HITRI plus

Heavy Ion Therapy Research Integration

State of the art Superconducting Magnets

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Content

- Why magnetic fields – basic equations – accelerators and magnets, detectors, confinement
- Type of magnets – longitudinal, transverse, toroidal; example with electromagnets
- Superconductivity and accelerators; type of superconductors
- Superconducting magnets for accelerators (and beam lines)
- From Tevatron to LHC; example of LHC magnets
- Beyond LHC: new magnets for HiLumi LHC
- Beyond Hilumi: HFM, Nb3Sn, HTS,
- New technologies: NI coils

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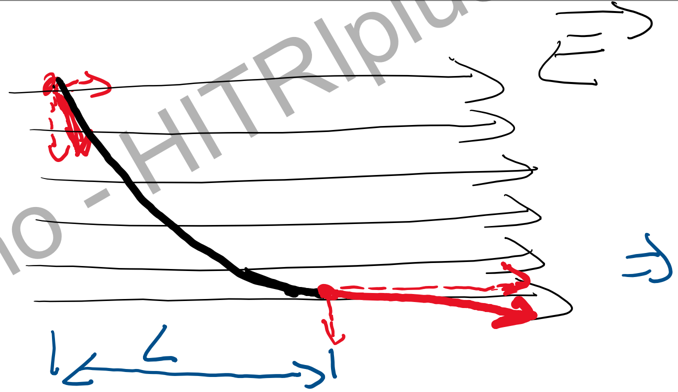
Motion of a charged particle in an electric and a magnetic field

$F = q\left(\vec{v}\times\vec{B}+\vec{E}\right)$

$\vec{E}$ Electric field accelerates (along the motion), i.e., gives momentum, energy

$\vec{v}\times\vec{B}$ Magnetic field act as **perfect centripetal force**,i.e., bend trajectories of charged particles, without changing the modulus of the momentum, i.e., the energy.



$E_n = q\int \underline{E}\cdot d\underline{s}$

$\Rightarrow \quad = E\,L$

$= \Delta V$

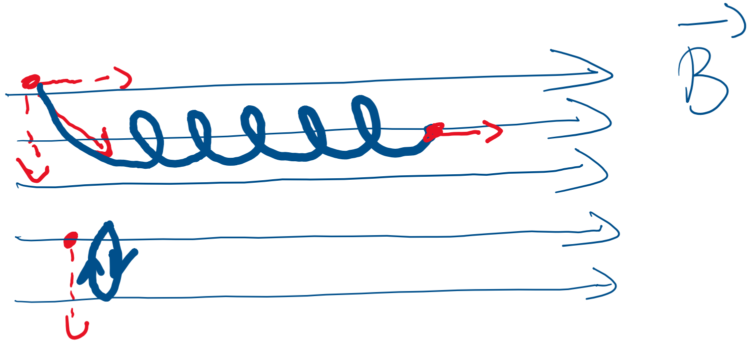
→

Considering B as the component perpendicular to the motion:

$F_c = m\frac{v^2}{\rho} \qquad F_m = qvB \qquad F_m = F_c$

$q\cancel{v}B = m\frac{v^{\cancel{2}}}{\rho} \Rightarrow B\rho = \frac{mv}{q}$

$B\rho = P/q$ MAGNETIC RIGIDITY $[T\cdot m]$



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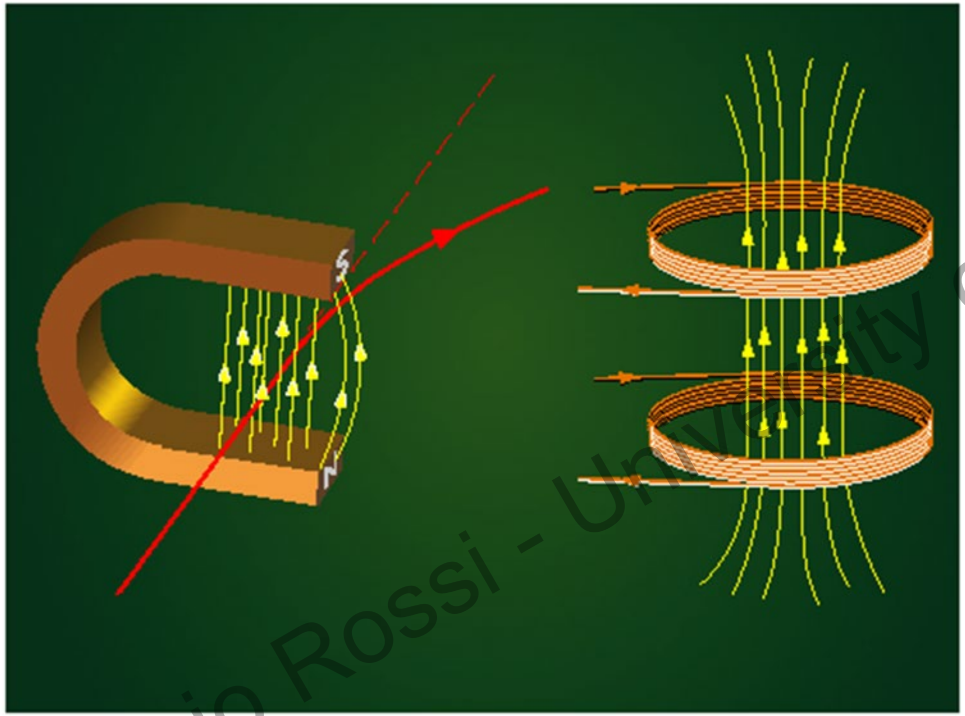
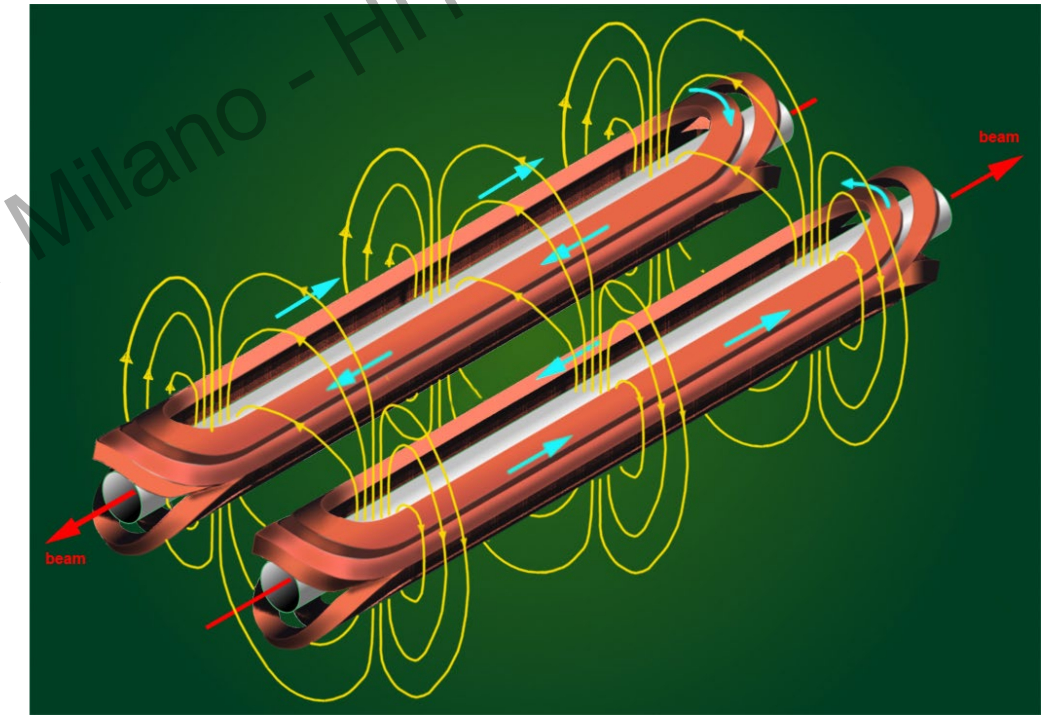
In accelerators we find two types of magnetic configuration

solenoidal fields to confine particle along trajectories or to bend particles trajectories in the midplane (in split coil configuration)

Transverse fields: long tube of fields perpendicular to trajectories (dipoles)





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Field-energy expression for non-relativistic case: classical cyclotron
Particles curved by magnetic field use same voltage many times…

NON-relativist case

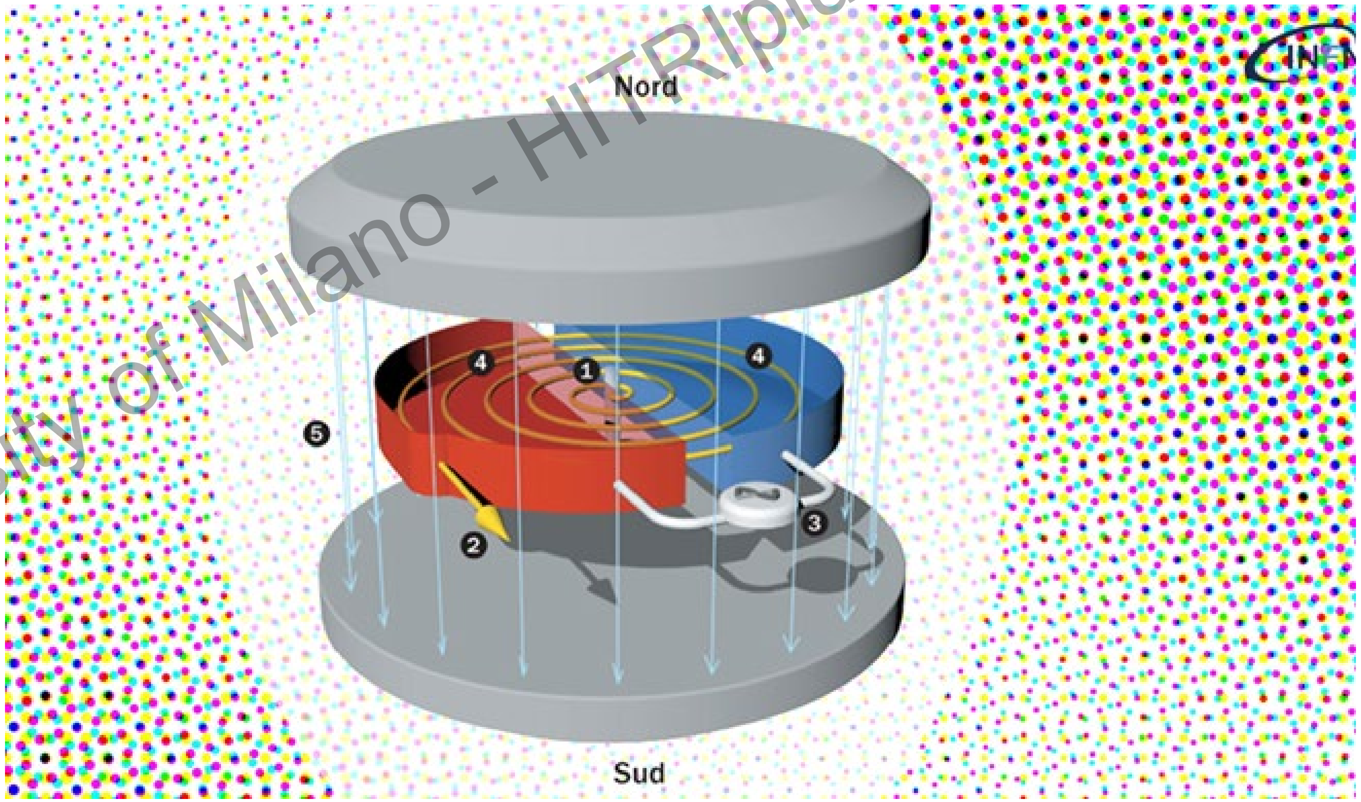
For proton or electron of charge *e and mass m, kinetic* energy E_k and field are related by:

$$E_k = \frac{1}{2}\frac{e}{m}(B\rho)^2$$

Where *B* is the magnetic field (perpend. To the motion) and ρ is the curvature radius.

For ions with charge *Z* and atomic no. *A*:

$$E_k/A = \frac{1}{2}\left(\frac{e}{m_p}\right)\left(\frac{Z}{A}\right)^2(B\rho)^2$$



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Relativistic case, most used for HEP syncrotron and colliders… and (more complex) general expression

c being the light velocity, the expression is (mass energy is negligible, $E_k \approx E$)

$$E = e\ c\ B\rho$$

Which makes the maximum energy in terms of practical units (GeV, tesla, m) very simple:

$$\boldsymbol{E_k \cong 0.3\ B\ \rho}$$

We here that beam energy scaled linearly with field and size of the accelerators.

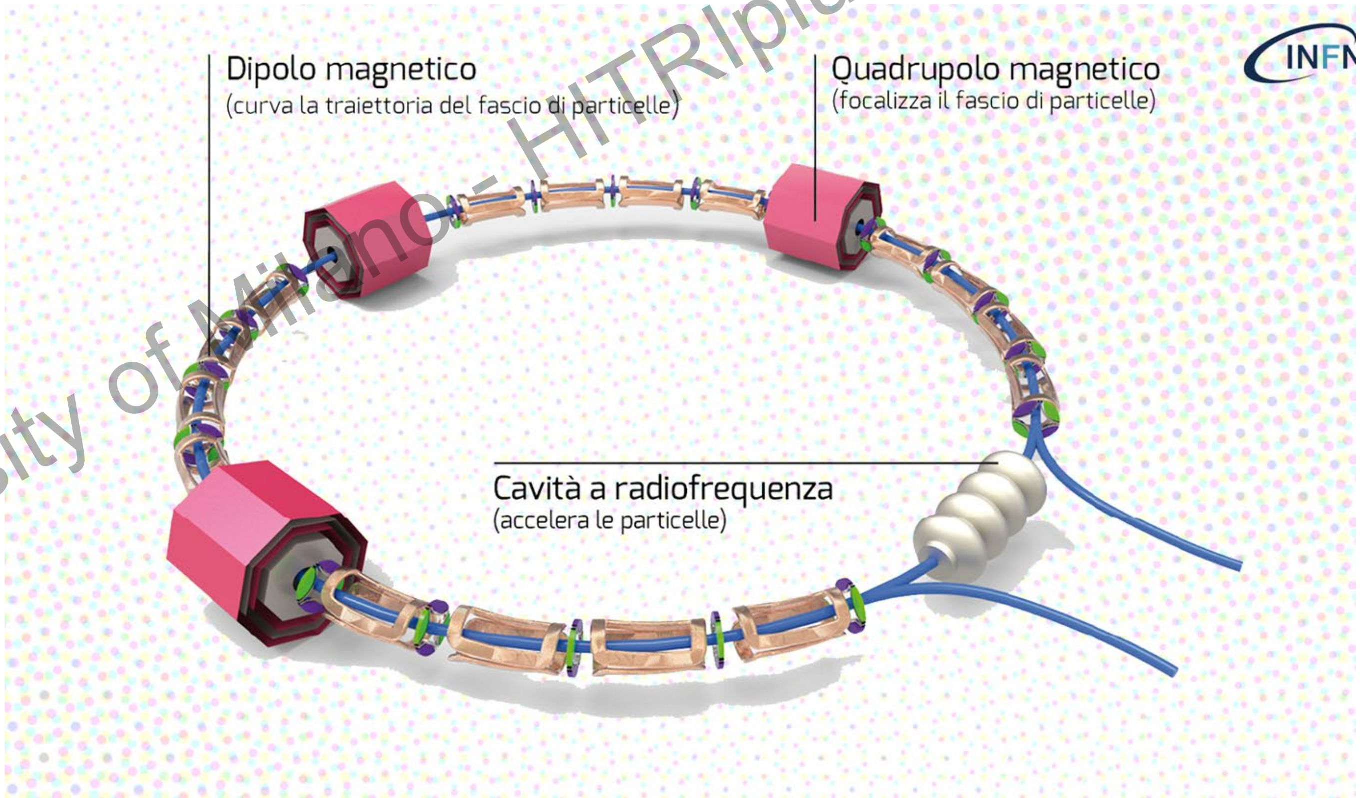
In intermediate energy we must use:

$$E^2 - E_0^2 = p^2c^2$$

$$E^2 - E_0^2 = e^2c^2\rho^2B^2$$

Again, dividing by *e* to have energy in eV:

$$E_k = \sqrt{E_0^2 + B^2\rho^2c^2} - E_0$$



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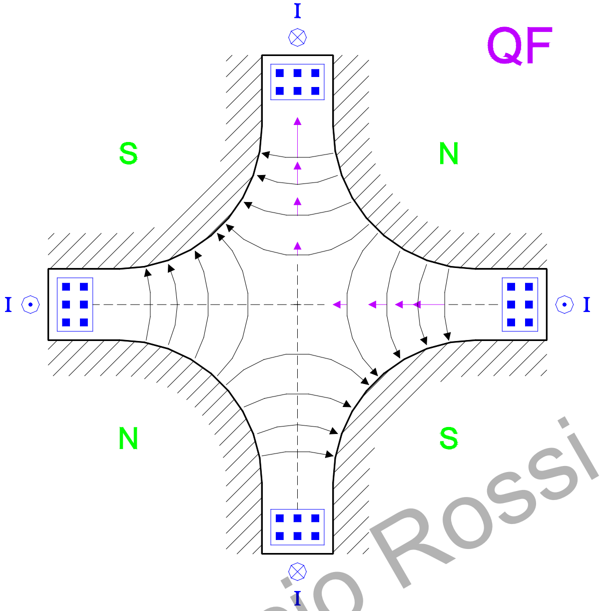
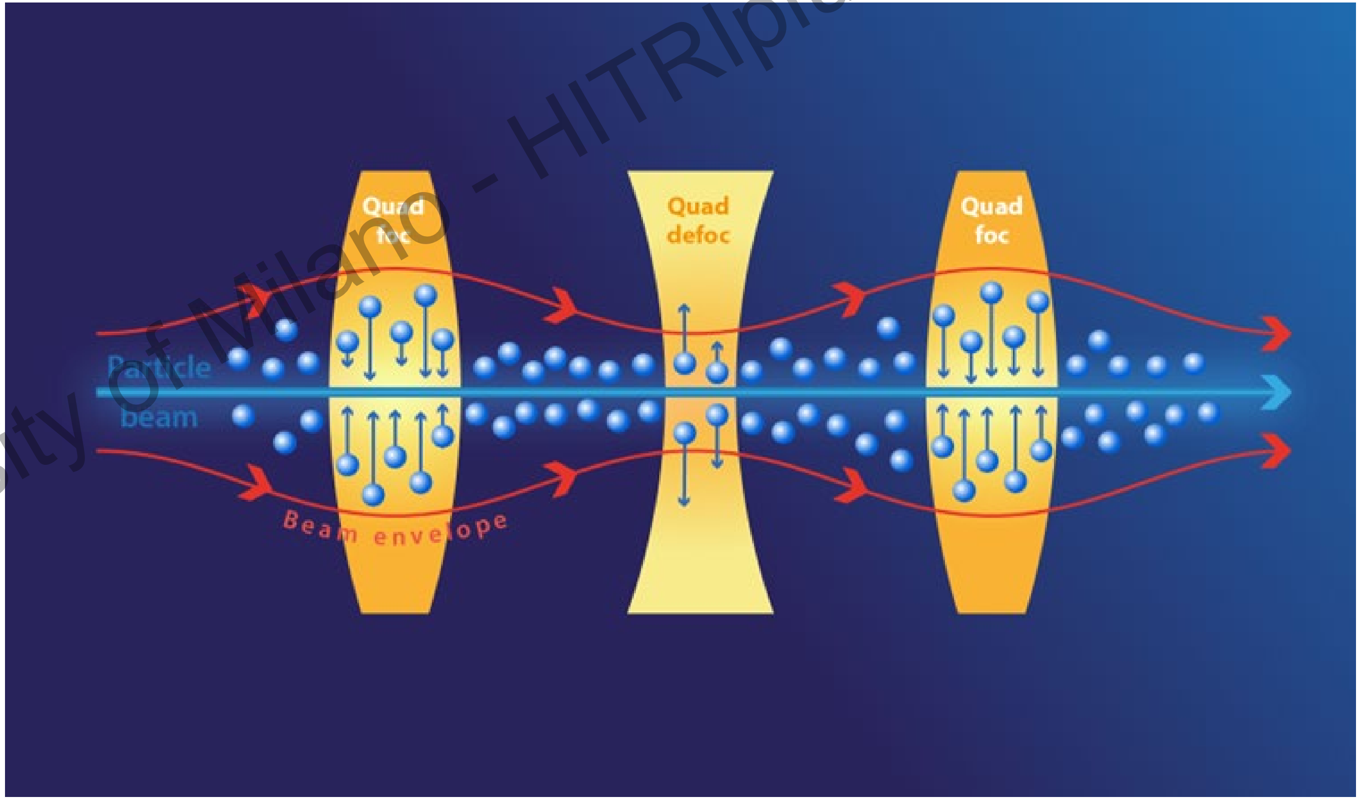
Magnetic forces are necessary for focusing particle beams (quads) and higher order (sextupoles, octupoles, etc…) are needed, too.

Quadrupoles are needed for focusing. When focusing in on plane (example: x-z) it defocus in the othe plan (y-z). So a doublet of FD or DF quads are needed; **total effect is focusing →**





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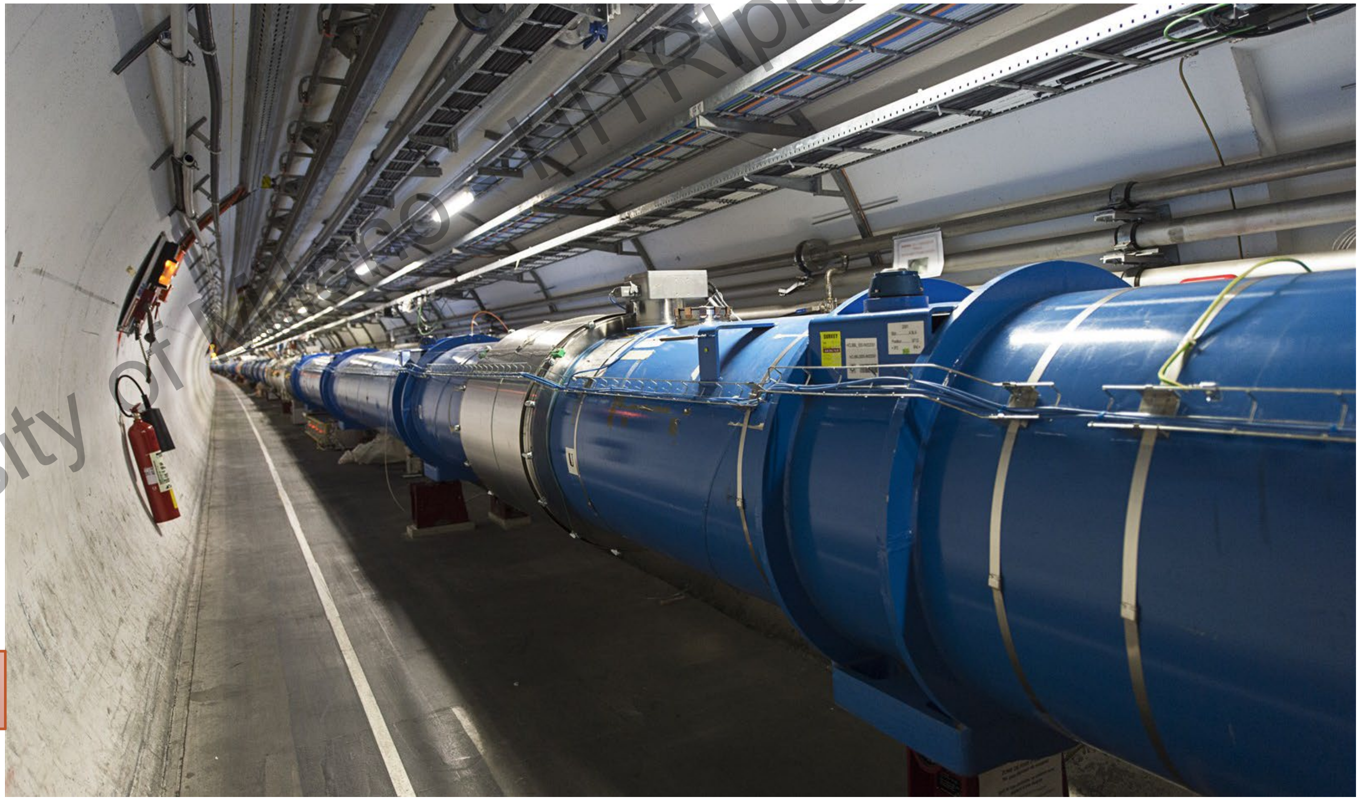
Magnets are key compoennts of any aprticle accerator for circular accelertors fills most of the tunnel

About 80% of the 27 km long Large Hadron Collider of CERN, the superaccelerator that has allowed the discovery fo the Higgs boson, is filled by a continuous lattice of 3 dipole (45 m) and one quadrupole – with HO magnets (about 5 m)

Series of dipoles in the LHC tunnel →



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Comparison between meeds for accelerator and detector magnets

- Magnetic fields needed for
  - electric charge identification
  - momentum spectrometry
  - $p = mv = q\,\rho\,B; \quad \phi = q/p \quad B\,L$
  - $\Rightarrow$ BL is often the comparison parameter
- If momentum analysis is done by tracking inside the field volume:
  - **$\Delta p/p \propto 1/BL^2 \Rightarrow$ large volume pays off better than high field**
  - Field homogeneity appreciated but NOT critical
  - (field knowledge of 0.1% usually suffices)

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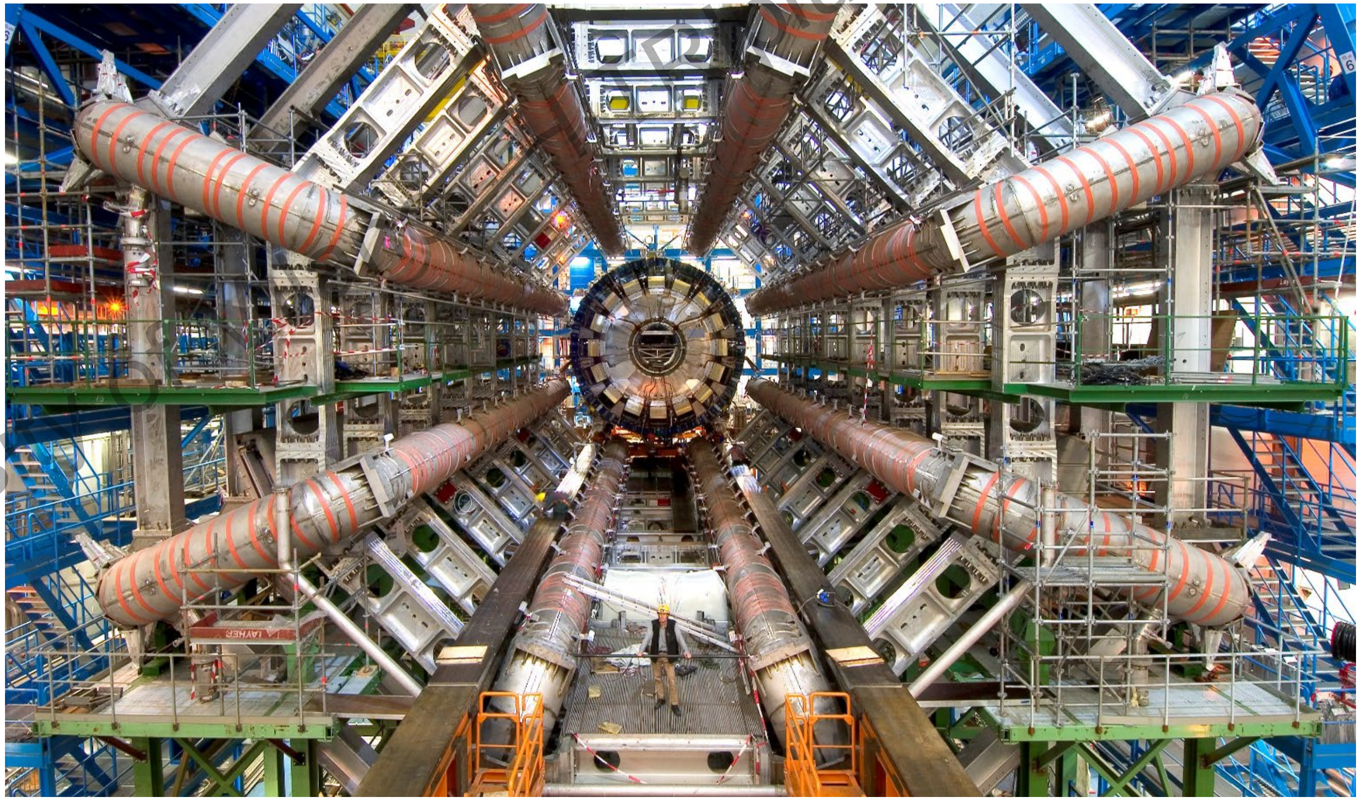
Toroids: a perfect transverse field with a heavy toll to efficiency

Toroidal field is always perpendicular to the particle trajectories , inany direction they go.

So they ae used for spectroscopy → ATLAS

Howeer the ratio bettwe useful fiel and peak field onthe coil si very bad. They are used only when realy needed like detectors or magnetic confinenement or when no magnetic moment is alowed (becuase of the closed field lines)

type	B_{useful}/B_{coil}
Solenoids	0.8-0.99
Dipoles	0.7-0.95
Toroids	0.25-0.6



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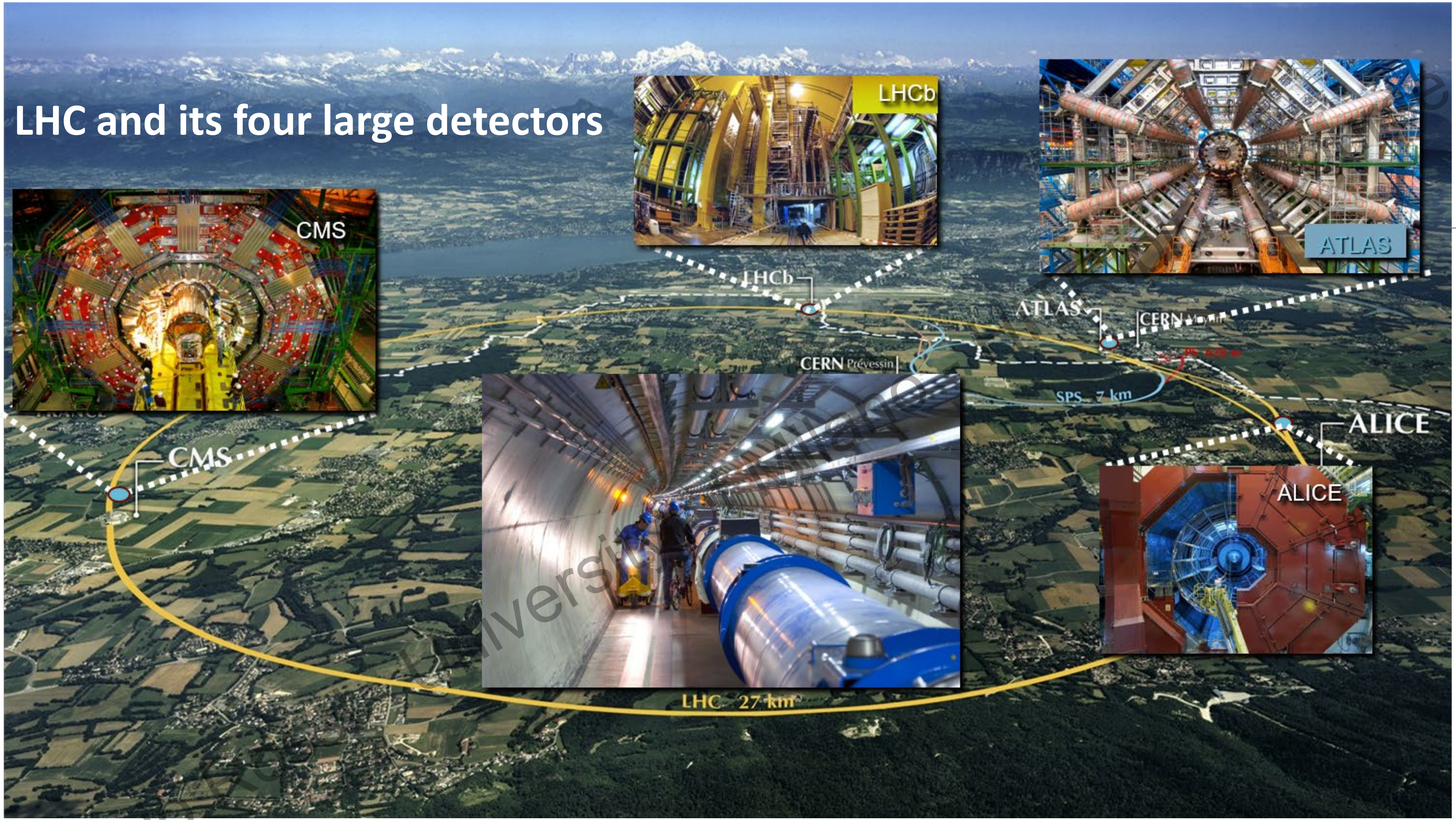
LHC and its four large detectors



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Field computation (no ferromagnetic material)

General formulation to compute field from current distribution

$$\mathbf{B} = \frac{\mu_0}{4\pi} I \int_c d\mathbf{l} \times \frac{\mathbf{r}}{r^3} dl \qquad \mathbf{B} = \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\mathbf{r}}{r^3} dv$$

for infinitely long wire

$$\mathbf{B} = \frac{\mu_0}{2\pi} \frac{I}{d} \mathbf{e}_\theta$$

for finite straight wire, *I* flowing from $\mathbf{r_1}$ to $\mathbf{r_2}$ (from Wilson book)

$$\mathbf{B} = \frac{\mu_0}{4\pi} I \frac{(\mathbf{r_1} \times \mathbf{r_2})}{r_1 r_2} \frac{r_1 + r_2}{r_1 r_2 + \mathbf{r_1} \cdot \mathbf{r_2}}$$

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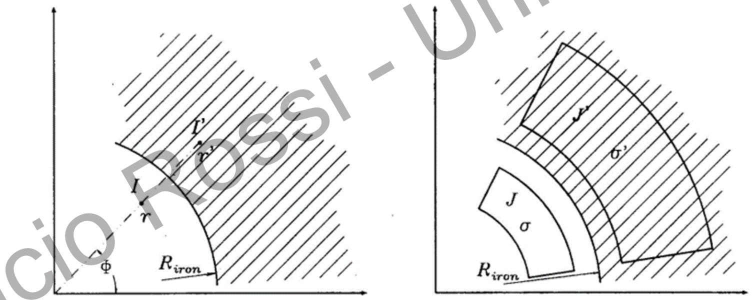
If there us iron → use FE codes Or a quick evaluation by IMAGE CURRENT methods

Use of iron yoke to contain the stray field is very common. Then image current methods (magnetic mirror) could be used, either with infinite (first guess) or finite μ_r.

$$I_{im} = I \frac{\mu_r - 1}{\mu_r + 1}$$

- ❑ The method is actually applicable when: μ_r is constant and known
- ❑ the iron has a shape that respects the symmetry of the problem (infinite iron plane, or circular iron fully surrounding the current region), see picture below.



Tip:

If iron is fully saturated, and the magnetization is known, the field is the sum of air core coil current plus the magnetization surface currents, $\boldsymbol{J_s} = \boldsymbol{M} \times \boldsymbol{n}$

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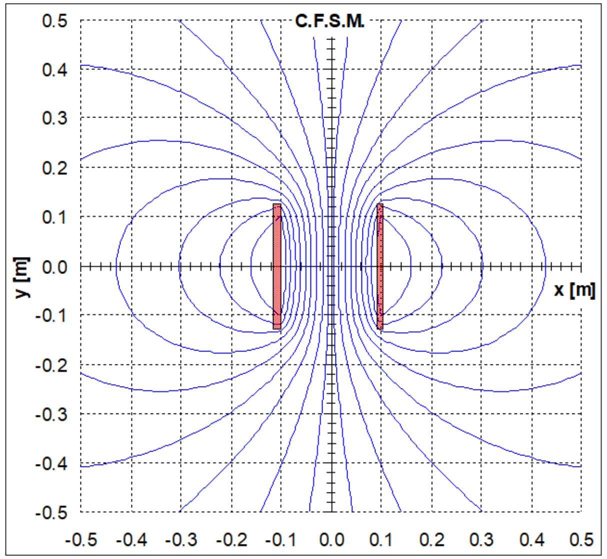
Solenoids – field computation

J_s = linear density of the surface current (A/m)

J = current density, t = coil thickness

IN/L = ampereturns (total current) per unit length

$$B = \mu_0 J_s = \mu_0 J \cdot t = \mu_0 I \frac{N}{L}$$



Most solenoids are not so far from this very easy computation.

When L/∅ = 1.25 the central field is about 15% less than the field infinite solenoid (with the same peak field on the coil.

Note that whatever long is the solenoid, at the ends B_{axis} is about half $B_{central}$ and that inevitably there is a large radial field (this is important for HTS tapes)

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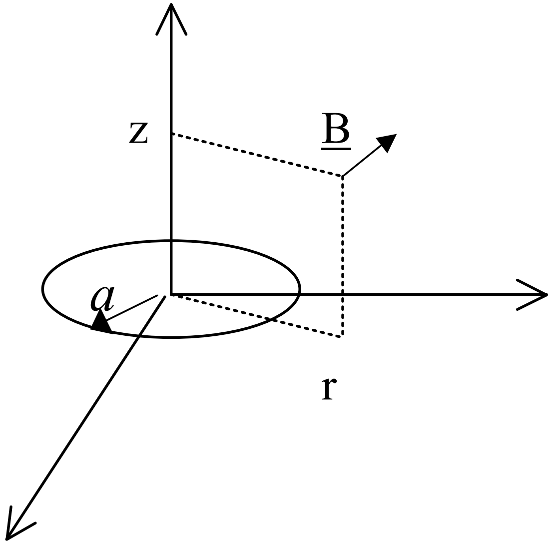
Solenoids – computation of field in any point

The formula of the loop can be analytically integrated only along the axis

$$\mathbf{B} = \frac{\mu_0}{2} I \frac{a^2}{(a^2+z^2)^{3/2}}$$



In a generic point (r,z) the field components are:

$$\begin{cases} B_z(r,z) = \dfrac{\mu_0 I}{2\pi}\dfrac{1}{\sqrt{(r+a)^2+z^2}}\left(J_1 + \dfrac{a^2-r^2-z^2}{(r-a)^2+z^2}J_2\right) \\ B_r(r,z) = \dfrac{\mu_0 I}{2\pi}\dfrac{z}{r\sqrt{(r+a)^2+z^2}}\left(-J_1 + \dfrac{a^2+r^2+z^2}{(r-a)^2+z^2}J_2\right) \end{cases}$$

$$J_1 = \int_0^{\Pi/2}\frac{1}{\sqrt{1-k^2 sen^2\varphi}}\,d\varphi \quad , \qquad J_2 = \int_0^{\Pi/2} d\varphi\,\sqrt{1-k^2 sen^2\varphi} \quad ; \qquad \mathrm{k} = \sqrt{\frac{4\mathrm{R_c r}}{(\mathrm{r}+\mathrm{R_c})^2+\mathrm{z}^2}}$$

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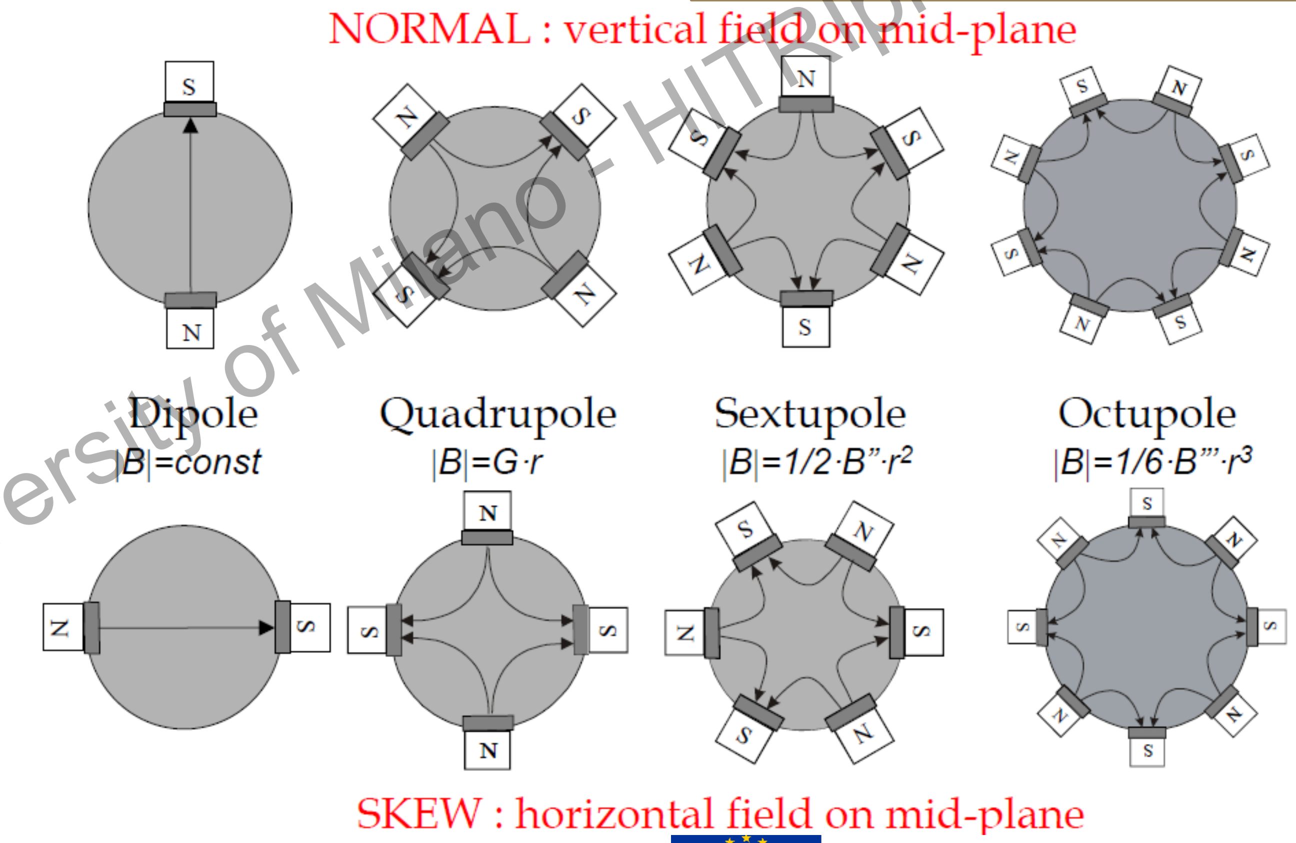
Transverse fields: any field can be represented as a sum of various multipoles

Courtesy of D. Tommasini, CERN, CAS Varna, 2010

Key point:
A dipole magnet generate "only" dipole field (the other components are inevitable errors… usually very small of the order of 10^{-5} to 10^{-2}



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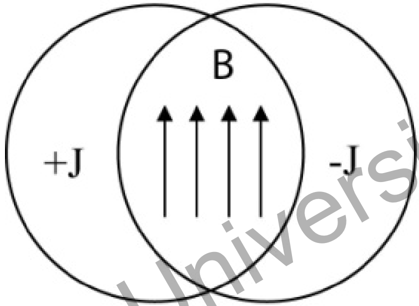
How to generate multipoles field with currents: overlapping cylinders or overlapping ellipses

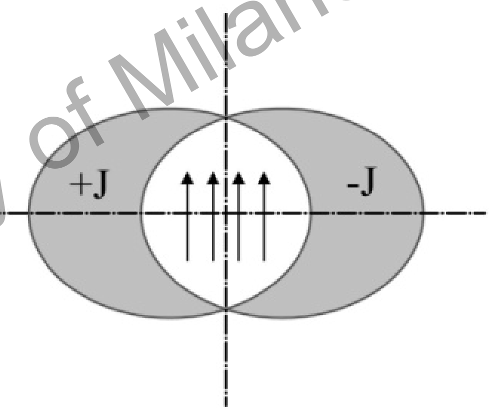
- Field shape DIPOLE
  - ~~Half the field of a solenoid for same J and coil thickness~~
    - J = $J_0 \cos\vartheta$
- Field shape QUADRUPOLES
    - J = $J_0 \cos 2\vartheta$

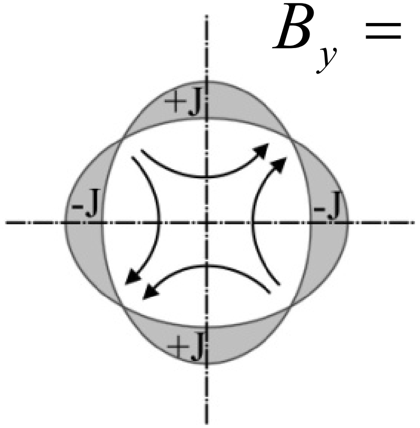
$$B_x = \frac{\mu_0 J(a-b)}{a+b} y$$

$$B_y = \frac{\mu_0 J(a-b)}{a+b} x$$

Field of a long solenoid with N turns and lenght L
B= μ_0 NI/L or B= μ_0 J d
So, a dipole of same J and same coil thinckness d gives half field of a solenoid (but is **transverse field**)







d is the separation between center of the cylinders, or coil thickness

$$\mathbf{B} = \frac{\mu_0 J d}{2}\mathbf{e}_\mathbf{y}$$

$$B_y = \frac{\mu_0 J b d}{a+b}$$

a,*b* elllipses parameters

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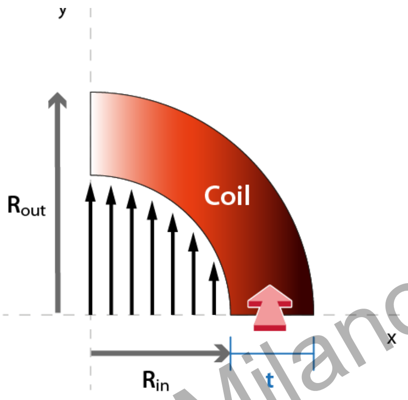
If the d (coil thickness) is constant ? (easy to manufacture) on can vary the J as costheta

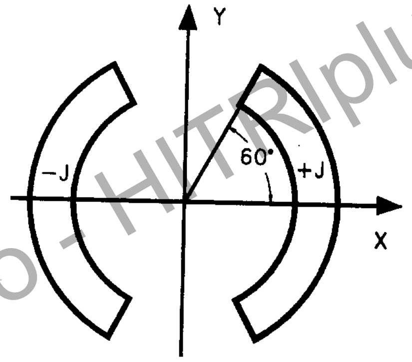
Constant internal radius, sector coils:

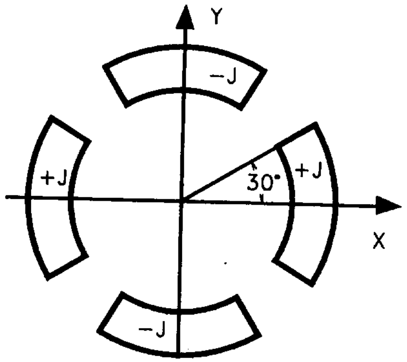
$J_s = J \cdot d \cdot \cos(\theta)$, $J_s = J \cdot d \cdot \cos(2\theta)$, …

d = t =coil thickness

These generate perfect dipole (quadrupole) field inside a circle

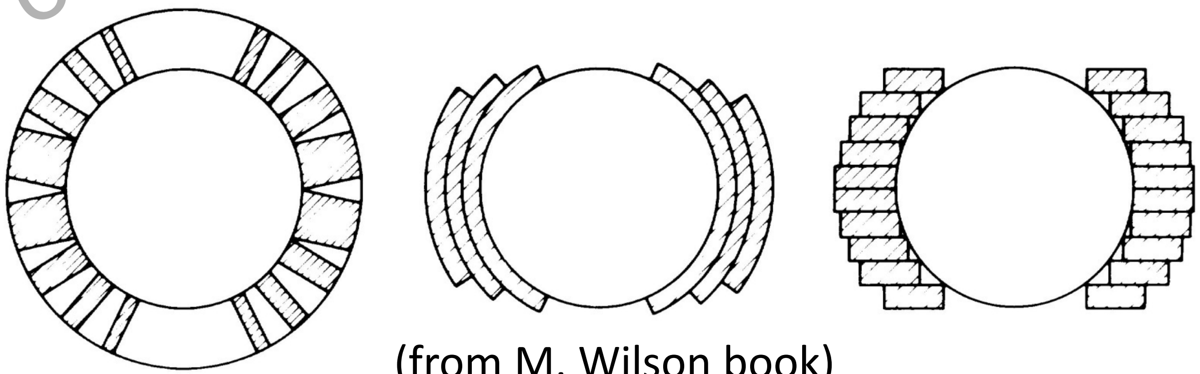






Approximation of cosθ with coil blocks (left) and multiple shells (centre) and of intersecting ellipses.

DEVIATION FROM PERFECT FIELD: **10^{-4}** (0.01%) that is taken as the **unit**.



(from M. Wilson book)

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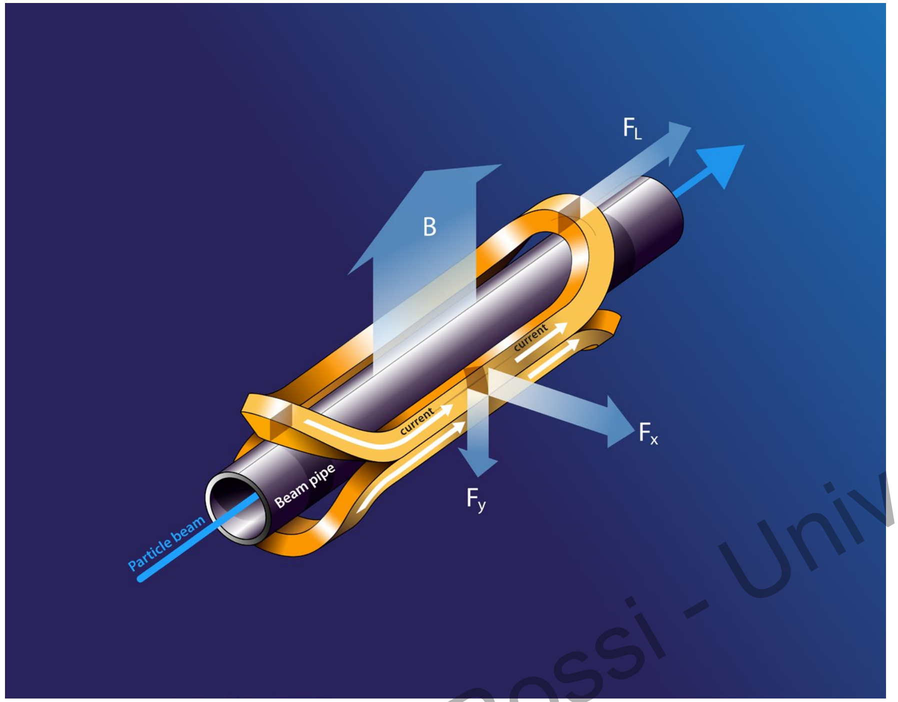
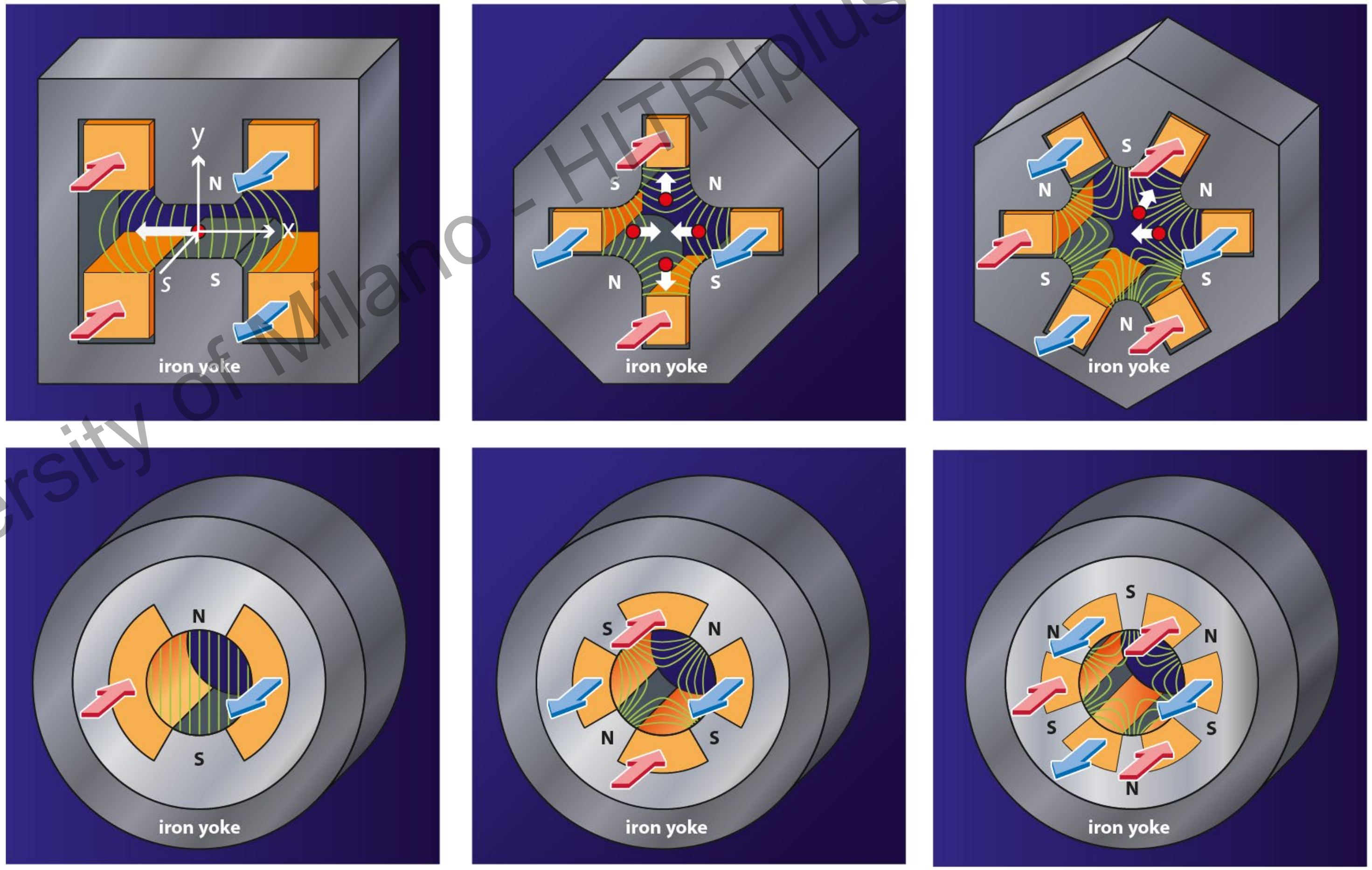
Again: a dipole 3D and 2D scheme of dipole, quadrupole, sextupole, both for iron and coil dominated





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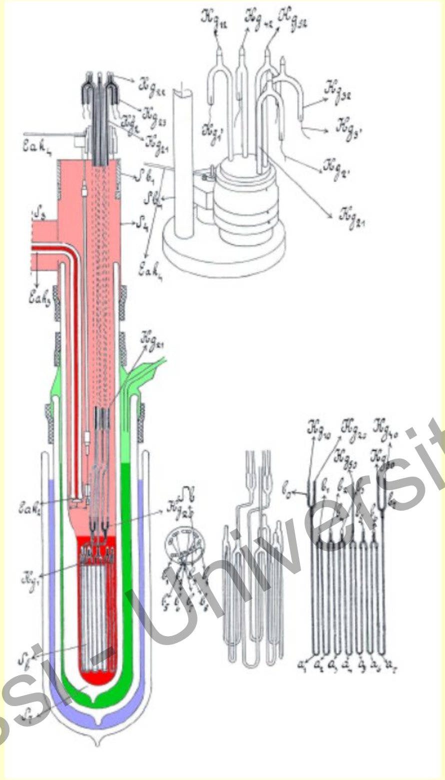
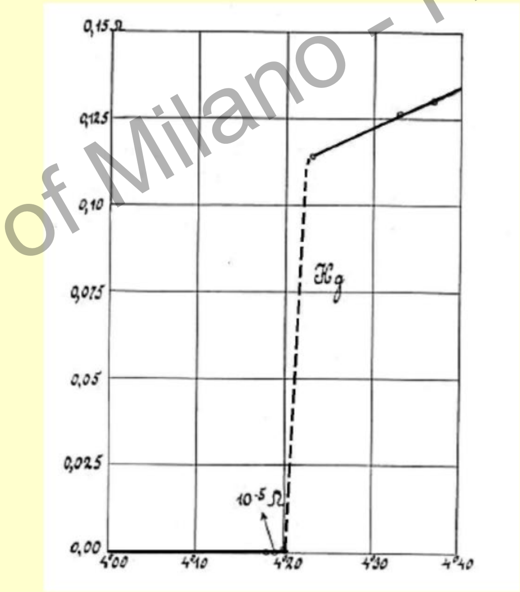
But how to get much current? Superconductivity… but at low T



Experiment of 26 October 1911 with the historic plot showing the resistance jump at 4.20 K.



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Why we need superconductivity

Superconducting LHC

Tunnel: 27 km

Field : 8.3 T

Cryoplant power at the plug: 40 MW: **always on**

~ 70 MW for LHC. 150 MW for the accelerator complex

180 MW for the whole CERN complex

Normalconducting LHC

Tunnel 120 km

Field : 1.8 T

Dissipated power at collision: ~ 2,200 MW

Average power (0.4 coefficient): 900 MW only for accelerator

However, power is required only when operating while power in SC magnets is needed to keep it cold… a factor 2 favorable in energy for NC

Zero resistance: really?

Gallop experiment on the current decay in a superconducting loop:

$$\rho < 10^{-26}\ \Omega m$$

One experiment lasted two years, with no sign of current decay and had to stop because the supply of LHe was interrupted by transport strike !

Resistivity table

Materials	ρ (Ωm)
↓	↓
Vacuum	∞
Insulators	$10^{20} \div 10^{10}$
Semiconductors	$10^{5} \div 10^{-3}$
Metals	$10^{-5} \div 10^{-10}$
Superconductors	≈ 0

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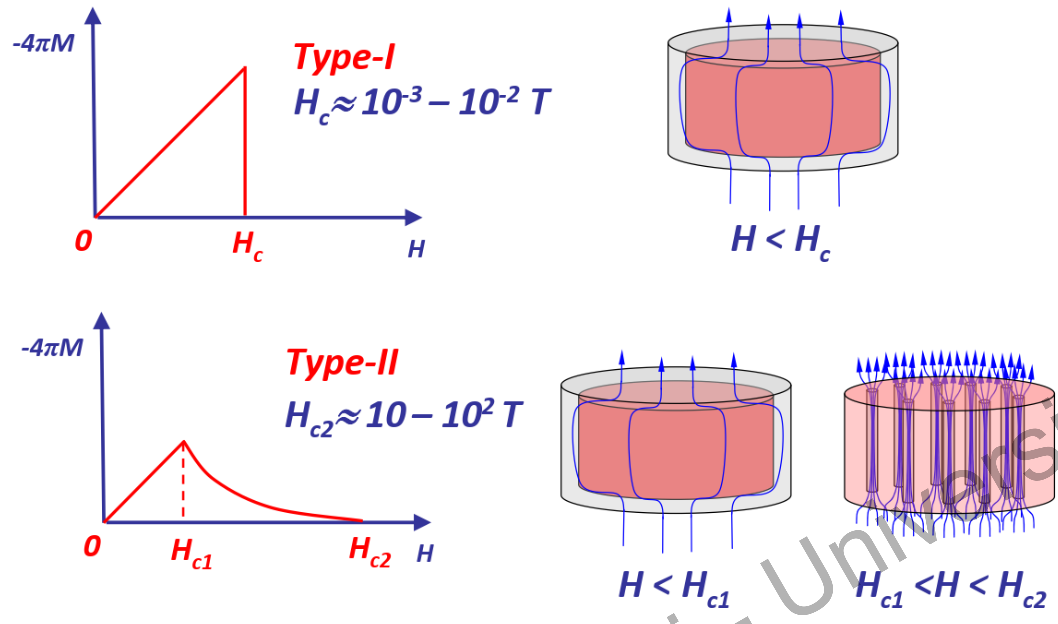
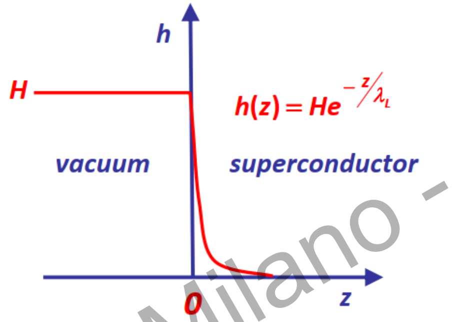
Superconductivity: more than zero resistance

Type-I and Type-II superconductors

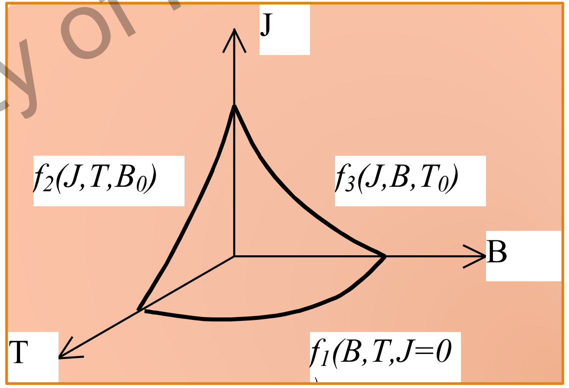


$-4\pi M = H - B$

Meissner-Ochsenfeld effect



$h(z) = He^{-z/\lambda_L}$



Superconductivity is a thermodynamic state defined by T, B, J similar to T,P,V for the ideal gas: P ⇔ B, V ⇔ J

Superconductivity exists only below the critical surface: increase one parameters depress possible value of others...

B and J are linked by consideration of free-energy and by Maxwell equations… So inevitably an increase in current brings also an increase in field…

Deception! B_c is very low: ~1-10 mT !

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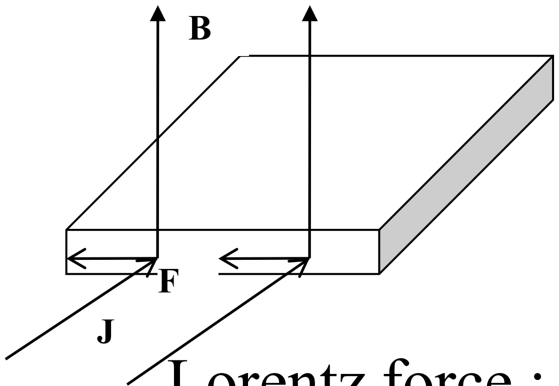
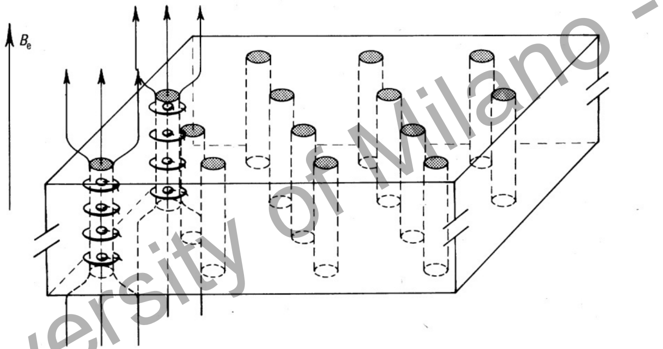
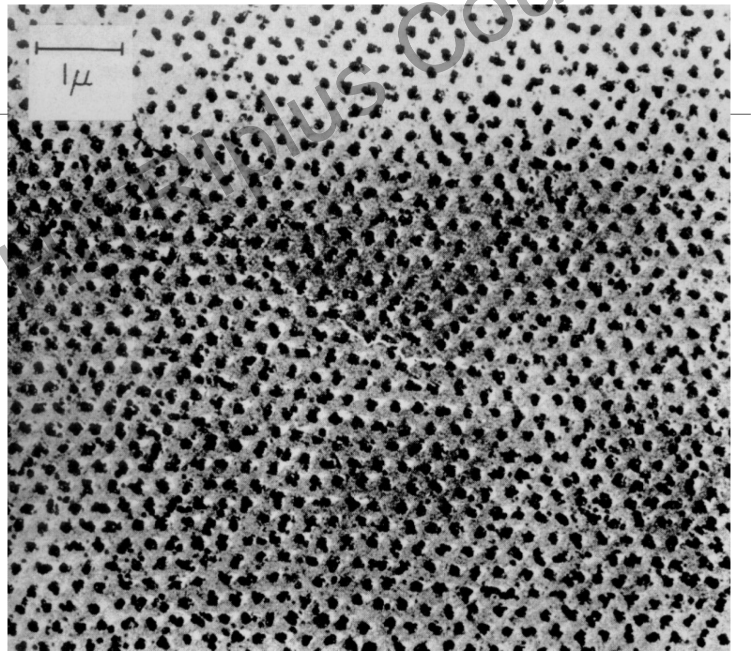
Fluxoids or quantum magnetic flux

Flux penetration in the material is in quanta:

$$\Phi = h/2e \cong 2\ 10^{-15}\ \text{Wb}$$







Lorentz force : $F_p = -J_c \times B$: to avoid movements and heating it is needed a **pinning given by defects.**

NbTi: $F_{p\,max} \approx 15$ GN/m^3 (or 15 N/mm^3 !!) $\Rightarrow J_c \approx 3$ GA/m^2 (3000 A/mm^2) at 5 T

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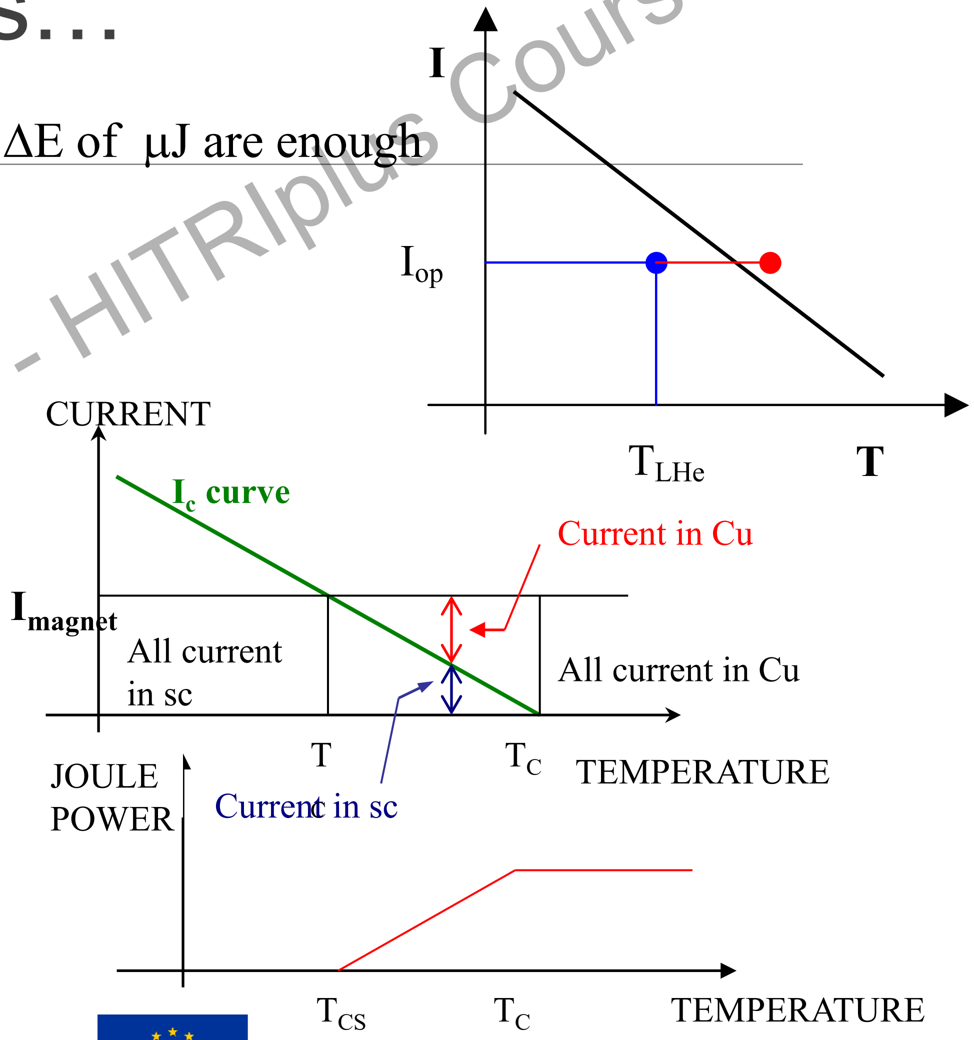
Stability margins…

Superconductors are NOT stable against perturbation albeit very small. ΔE of μJ are enough to drive superconductor normal!

Heat capacity drops at low temperature ($T \ll T_{Debey}$) :
$C \propto T^3 \Rightarrow \Delta T = \Delta E/\gamma C$. So even small ΔE generates sensible ΔT
$\Rightarrow$ operating point of the magnet beyond critical surface $\Rightarrow$ **QUENCH**



Electrodynamic stability: intimate contact between the superconductor and a good conductivity material.

Adiabatic (or intrinsic)stability: to cure the flux rearrangement that generates heat

Direct cooling : LHe and more HEII are very good coolant, capable to remove heating in milliseconds! Latent heat 10-1000 times that of solid specific heat!

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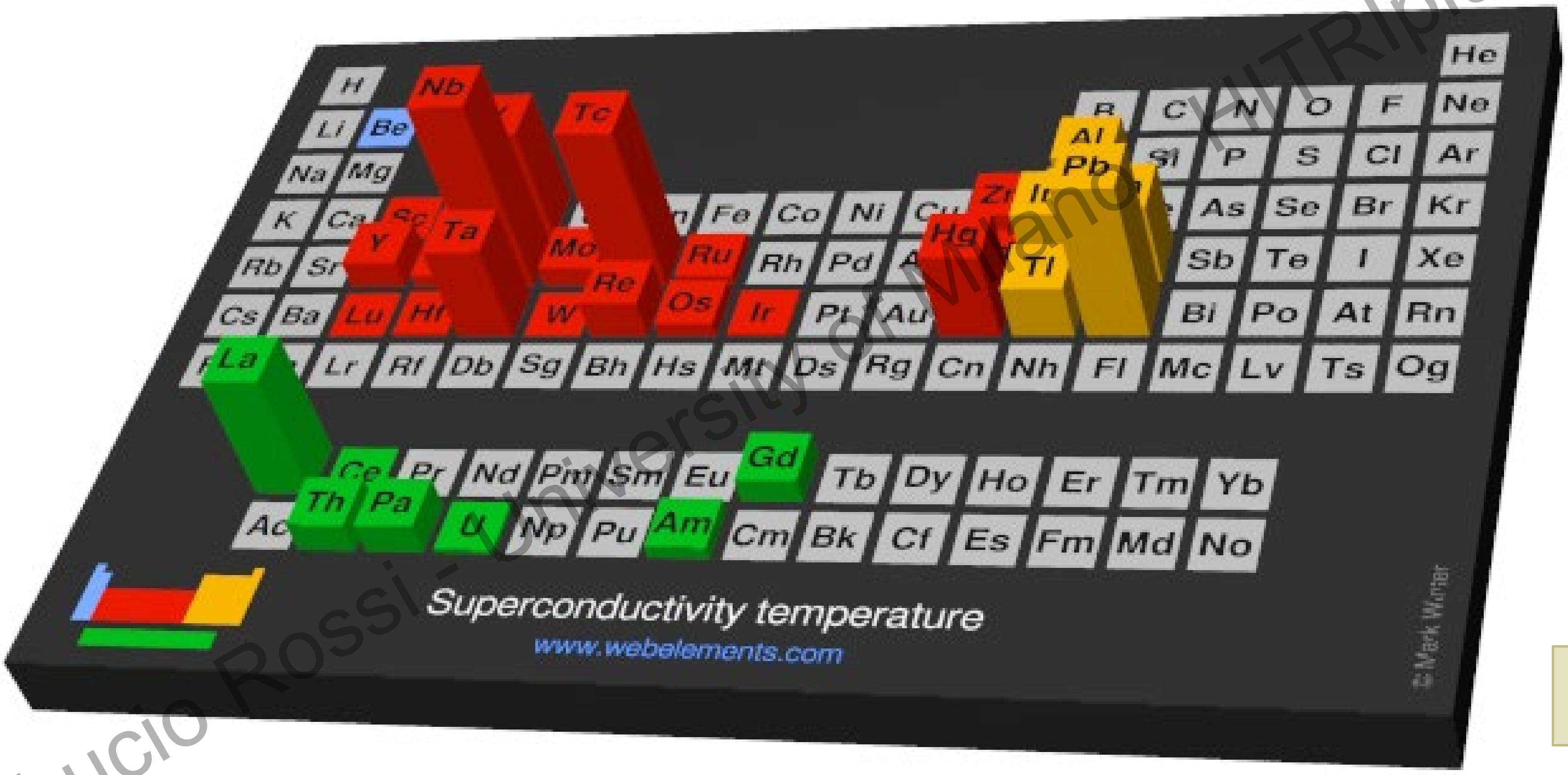
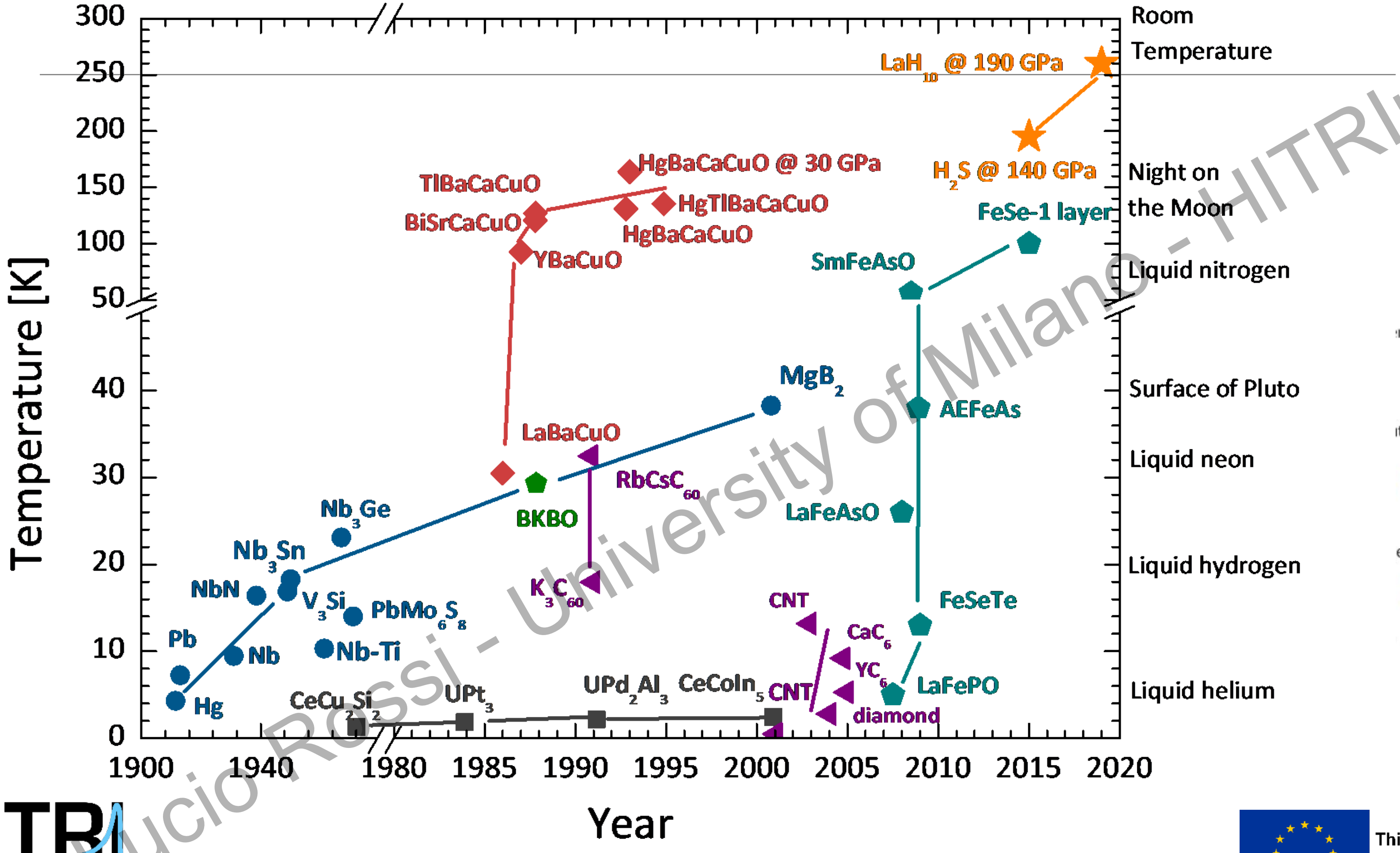
Critical temperatures on the Mendeleev table



Cortesy of D. Valentinis, KIT, Karlsruhe

funding from the European Union’s Horizon 2020
rogramme under grant agreement No 101008548

Critical temperature vs time…

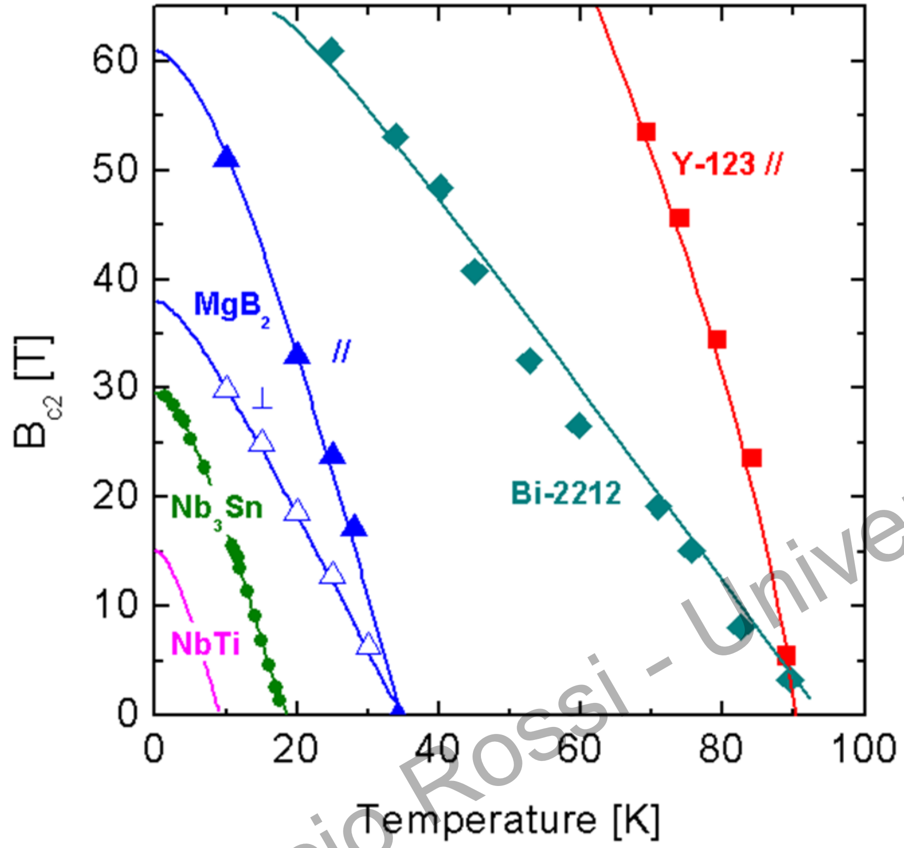


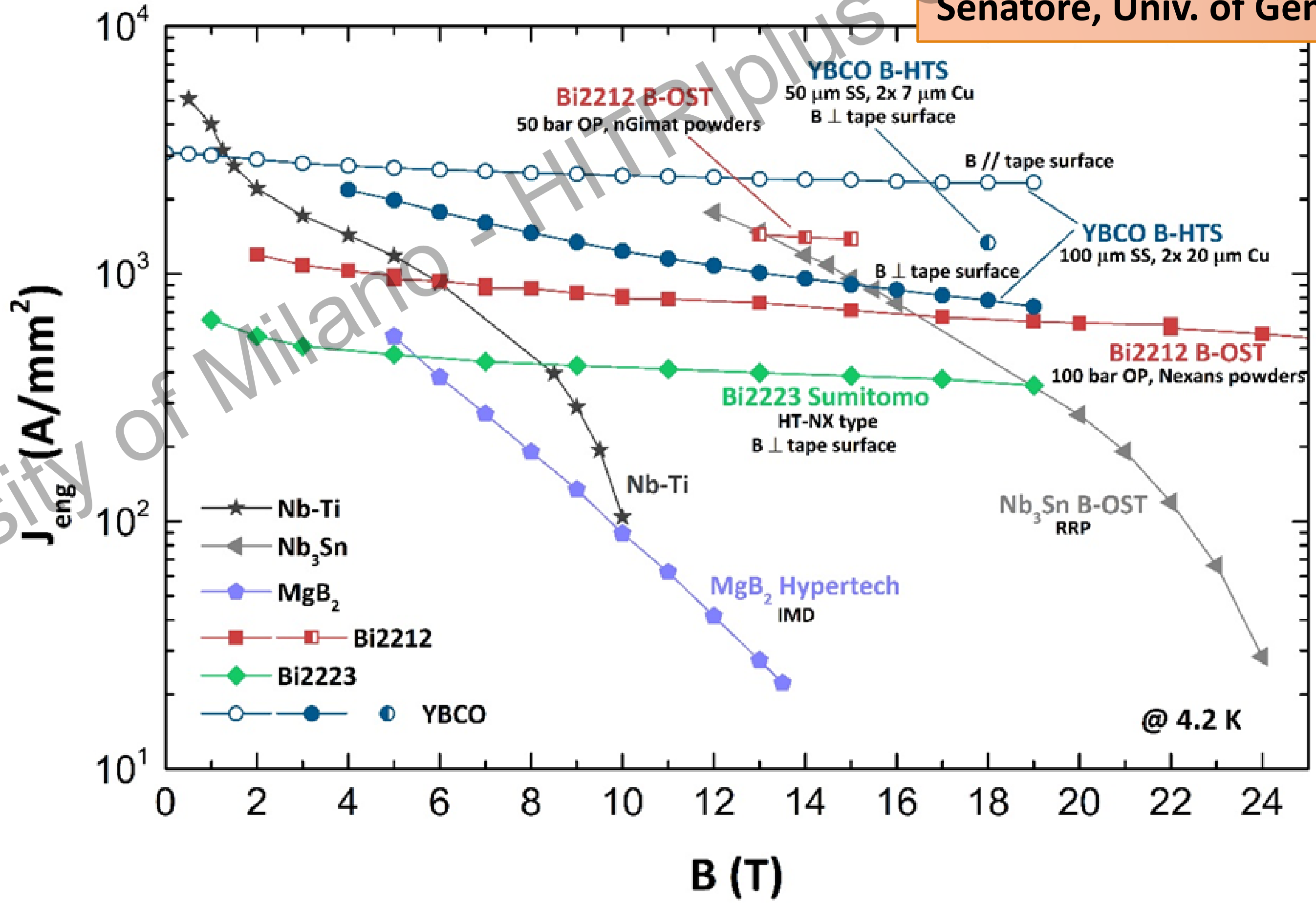
Thanks to C. Senatore, Univ of Geneva

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101008548

Critical field vs. temperature (at zero current)
Critical current density (eng.) vs field at fixed T

Plot courtesy of C. Senatore, Univ. of Geneva





Heavy Ion Therapy Research Integration

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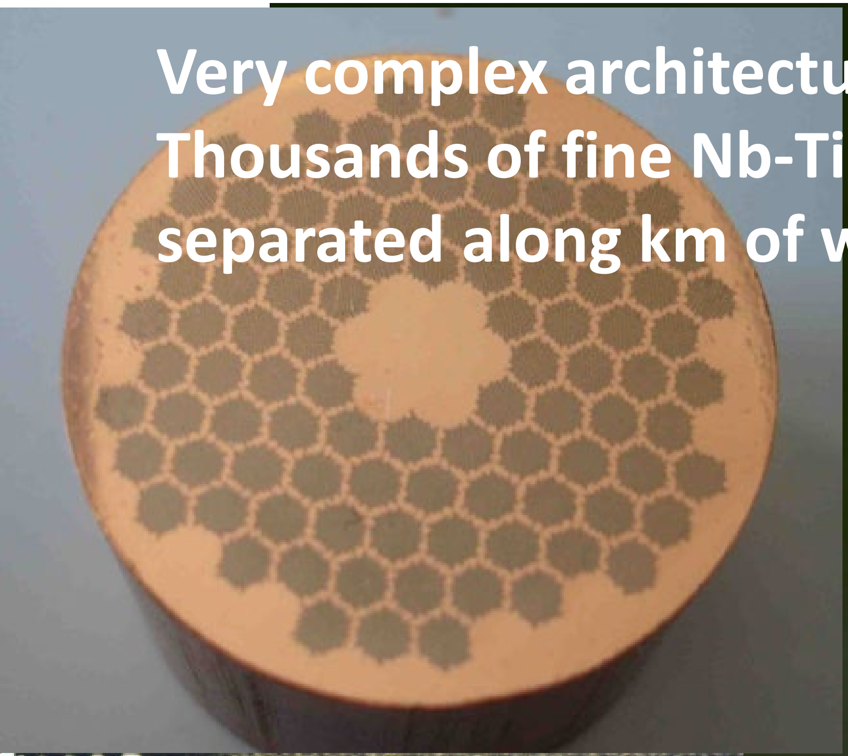
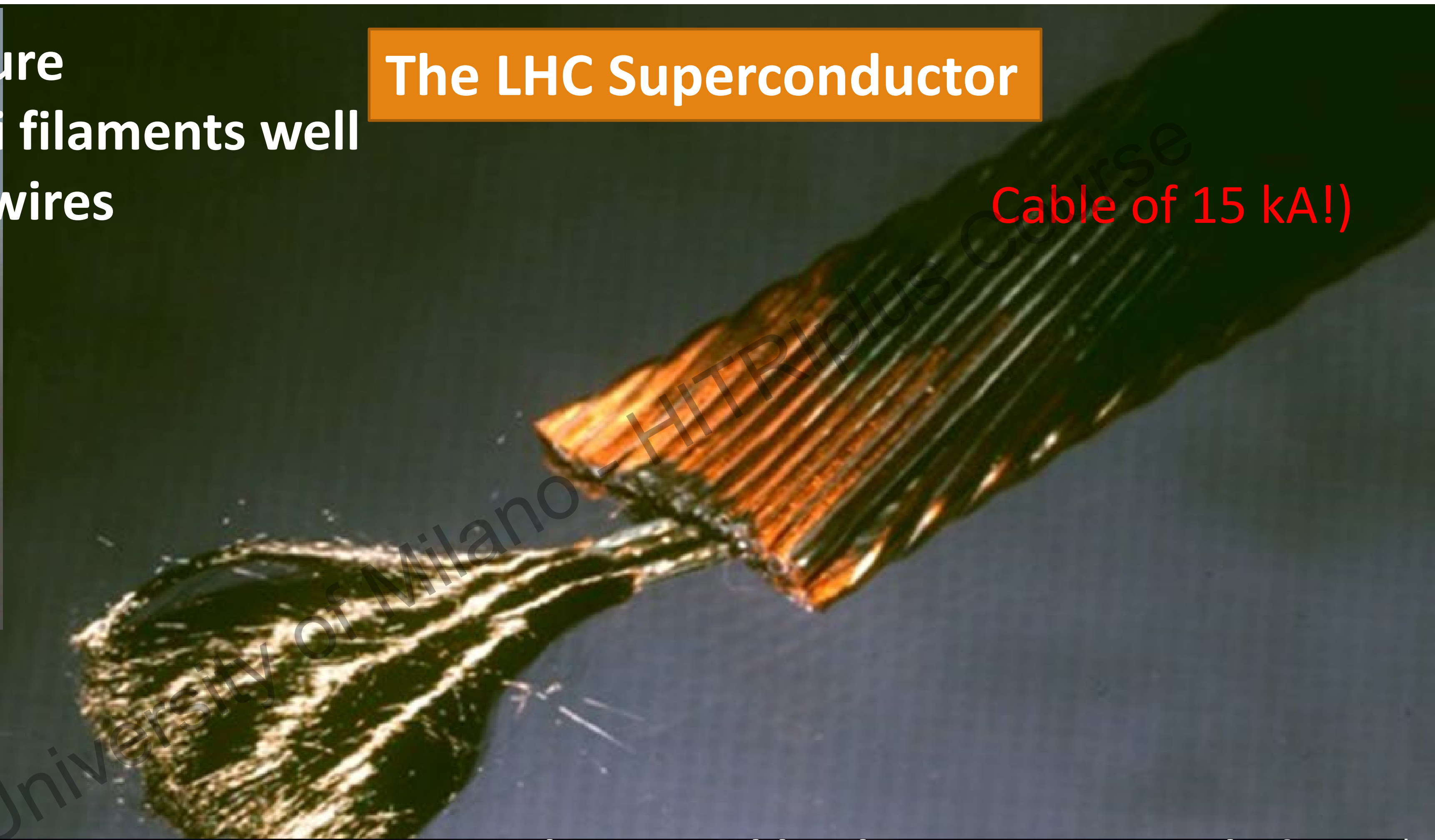
The LHC Superconductor

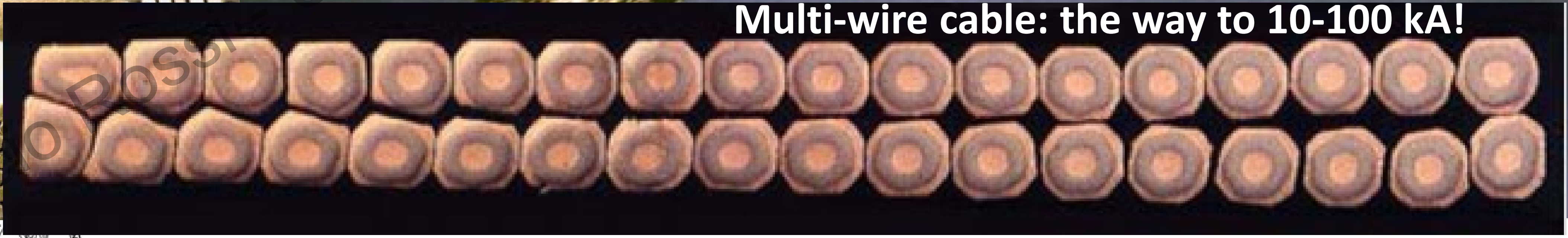


Very complex architecture
Thousands of fine Nb-Ti filaments well separated along km of wires



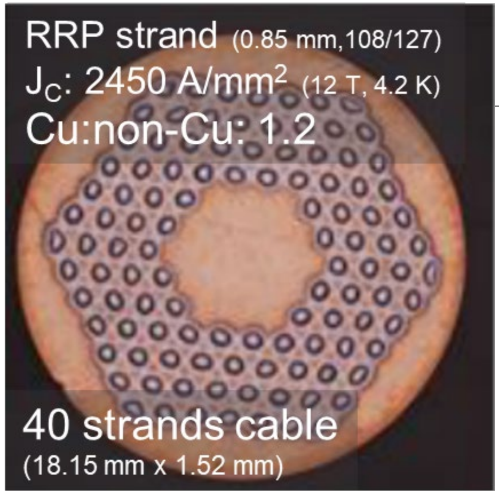
Cable of 15 kA!)

Fine filaments of Nb-Ti in a Cu matrix for an LHC dipole wire)



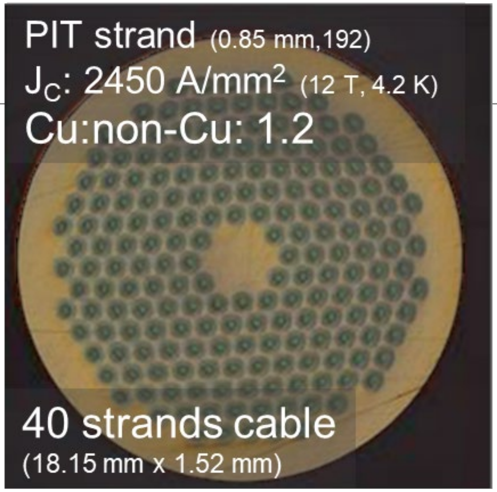
Multi-wire cable: the way to 10-100 kA!

Innovative materials: Nb_3Sn with high Jc



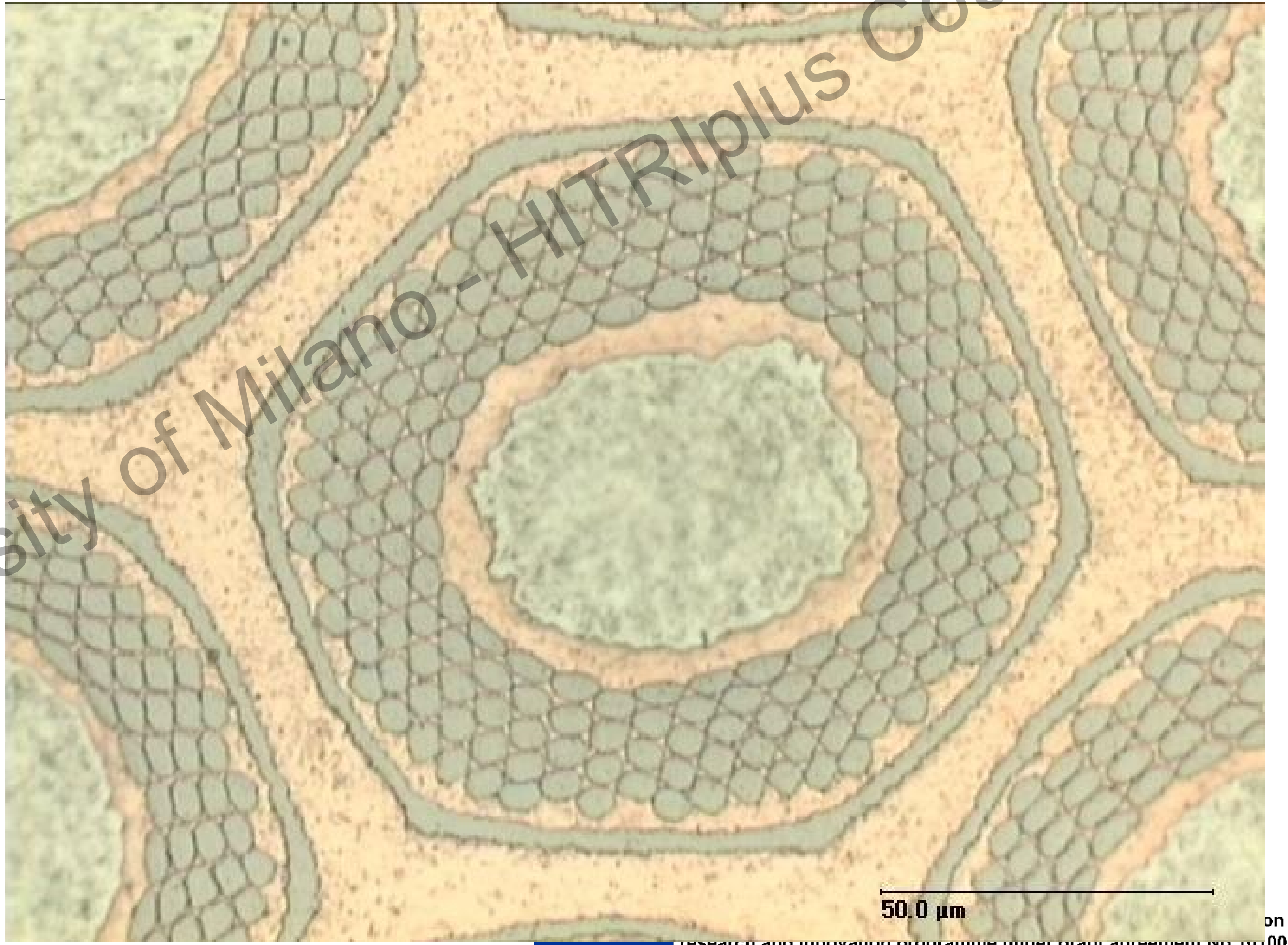
RRP strand (0.85 mm, 108/127)
J_C: 2450 A/mm^2 (12 T, 4.2 K)
Cu:non-Cu: 1.2

40 strands cable
(18.15 mm x 1.52 mm)



PIT strand (0.85 mm, 192)
J_C: 2450 A/mm^2 (12 T, 4.2 K)
Cu:non-Cu: 1.2

40 strands cable
(18.15 mm x 1.52 mm)



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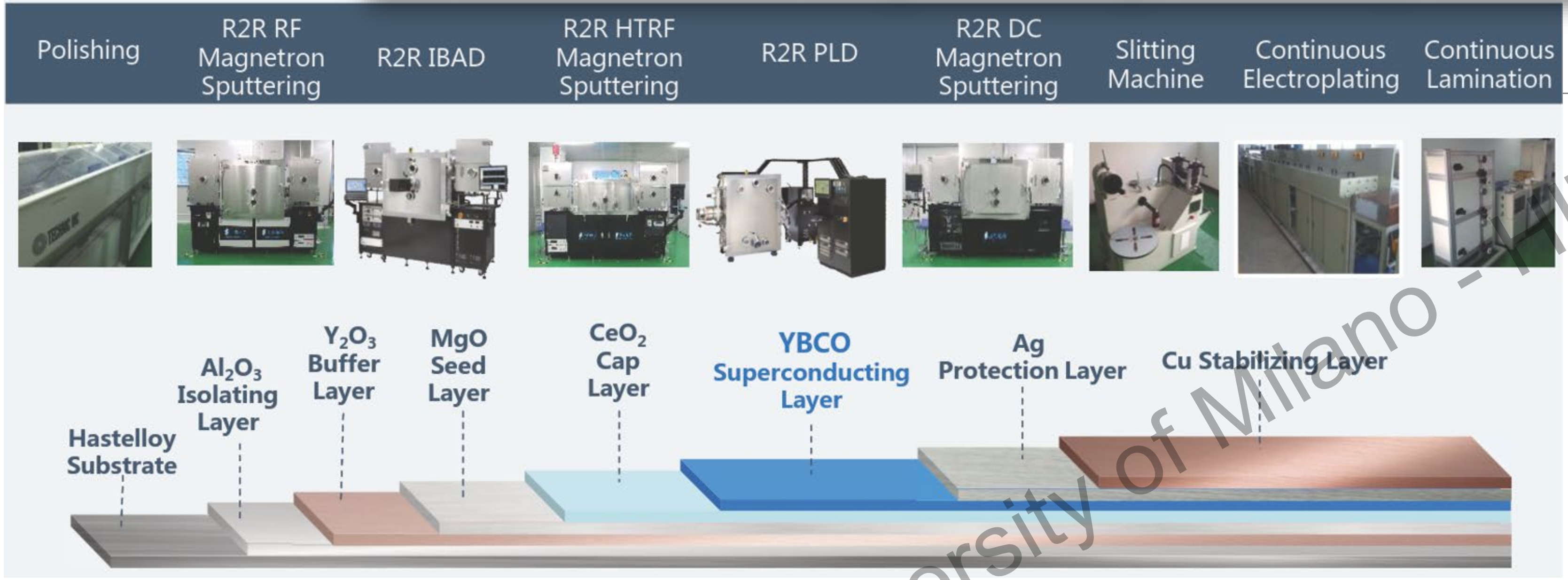
on 2020
research and innovation programme under grant agreement No 101008548

Inovative Materilas: HTS
Bi-2212 and especially YBCO / REBCO



Polishing | R2R RF Magnetron Sputtering | R2R IBAD | R2R HTRF Magnetron Sputtering | R2R PLD | R2R DC Magnetron Sputtering | Slitting Machine | Continuous Electroplating | Continuous Lamination

Hastelloy Substrate

Al_2O_3 Isolating Layer

Y_2O_3 Buffer Layer

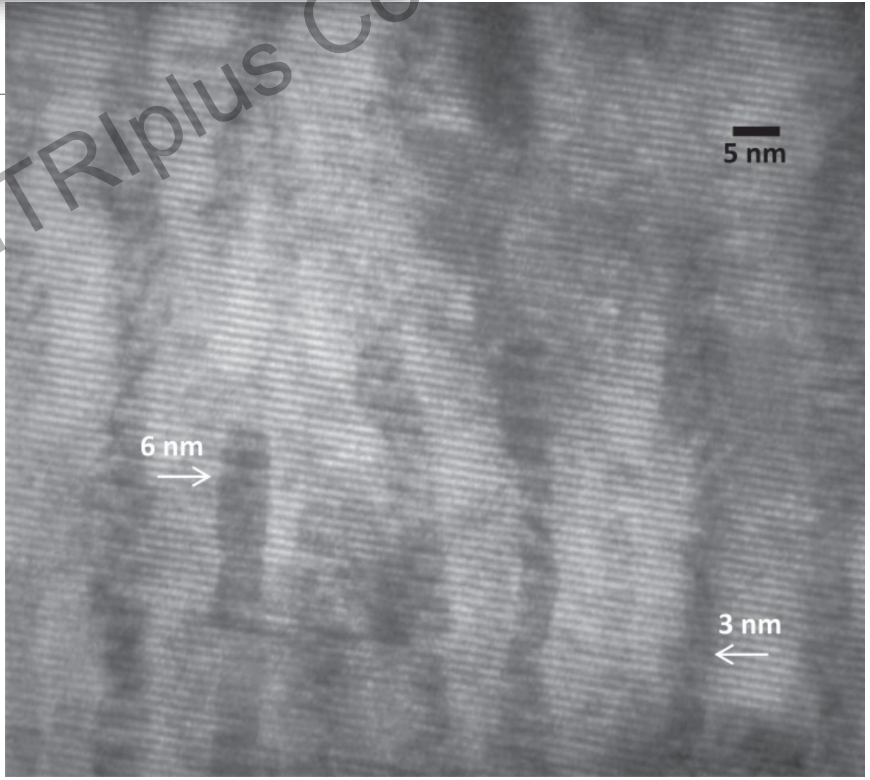
MgO Seed Layer

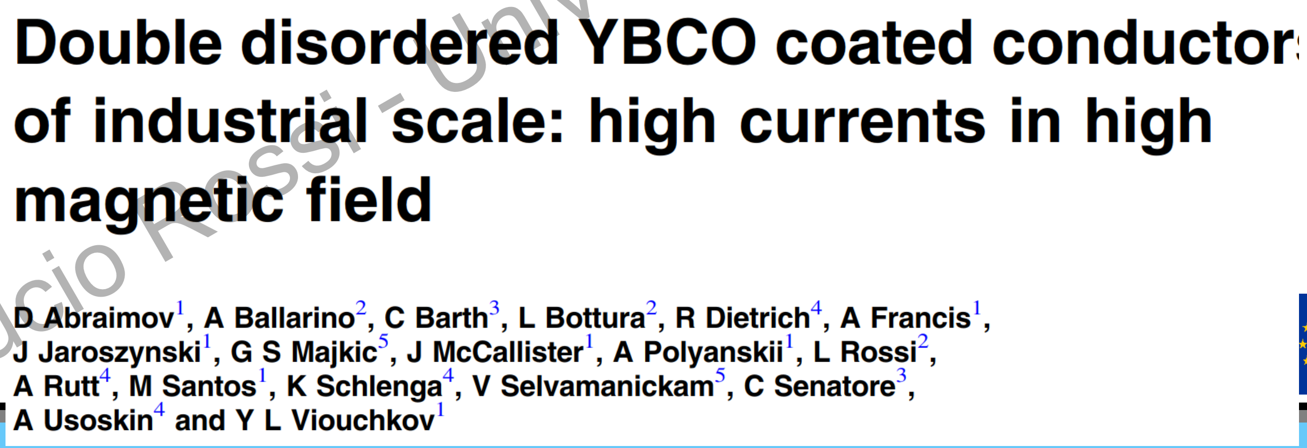
CeO_2 Cap Layer

YBCO Superconducting Layer

Ag Protection Layer

Cu Stabilizing Layer





Double disordered YBCO coated conductors of industrial scale: high currents in high magnetic field

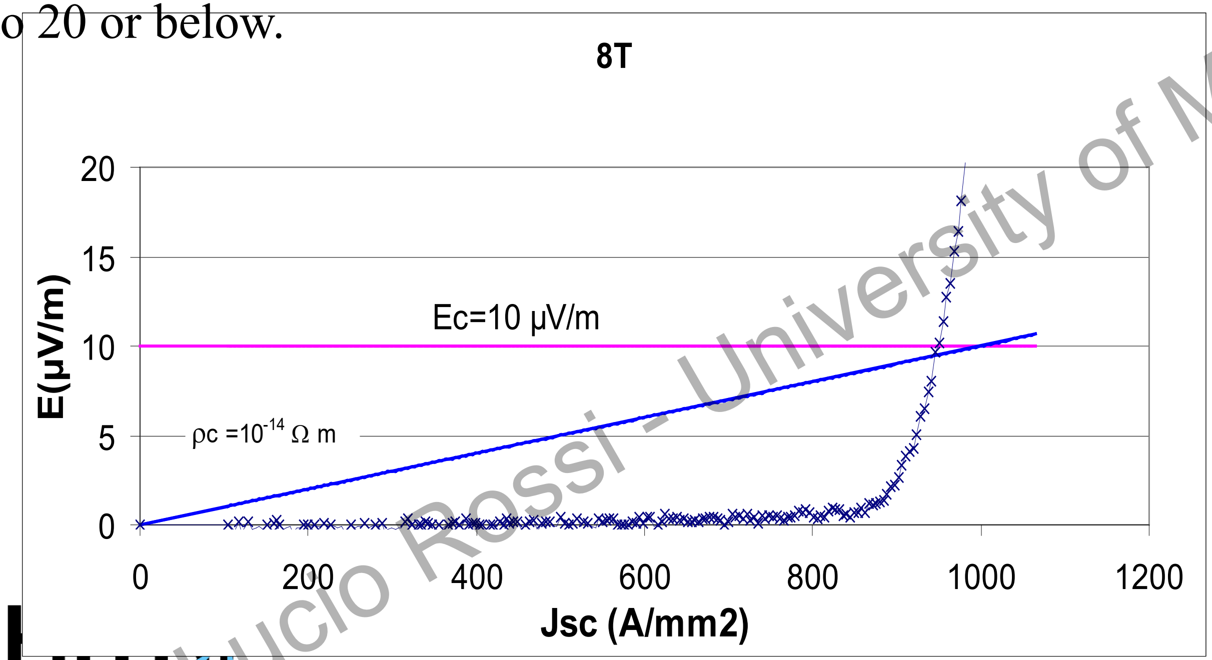
D Abraimov[1], A Ballarino[2], C Barth[3], L Bottura[2], R Dietrich[4], A Francis[1], J Jaroszynski[1], G S Majkic[5], J McCallister[1], A Polyanskii[1], L Rossi[2], A Rutt[4], M Santos[1], K Schlenga[4], V Selvamanickam[5], C Senatore[3], A Usoskin[4] and Y L Viouchkov[1]

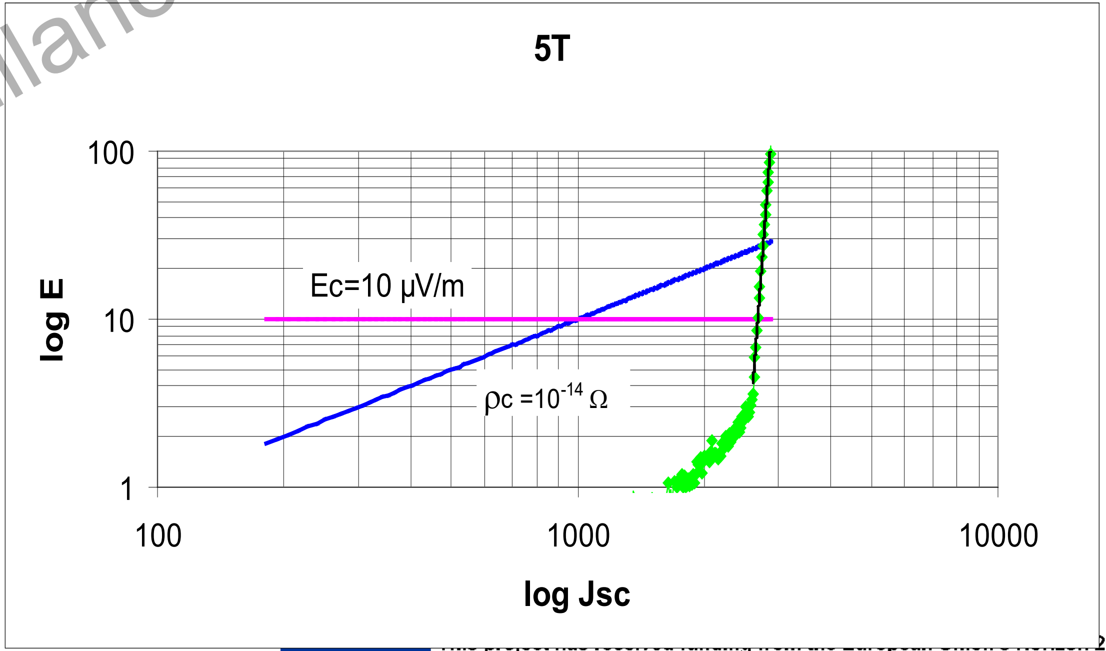
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

Max current in SC: I_c, E-J curve

Transition at fixed temperature: **$V = k I^n$** , so we have to adopt a criterion to define I_c.

Electric field. I_c is the current generating an electric field $E_c = 10^{-5}$ V/m $\Rightarrow E = E_c (J/J_c)^n$
Resistivity. I_c is the current showing an apparent resistivity of $\rho_c = 10^{-14}$ Ωm.
The exponent n, called also n-value or n-index, is related to the homogeneity of the material or of the superconducting properties. For good superconductors n ~30 – 60 or more. Near critical surface, $B > 0.9\ B_{c2}$ the n-values drops down to 20 or below.





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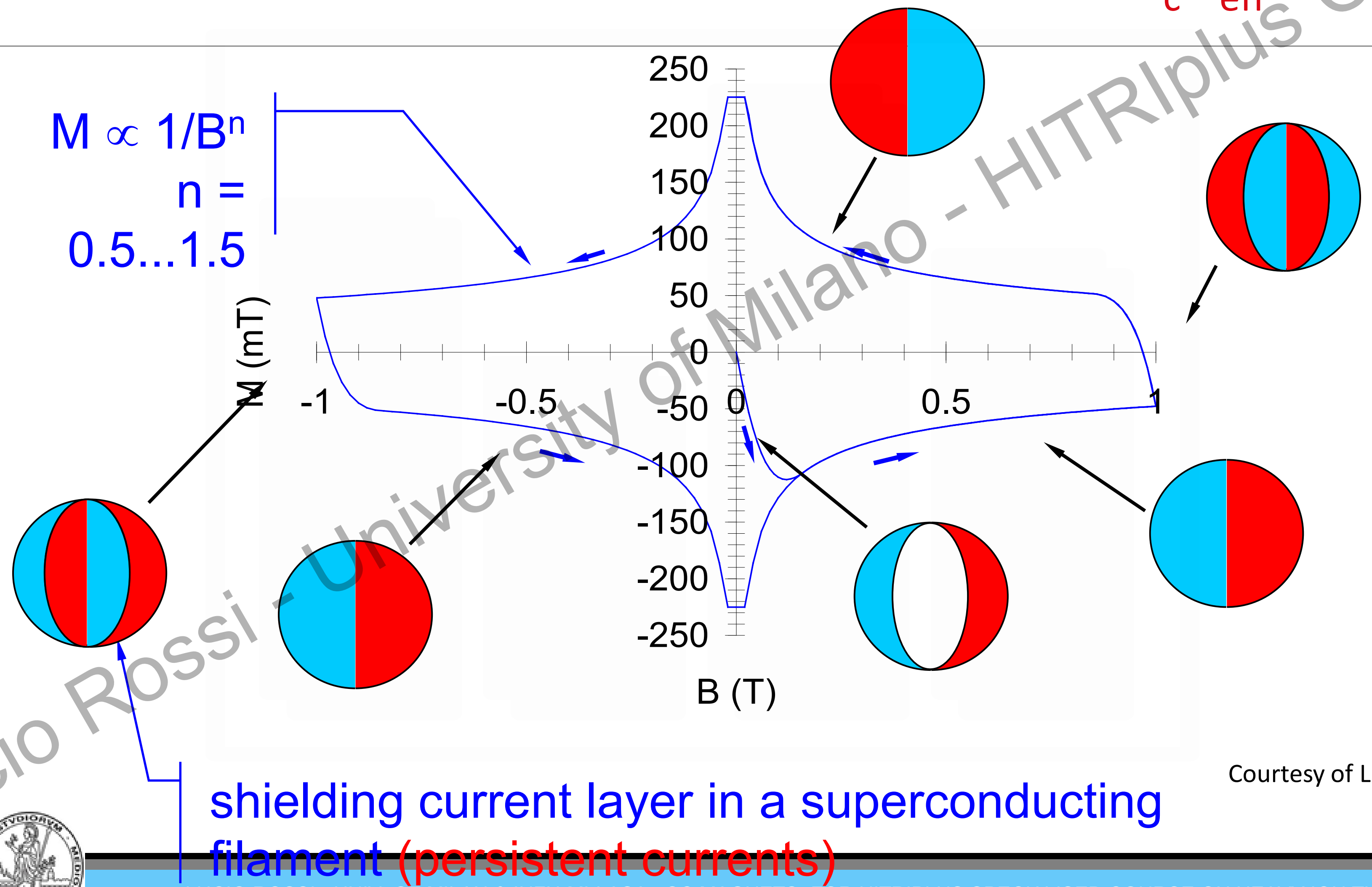
Carrying a lot of current: what a difference for magnets!

Resistive magnets of PS accelerator at CERN (1.5 tesla)

SC magnets at Tevatron at Fermilab (USA) 3 times more powerful!

(Dia)Magnetization and fine filaments

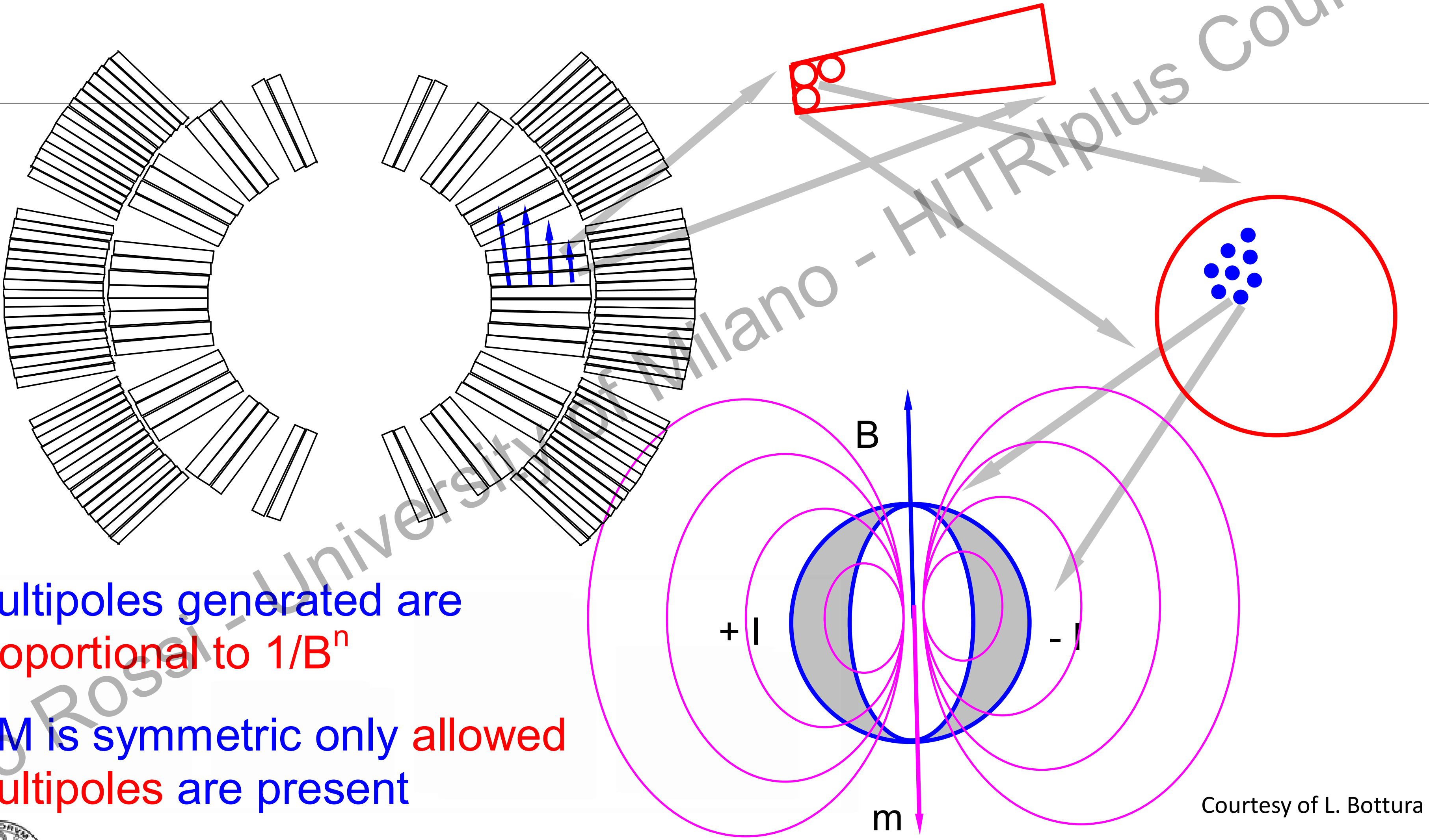
$M \cong J_c D_{eff}$



shielding current layer in a superconducting filament (persistent currents)

Courtesy of L. Bottura

Effect of magnetization



Multipoles generated are proportional to $1/B^n$

If M is symmetric only allowed multipoles are present

Courtesy of L. Bottura

jump

Graphics by courtesy of M.N. Wilson

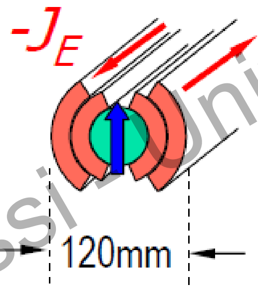
The advantage of high current density

- The field produced by an ideal dipole is:

$$B \approx 1/\pi \ \mu_0 \ J_E \ t$$

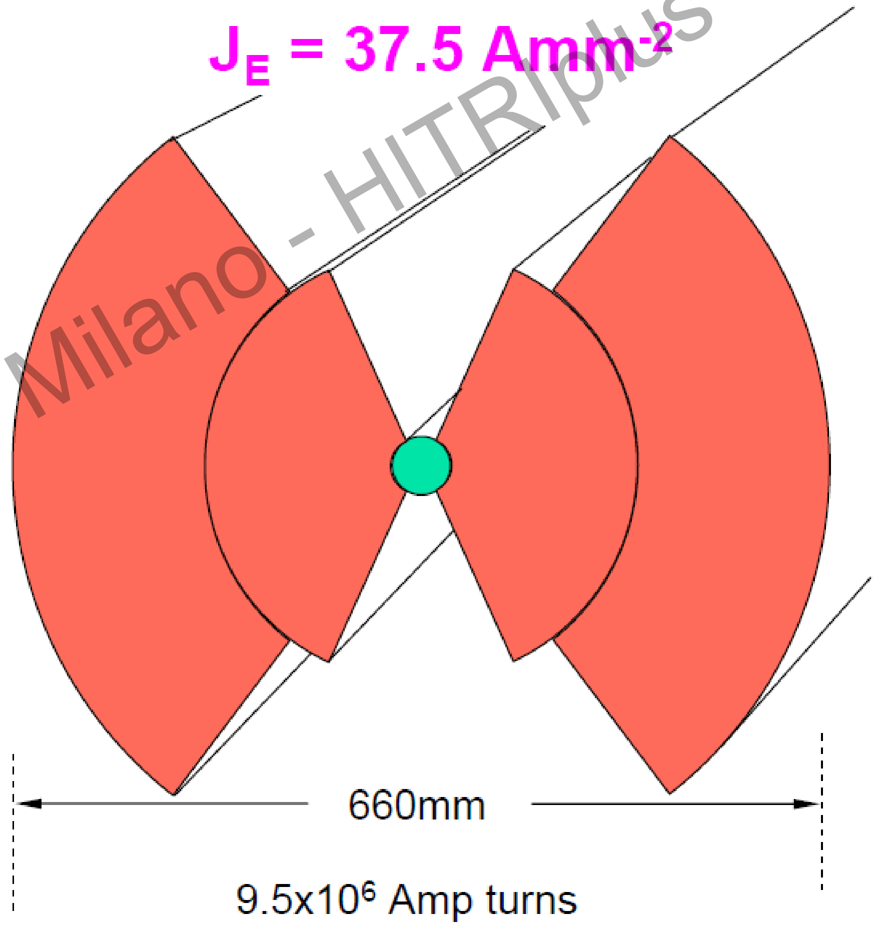
$J_E = 375 \text{ Amm}^{-2}$

LHC dipole



$9.5\text{x}10^5$ Amp turns
$=1.9\text{x}10^6$ A.m per m

$J_E = 37.5 \text{ Amm}^{-2}$



$9.5\text{x}10^6$ Amp turns
$=1.9\text{x}10^7$ A.m per m

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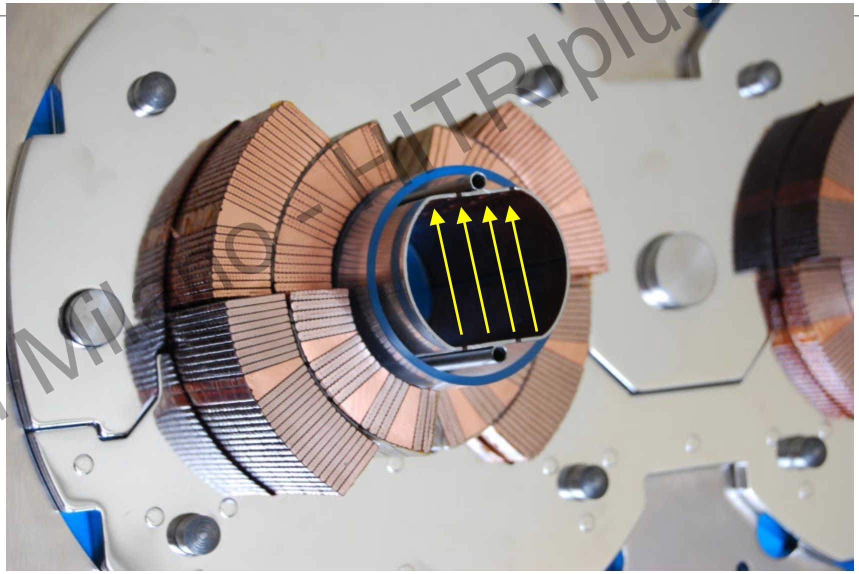
Accelerator magnets : basic - field

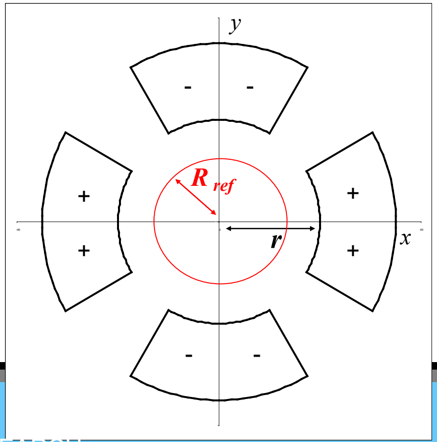
The basic shape : mix between cosϑ and shell

Shells with const J is a very good approximation

Field expansion



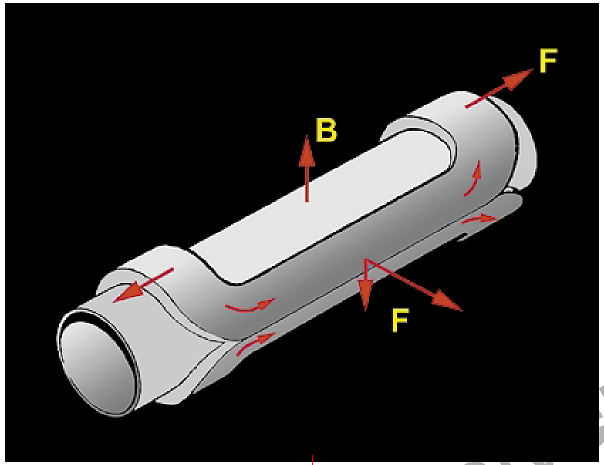
$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$



Accelerator Magnets: Basic Design - forces

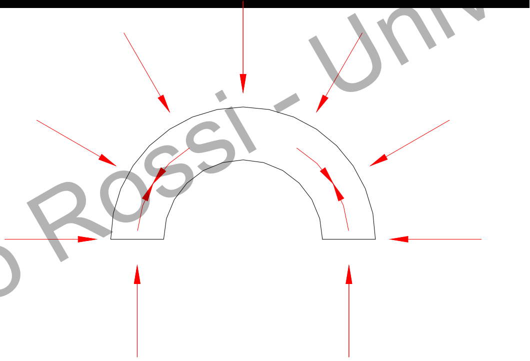
$J_{overall}$ ≈ 500 A/mm^2 ! e.m. forces are not kept by conductors but tend to torn apart the winding.

Principle



e.m. forces

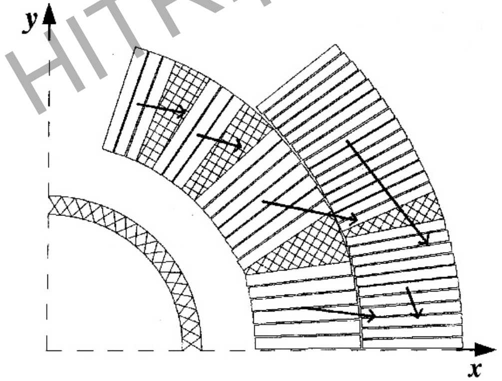
NOT SELF-SUPPORTING

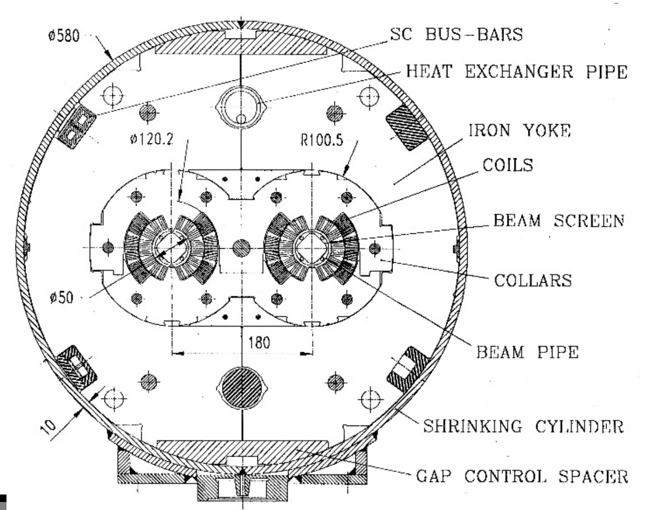


How to contain them

More difficult in twin magnets!

Reality





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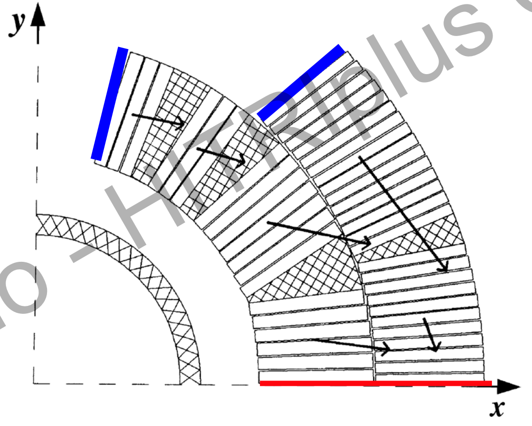
Accelerator magnets : total quality

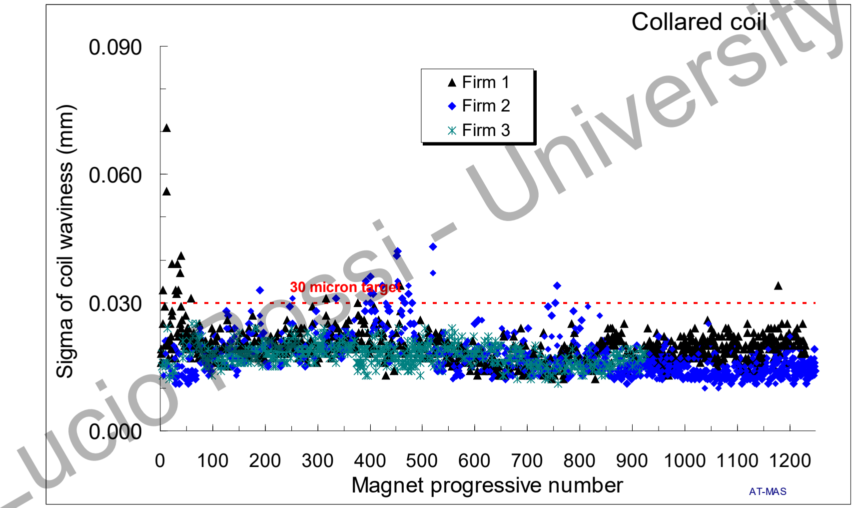
All in series

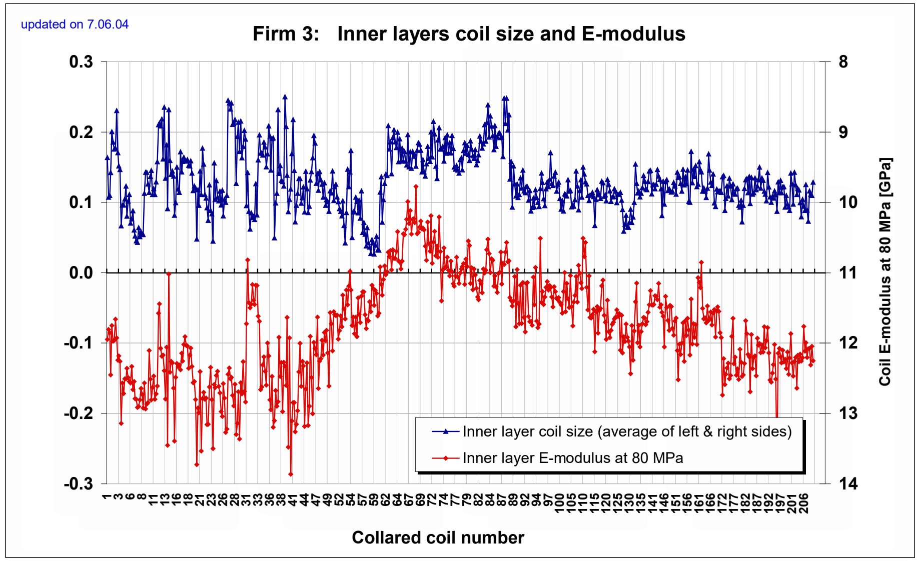
- The worst performing determines the accelerator energy
- They must be all equal (within few units , 1 u=10^{-4})

The field quality is typically controlled at a fraction of unit over a wide range.

- Coil positioning and e.m. forces



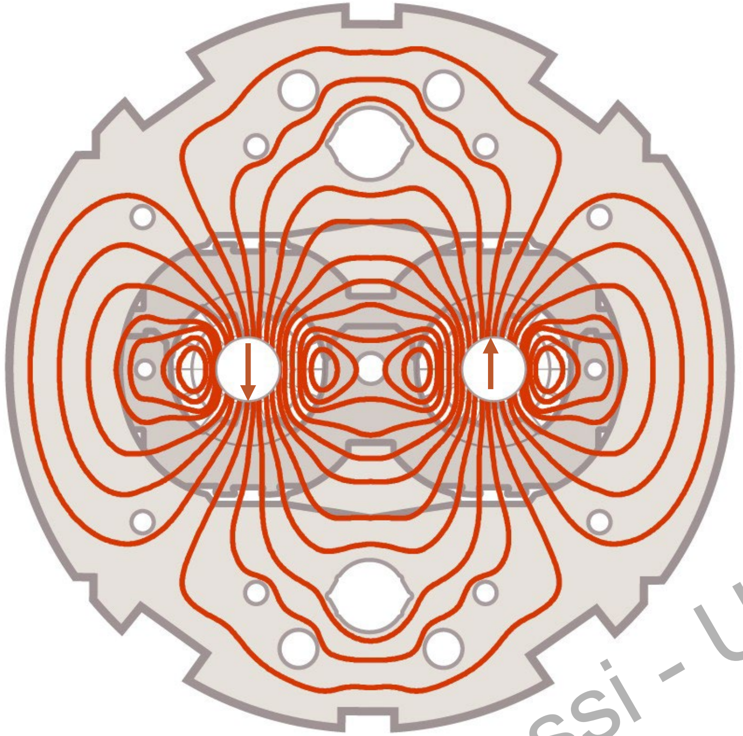


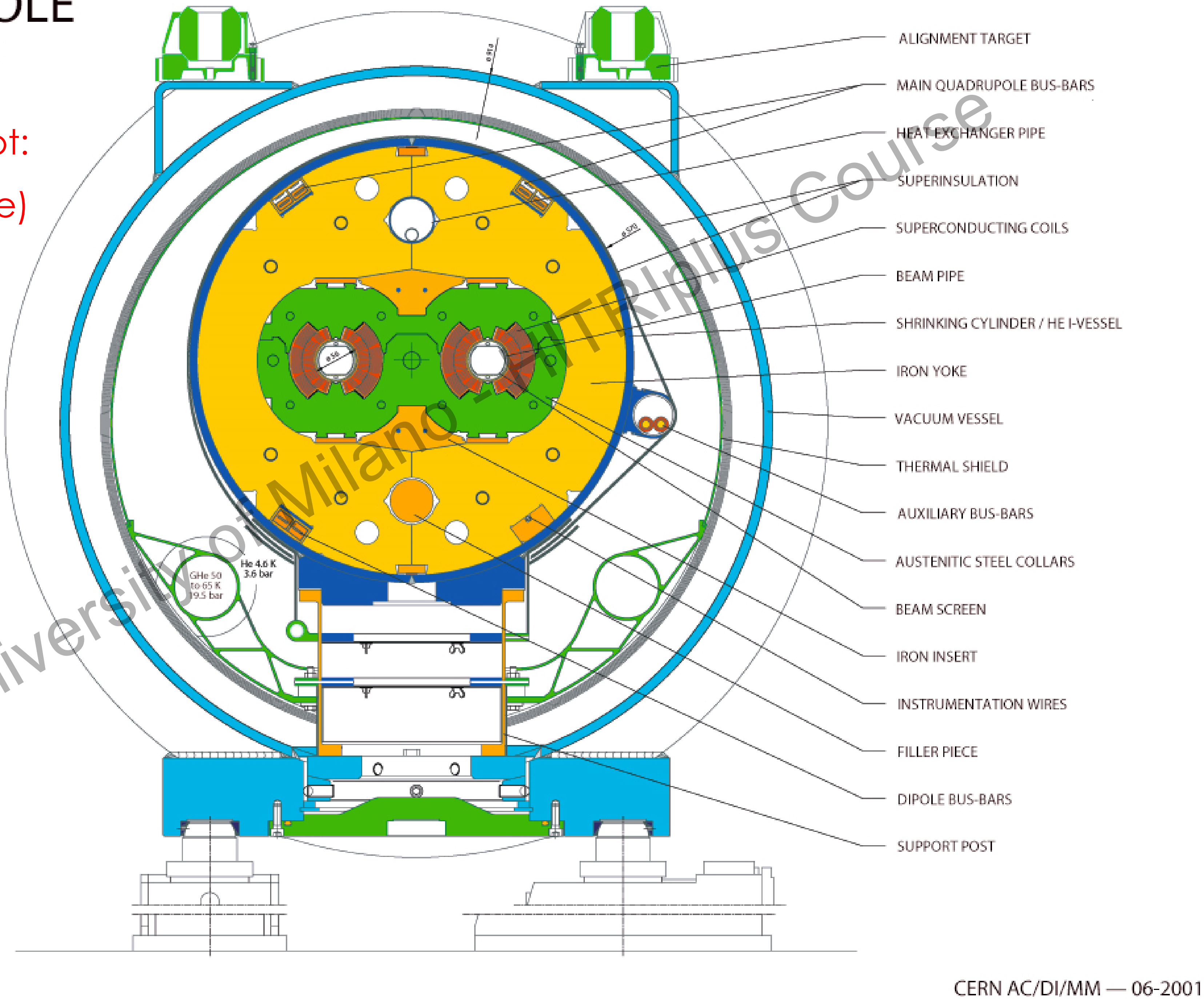


LHC DIPOLE
CROSS SECTION

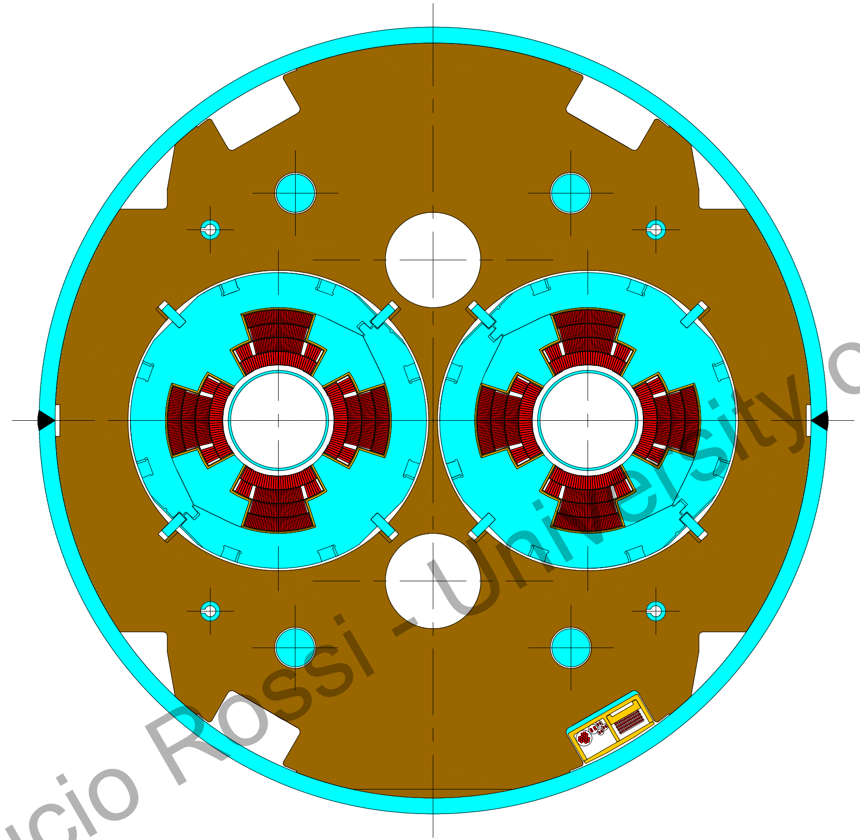
Twin Concept:

MB Main Bend (Dipole)





MQY wide aperture quadrupole



70 mm ID coil
G = 160 T/m at 4.5 K
I = 3620 A
E = 141 kJ/m/aperture
L_{mag} = 3.4

- Four-layer, graded shell coil.
- Free standing collars, fully supporting the forces.
- Two-in-one iron yoke.

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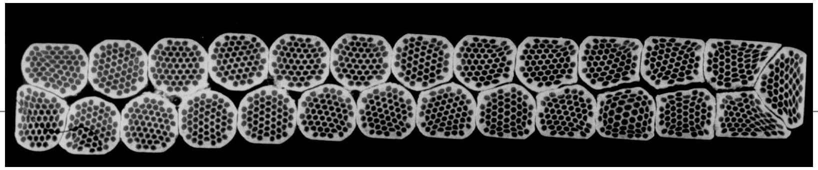
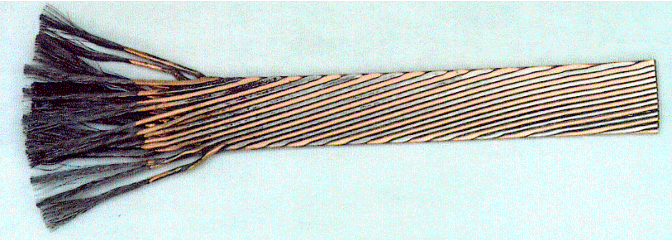
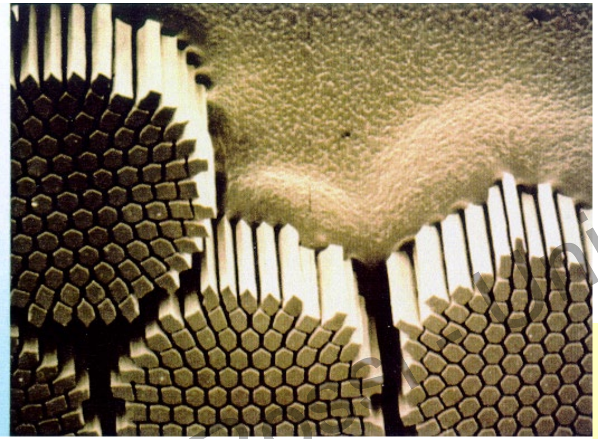
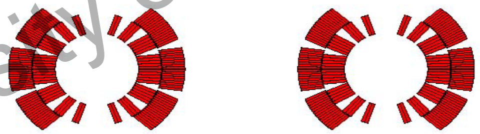
LHC MB X-sect: conductor (Rutherford cable)









designed with the ROXIE code developed at CERN for the LHC
(S. Russenschuck)

Conductor position optimization:

Control of harmonics
Balance of margin among blocks

Stable against inevitable errors

Minimum shear among conductors

Balance between T margin of inner/outer

No quench anymore in straight part

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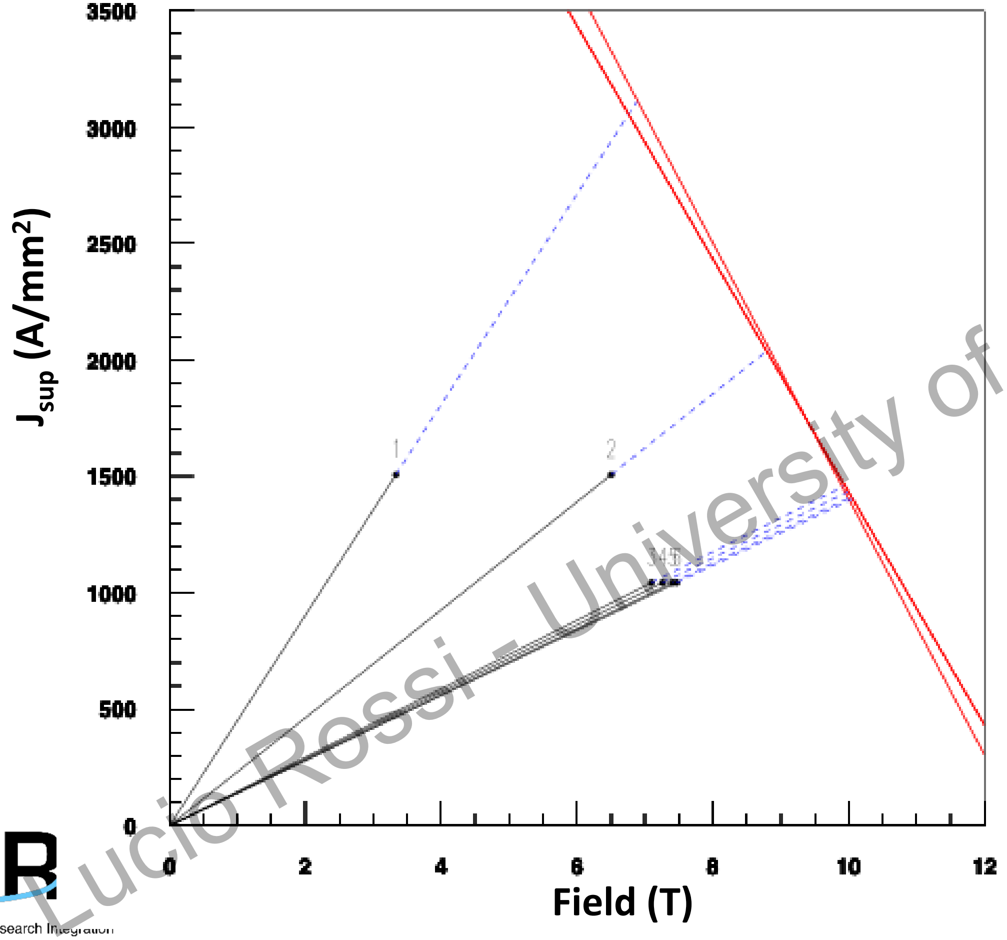
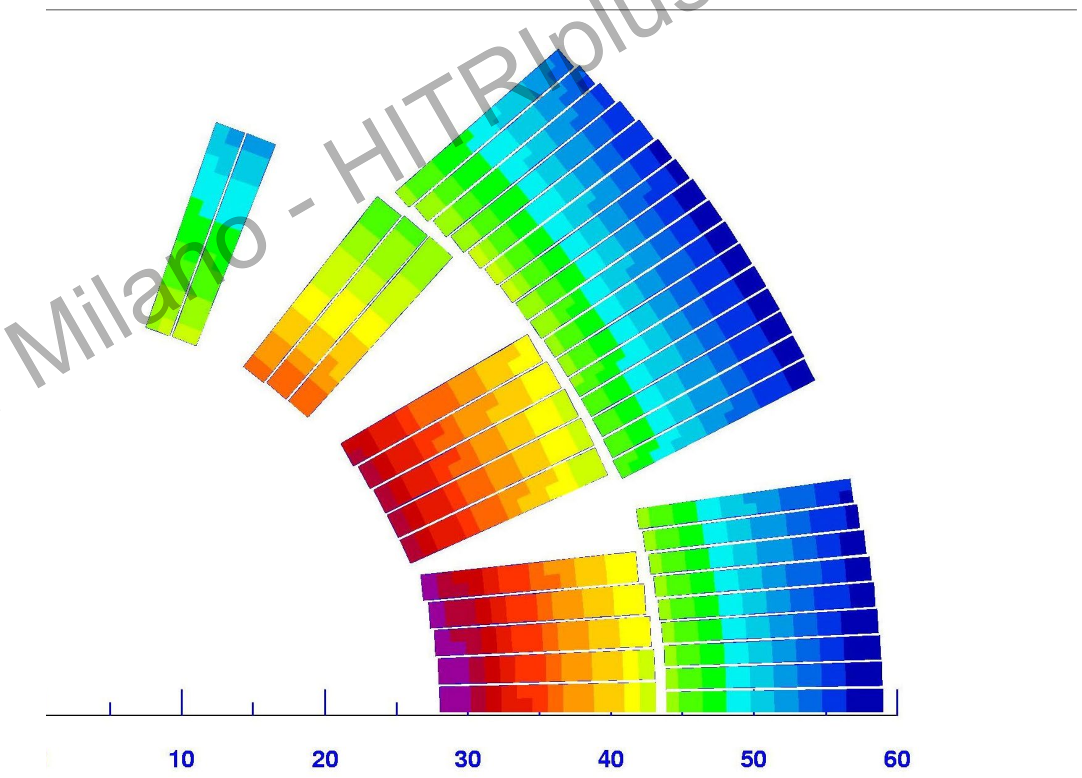
The basic relation: B vs I





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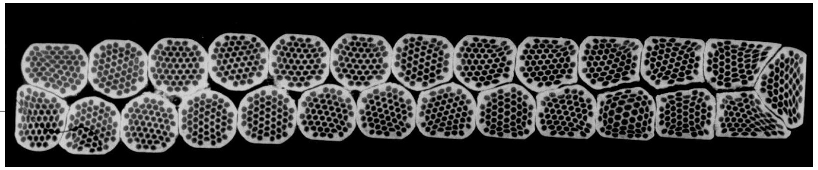
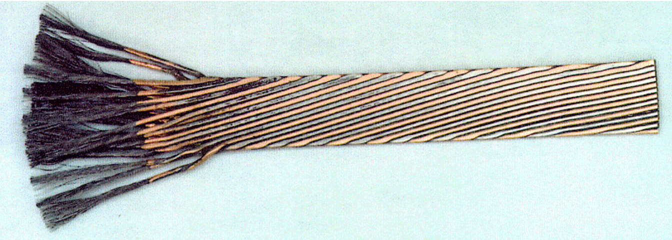
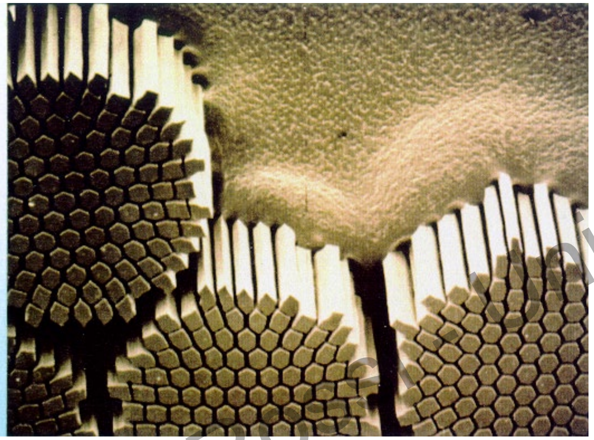
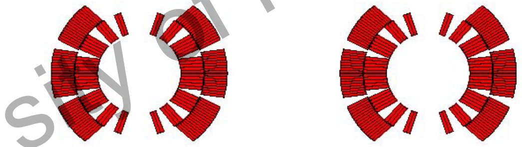
LHC MB X-sect: conductor (Rutherford cable)









Conductor position optimization:

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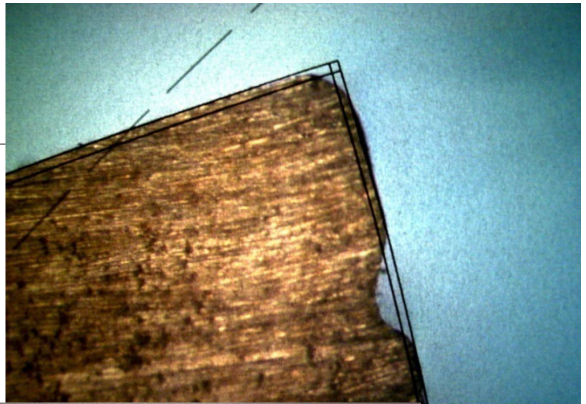
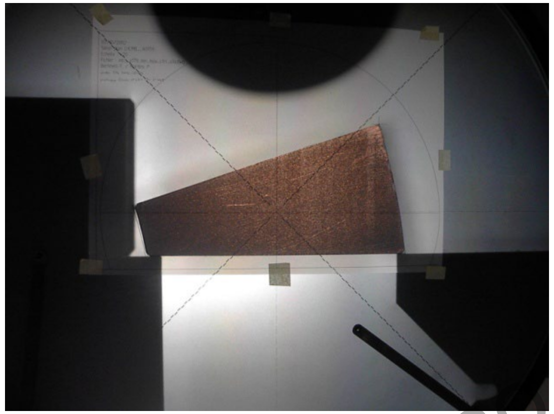
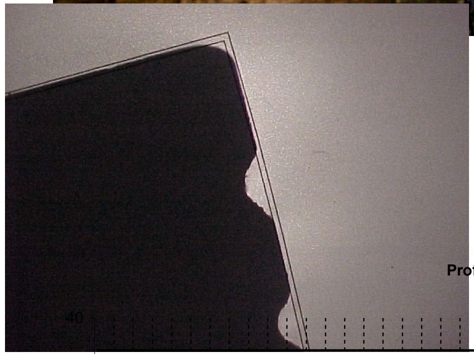
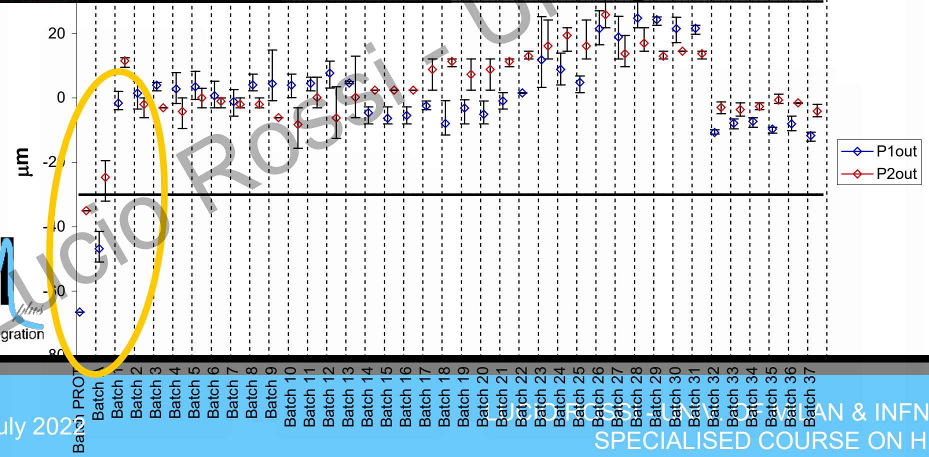
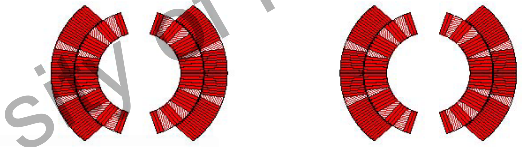
LHC MB X-sect: copper wedges











Cu Spacer

Precise at ±20 µm

Used to steer production

Change of Cu wedge 0.2-0.5 mm of inner wedges in July 2001 (3 CM, 15 CC).

Effect in 2002.

~35 CM old Xsect.

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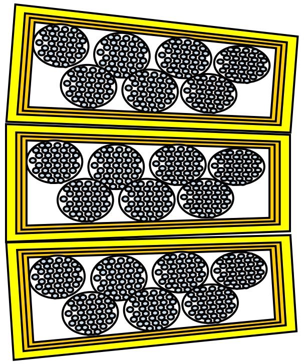
LHC MB X-sect: conductor and ground Insulation, Interlayer

Rutherford Cables Insulation

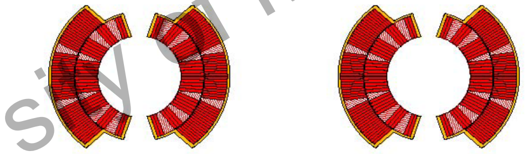


-2 layers of Apical 200 AV insulation

-1 layer Pixeo to glue cables together at 185°C (-0,+5 critical)

Ground isolation

Four layers 125AH



Polyimmide insulation

Around cable and around coils

Important elements are dimensions, ±3% of thickness, and creep (Apical creeps less than kapton)

Inter layer

To allow HEII to flow

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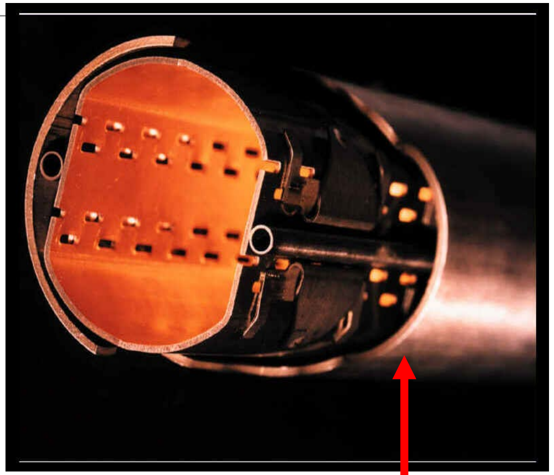
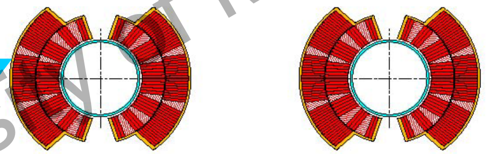
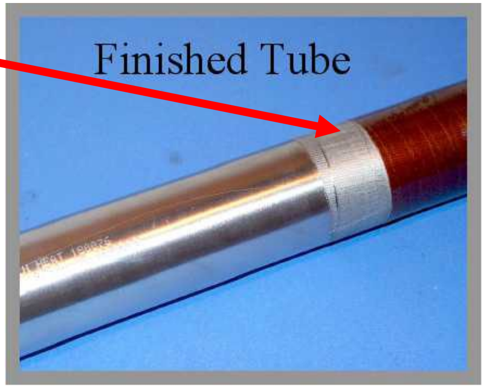
LHC MB X-sect: insulated CBT





CBT



Cold bore tube

StSt tubes

Insulation done at CERN
Special Insulation technique > 20 kV

Clearance between coils and insulated CBT is about 0.5 mm over the 15 m length

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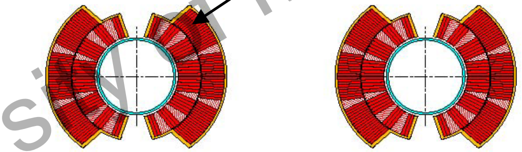
LHC MB X-sect: Quench Heater



Strips of stainless steels partially coated with copper to adjust resistance

Encapsulated like a sandwich in two foils of 75 μm of polyimide

Fired by current pulse, heat must diffuse from strip to coils in 20-50 ms !!

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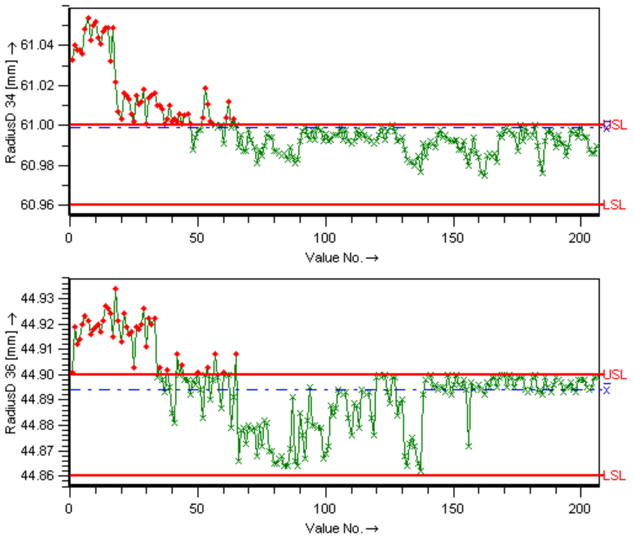
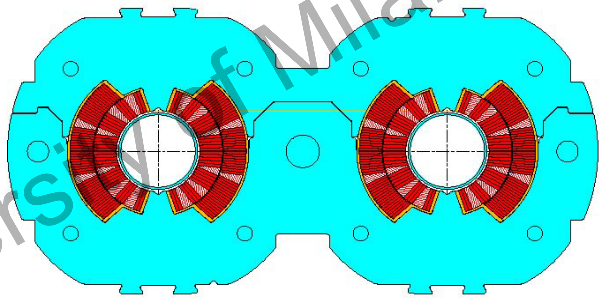
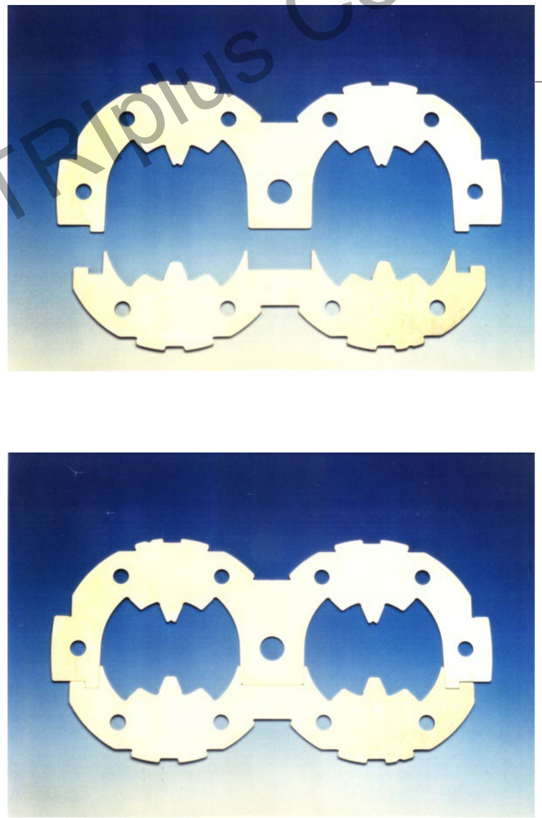
LHC MB X-sect: Collars







Collars and collaring are the main controllers of the final coil shape

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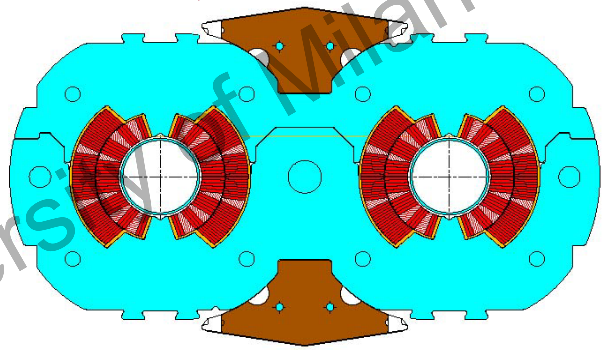
nd innovation programme under grant agreement No 101008548

LHC MB X-sect: magnetic insert

The iron Insert
Punched together with the yoke lamination



Introduced to ease the mechanical assembly

It serves for FQ

By tapering we cured unwanted quadrupole and octupole components

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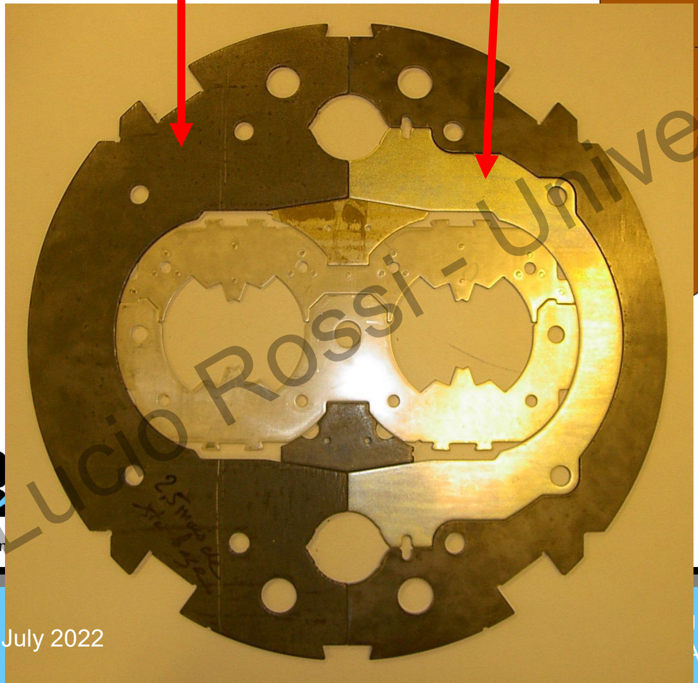
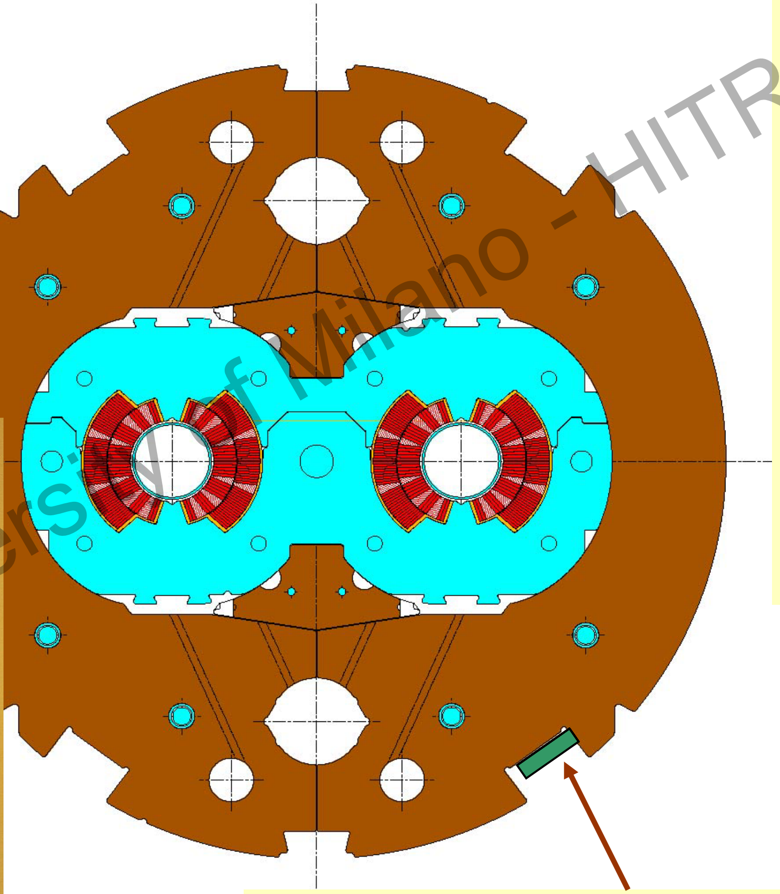
LHC MB X-sect: yoke laminations

One supplier for the steel
45,000 tons

Precise vertical gap

Regular ***Nested***





The iron yoke:

Stray field

15% field increase (but big gain in protection)

If saturates affect FQ (sextupole)

Trim of magnetic length

Temperature probe

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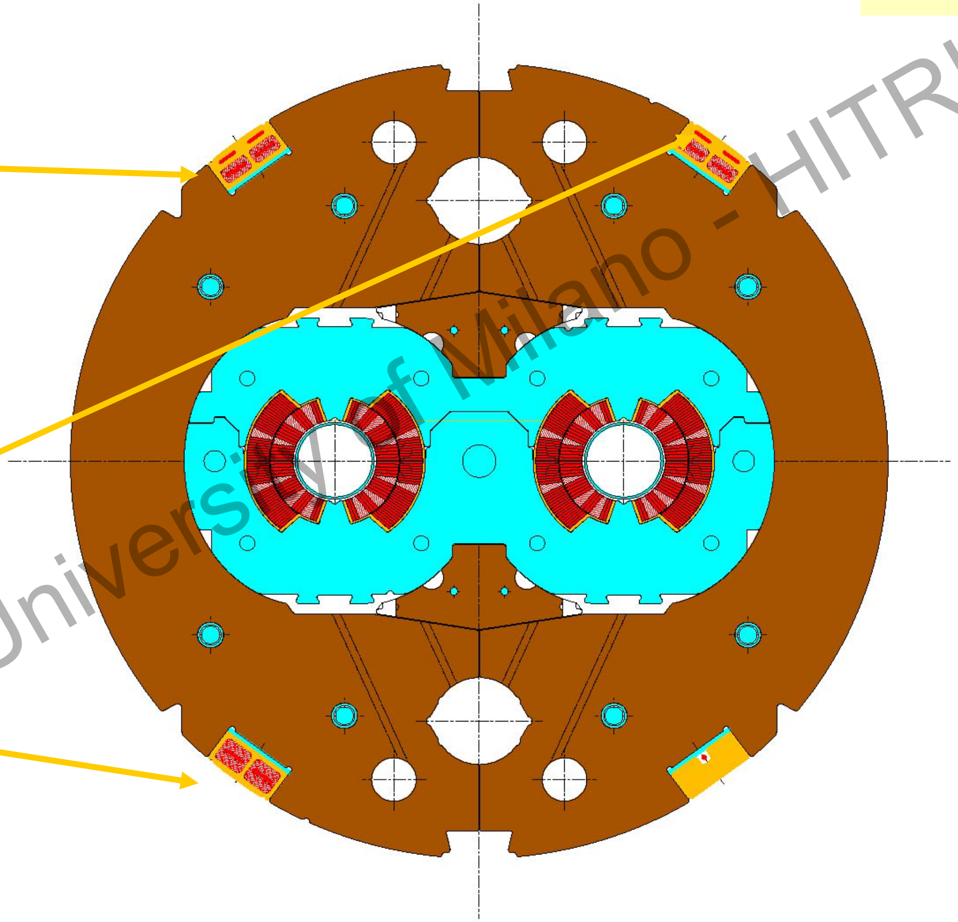
LHC MB X-sect: Bus Bars & fillers

160 km of main BusBars!!



Bus Bars

Quad BB
Focusing

Quad BB
Defocusing

Corrector circuit
bus bars on top
of Quad BB

Dipole circuit BB

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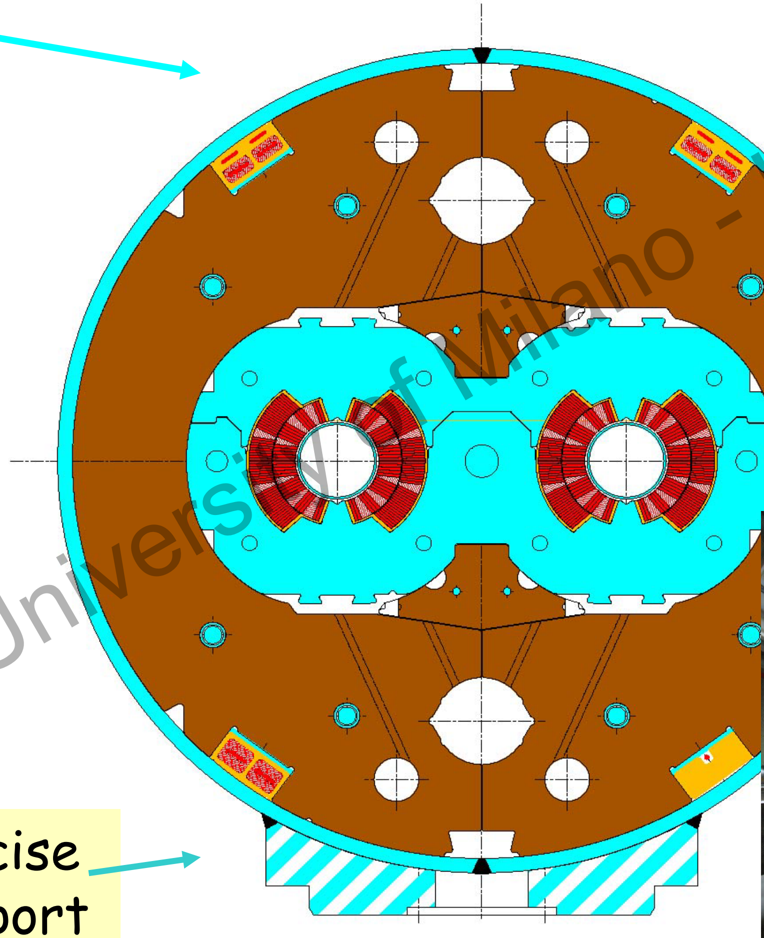
LHC MB X-sect: Shrinking cylinder and support

Two half shells, welded on the magnet

Many difficulties



Curvature released from ± 1 to ± 2.5 mm: still not OK.

To c ure this we went to sorting

Precise support

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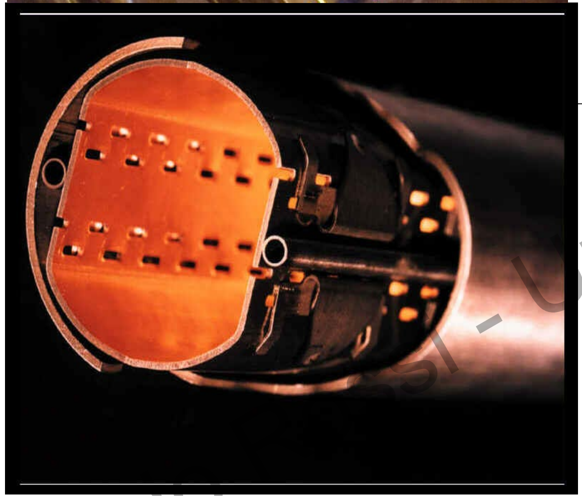
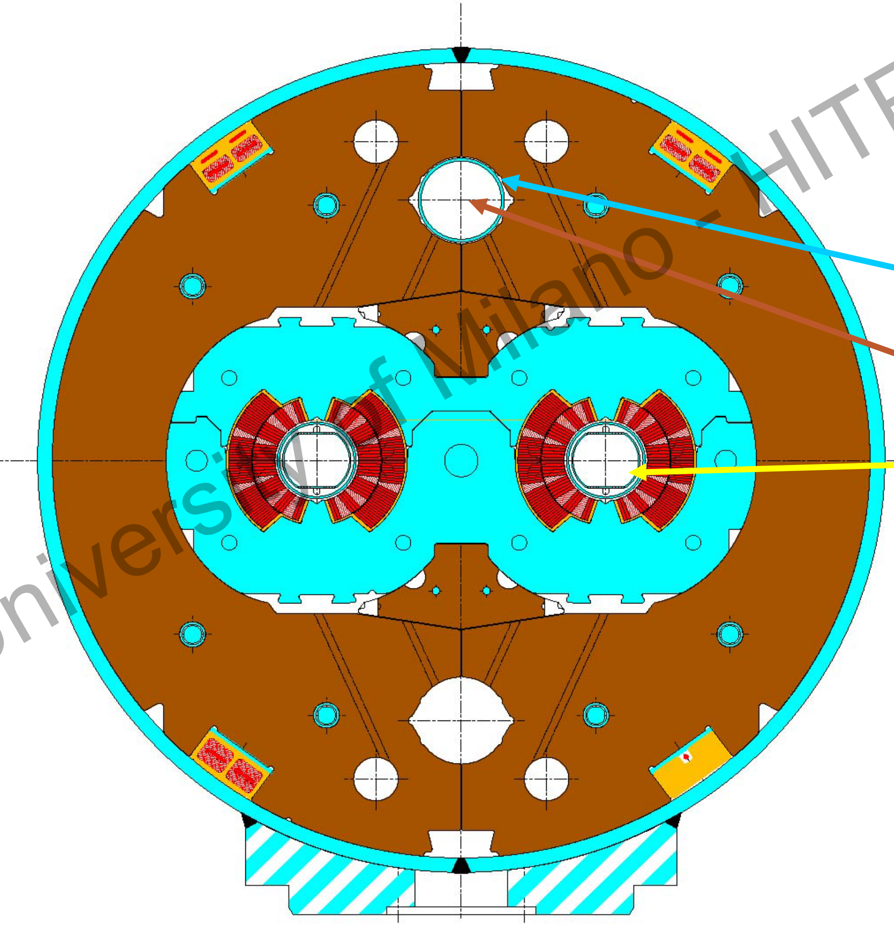
pean Union's Horizon 2020
t agreement No 101008548

LHC MB X-sect: beam screen and HXT





Copper Heat Exchange Tubes

HEII satur.

Beam Screen

Inserted at CERN just before insertion in the tunnel

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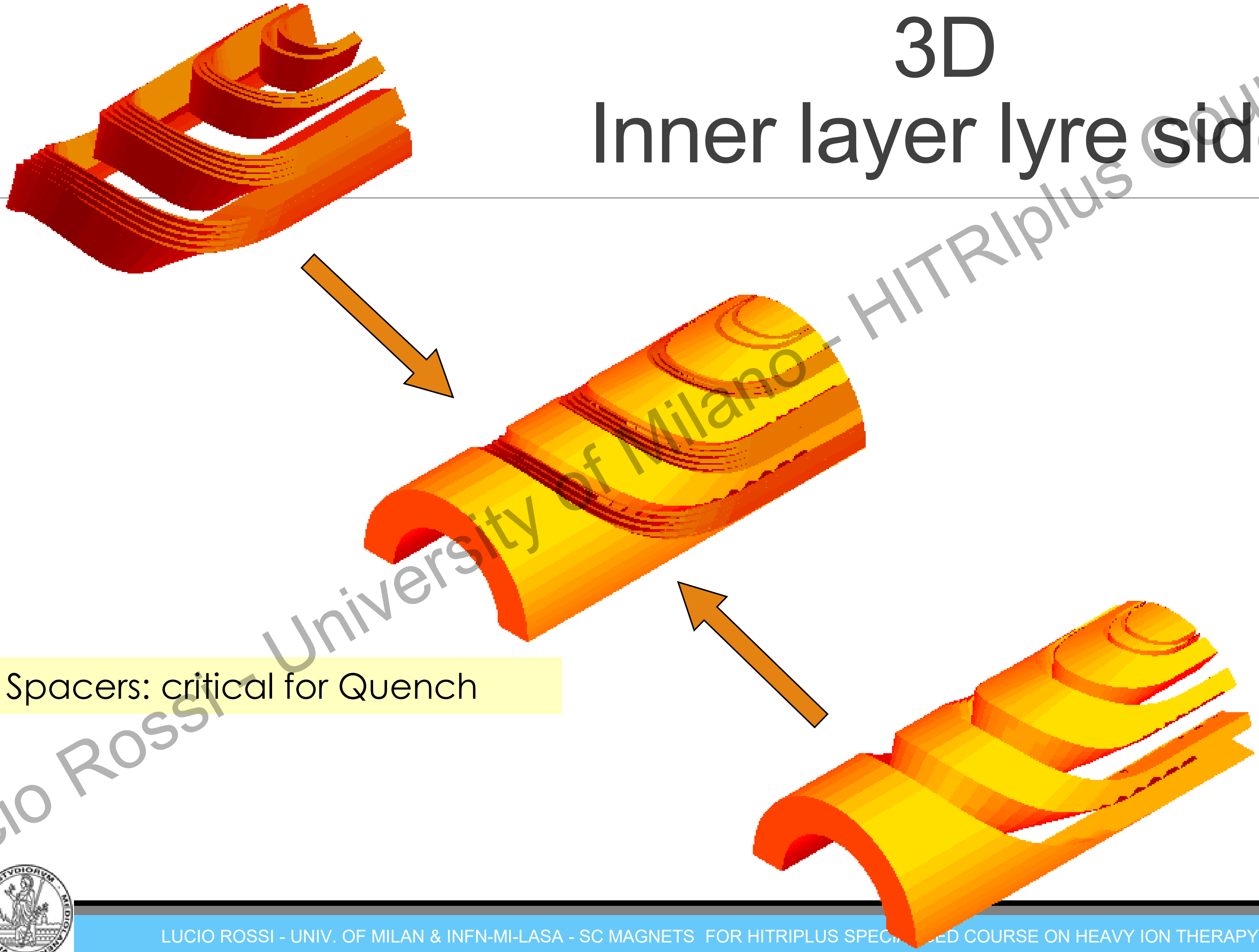
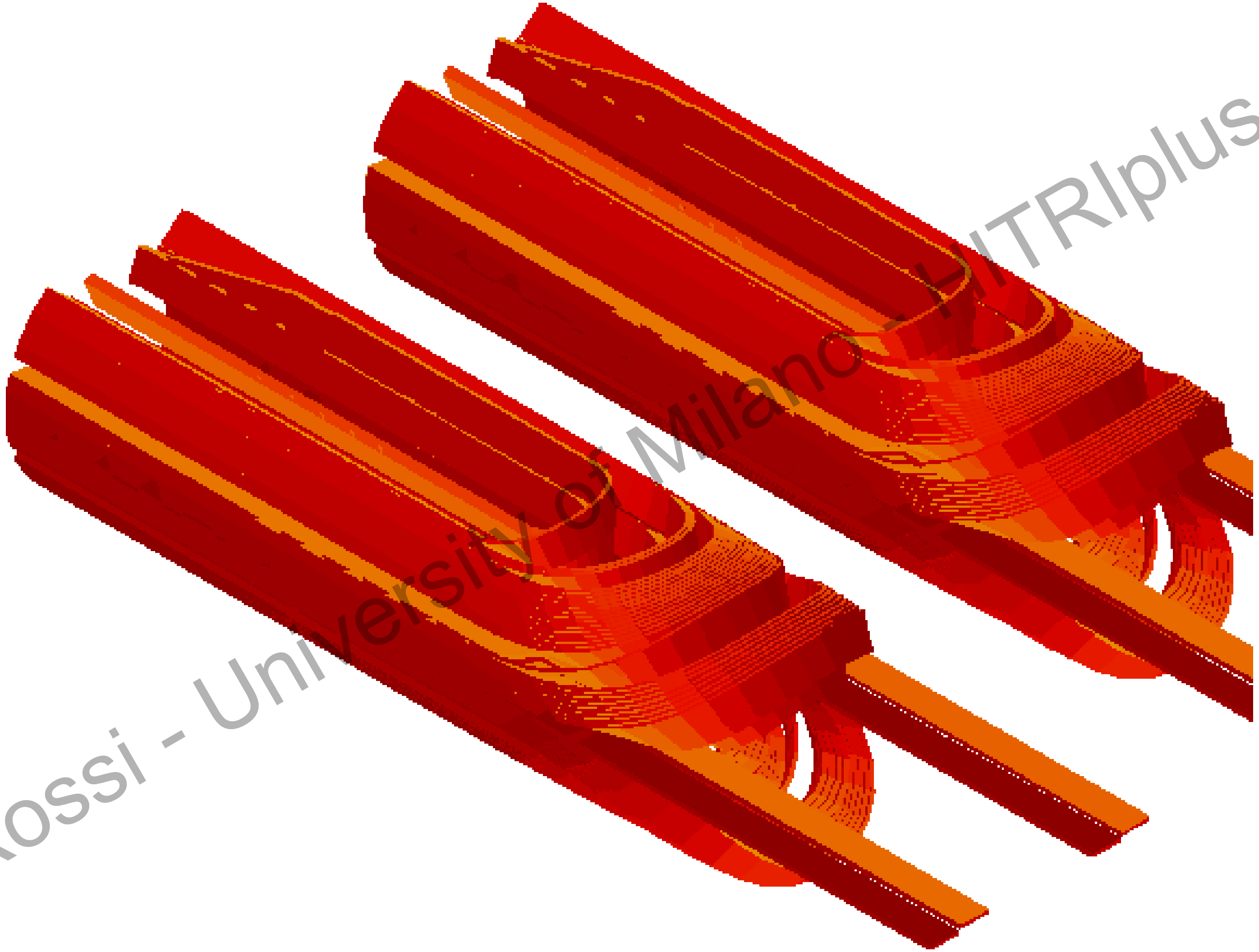
3D
Inner layer lyre side

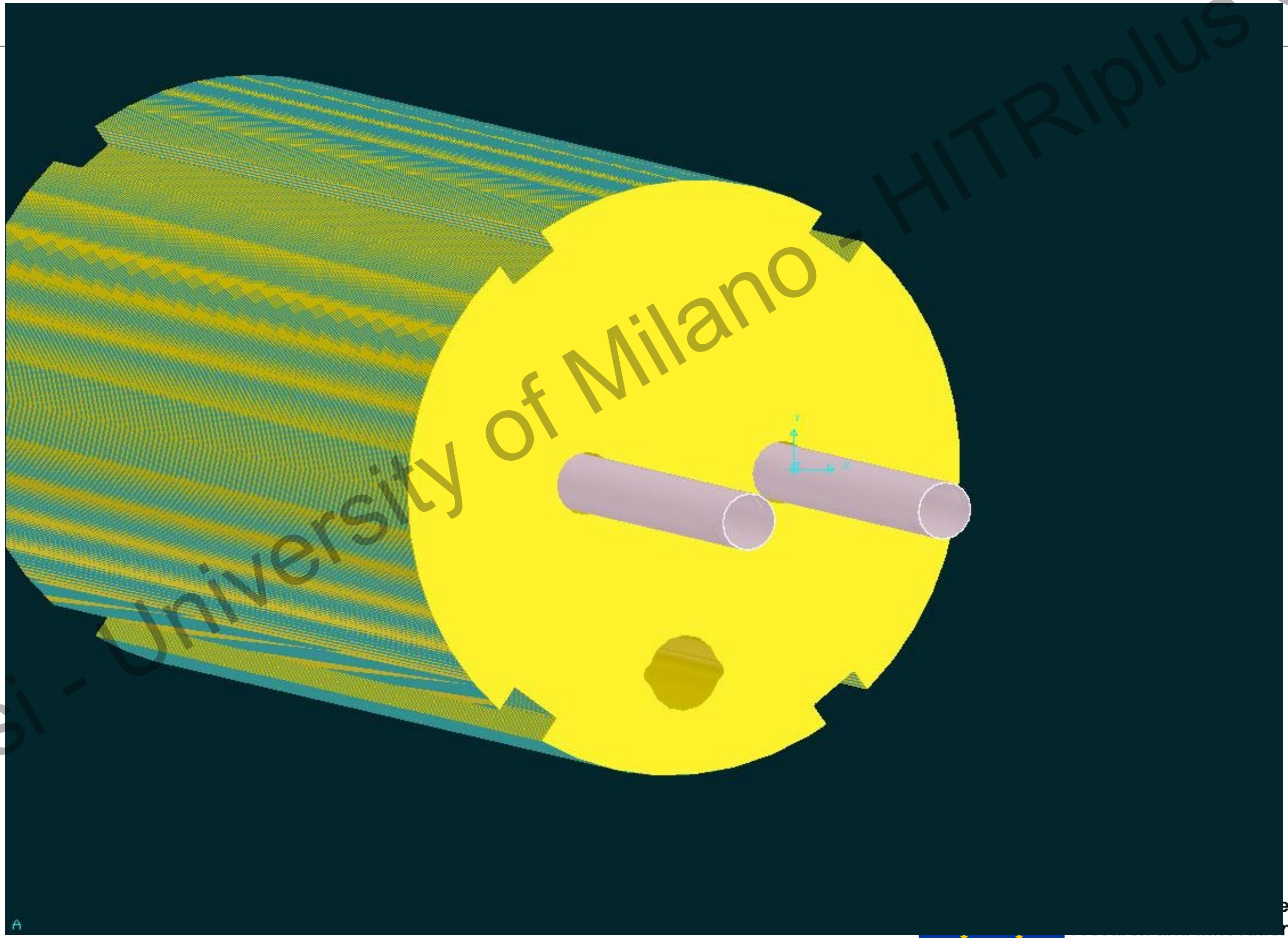


End Spacers: critical for Quench

3D
Connection side



LHC MB - end part
CBTs and Yoke



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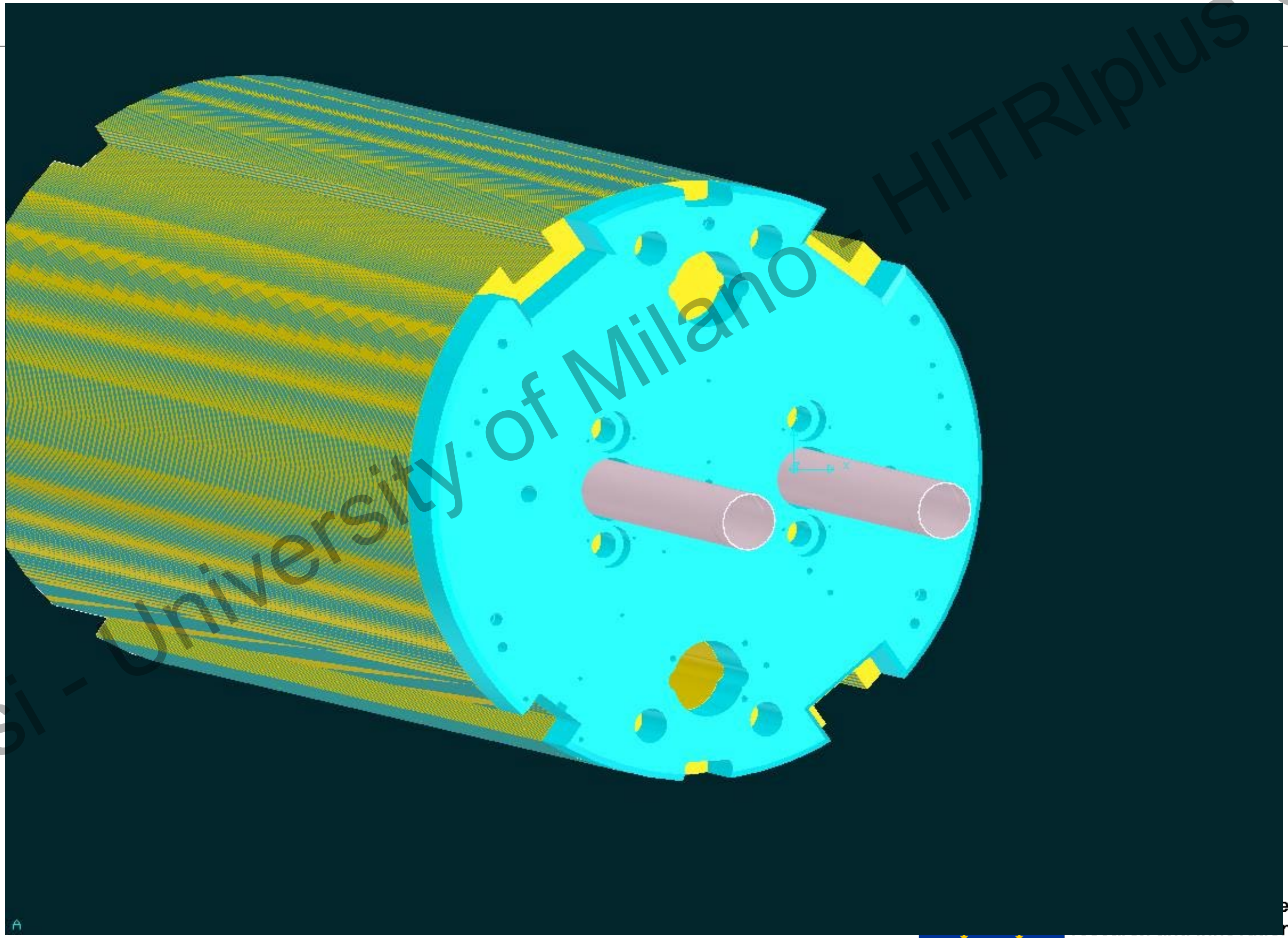
LHC MB -end part
end plate



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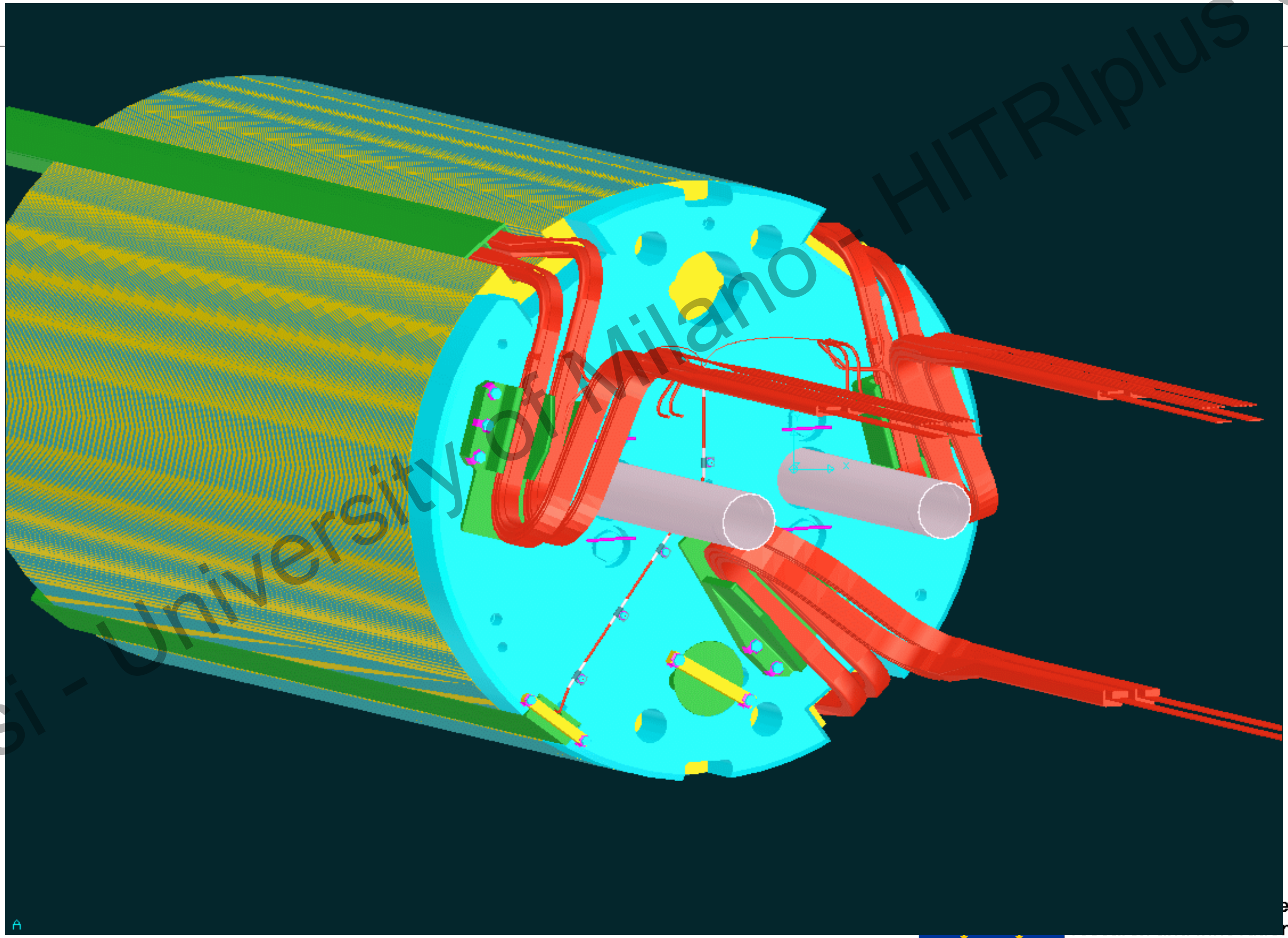
LHC MB-end part
Bus Bars postioning



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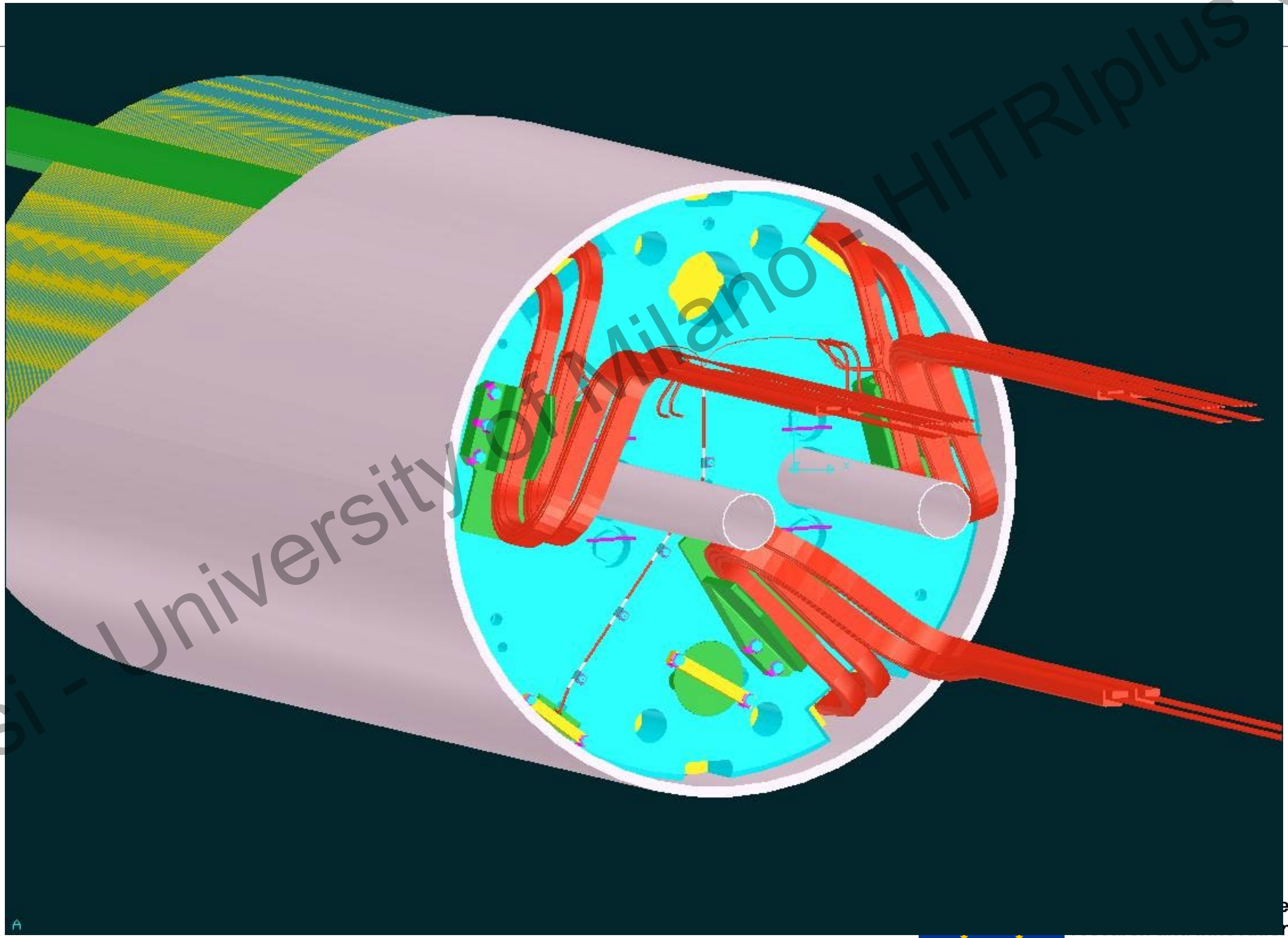
LHC MB -end part
Shrinking cyilinder



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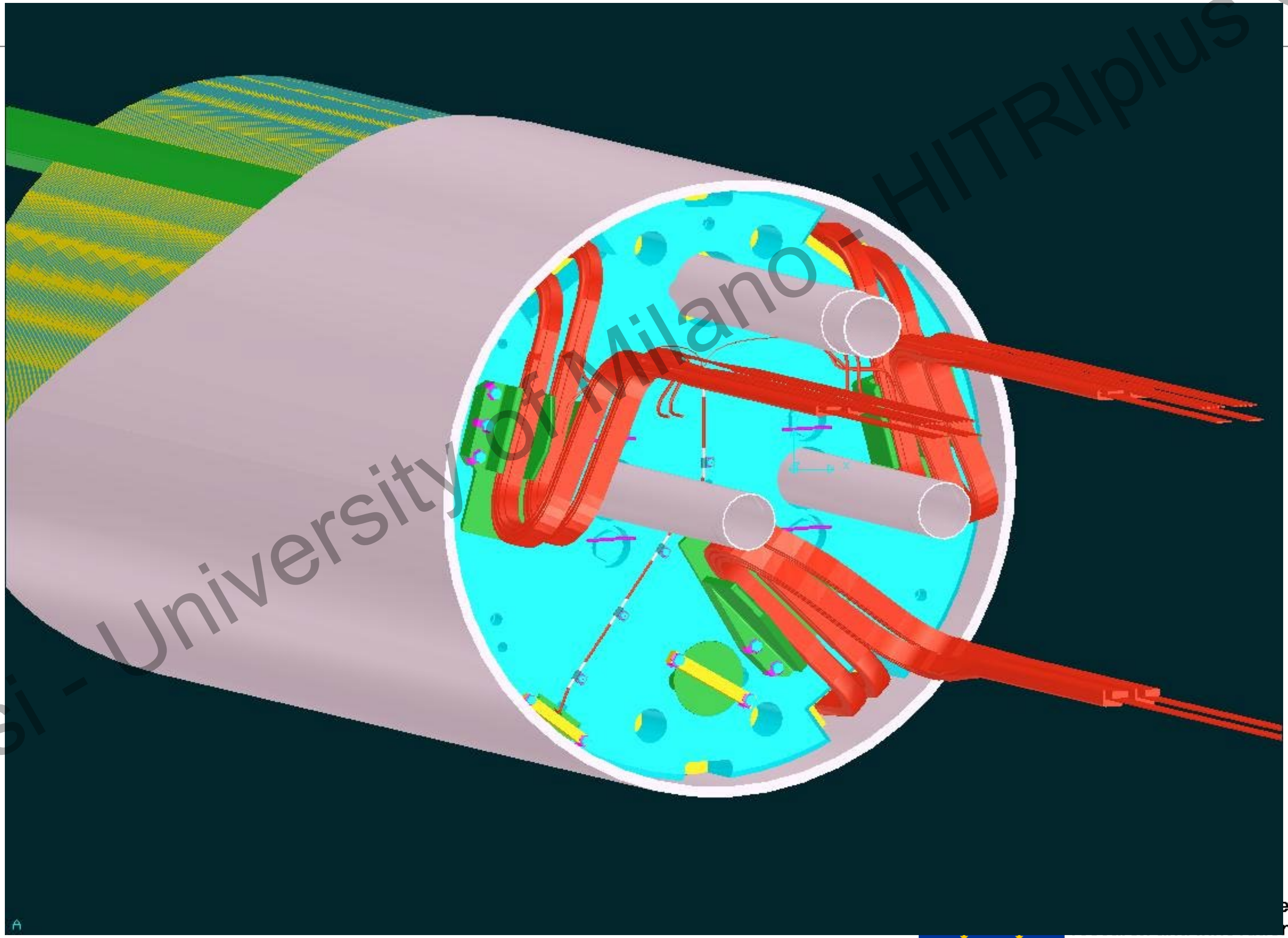
LHC Main Dipole -end part
Cu HXT



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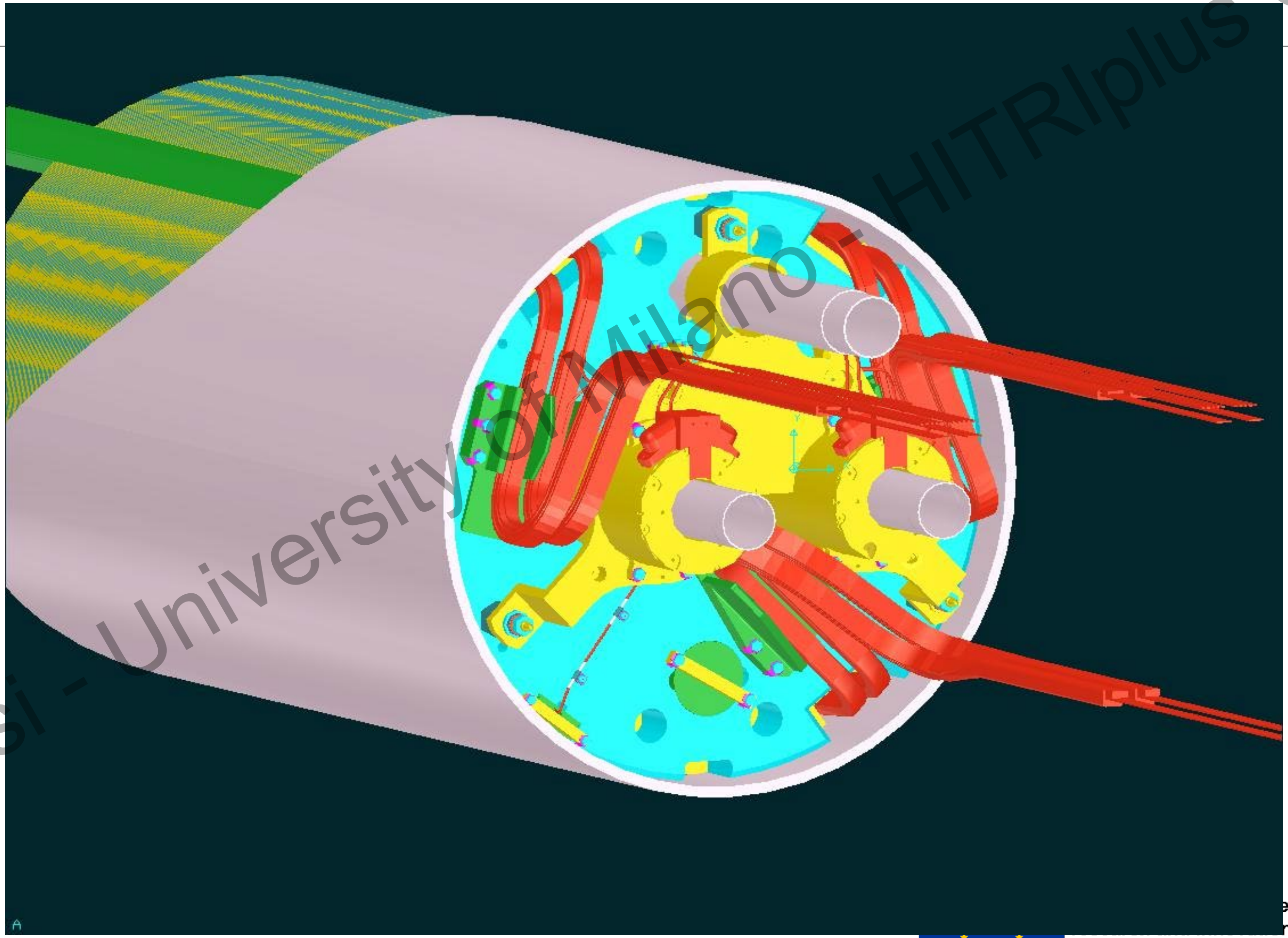
LHC Main Dipole -end part
Corrector Magnets (spool pieces)

Assembly in CMAs is purely mechanical

(tolerances of B axis wrt mech. frame given by supplier



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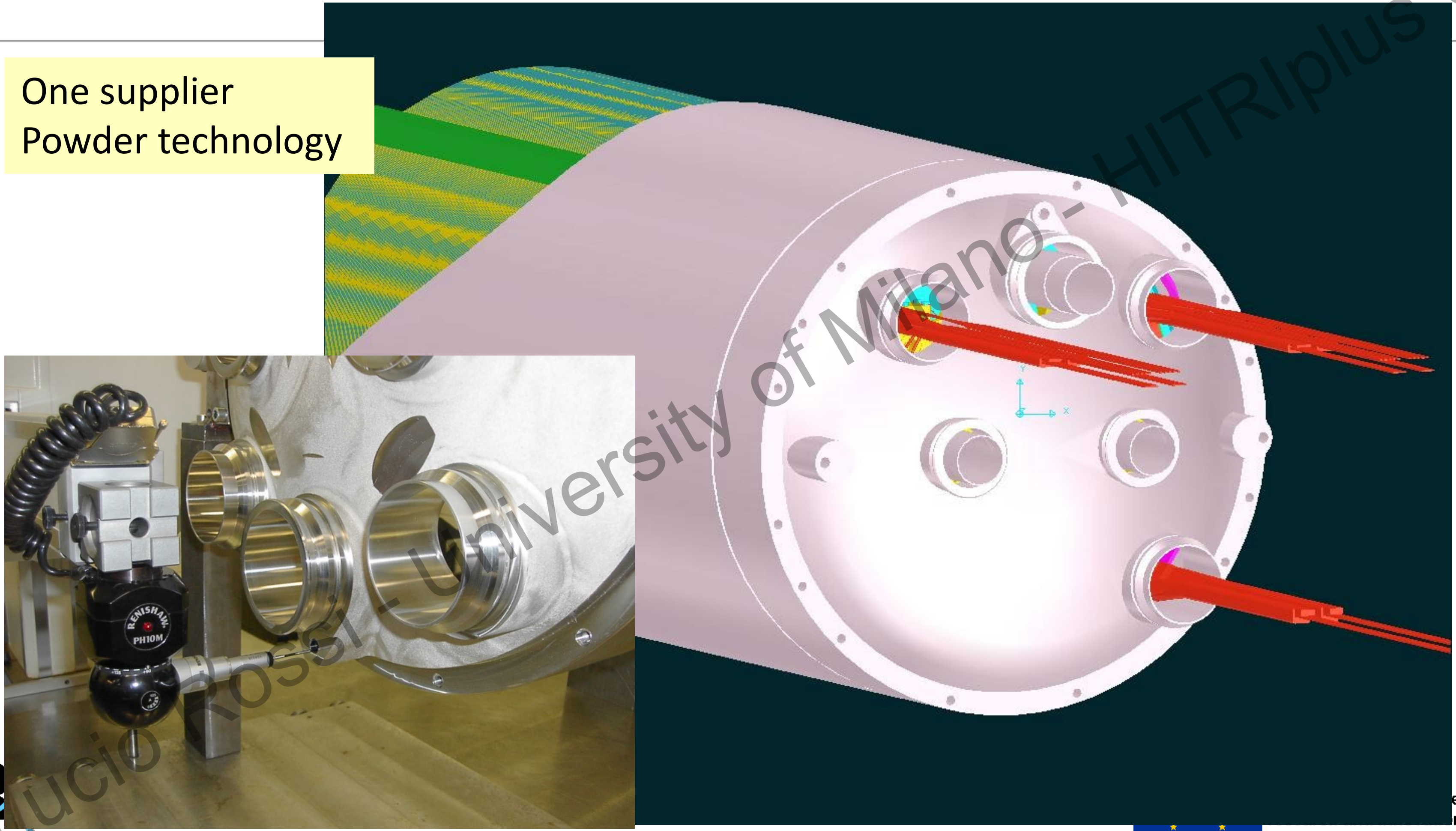
LHC Main Dipole -end part
End covers

One supplier
Powder technology



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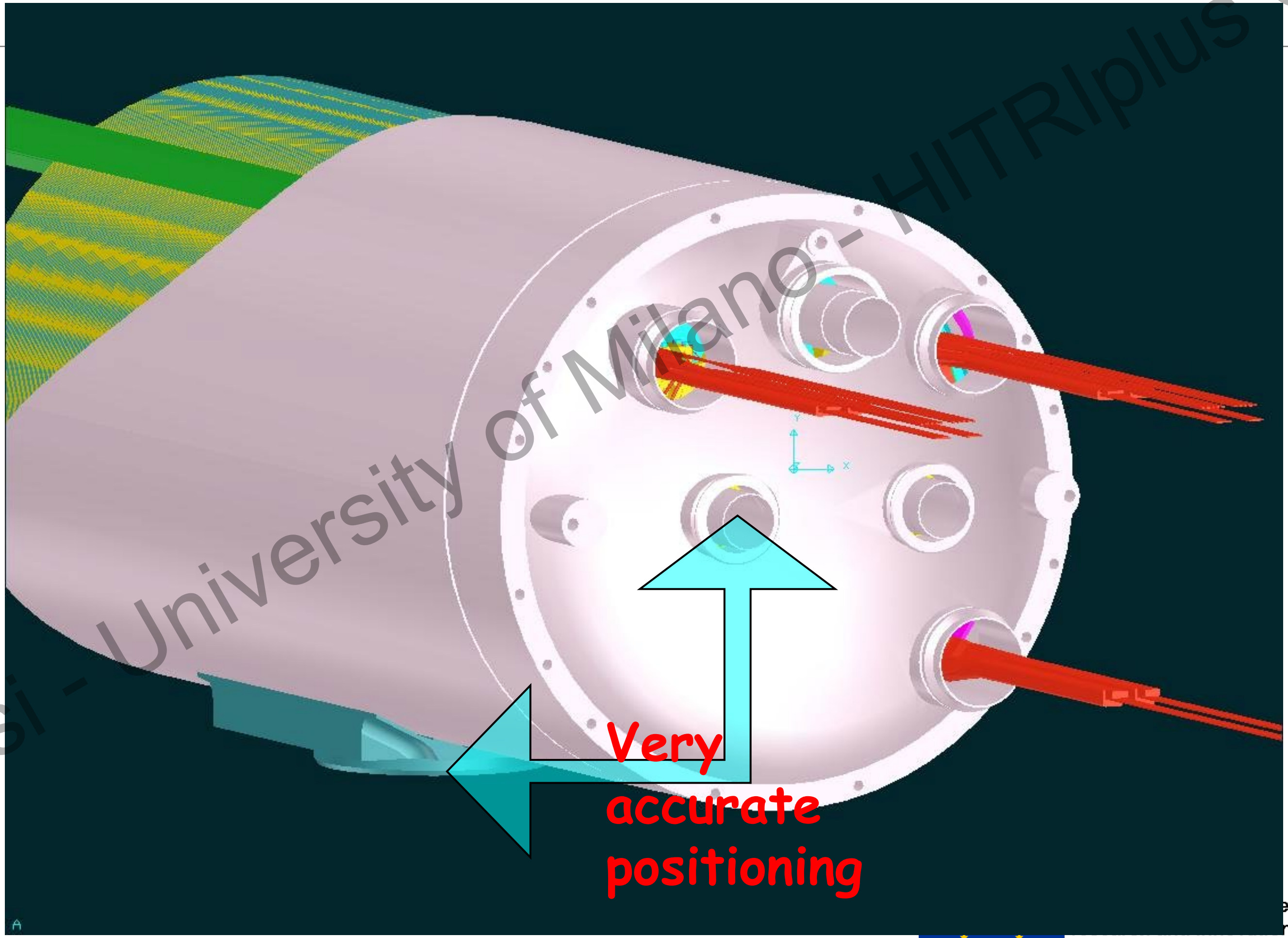
LHC Main Dipole -end part « Cold foot »



Very accurate positioning

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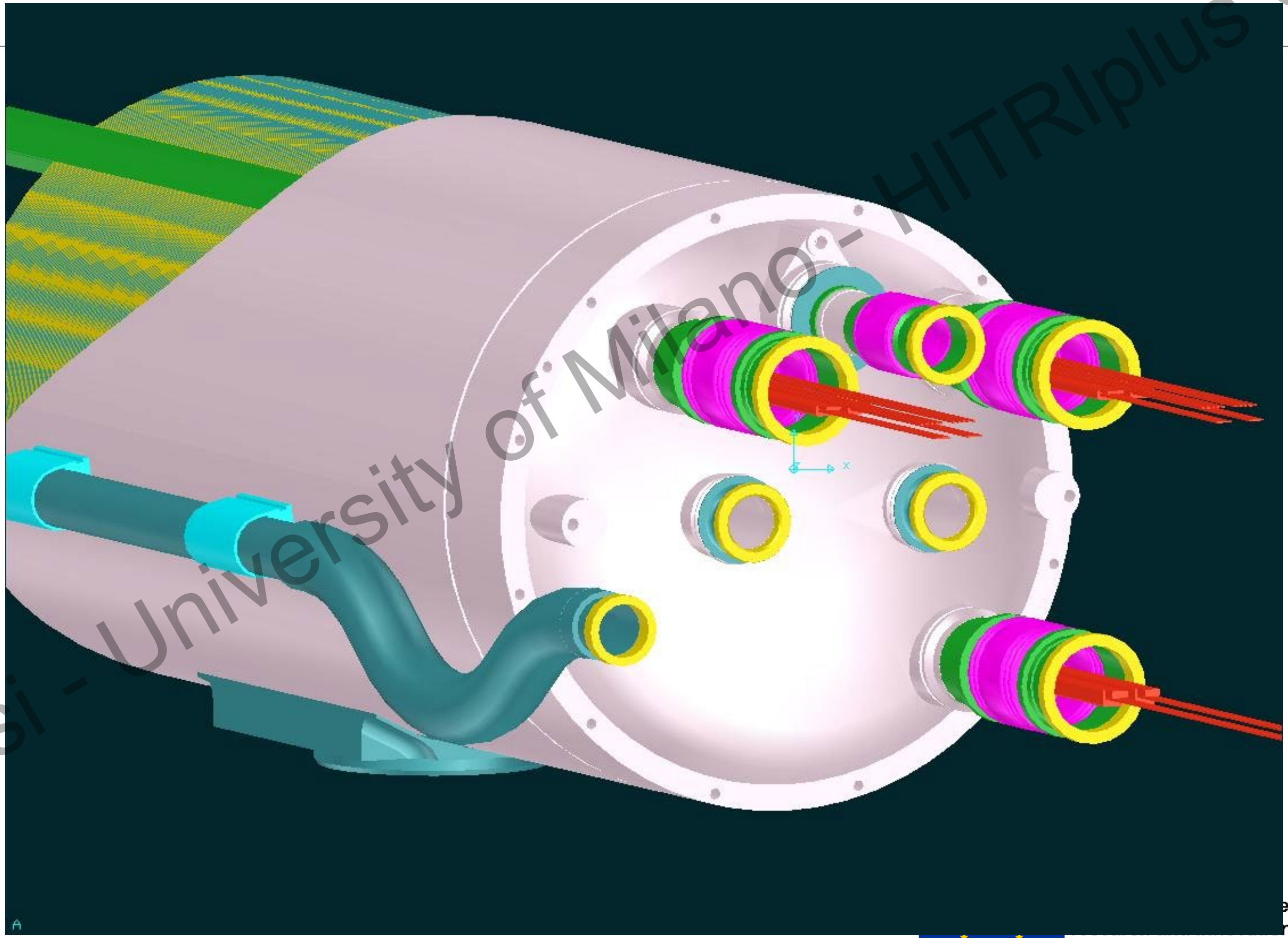
LHC Main Dipole -end part
Bellows and N-line



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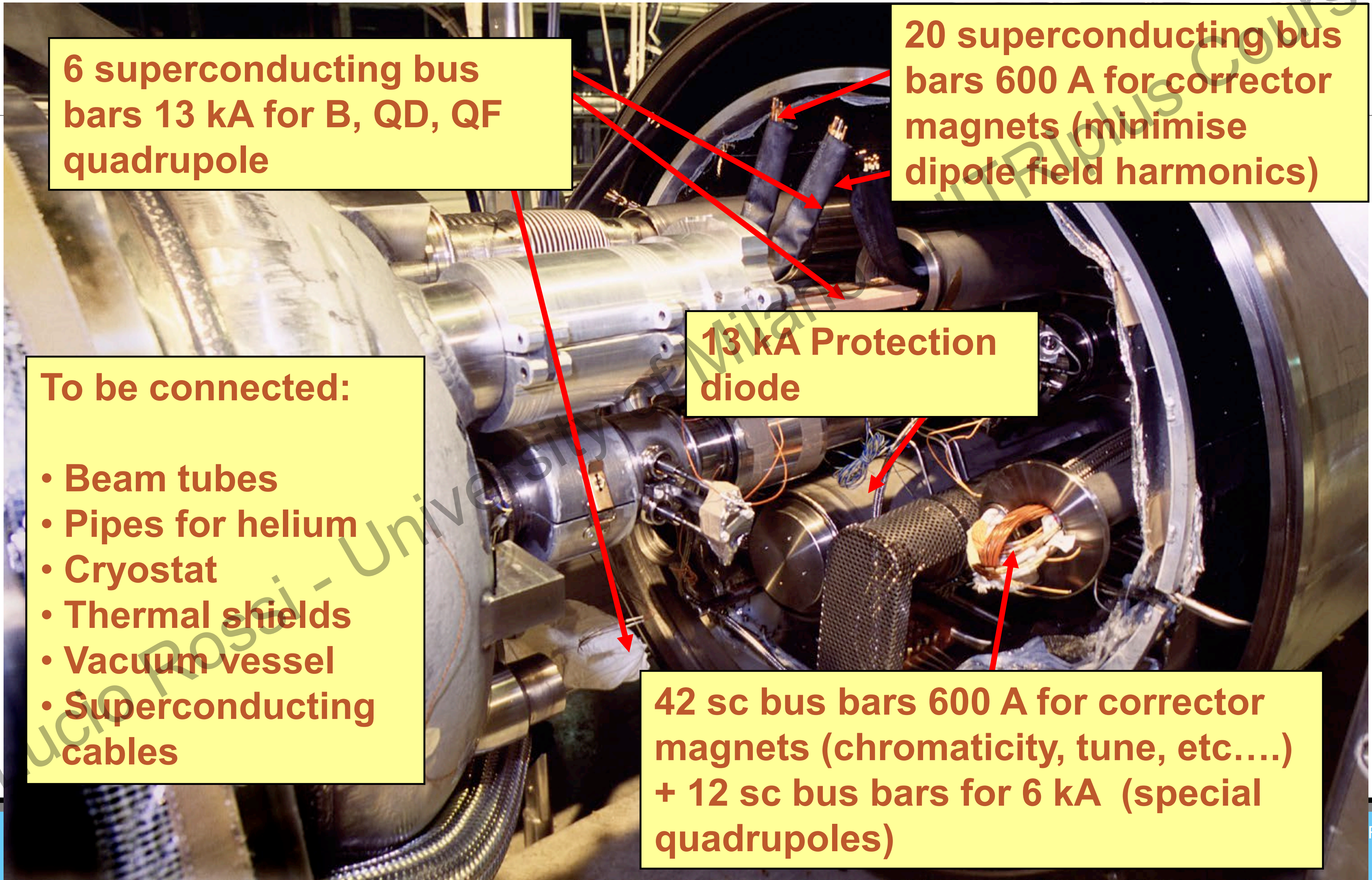
Interconnection between SC LHC dipoles



6 superconducting bus bars 13 kA for B, QD, QF quadrupole

20 superconducting bus bars 600 A for corrector magnets (minimise dipole field harmonics)

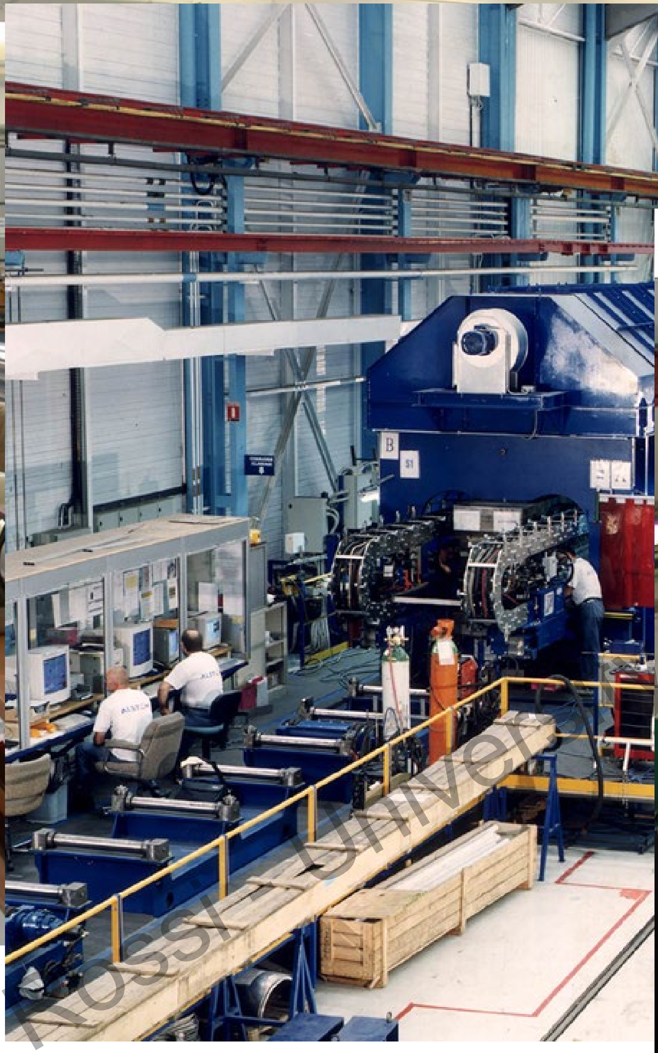
13 kA Protection diode

To be connected:

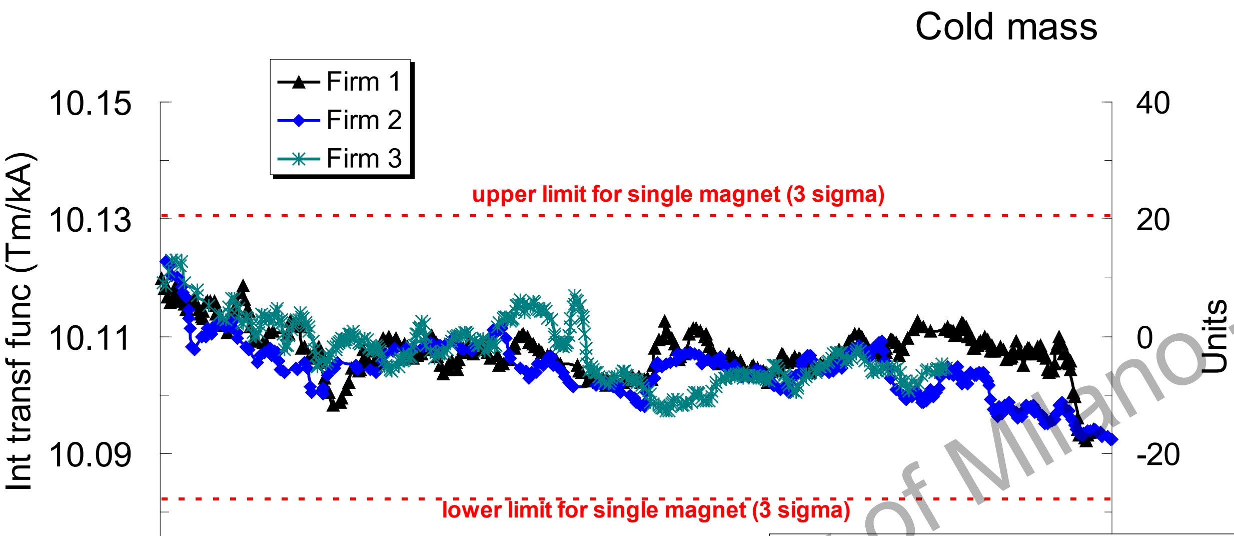
- Beam tubes
- Pipes for helium
- Cryostat
- Thermal shields
- Vacuum vessel
- Superconducting cables

42 sc bus bars 600 A for corrector magnets (chromaticity, tune, etc….) + 12 sc bus bars for 6 kA (special quadrupoles)

there is a series…



Steering production (and check assembly) Field Measurements - CERN supply

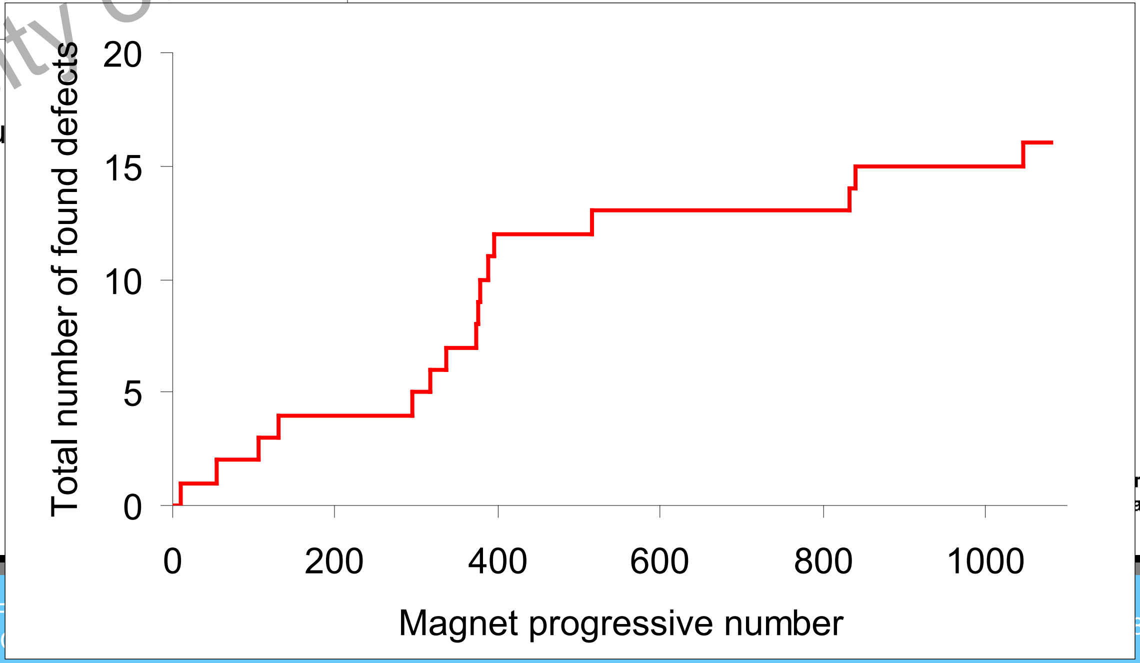


Introduced first to steer the FQ toward beam dynamics targets.

Note the uniformity among different manufacturers

It has also helped to detect a number of defects.

It has also been used to detect subtle electrical shorts



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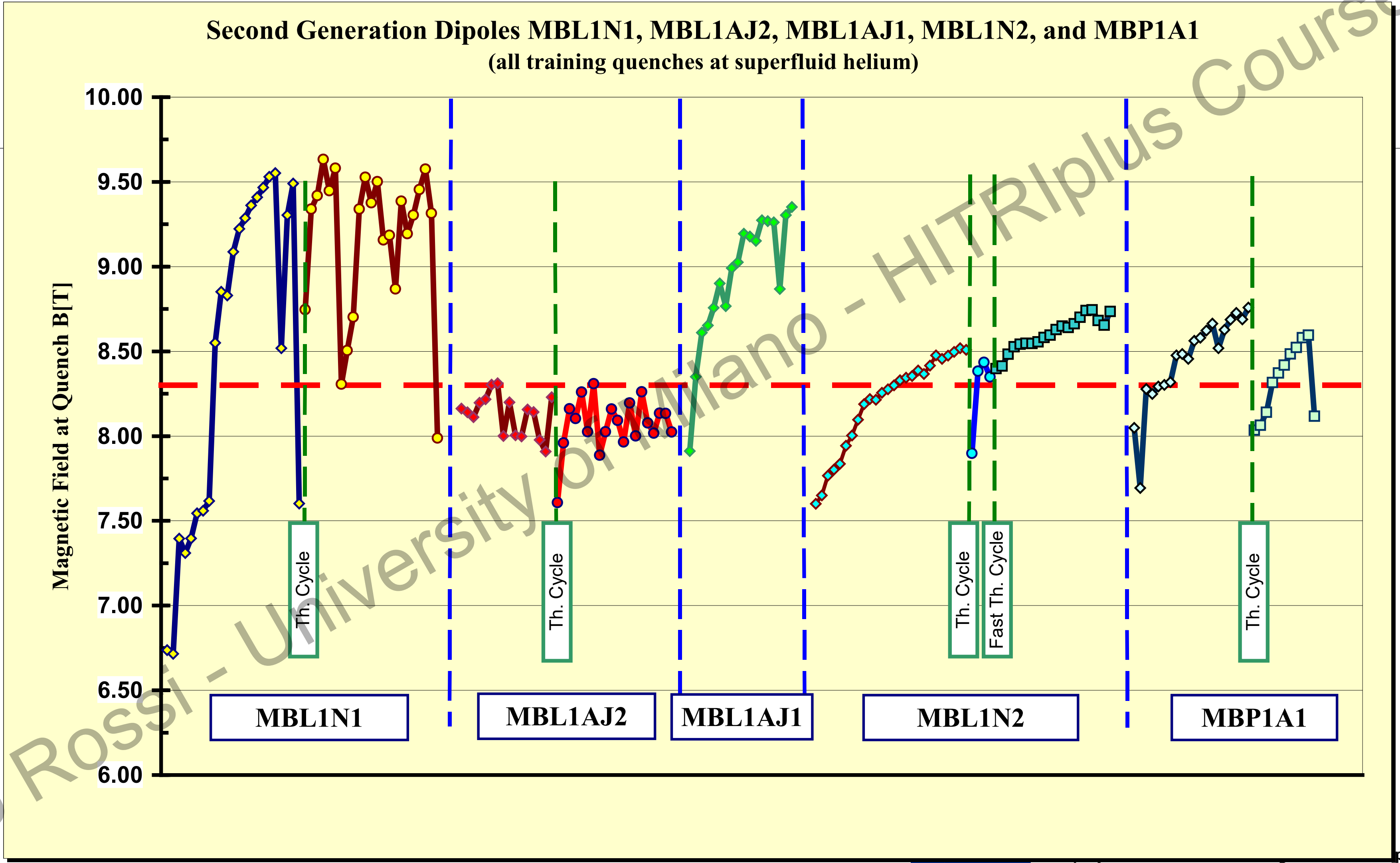
ant agreement No 101008548

Cold test at 4.2 K or 1.9 K: training curve…



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Why SC Magnets quench?
Tiny energy release (distubances) suffice to lose SC status

Time	**Space**	
	Point	Distributed
Transient	Energy (J)	Energy/Vol. (J/m^3)
Continuous	Power (W)	Power/Vol.(W/m^3)

Continuous Distributed Perturbances:

- AC losses (hysteretic and coupling losses, eddy currents)
- Intrinsic dissipation due to smooth transition (I_{op} too near or above I_c!)
- Thermal load (vacuum degradation,…). This could be a serious effect in cryocooled system.

These perturbations are usually predictable and estimate must be done at design level

🔔 coupling losses can depends on interstrand resistance, i.e. on manufacture technique and on prestress and e.m. forces $\Rightarrow$ more difficult to evaluate

Continuous Point Perturbances:

- Joints inside coils
- Release of mechanical energy (hysteresis of the stress-strain relation)
- Localised heat input (suspension rods with bad thermal anchoring)

These effects are well understood and predictable (it does not mean easy to cure !)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

The big enemy: The transient perturbances

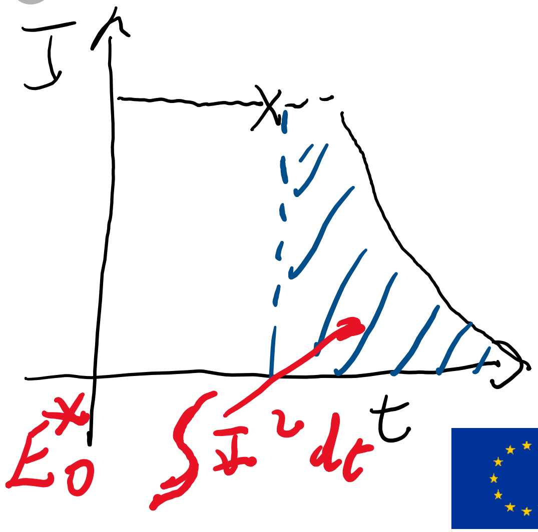
Transient Distributed/Point Perturbances

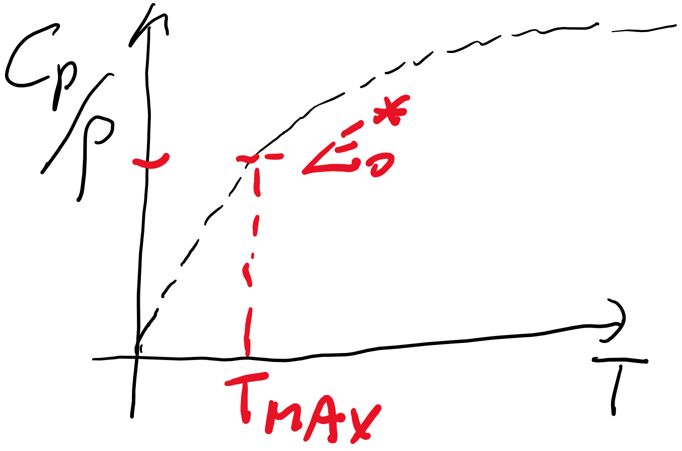
- Flux jumps. This effect is cured almost definitely for NbTi. Effects could be seen on NbSn with very high current density and very large effective filament diameter. This effect can be detected at low field, during current ramp.
- Mechanical origin: movements, friction, sudden release of elastic energy…
- crack in the resin

Basically these last two mechanism are now understood, in principle, and acoustic emission experiments did prove it almost visually.

Still they are less predictable and more difficult to avoid. They depend on magnet geometry, material properties, local conditions and on many details. They can depend on magnet history (previous quench, overheating, thermal induced stress, etc.)

$$\int_{T_{op}}^{T_{hot}} \frac{C}{\rho}\, dT = \frac{1}{A_{cu} A_{tot}} \int_{0}^{\infty} I_{op}^{2}\, dt$$





Heavy Ion Therapy Research Integration

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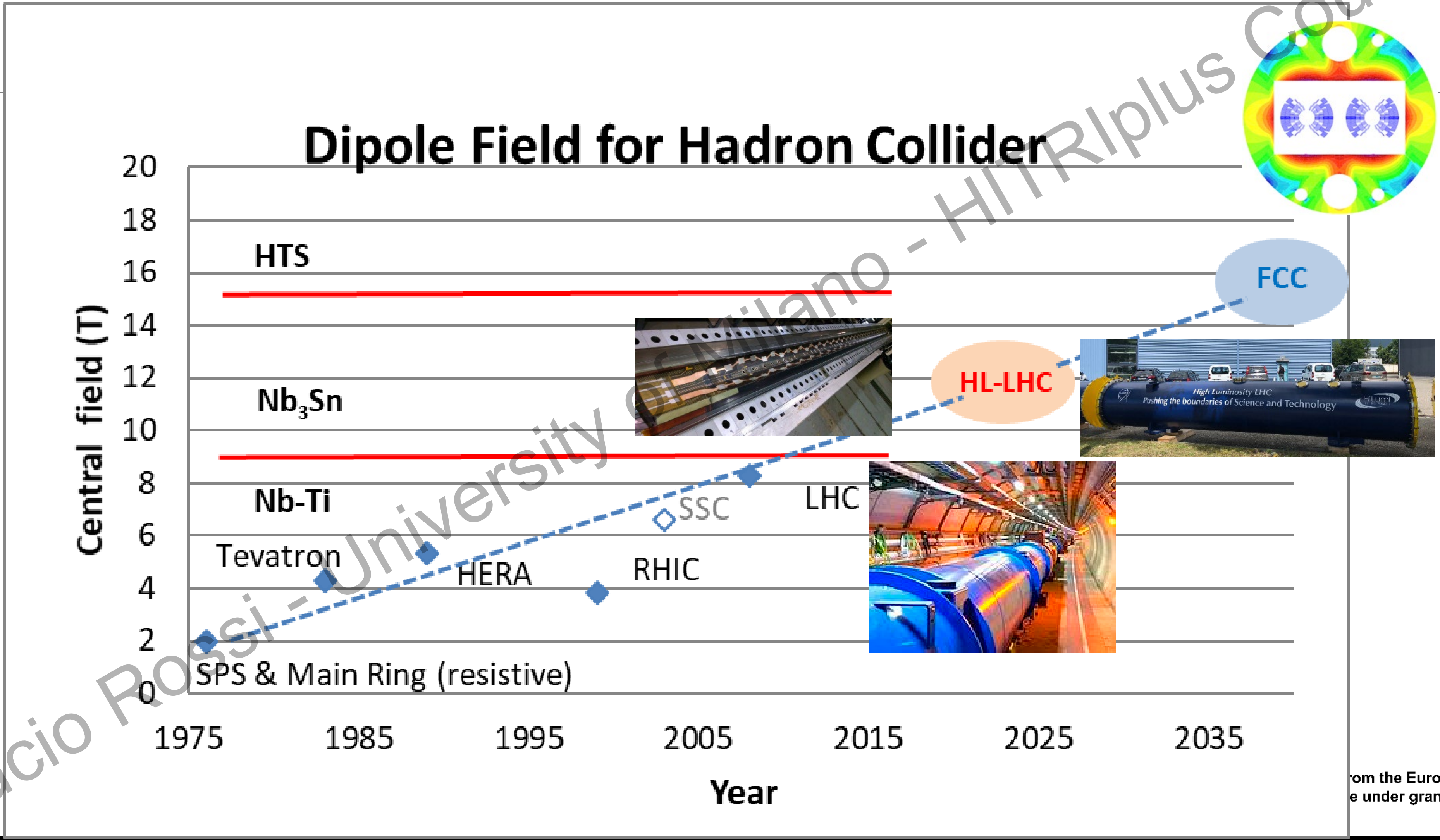
HiLumi LHC:
preparing technology for next big steps



HITRI plus
Heavy Ion Therapy Research Integration

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e under grant agreement No 101008548

Actually the next step started in 2010…The High Luminosity LHC project aims at increase the luminosity by 10 time

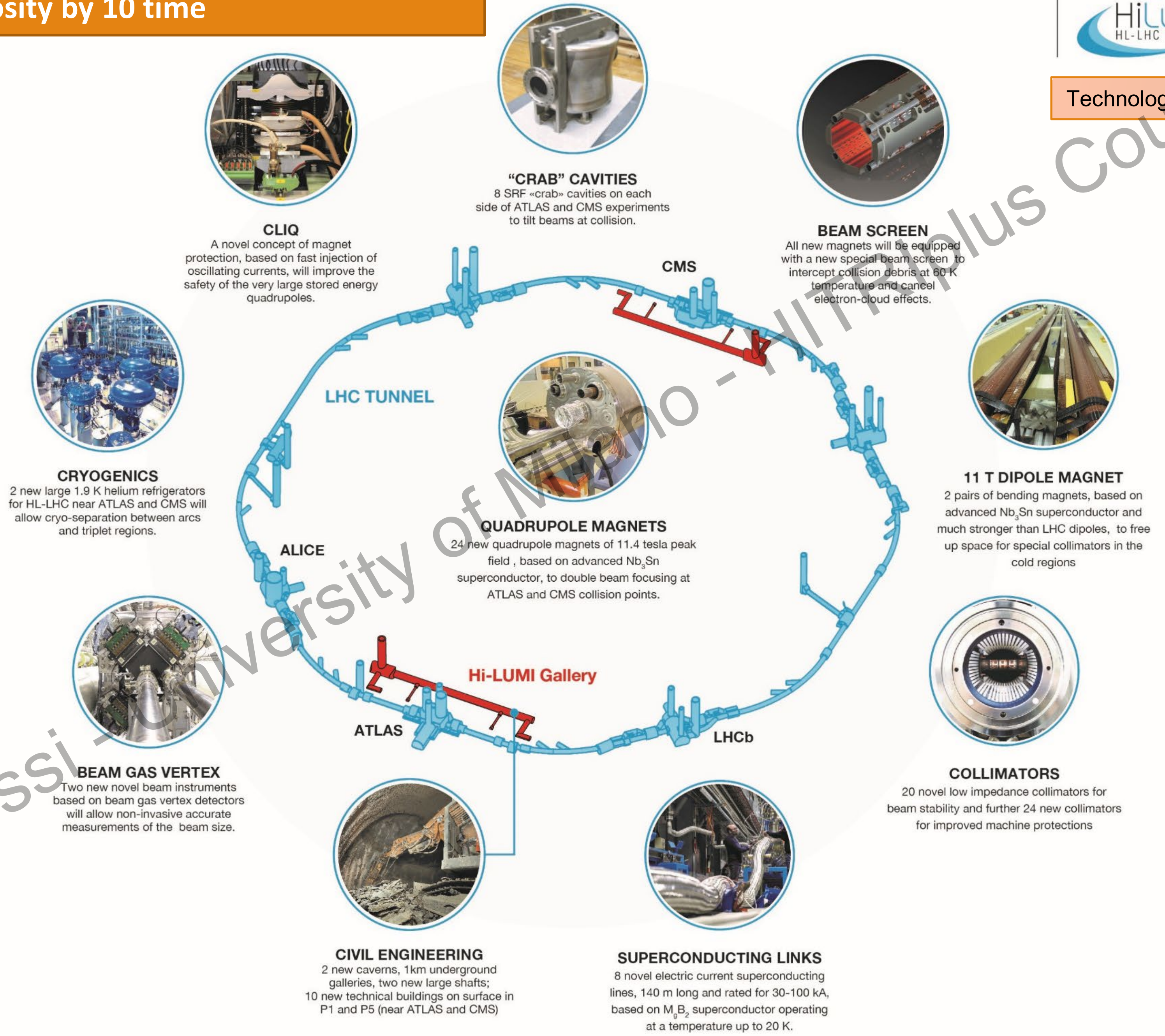
LHC is already highly optimized… an upgrade need a broad spectrum of new technologies, especially (not only) for magnets…

HL-LHC is a technology intensive project!

HiLumi HL-LHC PROJECT

CERN 2019

Technology landmarks



CLIQ
A novel concept of magnet protection, based on fast injection of oscillating currents, will improve the safety of the very large stored energy quadrupoles.

"CRAB" CAVITIES
8 SRF «crab» cavities on each side of ATLAS and CMS experiments to tilt beams at collision.

BEAM SCREEN
All new magnets will be equipped with a new special beam screen to intercept collision debris at 60 K temperature and cancel electron-cloud effects.

CRYOGENICS
2 new large 1.9 K helium refrigerators for HL-LHC near ATLAS and CMS will allow cryo-separation between arcs and triplet regions.

QUADRUPOLE MAGNETS
24 new quadrupole magnets of 11.4 tesla peak field, based on advanced Nb$_3$Sn superconductor, to double beam focusing at ATLAS and CMS collision points.

11 T DIPOLE MAGNET
2 pairs of bending magnets, based on advanced Nb$_3$Sn superconductor and much stronger than LHC dipoles, to free up space for special collimators in the cold regions

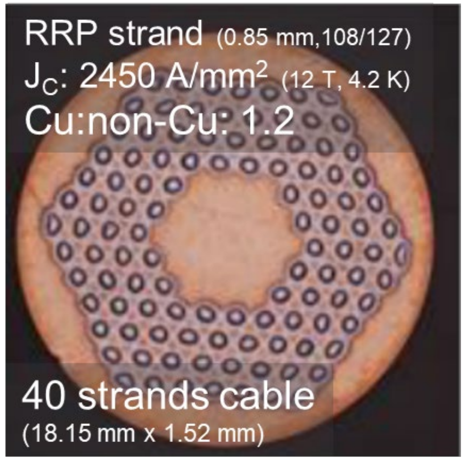
BEAM GAS VERTEX
Two new novel beam instruments based on beam gas vertex detectors will allow non-invasive accurate measurements of the beam size.

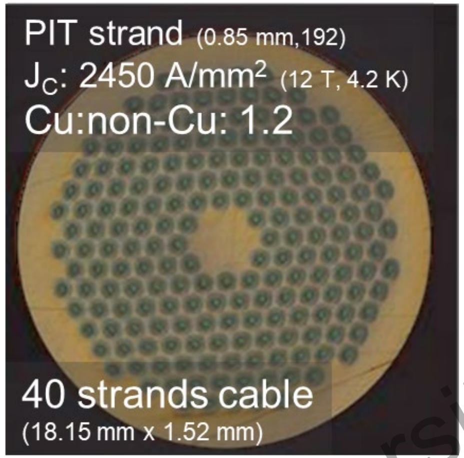
COLLIMATORS
20 novel low impedance collimators for beam stability and further 24 new collimators for improved machine protections

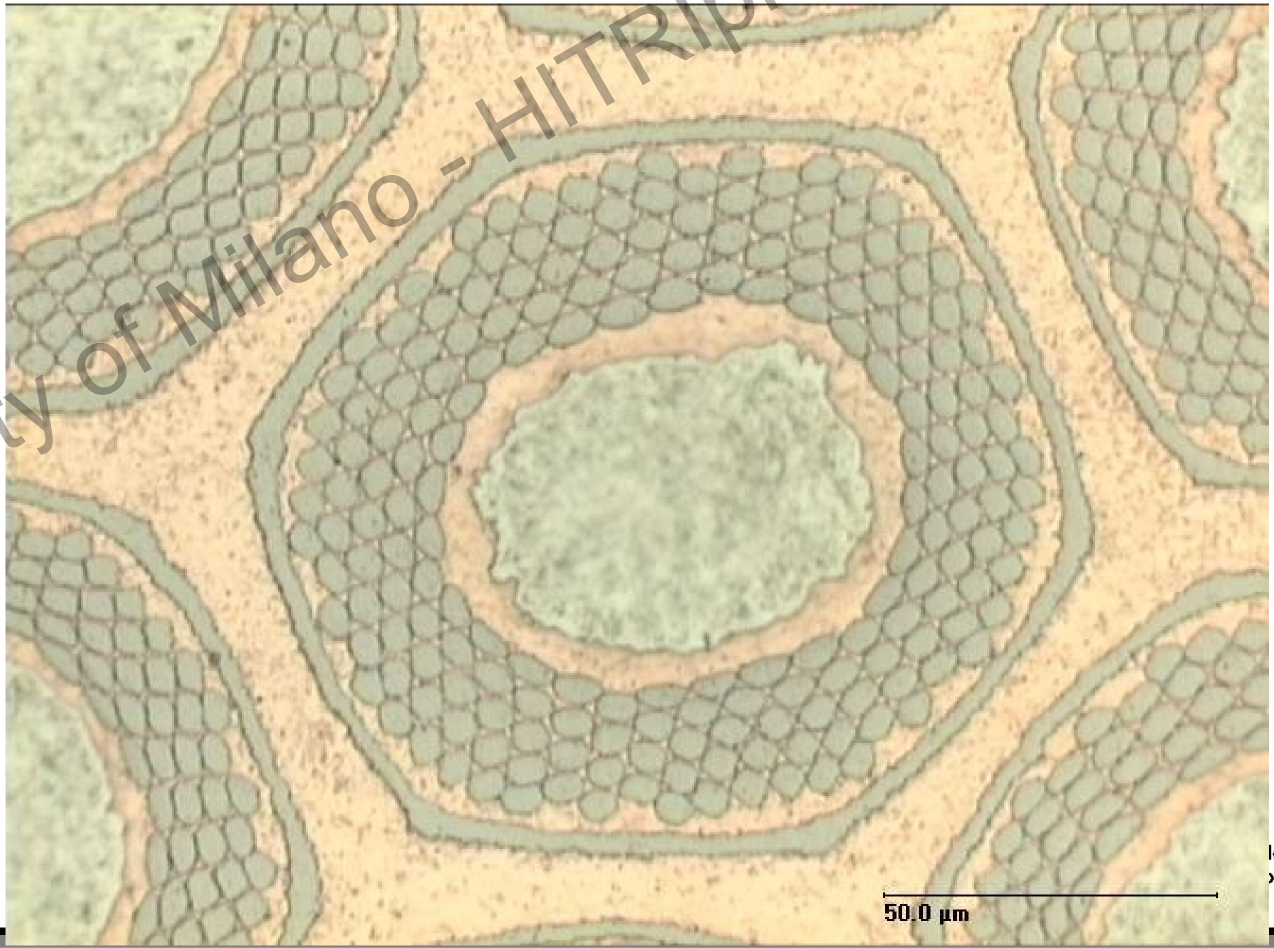
CIVIL ENGINEERING
2 new caverns, 1km underground galleries, two new large shafts; 10 new technical buildings on surface in P1 and P5 (near ATLAS and CMS)

SUPERCONDUCTING LINKS
8 novel electric current superconducting lines, 140 m long and rated for 30-100 kA, based on MgB$_2$ superconductor operating at a temperature up to 20 K.

Nb_3Sn : high **Je** also at 12- 16 T but it is brittle and needs thermal treatment of whole coil @ 700 °C !



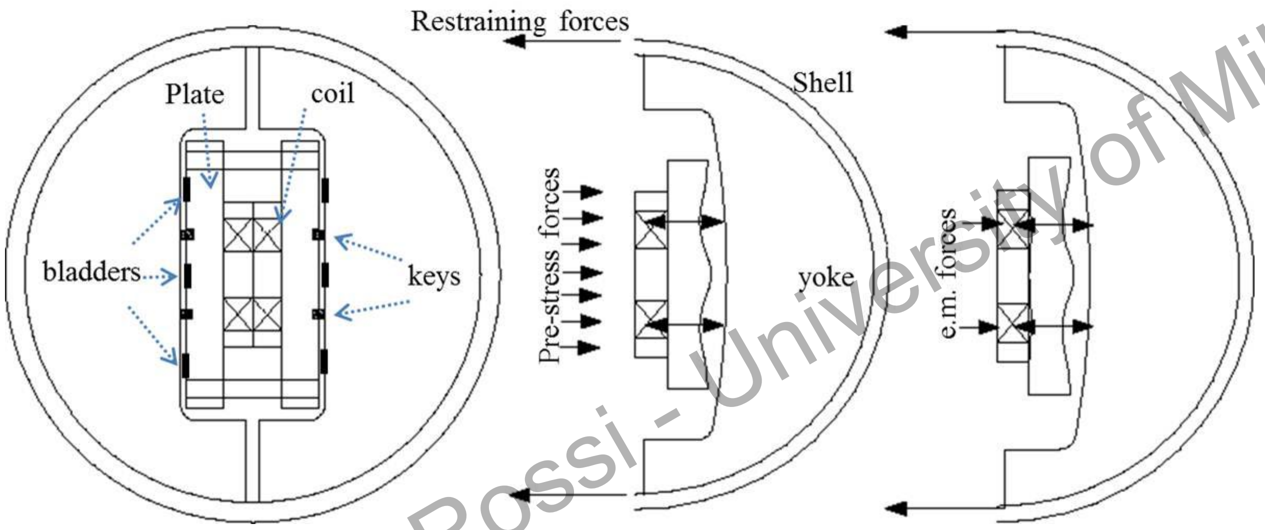




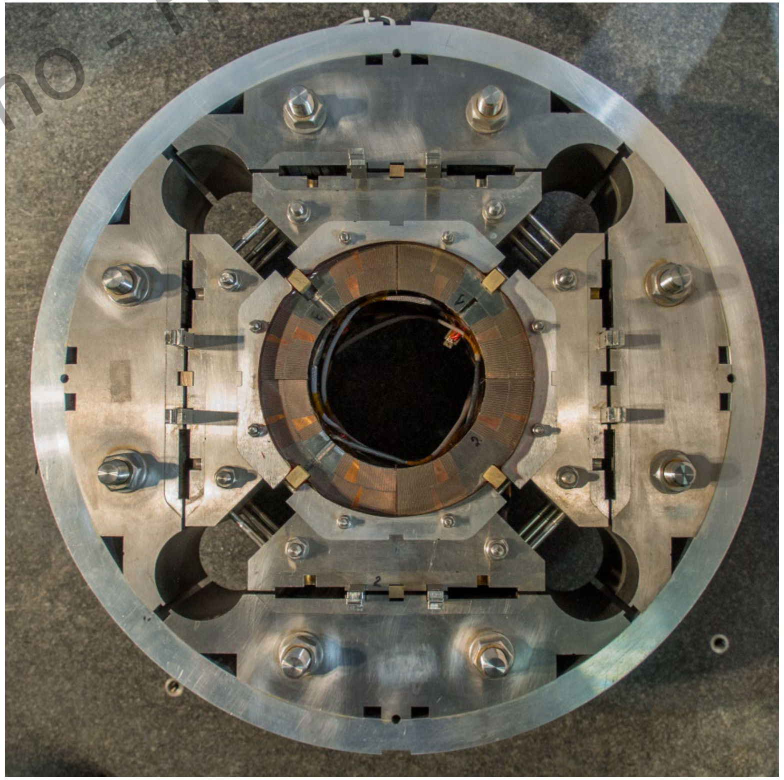
Heavy Ion
lorizon 2020
101008548

New way to keep the stress : HiLumi paves the way to reach a controlled precompression of ~130 MPa

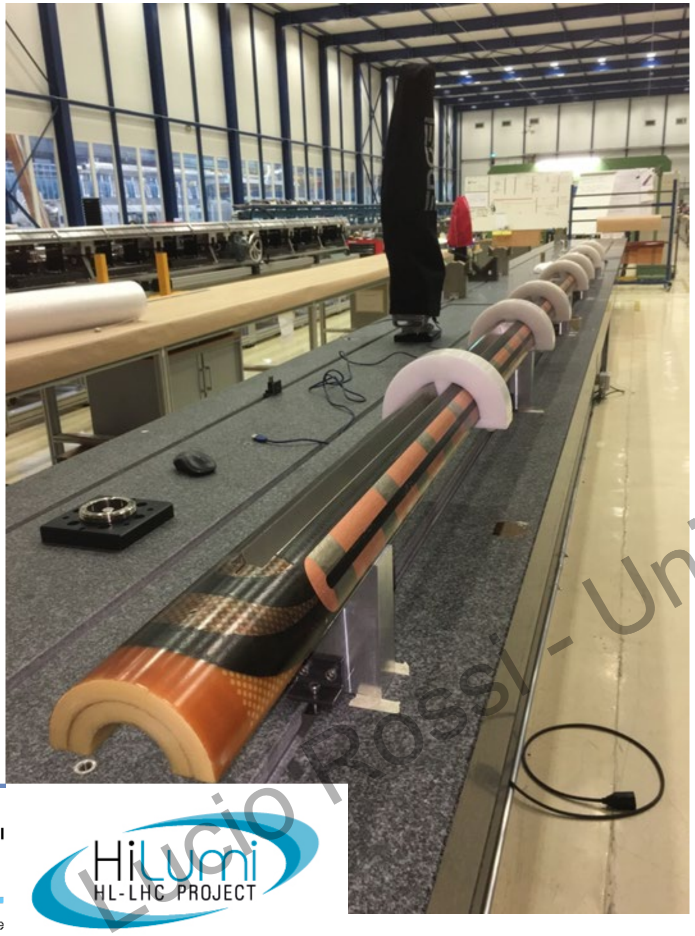
New concept: bladders and keys

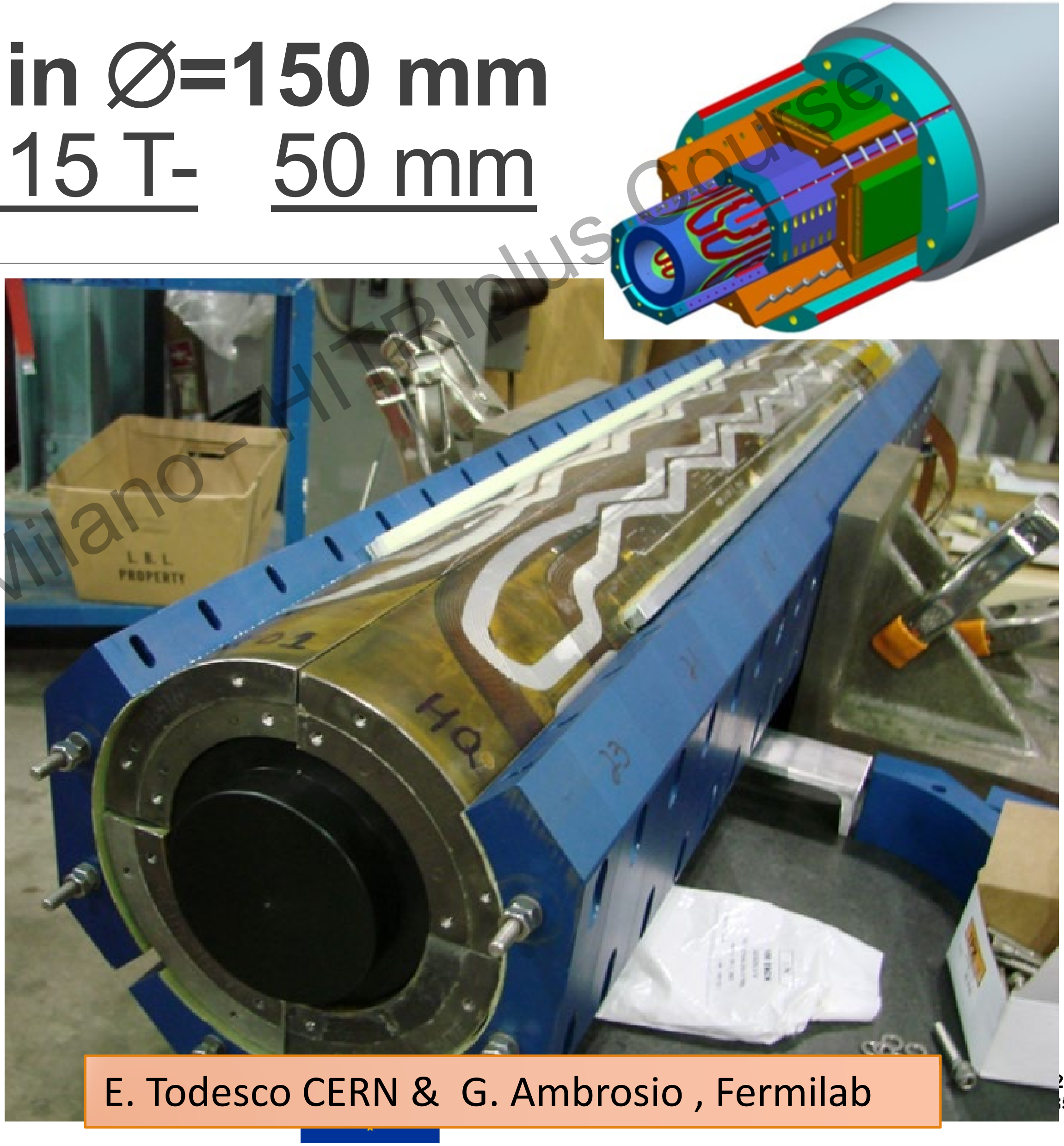


Cross section of the Quad for HiLumi



The HiLumi Quad: **12 T in ∅=150 mm**
~ equivalent to a dipole 15 T-   50 mm



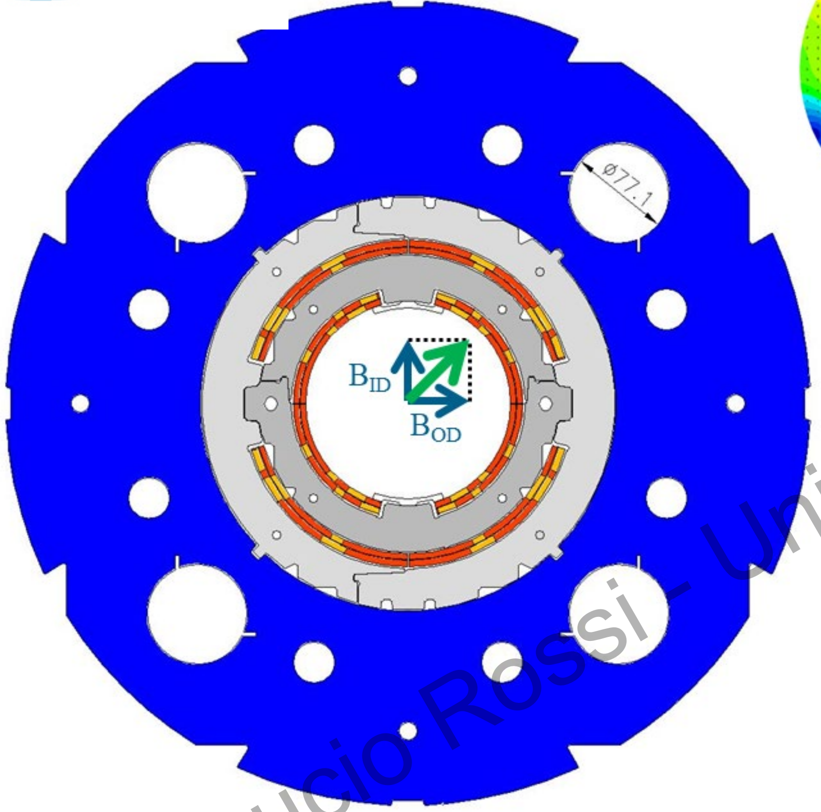


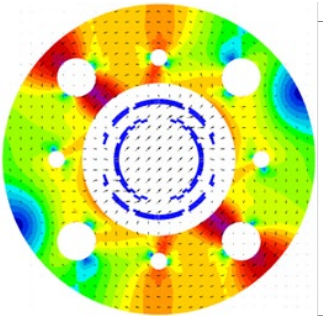
E. Todesco CERN & G. Ambrosio , Fermilab

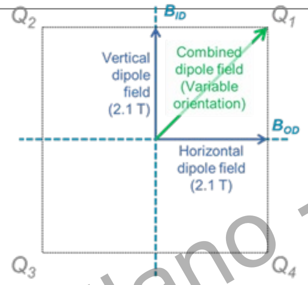
2020
548

Other development with classical Nb-Ti: nested X-Y dipole
Steering – Bending with compact magnet, space is precious…

HiLumi
HL-LHC PROJECT







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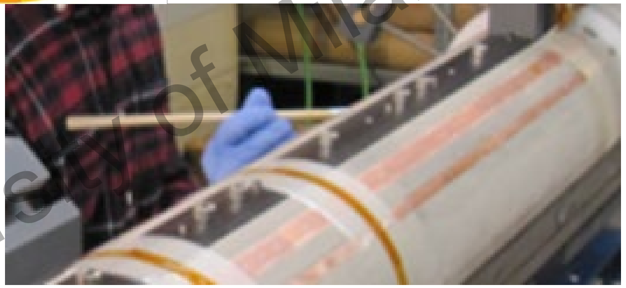
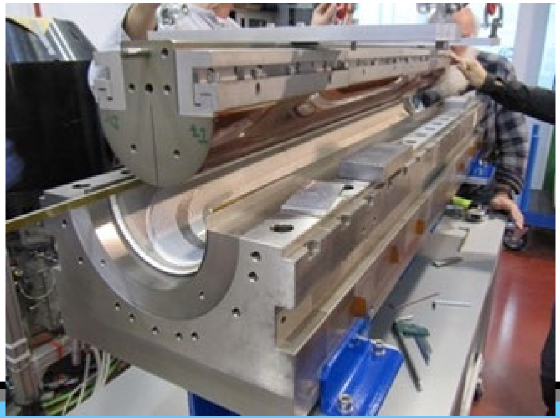
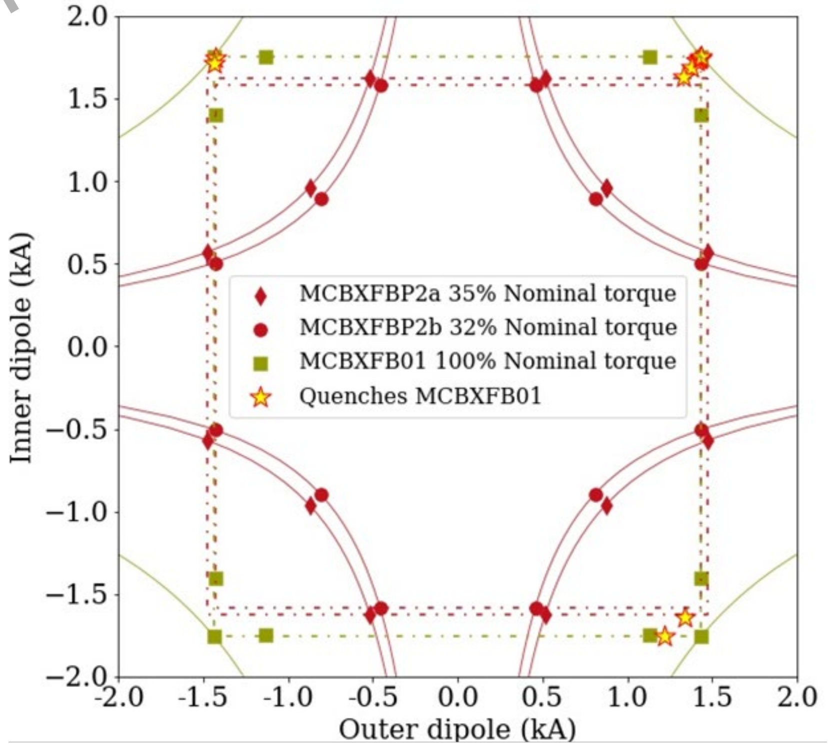
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas







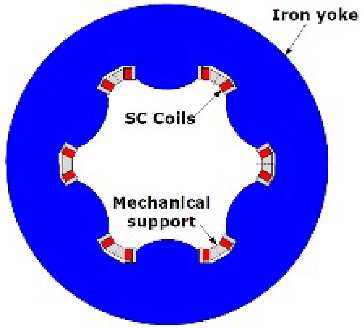
Courtesy S.Ferradas (CERN)

Thanks to F. Toral, Ciemat

Superferric magnet technology: 2-3 T iron driven by SC coils very convenient in terms of performance/cost

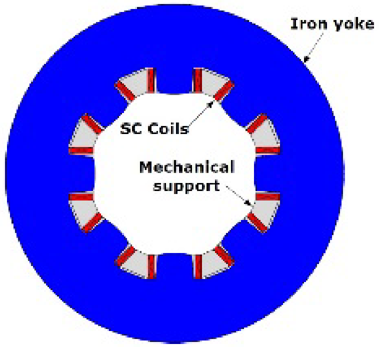
Thanks to M. Statera, INFN-LASA

OD=320 mm



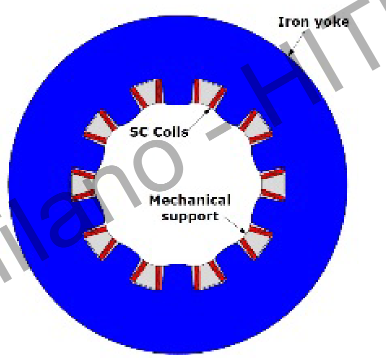
Sextupole

OD=320 mm



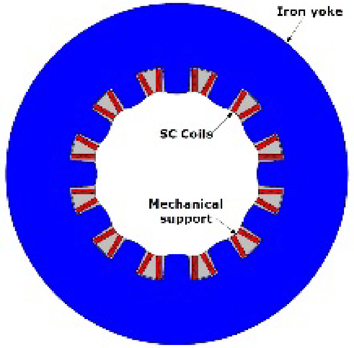
Octupole

OD=320 mm



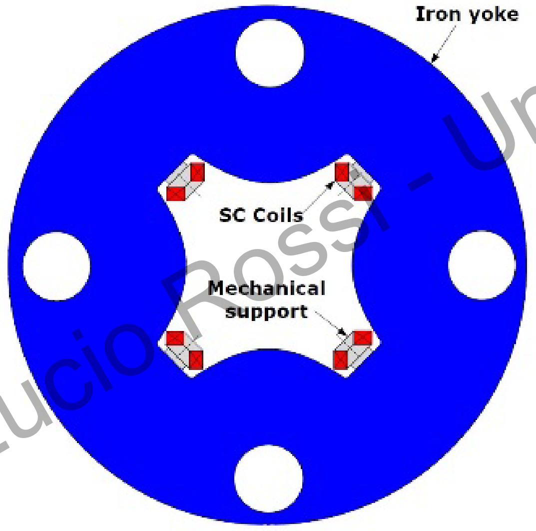
Decapole

OD=320 mm



Dodecapole

OD=460 mm

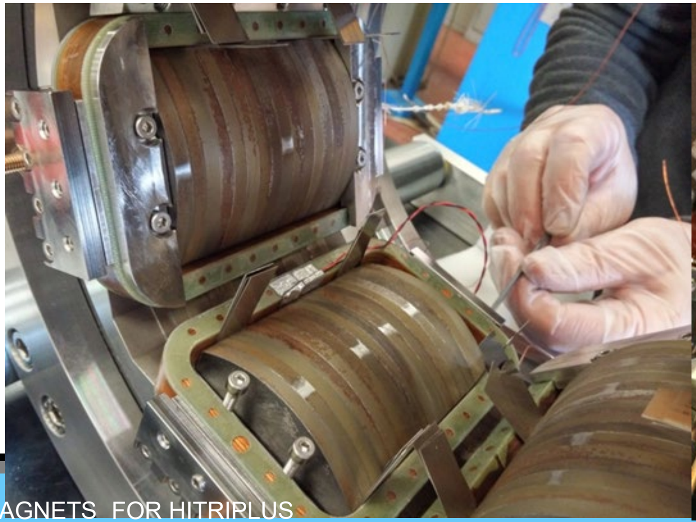


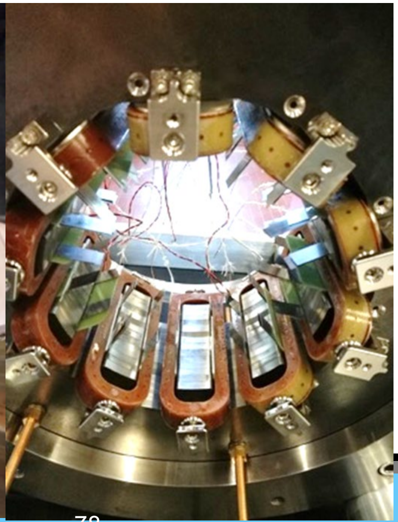
Skew quad

Physical lenght:

- 90-120 mm from 6-pole to 10-pole
- 430 mm 12-pole normal
- 840 mm 4-pole skew

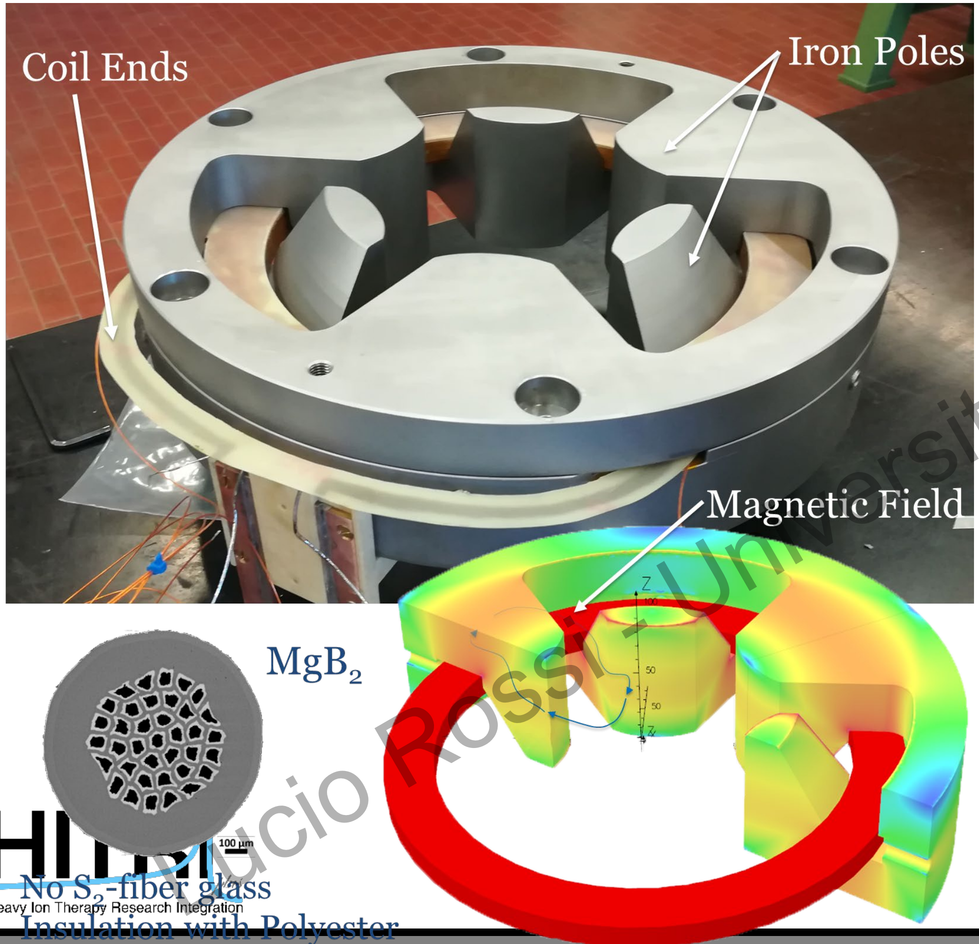
Conductor type: NbTi
Peak field on cond.: 2-3 T
Operating current: 120-180 A
Margin on load line: 40%



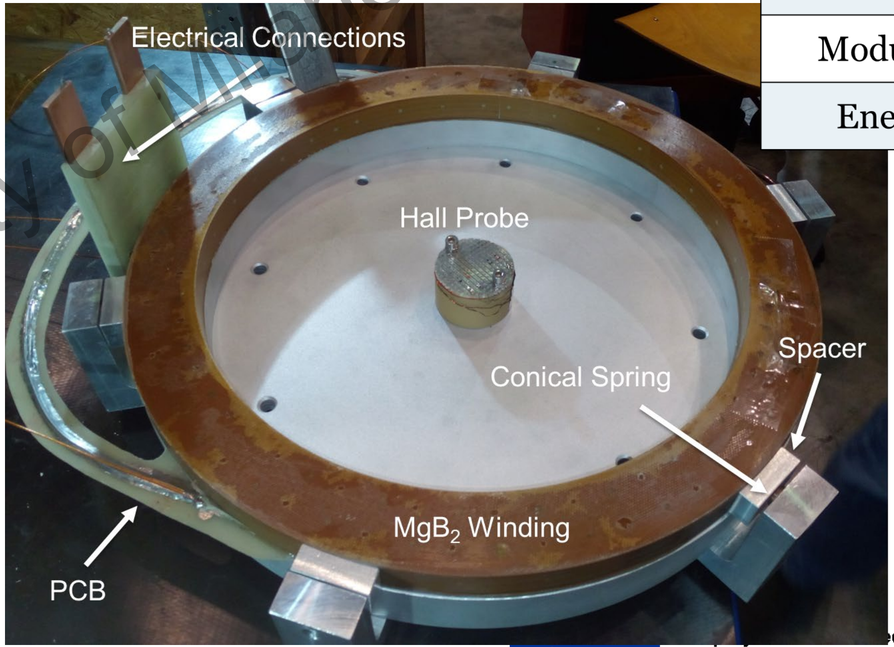


Next step for superferric: going cryogen-free HTS or RCSM design with MgB_2

S. Mariotto and R. Valente
INFN-Mi-LASA



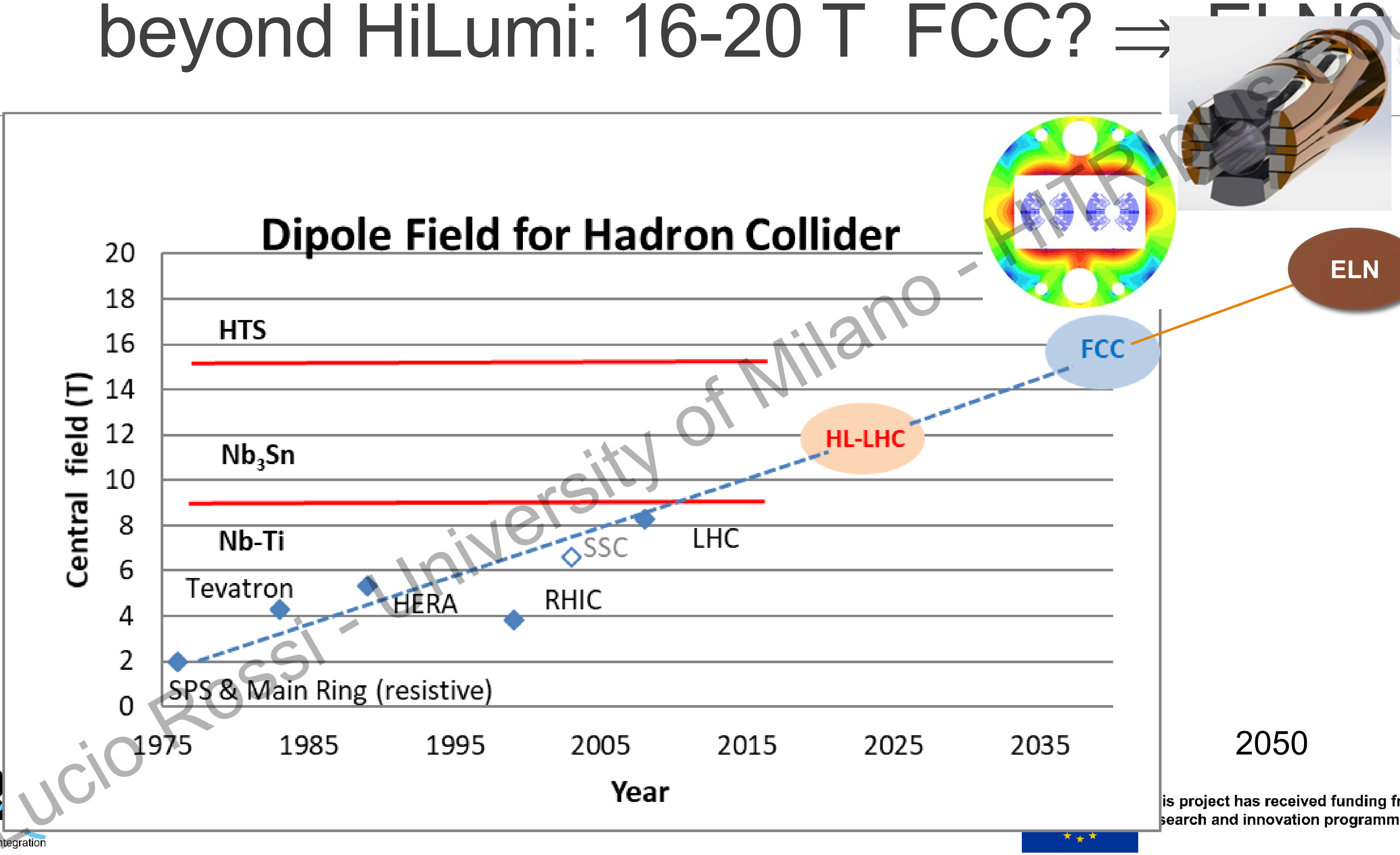
	Value
Integrated Field @ R=50 mm	70.06
B_{max} on SC @ I_{op}	1.37 T
B_{max} on Iron @ I_{op}	3.52 T
Module Lenght	384 mm
Energy @ I_{op}	3754 J



Istituto Nazionale di Fisica Nucleare

…d funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

Can we extrapolate linearly from the past beyond HiLumi: 16-20 T FCC? ⇒



5T HTS demos

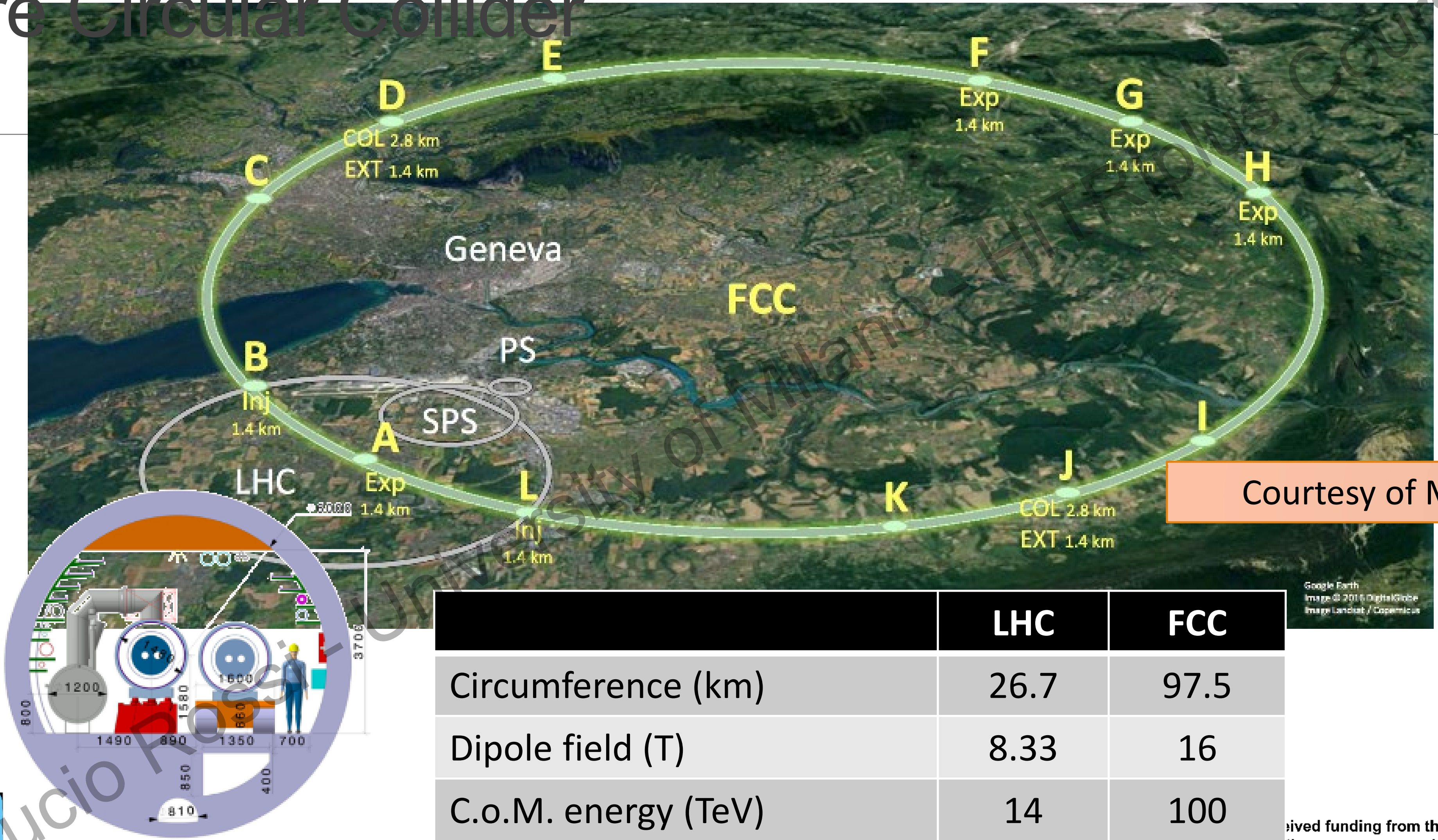
EuCARD²

HITR

Heavy Ion Therapy Research Integration

is project has received funding from the European Union's Horizon 2020
search and innovation programme under grant agreement No 101008548

Future Circular Collider



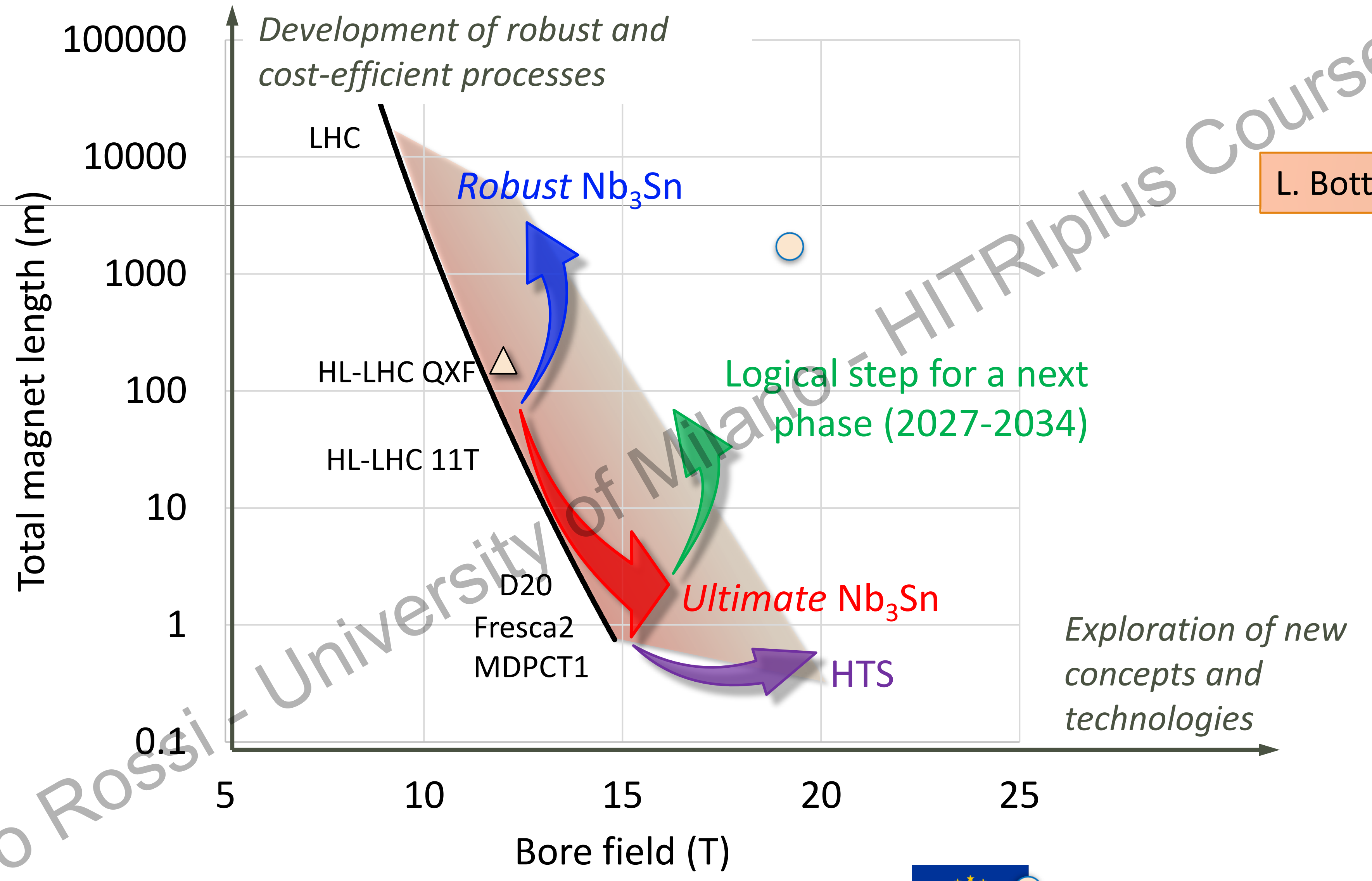
Courtesy of M. Benedikt, FCC

	LHC	FCC
Circumference (km)	26.7	97.5
Dipole field (T)	8.33	16
C.o.M. energy (TeV)	14	100

eived funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

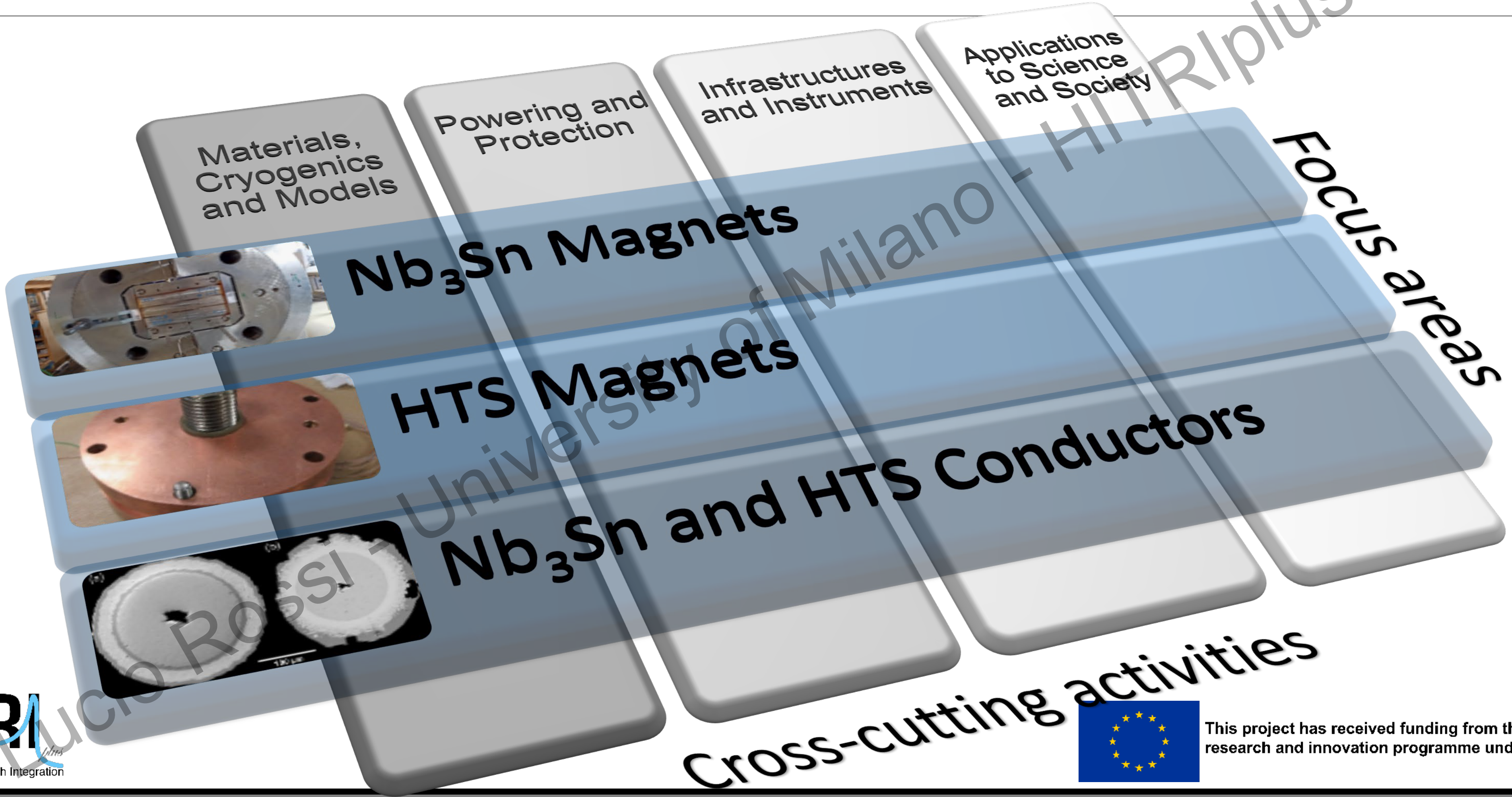
HITRI Heavy Ion Therapy Research Integration

L. Bottura, CERN



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

Activities – Topics matrix



Materials, Cryogenics and Models

Powering and Protection

Infrastructures and Instruments

Applications to Science and Society

Nb_3Sn Magnets

HTS Magnets

Nb_3Sn and HTS Conductors

Focus areas

Cross-cutting activities

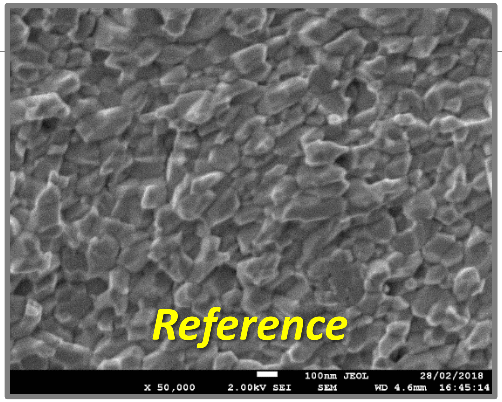
Heavy Ion Therapy Research Integration

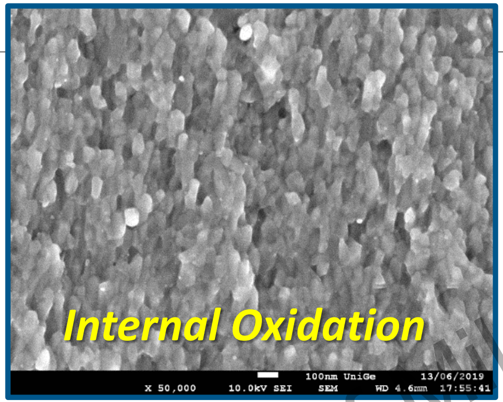
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

Towards the ultimate performance of Nb_3Sn

Performance target for FCC-hh J_c(4.2K,16 T) = 1'500 A/mm^2

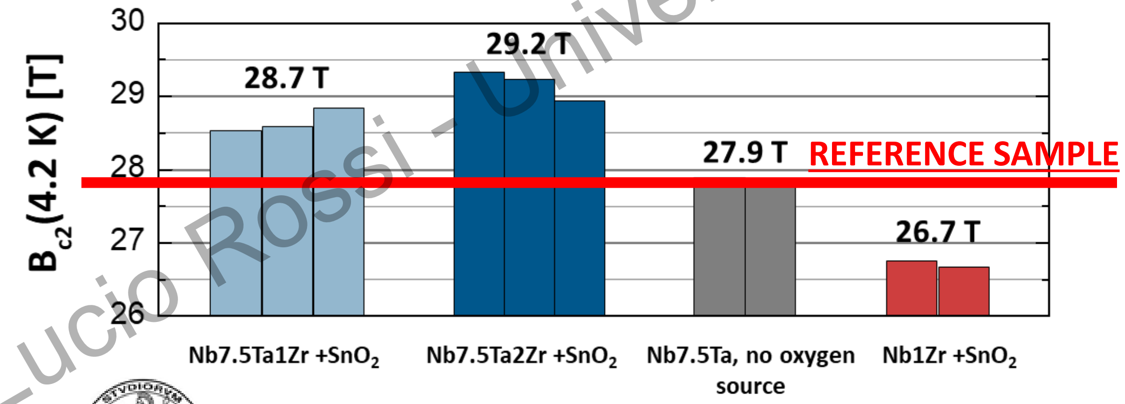
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
DQMP
http://supra.unige.ch



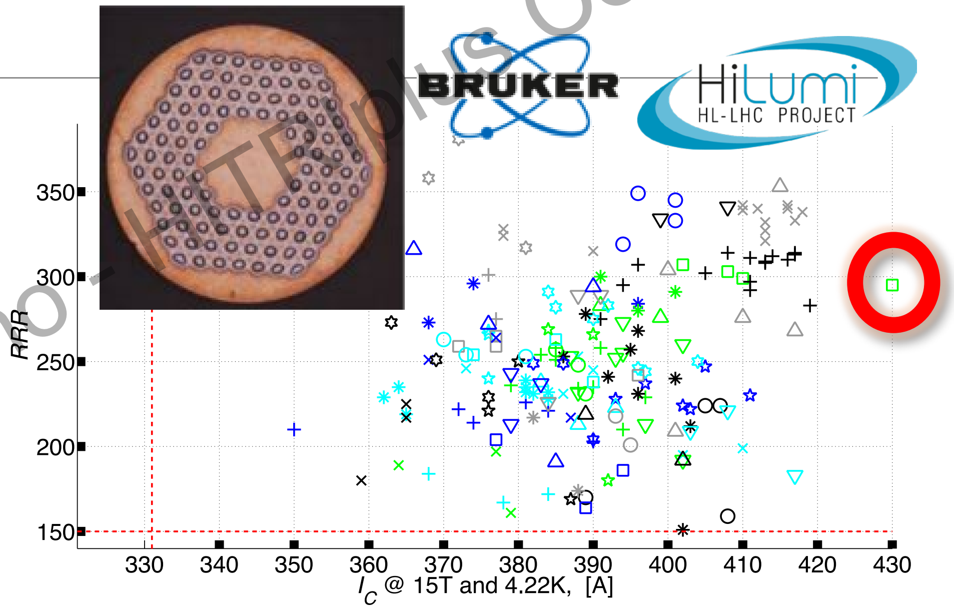


Grain refinement from 120 nm (left) to 60 nm (right)

Enhanced grain boundary pinning



BRUKER
HiLumi HL-LHC PROJECT



1750 A/mm^2 @ 15T, 4.2K

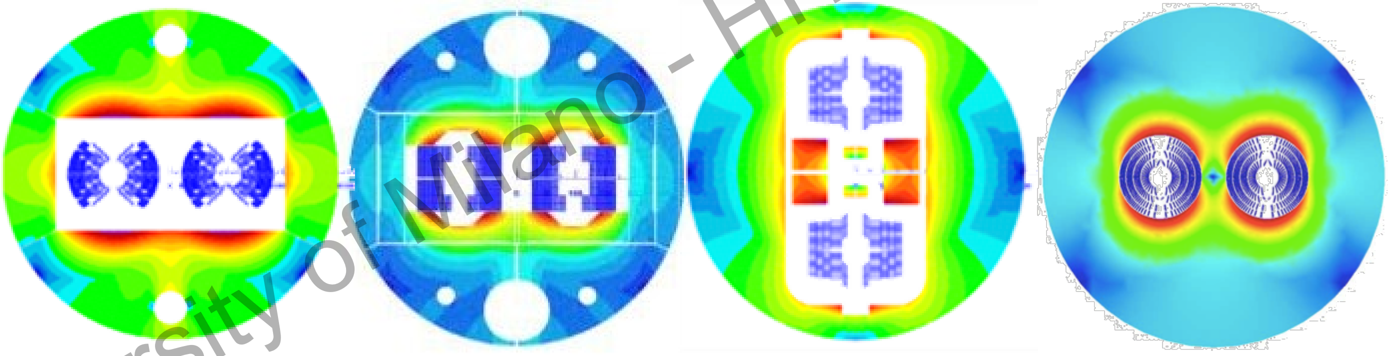
≈ 1400 A/mm^2 @ 16T, 4.2K

And record-high upper critical field !!

LNCMI-Grenoble

If advanced superconductors are there, magnets come

OD = 600 mm
L = 2 m
50 mm aperture
$B_{ultimate}$ = 16 T

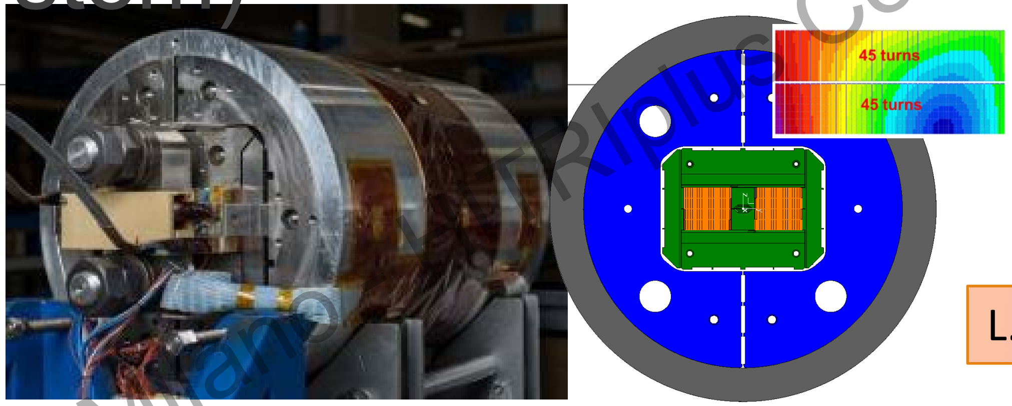


		cos(θ)	blocks	common coil	CCT
Current	(A)	10000	11230	16100	18055
Inductance	(mH/m)	50	40	19.2	19.2
Stored energy	(kJ/m)	2500	2520	2490	3200
Coil mass	(tons)	7400	7400	9200	9770

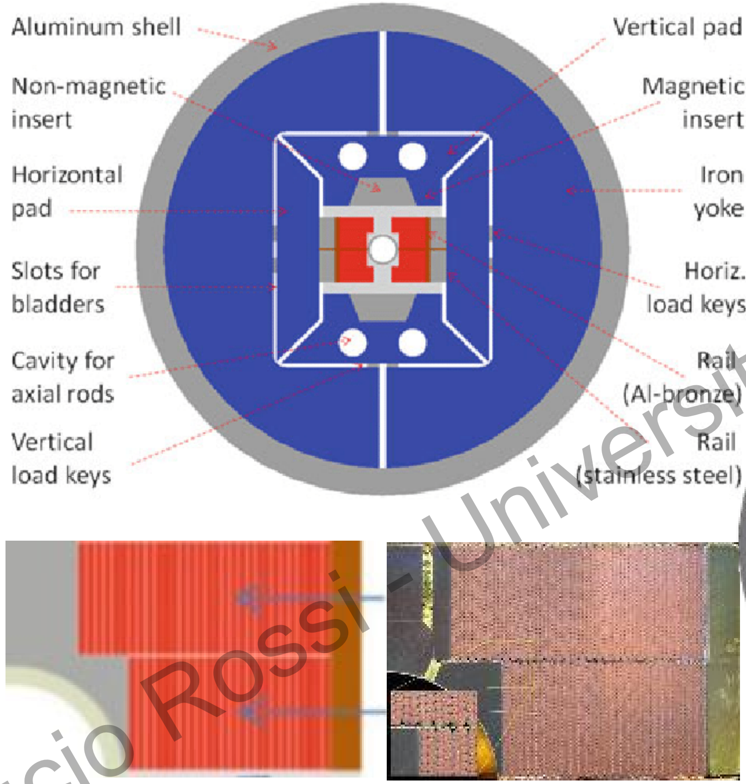
ean Union's Horizon 2020
agreement No 101008548

Exploring new coil lay-out (again with bladder-key system)

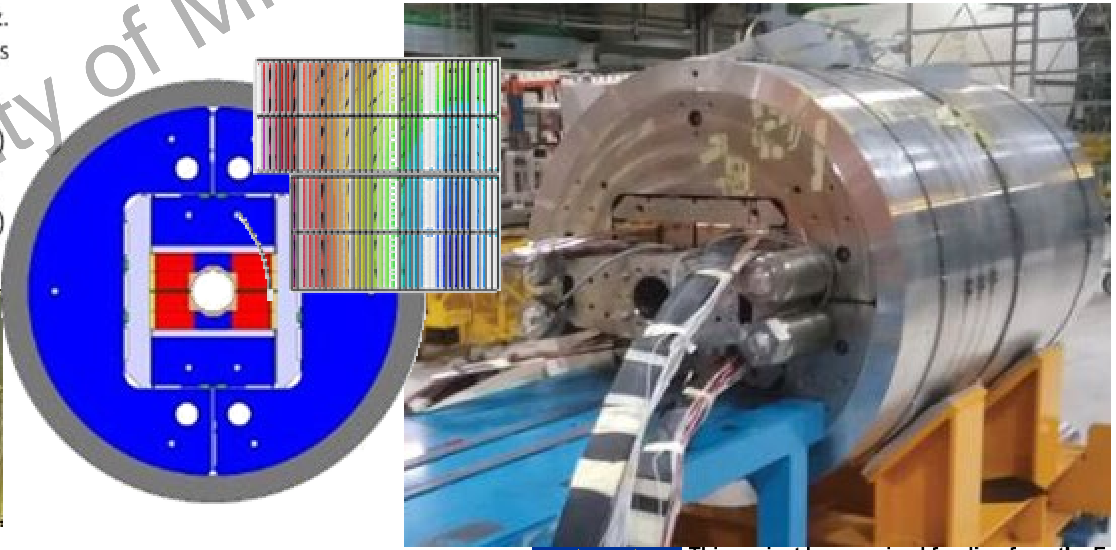
RMC/eRMC (2-decks, no aperture), 16.5 T



L. Bottura, CERN



HD2 (2-decks, 36 mm), 13.8 T

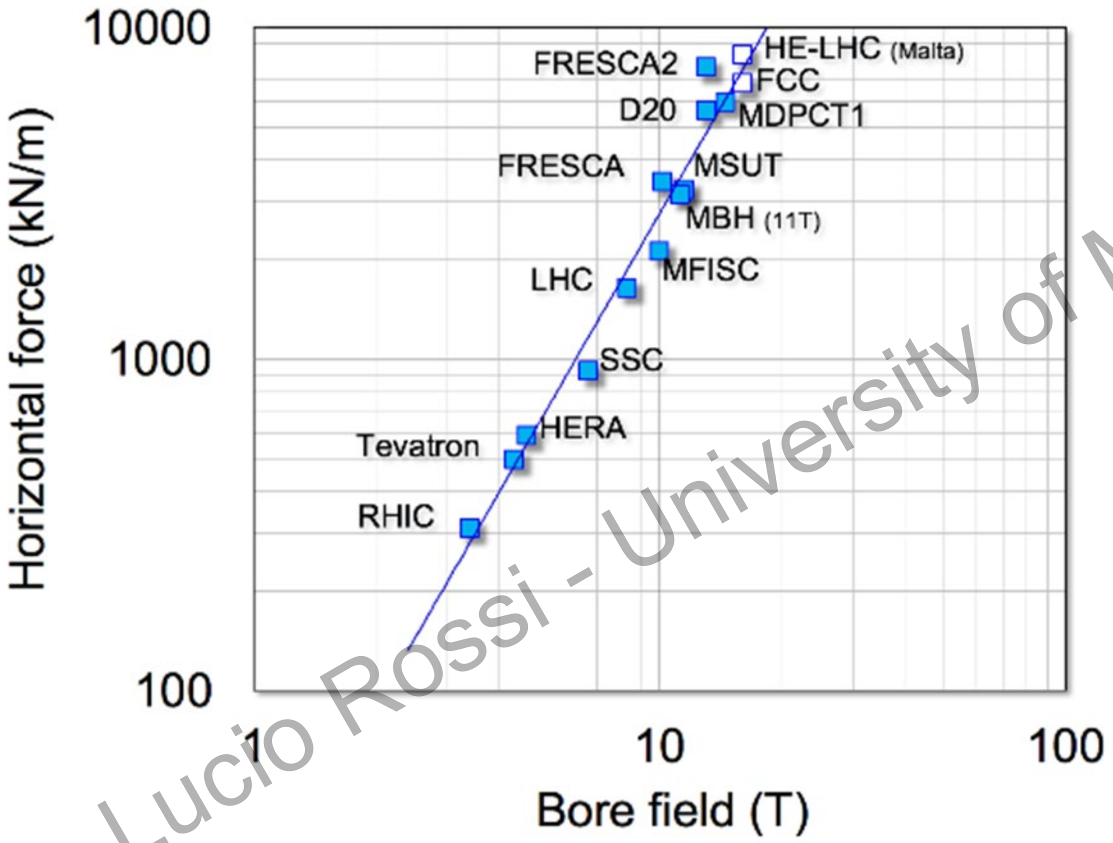


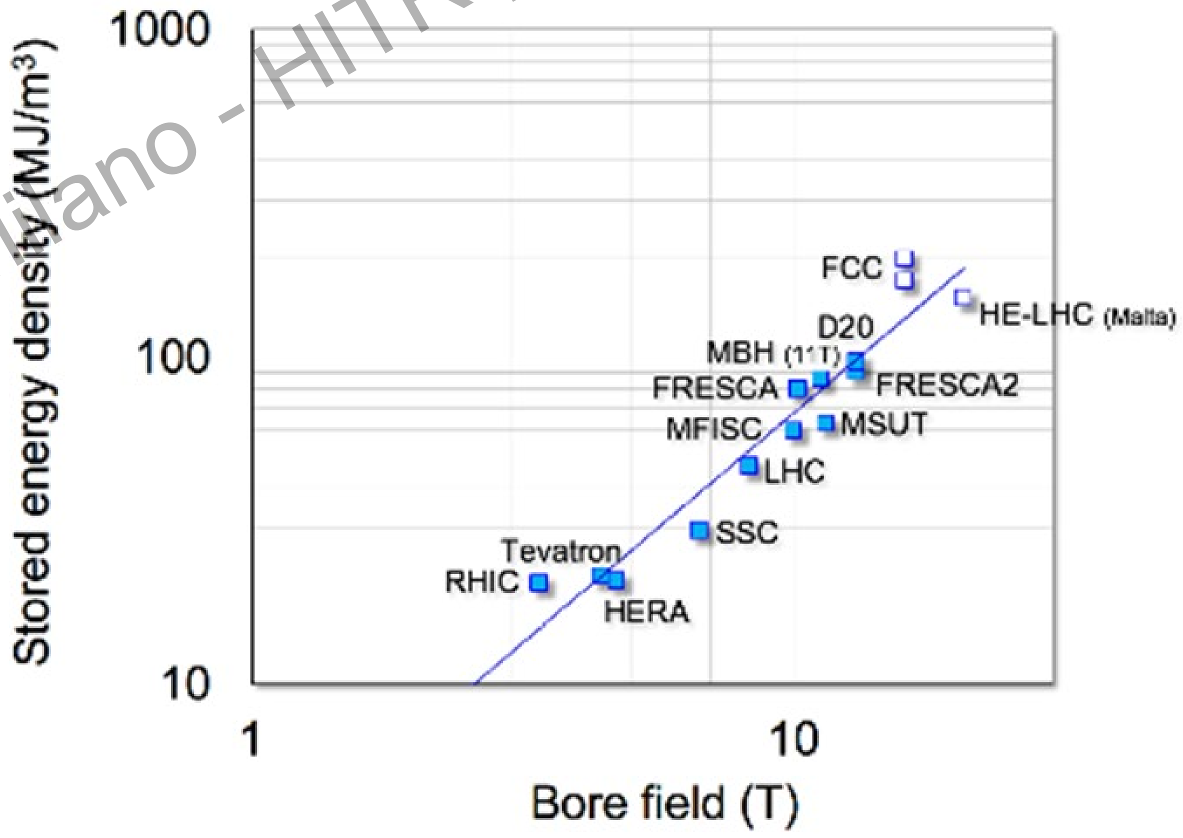
FRESCA2 (4-decks, 100 mm), 14.6 T

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

New structure to support forces/stresses Effort in making magnets with huge energy safe

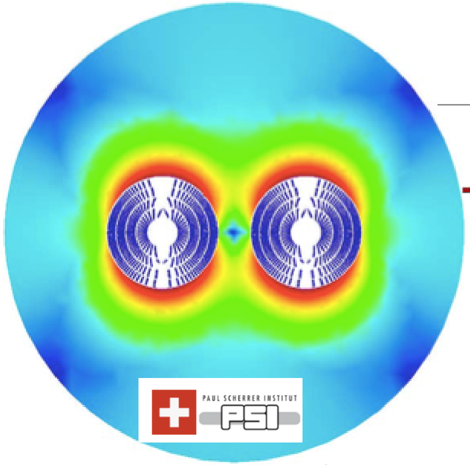
L. Bottura, CERN

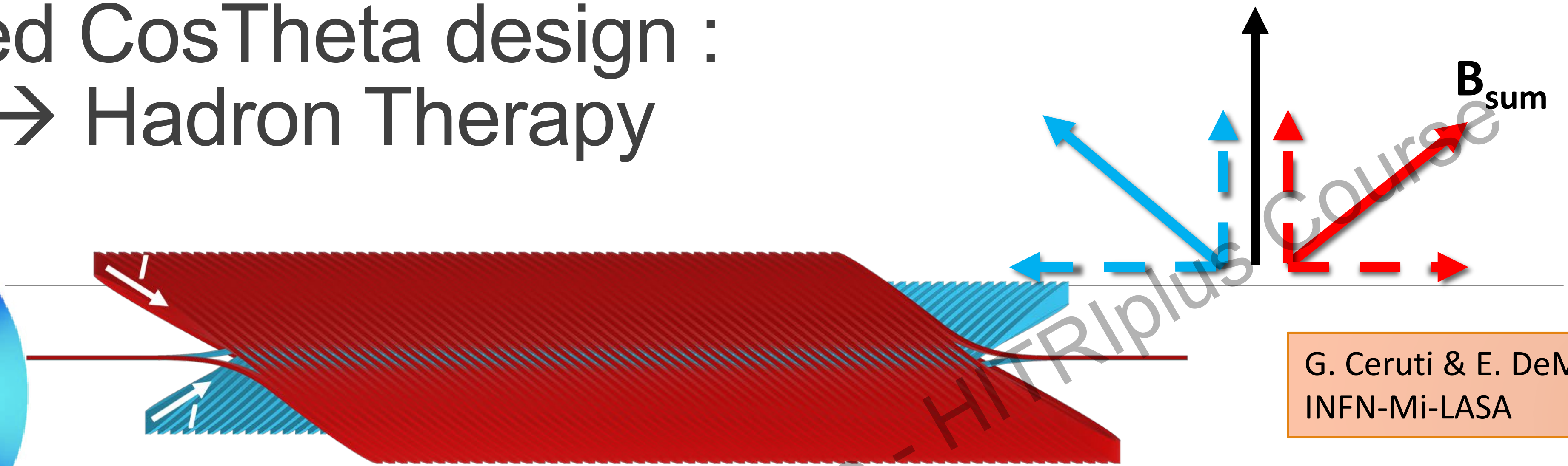




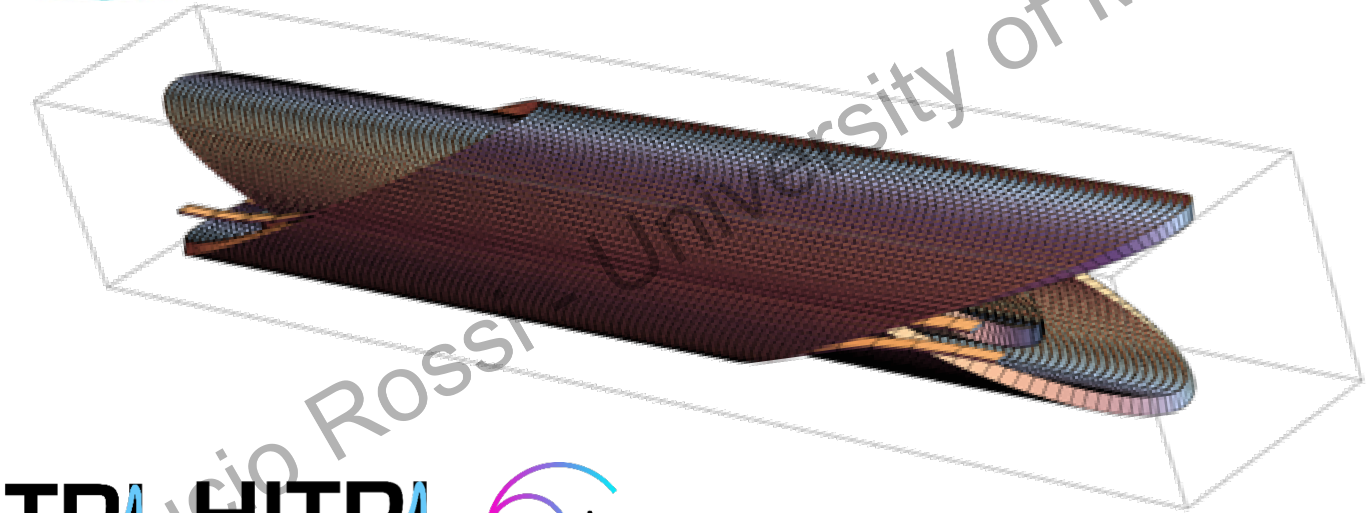
Heavy Ion Therapy Research Integration

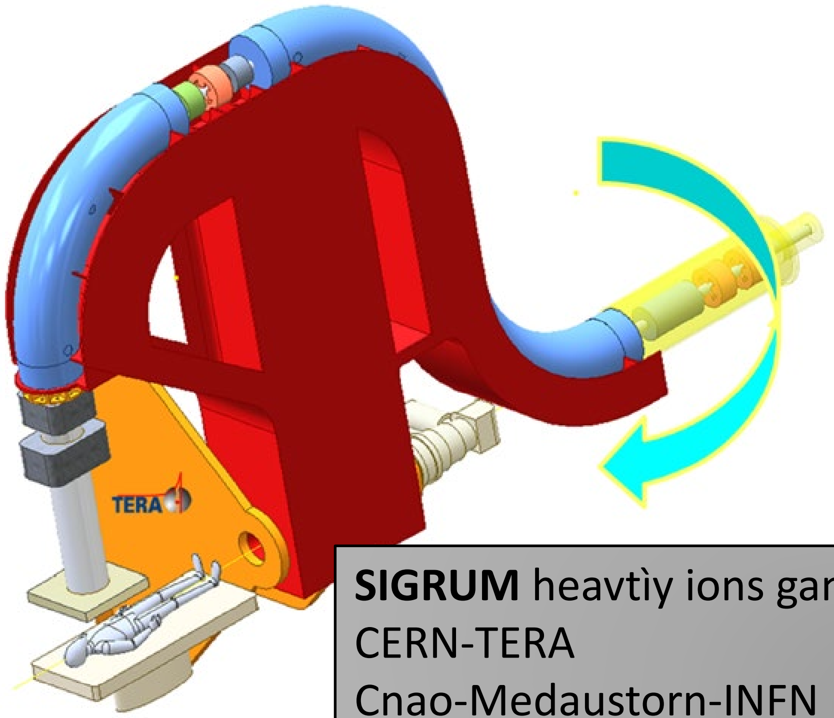
CCT Canted CosTheta design : from FCC → Hadron Therapy





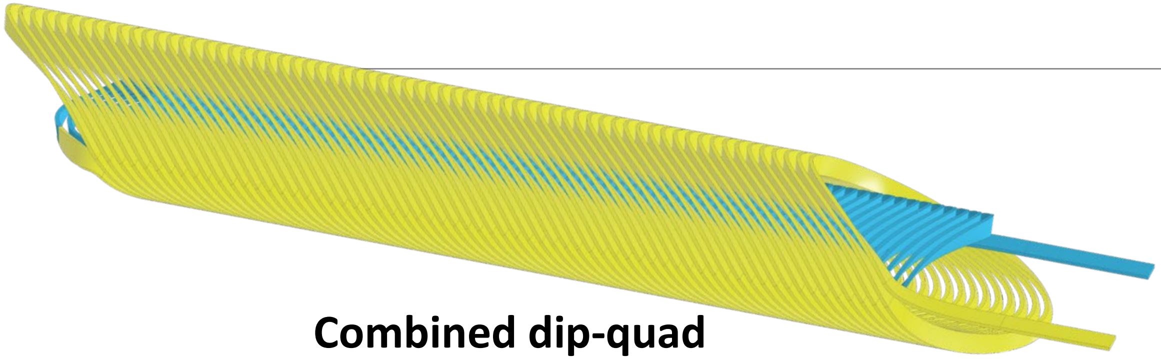
G. Ceruti & E. DeMatteis, INFN-Mi-LASA





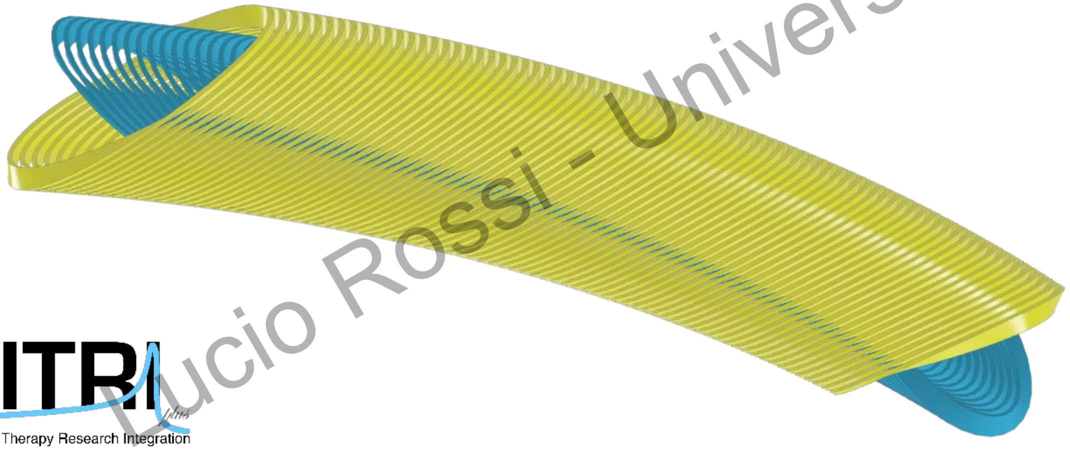
SIGRUM heavtìy ions gantry
CERN-TERA
Cnao-Medaustorn-INFN

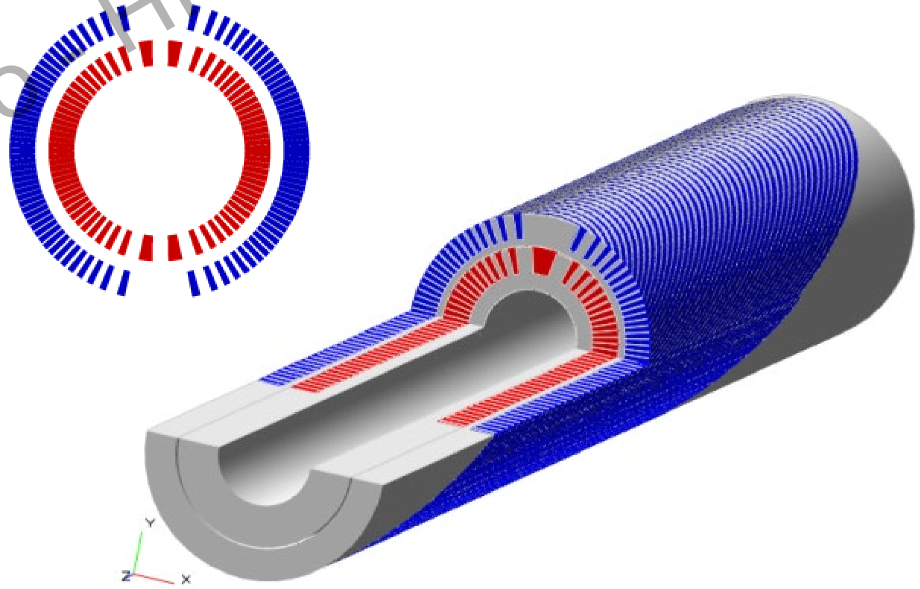
The CCT is perfect Costheta (in the bore)



Combined dip-quad

Curved 4 T – 0.4T/s





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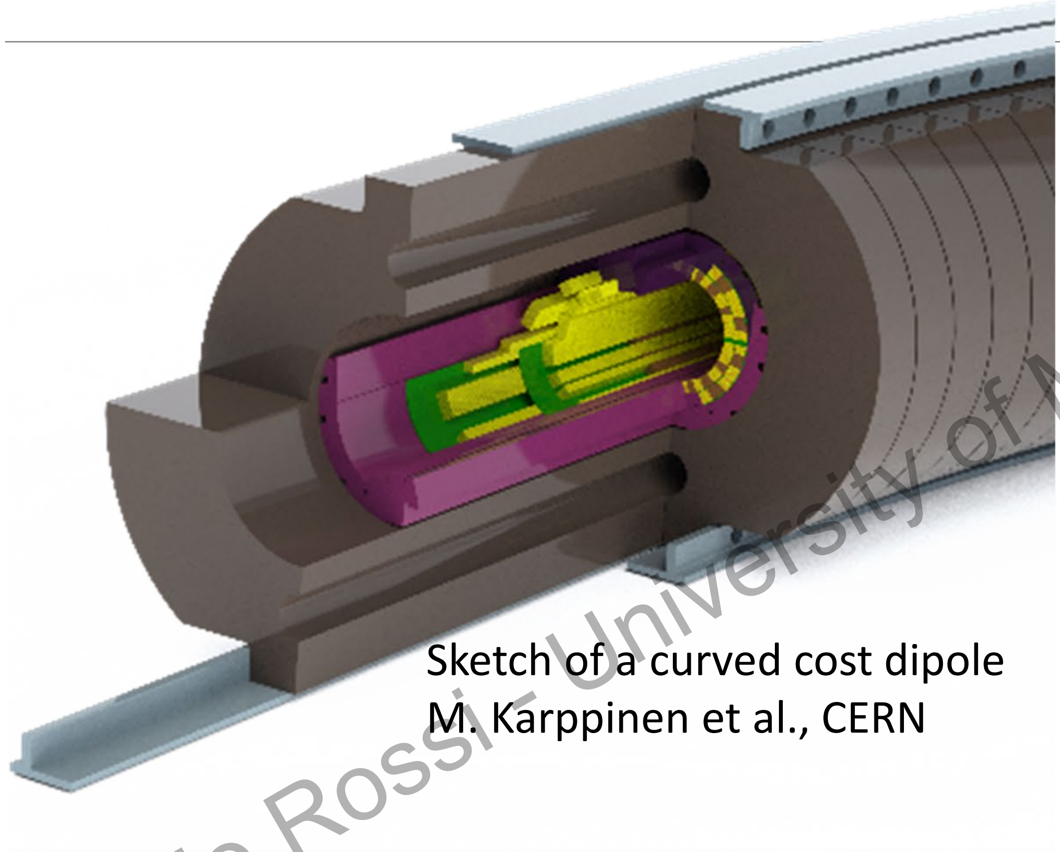
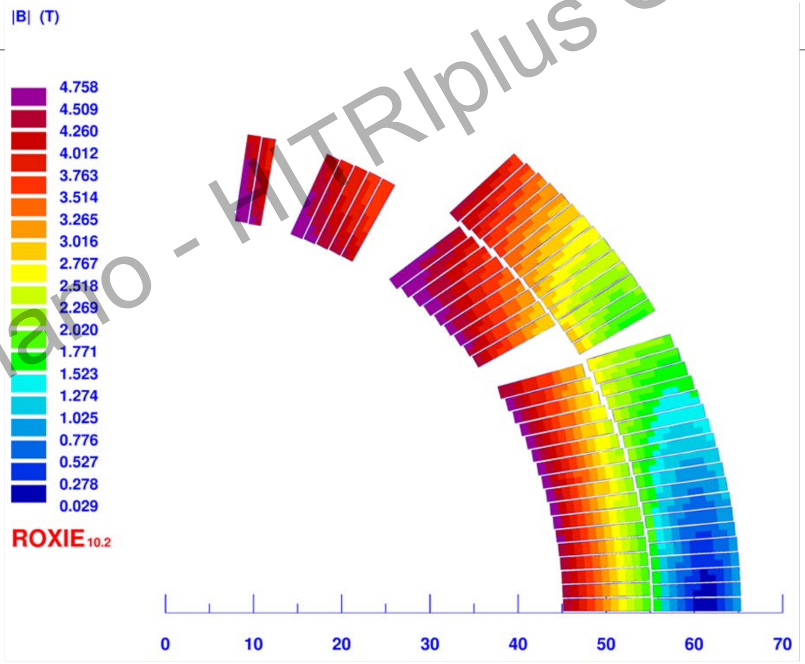
But also the “classical” CosTheta is ebing conidere for curved dipole for gantry (INFN-SIG project inde the SIGRUM project)



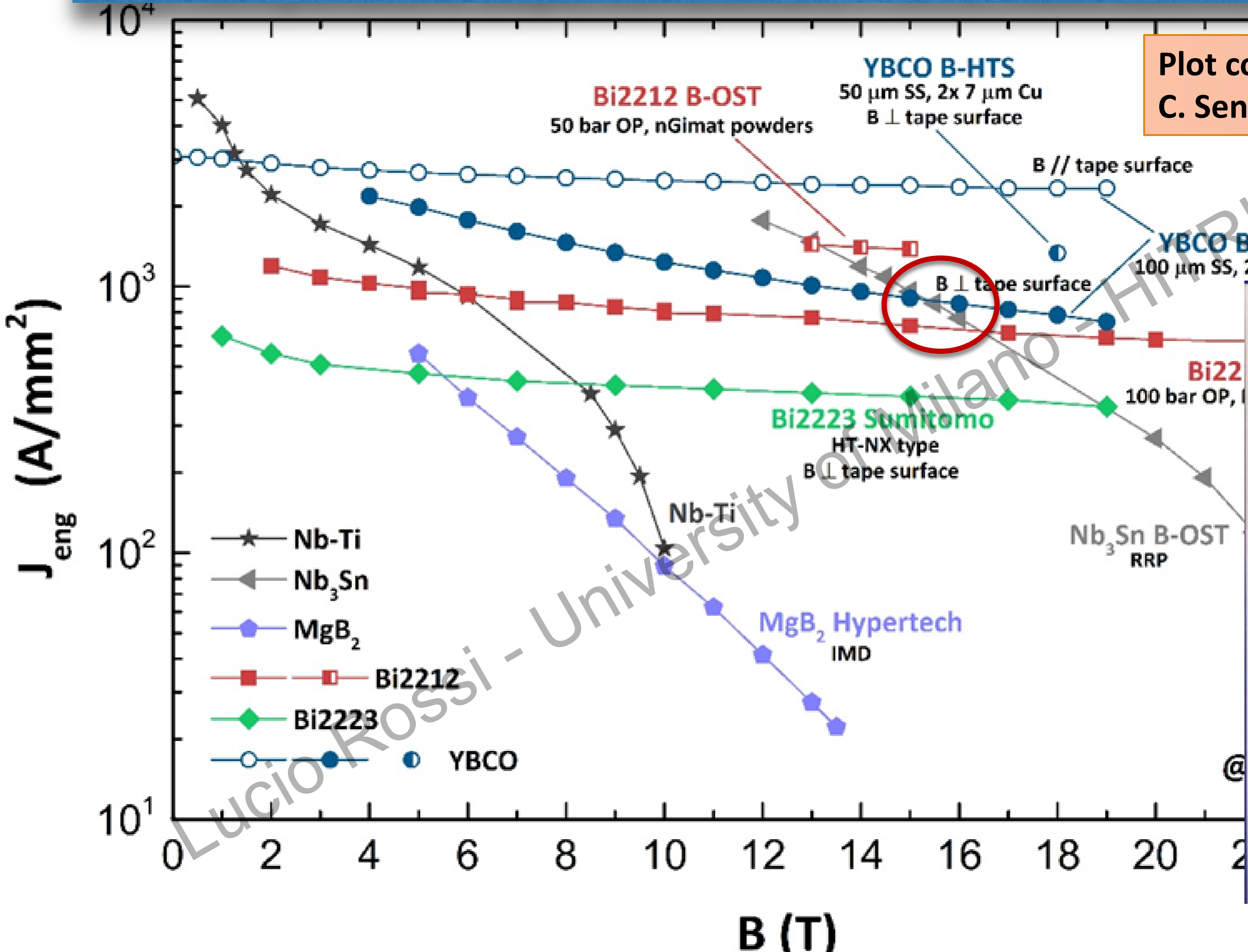
Sketch of a curved cost dipole
M. Karppinen et al., CERN



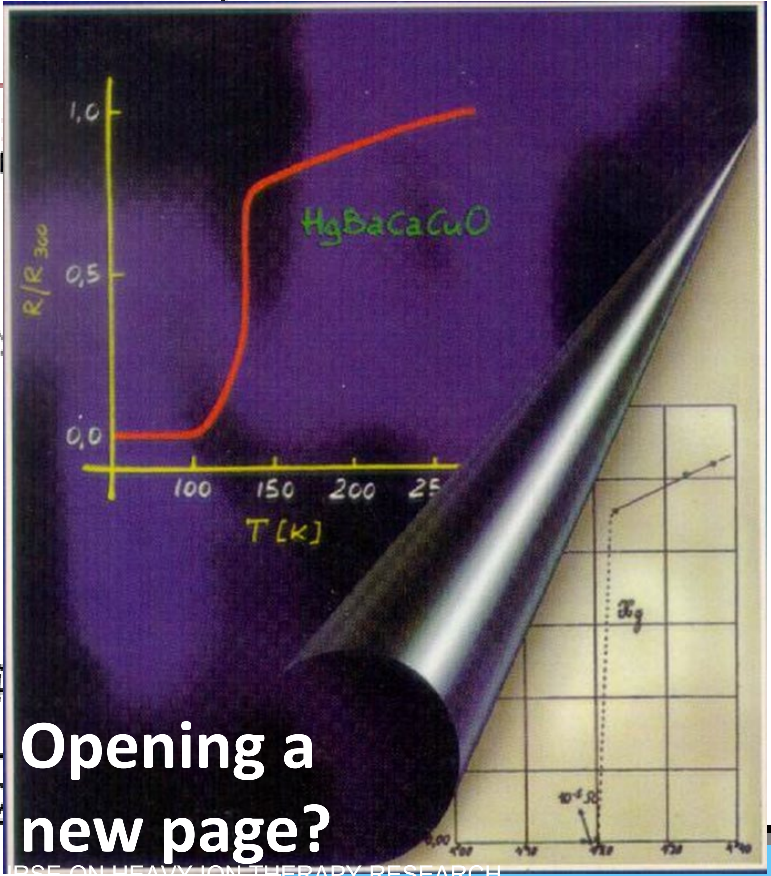
SIG project
INFN-LASA

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101008548

High Temperature Superconductors – HTS: next technology step

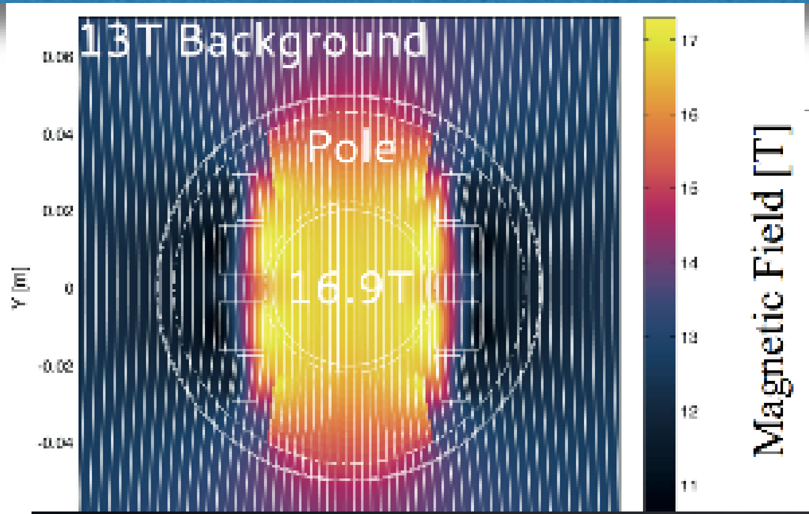


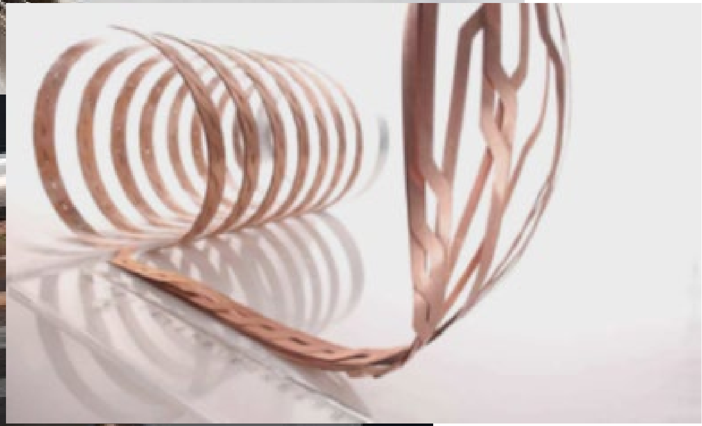
Plot courtesy of
C. Senatore, UNIGE



Opening a new page?

High Temperature Superconductors – HTS
The dream of 20-25 tesla! (2 x HilumiLHC!)



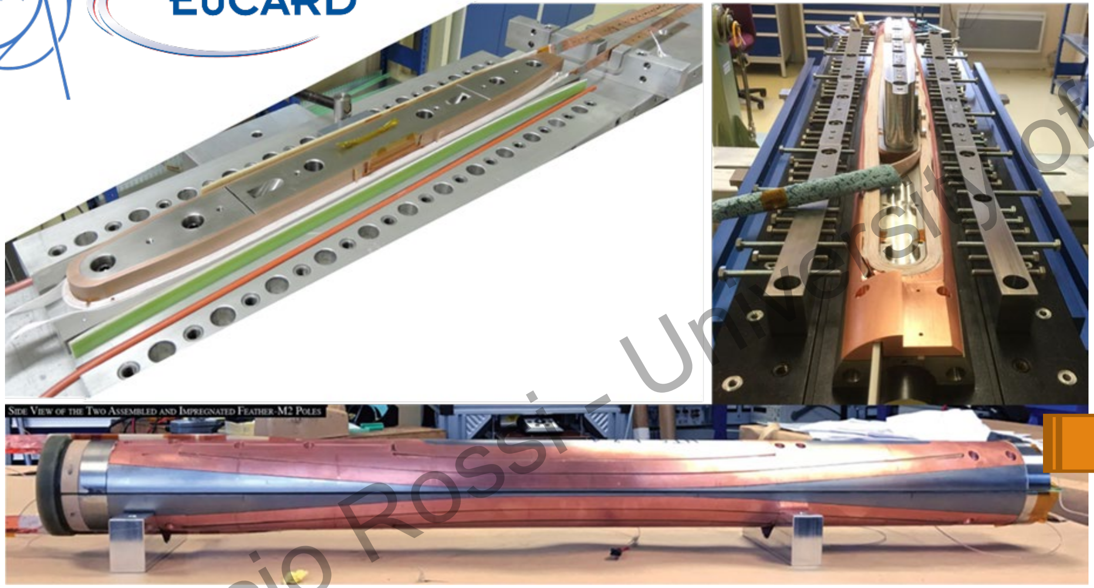


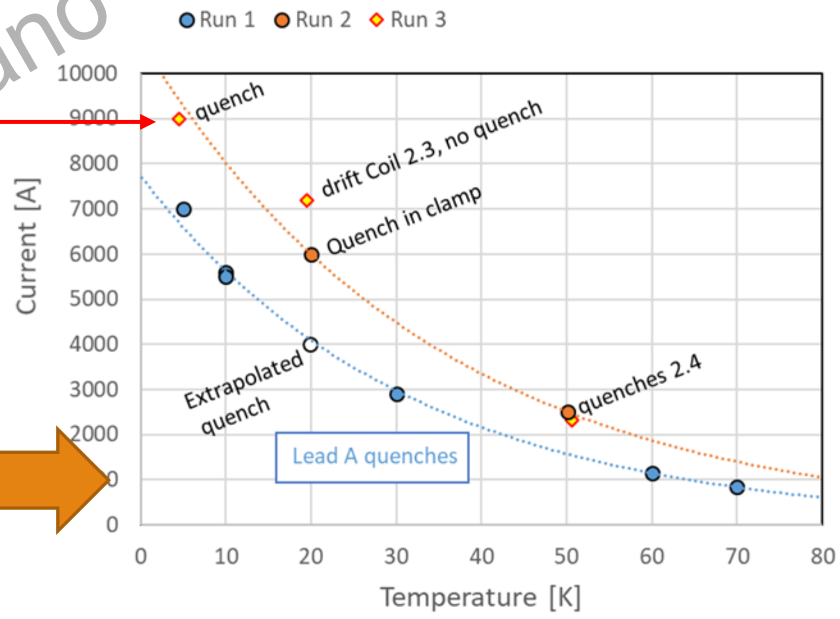
A 5 T, 40 mm bore HTS based dipole demonstrator

HTS for accelerator magnets: Eucard2 results

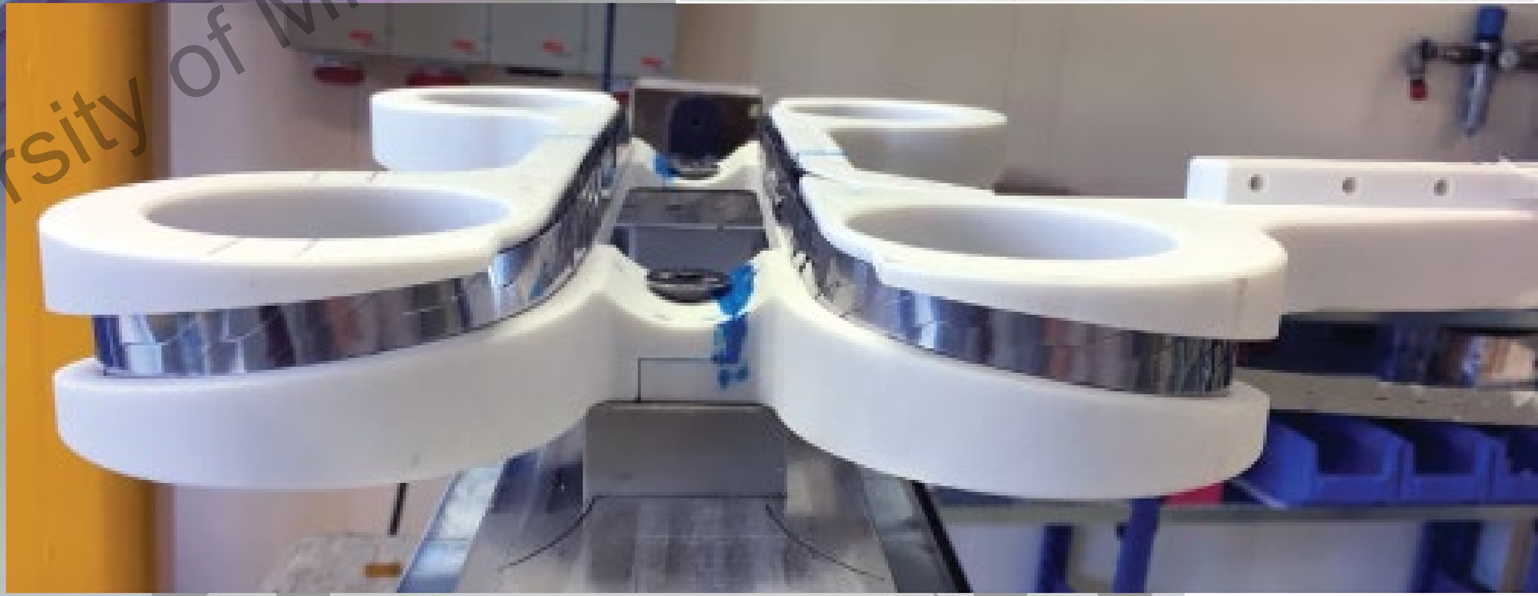
CERN Feather_M2: flare end race track, REBCO Roebel cable, 40 mm bore

> 3 T in 2017; 1st magnet
> 4.5 T in 2019; 2nd magnet



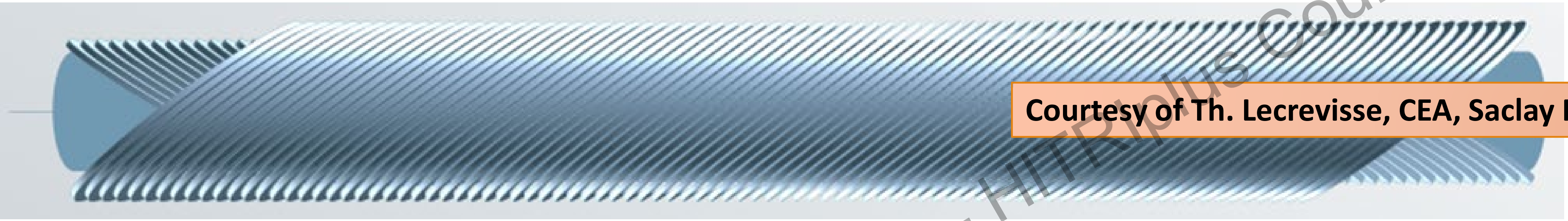


Trying the magnets of the future… 20 tesla or more…



J. Van Nugeteren – Little Beast Enginering,
Glyn Kirby CERN

HTS dipoles with HTS superconductor



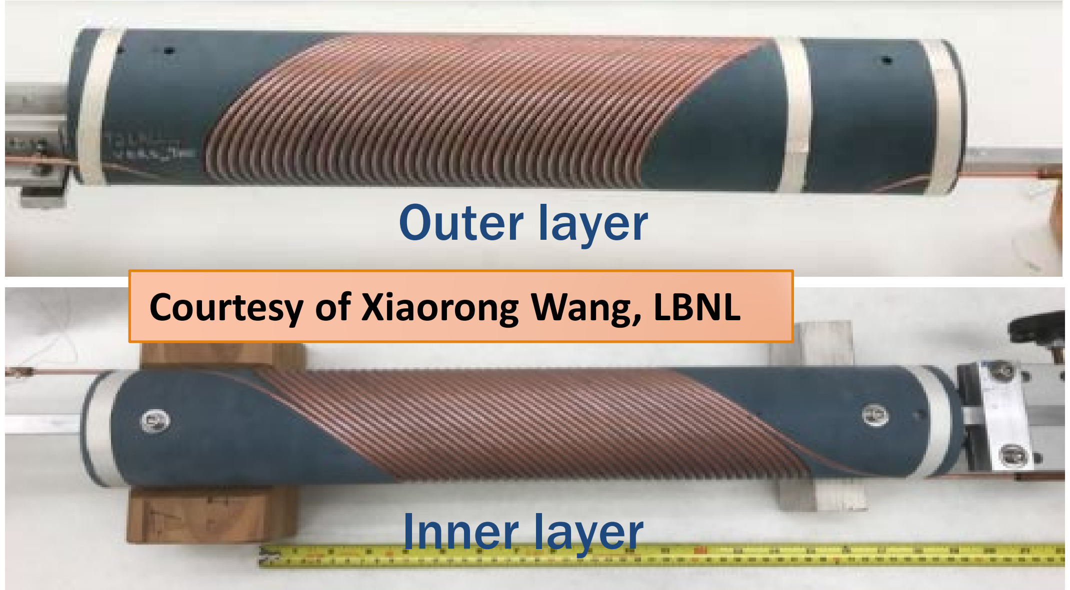
Courtesy of Th. Lecrevisse, CEA, Saclay FR

2-layer insulated CCT dipole of 88 Turns considering Frenet-Serret path without hardway bending, suitable for using HTS tape, under study in H202-I.FAST by CEA and INFN-Mi-LASA.

CORC® By Advanced Conductor Technologies

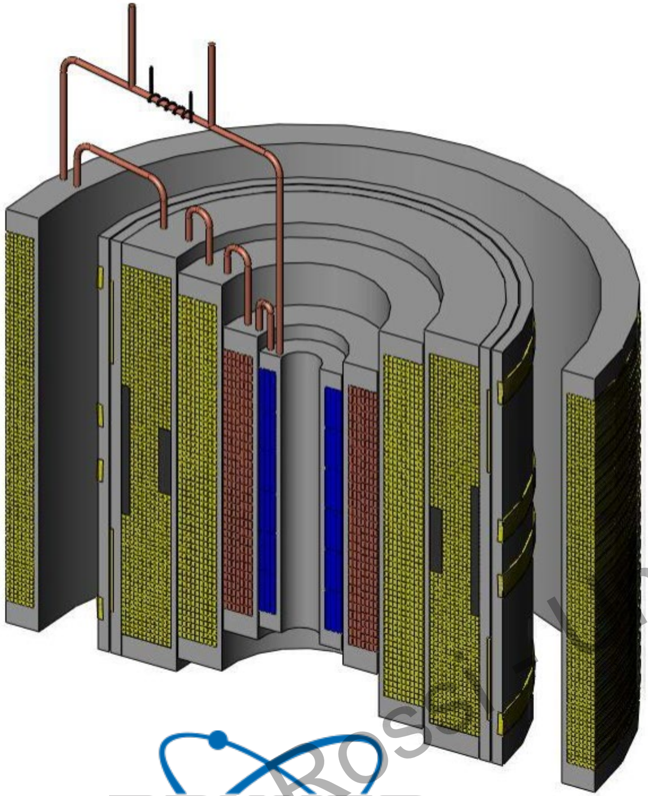
BERKELEY LAB

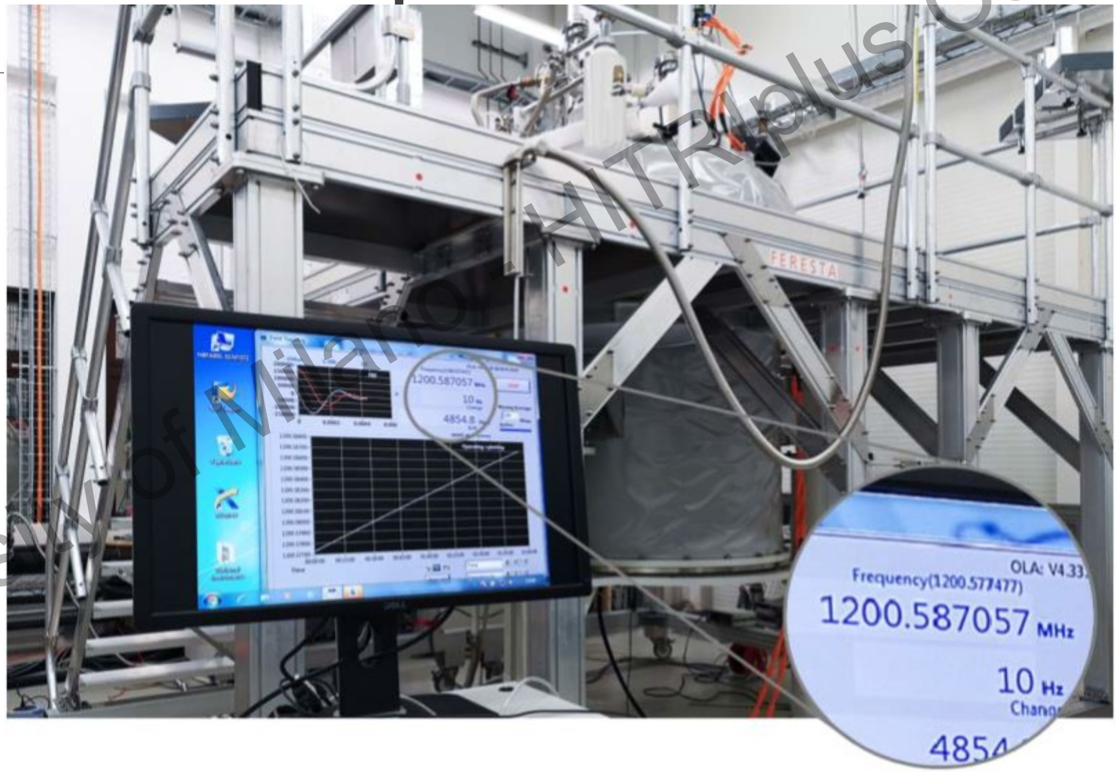
CCT program at LBNL for various applications: HEP, Hadron therapy…



Courtesy of Xiaorong Wang, LBNL

A big leap forward by a private company… Bruker Biospin



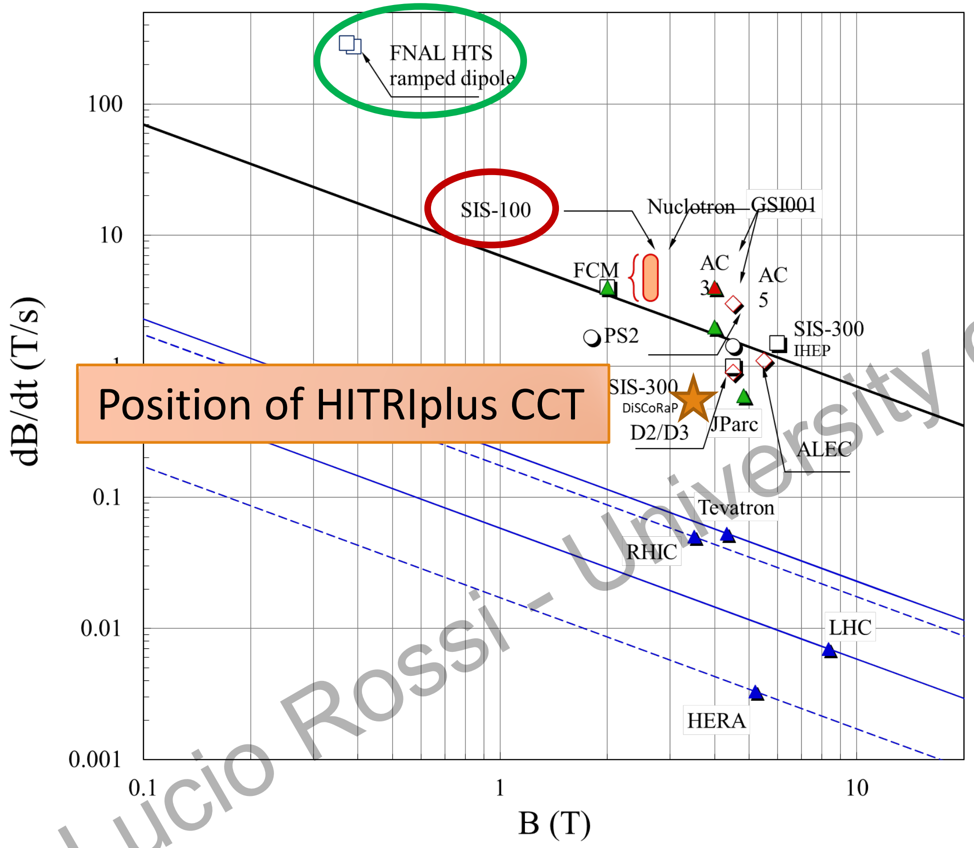


The First 1.2 GHz (28.2 T) NMR Magnet Reached Full Field in 2019, with HTS insert coil

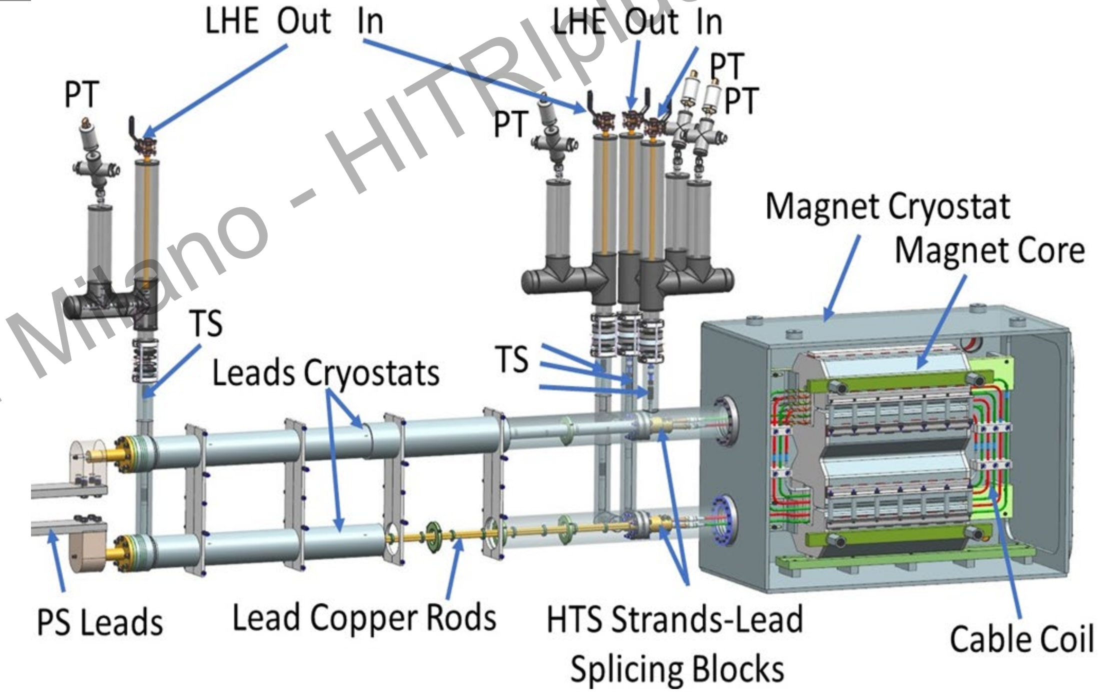
Heavy Ion Therapy Research Integration

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

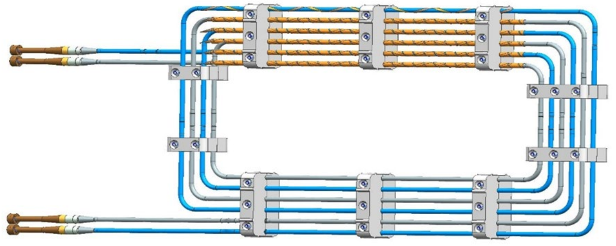
SC Magnets for ramped operation
RCS for hadrons, Muon-C acceleration, Hadron Therapy



Position of HITRIplus CCT

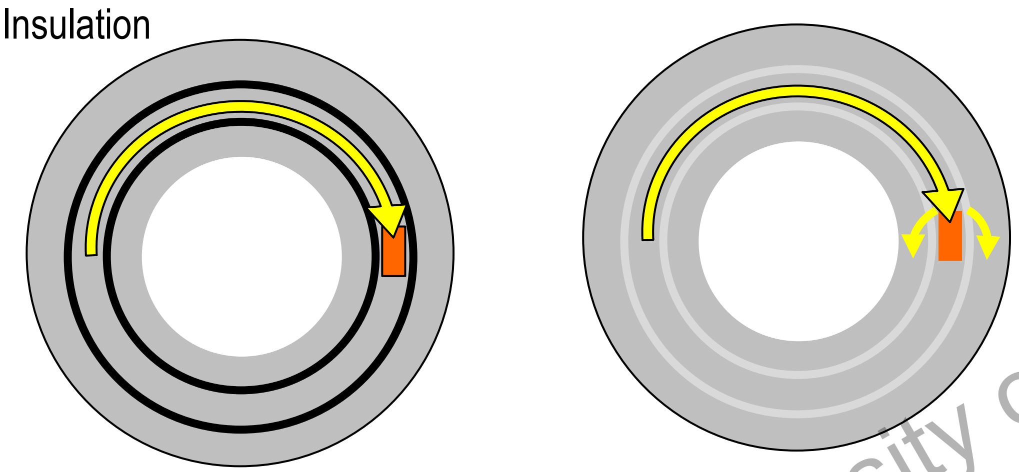


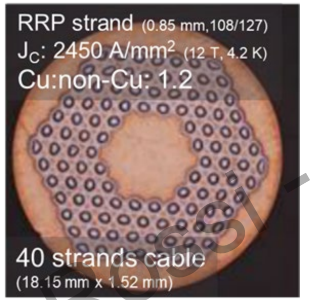
B= 0.3 T
dB/dt ~ 300 T/s
RepRate: 10 Hz
For RCS, for Muon-C…

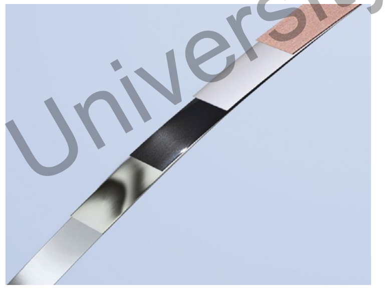


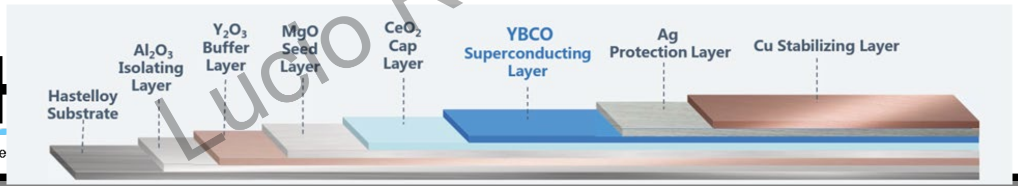
The new frontier: why to insulate a coils? The raise of NI (non-insulated) coil…

Courtesy Prof. S. Hahn, NHMFL









LNCMI/CEA Nougat HTS insert
32.5 T in 50 mm
(12. 5 T HTS + 20 T resistive)

Sunam NI one-body HTS magnet
26.4 T in 35 mm
(26.4 T HTS multi-width)

Need to understand and control transient effects and control Field Quality during ramping up

Horizon 2020
No 101008548

A few refeences (only -old- books)

for papers you can google th ename reported in the paper or few other colleagues (E. Todesco, CERN, Soren Prestemon & P. Ferracin, LBNL, A, Ballarino (CERN), ecc…) or the CAS school on Superconduting magnets (2013)

- ✓ **M.N. Wilson, *Superconducting Magnets,* Clarendon Press Oxford**
- ✓ H.A. Brechna, *Superconducting Magnet Systems*, Springer Verlag
- ✓ K.-H. Mess, P. Schmüser, S. Wolff, *Superconducting Accelerator Magnets*, World Scientific
- ✓ E.W. Collings, *Applied Superconductivity,* Plenum Press
- ✓ B. Seeber (editor), *Handbook of Applied Superconductivity,* IoP Publishing
- ✓ L. Dresner, *Stability of Superconductors,* Plenum Publ. Corp.
- ✓ Y. Iwasa, *Case Studies in Superconducting Magnets*, Plenum Publ. Corp.

HITRI plus
Heavy Ion Therapy Research Integration

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Thank you!

Heavy Ion Therapy Research Integration

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