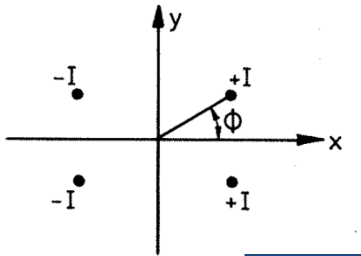
$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

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

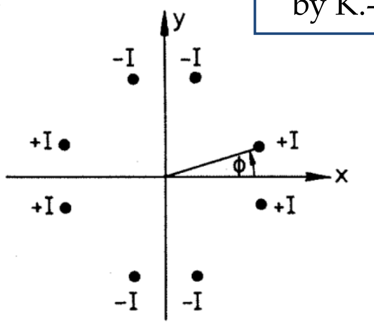
Field representation
Harmonics

- One can demonstrate that with line currents with a **dipole** or a **quadrupole symmetry**, most of the **multipoles cancelled**

- For n=1→ *dipole*
  - Only b_3, b_5, b_7, ….. are present



- For n=2→ *quadrupole*
  - Only b_6, b_{10}, b_{14}, ….. are present



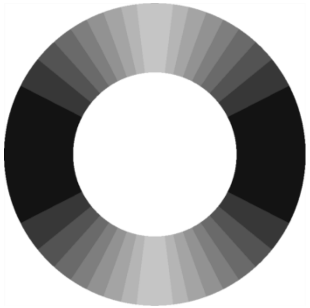
by K.-H. Mess, *et al.*

- …and so on

- These multipoles are called ***allowed multipoles***
- The field quality optimization of a coil lay-out concerns only a **few** quantities
  - For a dipole, usually *b3* , *b5* , *b7* , and possibly *b9* , *b11*

Back to the original issue: From ideal to practical configuration

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



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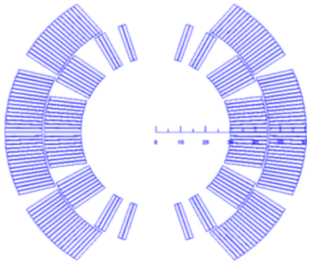
- Better ones
  - More **layers** and **wedges** to reduce *J* towards 90°



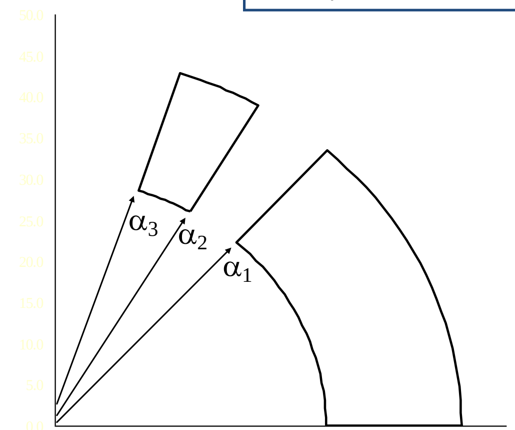
- Now, I can use the multipolar expansion to **optimize** my "practical" **cross-section**

A “good” field quality dipole
Sector dipole

by E. Todesco

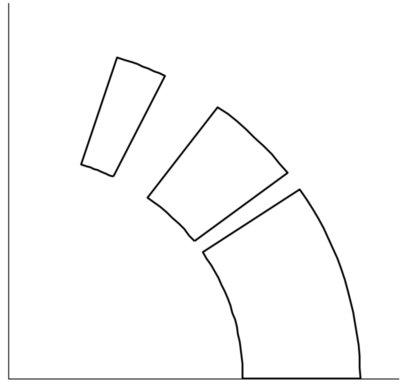
- We compute the central field given by a **sector dipole with 2 blocks**
  - Equations to set to zero **B_3, B_5 and B_7**

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



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

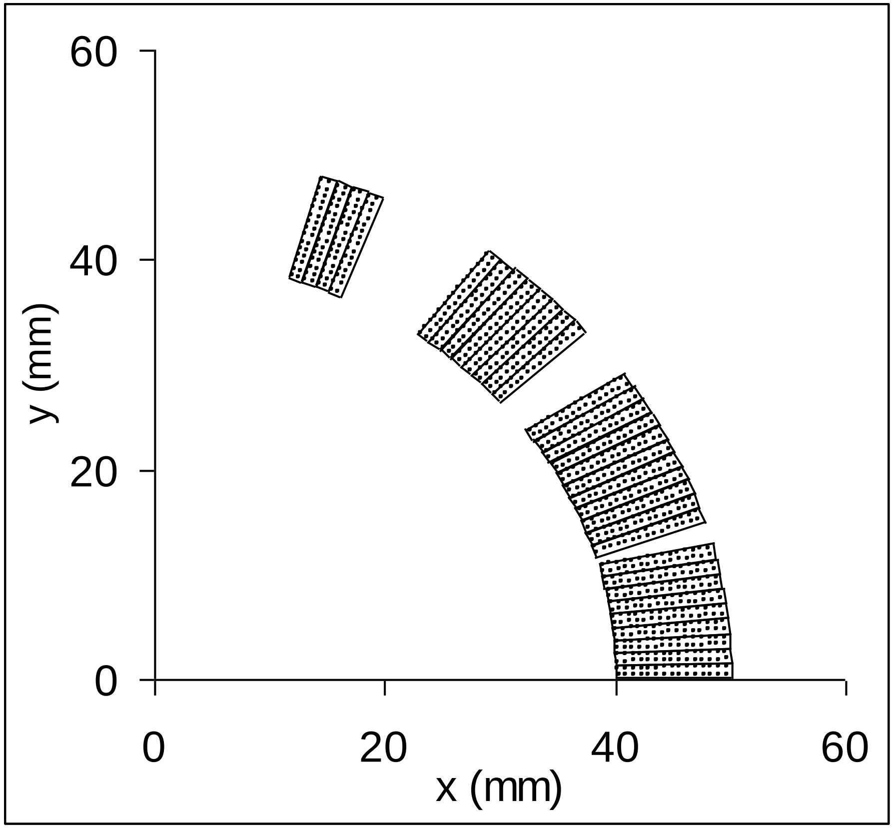
$$\sin(3\alpha_5) - \sin(3\alpha_4) + \sin(3\alpha_3) - \sin(3\alpha_2) + \sin(3\alpha_1) = 0$$
$$\sin(5\alpha_5) - \sin(5\alpha_4) + \sin(5\alpha_3) - \sin(5\alpha_2) + \sin(5\alpha_1) = 0$$
$$\sin(7\alpha_5) - \sin(7\alpha_4) + \sin(7\alpha_3) - \sin(7\alpha_2) + \sin(7\alpha_1) = 0$$
$$\sin(9\alpha_5) - \sin(9\alpha_4) + \sin(9\alpha_3) - \sin(9\alpha_2) + \sin(9\alpha_1) = 0$$
$$\sin(11\alpha_5) - \sin(11\alpha_4) + \sin(11\alpha_3) - \sin(11\alpha_2) + \sin(11\alpha_1) = 0$$

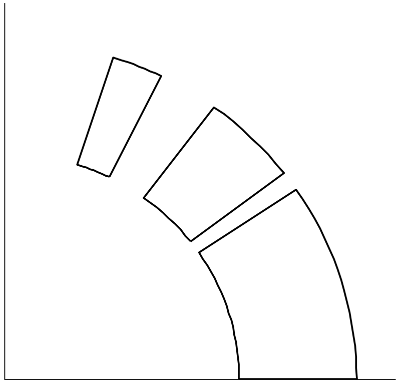


Two wedges, $b_3=b_5=b_7=b_9=b_{11}=0$
[0°-33.3°,37.1°-53.1°,63.4°- 71.8°]

A "good" field quality dipole
Sector dipole

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

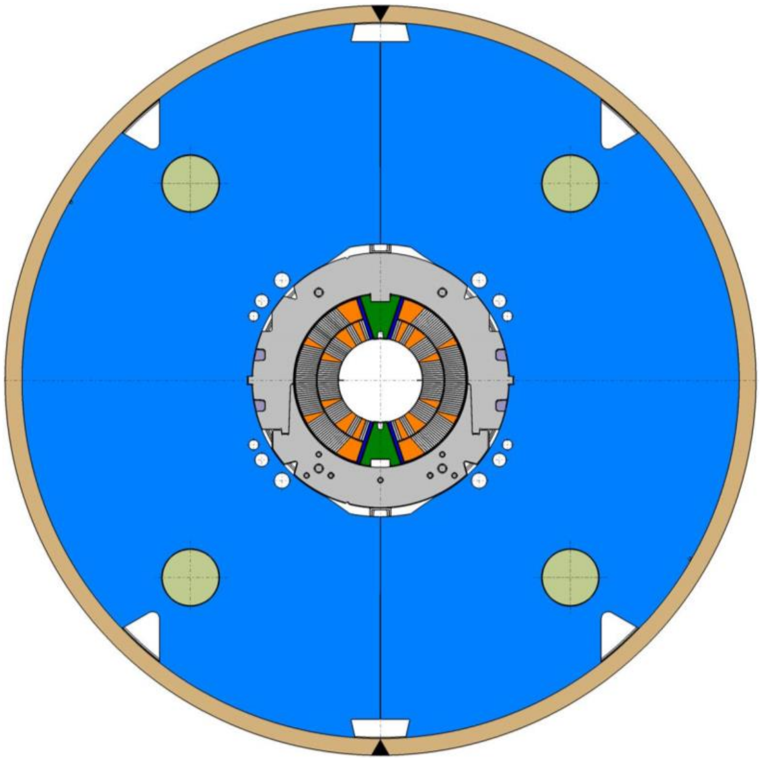




Two wedges, $b_3=b_5=b_7=b_9=b_{11}=0$
[0°-33.3°,37.1°-53.1°,63.4°- 71.8°]

Iron yoke

- Keep the **return magnetic flux** close to the coils, thus avoiding fringe fields
- In some cases the iron is partially or totally contributing to the **mechanical structure**
- Considerably **enhance the field** for a given current density
  - The increase is relevant (10-30%), getting higher for thin coils
  - This allows using lower currents, easing the protection



Iron yoke

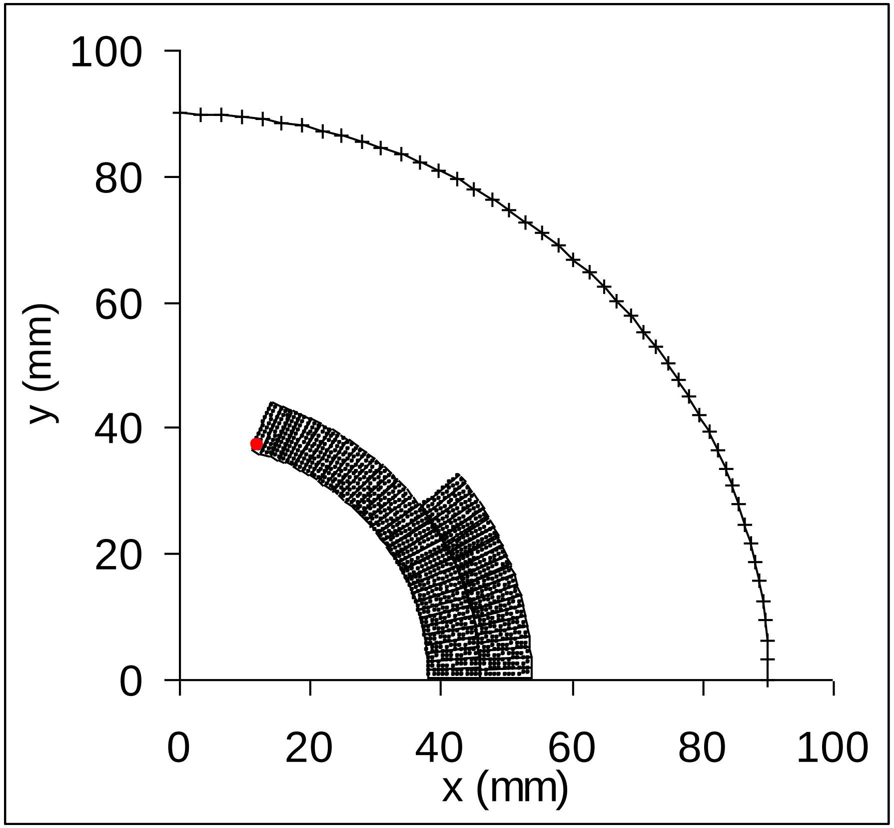
- A **rough estimate** of the **iron thickness** necessary to avoid fields outside the magnet
  - The iron cannot withstand more than 2 T
  - **Shielding condition** for dipoles: $$rB \sim t_{iron} B_{sat}$$
    - i.e., the iron thickness times 2 T is equal to the central field times the magnet aperture – One assumes that all the field lines in the aperture go through the iron (and not for instance through the collars)
    - Example: in the LHC main dipole **the iron thickness is 150 mm**

$$t_{iron} \sim \frac{rB}{B_{sat}} = \frac{28*9}{2} \sim 130 \text{ mm}$$

  - Shielding condition for quadrupoles: $$\frac{r^2 G}{2} \sim t_{iron} B_{sat}$$

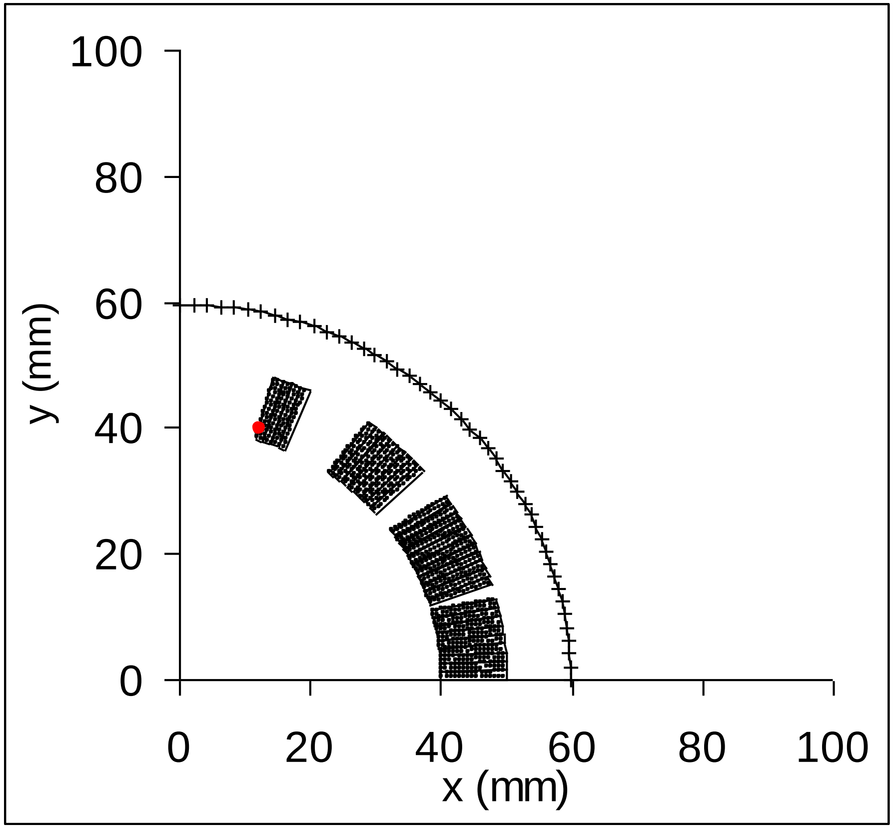
A review of dipole lay-outs

- Tevatron MB



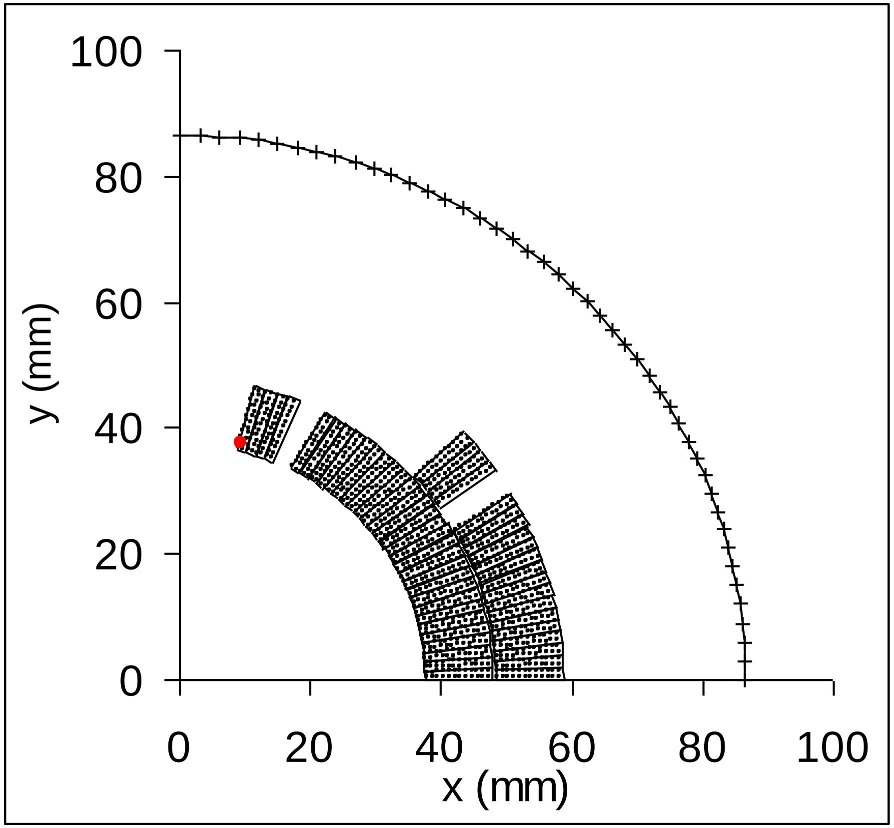
A review of dipole lay-outs

- RHIC MB



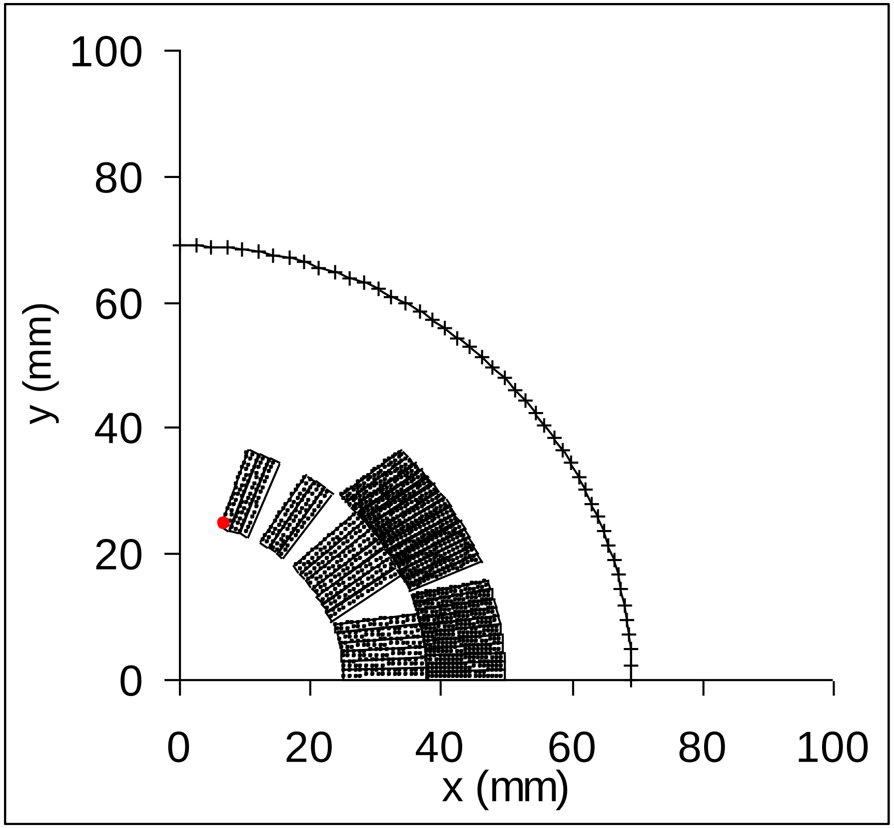
A review of dipole lay-outs

- HERA MB

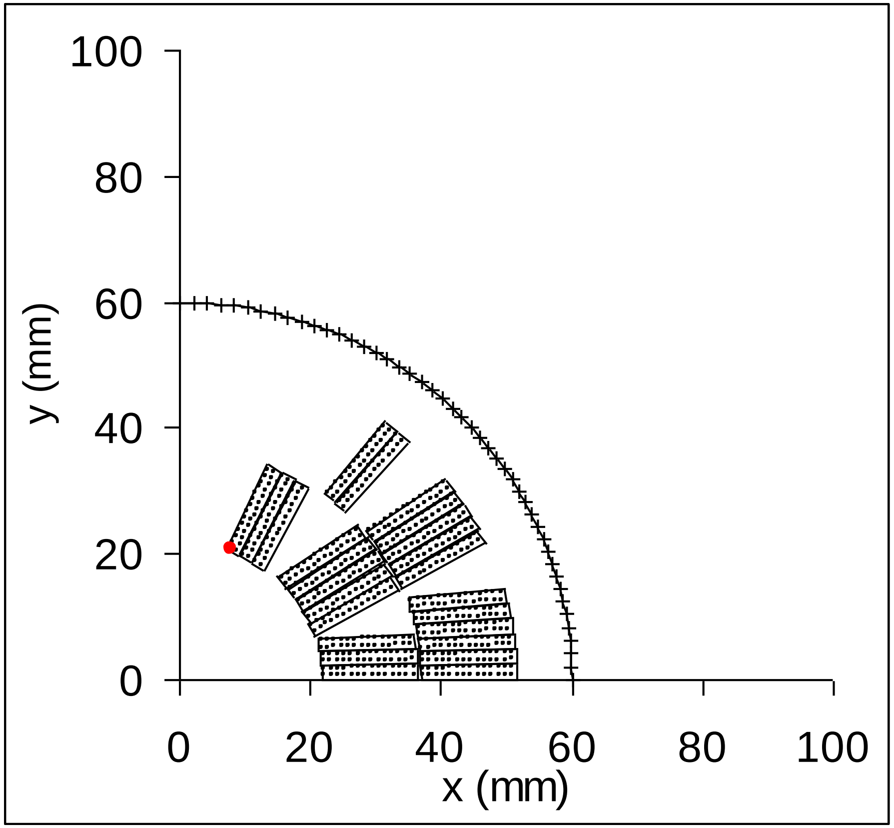


A review of dipole lay-outs

- SSC MB

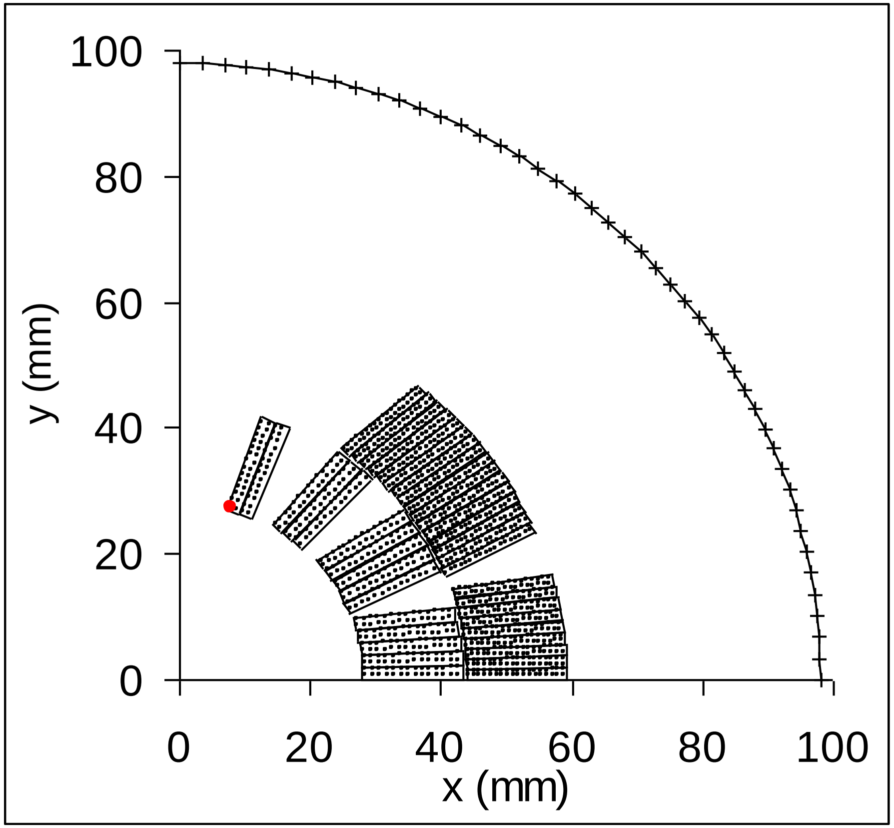


- HFDA dipole



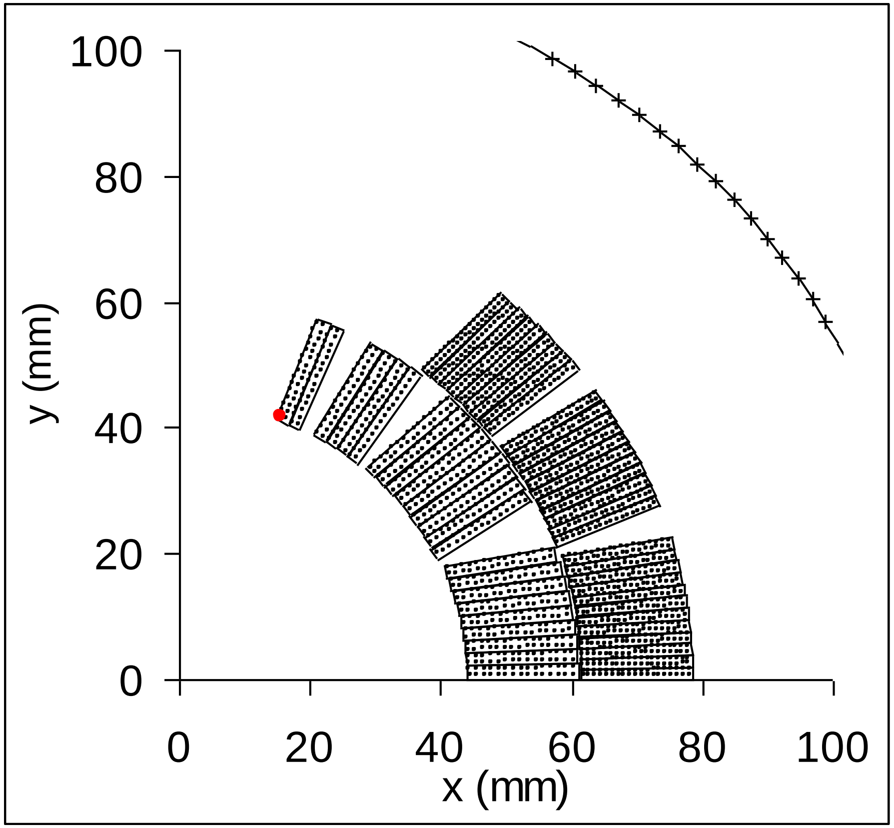
A review of dipole lay-outs

- LHC MB



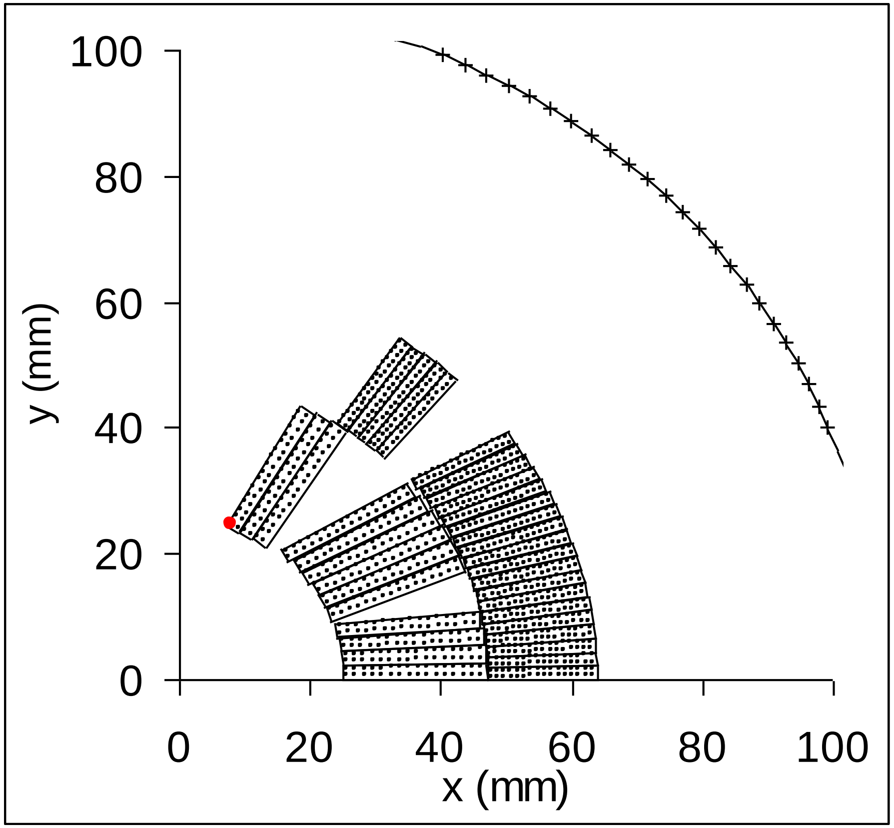
A review of dipole lay-outs

- FRESCA



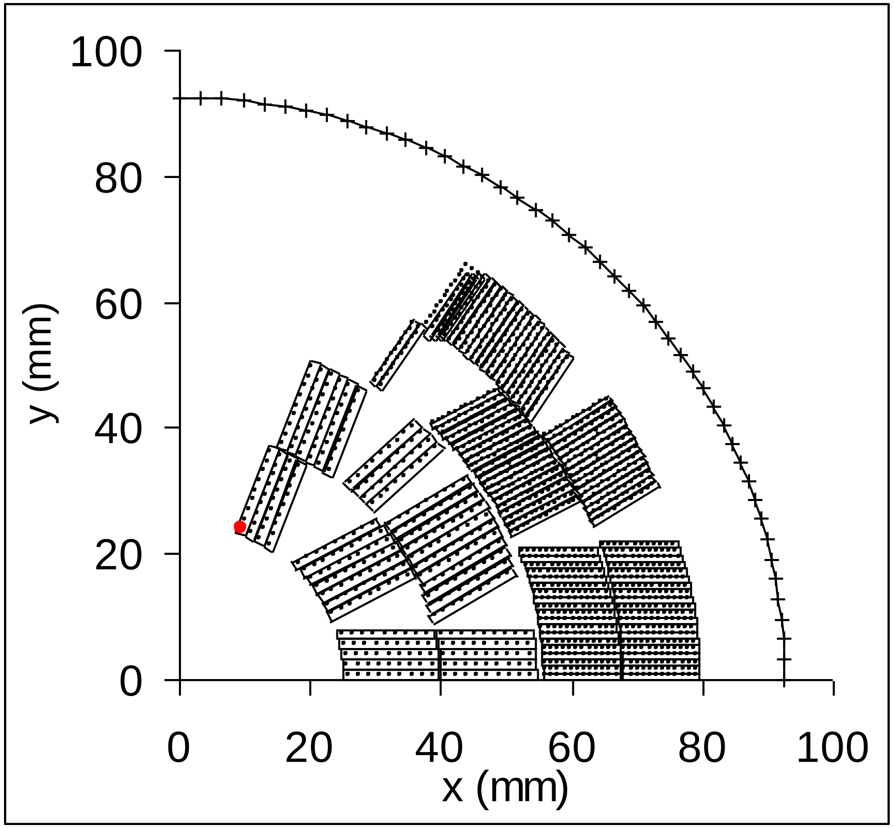
A review of dipole lay-outs

- MSUT



A review of dipole lay-outs

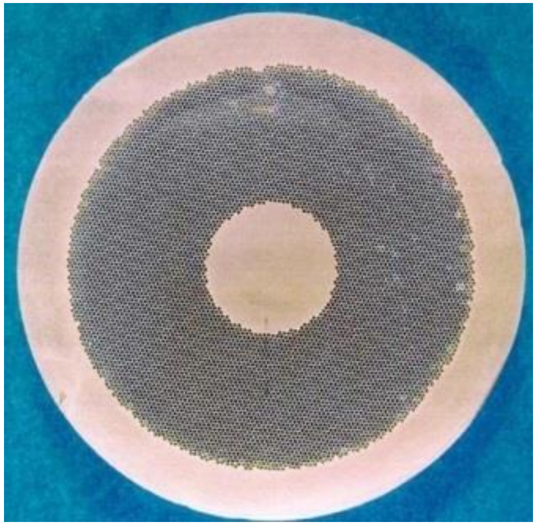
- D20



Appendix

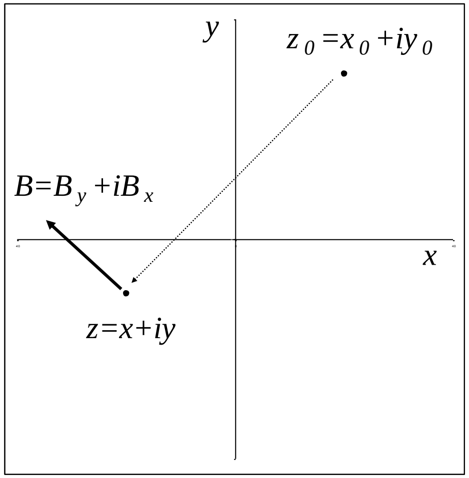
Practical superconductors
Fabrication of Nb-Ti multifilament wires

- **Copper to superconductor ratio**
  - ensure quench protection without compromising the overall critical current of wire.
- **Filament diameter**
  - Minimize flux jumps and persistent currents
  - Minimizing the wire processing cost
- **The inter-filament spacing**
  - small so that the filaments, harder then Cu, support each other during drawing operation
  - large enough to prevent filament couplings
- Cu **core** and **sheath** to reduce cable degradation
- Main manufacturing issue: **piece length**
  - It is preferable to wind coils with single-piece wire (to avoid welding)
    - LHC required piece length longer than 1 km



Field representation
Harmonics

- Important property: starting by the multipolar expansion of a current line (Biot-Savart law)



$$B(z) = B_y(z) + iB_x(z)$$

$$B(z) = \frac{I\mu_0}{2\pi(z - z_0)} = -\frac{I\mu_0}{2\pi z_0}\frac{1}{1-\frac{z}{z_0}}$$

$$B(z) = -\frac{I\mu_0}{2\pi z_0}\sum_{n=1}^{\infty}\left(\frac{z}{z_0}\right)^{n-1} = -\frac{I\mu_0}{2\pi z_0}\sum_{n=1}^{\infty}\left(\frac{R_{ref}}{z_0}\right)^{n-1}\left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$

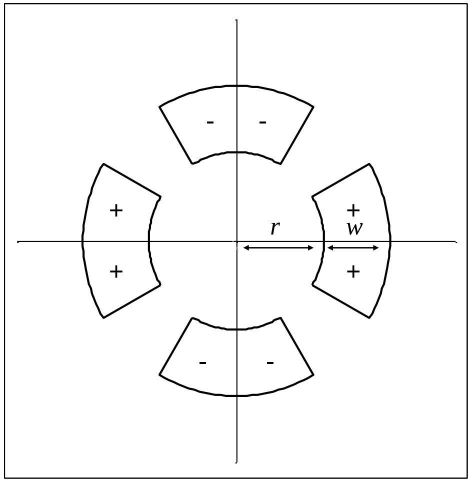
$$B_y + iB_x = 10^{-4}B_1\sum_{n=1}^{\infty}(b_n + ia_n)\left(\frac{x+iy}{R_{ref}}\right)^{n-1} \qquad b_n + ia_n = -\frac{I\mu_0 10^4}{2\pi z_0 B_1}\left(\frac{R_{ref}}{z_0}\right)^{n-1}$$

A "good" field quality dipole
Sector quadrupole

- Let's look at the quadrupoles
- First allowed multipole B_6 (dodecapole)

$$B_6 = \frac{\mu_0 j R_{ref}^5}{\pi} \frac{\sin(6\alpha)}{6} \left(\frac{1}{r^4} - \frac{1}{(r+w)^4} \right)$$

for α=π/6 (i.e. a **30° sector coil**) one has $\mathbf{B_6=0}$



- Second allowed multipole B_{10}

$$B_{10} = \frac{\mu_0 j R_{ref}^8}{\pi} \frac{\sin(10\alpha)}{10} \left(\frac{1}{r^8} - \frac{1}{(r+w)^8} \right)$$

for α=π/10 (i.e. a **18° sector coil**) or for α=π/5 (i.e. a **36° sector coil**) one has $\mathbf{B_{10}=0}$

- The conditions look similar to the dipole case …