International High School Teacher Programme

13th July 2017

Engineering at CERN

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(CERN TE-MSC-LMF)

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- Engineering core competencies available at CERN
- Example of superconductivity and superconducting magnets
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- Future scenarios and development work

Acknowledgements

- **Susana Izquierdo Bermudez** (TE-MSC-MDT), *Many slides taken from the International High School Teacher Programme 2015, 2016*

- Christian Scheuerlein (TE-MSC-LMF)
- Frédéric Savary (TE-MSC-LMF)
- Said Athie (EN-MME)
- Colleagues from TE-MSC and EN-MME

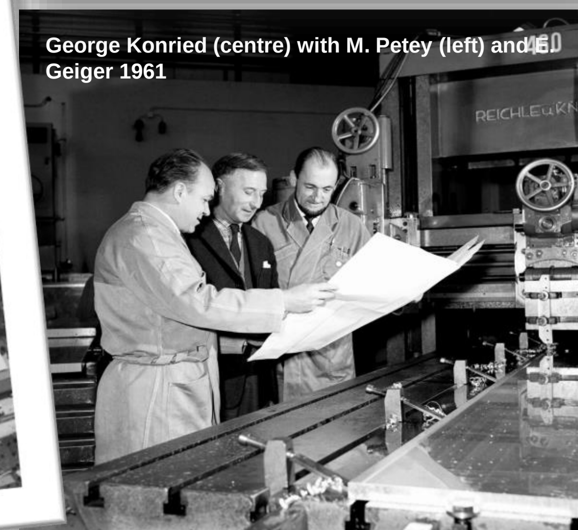
The CERN structure

CERN Departments structure 2017:

- Beams
- Engineering
- Experimental Physics
- Finance and Administrative Processes
- Human Resources
- Industry, Procurement and Knowledge Transfer
- Information Technology
- Site Management and Buildings
- Technology
- Theoretical Physics

A large history: CERN Main workshop

The heart of CERN’S engineering:



George Konried (centre) with M. Petey (left) and E. Geiger 1961

Cryogenics: Low temperatures, high performance

Large Hadron Collider (LHC):
Largest cryogenic system in the world and one of the coldest places on Earth.

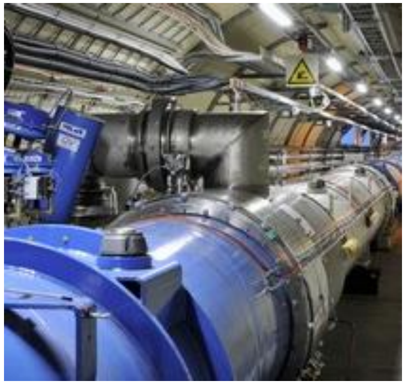
Main magnets:
Operate at a temperature of 1.9 K (-271.3°C), colder than the 2.7 K (-270.5°C) of outer space.

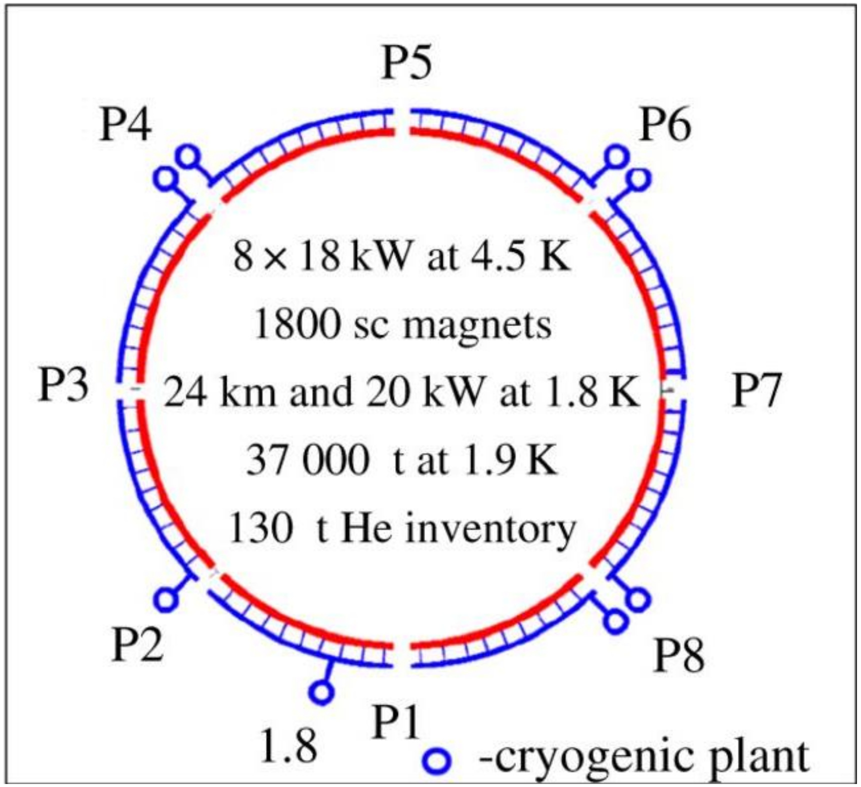
This requires 40,000 leak-tight pipe seals, 40 MW of electricity.
120 tonnes of helium to keep the magnets at 1.9 K.

Cryogenics: Sectoring and plants

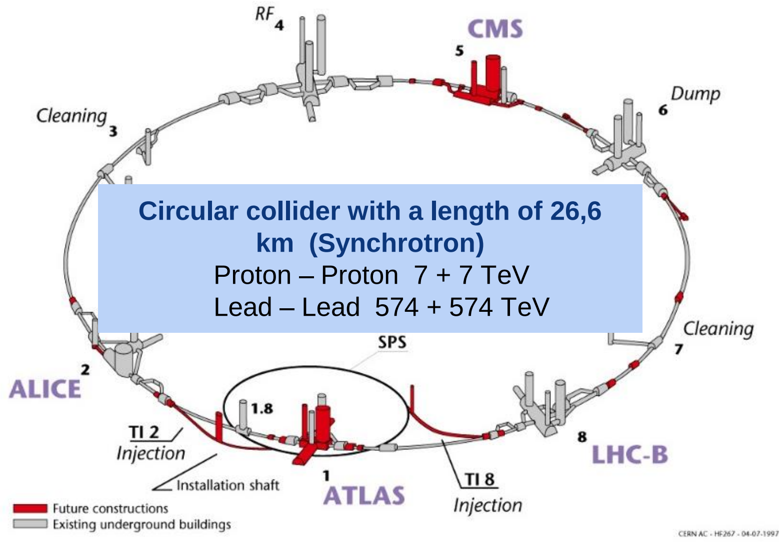
8 cryogenic plants (8 x 18kW @ 4.5 K)

24 km & 20 kW @ 1.8 K





Superconducting electromagnets



Circular collider with a length of 26,6 km (Synchrotron)
Proton – Proton 7 + 7 TeV
Lead – Lead 574 + 574 TeV

The Large Hadron Collider (LHC) is currently operating at the energy of 6.5 TeV per beam.

At this energy, the trillions of particles circle the collider's 27-kilometre tunnel 11,245 times per second.

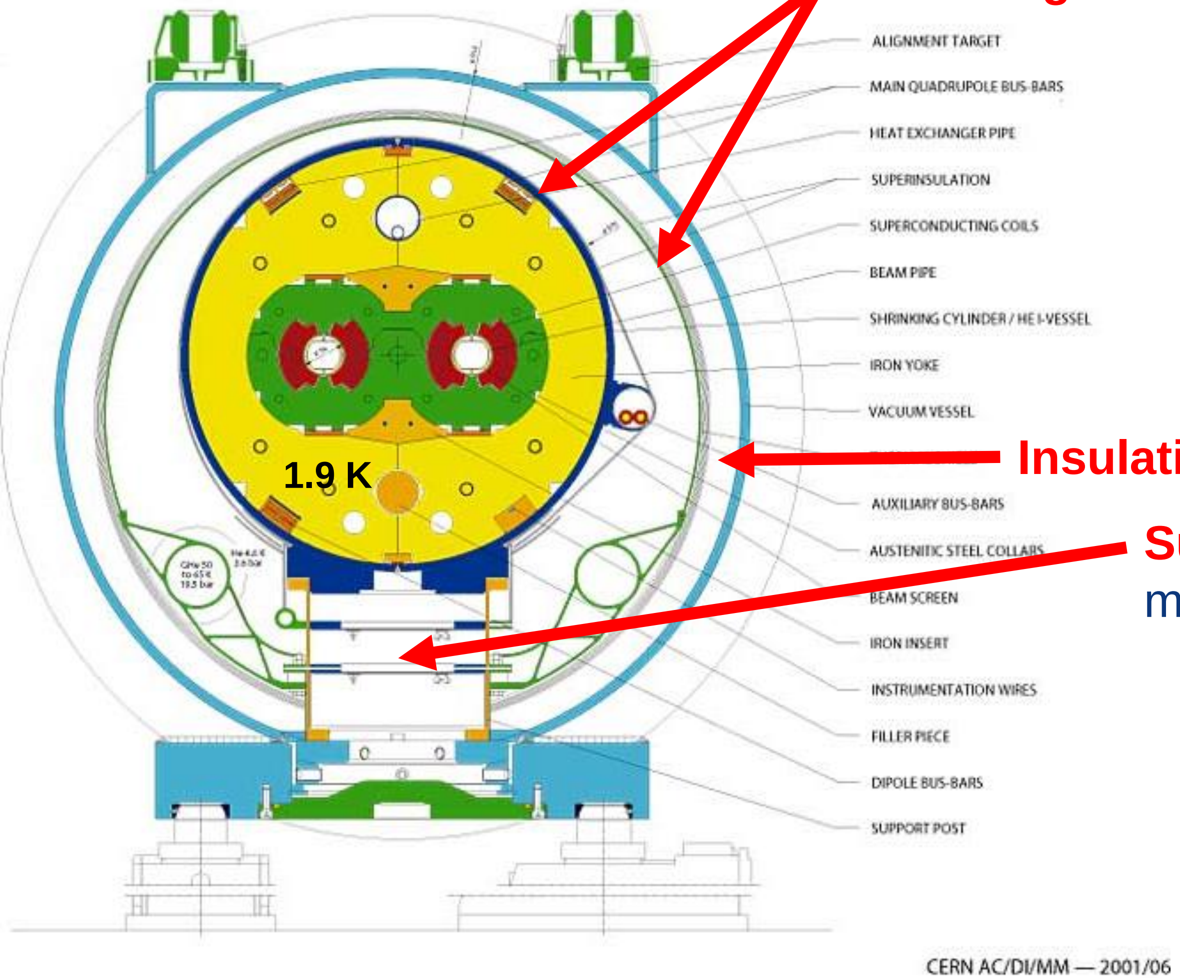
More than 50 types of magnets are needed to send them along complex paths without their losing speed.

All the magnets on the LHC are electromagnets. The 1232 main dipoles generate powerful 8.3 tesla magnetic fields (100,000 times more powerful than the Earth's magnetic field).

The electromagnets use a current of 11,080 amperes to produce the field, and a superconducting coil allows the high currents to flow without losing any energy to electrical resistance.

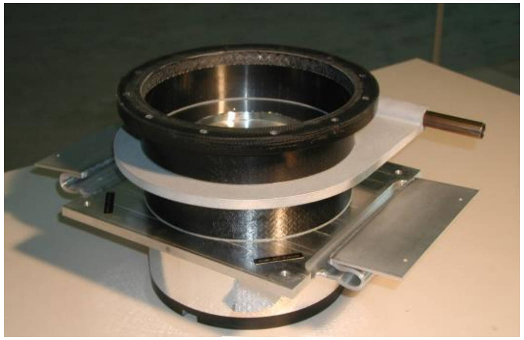
Cryostat

Insulating material



Insulation vacuum

Support made with a composite material to reduce heat conduction.



Vacuum

In the LHC, three different vacuum systems with different aims:

1. Cryo-magnets;
2. Helium distribution line (QRL);

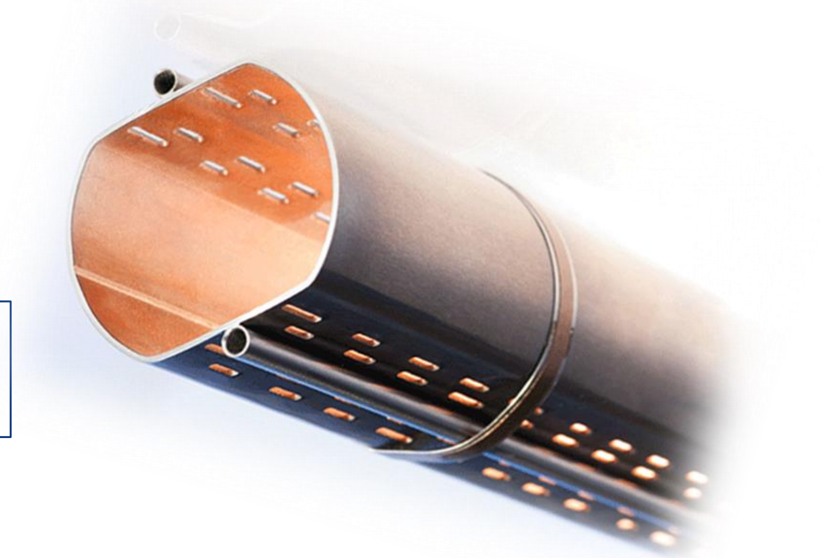
Thermal insulator
50 km, 10^{-6} mbar

3. Vacuum in the **beam** pipes.

(54 km, 10^{-10} to 10^{-11} mbar)

Largest operational vacuum system in the world, **Total length of vacuum piping: 104 km**

In the region where the beam circulates, vacuum almost as rarefied as that found on the surface of the Moon!



LHC – beam screen

Radiofrequency cavities

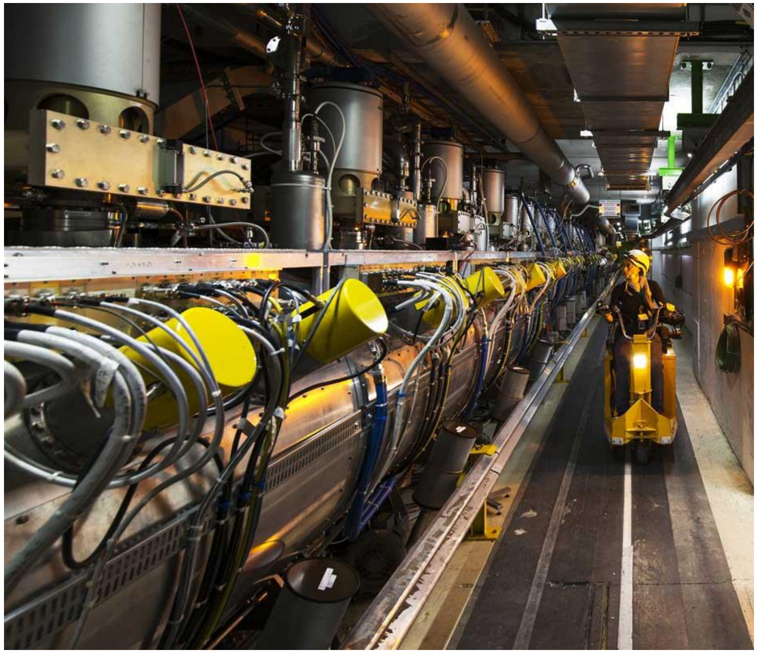
Main function of the cavities:

- Keep the particles properly **grouped** to ensure high luminosity in the interaction region. Provide **energy** to the beam during the **ramp.**

Technology: Niobium coated copper superconducting cavities:

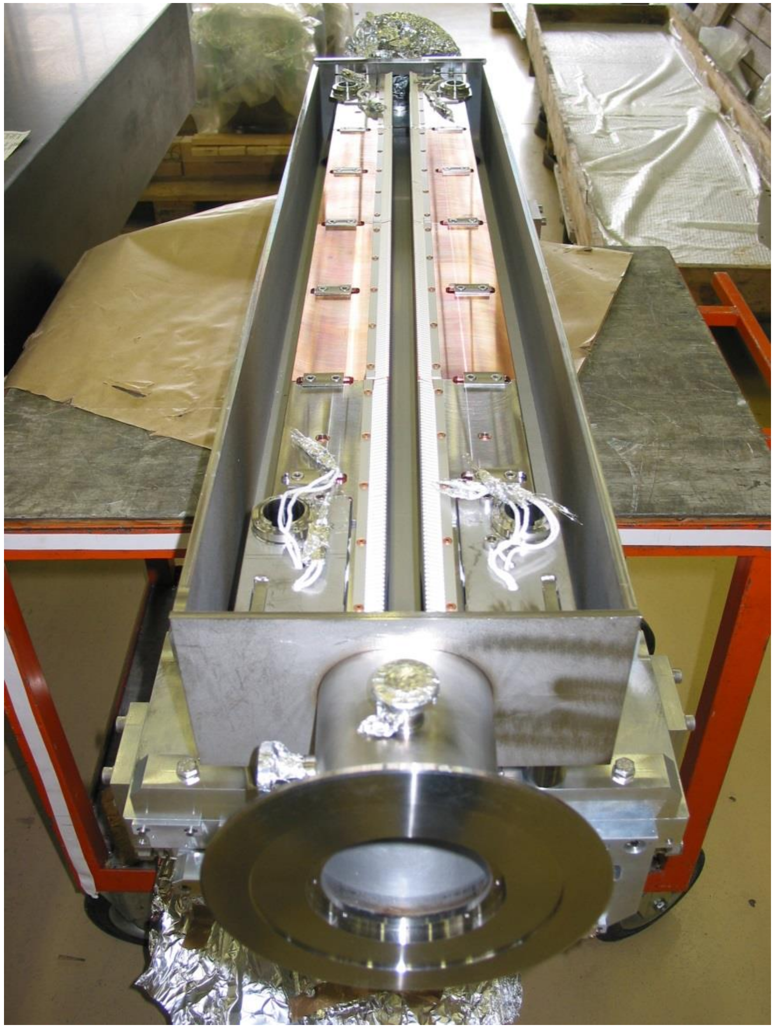
- Low energy losses;
- Large stored energy;
- They can fulfil the radio-frequency conditions required in the LHC.

On the Large Hadron Collider (LHC), each RF cavity is tuned to oscillate at 400 MHz.



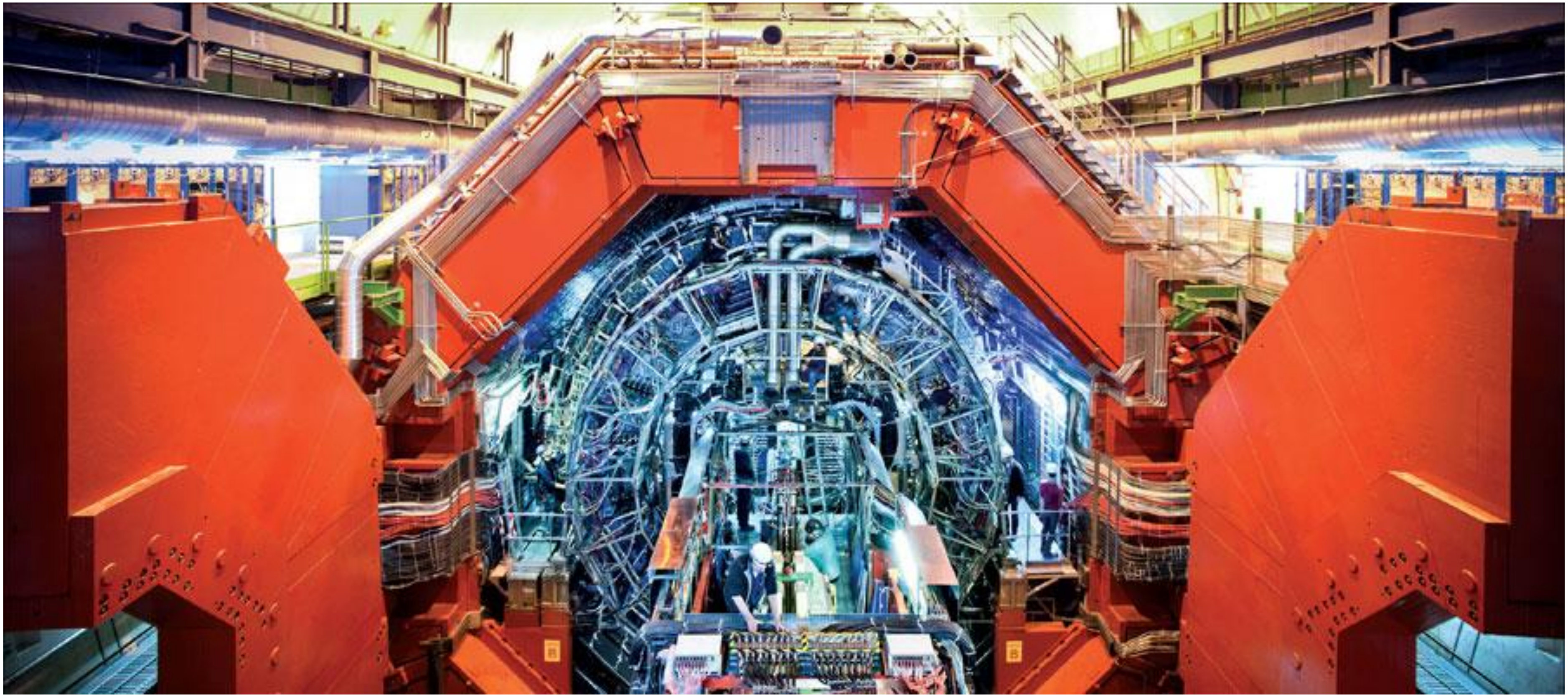
Collimators

- The energy stored in the LHC beam is enough to melt almost 1 ton of copper.
- A small fraction of this energy is enough to provoke a quench in a superconducting magnet or even to destroy some parts of the accelerator.
- A fraction 10^{-5} of the nominal beam energy will damage copper.
- The **function** of the collimators: **protect the accelerator** against unavoidable regular and irregular beam loss.



http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/default.php

Detectors



- Micro-electronics;
- Data acquisition and treatment;
- Normal and/or superconducting; magnets;
- Cryogenics;
- Powering;
- Mechanical structures;
- Instrumentation/monitoring;
- Ultra high vacuum.

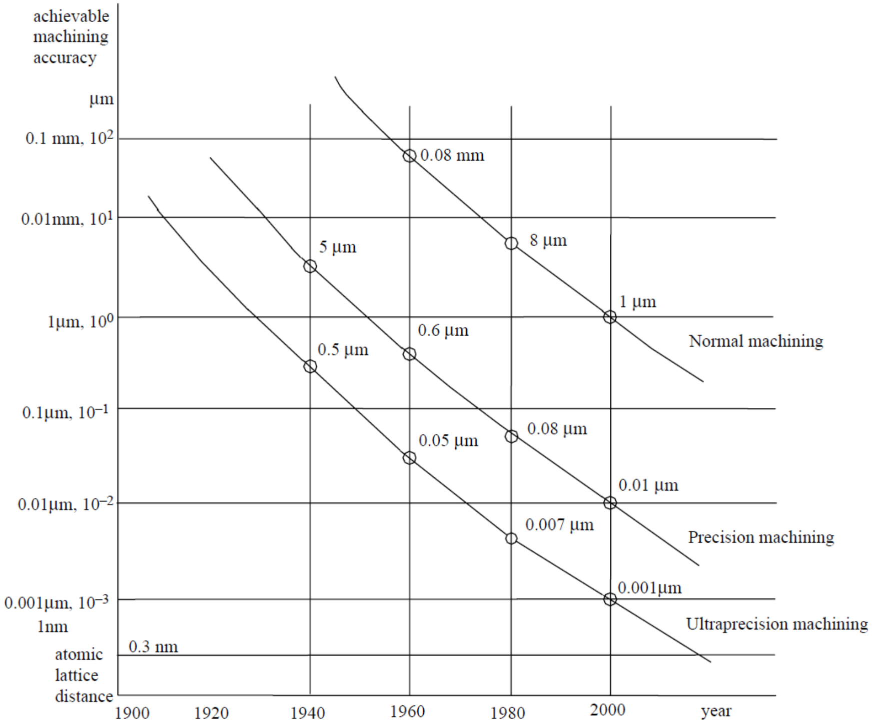
Civil Engineering

- The LHC is built 100 m below ground;
- Most of the tunnel was built at the time of LEP, only caverns for ATLAS and CMS had to be built for the LHC (width 35m, height 42m length 82m).

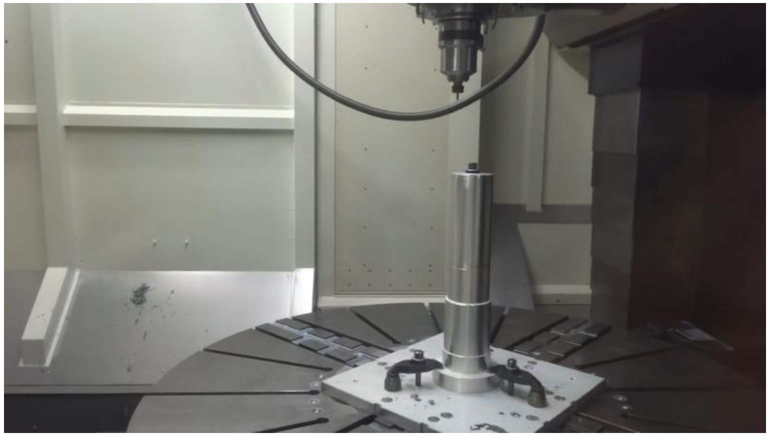
http://www.tunneltalk.com/CERN-Aug01-Construction-of-great-excavations.php

Transport

Manufacturing technics in EN-MME



- An interpretation of the Taniguchi curves, made in 1983, depicting the general improvement of machine accuracy capability with time during much of the twentieth century.

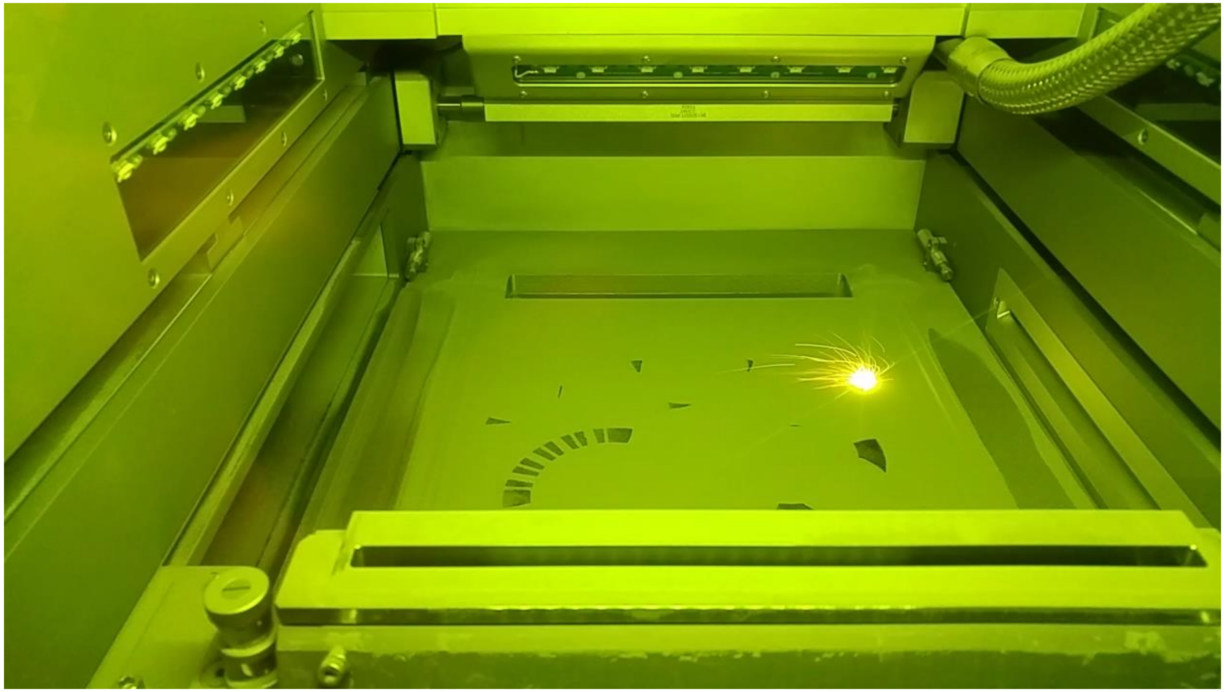


… Ceramic machining, vacuum brazing, electrohydraulic forming (EHF), laser welding …

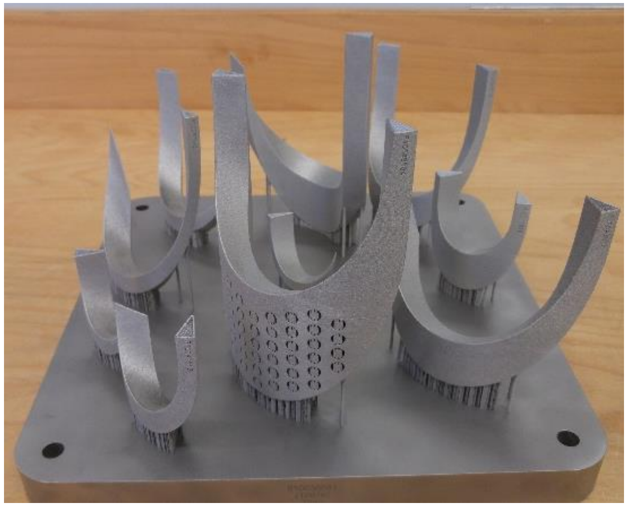
Courtesy S. Atieh, EN-MME

Staying at the pulse…

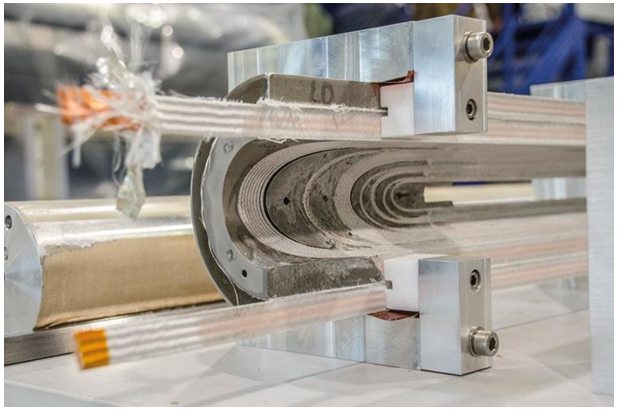
Additive Manufacturing
SLM - **S**elective **L**aser **M**elting in **EN-MME**



Contact: Romain Gérard (EN/MME)

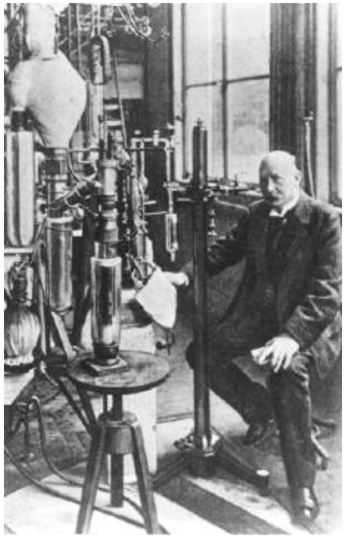


End-spacers for
superconducting magnet
Approx. height: 150 mm

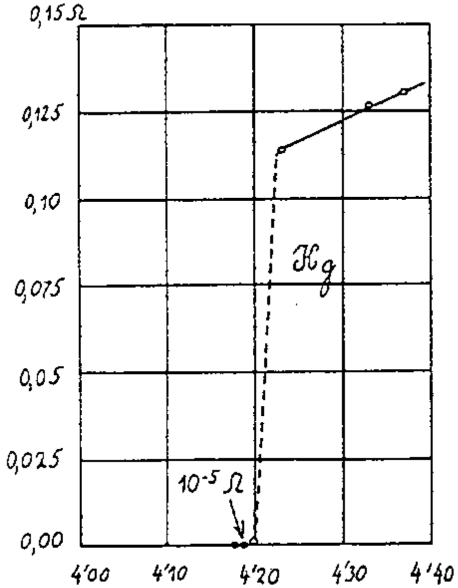


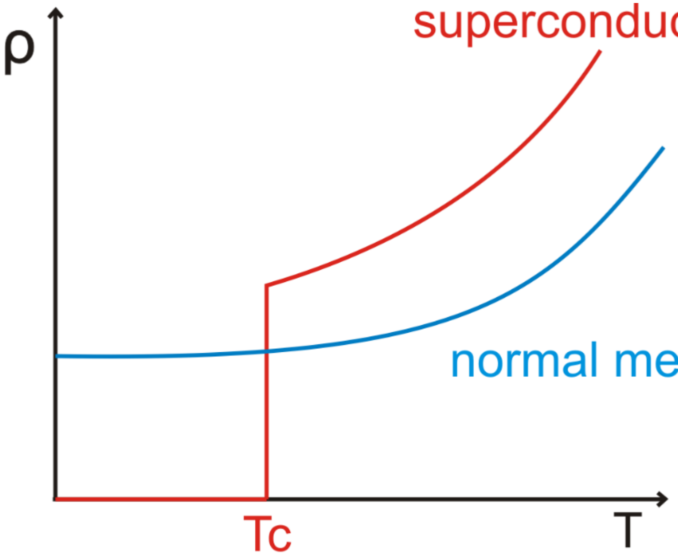
Superconductivity

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



Source: © Rijksmuseum

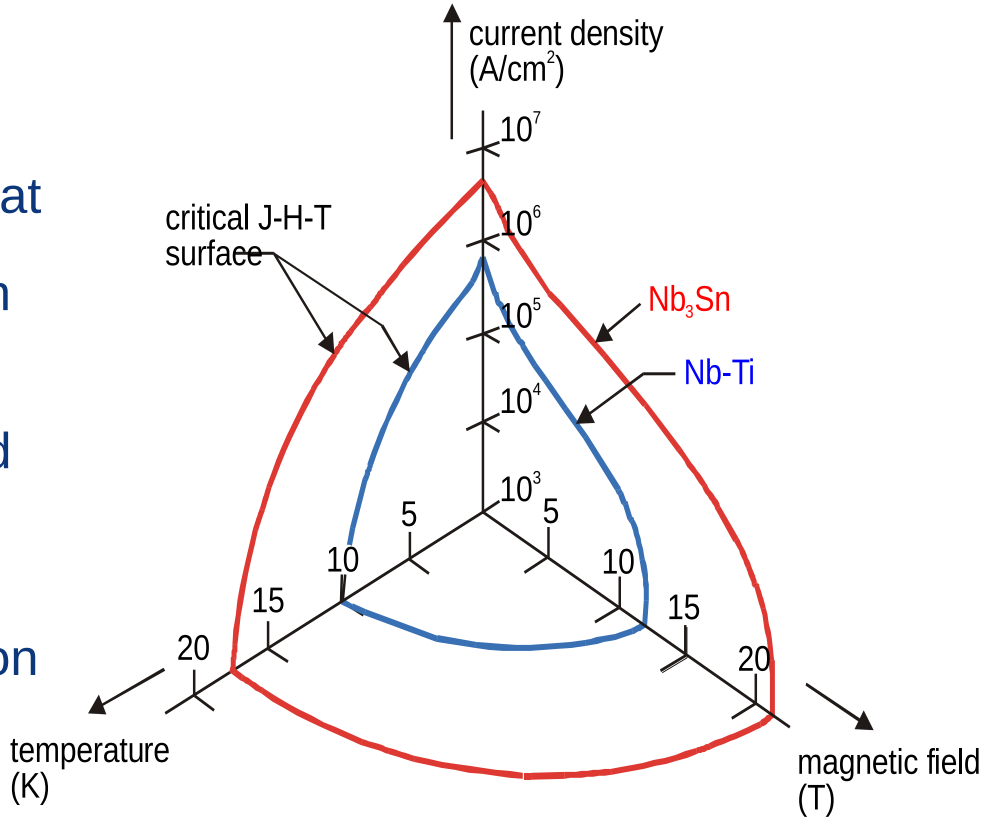




- The temperature at which the transition takes place is called **critical temperature T_c;**
- Observed in many materials;
  - Not observed for normal conductors (Cu, Ag, Au);
- At $T > T_c$, superconductors show poor electrical performance.

Critical limits of superconductivity

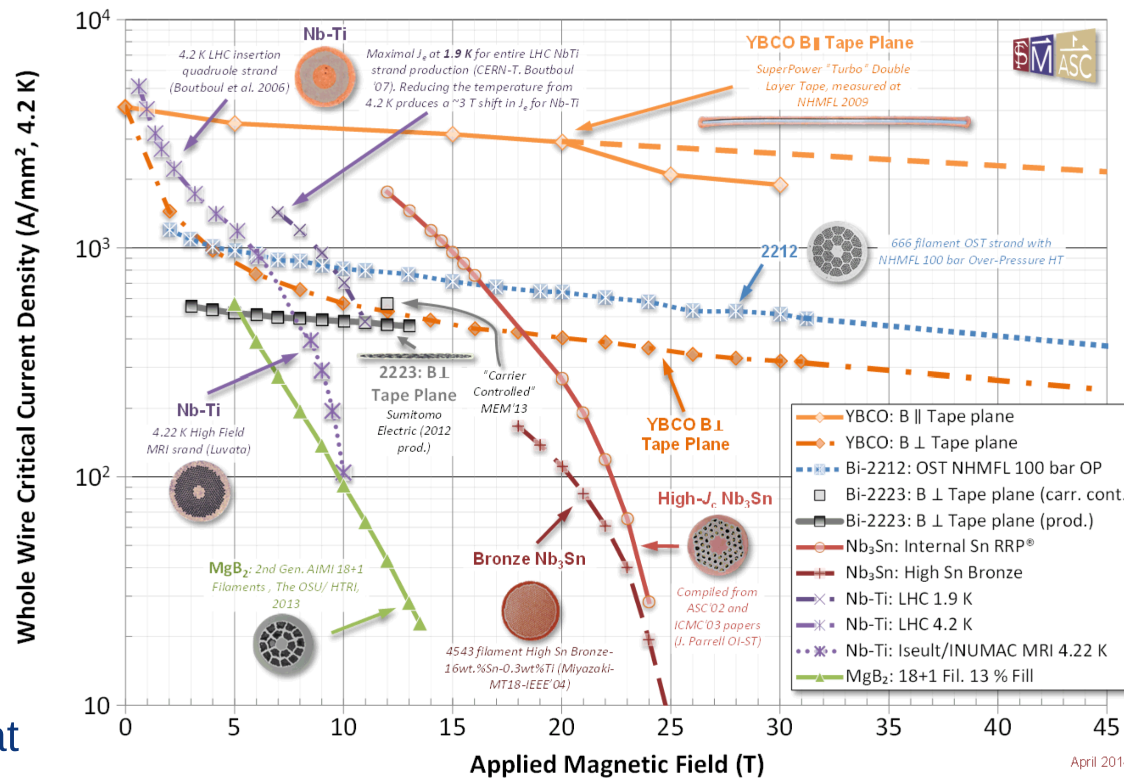
- Superconductors can be characterised by their critical temperature (T_c), critical field (B_c), and critical current density (J_c).
- T_c are B_c are materials properties that can be modified only slightly. By clever materials engineering J_c can be varied by many orders of magnitude.
- Very high J_c values can be achieved in type 2 superconductors by introducing defects that can pin the magnetic flux lines.
- Such defects can be for instance non superconducting phases or grain boundaries.
- For accelerator magnets high J_c values above 1.5 kA/mm^2 at operating conditions are typically required.



Critical surface for Nb-Ti and Nb_3Sn

Overall current densities of composite conductors used for superconducting magnets

- Practical superconductors are composite materials. A good metallic conductor component (typically Cu or Ag) is needed for electromagnetic stability and protection.
- In some cases a mechanical reinforcement is added for improving electromechanical properties.
- The engineering current density (J_e) gives a meaningful comparison between different conductors, taking into account the amount of superconductor that can be inserted in the composite conductors (typically 1 vol.% for coated conductors, 30 vol.% for Bi-2212 and up to 50% for Nb–Ti and Nb_3Sn).

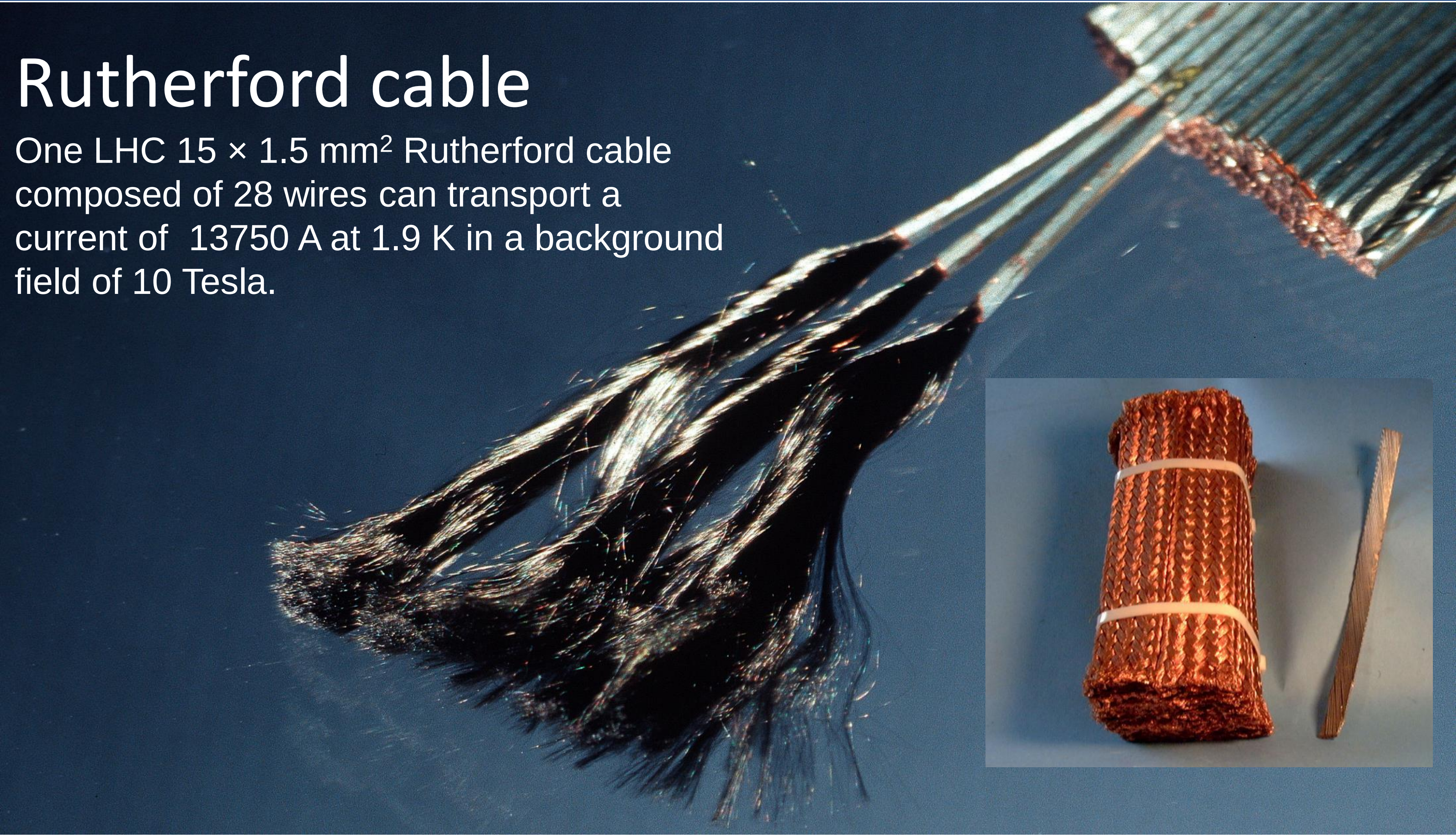


Critical current density of state-of-the-art superconductors as a function of applied field at 4.2 K. From Peter Lee, NHMFL [http://fs.magnet.fsu.edu/~lee/plot/plot.htm]

Nb-Ti

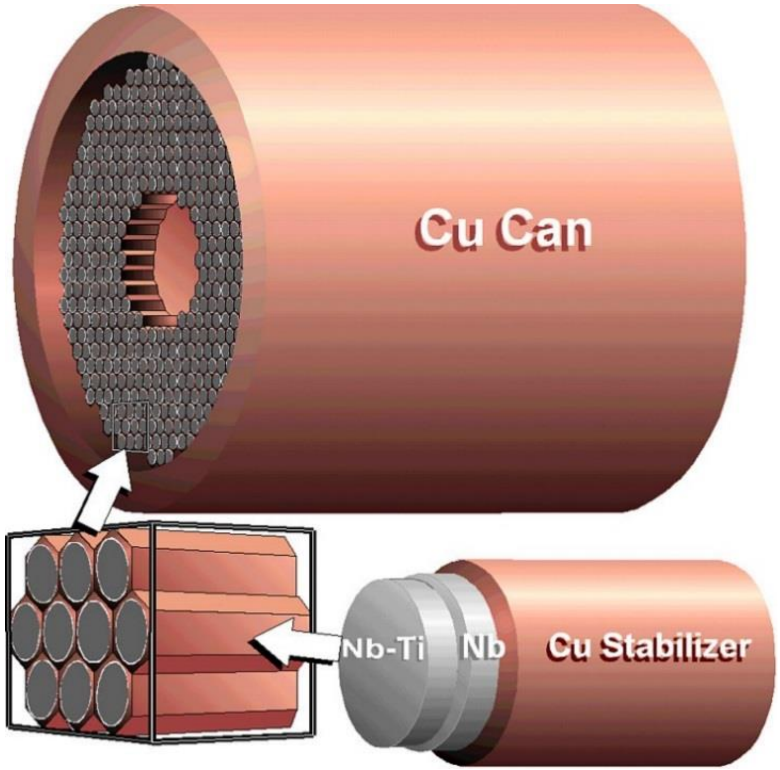
Rutherford cable

One LHC 15 × 1.5 mm^2 Rutherford cable composed of 28 wires can transport a current of 13750 A at 1.9 K in a background field of 10 Tesla.



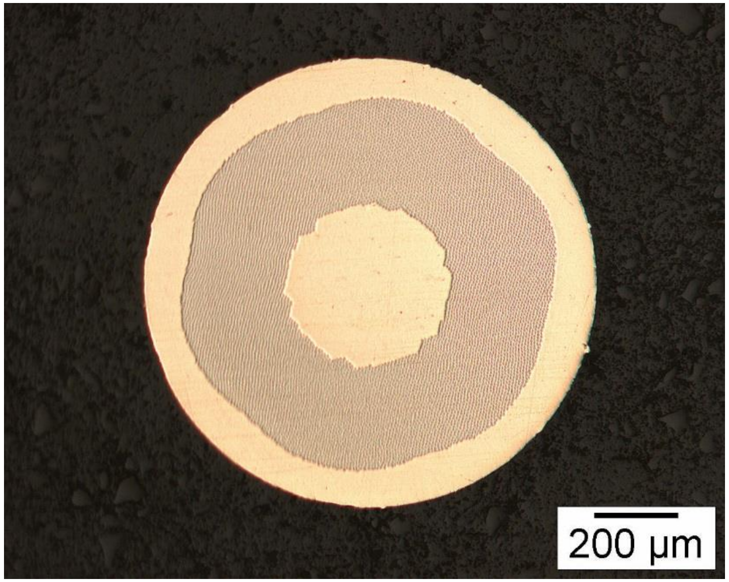
Nb-Ti wire fabrication

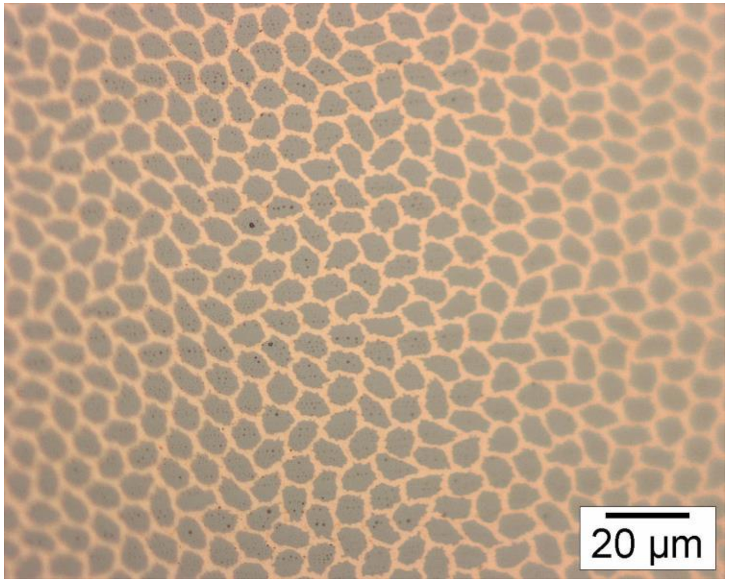
- **Ductile alloy superconductor; the workhorse in applied superconductivity**
- The Nb-Ti/Cu composite wires are produced from Nb-Ti bars, which are inserted into a Cu can.
- In a sequence of several metallurgical processes, such as extrusion and drawing, the initial Nb-Ti bar diameter of typically 200 mm ø, 750 mm long.
- Reduced by plastic deformation down to the final filament diameter of about 7 μm.
- 490 tons of high homogeneity Nb-Ti alloy were needed to fabricate the LHC superconducting wires.



Schematic illustration of Nb-Ti/Cu composite billet assembly starting from a Nb-Ti rod, a Nb diffusion barrier wrap and a Cu extrusion can. The hexagonal monofilament rods are re-stacked in a Cu can.
From P. J. Lee and D. C. Larbalestier, Wire Journal International, 36(2)

Nb-Ti/Cu composite wires





Metallographic cross sections of LHC Nb-Ti/Cu conductor made of about 8000 Nb-Ti Ø=7 µm filaments.

Why small filaments are needed?

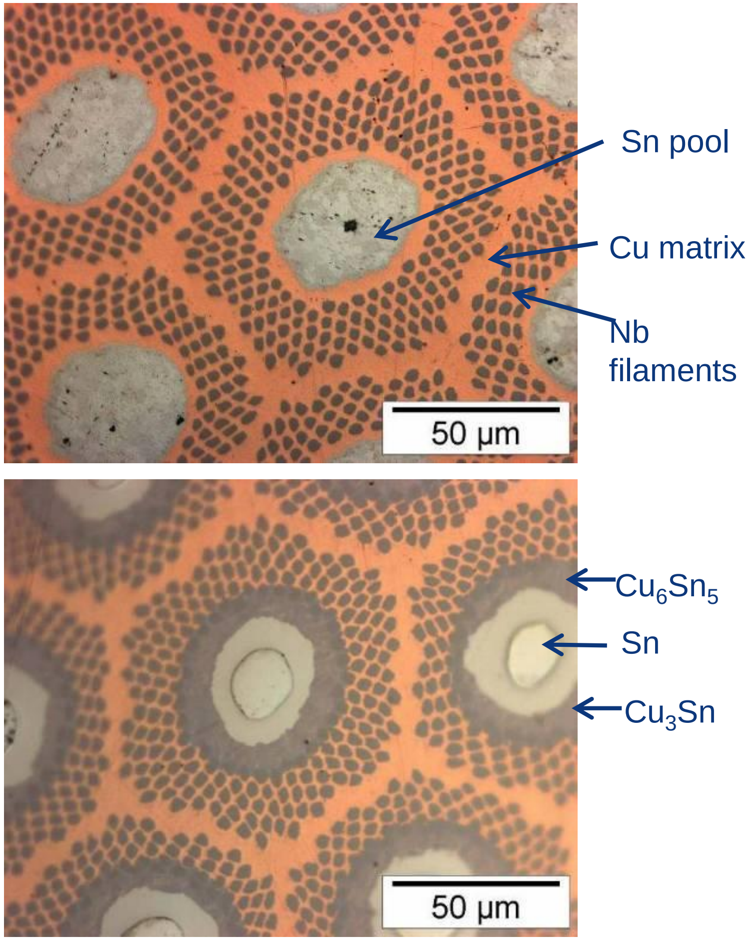
- Stability (flux jumps);
- Magnetic field quality;
- Persistent currents, Inter-filament coupling currents.

Why the are embedded in a copper matrix?

- Protection, to redistribute the current in case of quench.

Phase transformations during Nb_3Sn processing

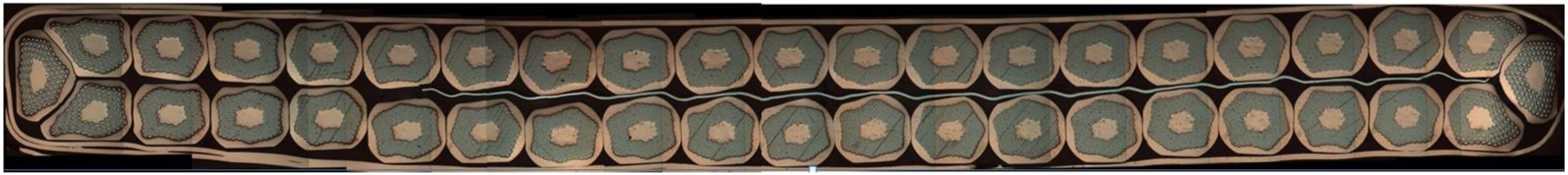
- **Intermetallic superconductor for the next generation of accelerator magnets beyond the ultimate performance limit of Nb-Ti.**
- Brittle superconductors like the Nb_3Sn intermetallic are produced from the precursor materials by a processing heat treatment (HT) when the conductor is in its final size and shape.
- During the Nb_3Sn HT the precursor elements Nb and Sn and the Cu matrix interdiffuse, forming various intermetallic phases and finally the superconducting Nb_3Sn.
- The phase transformations occurring during the HT prior to the Nb_3Sn formation can influence the performance of the fully processed wire.



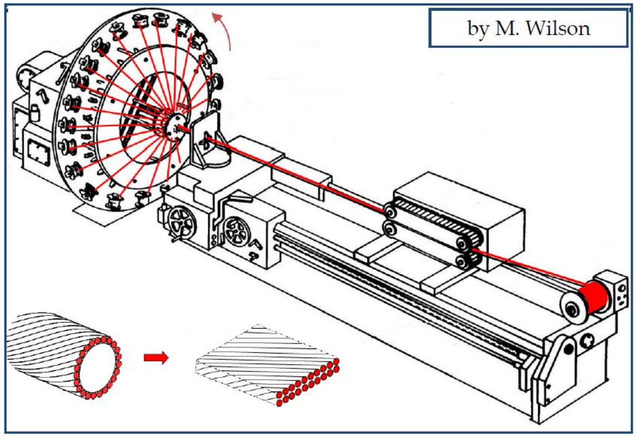
Metallographic cross sections of an Internal Tin (IT) Nb_3Sn wire as-drawn and after 9 days at 220 °C HT.

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.**



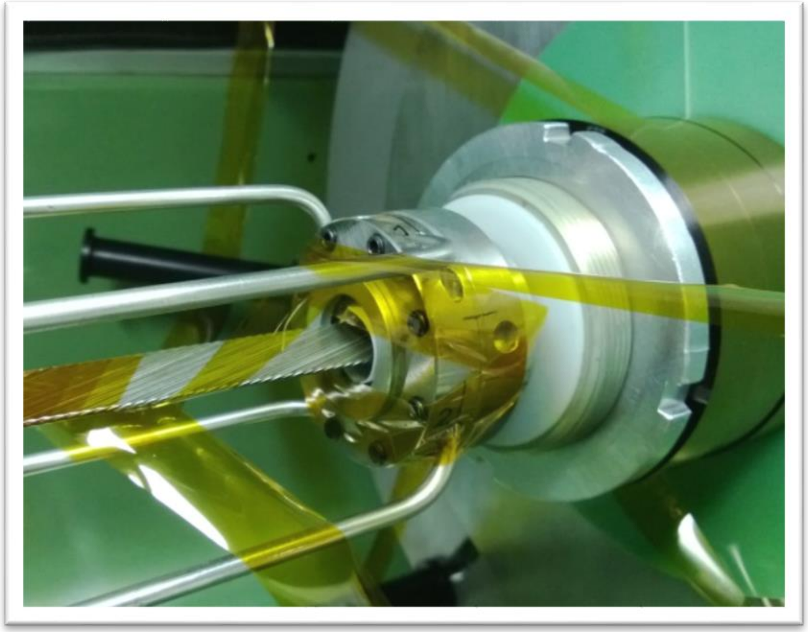
- Strands wound on spools mounted on a rotating drum;
- Strands twisted around a conical mandrel into rolls;
- The rolls compact the cable and provide the final shape.



The 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.**

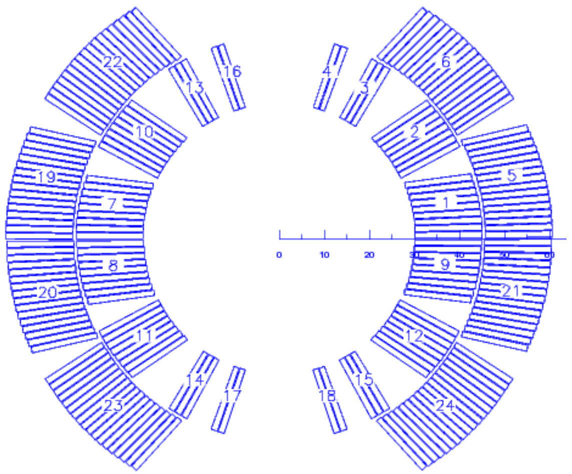


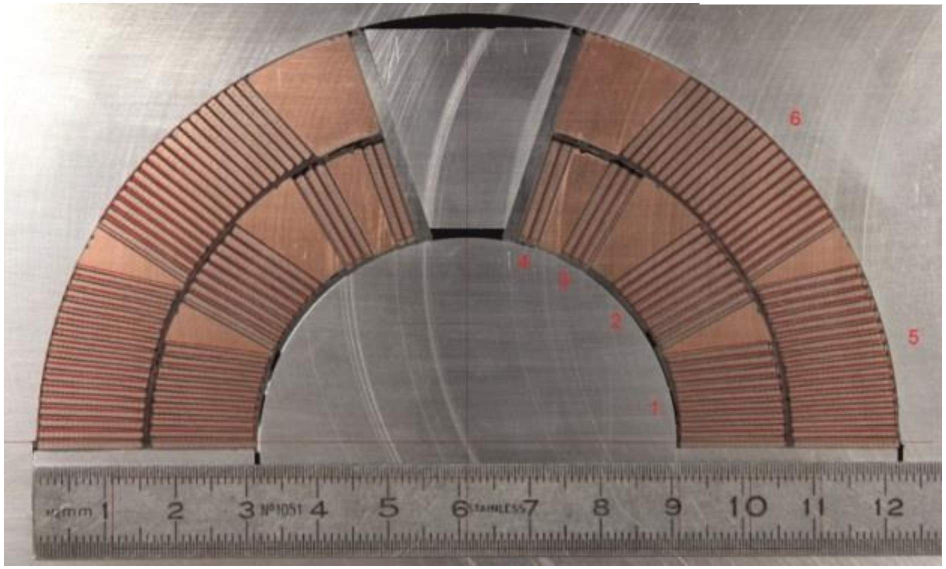
Polyimide insulation for Nb-Ti

Fiber glass insulation for Nb_3Sn

Coil fabrication

- The coil: most **critical component** of a superconducting magnet;
- **Cross-sectional accuracy** of few tens of micrometers over ~15 m;
- Manufacturing tolerances (~30 µm on blocks position) are accounted as random components for field quality.





Cross section of a Nb_3Sn practice coil

How to create a dipole field?

Perfect dipole:

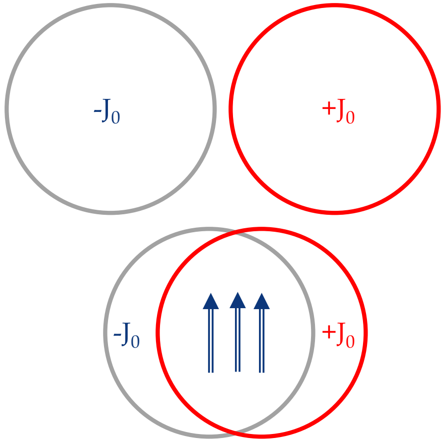
- Within a cylinder carrying ***j_0***, the field is perpendicular to the radial direction and proportional to the distance to the centre ***r***:

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

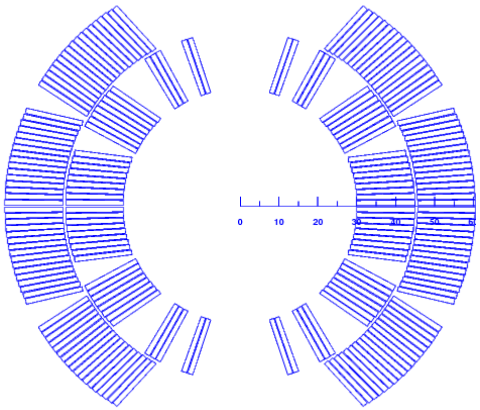
  - Combining the effect of two intersecting cylinders

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

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



From ideal to practice configuration

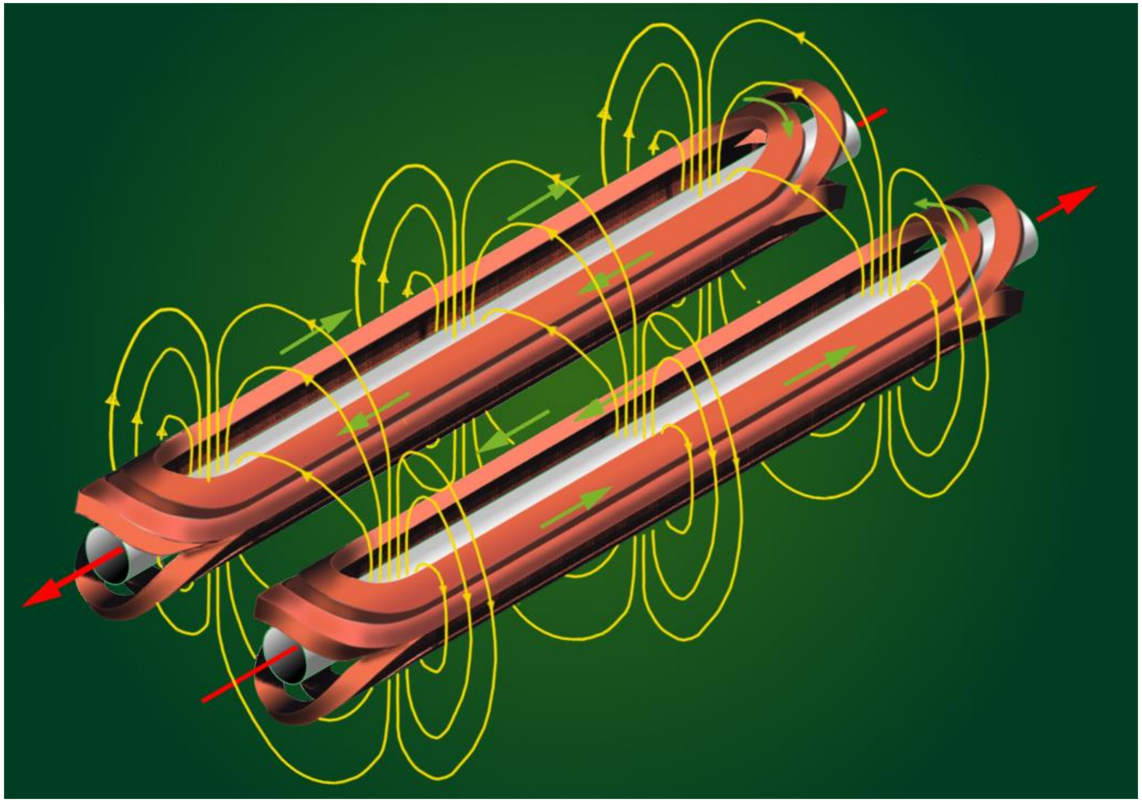


Practical challenges:

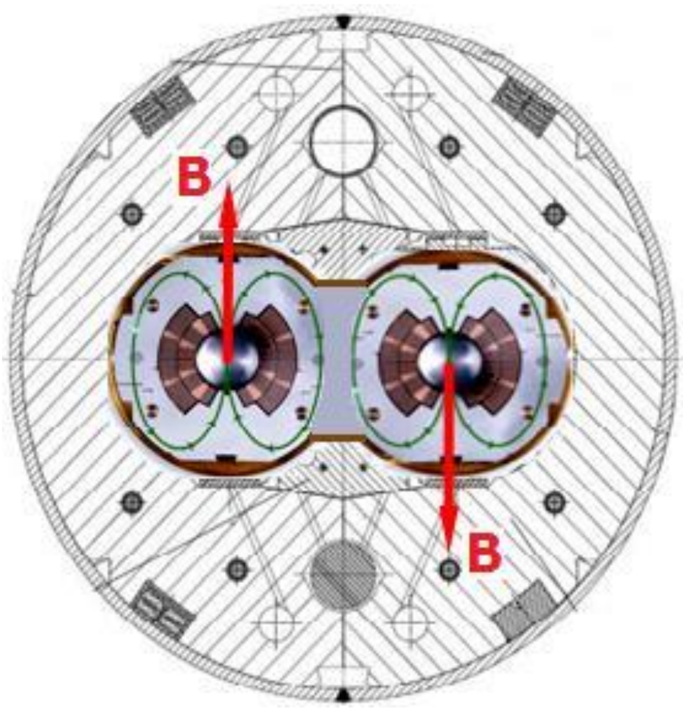
- The aperture is not circular;
- Not easy to simulate with a flat cable.

The idea: reproduce a ***cosθ*** current distribution with a cable (Rectangular cross-section and constant *J).*

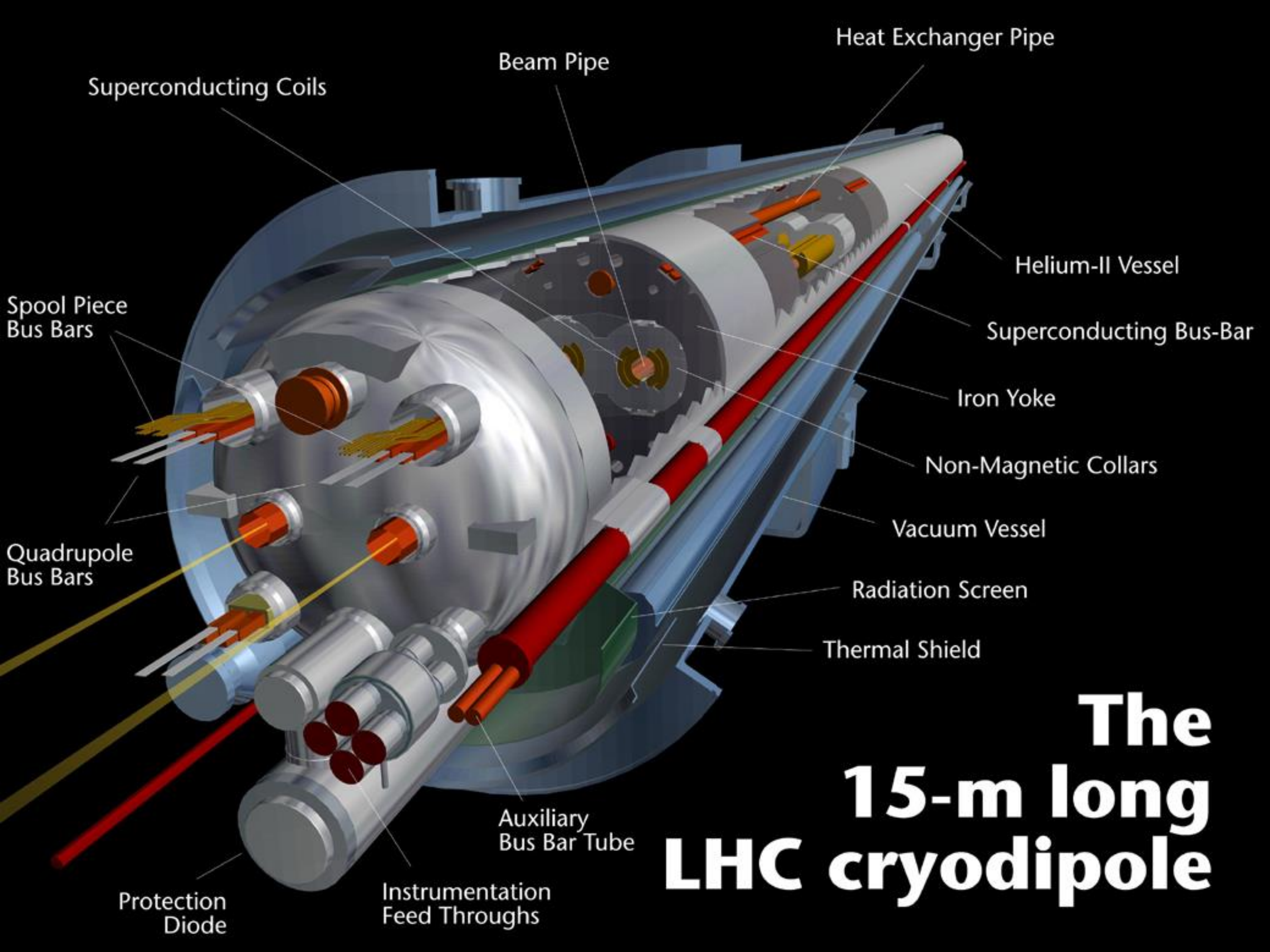
How to create a dipole field?



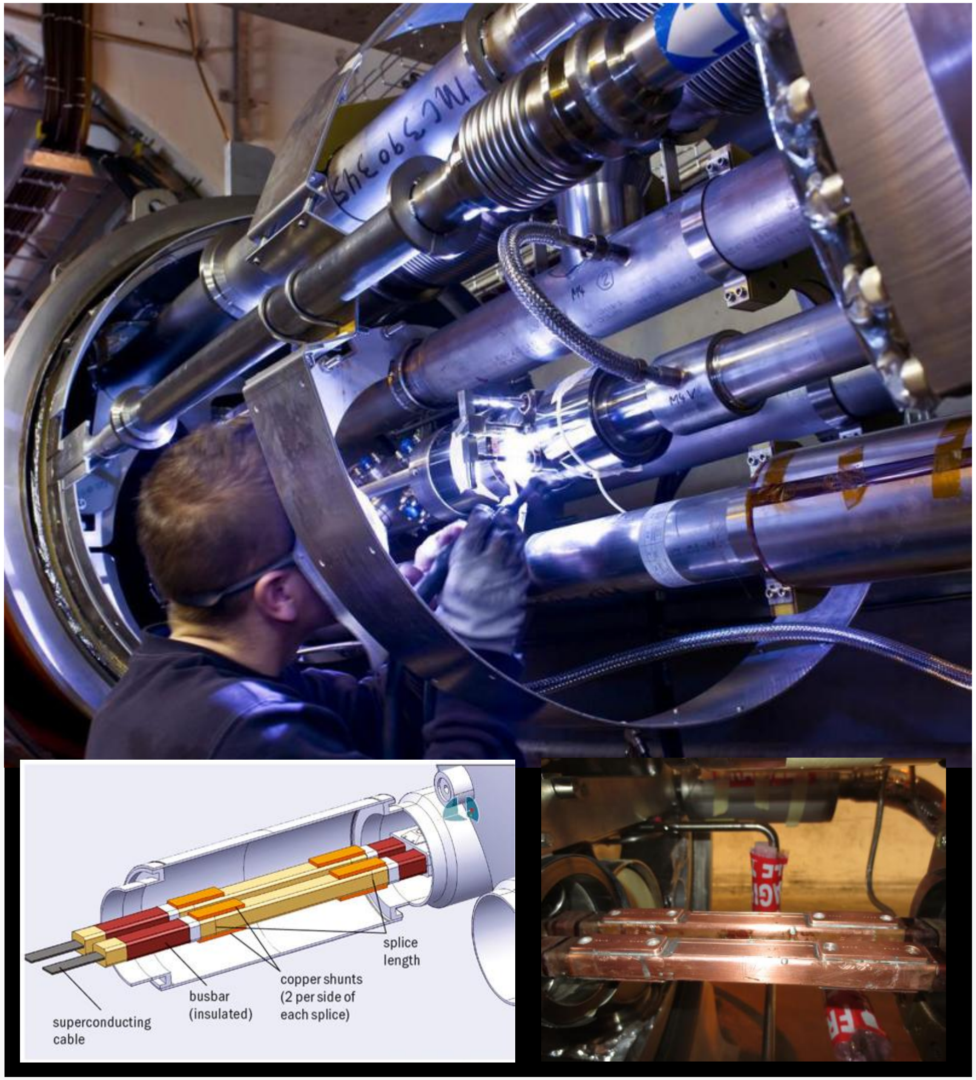
LHC main dipole, electromagnetic field in the two apertures…



Cross-sectional view on the LHC main dipole magnet…


Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole
Bus Bars
Radiation Screen
Thermal Shield
Auxiliary
Bus Bar Tube
Protection
Diode
Instrumentation
Feed Throughs
The
15-m long
LHC cryodipole

Interconnections



Some key aspects of the interconnections:

- Flexible components to compensate the thermal contraction required. (~3mm/m → 45 mm/dipole). Challenging in terms of leak tightness
- It is very important to guarantee the electrical integrity of the 12 kA circuit
- Avoid stress in the splicing region due to electromagnetic forces
- Guarantee low resistance in the splice region to avoid quenching

LS1 – SMACC project

Courtesy JPh. Tock, TE-MSC

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.

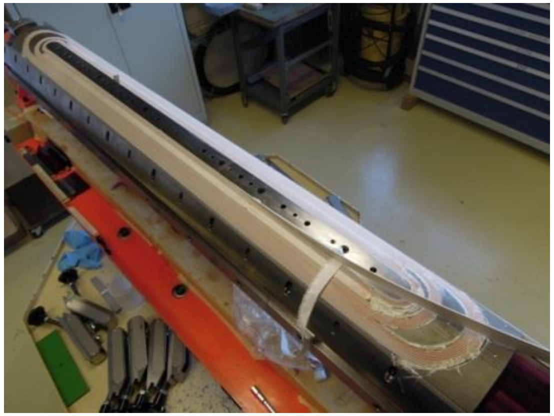
Reaction

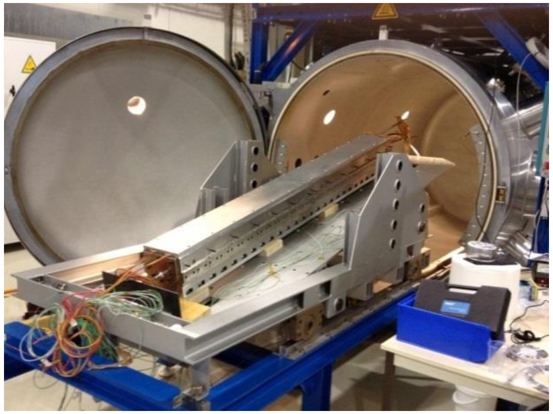
Sn and Nb are heated to 650-700 C in vacuum or inert gas (argon) →Nb_3Sn.

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.**

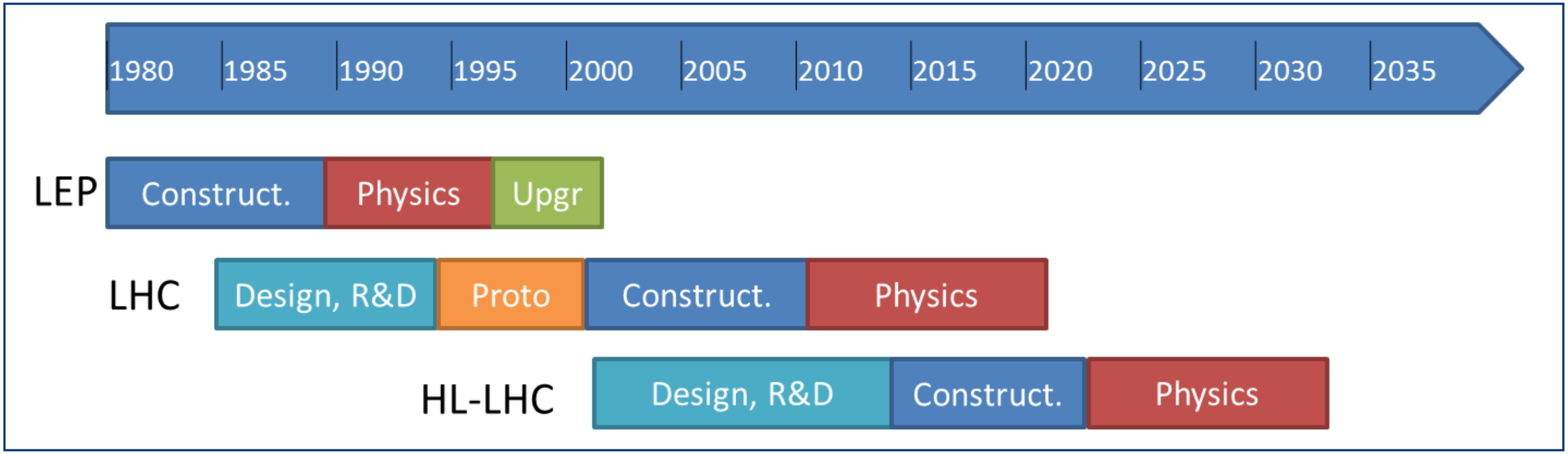




Large Magnet Facility, a unique place…

http://te-dep.web.cern.ch/

Hi-Lumi LHC



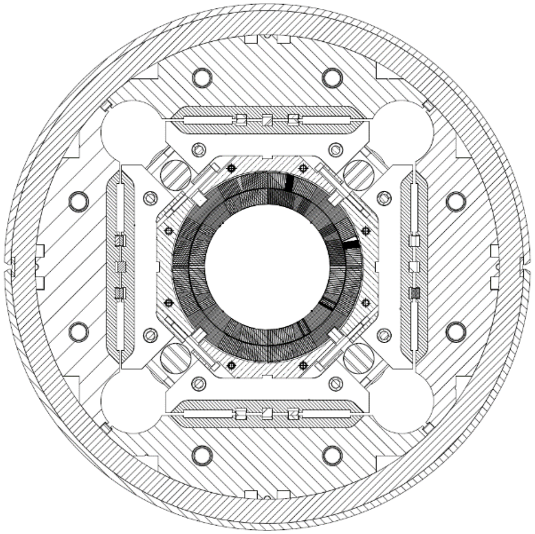
- From LHC to HiLumi LHC;
  - Integrated *L*: ~300 → $3000 fb^{-1}$
- Reduce beam size in Interaction regions (IR) by **factor 2;**
- Triplet quadrupole **aperture doubled** (70 mm → 150 mm).

HiLumi LHC

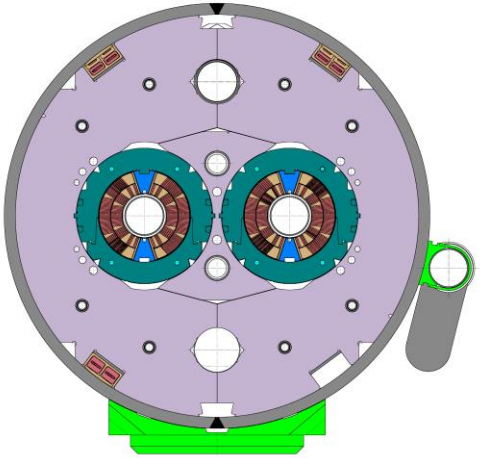
1.2 km of machine will be replaced

The challenges:

- Produce **Nb_3Sn** magnets "accelerator quality" (up to now only Nb-Ti).
  - Coil technology for 7 m based on Nb_3Sn
    Electromagnetic forces:
    - ~4 times in straight section and ~6 times in the ends with respect to current triplets
  - Quench protection
    - Large stored energy per unit volume
- **Crab cavities**
  - New concept
- **Civil engineering**
  - Run in parallel the LHC and the required engineering
- **Radiation** protection



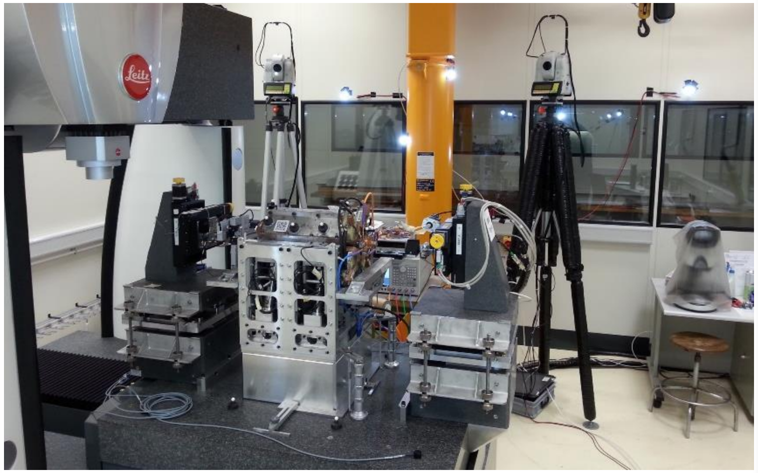
MQXFB Quadrupole



11 T dipole magnet

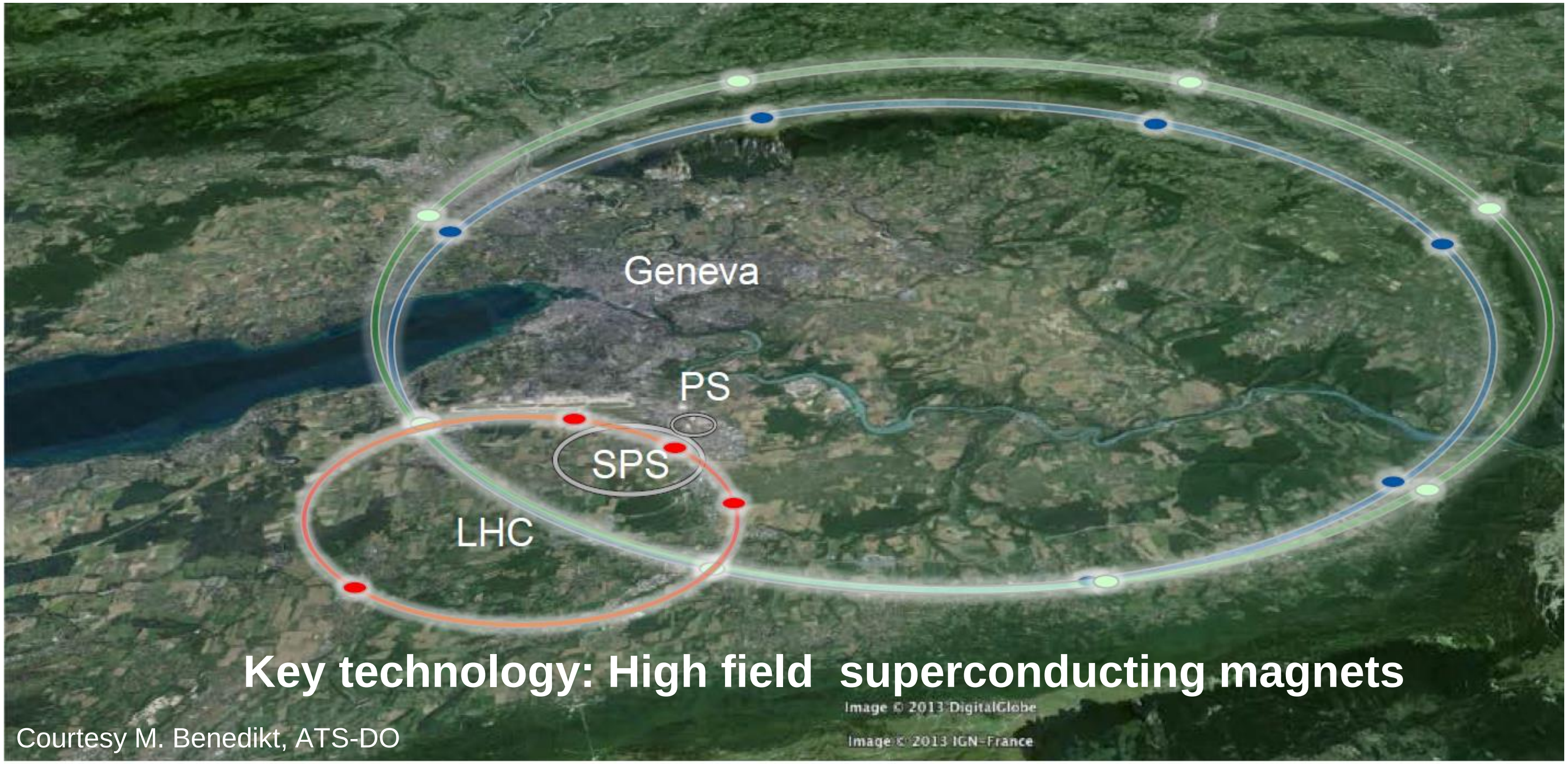
The CLIC study

- **Electron-positron machine** (Linear machine, particles would otherwise loose an enormous amount of energy circulating in a circular structure as the LHC);
- Accelerating gradient: 360 GeV to 3 TeV;
- Very high precision on the components! For some parts, the mechanical tolerances are 2 µm, a big challenge from the manufacturing point of view;
- Key technology: High-gradient accelerating structures.
- CLIC aims at an acceleration of 100 MV/m, 20 higher tan the LHC;
- Requires a nm stabilization system for quadrupole magnets.



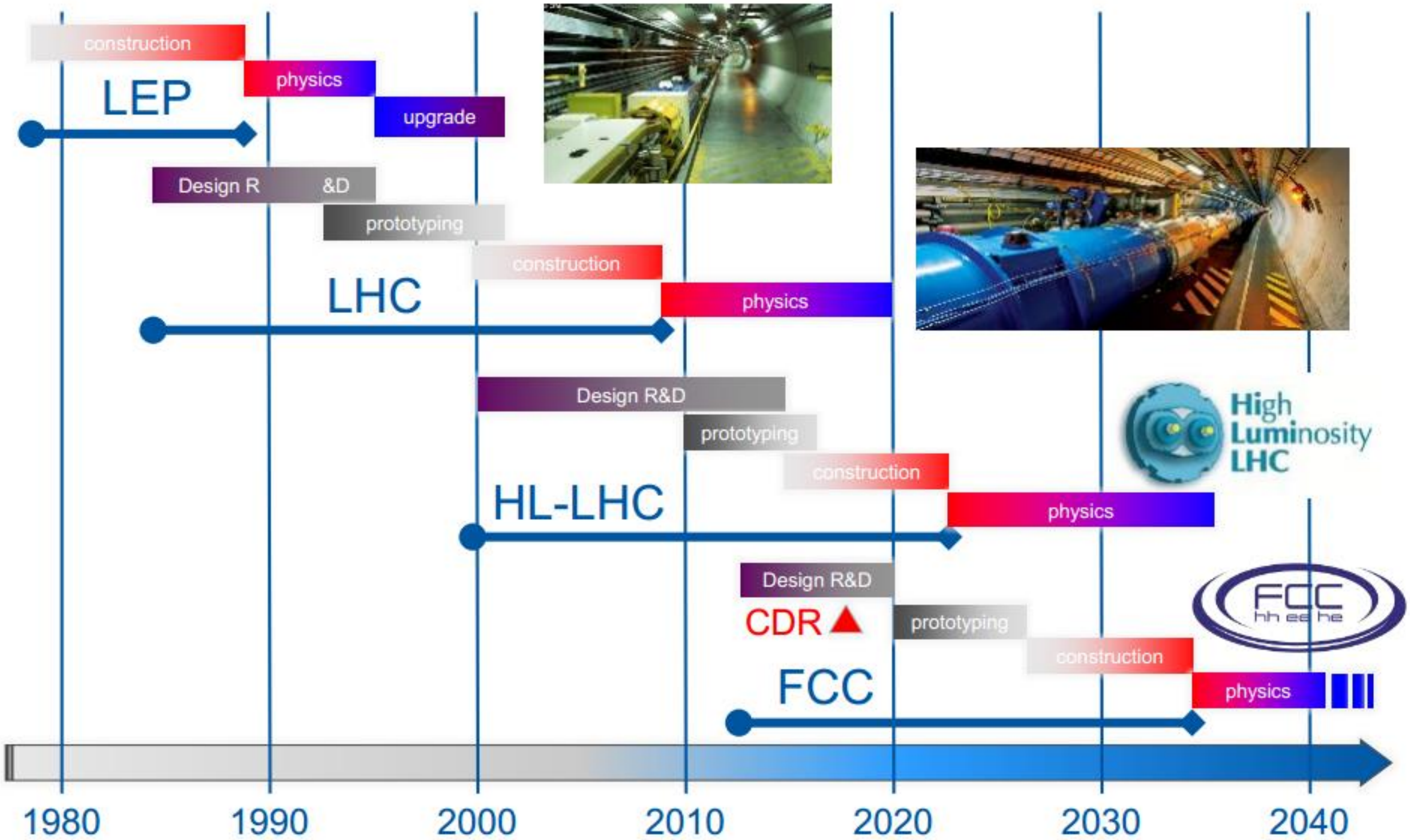
Courtesy H.M. Durand (EN-ACE), K. Artoos (EN-MME)

The FCC study



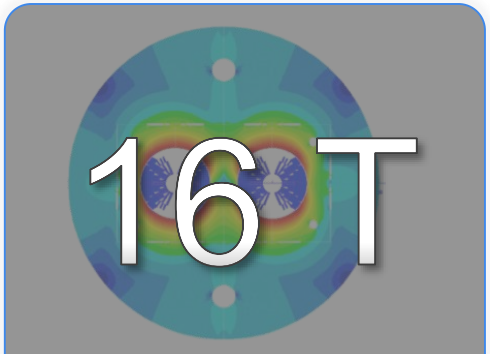
LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)
1300 tons NbTi	3000 tons LTS 700 tons HTS	9000 tons LTS 2000 tons HTS	6000 tons Nb3Sn 3000 tons NbTi

Thoughts towards post LHC

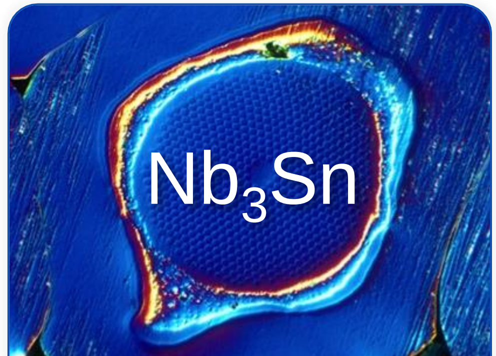


Courtesy M. Benedikt, ATS-DO

Key technologies for future accelerators

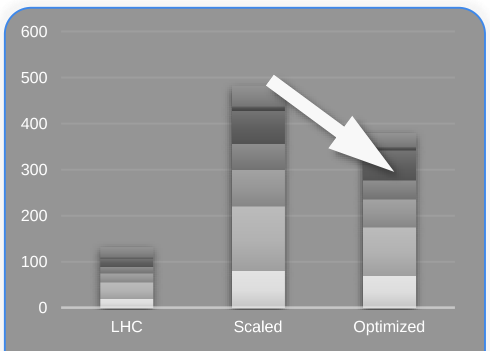


High-field Magnets



Novel Materials and Processes

Large-scale Cryogenics

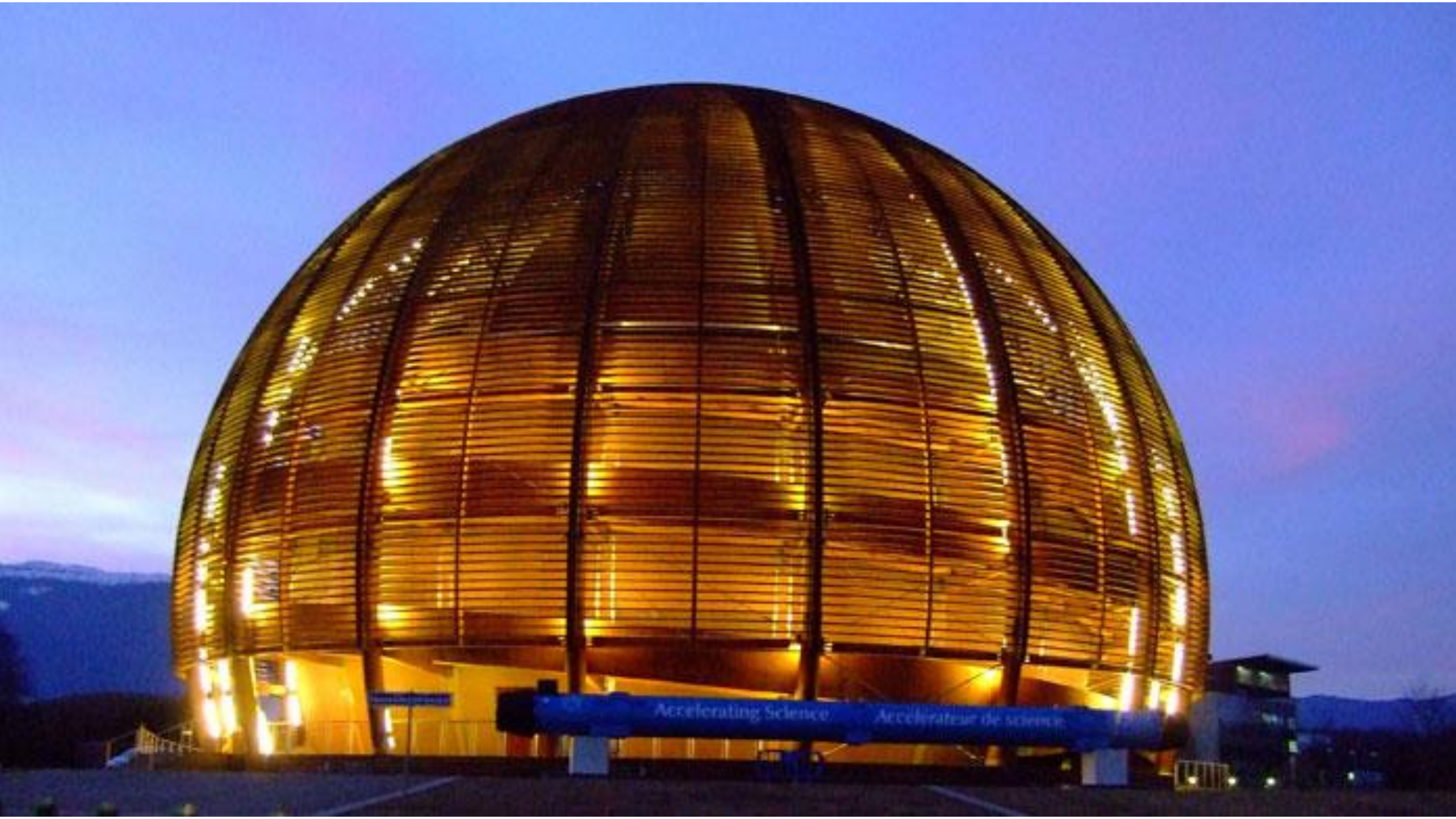


Power Efficiency

Reliability & Availability

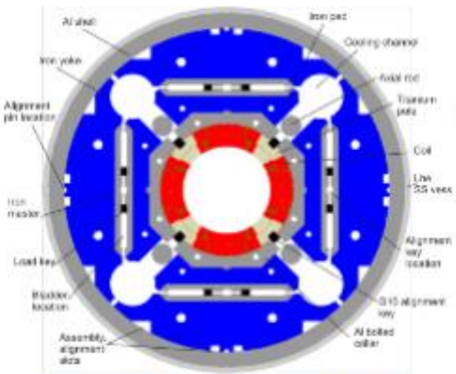
Global Scale Computing

Thank you for your attention

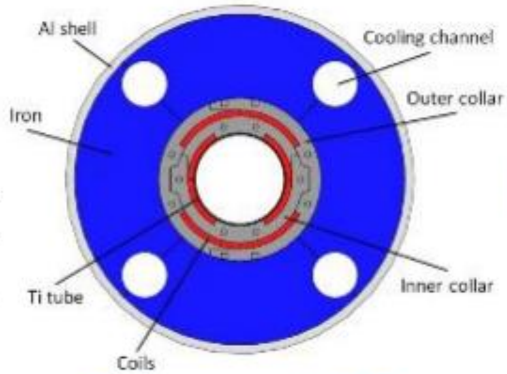


Additional slides

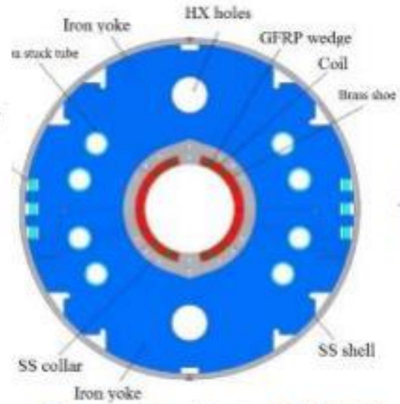
HL-LHC magnet zoo



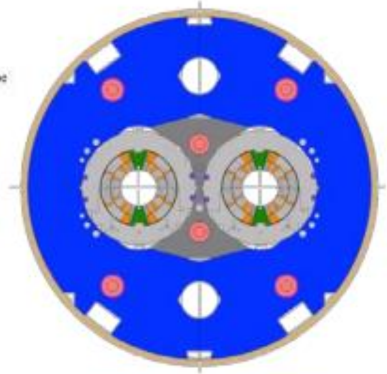
Triplet QXF (LARP and CERN)



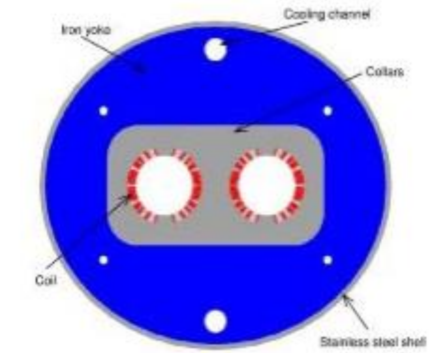
Orbit corrector (CIEMAT)



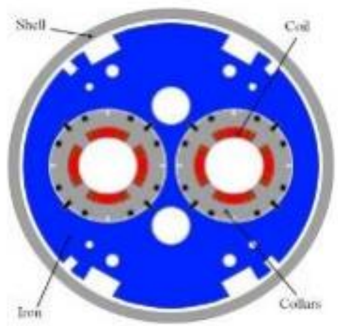
Separation dipole D1 (KEK)



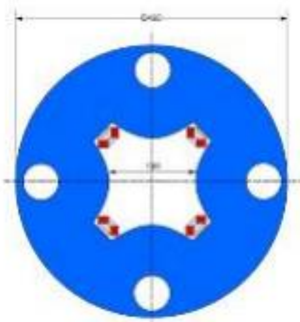
11 T dipole (CERN)



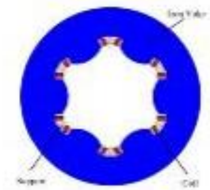
Recombination dipole D2
(INFN design)



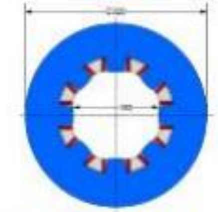
Q4 (CEA)



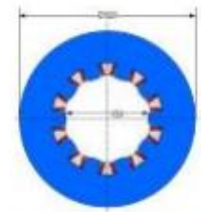
Skew quadrupole (INFN)



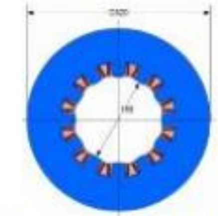
Sextupole (INFN)



Octupole (INFN)



Decapole (INFN)

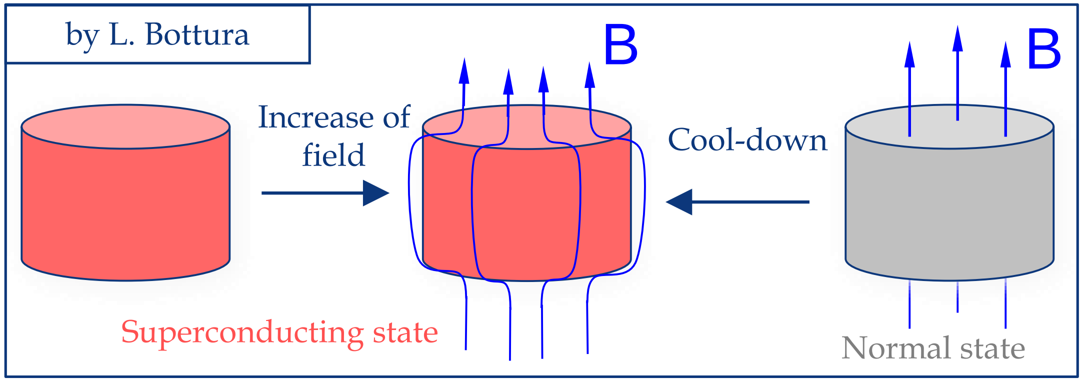


Dodecapole (INFN)

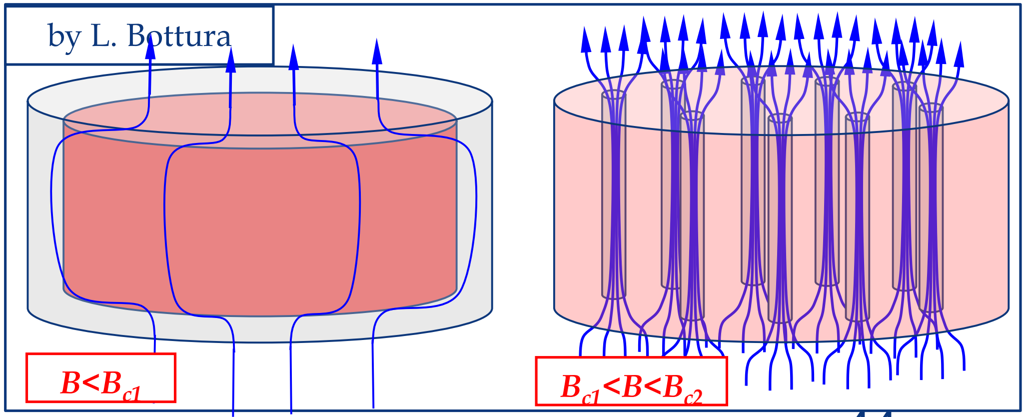
Approximately 200 magnets for HL-LHC

Superconductivity

- For 40-50 years, only "**Type I**" superconductors were known. ↓
  - Perfect diamagnetism. With $T<T_c$ magnetic field is expelled
  - But, the *B* must be < critical field B_c. Otherwise, superconductivity is lost
  - Unfortunately, B_c *very low* (≤ 0.1 T), not practical for electro-magnets



- Then, in the 50's, "**Type II**" superconductors
  - Between $\boldsymbol{B_{c1}}$ and $\boldsymbol{B_{c2}}$: mixed phase
    - ***B*** penetrates as flux tubes: *fluxoids*
  - Much higher fields and link between $\boldsymbol{T_c}$ and $\boldsymbol{B_{c2}}$



The strand: multifilament wire

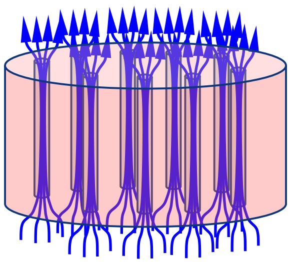
WHY a multi-filament wire?

1. Flux jumps

Thermal disturbance → the local change in J_c → motion or "**flux jump**" → power dissipation
Stability criteria for a slab (adiabatic condition)

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

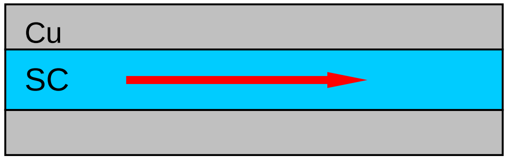
a is the half-thickness of the slab
j_c is the critical current density [A m^{-2}]
γ is the density [kg m^{-3}]
C is the specific heat [J kg^{-1}]
θ_c is the critical temperature.

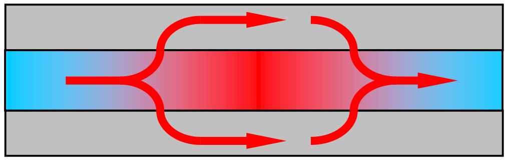


$B_{c1}<B<B_{c2}$

2. 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**



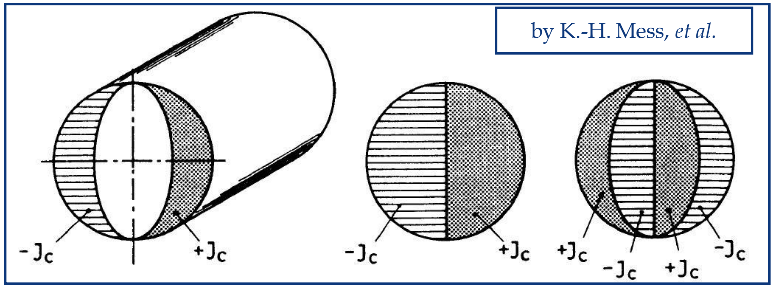


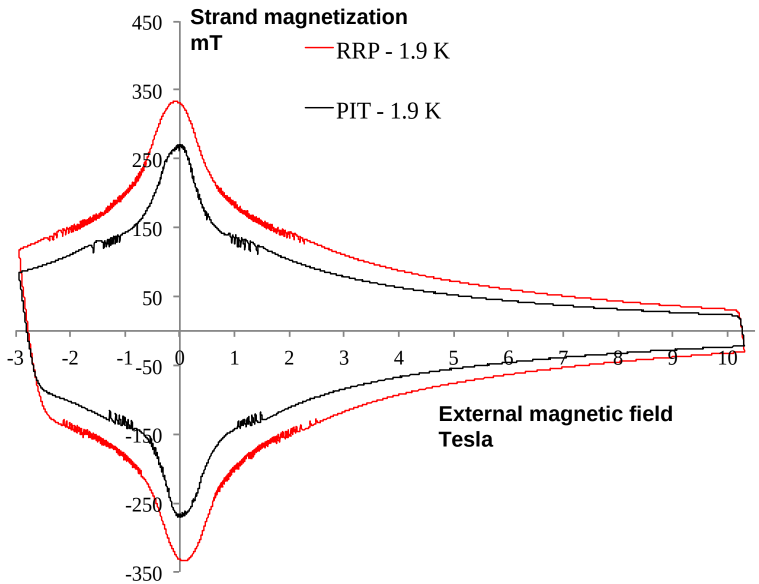
The strand: multifilament wire

3. Persistent currents

When a filament is in a varying B_{ext}, its inner part is shielded by currents distribution in the filament periphery

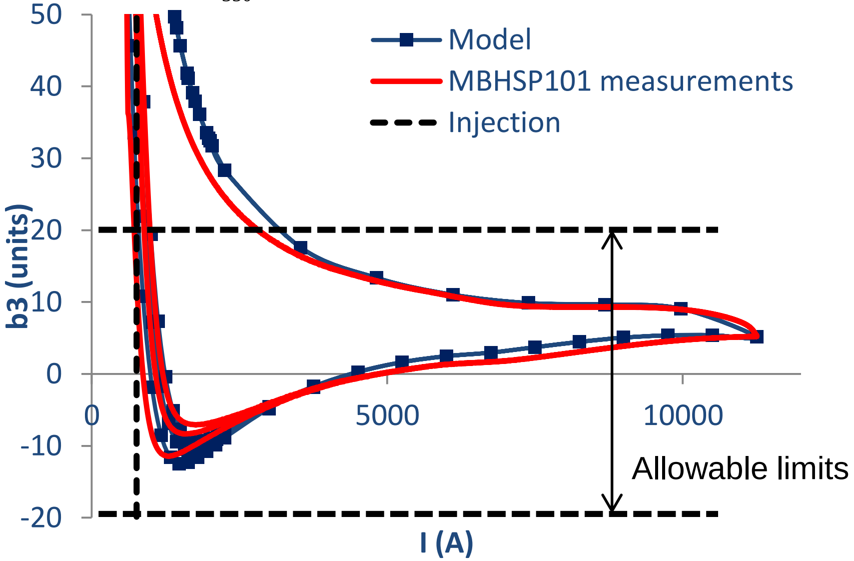
They **do not decay** when B_{ex} is held constant → **persistent currents**





These currents produce **field errors** that are particular important at low energy **(when the beam is injected),** which are proportional to the filament diameter (d_{sub}) and the current density.

$$M(B) \propto d_{sub} \cdot J_c\,(B)$$

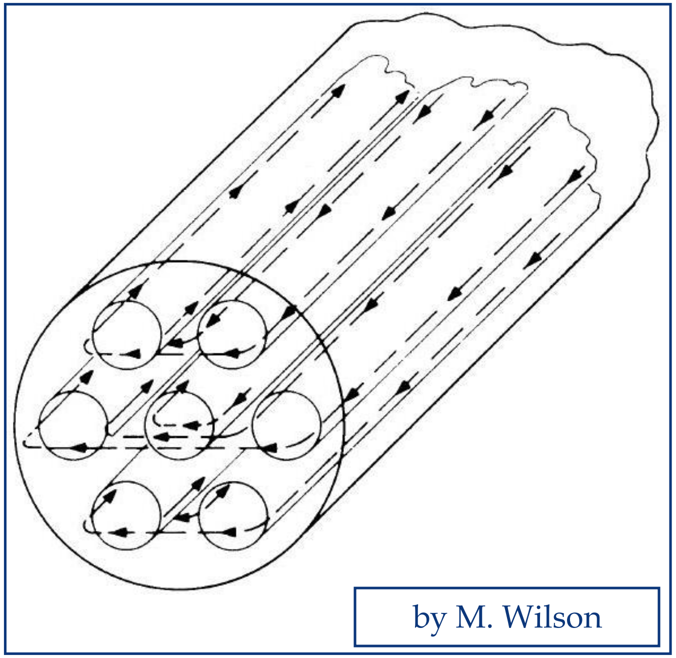


CERN

The strand: multifilament wire

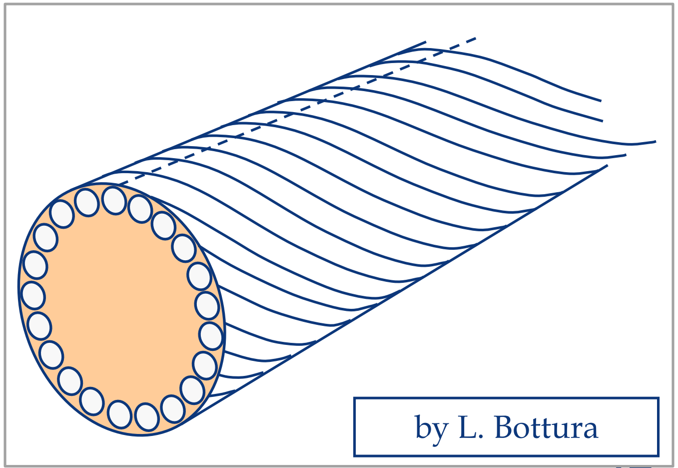
4. Inter-filament coupling

- 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**

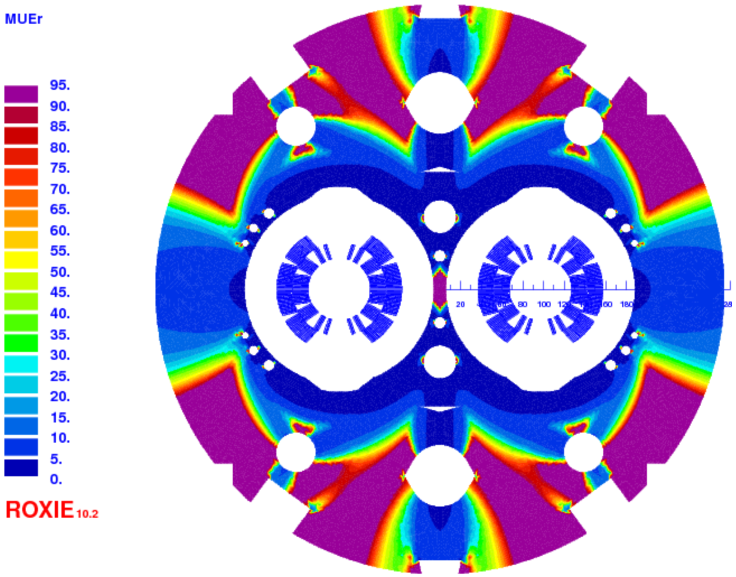
- twist pitch of the order of 20-30 times of the wire diameter.



Iron yoke

An iron yoke usually surrounds the collared coil – it has several functions:

- 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



When the iron saturates (~ 2T):

- The main field is not $\propto$ current $\rightarrow$ transfer function *B/i* drops of several (tens) of units
- Since the field in the iron has an azimuthal dependence, some parts of the iron can be saturated and others not $\rightarrow$ variation of low order harmonics