DE LA RECHERCHE À L'INDUSTRIE

CERN ACCELERATOR SCHOOL

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Advanced magnet technologies

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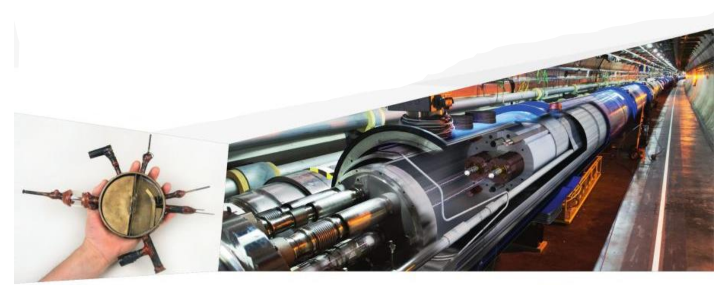

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“MAGNET” DEFINITION

From the Collins English Dictionary:

(1) *A person that exerts a great attraction*

For physics:

(2) *A magnet creates a force that acts on any other magnet, electric current, or moving charged particle.*

Sorry, but main subject of my talk…

A LARGE RANGE OF MAGNITUDE

The very first magnet!


0,4 Gauss / 4.10-5 T
in London

Permanent magnet
(NdFeB, 0.5T)

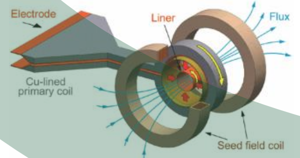
Resistive
magnet (2T)

MRI magnet
(Siemens 3T)

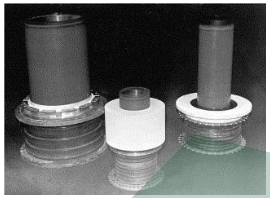
LHC Dipole
(8,3T)

Bruker 1 GHz NMR
(23,5T)

NHMFL
Tallahassee
Hybrid magnet
(40 T)

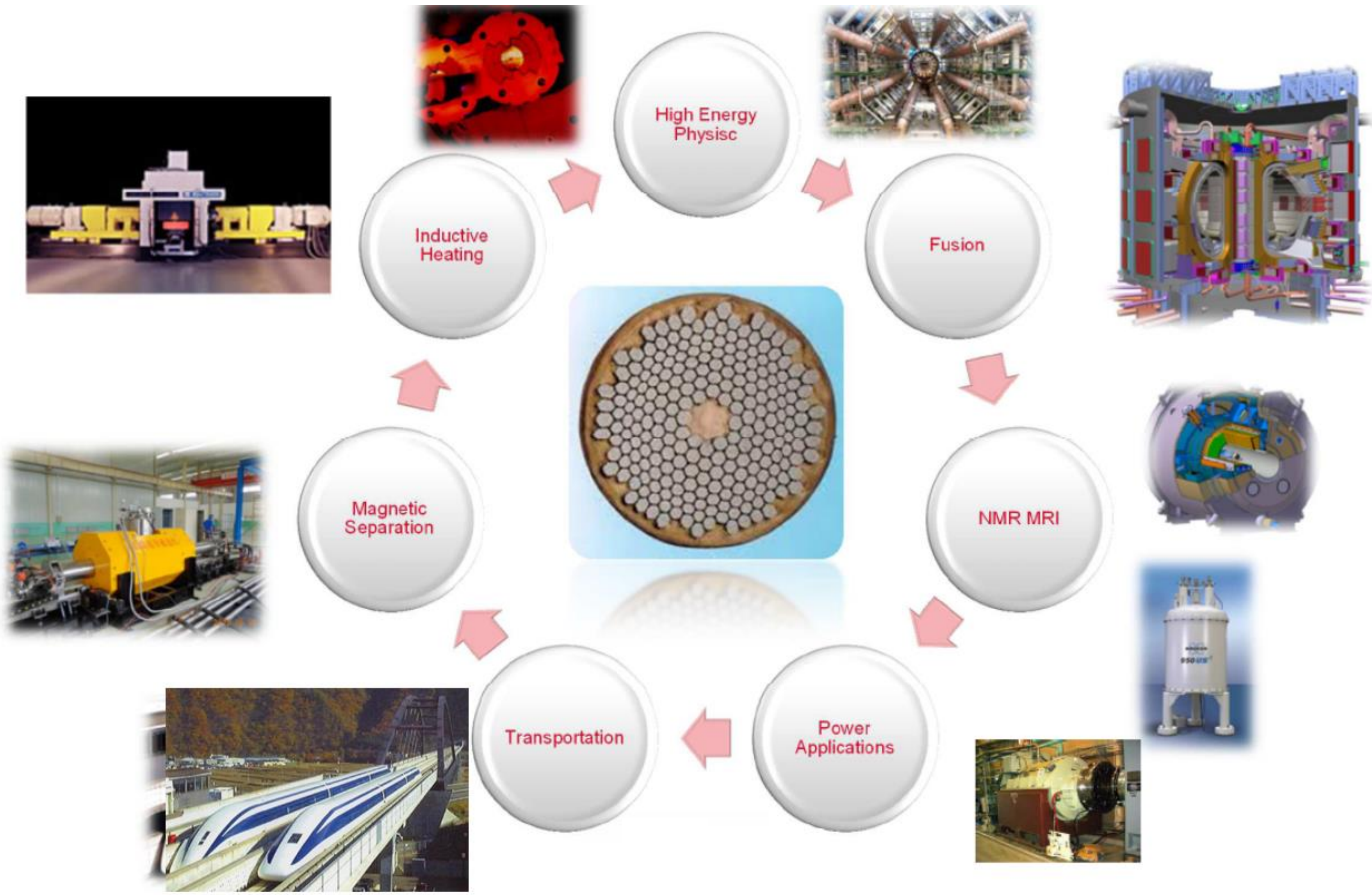


ISSP (Japan)
(750 T)

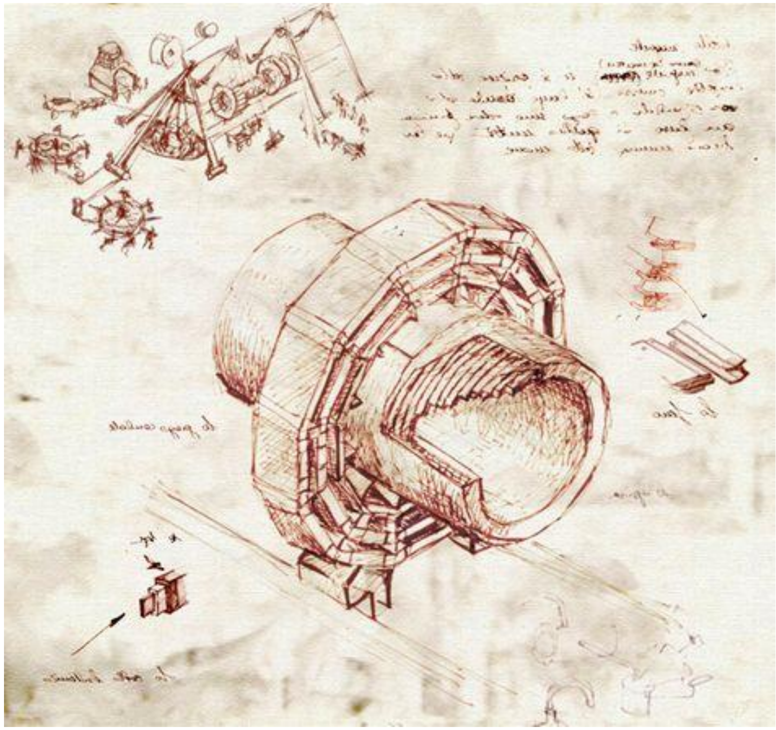


VNIIEF MC-1 (Russia)
2,8 kT

AND A LOT OF APPLICATIONS!



MAGNET OPTIMISATION IS A COMPLEX PROBLEM…



How physicists depict the CMS detector…

How engineers built it…

THE FUNDAMENTAL EQUATIONS

A set of only four equations describes the relations between electricity and magnetism:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

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

A Dynamical Theory of the Electromagnetic Field", James Clerk Maxwell, 1865

FIELD MAP SPECIFICATION

A specification can be wide…

- Central field value (usually the highest…)
- Shape (solenoid, toroid, dipole, quadrupole…)
- Magnet aperture (usually the largest…)
- Useful area or volume (usually the largest…)
- Field quality (dipole uniformity, field gradient, field integral, sagitta, momentum resolution,…)
- Fringe field (usually very low, even closed to the magnet)
- Operating mode (AC/DC)
- Etc…

ADVANCED TECHNOLOGIES ARE REQUIRED…

Let’s focus on two examples

- LHC dipoles

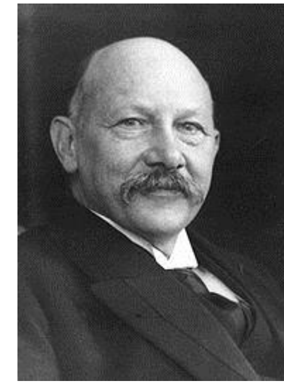
- High field MRI magnets

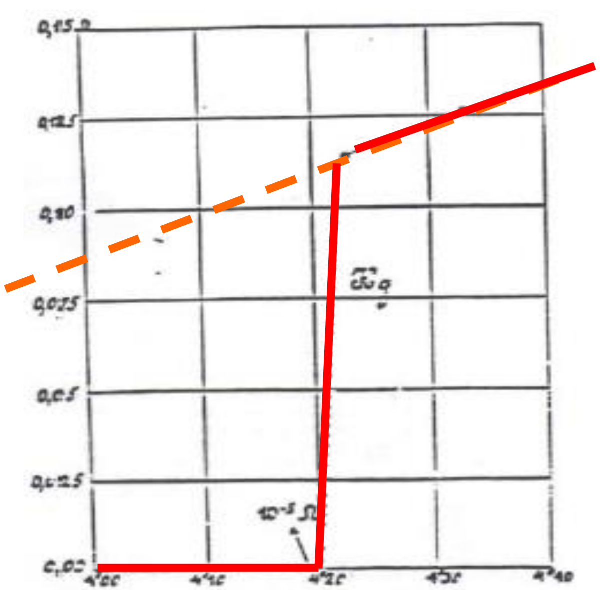
Both are based on the SC technology!

WHY SUPERCONDUCTIVITY ?

Gilles Holst, student of Kamerlingh Onnes writes a short note to the Royal Academy of the Netherlands on April 8th, 1911 :

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



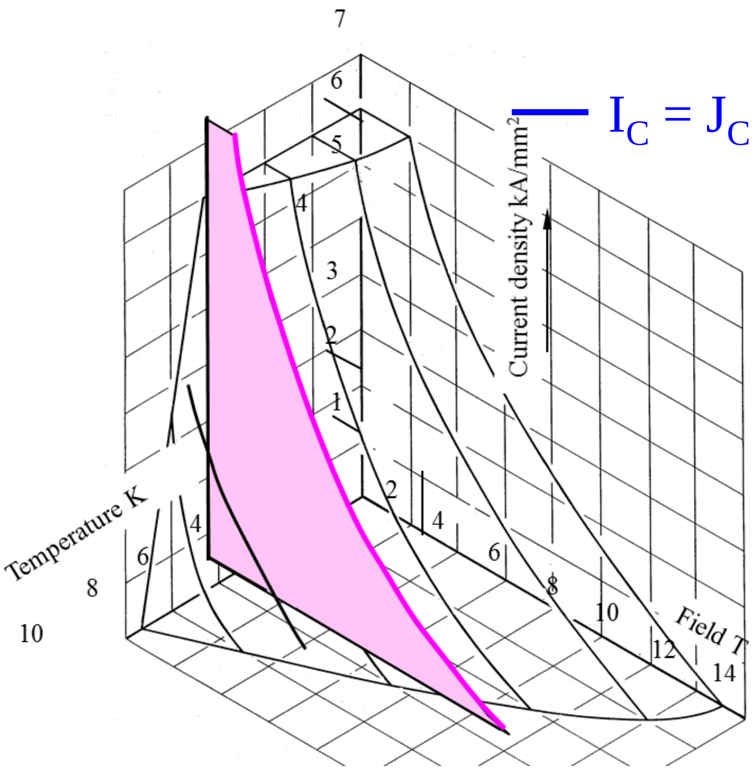


Ohms’ law is not longer valid!

- **Low electrical consumption** (mainly to operate the cryogenic system)
- **High current density**
- **Compact winding** that can generate high magnetic fields in a large volume

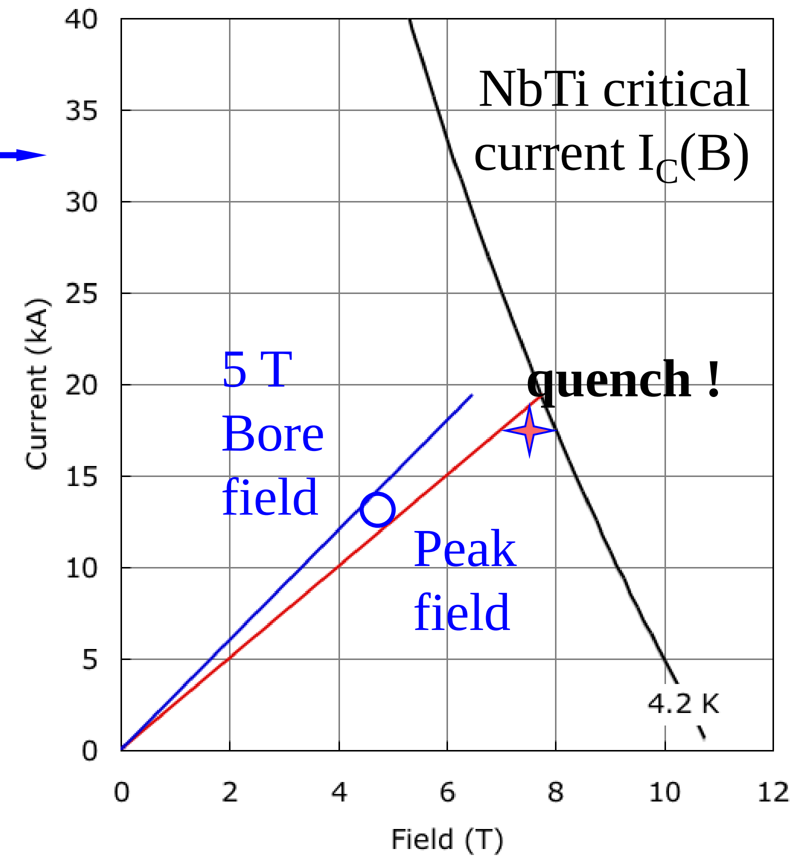
CRITICAL LINE AND MAGNET LOAD LINES

NbTi critical surface



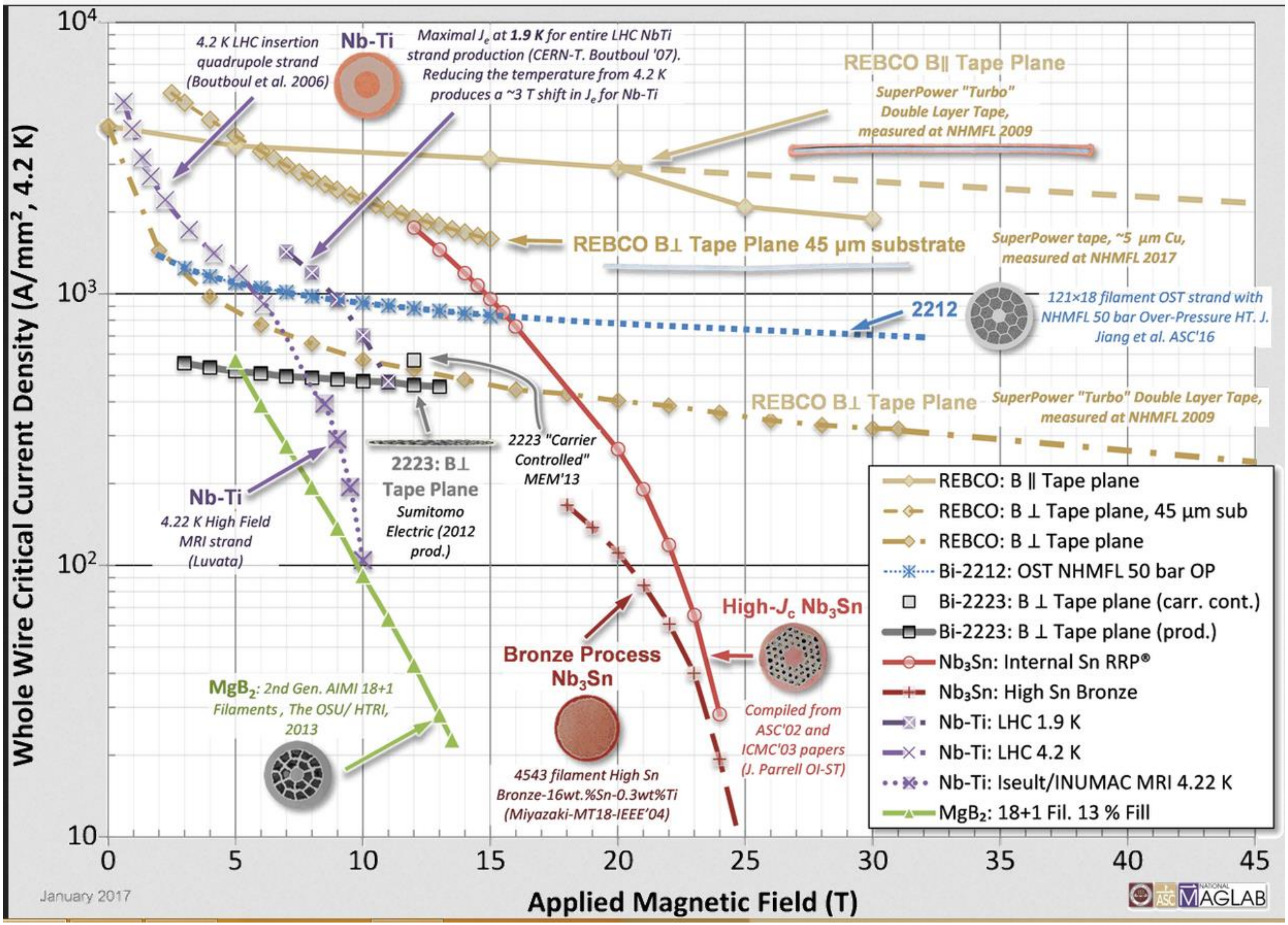
$$I_C = J_C \times A_{SC}$$

e.g. a 5 T magnet design made of NbTi



The magnet becomes resistive (**'quench'**) where the peak field load line crosses the critical current line

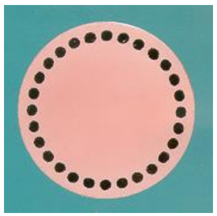
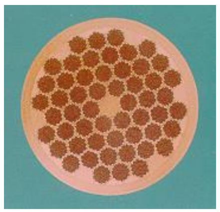
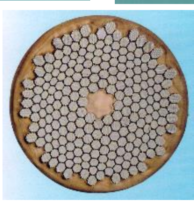
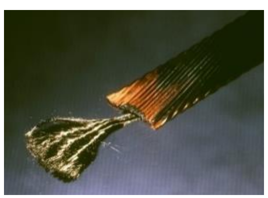
Jeng in LTS and HTS conductors at 4.2K and 1.9K



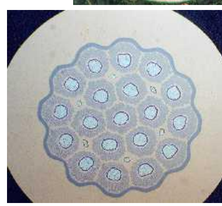
Conductor Source: http://fs.magnet.fsu.edu/~lee/plot/plot.htm

A LARGE CHOICE OF SC MATERIALS

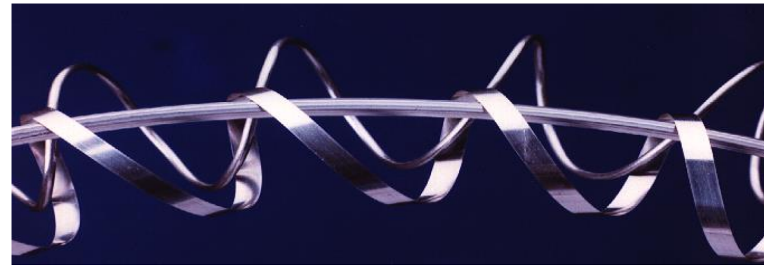
NbTi

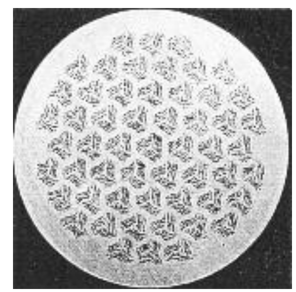
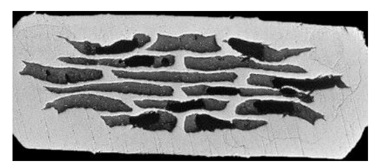
Nb_3Sn, Nb_3Al

YBCO



BSCCO


MgB_2

A LARGE CHOICE OF SC MATERIALS

NbTi

- Dominant commercial superconductor
- MRI is biggest user of NbTi SC wire
- Bendable, ductile, low cost ($1/kA.m)
- Tc=9,3K, Bc2=11,4 @ 4,23K

Nb_3Sn

- Primary high field SC
- Brittle
- Tc=18K, Bc2 ≈ 23-29K
- Higher cost (x 5 price of NbTi)

MgB_2

- Brittle
- Tc=39K, Bc2=40T
- Higher cost (x 5 price of NbTi)

ReBCO technology based on is still very expensive ($50-100/kA.m) and not mature enough for large industrial applications

A complex problem…

- Field map specification
- Current transport capacity (choice of conductor)
- Operating temperature and cooling method
- Peak field on the conductor
- Quench protection
- Mechanical stresses
- Manufacturing techniques
- Economical constraints

MAIN TECHNICAL CHALLENGES OF SC MAGNETS

High magnetic field, high current, large useful volume, large stored energy, high mechanical forces and stresses

SC state requires low temperatures

Complex cryogenic system; have to be optimized (compact, autonomous, minimum consumption)

Protection in case of quench

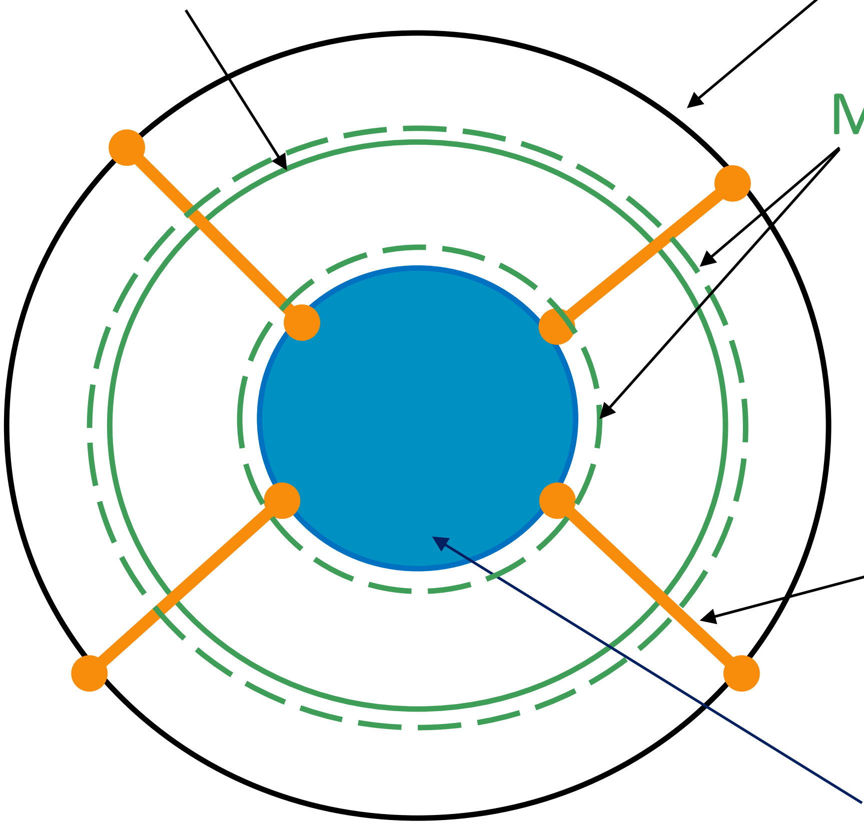
- Where to dissipate the stored energy?
- Manage the quick temperature elevation in the SC system
- Manage the large stresses

Advanced manufacturing techniques required

- Superconductors
- Electrical insulation
- Challenging manufacturing techniques

CRYOSTAT GENERAL CONCEPT

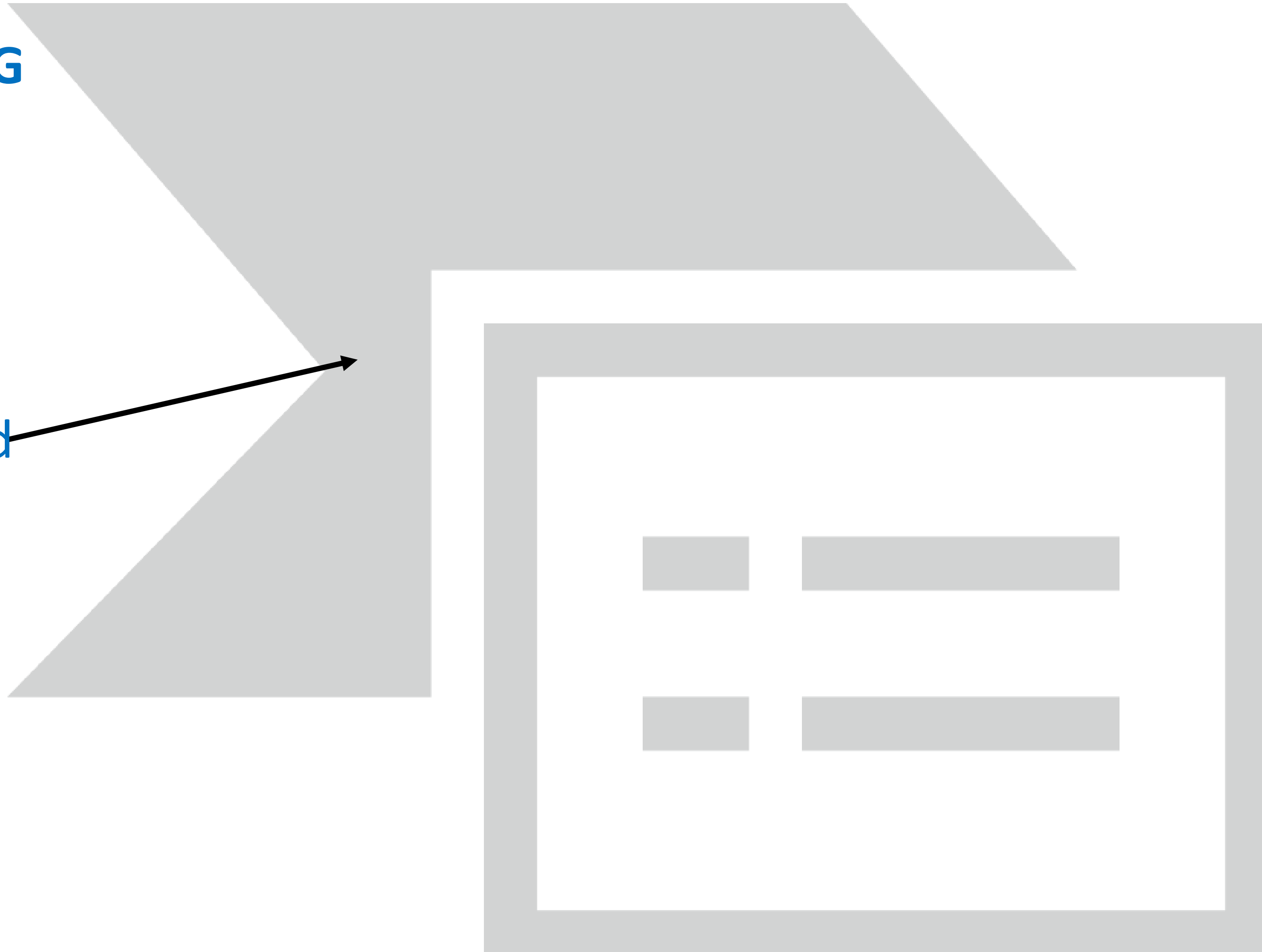
Minimize the thermal losses on the superconducting coil!



COOLING (1/3)

DIRECT COOLING

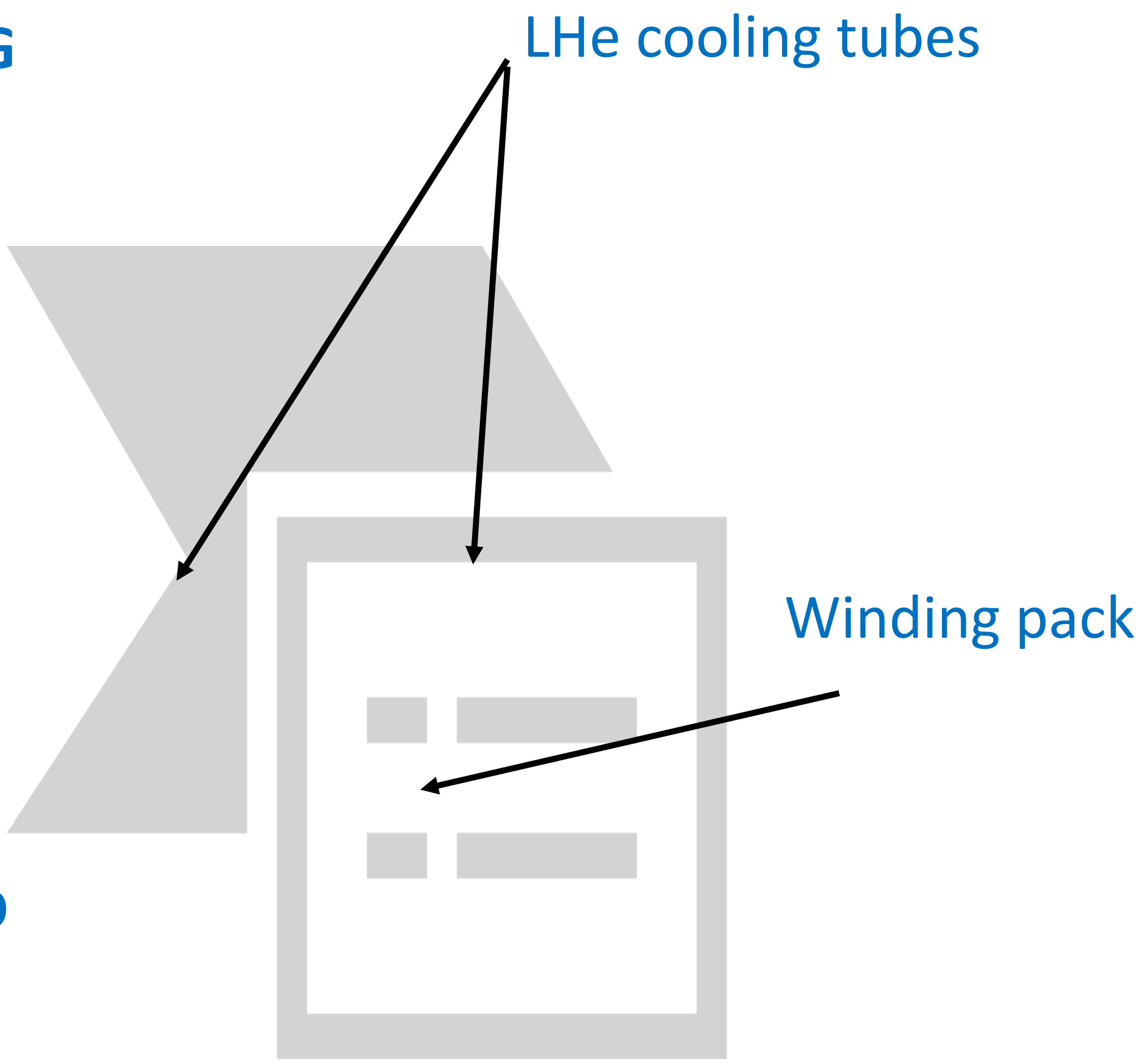
SC magnets directy cooled in a LHe bath



LHC DIPOLE

COOLING (2/3)

INDIRECT COOLING



CMS SOLENOID

COOLING (3/3)

OTHER OPTIONS

Forced flow of helium inside a hollow conductor (fusion)

ITER conductor

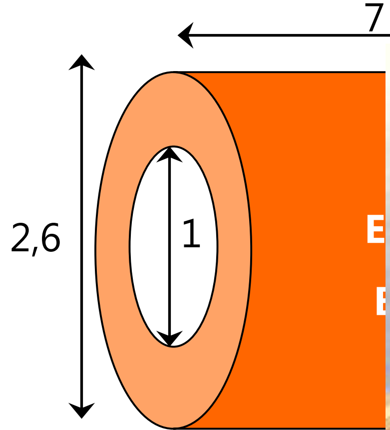
Cryocooler for a small system with low losses

Sumitomo RDK-408D2
2-stage cold-head

MAGNET PROTECTION (1/2)

The goal is to protect the magnet in case of quench (transition from the superconducting state to the resistive state)

Resistive magnet (copper)



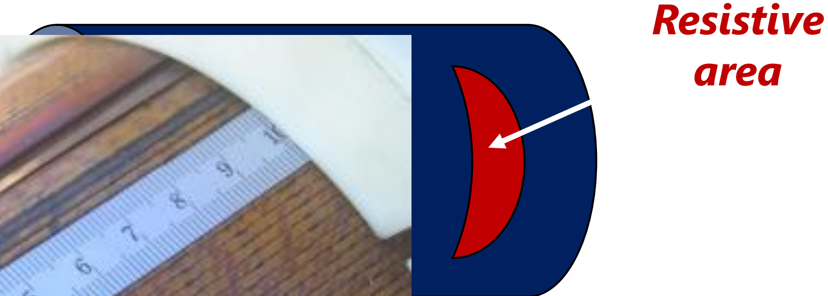
j_{Cu} = 2 A/mm²

V_{tot} = π (1,3² – 0,5²) 7 =

Dissipation : **E/V = 32**

T = 65 K

SC magnet



thickness / 10

V_{tot} = 1,9 m³

heat the resistive

= 5 10⁹ J/m³

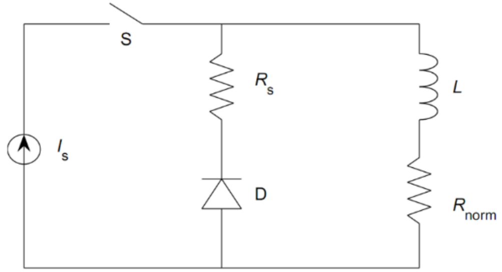
T = 1400 K

Courtesy P. Fazilleau

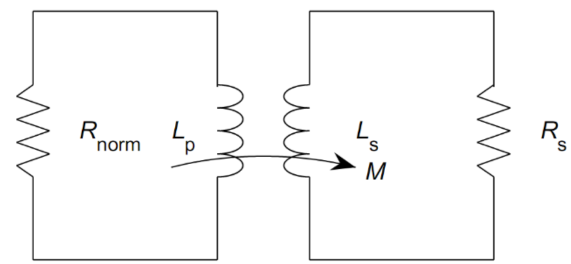
MAGNET PROTECTION (2/2)

- **Propagate the quench quickly and into the largest possible volume**
- **Minimize the hot spot in the winding and thermal gradients (source of mechanical stresses)**

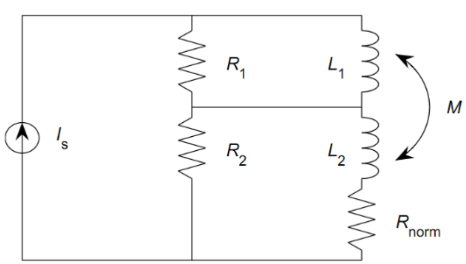
External dump resistor



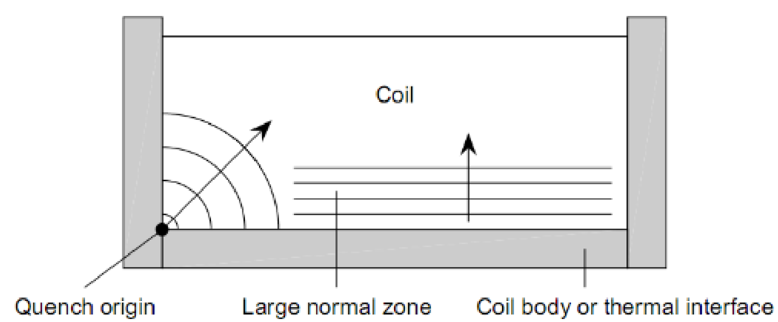
Protection using coupling effect between two circuits (transformer)



Subdivision



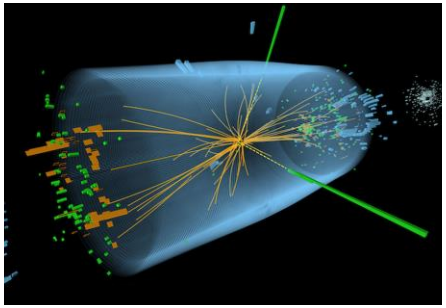
Quench-back
(Use of Eddy currents created by the magnetic field variation to heat the winding and help the quench propagation »)

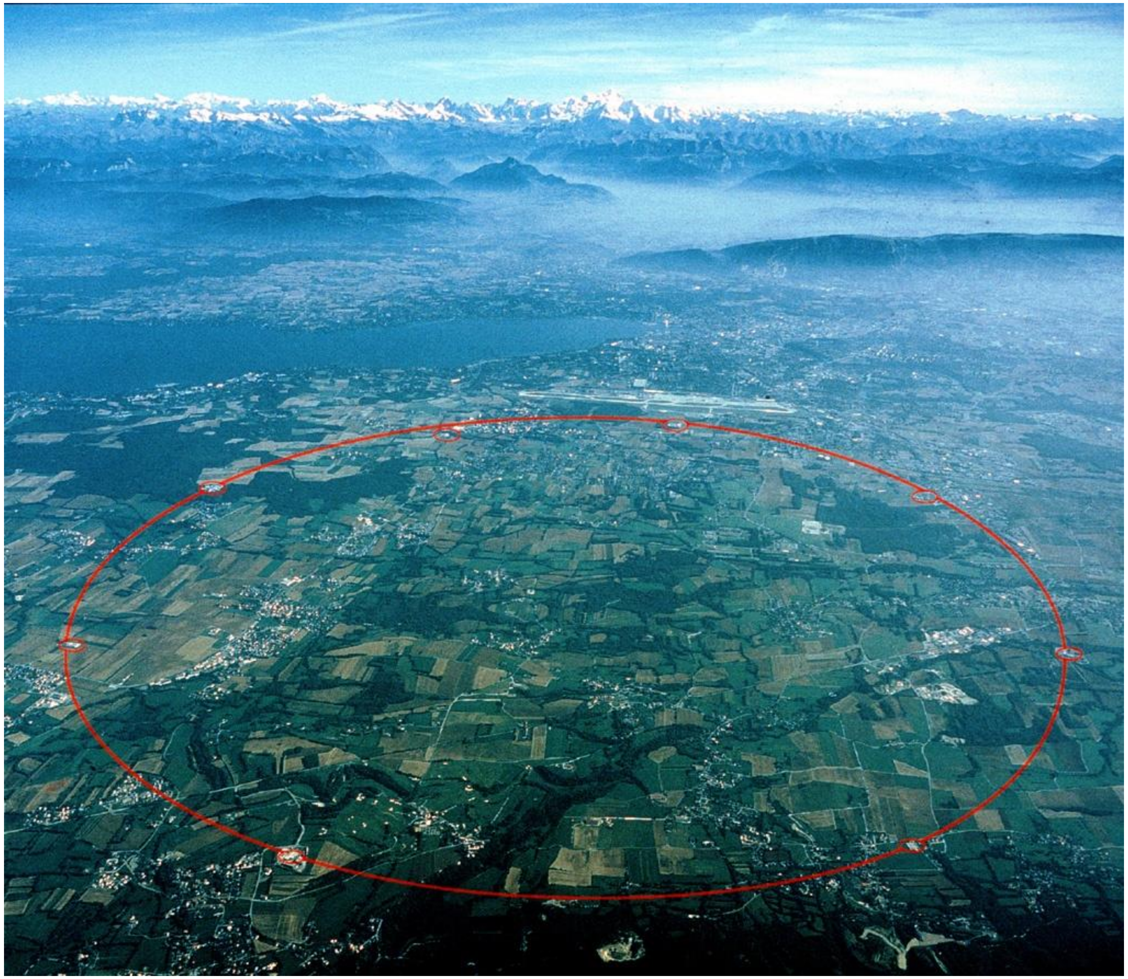


Courtesy P. Fazilleau

THE LHC DIPOLE

THE LHC: A UNIQUE FACILITY FOR PARTICULE PHYSICS





7000 km of NbTi

27 km of SC magnets:

- 1232 dipoles,
- 474 quadrupoles,
- 7612 correction coils

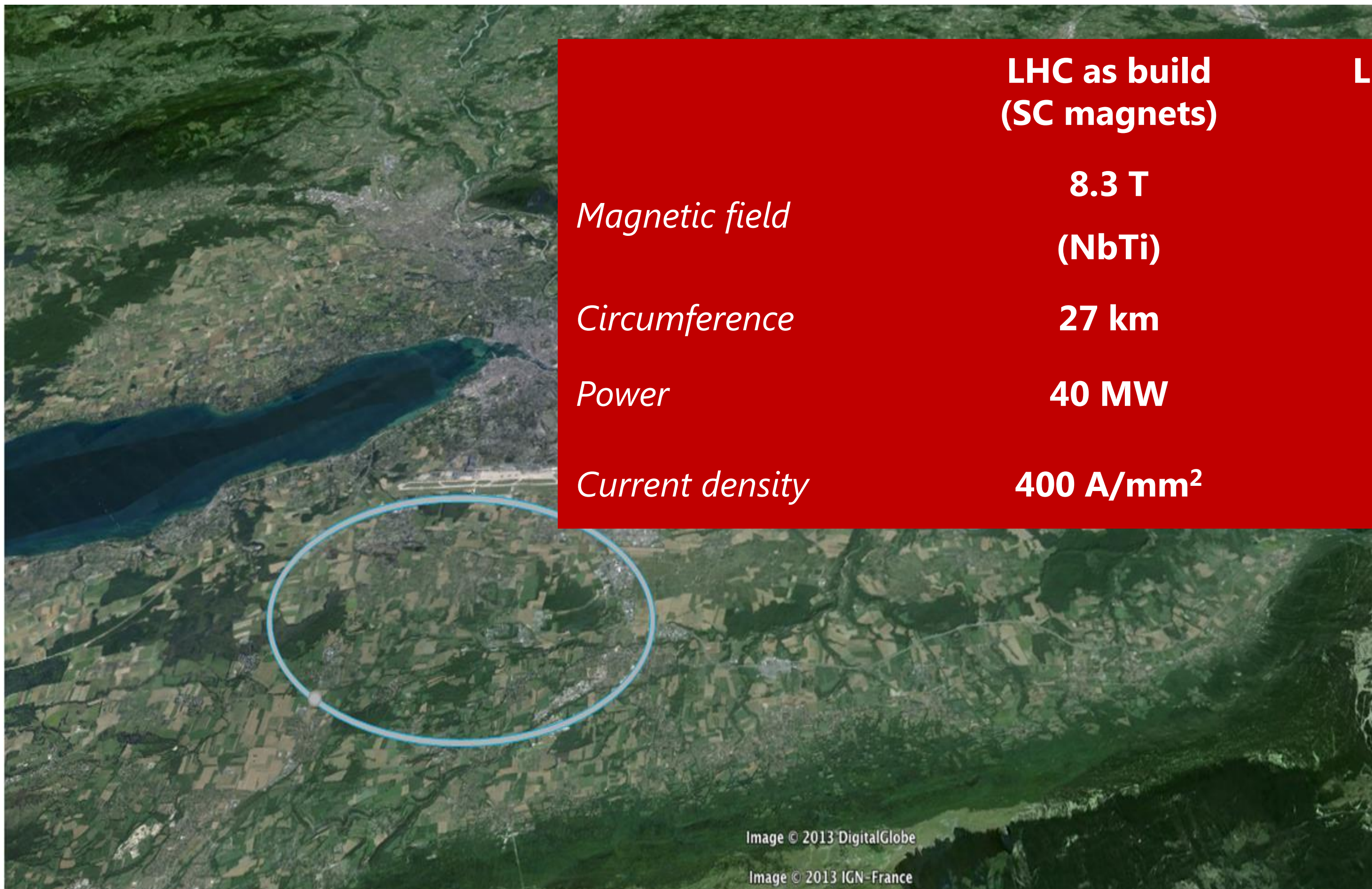
Cooled @ 1,9K with superfluid helium

SC MAGNETS VS. RESISTIVE MAGNETS

$$E[TeV] = 0{,}3 \times B[T] \times r[km]$$

Beam energy | Magnetic field | Curvature

LHC
14 TeV



	LHC as build (SC magnets)	LHC with resistive magnets
Magnetic field	8.3 T (NbTi)	1.8 T (iron)
Circumference	27 km	125 km
Power	40 MW	900 MW
Current density	400 A/mm^2	10 A/mm^2

FROM MAXWELL EQ. TO FIELD HARMONICS

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

- For a constant longitudinal field, in absence of charge and of magnetic material:

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

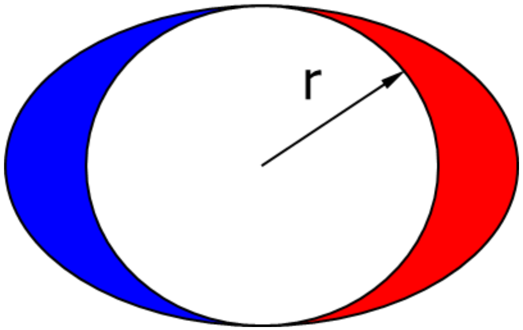
- The magnetic field can be therefore expressed using harmonics
- The coefficients *bn*, *an* are called normalized multipoles

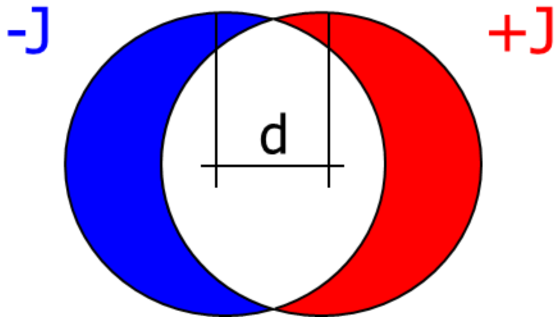
$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

DESIGN OF AN IDEAL DIPOLE MAGNET

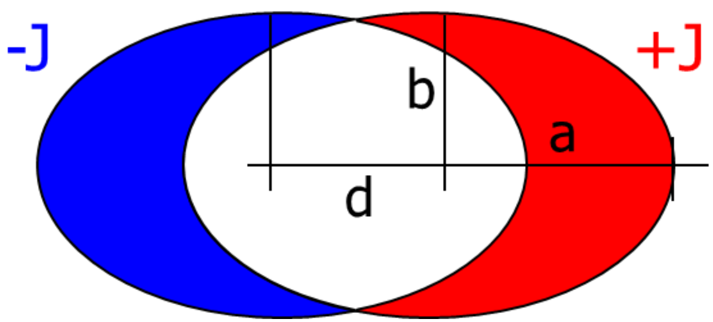
$I = I_0 \cos(\theta)$ ➡ $B_1 = -\mu_0 I_0/2r$

Intersecting circles ➡ $B_1 = -\mu_0 J d/2$





Intersecting ellipses ➡ $B_1 = -\mu_0 J d\, b/(a+b)$

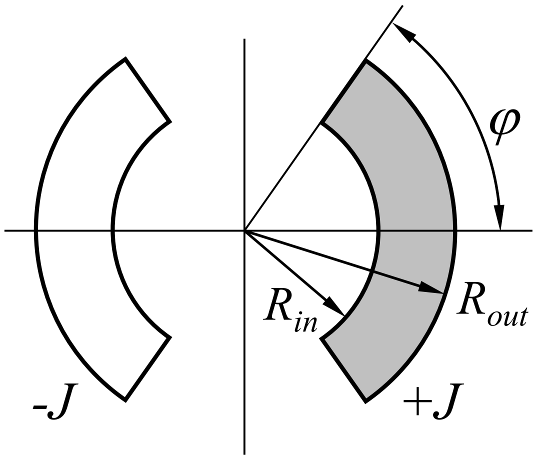


Several solutions are possible and can be extended to higher order multi-pole magnets

Not really practical…

Courtesy L. Bottura

DIPOLE MAGNETIC DESIGN - SECTOR COILS



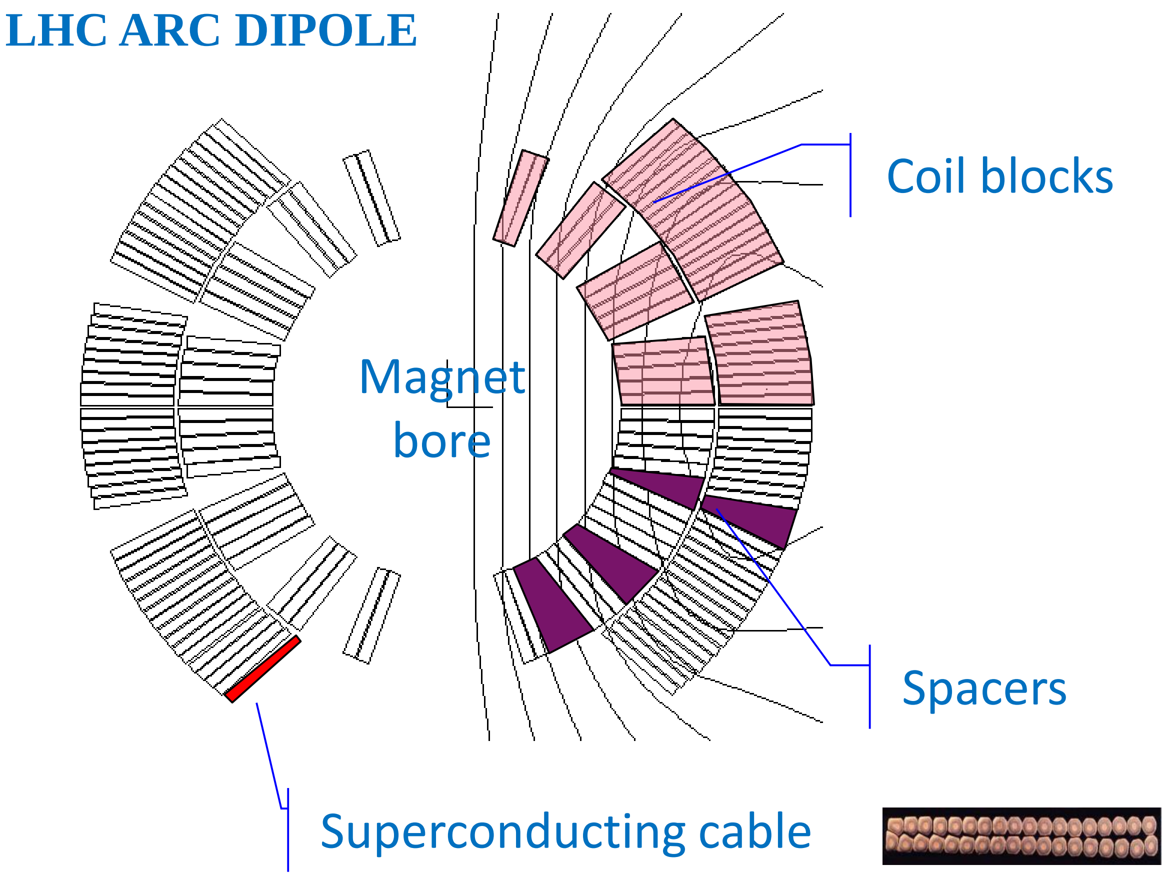
Courtesy L. Bottura

$$B=-2\mu_0/\pi \boxed{J\ (R_{out} - R_{in})} \sin(\varphi)$$

The field is proportional to the current density **J** and the coil width (***R$_{out}$* - *R$_{in}$***)

Looks more interesting…

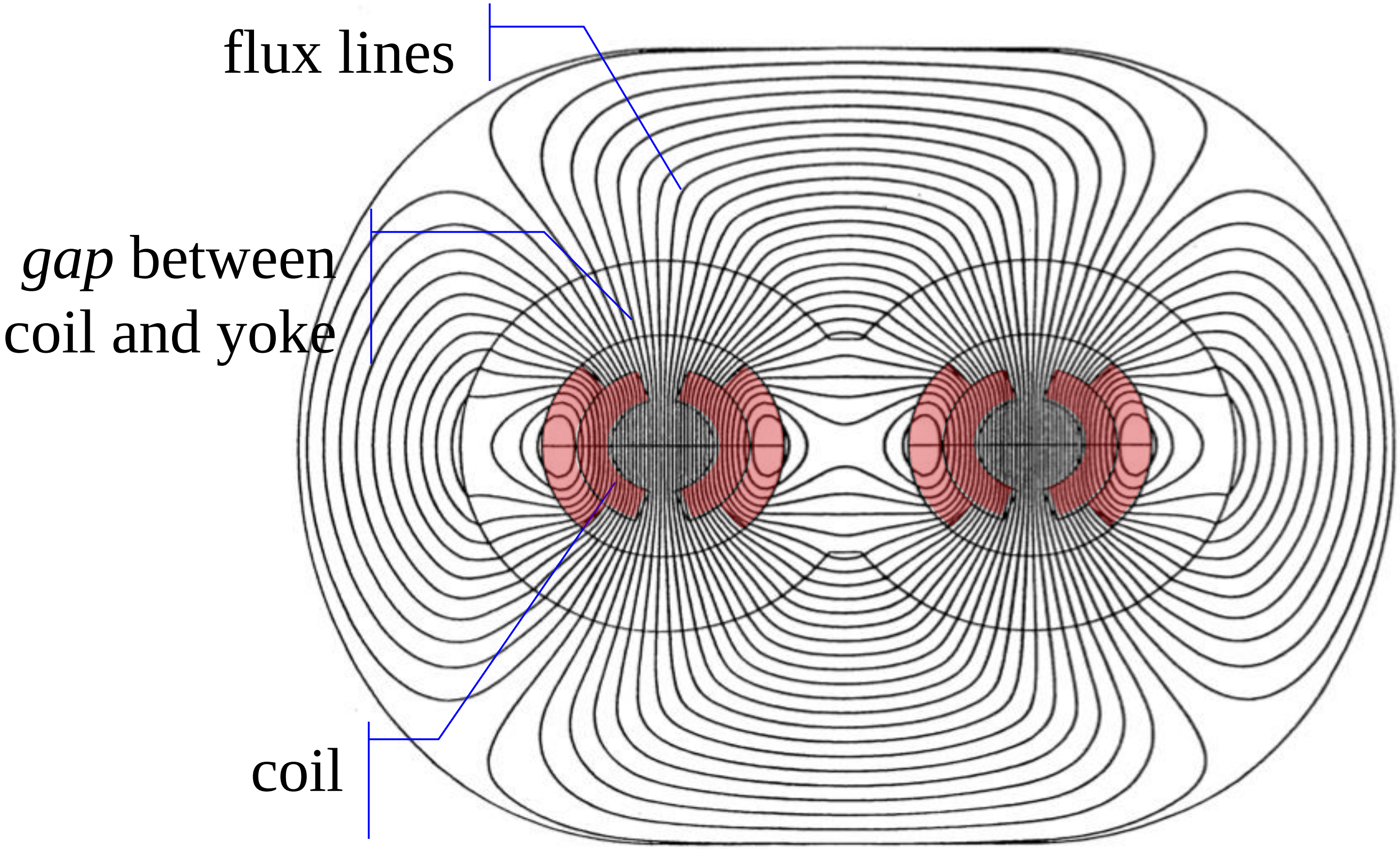
REAL COIL WINDINGS



Courtesy L. Bottura

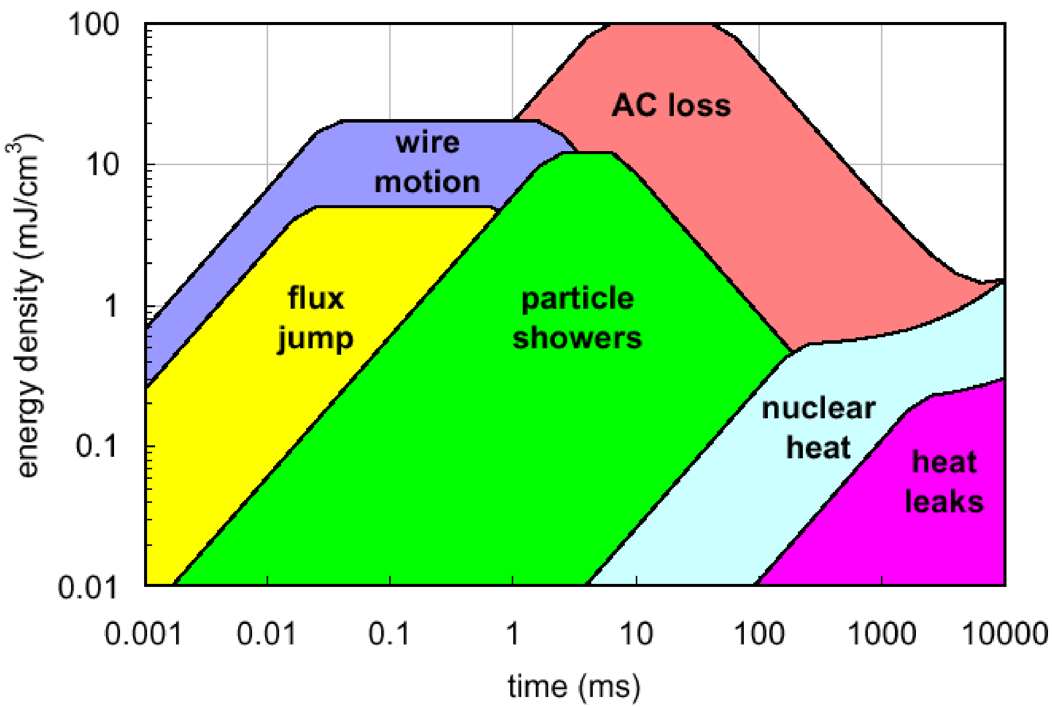
Conductor location **optimized** to create a very homogenous field (minimum normal/skew coeffs)

IRON TO CLOSE THE MAGNETIC CIRCUIT



CERN 87-05, G. Brianti and K. Hubner Ed.

A quench is generally induced by a local heating



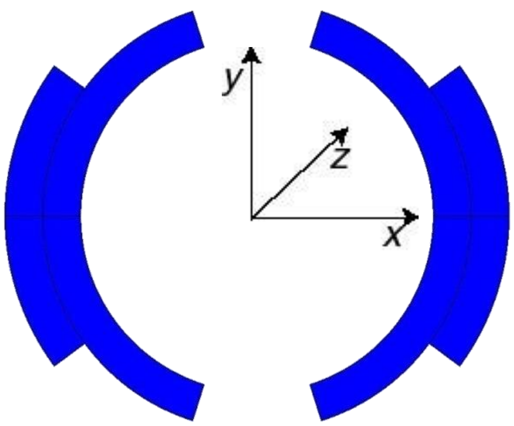
Thermal energy released by

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

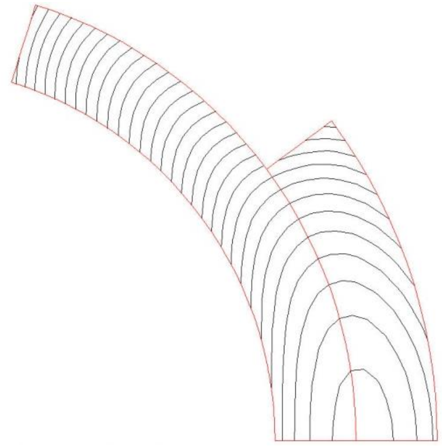
Typical range is from a few to a few tens of **mJ/cm³**

The electromagnetic forces in a dipole magnet tend to push the coil:

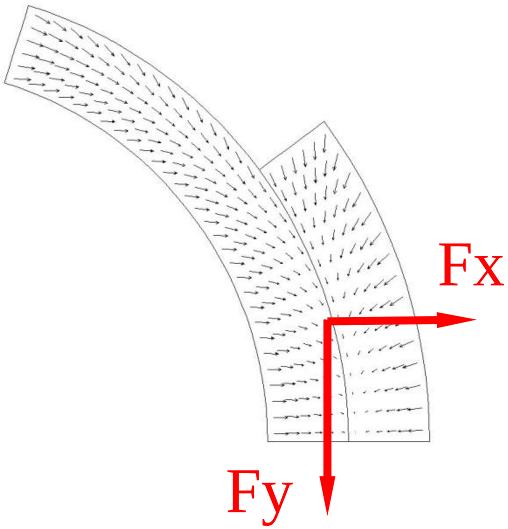
- Vertically, towards the mid plane (Fy < 0)
- Horizontally, outwards (Fx > 0)



Magnetic field



Force

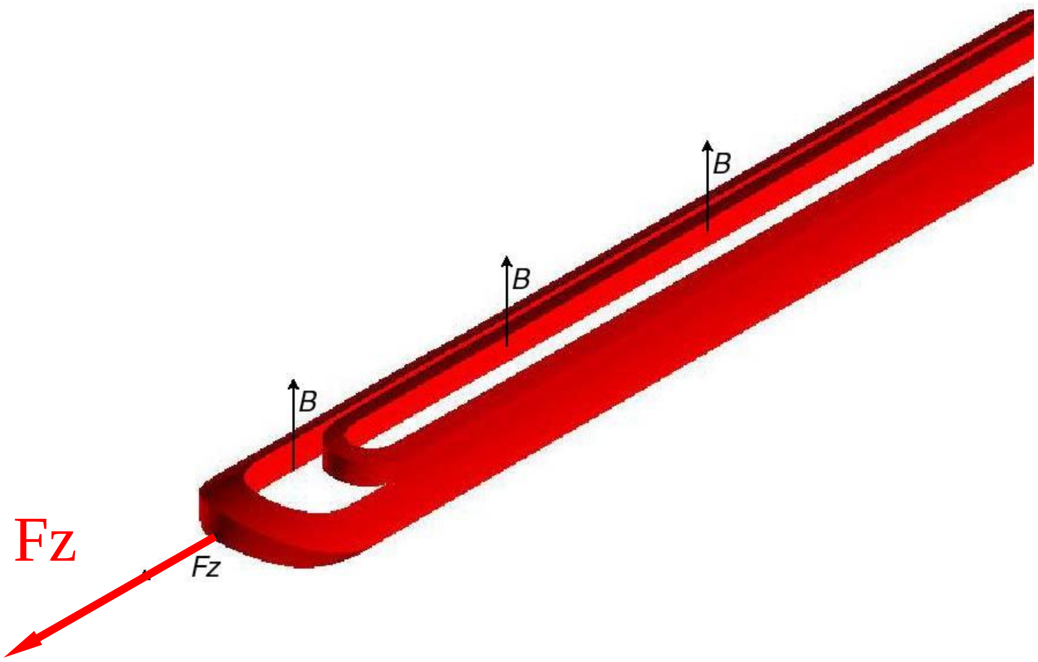


Graphics by courtesy of L. Bottura

ELECTROMAGNETIC FORCES - ENDS

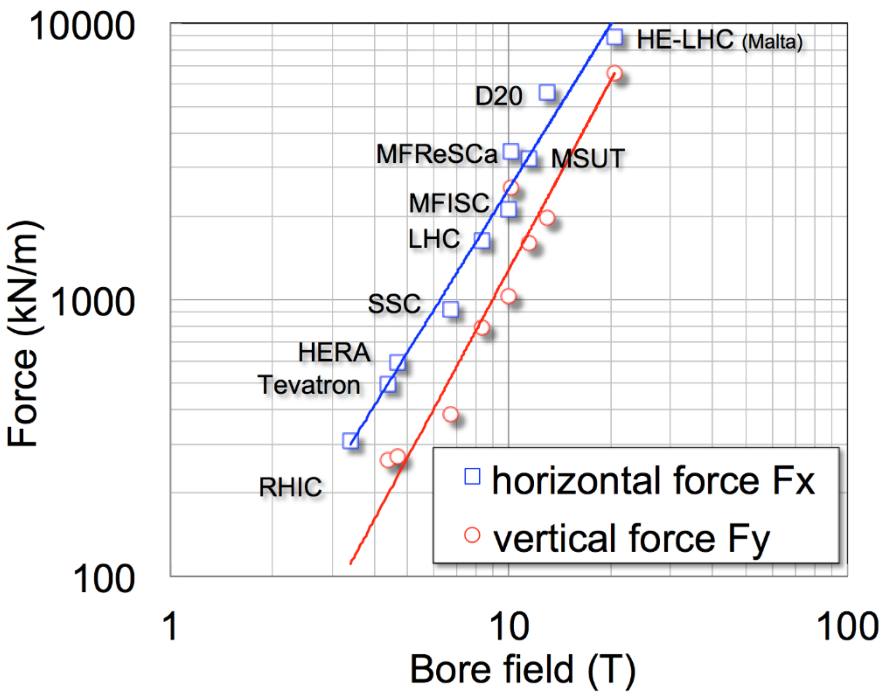
In the coil ends the Lorentz forces tend to push the coil:

- Outwards in the longitudinal direction (Fz > 0),
- And, similar to solenoids, the coil straight section is in tension



Graphics by courtesy of L. Bottura

THE REAL CHALLENGE OF VERY HIGH FIELDS



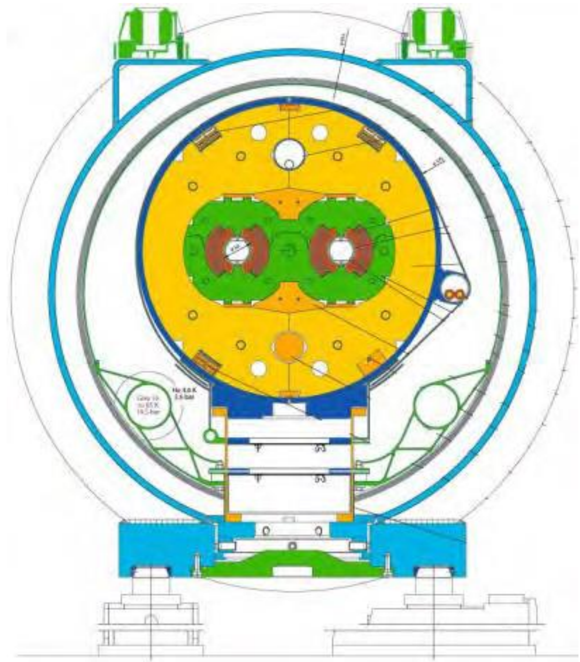
Force per coil quadrant in high-field dipoles built or designed for accelerators applications and R&D

- Force proportional to the square of the bore field
- Requires massive structures (high-strength materials, volume, weight)
- Stress limit is usually inside the superconducting coil

Design of high field magnets is limited by mechanics!!!

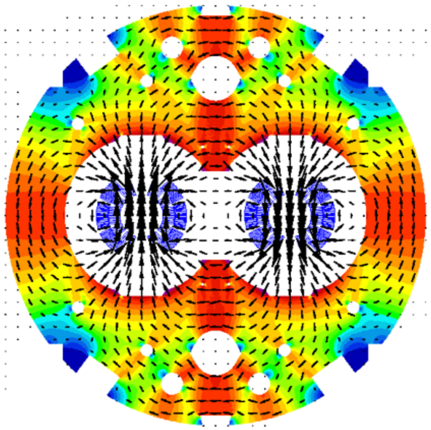
The coil is placed inside a strong support structure designed for:

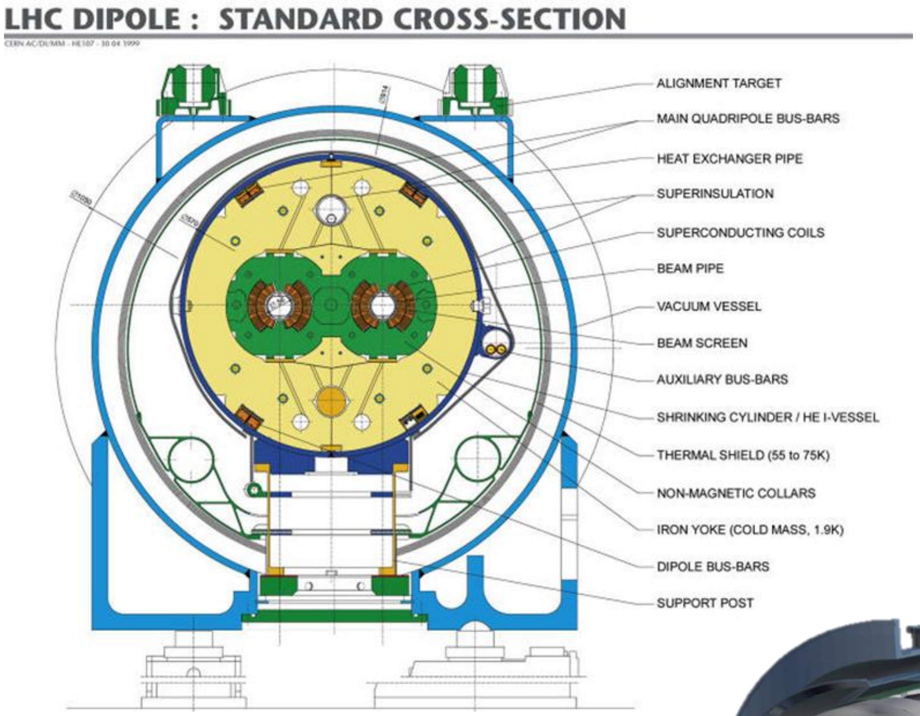
- providing the required pre-stress to the coil after cool-down to reduce conductor displacement
- withstanding the electro-magnetic forces
- providing LHe containment

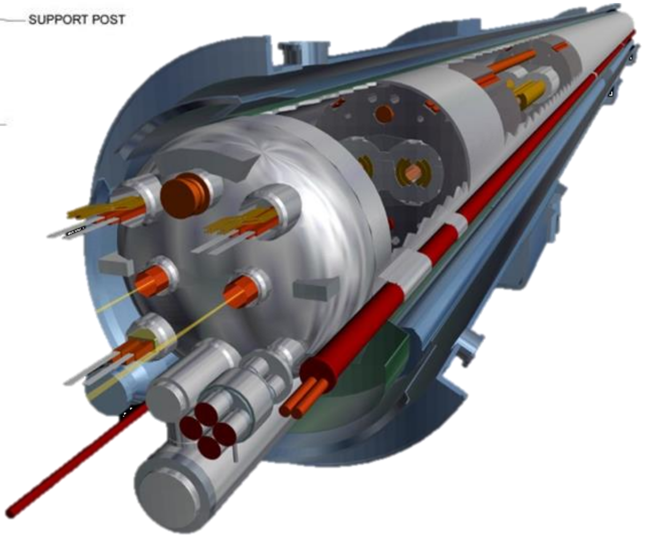


LHC DIPOLE

LHC DIPOLE







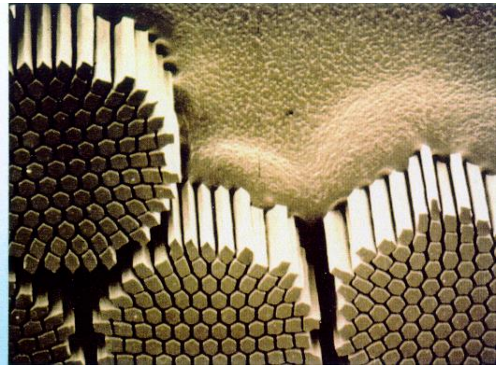
$B_{nominal}$	8.3 T
current	11850 A
stored energy	≈ 10 MJ
cold mass	≈ 35 tonnes

FROM THE WIRE TO THE CABLE

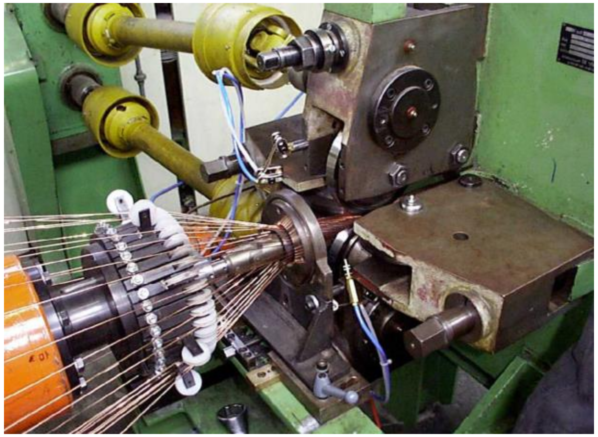
Strand spools
on rotating tables

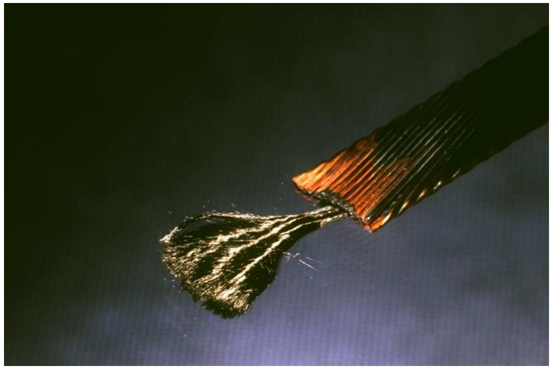
Rutherford cable machine @ CERN

Strands fed through a
cabling tongue to
shaping rollers



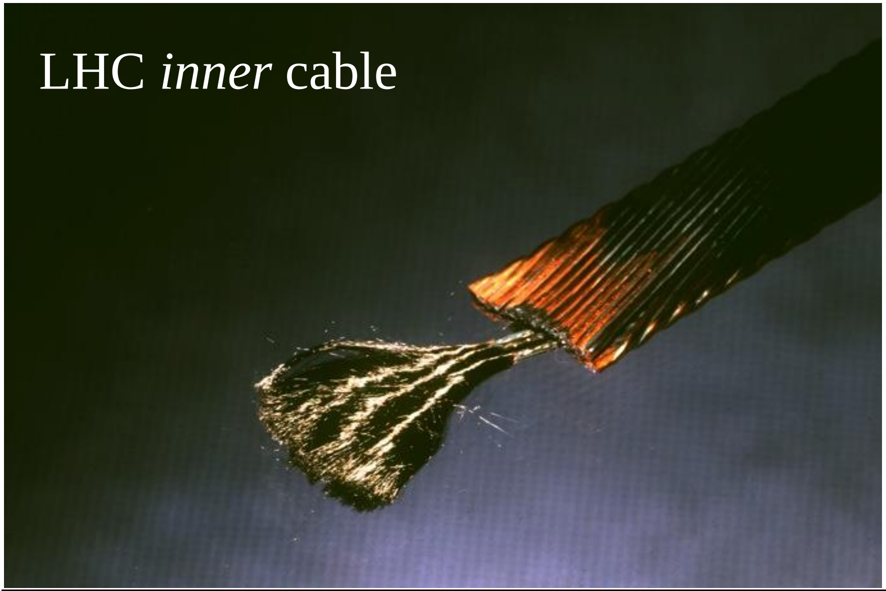
LHC Nb-Ti strand

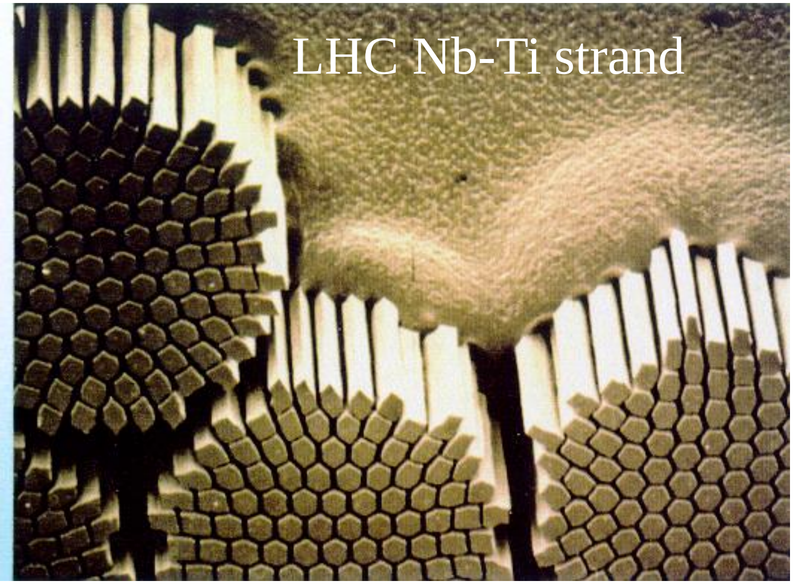




LHC outer cable cross section

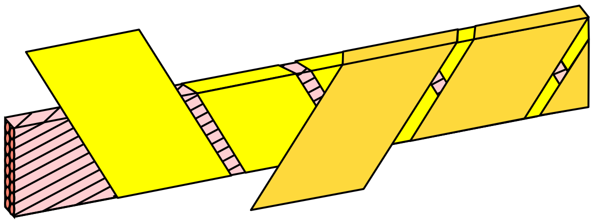
RUTHERFORD CABLES



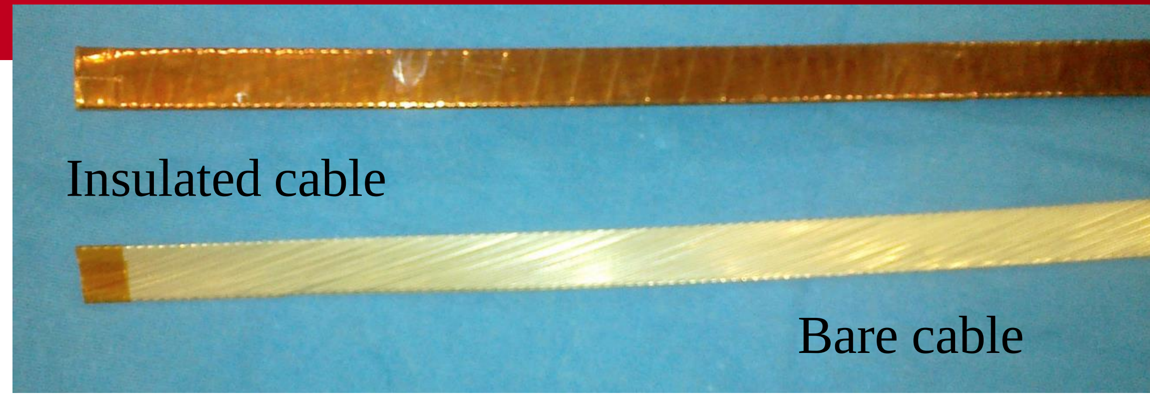


7500 km of superconducting cables

COIL WINDING



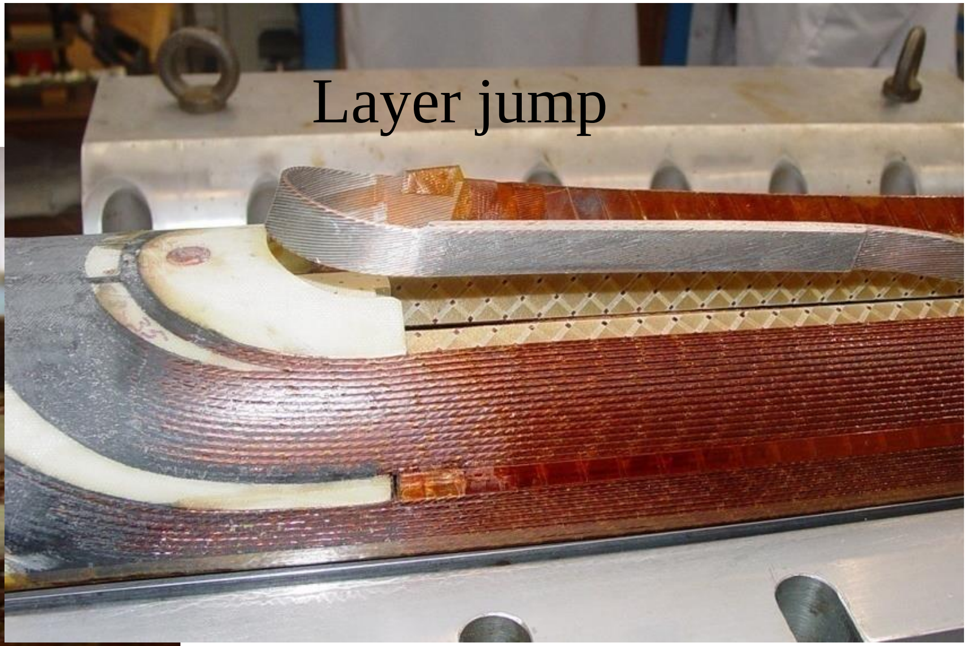
Cable insulation wraps



Coil winding machine

Coil assembly

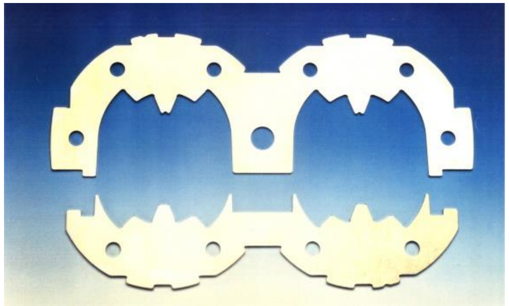
ENDS

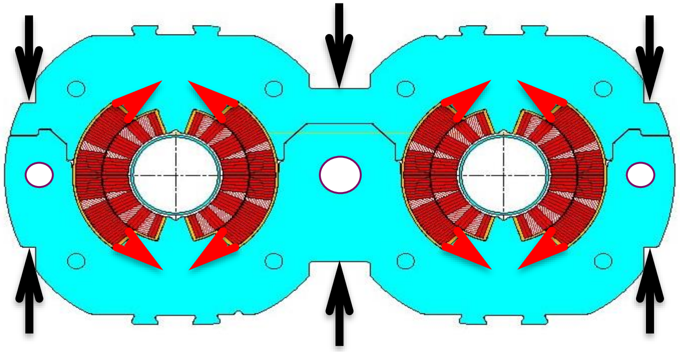


Ends, transitions, and any deviation from the regular structure are the most delicate parts of the magnet

COLLARING OPERATION

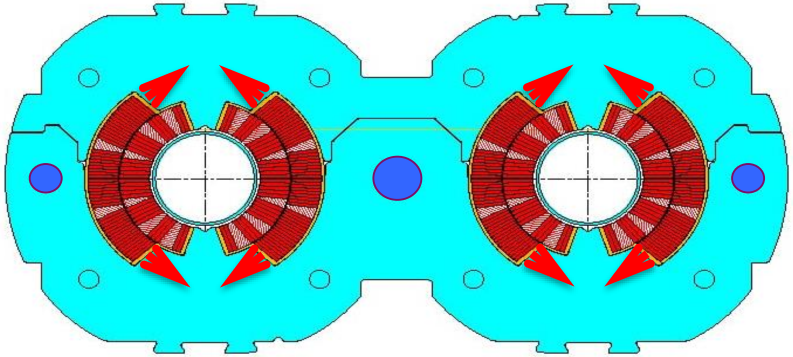
By clamping the coils, the collars provide
- coil pre-stressing
- rigid support against magnetic forces
- precise cavity



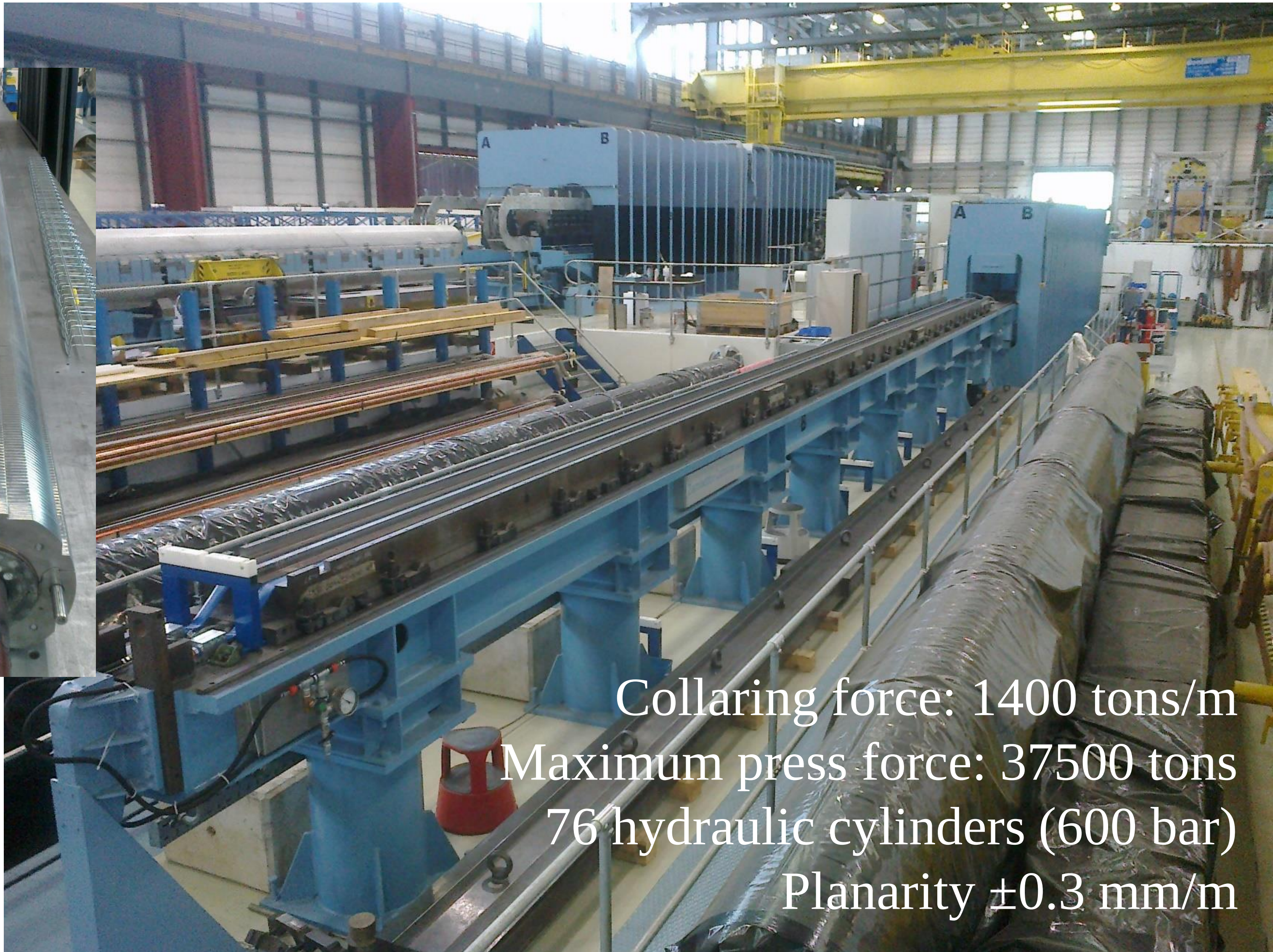


Pre-collared coil assembly under a press, **load the coil** to the desired pre-stress (in the range of 50…100 MPa)

Insert **keys** to “lock” the collars, **unload** the assembly that is now self-supporting and provides the desired **pre-load** to the coil

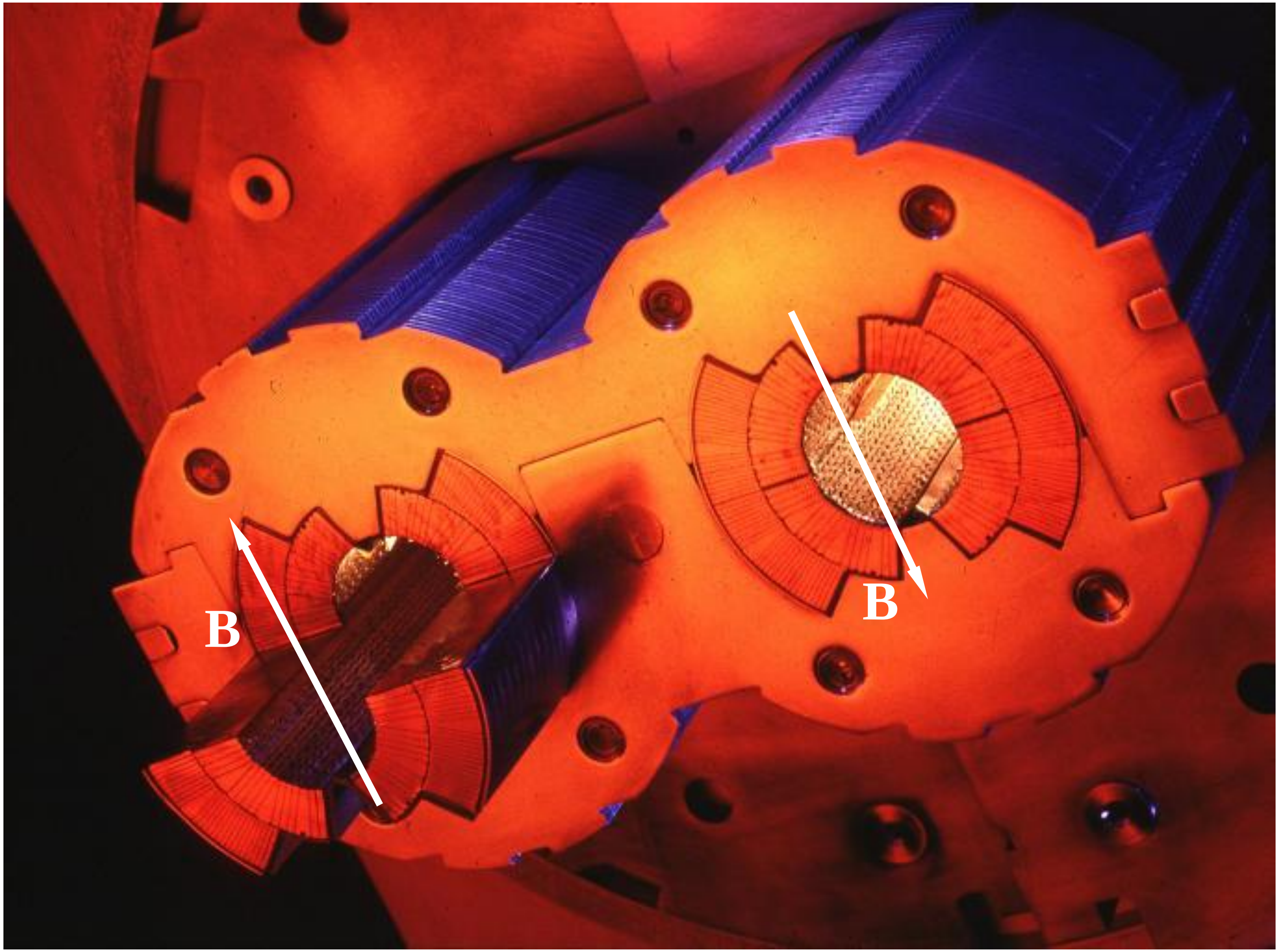


COLLARING OF AN LHC DIPOLE



Collaring force: 1400 tons/m
Maximum press force: 37500 tons
76 hydraulic cylinders (600 bar)
Planarity ±0.3 mm/m

LHC DIPOLE COILS AFTER THE COLLARING



IRON YOKE

As the collars, iron yoke are made in laminations (several mm thick).

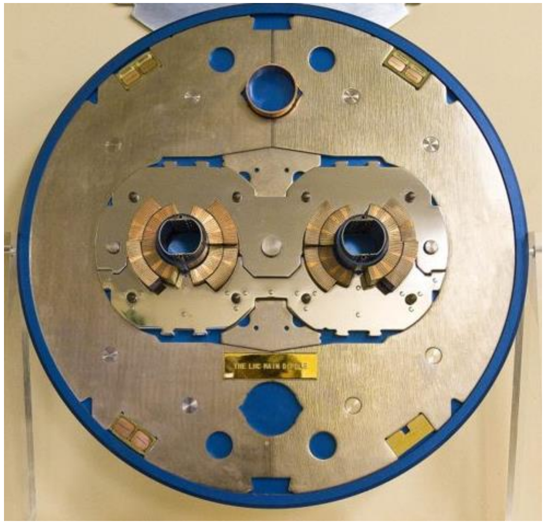
Magnetic function: contains and enhances the magnetic field.

Structural function:

- tight contact with the collar
- contributes to increase the rigidity of the coil
- support structure and limit radial displacement.

Holes are included in the yoke design for:

- Correction of saturation effect
- Cooling channel
- Assembly features
- Electrical bus



OUTER SHELL

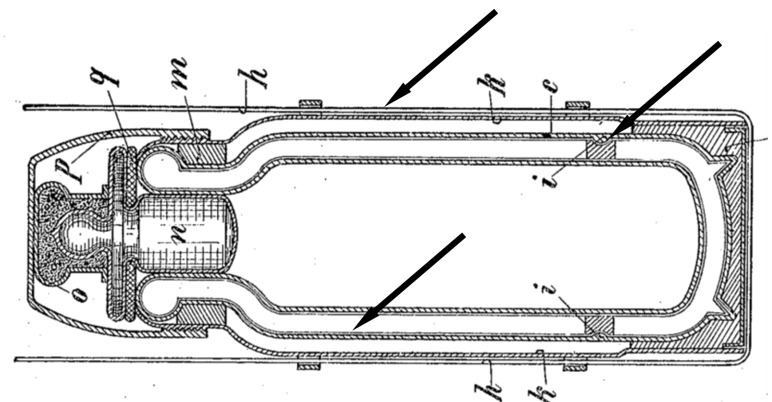
- The cold mass is contained within a shell
- The shell constitutes a containment structure for LHe.
- Composed by two half shells of stainless steel **welded** around the yoke with high tension (about 150 MPa for the LHC dipole).
- With the iron yoke, it contributes to create a rigid boundary to the collared coil.
- During the welding process, the welding press can impose the desired curvature on the cold mass

YOKE WELDING PRESS

Yoking force: 400 tons/m
Maximum press force: 19000 tons
48 hydraulic cylinders (600 bar)

COLD MASS PRERATION

CRYOSTAT



Vacuum enclosure

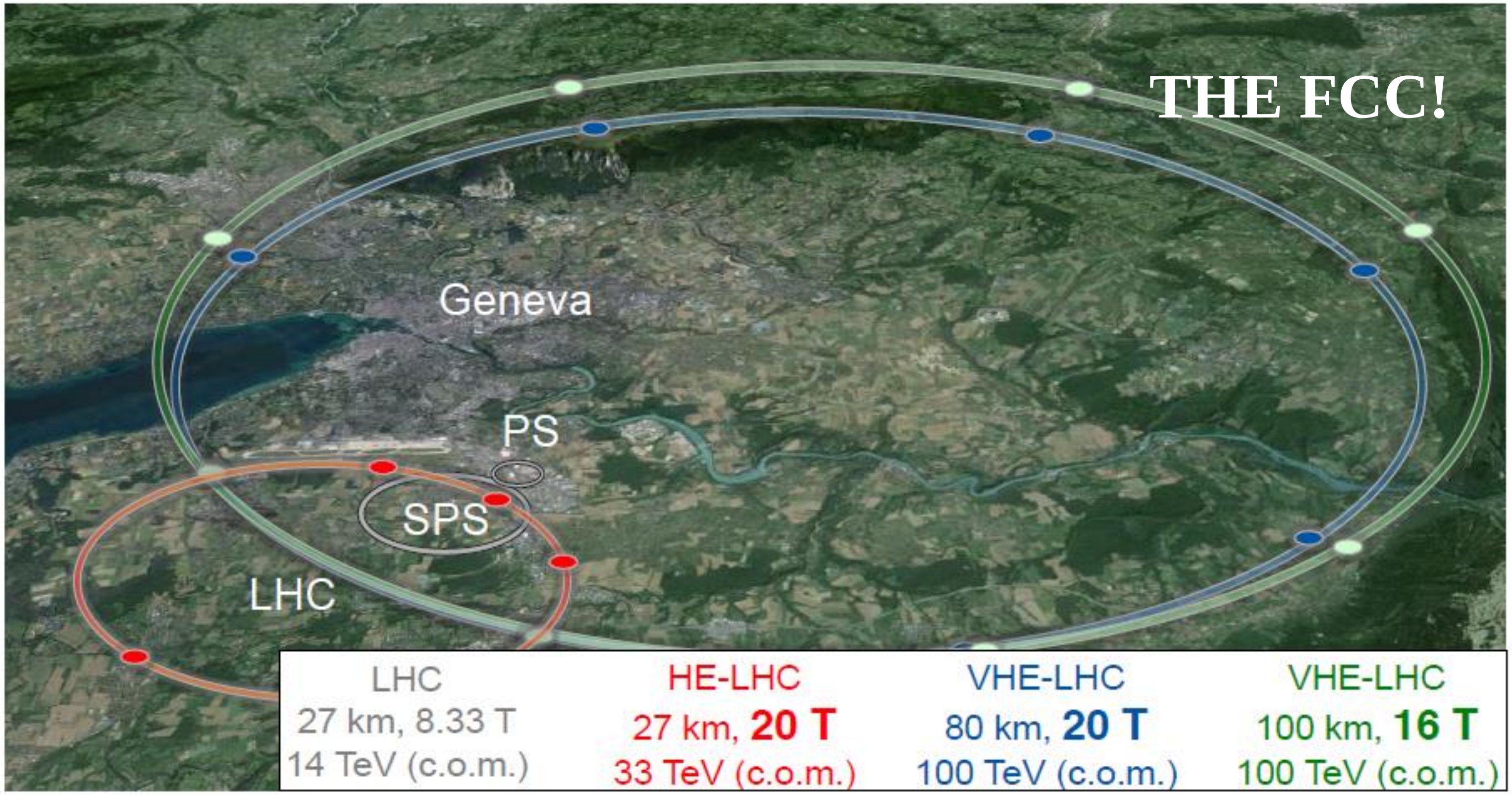
MLI

Thermal screens

Low conduction foot

Higgs Boson discovery - July 2012

WHAT'S NEXT…



LHC	HE-LHC	VHE-LHC	VHE-LHC
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.)

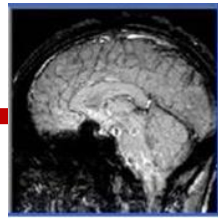
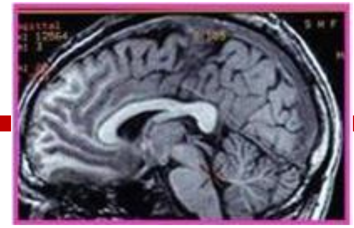
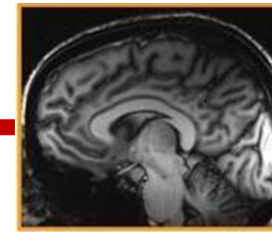
100 TeV !

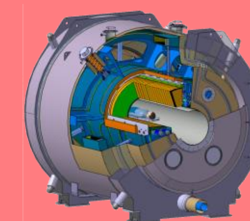
Magnet cost: 8T-60%; 16T-70%-20T-80%

- Need to increase the field, while reducing the cost
- Not just innovations… But real breakthroughs are needed!

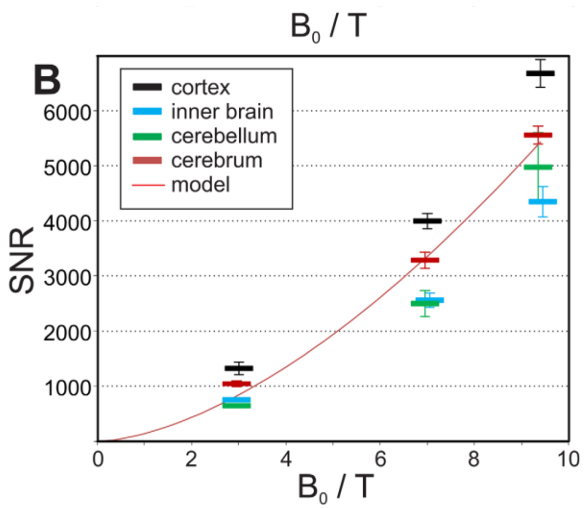
THE 11,75T ISEULT MRI MAGNET

WB MRI MAGNETS TYPICAL SIZE


Field	1,5 T	3 T	7 T	11,75 T
				
	GE-SHFJ/CEA	*Siemens*	*Siemens*	*Iseult*
Length (m)	1,25 - 1,7	1,6 - 1,8	~ 3	4
Diameter (m)	1,9 - 2,1	1,90 - 2,1	> 2,50	4,6
Mass (tons)	~ 5	~ 8	~ 25	~ 135

SNR GAIN ∝ B_0



$SNR \sim B_0^{1.65}$

Pohmann et al.
Magn Reson Med 2016;75:801–809

Improvement of spatial and temporal resolution

3T

7T

THE ISEULT 11.7 T MRI PROJECT

- B0 / Aperture 11.75 T / 900 mm
- Field stability 0.05 ppm/h
- Homogeneity < 0.5 ppm on 22 cm DSV
- 170 wetted double pancakes for the main coil
- 2 shielding coils to reduce the fringe field
- NbTi conductor @ 1.8 K

Stored Energy	338 MJ
Inductance	308 H
Current	1483 A
Length	5.2 m
Diameter	5 m
Weight	132 t

Iseult Magnet parameters

Neurospin Center
CEA Saclay, France

MRI MAGNET REQUIREMENTS

Field uniformity and stability

- Design Uniformity: 10 parts-per-million (ppm) in ~25 cm diameter volume
    - Multiple-coil configuration
    - Sweet spot
- Field decay:
    - short-term decay: 1 ppb during sequence (EMI, vibration)
    - Long-term decay: less than 0.1 ppm/hour on average, less than 0.1% per year

Shielding

- Magnetic field outside of the scanning suite shall be less than 5 gauss (industry standard)

MAGNETIC FIELD OPTIMIZATION

Inside a sphere with a center O and radius r_{max} « magnetically » empty, the B_z component of the magnetic field can be expressed using a spherical harmonic expansion based on Legendre functions *P*.

$$\Delta B_z = 0$$

$$\frac{B_z(r,\vartheta,\varphi)}{B_0} = 1 + \sum_{n=1}^{\infty}\left(\frac{r}{r_0}\right)^n \left[H_n P_n(\cos\vartheta) + \sum_{m=1}^{n}\left(I_n^m \cos m\varphi + J_n^m \sin m\varphi\right) W_n^m P_n^m(\cos\vartheta) \right]$$

$$\left| W_n^m P_n^m(\cos\vartheta) \right| \leq 1$$

$$H_n,\, I_n^m,\, J_n^m \propto \left(\frac{r_0}{a_1}\right)^n$$

Unique set of coefficients $\rightarrow \vec{B}, \vec{A}, V^*, \vec{\Theta}$

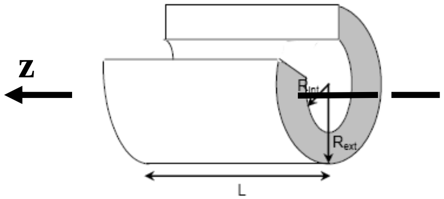
Courtesy Pr. Guy Aubert

Optimization of the homogeneity:
cancel $H_n,\, I_n^m,\, J_n^m$

BACK TO THE BASIS

Set of coils of axe Oz, with a rectangular section and an uniform current density.
Symmetry with respect to the xOy plan → H_{2p+1}=0 and *I, J* = 0

$$\frac{B_z(r,\vartheta,\varphi)}{B_0} = 1+\sum_{p=1}^{\infty}\left(\frac{r}{r_0}\right)^{2p} H_{2p} P_{2p}(\cos\vartheta)$$

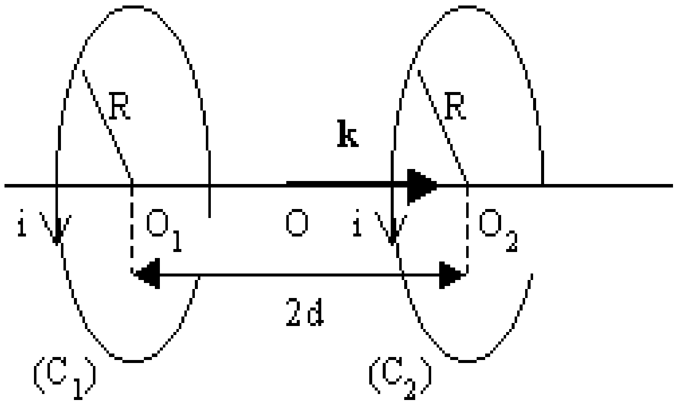


Minimize the coil volume for a given B_0 with $H_2=H_4=\ldots=H_{2p_0}=0$
→ the non homogeneity is driven by the term $H_{2(p_0+1)}$

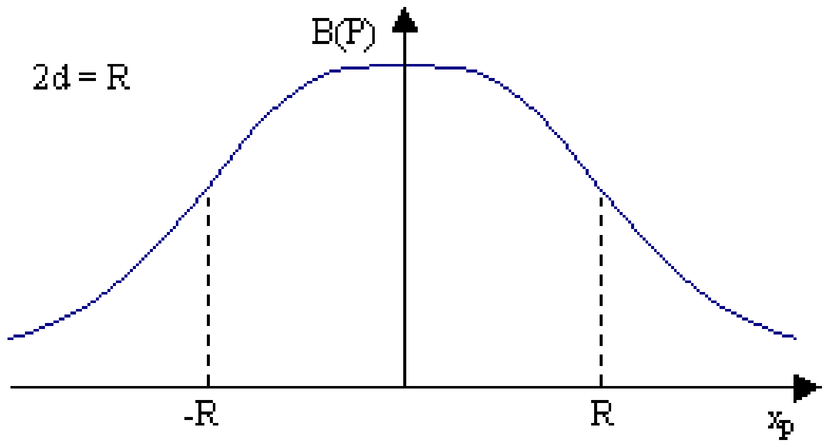
Need at least p_0+1 coils to realize homogenous magnet at the $2(p_0+1)$ order
« shimming theorem»

Courtesy Pr. Guy Aubert

HELMOTZ COILS



$$B(z) = \frac{\mu_0}{2}\left[\frac{R^2}{\left[R^2+(z+d)^2\right]^{3/2}} + \frac{R^2}{\left[R^2+(z-d)^2\right]^{3/2}}\right]$$

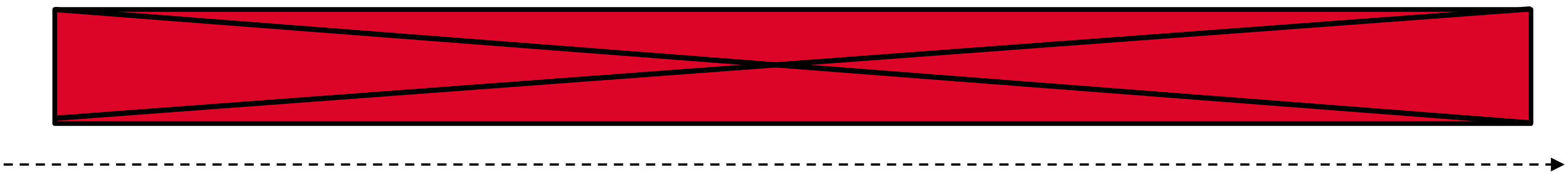


$$B_z(0,z) = B_z(0,0) + z\,\cancel{\frac{\partial B_z(0,z)}{\partial z}} + \frac{z^2}{2}\,\cancel{\frac{\partial^2 B_z(0,z)}{\partial z^2}} + \ldots$$

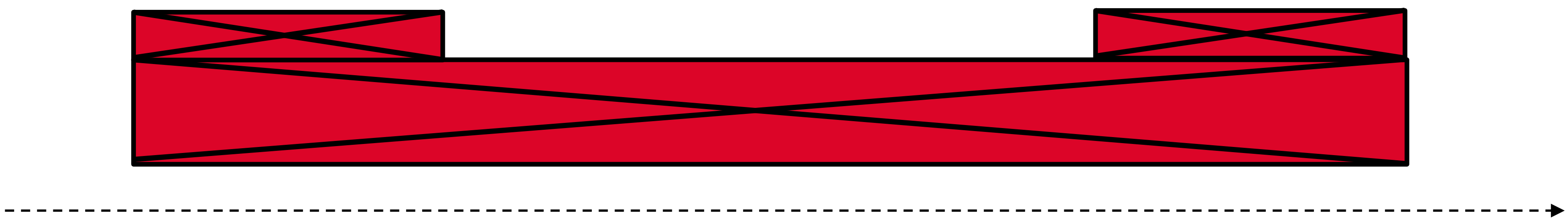
Cancellation of the first two on-axis coeff. of the SHE

GENERATION OF A HOMOGENEOUS FIELD

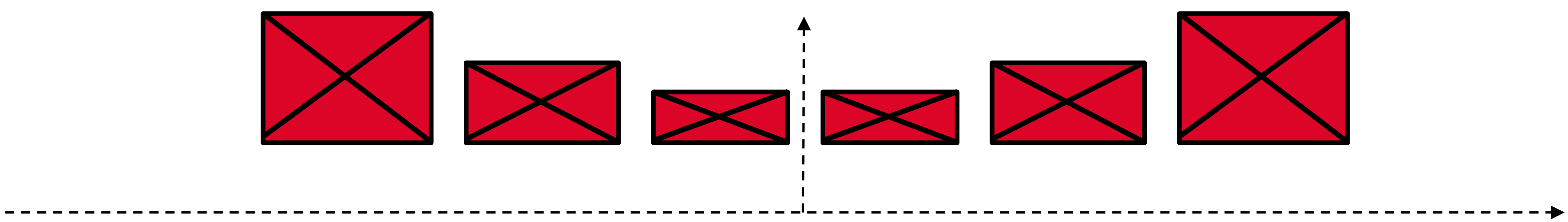
Magnet with infinitely long solenoid or DP



Shorter magnet with a shorter solenoid and compensation coils



Even shorter magnet made of discrete and very short solenoids



There are two main families of errors:

- **Errors that respect the basic symmetry**
  They are “built-in” in the design or they come from systematic manufacturing errors (coils systematically too large,...)

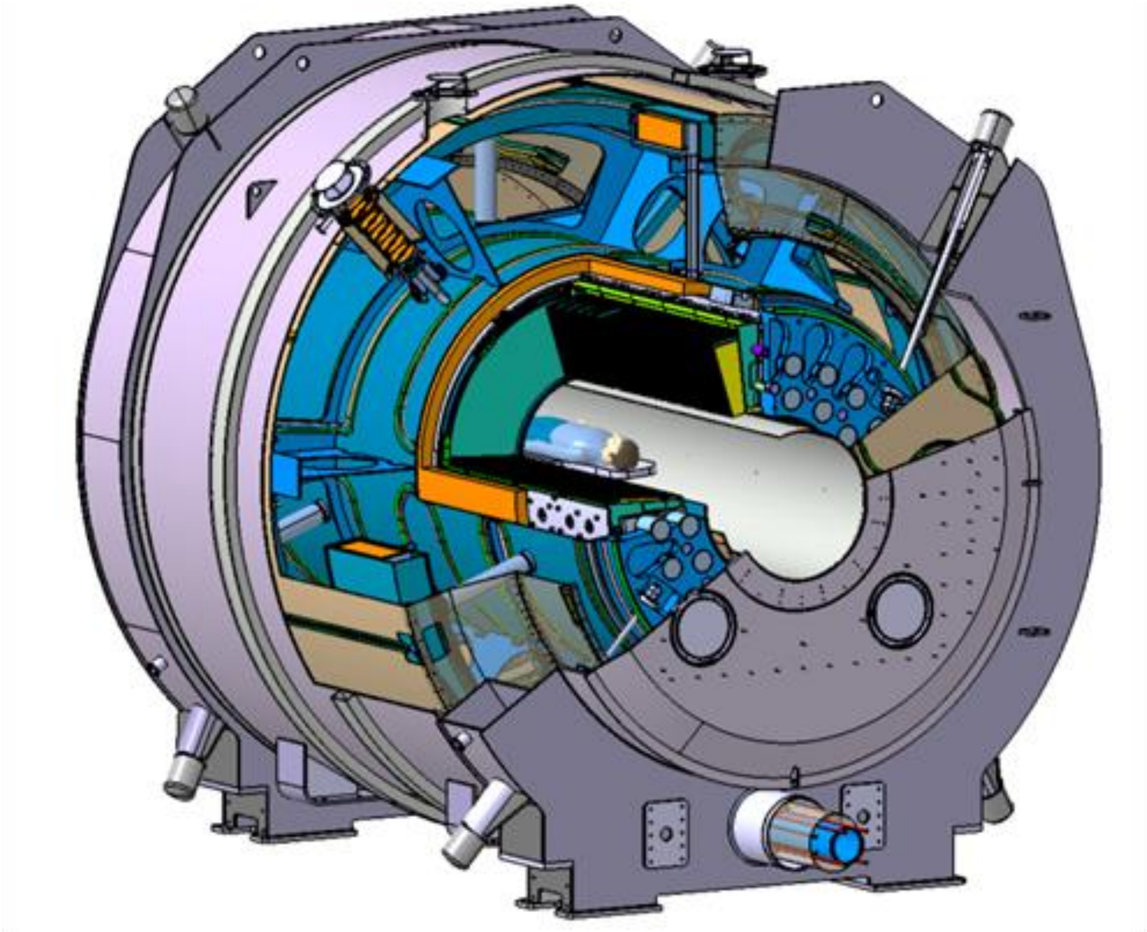
  → Creates H_{2p} terms

- **Errors out of the basic symmetry**
  Scattering in material tolerances, in manufacturing and assembly,...

  → Creates H_{2p+1} ; I, J terms (difficult to correct)

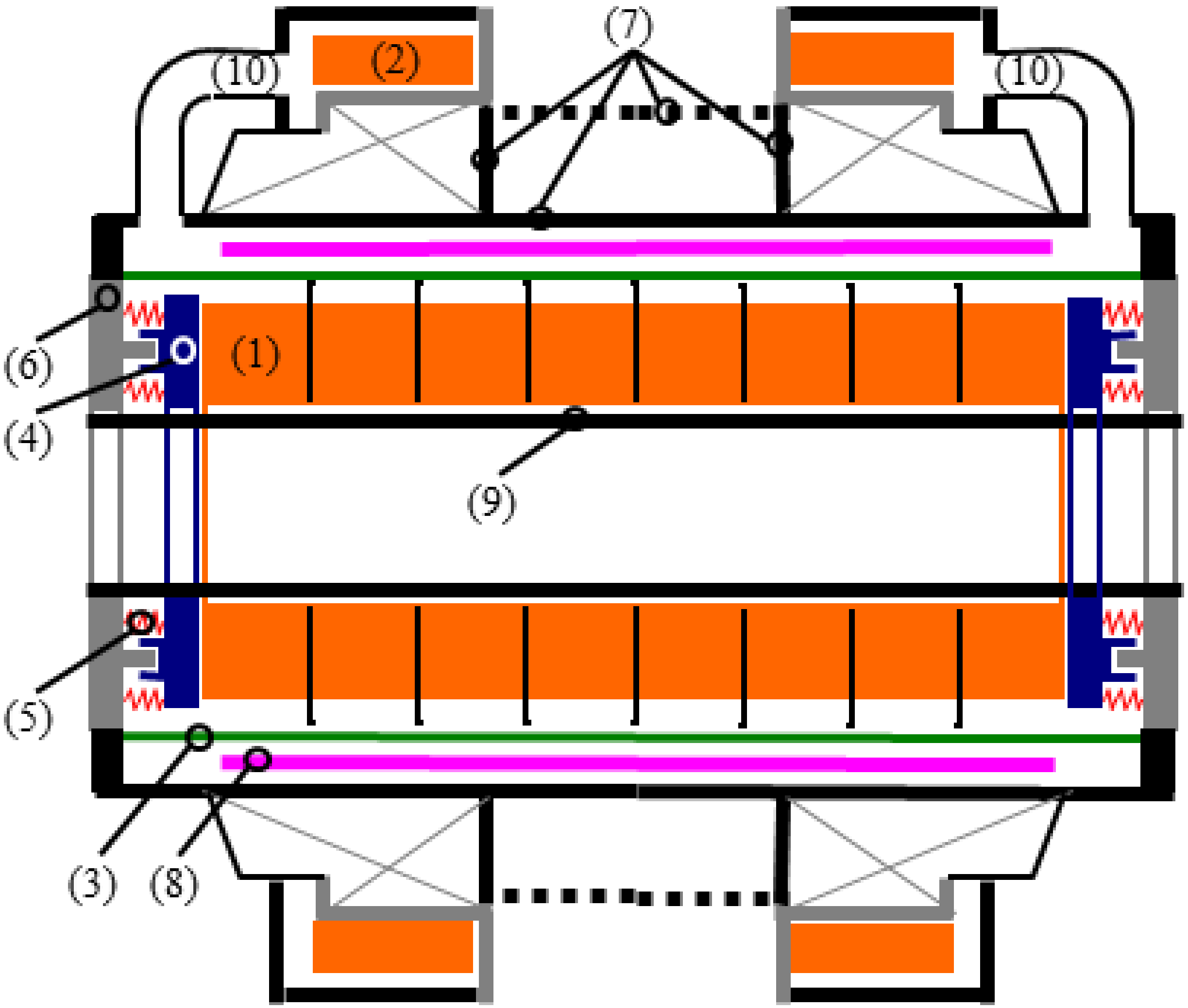
→ **Need for compensation and shim coils to achieve the required homogeneity**

THE ISEULT 11.7 T MRI MAGNET



11.7 T magnet windings (orange) / mechanical structure at 1.8 K (blue)/ cryostat (gray)

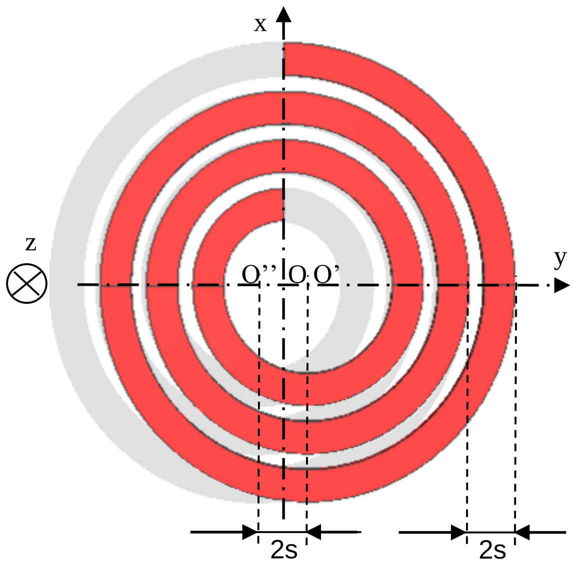
ISEULT HELIUM VESSEL ASSEMBLY PRINCIPLE

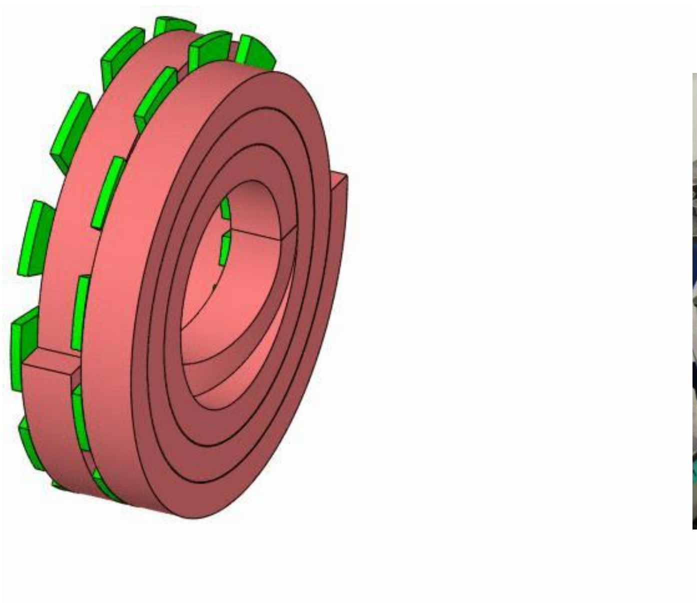


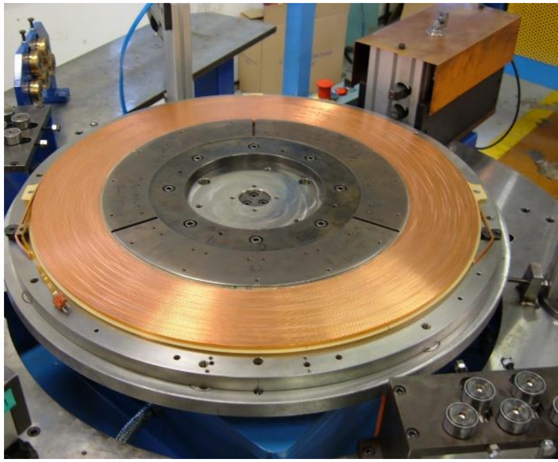
(1) Main Coil
(2) Shielding Coil
(3) MC outer cylinder
(4) MC base plate
(5) Belleville washer stacks
(6) Cold mass end-plate
(7) Cold mass structure
(8) Cryoshim
(9) Helium vessel inner cylinder
(10) Coils connection pipe.

INNOVATIVE DESIGN OF DOUBLE PANCAKE

$$B_z(r,\theta,\varphi) = B_0 + \sum_{n=1}^{\infty} r^n \left[Z_n P_n(\cos\theta) + \sum_{m=1}^{n} \begin{pmatrix} \cancel{X_n^m} \cos m\varphi \\ + \\ \cancel{Y_n^m} \sin m\varphi \end{pmatrix} W_n^m P_n^m(\cos\theta) \right]$$





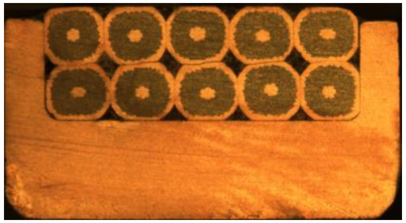


Magnet is theoretically **intrinsically** homogeneous

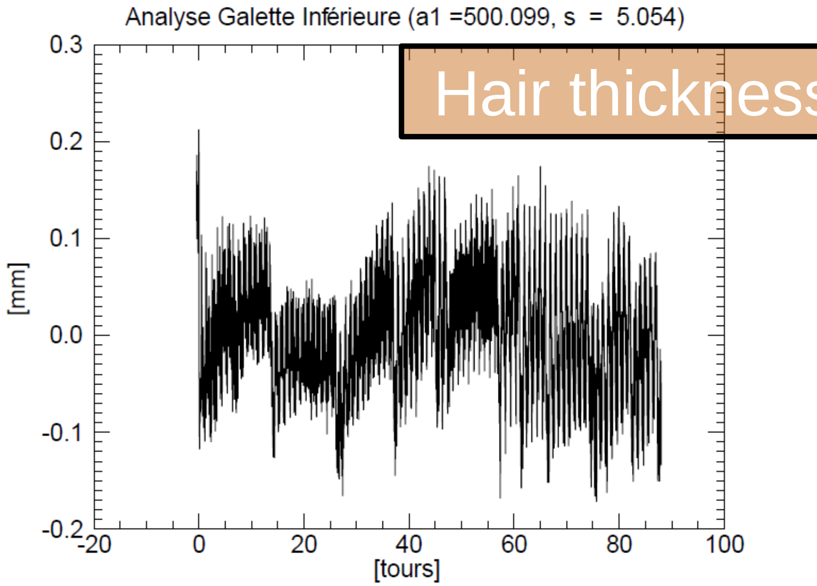
DOUBLE PANCAKE WINDING

170 DG wound and controlled (external diameter of 2 m)

- 330kg each
- Tolerance at inner bore +/-0,05mm
- Control of each +/-0,2mm
- Planarity 0,1mm
- Parallelism à 0,2mm

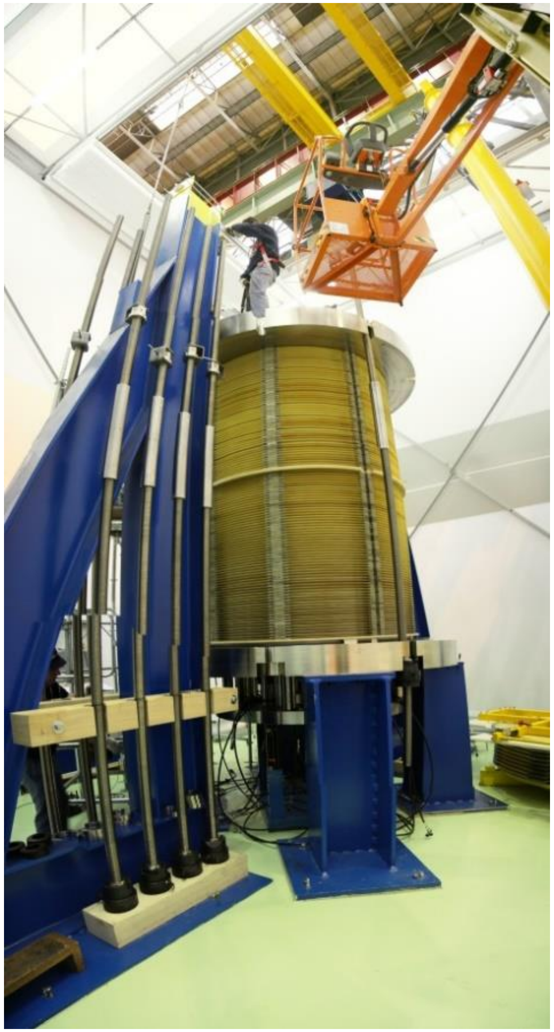


Main coil conductor
NbTi CIC



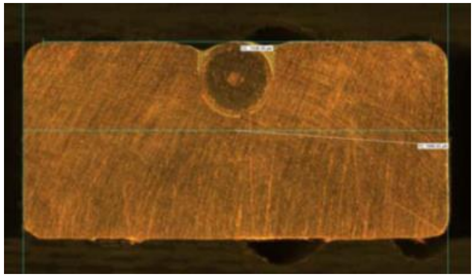
DOUBLE PANCAKE STACKING AND CURING

Position of each DP checked with laser tracker



SHIELDING COIL MANUFACTURING

Inner radius	1.97 m
Outer radius	2.15 m
Layers number	36
Turns per layer	53
Mass (per coil)	12 tons
Peak field	3,86 T
Conductor length (for one coil)	24700 m
WIC dimensions	9,1 mm x 4,2 mm
Ic	2100 A @ 5T @ 1.8 K



Shielding coils conductor NbTi WIC

CRYOSTATING

Helium vessel
closure

MLI

Cryostat integration

Final leak tests

SHIPPING AND INSTALLATION

Shipping frame

Departure from the factory

Iseult leaving the manufacturing area

Iseult in its arch

Commissioning completion expected in 2018

CONCLUSIONS

- Magnets are everywhere, specially SC magnets

- Very important developments in superconductivity technologies over the last 40 years, thanks to particle physics and MRI business

- SC technologies are a combination of various skills (magnetism, cryogenics, mechanics, electrical engineering, instrumentation, DAQ…)

- Technical challenges to build bigger and stronger magnets:
    - use Nb_3Sn and HTS materials
    - increase the operating temperature and simplify the cryogenics
    - **reinforce conductor mechanical strength** and protect the coils against quenches.

Thank you for your attention

And join our team!
Positions are open at CEA Saclay

lionel .quettier@cea.fr

And thanks for contribution of material
to Guy Aubert, Luca Bottura, Philippe Fazilleau, Hélène Felice, Paolo Ferracin and Pierre Védrine

FURTHER READINGS

- Y. Iwasa - "Case Studies in Superconducting Magnets", ISBN 978-0-387-09799-2
- M. Wilson - "Superconducting Magnets", ISBN 978-0-19-854810-2
- L. Dresner - "Stability of Superconductors", by, ISBN 0-306-45030-5
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- Y. Lvovsky, W. Stautner and T. Wang - "Novel technologies and configurations of superconducting magnets for MRI", Superconductor Science and Technology, 26 p. 1-71 (2013)
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- Design of a cryostat for superconducting accelerator magnet: the LHC main dipole case, Ph. Lebrun, CERN.