CERN Solvay Camp – 2024

Introduction to Superconducting Magnets

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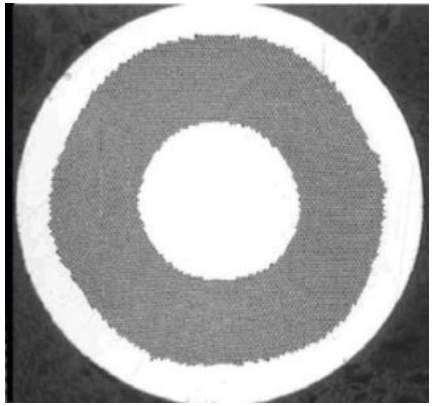
Goal of the course

- Overview of superconducting magnets for particle accelerators (dipoles and quadrupoles)
- Exciting, fancy and dirty mixture of physics, engineering, and chemistry
  - 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 and their protection
  - Cryogenics: keep them cool …
  - Cost optimization also plays a relevant role

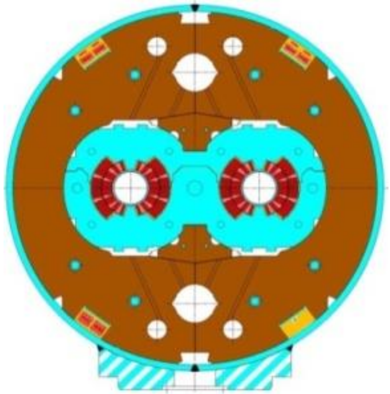
Superconducting strand



Superconducting cable

Superconducting coil

Superconducting magnet



References

Superconducting magnets for particle accelerators are a vast domain. This lecture will be especially focused on magnets for colliders, with a special eye on the CERN high energy infrastructures (LHC and HL-LHC). They are based on:

- P. Ferracin, E. Todesco, S. Prestemon, "*Superconducting accelerator magnets*", US Particle Accelerator School, www.uspas.fnal.gov.
- E. Todesco, "Masterclass -Design of superconducting magnets for particle accelerators", https://indico.cern.ch/category/12408/

Many thanks to Paolo F., Ezio T. and Luca B., for all the material I took from them for this course, and for everything I learnt from them on superconducting magnets!

Outline

- Particle accelerators, magnets and the need of superconductors
- Superconducting magnets
  - Conductor
  - Magnetic design and coil fabrication
  - Mechanical design and assembly
  - Quench, training and protection
- Future outlook

Outline

- **Particle accelerators, magnets and the need of superconductors**
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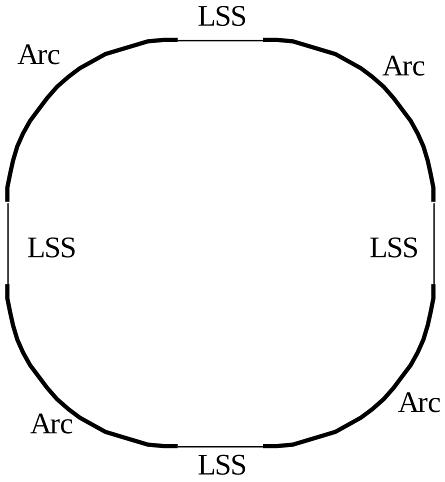
- Future outlook

The LHC

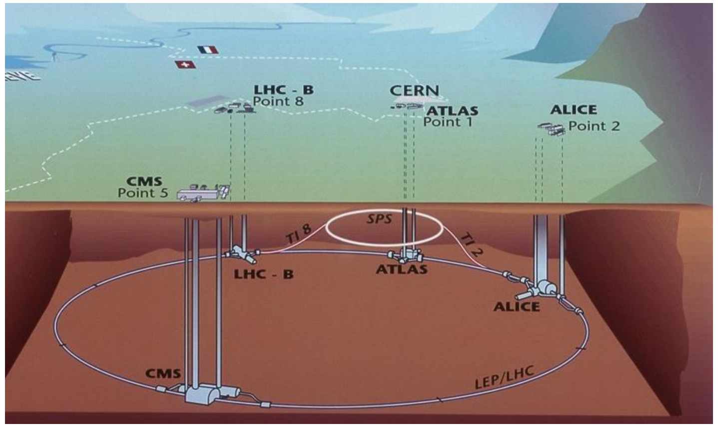
“The Arc”

- **Dipoles**: magnetic field steers (bends) the particles in a ~circular orbit
- **Quadrupoles**: magnetic field provides the force necessary to stabilize linear motion.
    - 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!)
- **Correctors**



“Long straight sections (LSS)”

- Interaction regions (IR) where the experiments are housed
    - Quadrupoles for strong focusing in interaction point
    - Dipoles for beam crossing in two-ring machines
- Regions for other services
    - Beam injection (dipole kickers)
    - Accelerating structure (RF cavities)
    - Beam dump (dipole kickers)
    - Beam cleaning (collimators)



Energy level in the LHC

Energy: Ability of making a work. Typically, we measure it in Joules or Calories. In the LHC, in Tera-Electron-Volts (13 TeV). How much is that?

- A Tera is One Million of Millions
- An Electron-Volt is the energy acquired by one electron (or proton) accelerated by a potential of 1 volt.

The **energy of each proton** is: :

$$7TeV=7\cdot 10^{12}eV=7\cdot 10^{12}\cdot 1.6\cdot 10^{-19}C\cdot 1V=\mathbf{1.1\cdot 10^{-6}J}$$

In the beam, we have about 310.000 billons of protons (which can seem a lot, but they are $5\cdot 10^{-10}g$), so the **energy of the beam** is:

$$310\cdot 10^{12}\cdot 1.1\cdot 10^{-6}J = \mathbf{340\ MJ}\ (340.000\ kJ)$$

If we compare it with a Bic Mac:

A Bic Mac is 500 kcal = 2MJ, and its weight is around 200 grams
The beam energy in the LHC is 340 MJ concentrated in a mass of $5 \cdot 10^{-10}$ grams.
Thus, the LHC beam has the energy of 170 Bic Mac, concentrated in a mass 400.000.000.000 (400 billons) smaller.

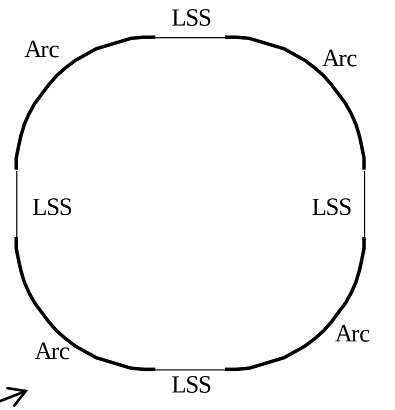
Do we need superconductors?

Principle of synchrotrons:

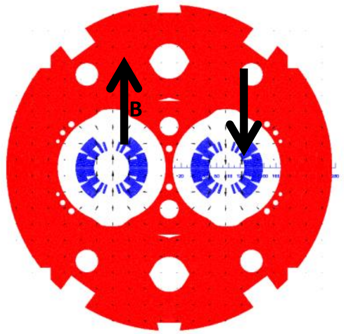
Driving particles in the same accelerating structure several times.

- Electro-magnetic field accelerates particles

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



- Magnetic field steers the particles in a ~ circular orbit



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

$$\overset{\uparrow}{p} = e\overset{\uparrow}{B}\underset{\searrow\ \text{Constant}}{\rho}$$

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

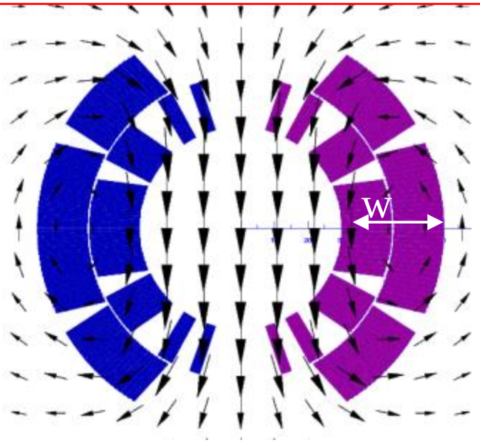
Lesson 1: If we want more energetic particles, either we make stronger magnets or we increase the size of our accelerator.

Do we need superconductors?

The magnetic field produced by an electromagnets is proportional to the current density and the size of the coil .

$$B_y = -\frac{\mu_0 J_0}{2} w$$

J_o = current density
w = coil width



In normal conducting magnets, $J \sim 5\ \text{A/mm}^2$
In superconducting magnets, $J_e \sim 600\text{-}700\ \text{A/mm}^2$

Lesson 2: If we want magnets with B>2T and a reasonable size (and energy consumptions), superconductors are needed

So the answer to the question if we need superconductors is:

¡YES!

Do we need superconductors?

Lesson 1: If we want more energetic particles, either we make stronger magnets or we increase the size of our accelerator.

Lesson 2: If we want magnets with B>2T and a reasonable size (and energy consumptions), superconductors are needed

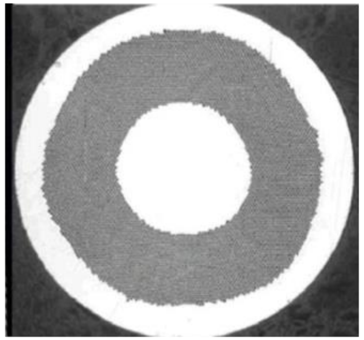
So the answer to the question if we need superconductors is:

¡YES!

Outline

- Particle accelerators, magnets and the need of superconductors
- **Superconducting magnets**
  - **Conductor**
  - **Magnetic design and coil fabrication**
  - **Mechanical design and assembly**
  - **Quench, training and protection**

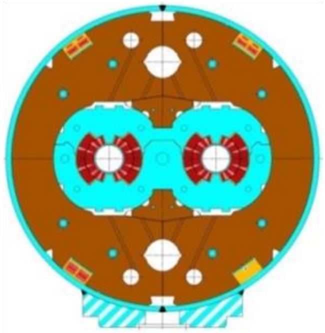
Superconducting strand



Superconducting cable

Superconducting coil

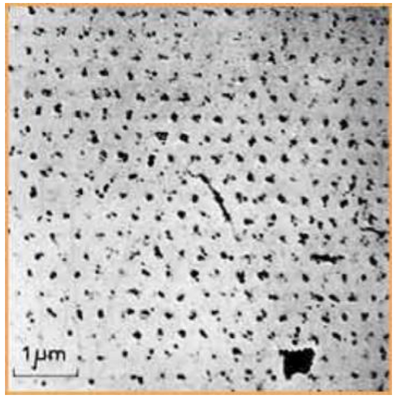
Superconducting magnet



- Future outlook

Superconducting magnets

- The science of superconducting magnets is an exciting, fancy and dirty mixture of physics, engineering, and chemistry
    - 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 and their protection
    - Cryogenics: keep them cool …
- Very different order of magnitudes



Quantized fluxoids penetrating a superconductor used in accelerator magnets

A 15m truck unloading a 27 tons LHC dipole

Large Hardon Collider
27 km, 8.33 T,14 TeV
1300 tons NbTi

- The cost optimization also plays a relevant role

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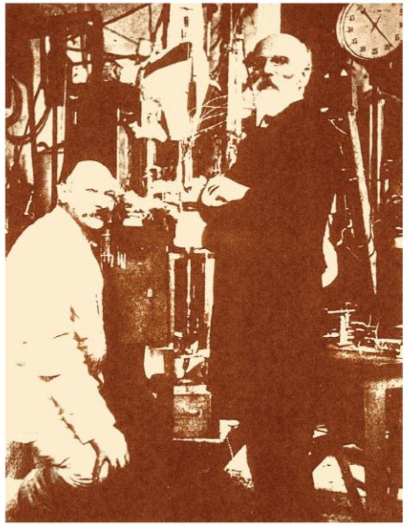
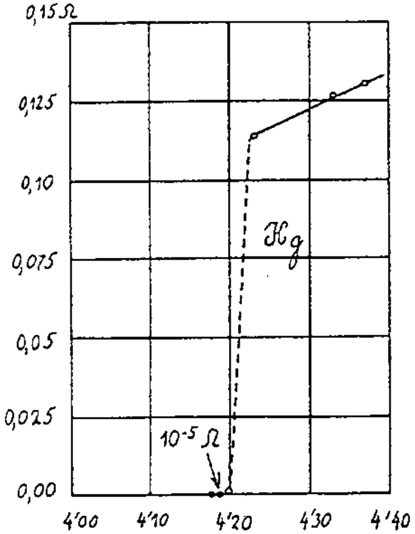
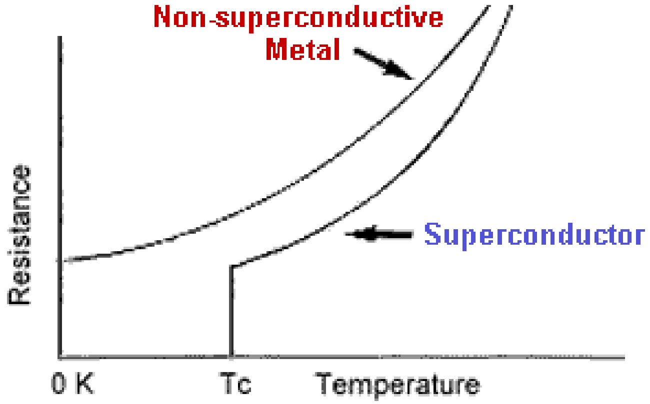
Superconductivity

- In 1911, Kammerling-Onnes, discovered superconductivity (**ZERO resistance** of mercury wire at 4.2 K)





- The temperature at which the transition takes place is called **critical temperature T_c**
- Observed in may materials
  - but not in the typical best conductors (Cu, Ag, Au)
- At $T > T_c$, superconductor very poor conductor



Practical superconductors

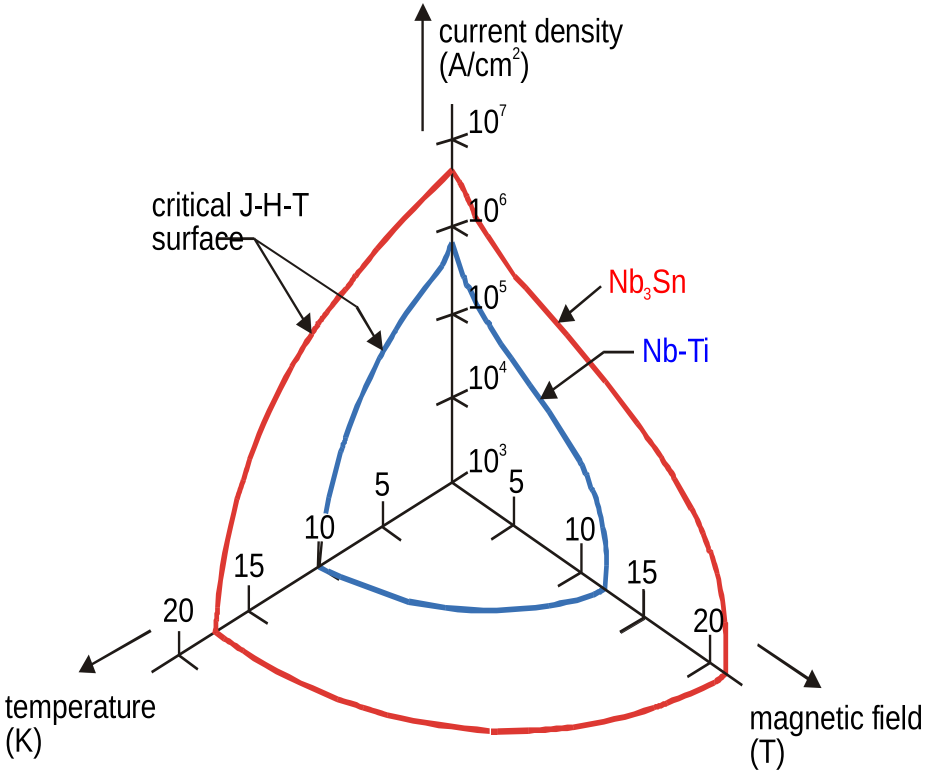
50 years later …

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℃*
- 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)

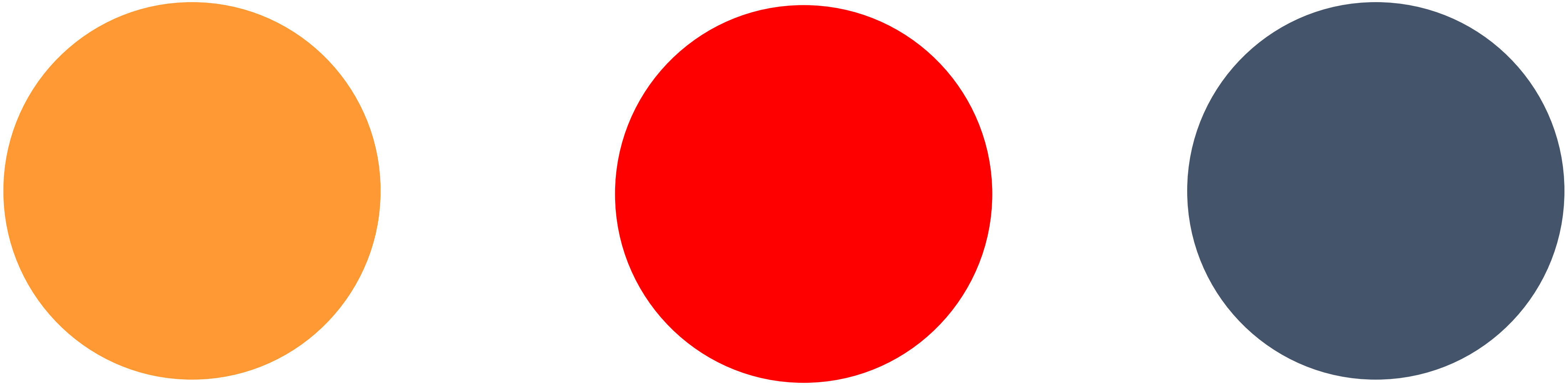


Critical surface for Nb-Ti and Nb$_3$Sn

Practical superconductors

Typical operation parameters

(for a 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

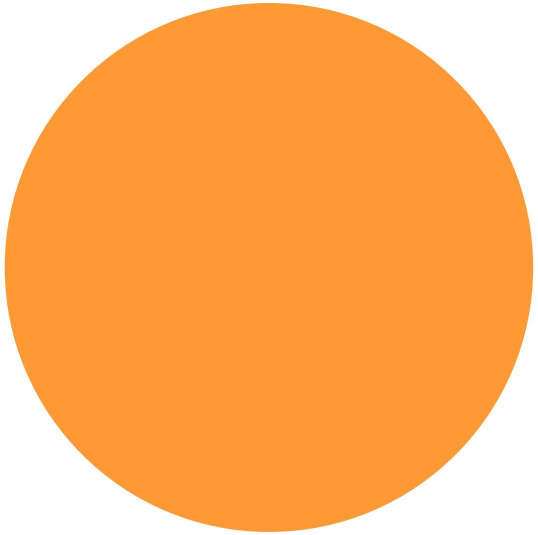
$B = 12\text{-}13$ T

Practical superconductors

Typical operation parameters

(for a 0.85 mm diameter strand)

Cu

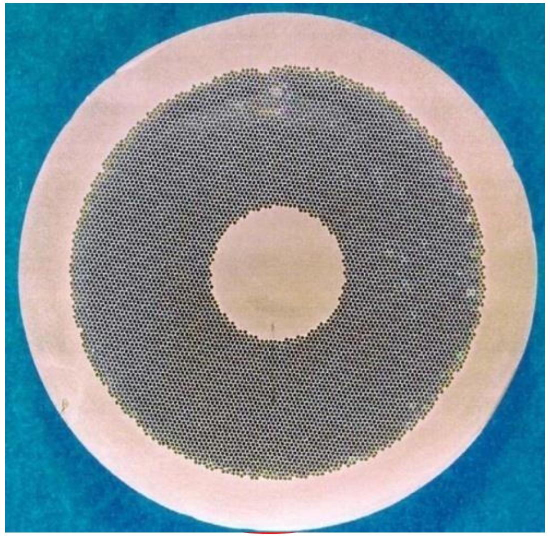


J_e ~ 5 A/mm^2

I ~ 3 A

B = 2 T

Nb-Ti

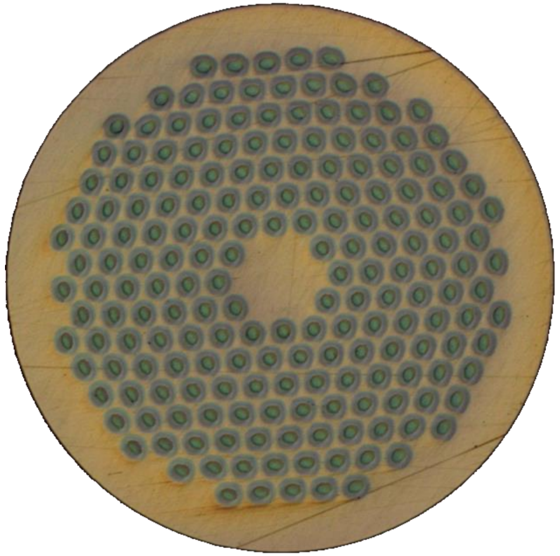


J_e ~ 600-700 A/mm^2

I ~ 300-400 A

B = 8-9 T

Nb_3Sn

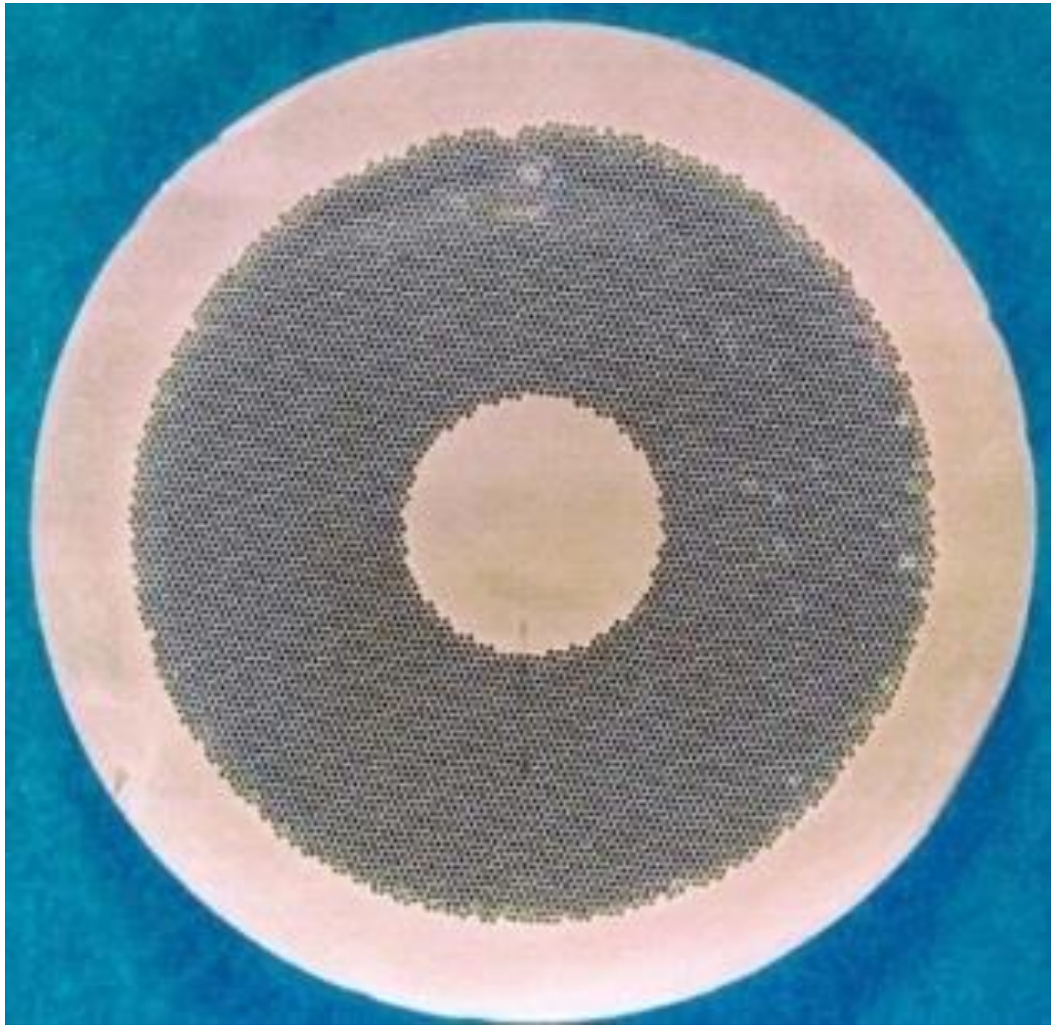


J_e ~ 600-700 A/mm^2

I ~ 300-400 A

B = 12-13 T

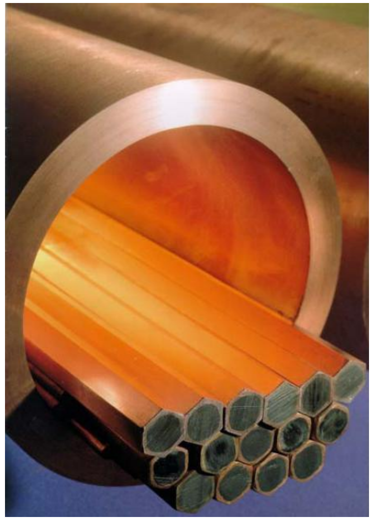
Strand: a multifilament wire

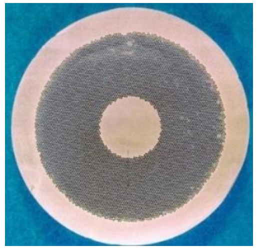


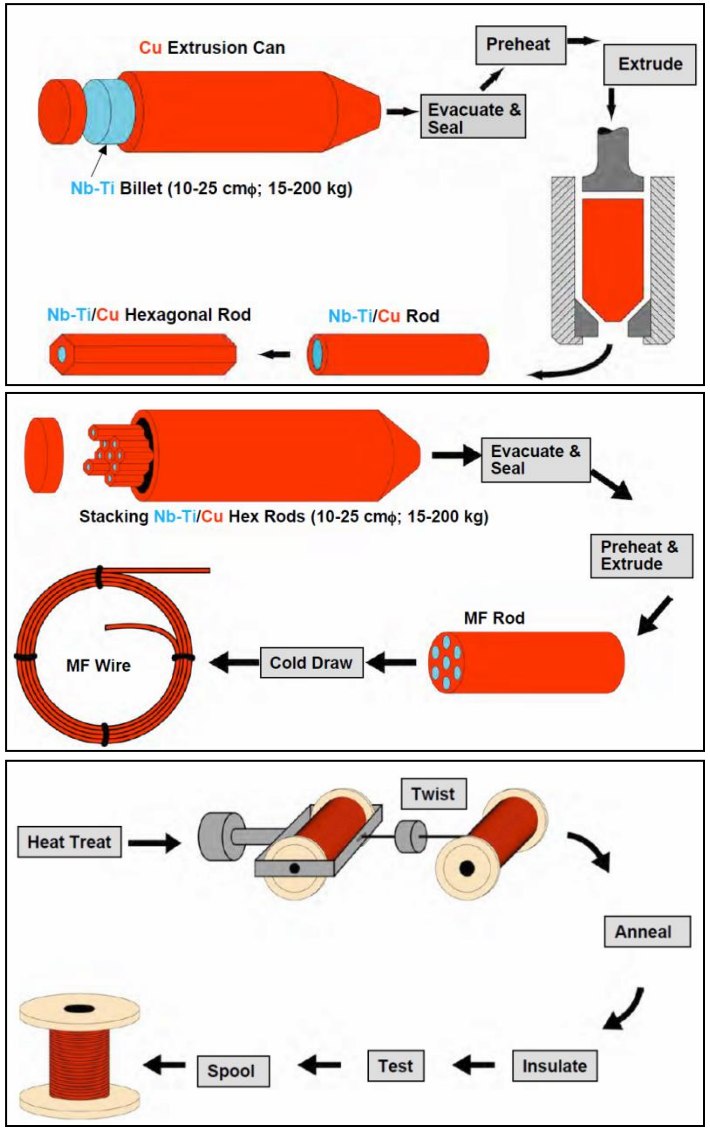
- Superconducting materials are produced in small filaments and surrounded by a stabilizer (typically copper) to form a “*multi-filament wire*” o “*strand*”
- **Why small filaments are needed?**
  - **Stability** (flux jumps)
  - **Magnetic field quality**
    - Persistent currents
    - Inter-filament coupling currents
- **Why are they embedded in a copper matrix?**
  - **Protection**, to redistribute the current in case of quench

Strand: Manufacturing process (NbTi)

- **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**







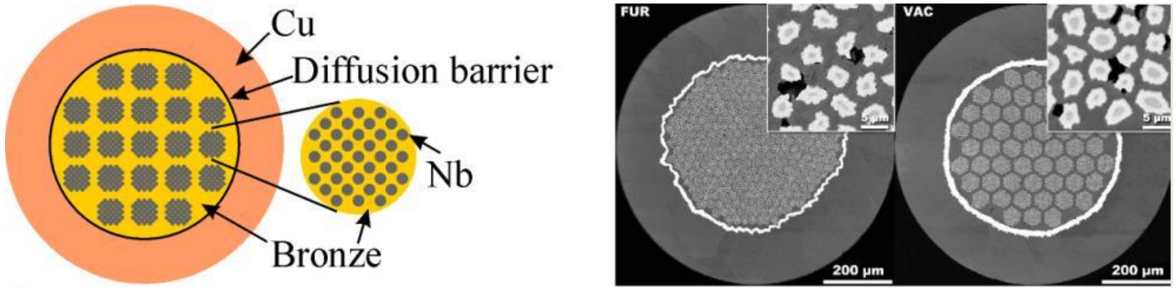
Strand: Manufacturing process (Nb_3Sn)

See lecture
Michael Eisterer

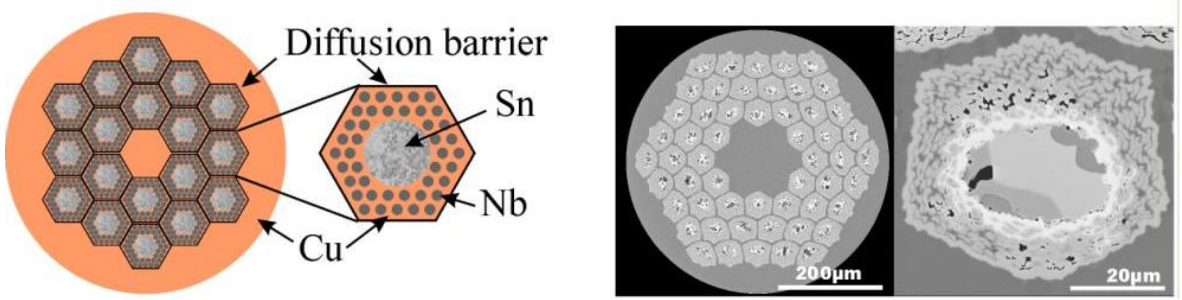
- Since Nb_3Sn is brittle
  - It cannot be extruded and drawn like Nb-Ti. It must be formed at the end of the fabrication of the cable (or the coil).
- Process in several steps
  - Fabrication of the wire, assembling multifilament billets from with **Nb and Sn separated**. Different processes tried in industrial scale (bronze process, internal tin process, powder in tube process)
  - Fabrication of the cable
  - Fabrication of the coil. Two different techniques:
    - **Wind & react”** (more common). First coil winding and then formation of Nb_3Sn
    - **“React & wind”.** First formation of Nb_3Sn and then coil winding
  - **Reaction.** Heating to about 600-700 C in vacuum or inert gas (argon) atmosphere, and the Sn diffuses in Nb and reacts to form Nb_3Sn.

by A. Godeke

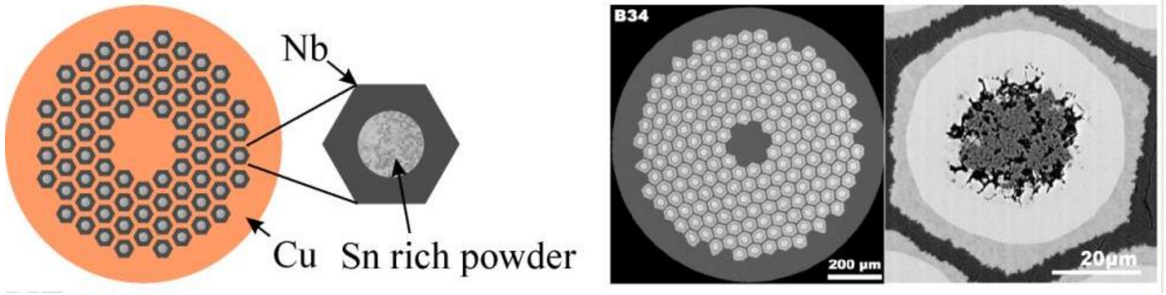
Bronze process



Internal tin process



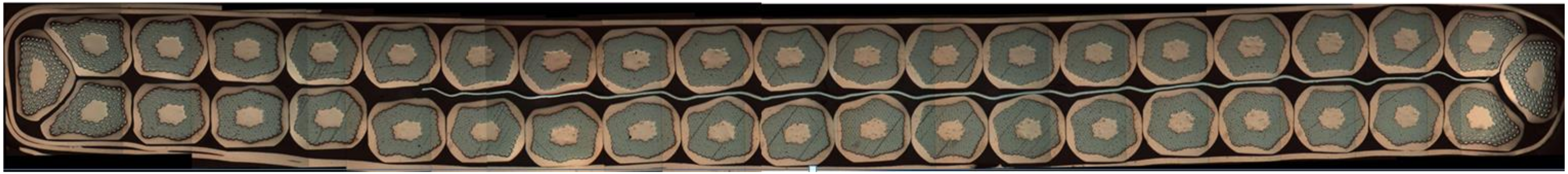
Powder in tube process



The cable

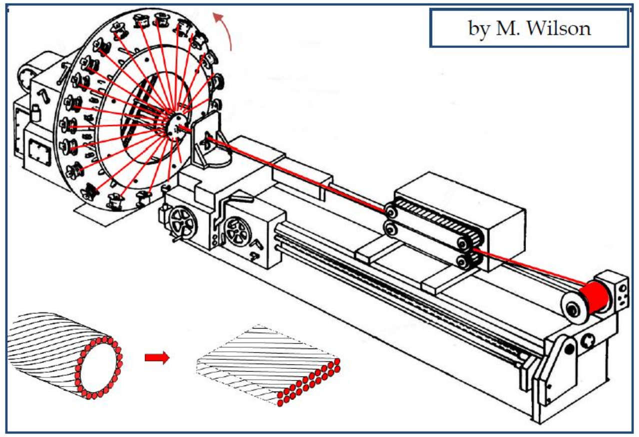
- Most of the superconducting coils for particle accelerators wound from a multi-strand cable (**Rutherford cable**). The strands are **twisted** to
  - Reduce **inter-strand coupling currents**
    - Losses and field distortions.
  - Provide more **mechanical stability**
  - **Current redistribution** (in case a defect in one strand)
  - Reduction the **number of turns** (easier winding, lower inductance)
  - Reduction strand **piece length**

Picture by Charlie Sanabria



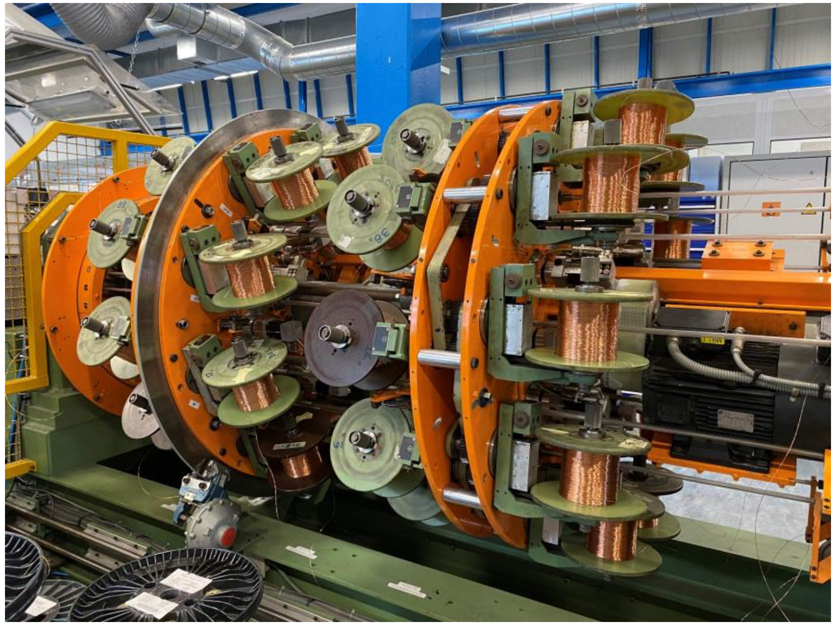
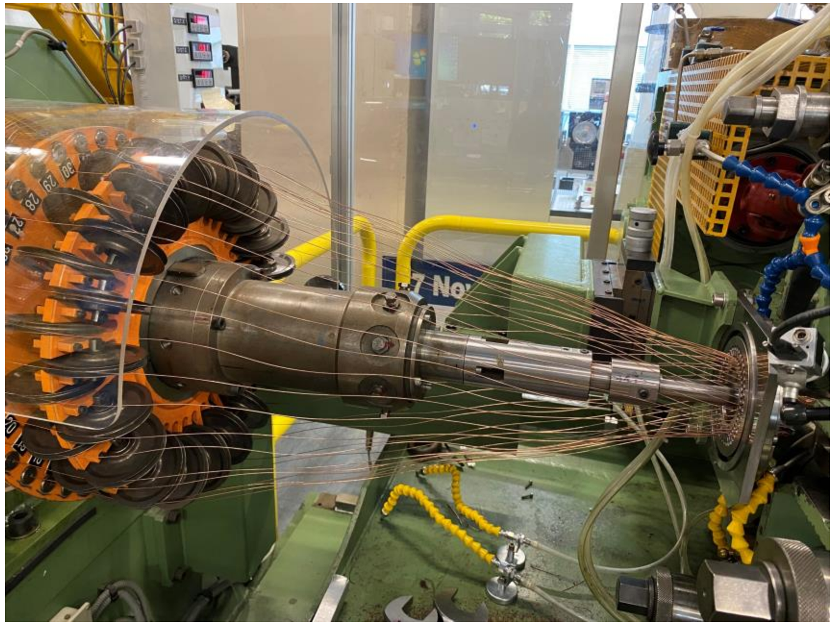
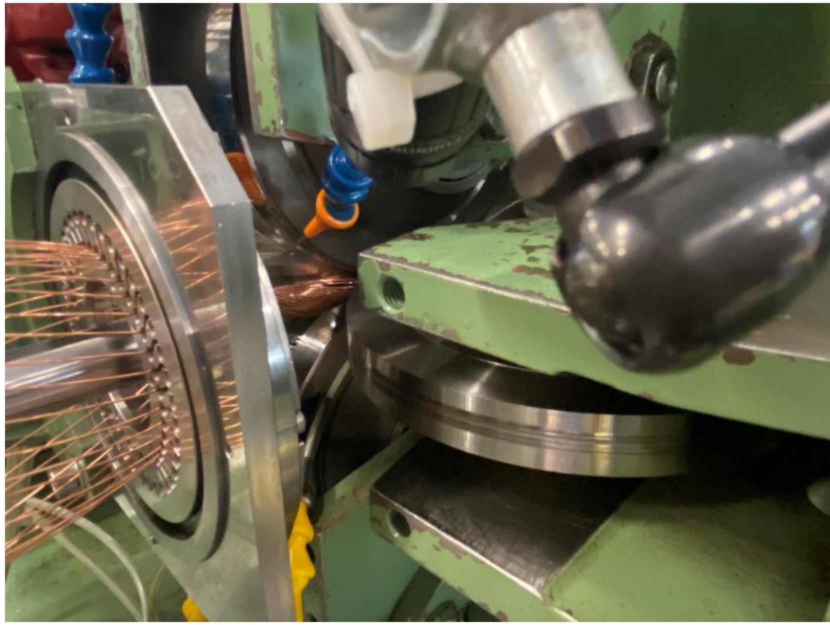
Picture by Jerome Fleiter

Fabrication of the Rutherford cable



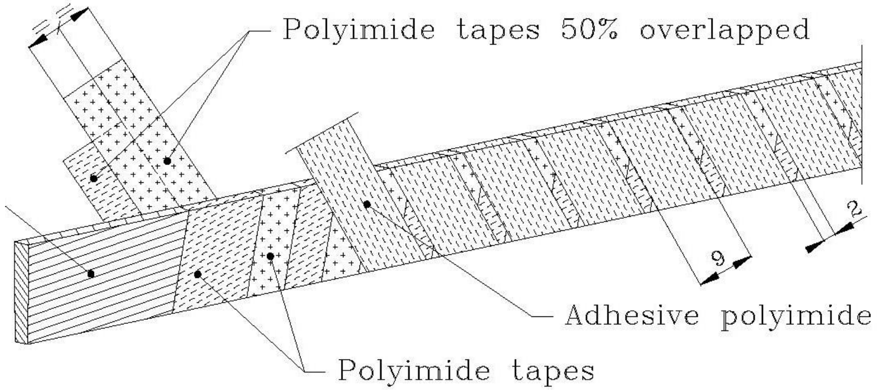
- Fabrication of the Rutherford cable:
  - Strands wound on spools mounted on a rotating drum
  - Strands twisted around a conical mandrel into rolls
  - The rolls compact the cable and provide the final shape

CERN cabling machine

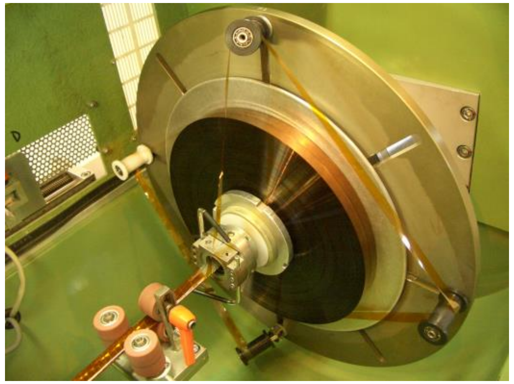




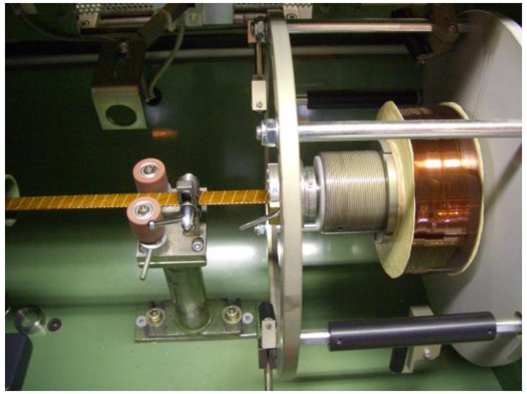
Cable insulation

- 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 (for non-impregnated coils)
  - **Radiation hardness** (depending on the location in the machine)
- In Nb-Ti magnets the most common insulation is a series of overlapped layers of polyimide (Kapton®).
- In the LHC case: two polyimide layers 50.8 μm thick wrapped around the cable with a 50% overlap, with another adhesive polyimide tape 68.6 μm thick wrapped with a spacing of 2 mm.




Polyimide insulation for Nb-Ti

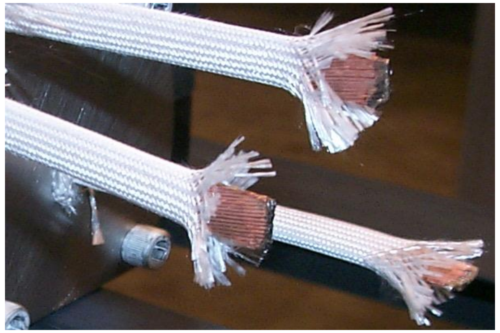




Cable insulation

- In Nb_3Sn magnets, where cable are reacted at 600-700 °C, the most common insulation is fiberglass: tape or sleeve or braided.
  - Braided insulation is done in industry for HL-LHC cables
- Typically, the insulation thickness varies between 100 and 200 µm.

Fiber glass insulation for Nb_3Sn



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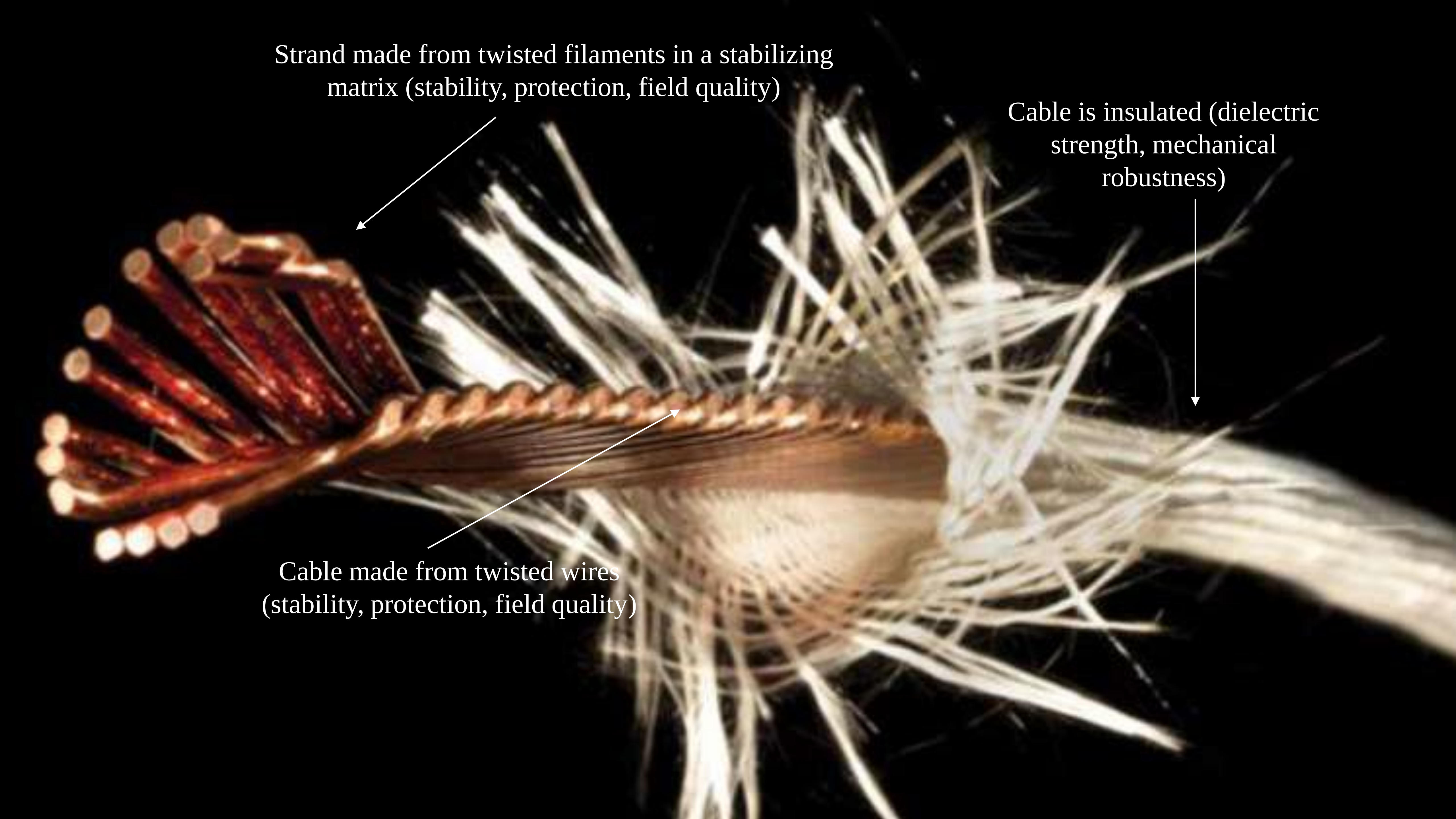


Strand made from twisted filaments in a stabilizing matrix (stability, protection, field quality)

Cable is insulated (dielectric strength, mechanical robustness)

Cable made from twisted wires (stability, protection, field quality)

How to create a dipole field?

Perfect dipole

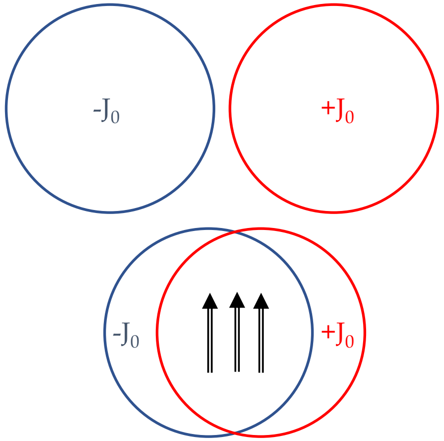
- Within a cylinder carrying ***j₀***, the field is perpendicular to the radial direction and proportional to the distance to the centre ***r***:

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

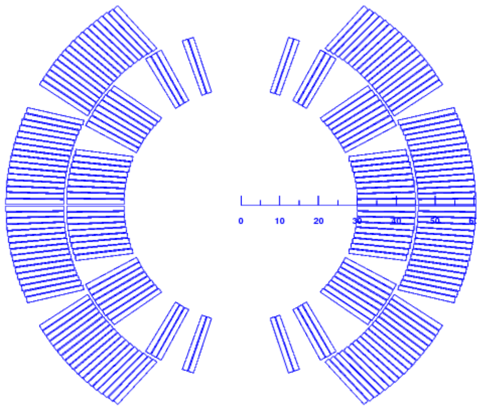
  - Combining the effect of two intersecting cylinders

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

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



From ideal to practice configuration



But…

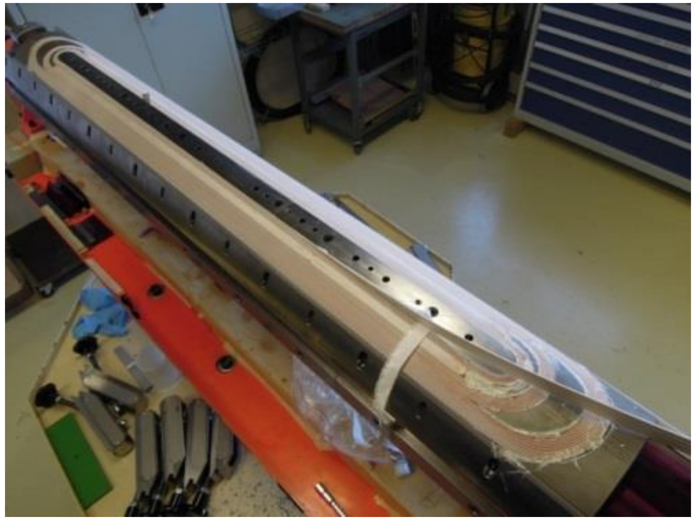
- The aperture is not circular
- Not easy to simulate with a flat cable

The idea: reproduce a ***cosθ*** current distribution with a cable
(Rectangular cross-section and constant *J)*
It will not be a perfect field…but it can be pretty close!

Coil fabrication (Nb_3Sn)

Winding & Curing

The cable is wound around a pole on a mandrel.
A ceramic binder is applied and cured (T~ 150 C) to have a rigid body easy to manipulate.



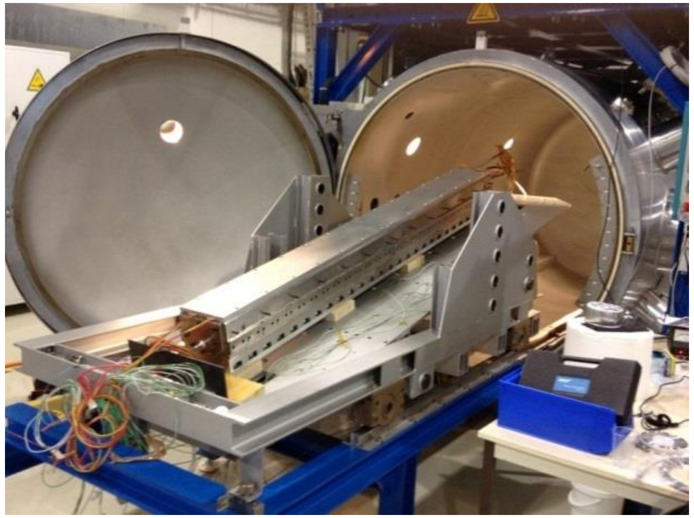
Reaction

Sn and Nb are heated to 650-700 C in vacuum or inert gas (argon) → Nb_3Sn

The cable becomes brittle

Impregnation

In order to have a **solid block**, the coil placed in a impregnation fixture
The fixture is inserted in a vacuum tank, evacuated → **epoxy injected**



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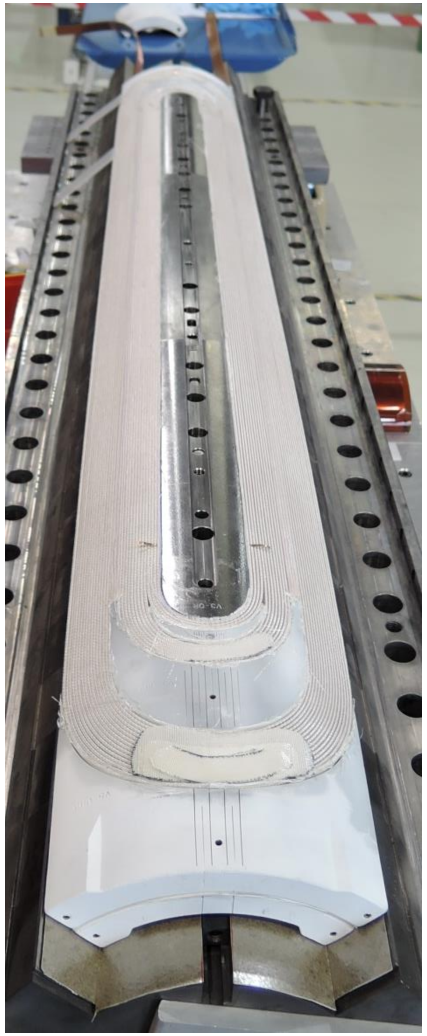
Coil at different manufacturing steps



After curing

After reaction

After impregnation

Mechanical design

- In the presence of a magnetic field ***B***, an electric charged particle ***q*** in motion with a velocity ***v*** is acted on by a force ***F_L*** called electro-magnetic (Lorentz) force [N]:

$$\vec{F}_L = q\vec{v} \times \vec{B}$$

- A conductor element carrying current density J (A/mm^2) is subjected to a force density ***f_L*** [N/m^3]

$$\vec{f}_L = \vec{J} \times \vec{B}$$

Some examples (values per aperture):

Nb-Ti LHC MB (8.3 T)

- F_x = **340 t** per meter
  - ~300 compact cars
- F_z = **27 t**

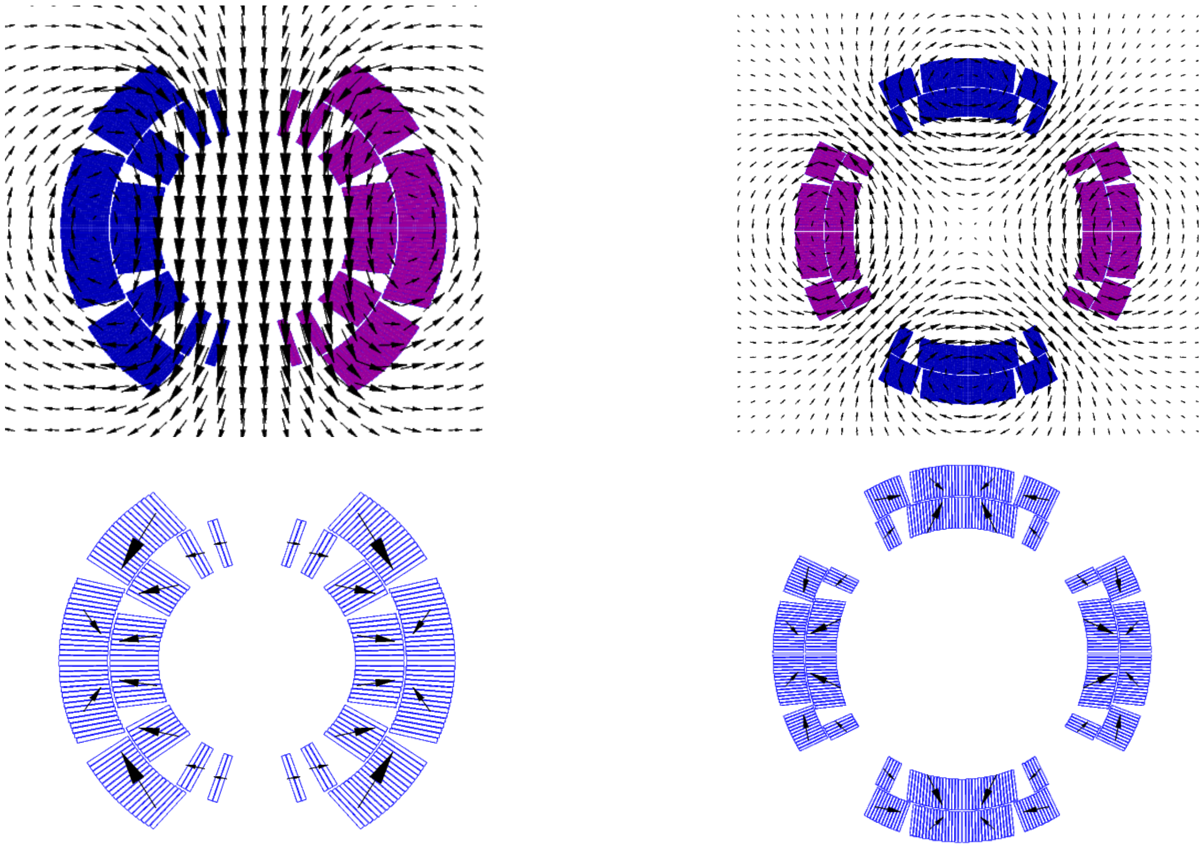
Nb_3Sn DS dipole (11T)

- F_x = **620 t** per meter
- F_z = **47 t**

Susana Izquierdo Bermudez

Electro-magnetic force

- The e.m forces in a dipole/quadrupole magnet tend to push the coil
  - Towards the mid-plane in the azimuthal direction
  - Outwards on the radial direction.



Electro-magnetic force

- In the coil ends, the electromagnetic forces tend to push the coil outwards in the longitudinal direction ($F_z > 0$)

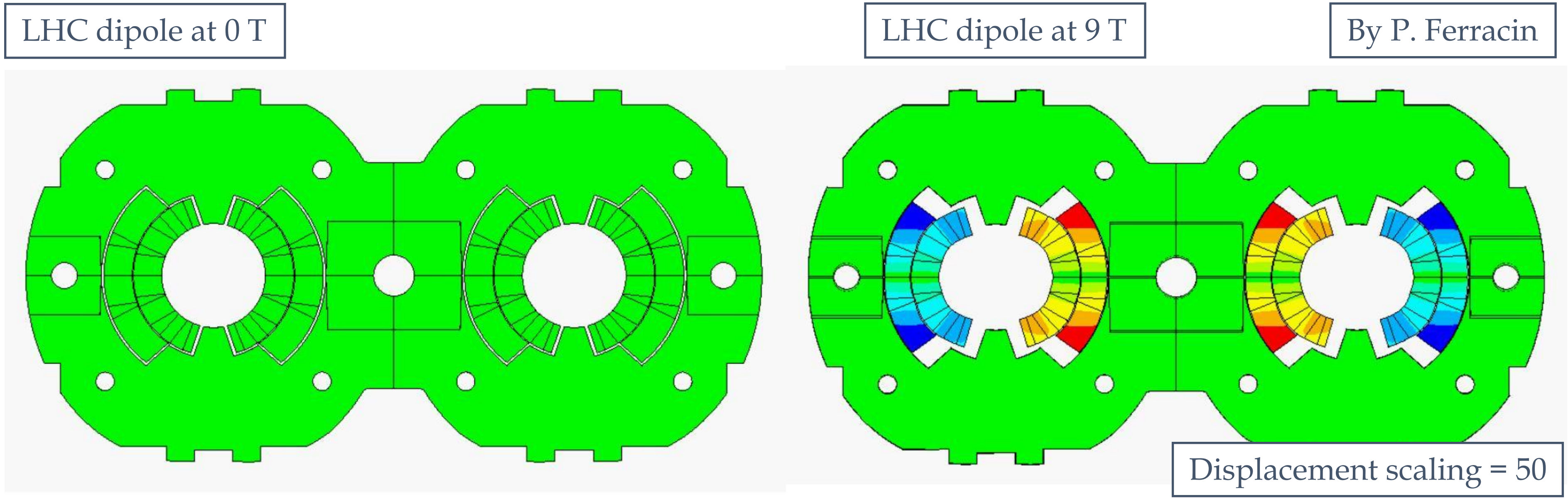
11 T dipole for HL-LHC

MQXF quadrupole for HL-LHC

Susana Izquierdo Bermudez

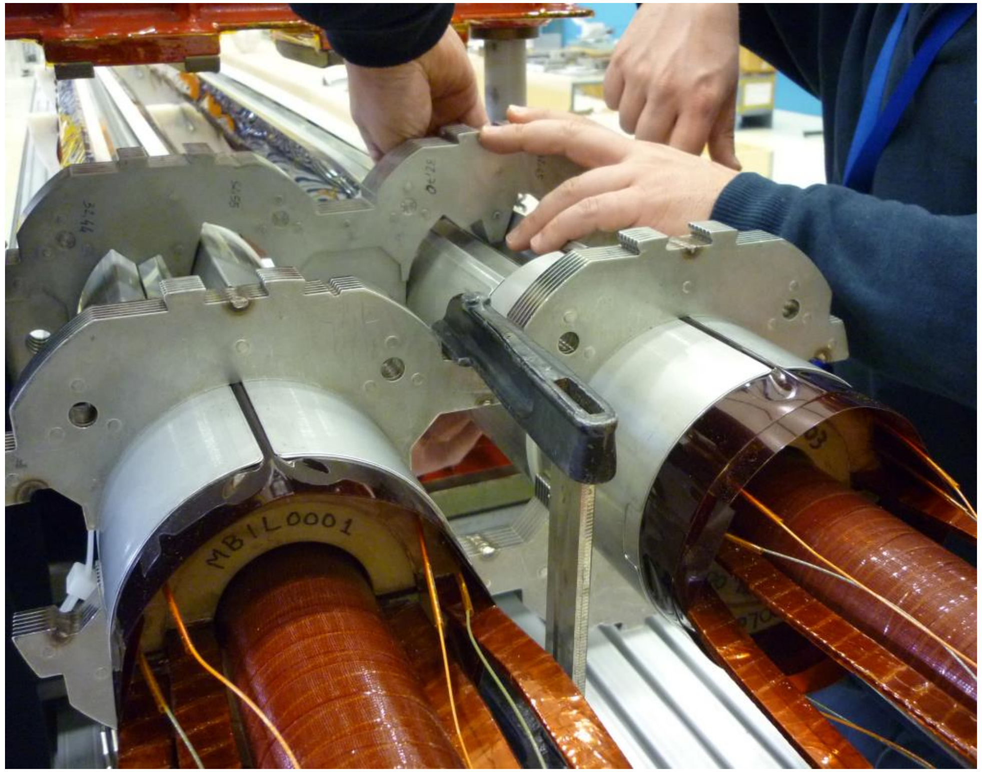
Deformation and stress

- Effect of e.m forces
  - change in **coil shape** → effect on field quality
  - a **displacement** of the conductor → potential release of frictional energy
  - Nb-Ti magnets: possible **damage** of kapton **insulation** at~150-200 MPa.
  - Nb_3Sn magnets: possible **conductor degradation** at about 150-200 MPa.
- All the components must be below stress limits.



Overview of the coil stress

1. **Collaring**: By clamping the coils, the collars provide
   - coil **pre-stressing**;
   - **rigid support** against e.m. forces
   - **precise cavity**



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   - Magnetic function
   - Mechanical function (increase the rigidity of the coil support structure and limit radial displacement)
   - Alignment, assembly features…

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3. **Shell welding**: two half shells welded around the coil to provide
    - Helium container
    - Additional rigidity
    - If necessary, the welding press can impose the desired curvature on the cold mass

Overview of coil stress

4. Cool-down

- Components shrink differently
  - Again, coil positioning within 20-50 μm
- Significant **variations of coil stress**

5. Excitation

- The pole region of the coil unloads
  - Depending on the pre-stress, at nominal field the coil may unload completely

All these contributions taken into account in the **mechanical design:**

- Minimize **coil motion** (pre-stress)
- Minimize **cost and dimension** of the structure
- Maintain the maximum stress of the component **below the plasticity limits**
- …and for (especially) Nb_3Sn coils, **limit coil stress** (150-200 MPa).

Quench definition

Quench = irreversible transition to normal state

- **Heat generation > cooling**

Why do magnets quench?

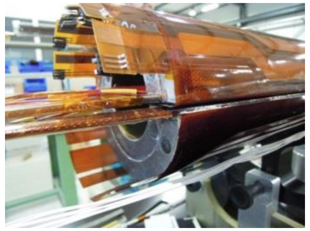
Thermal energy released by

- **Mechanical events**
  - Frictional motion
  - Epoxy cracking
- **Electromagnetic events**
  - Flux-jumps ,AC loss
- **Thermal events**
  - Degraded cooling
- **Nuclear events**
  - Particle showers

What do we do when a magnet quenches?

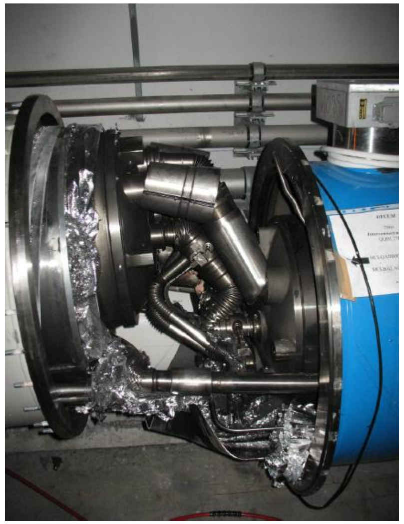
Conversion **magnetic energy** → **thermal energy** (redistribute the energy in the whole coil volume, joule heating)

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



Why is it a problem ?

- Quench is the result of the resistive transition, leading to appearance of voltage, temperature increase, thermal and electro-magnetic forces, and cryogen expulsion
- If the process does not happen uniformly: as little as 1 % of the magnet mass may absorb the total energy – large damage potential !

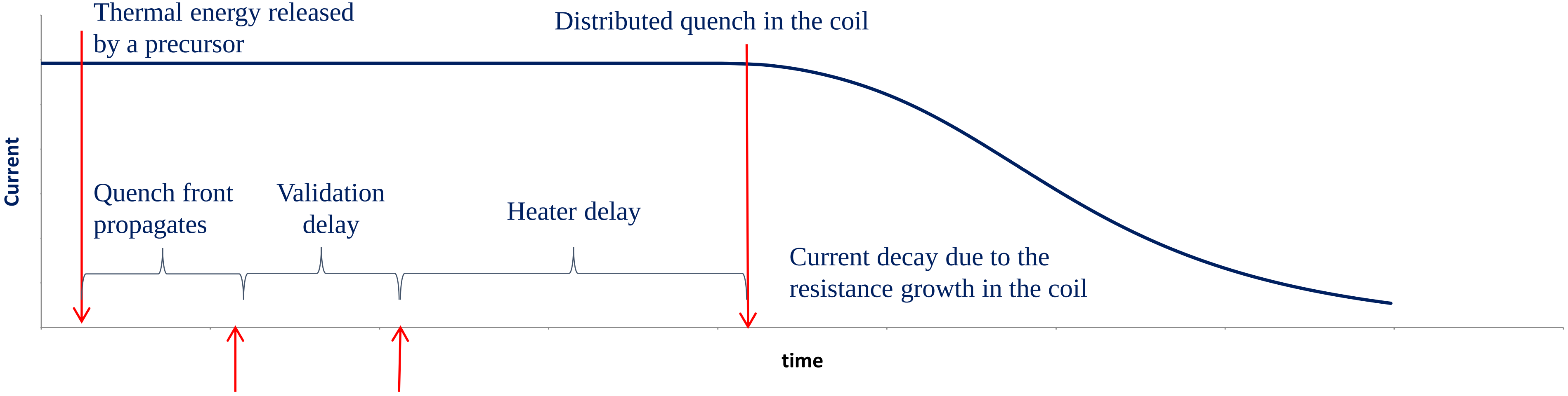


Result of the chain of events triggered by a quench in an LHC bus-bar

Result of degradation due to local heating in a NbTi coil

Result of electrical short circuit quench heater to coil in a Nb_3Sn coil

The quench event: summary



Quench starts
Thermal energy released by a precursor

Heaters effective
Distributed quench in the coil

Quench front propagates

Validation delay

Heater delay

Current decay due to the resistance growth in the coil

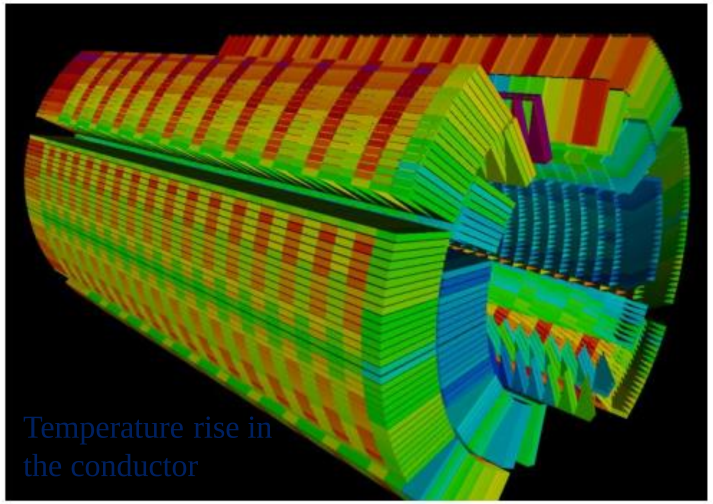
Quench detected

Quench validated
(power supply off, protection system fired)

Typical time scale:

- From quench start to quench detected ~ 5 ms
- Validation delay ~ 10 ms
- Heater delay ~ 20 ms
- Current decay ~ 100-200 ms

Maximum acceptable temperature: **350K**



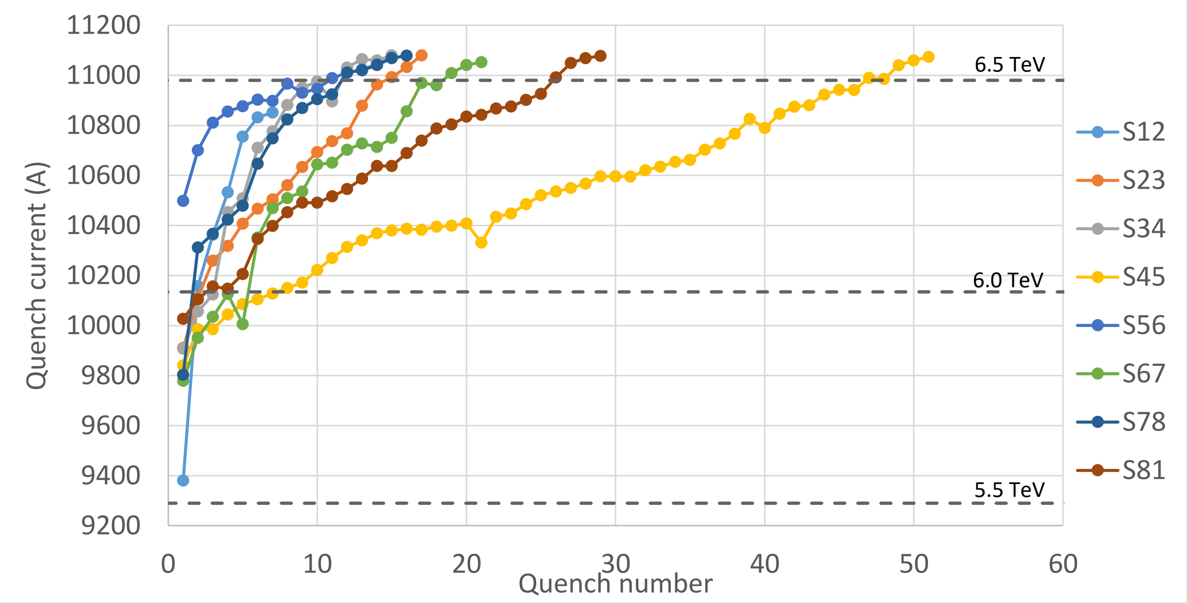
Temperature rise in the conductor

Training

- **Training is characterized by two phenomena:**
  - The occurrence of premature quenches (below short sample limit)
  - The progressive increase of quench current, ramp after ramp
- The magnet «improves» ramp after ramp to reach the nominal performance = operating point with margin

- **Main identified causes :**
  - Frictional motion
    - E.m. forces → motion → quench
    - Coil progressively locked by friction in a secure state
  - Epoxy failure
    - E.m. forces → epoxy cracking → quench
    - Once epoxy locally fractured, further cracking appears only when the e.m. stress is increased.

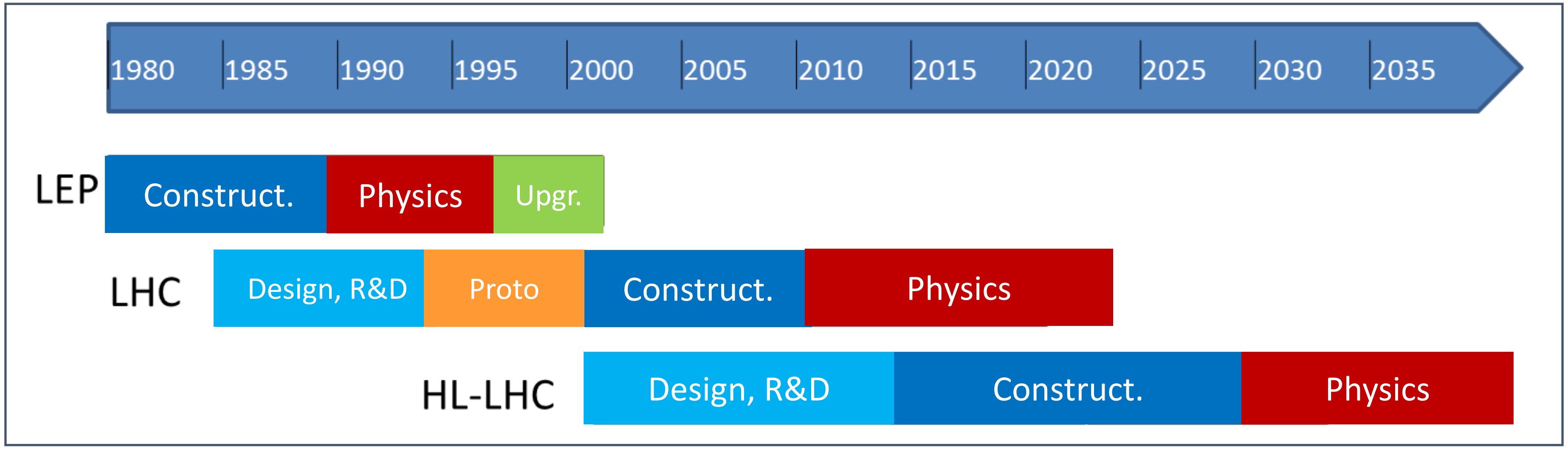
Training of LHC sectors to 6.5 TeV



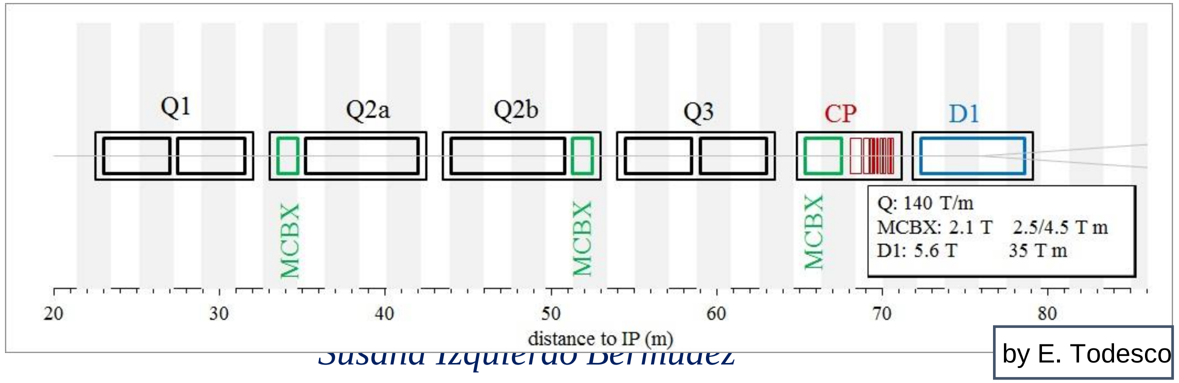
Outline

- Particle accelerators, magnets and the need of superconductors
- Superconducting magnets
  - Conductor
  - Magnetic design and coil fabrication
  - Mechanical design and assembly
  - Quench, training and protection
- Future outlook

Hi-Lumi LHC



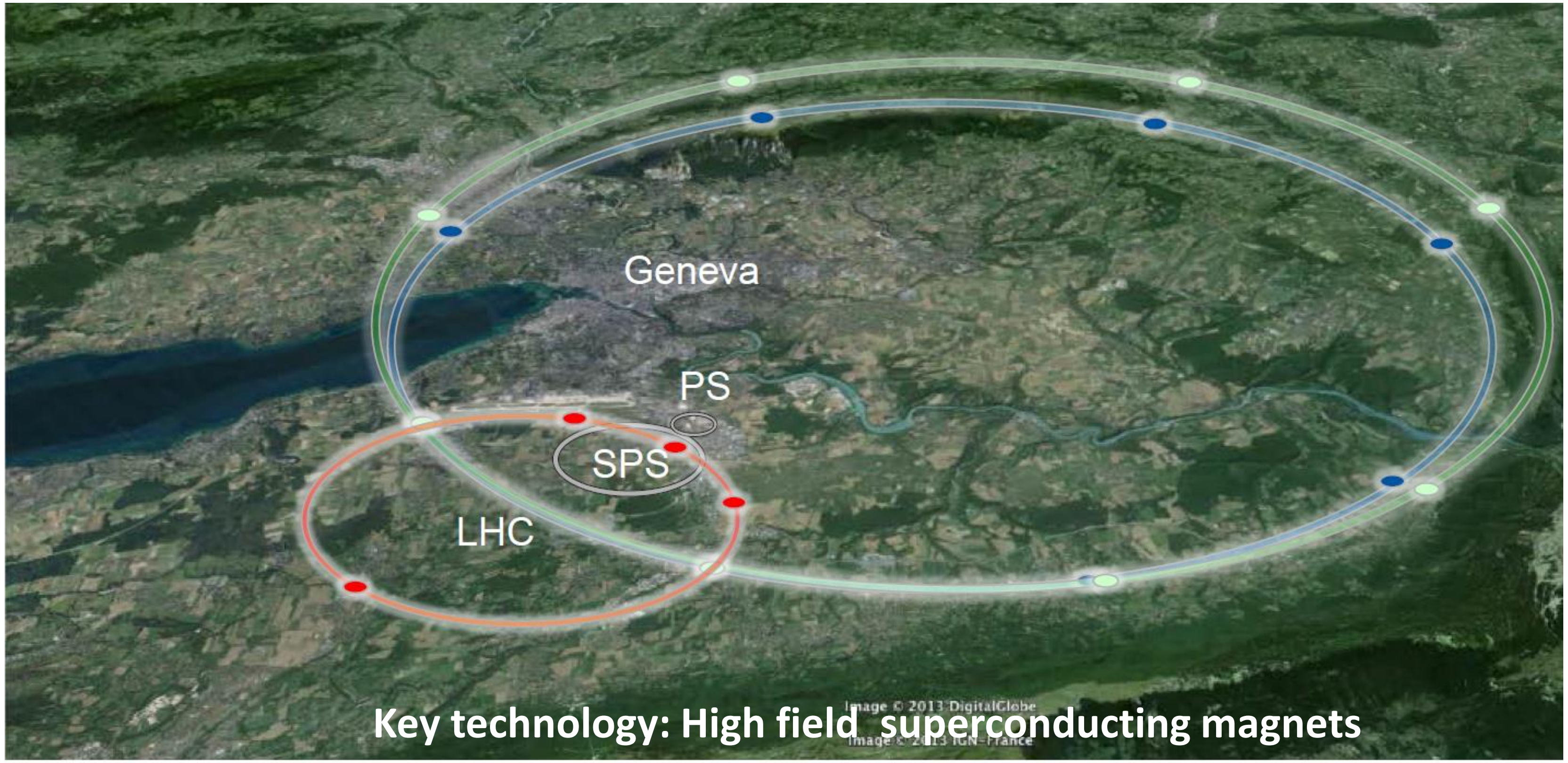
- From LHC to HiLumi LHC
  - Integrated L: ~300 → 3000fb^{-1}
- Reduce beam size in Interaction regions (IR) by **factor 2**
- Triplet quadrupole **aperture doubled** (70 mm → 150 mm)



by E. Todesco

We are in the middle of the series construction of the magnets needed for HL-LHC

Post LHC: The FCC playground

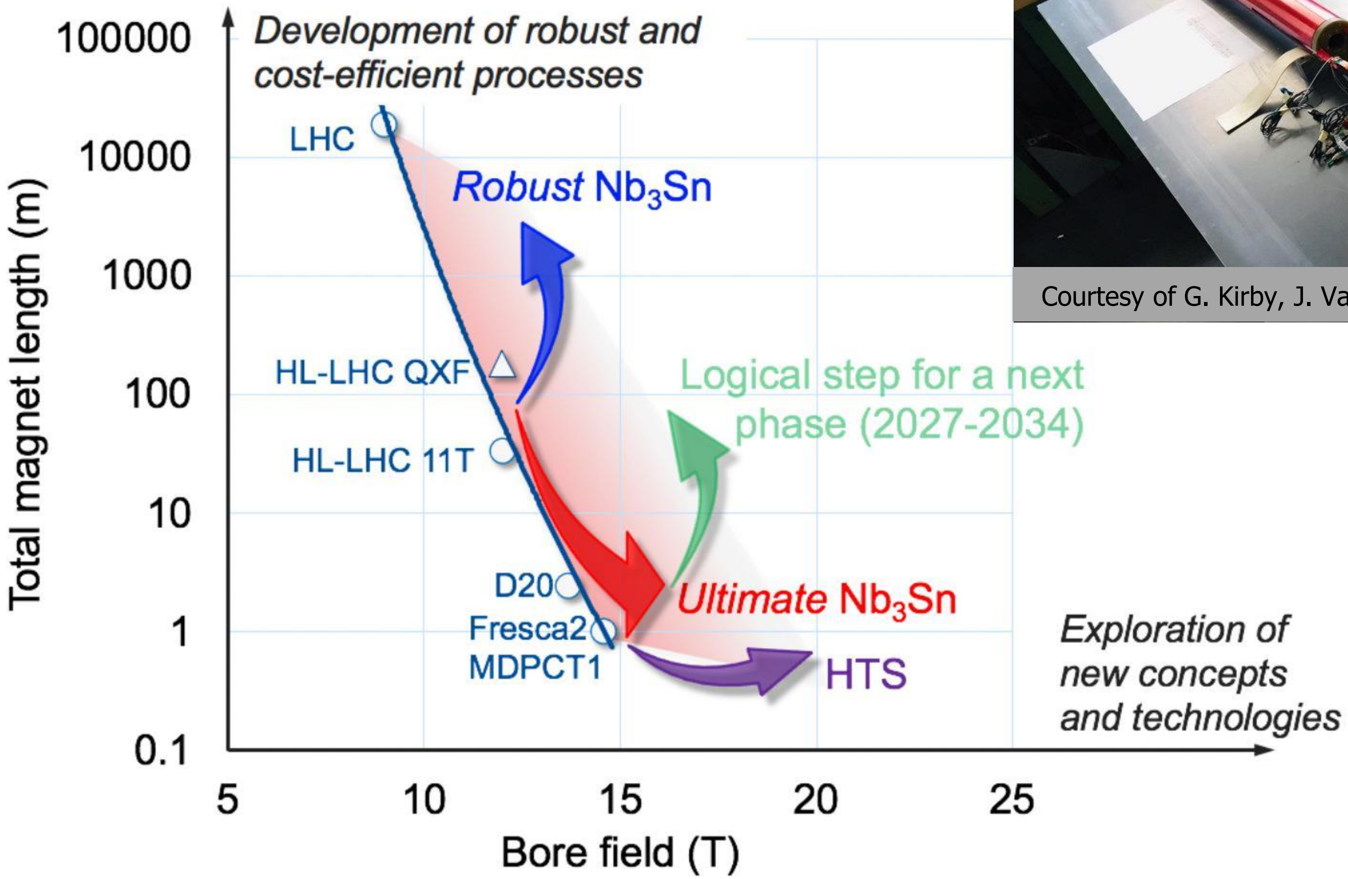


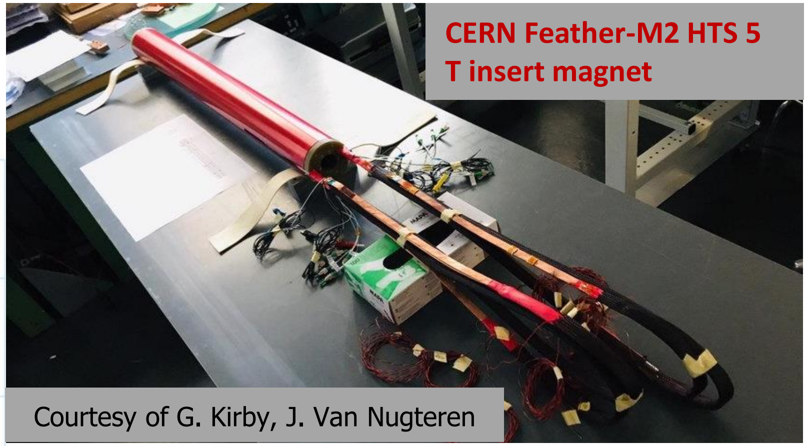
Key technology: High field superconducting magnets

LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)
1300 tons NbTi	3000 tons LTS 700 tons HTS	9000 tons LTS 2000 tons HTS	6000 tons Nb3Sn 3000 tons NbTi

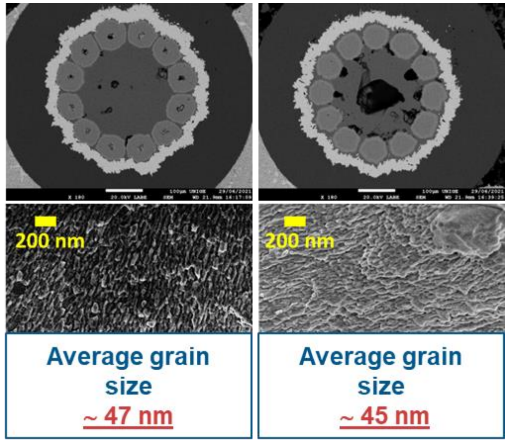
The High Field Magnet program

https://hfm.web.cern.ch/

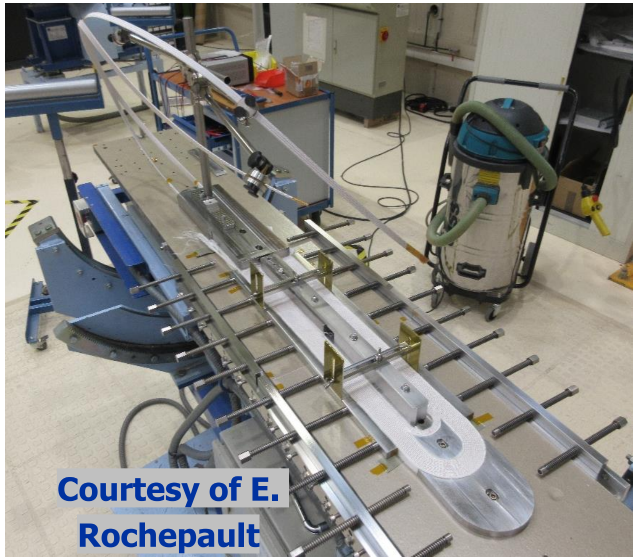



CERN Feather-M2 HTS 5 T insert magnet

Courtesy of G. Kirby, J. Van Nugteren



Courtesy of C. Senatore


Courtesy of E. Rochepault

Thank you

For questions, don't hesitate!

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