Magnets and Superconductivity at the LHC

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A few references

Basic Superconductivity:

- M. Tinkham, *Superconductivity*, Gordon & Breach Publisher
- A.C. Rose-Innes, E.H. Rhoderick, *Introduction to Superconductivity*, Pergamon Press
- W. Buckel, *Superconductivity, Fundamental and Applications*, VCH Publisher
- J. Evetts (editor), *Coincise Encyclopedia of Magnetic and Superconducting Materials*, Pergamon Press
- H.W. Weber *High Tc Superconductivity*, Plenum Press
- G. Vidali, *Superconductivity: the next revolution* , Cambridge University Press

Applied Superconductivity

- ✓ **M.N. Wilson, *Superconducting Magnets*, Clarendon Press Oxford**
- ✓ **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.

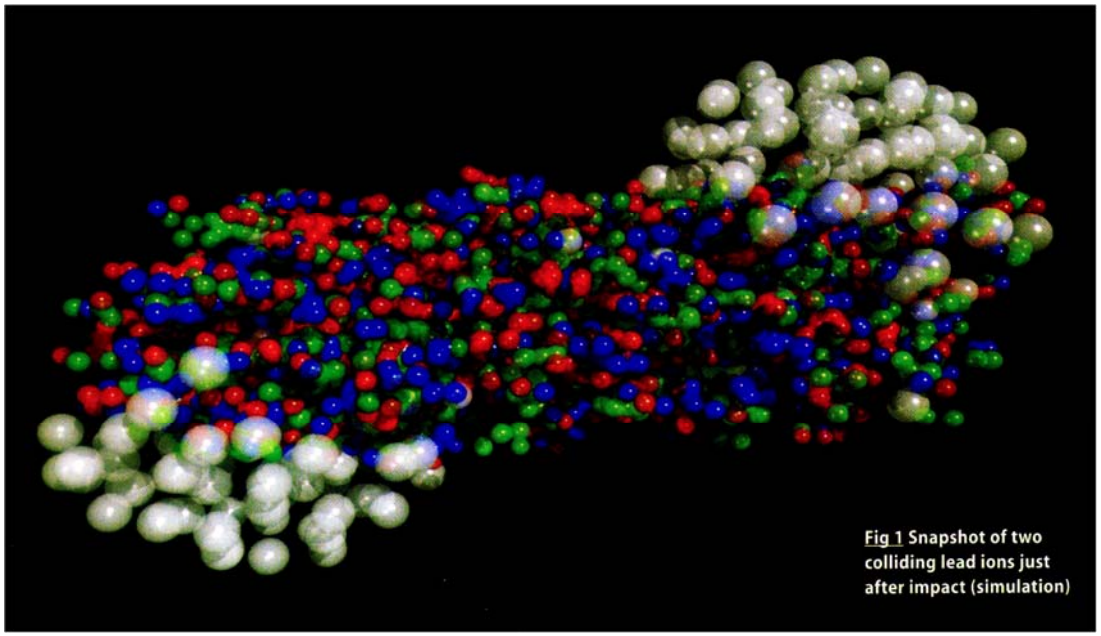
Previous CERN Academic Training

- 1999 : Ph. Lebrun - Superfluid Helium
- 2000 : L. Rossi - Superconducting Magnets
- 2002 : D. Larbalestier - Superconducting Materials
- 2003 : O. Bruning, L. Rossi, Ph. Lebrun et al. - LHC Techniologies

Content

- HEP ⇒ Collider ⇒ Magnets ⇒ Superconductivity
- Superconductivity: more than zero resistance
- Basic SC magnet design and protection
- The LHC main magnets
- Steering the production by Field Quality
- More than Field Quality: installation QA
- ***What's beyond the present LHC ? LHC-up !!!***

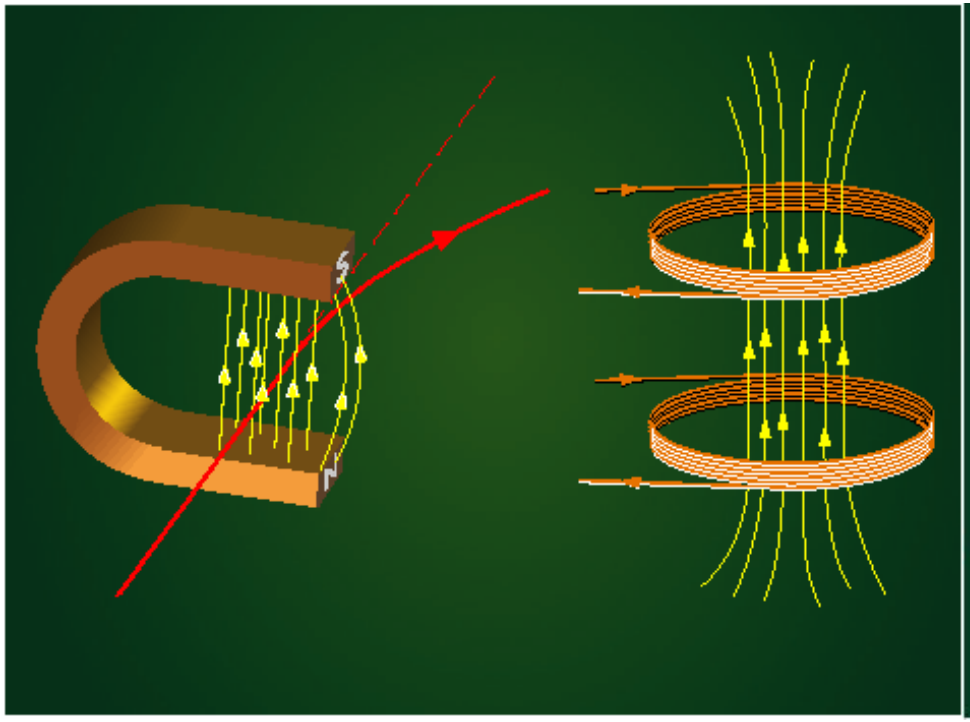
Hadron Colliders

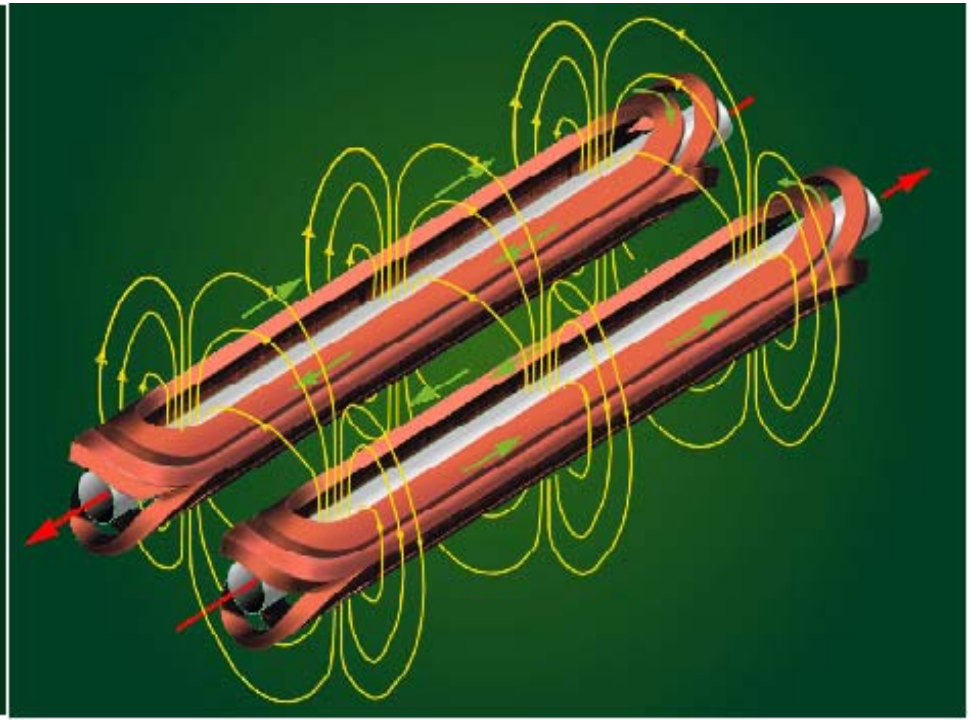


- Very detailed microscope : $\lambda = h/p$
  $T = 10$ TeV $\Rightarrow \lambda \cong 10^{-19}$ m
- Trip back toward the Big Bang: $t_{\mu s} \cong 1/E^2_{GeV}$
  - $T \cong 1$ ps for single particle creation
  - $T \cong 1$ μs for collective phenomena QGS (Quark-Gluon Soup)

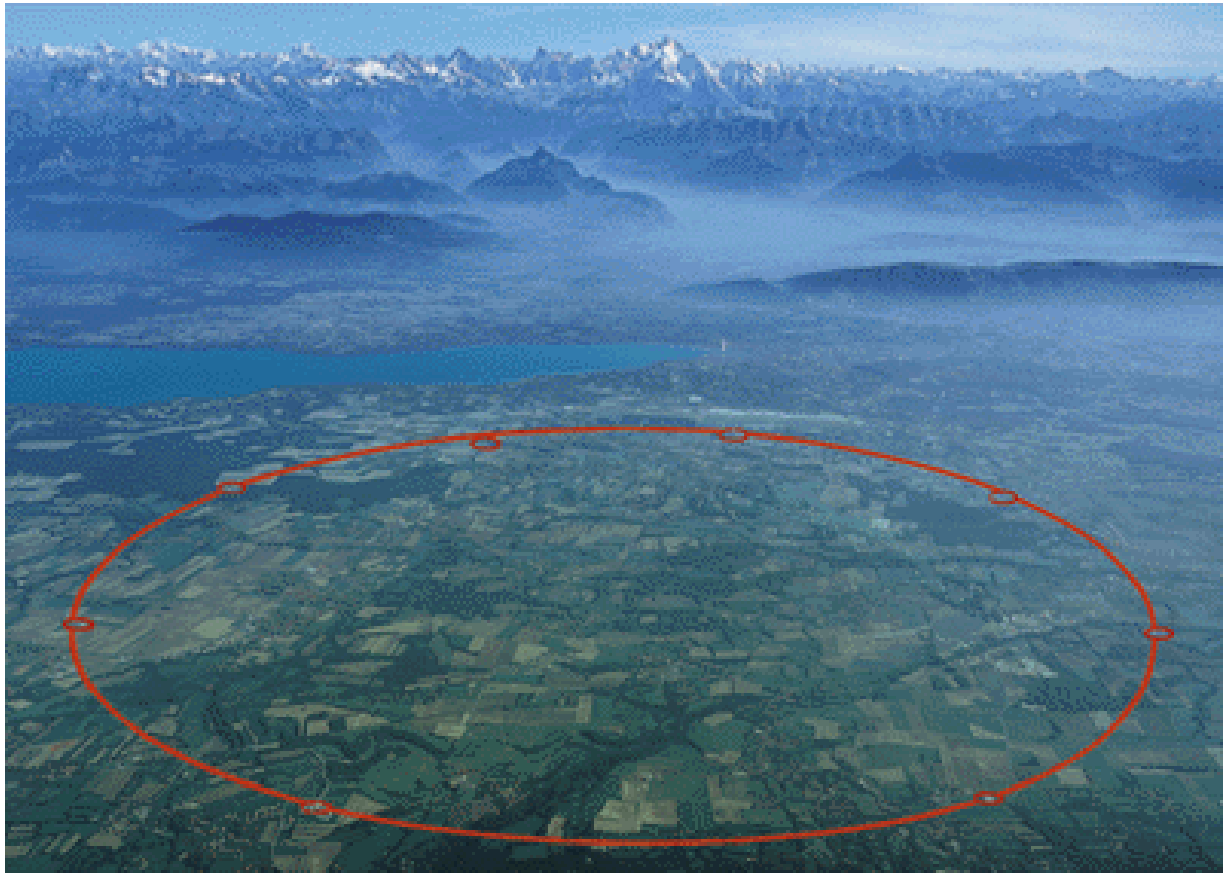
Circular accelerators

- We need energy supplied by RF cavities (sometimes SC as well). Beam has to recirculate through them to build up energy:
  circular or racetrack accelerator concept (based on DIPOLAR FIELD)
- Low Energy Physics (Cyclotrons) HEP (Synchtrons. Colliders)





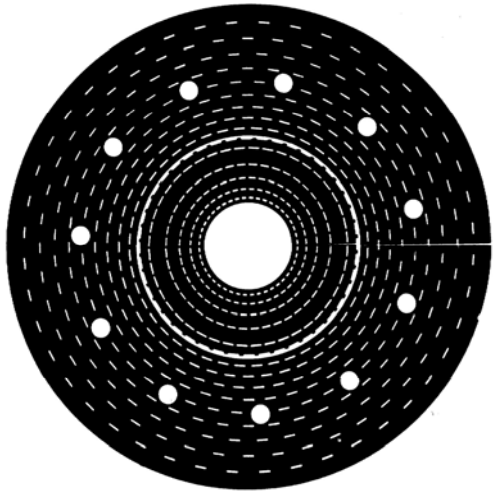
We need magnets



- $E_{beam} \approx 0.3\ B_{dipole}\ R$ [TeV, T, km]
- $R_{eff} \approx$60-70% L_{TOT}
- Bending for beam guidance : dipoles
- Beam optics: quads & multipoles
- Precise and all identical $\approx 10^{-4}$
- economy for large scale projects (SSC lessons !!!)

We need SC magnets!

- Iron dominated magnets limited by iron saturation at 2 T !
- Permanent magnets practically limited in the range 1-2 T
- Copper (or Al) dominated magnets 50-100 T but for ms !!!

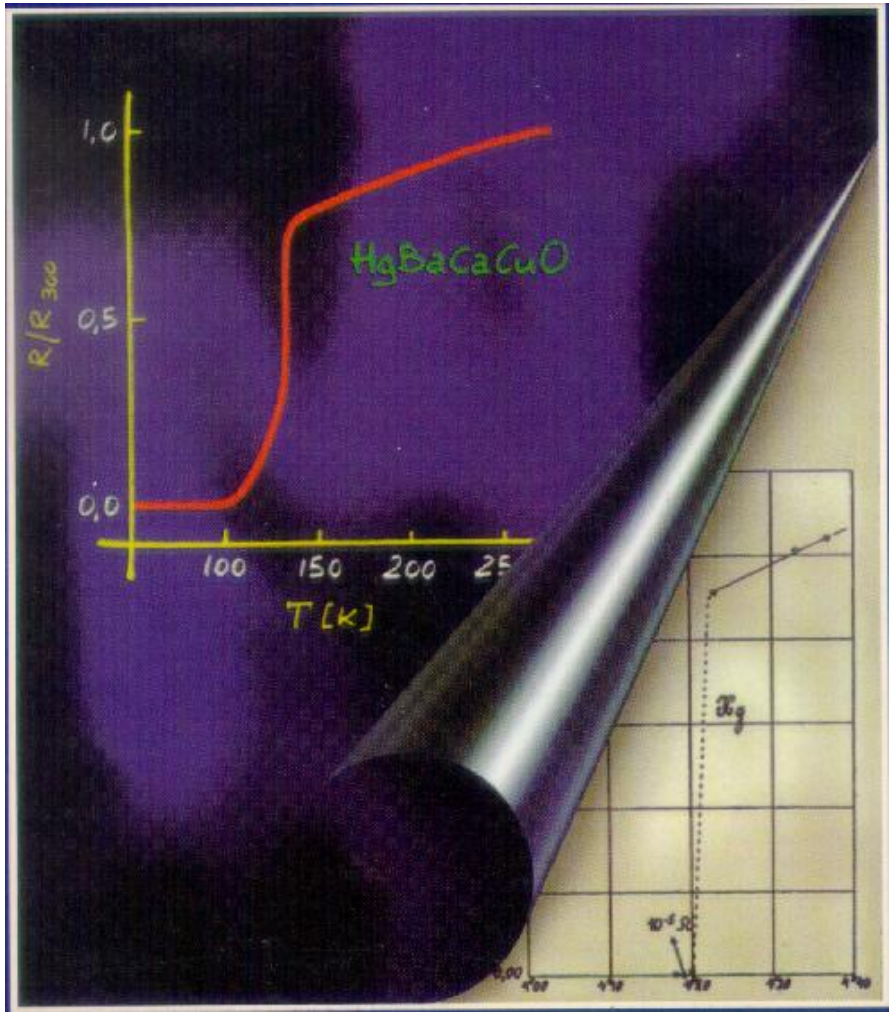


Disk of Bitter magnets (up);

pulsed cryogenic magnet for 40 T - 5 ms

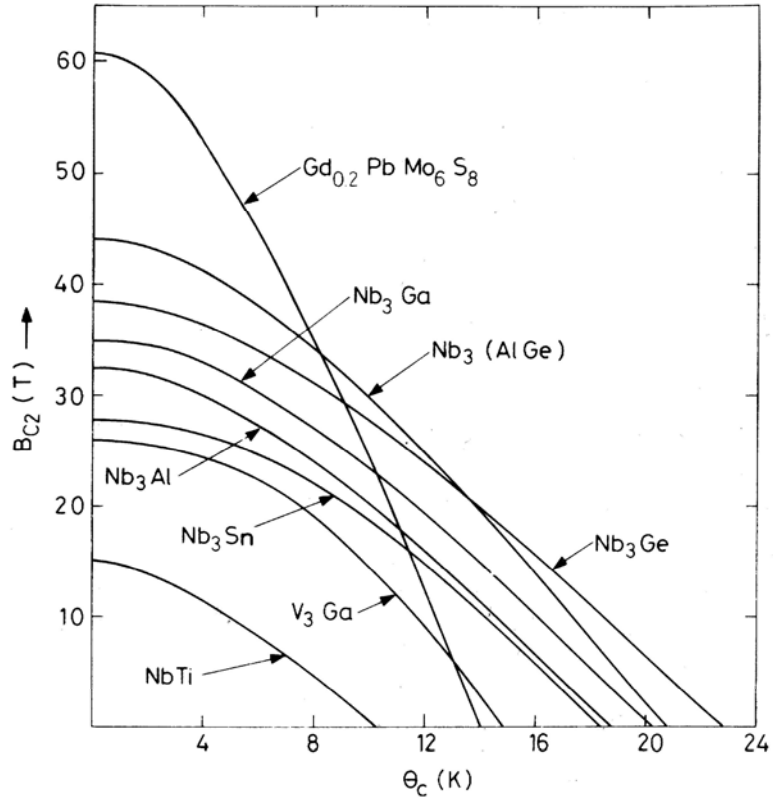
Superconductivity: zero R

- 1908 First helium liquefaction by Heike Kammerlingh-Onnes in the Netherlands.
- 1911 H. Kammerlingh-Onnes discovered superconductivity: zero electrical resistance in a mercury sample (~ 4 K) (Nobel in 1913)
- 1986 : Bednorz and Muller discovered Cu oxides
- 1988: BSCCO (Bi-Sr-Ca-Cu-O) 110 K
- Hg: record Tc ≈ 135 K
- 2001 new class: MgB_2 Tc ≈ 30 K

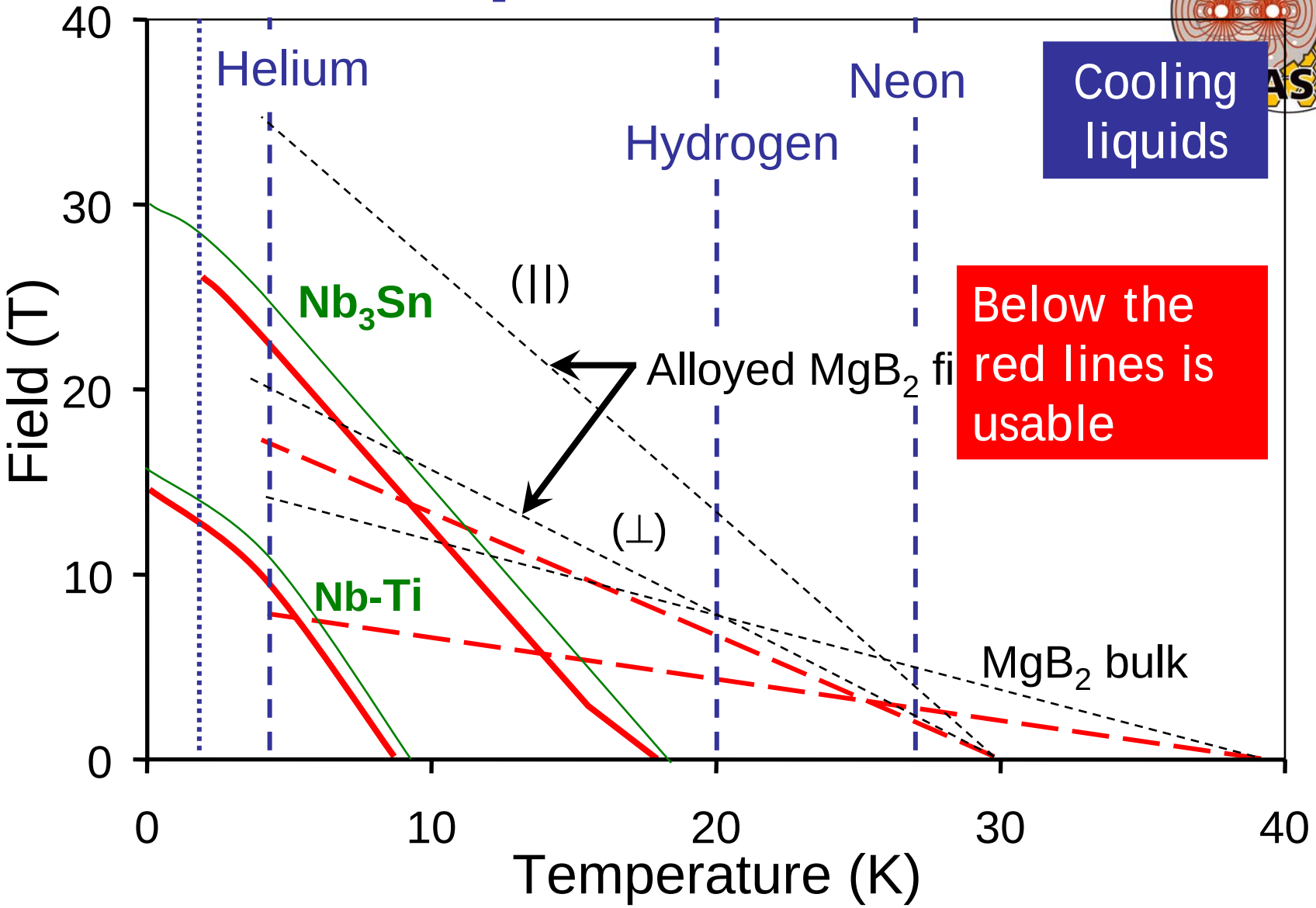


Critical Field

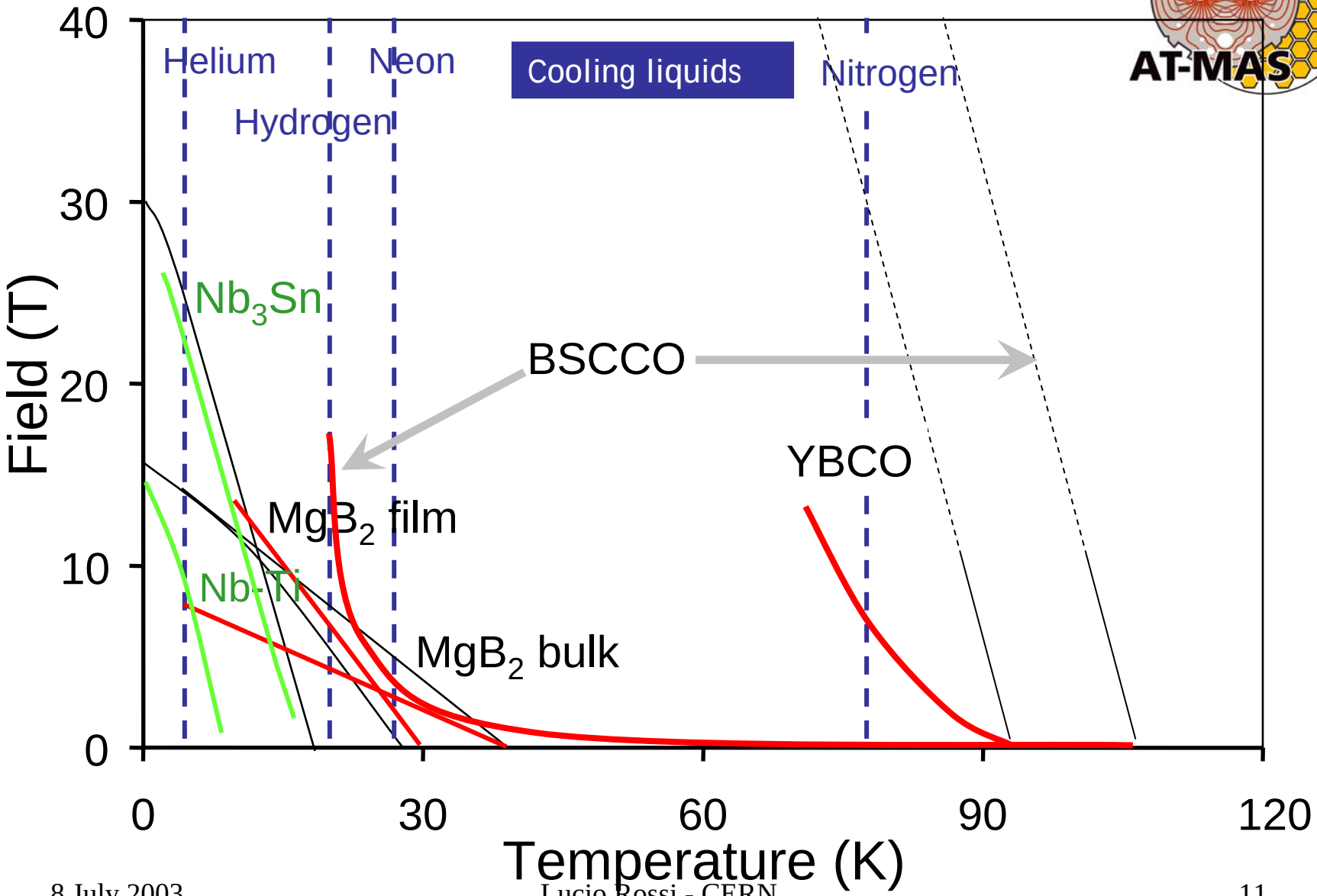
- A Sc is not a simple perfect conductor
- Jsc is limited by magnetic field (and T!!)
- The first Sc materials (pure element) had Bc of 10-100 mT !!
- In the 1950-60s alloys were discovered with Bc of 10-20 T !!!
- Ceramic HTS have Bc 100 T
- MgB_2 has Bc around 15 T



H*-T plane for LTS



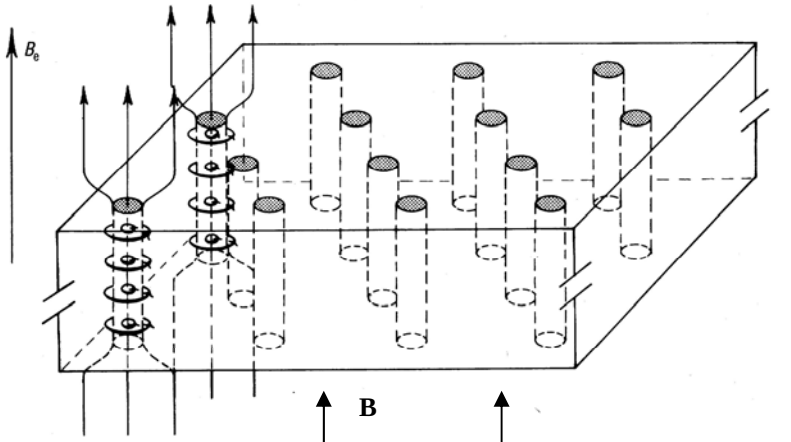
H*-T plane for LTS and HTS

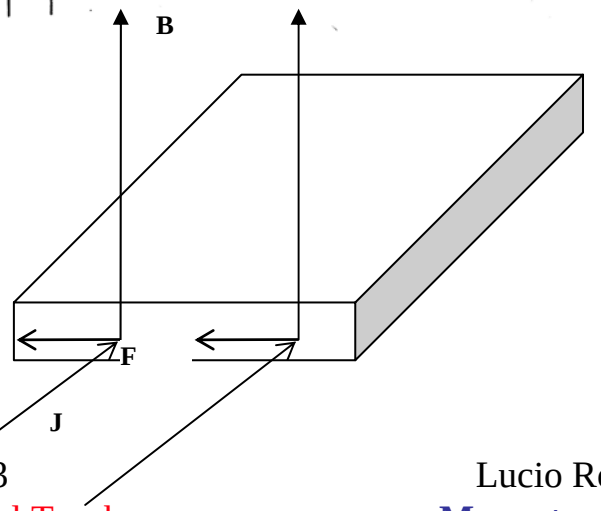


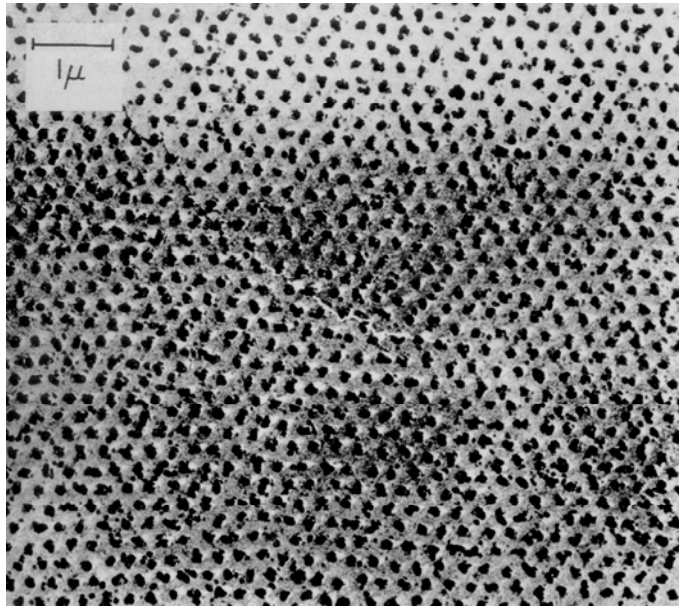
More than “simple perfect conductors”: type II SC

Flux penetration in the material is in quanta:

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







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

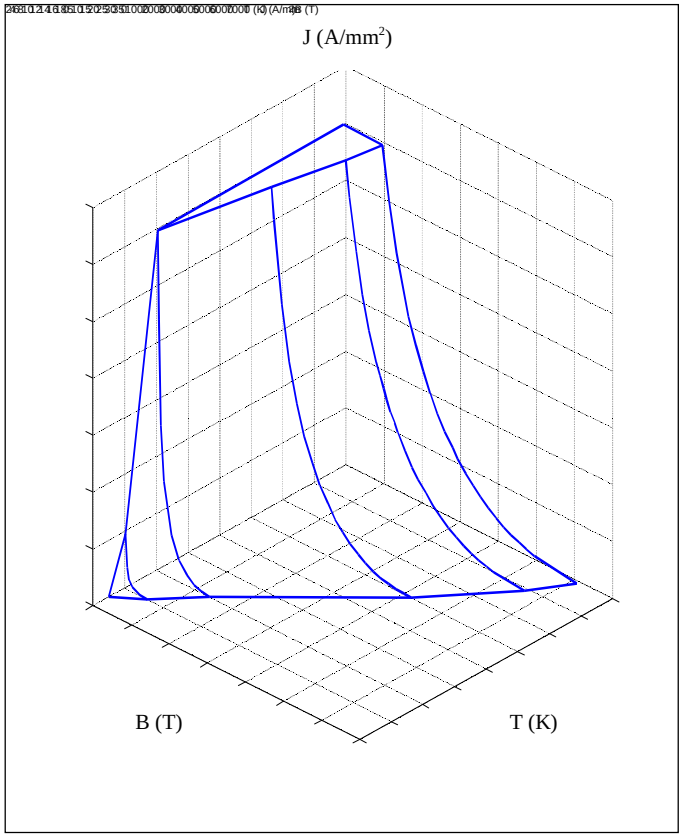
NbTi: $F_{p\,max} \approx 15$ GN/m^3 (or 15 N/mm^3 !!) $\Rightarrow J_c \approx 3$ GA/m^2 (3000 A/mm^2) at 5 T

Practical Materials

Long journey from material discovery to magnet application

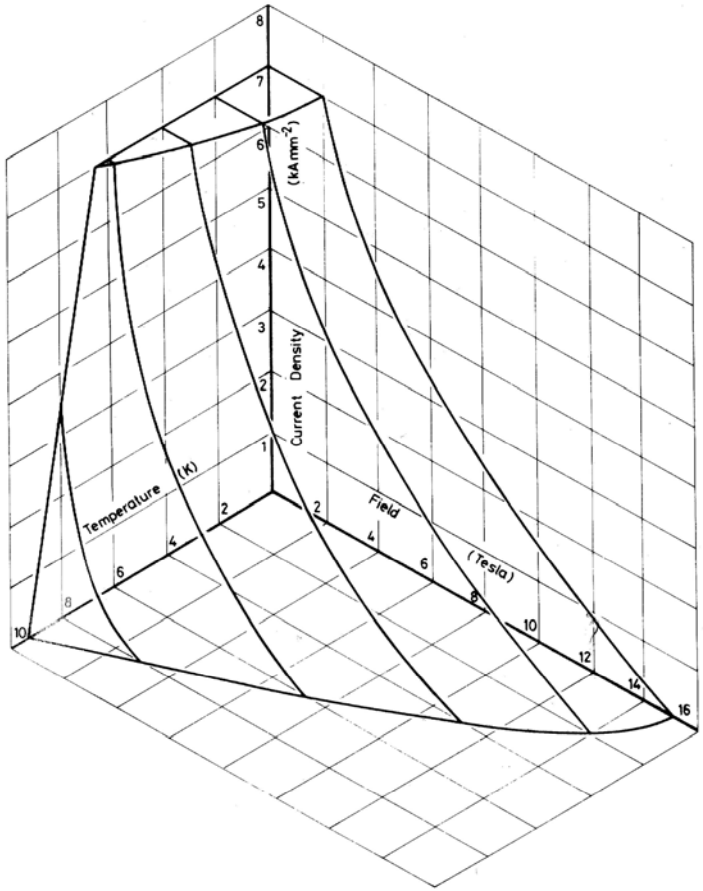
Iwasa table on the long route

Criterion	*Number*
Superconducting	~ 10,000
$T_c \cong 10$ K .and. $B_{c2} \cong 10$ T	~ 100
$J_c \cong 1$ GA/m^2 @ B > 5 T	~ 10
Magnet-grade superconductor	~ 1



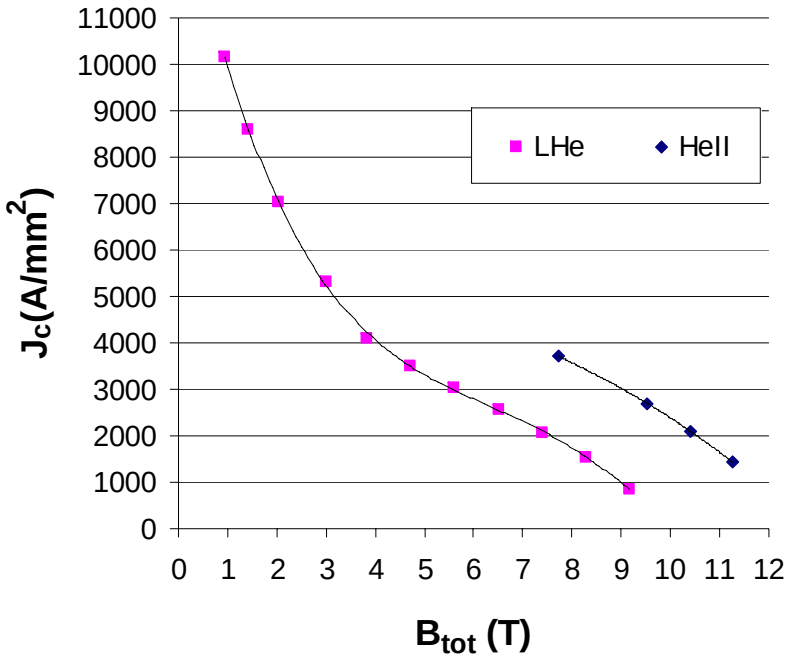
Critical surface for Nb_3Sn
INFN-LASA, 1999

Niobium-Titanium



Critical surface of NbTi (from Wilson textbook)

Critical current density vs field measured on NbTi multiflamentray wire at 4.22 and 2.17 K

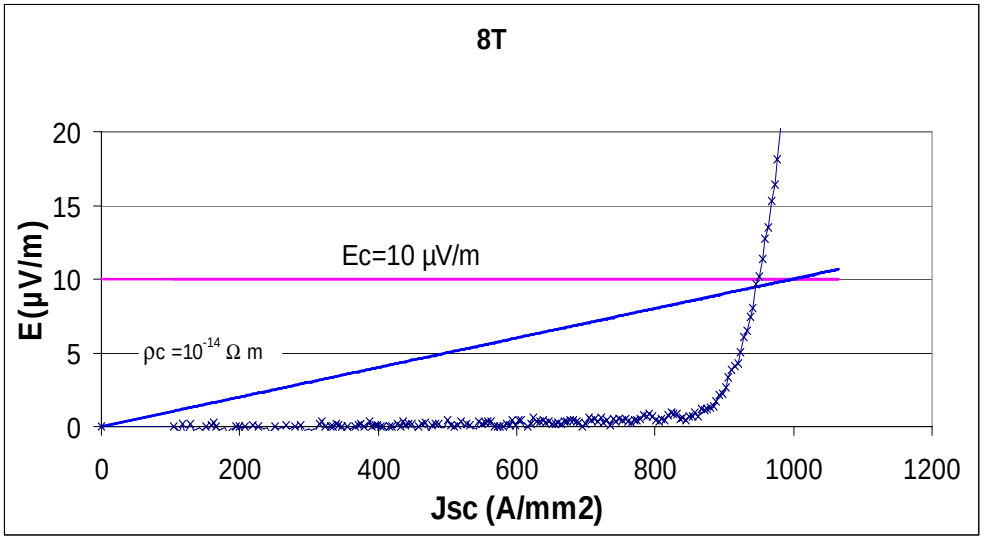


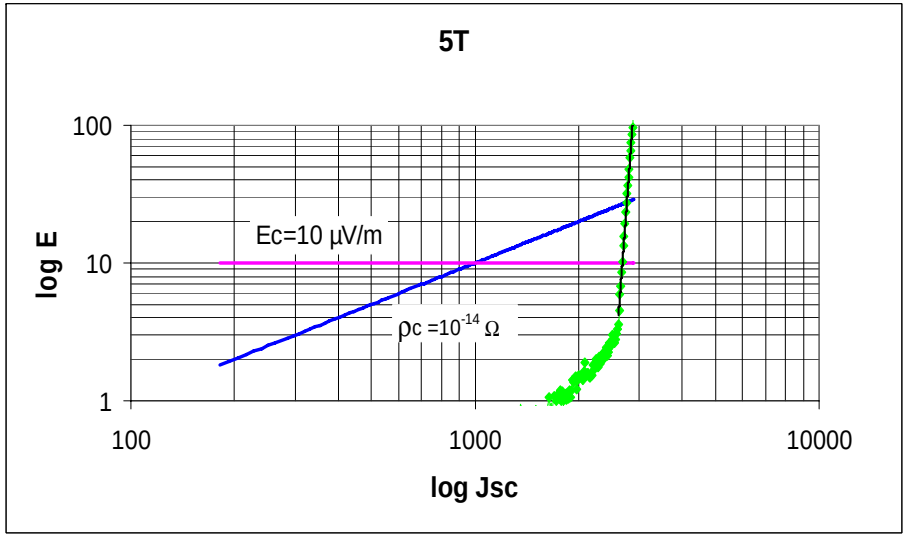
Critical current of best Cu/NbTi with typical **3 T field shift at superfluid helium** (INFN-LASA lab, february 2000)

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.

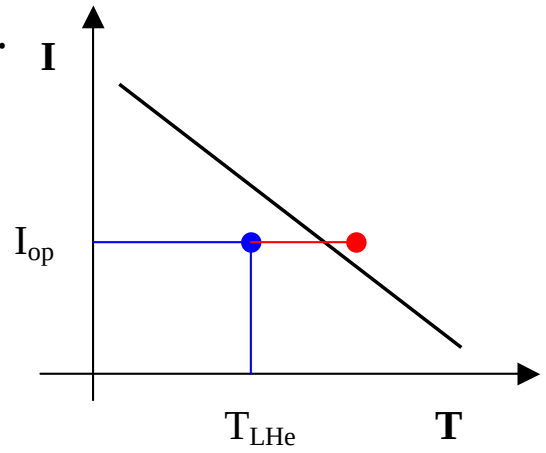




Superconductors are not stable!

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

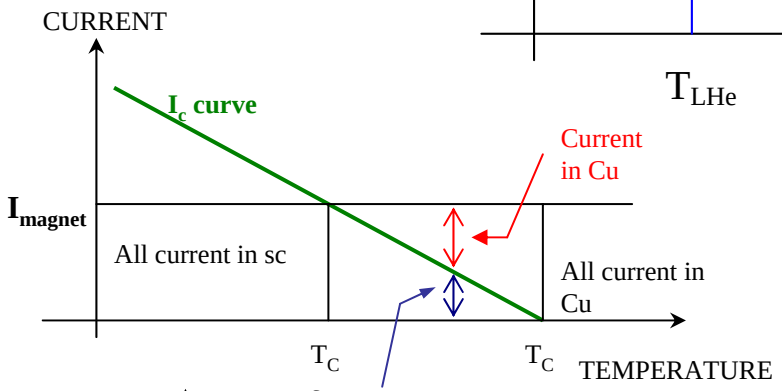
Heat capacity drops at low temperature ($T << T_{Debey}$) :
$C \propto T^3 \Rightarrow \Delta T = \Delta E/\gamma C$. So even small ΔE generates sensible ΔT
$\Rightarrow$ operating point of the magnet beyond critical surface $\Rightarrow$ **QUENCH**

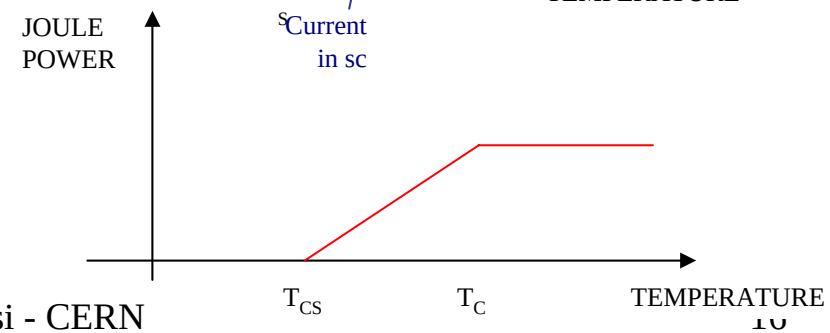


Electrodynamic stability: intimate contact between the superconductor and a good conductivity material.

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

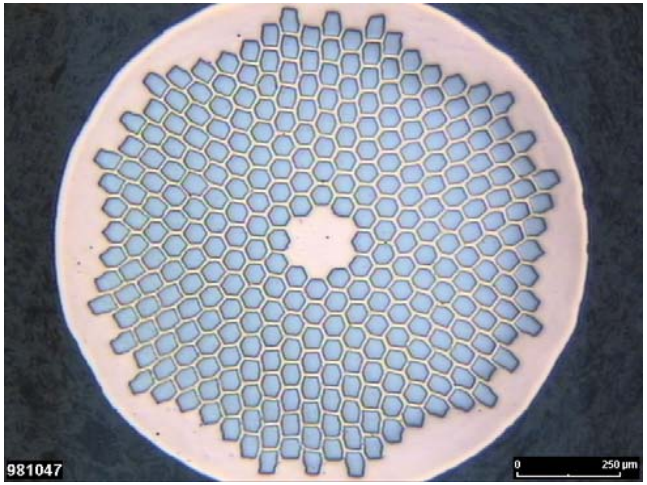
Direct cooling : LHe and more HEII are very good coolant, capable to remove heating in milliseconds! Latent heat 10-1000 times that of solid specific heat!





Wires and cables

multifilamentary wires, where hundreds if not thousands of fine filaments are embedded in a stabilising matrix. Strongly twisted (5-50 mm pitch length) for stability in varying field and for self stability.

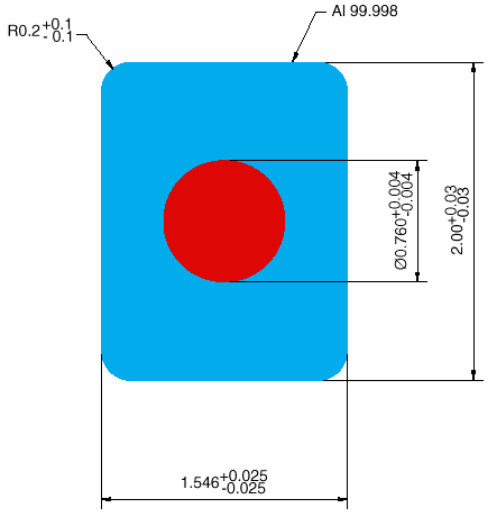


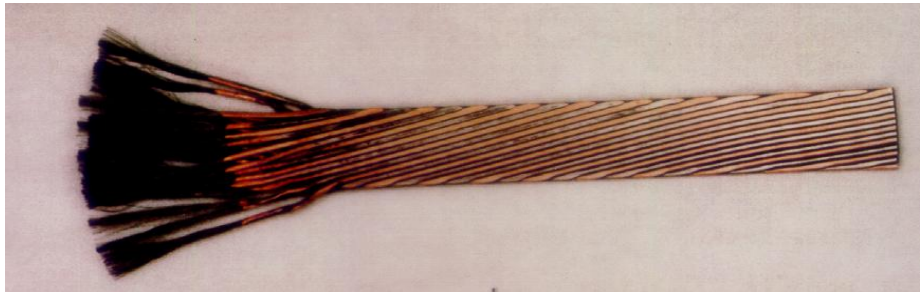
← Atlas Cu/NbTi wire

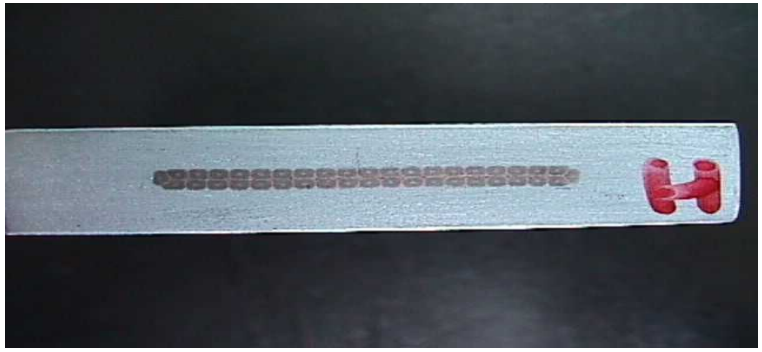
AMS-02 Cu/NbTi/Al →

Rutherford cable for
↓ LHC dipole

Atlas conductor
(Rutherford coextr.
with pure Al) ↓







Controlling the Stabilizer content

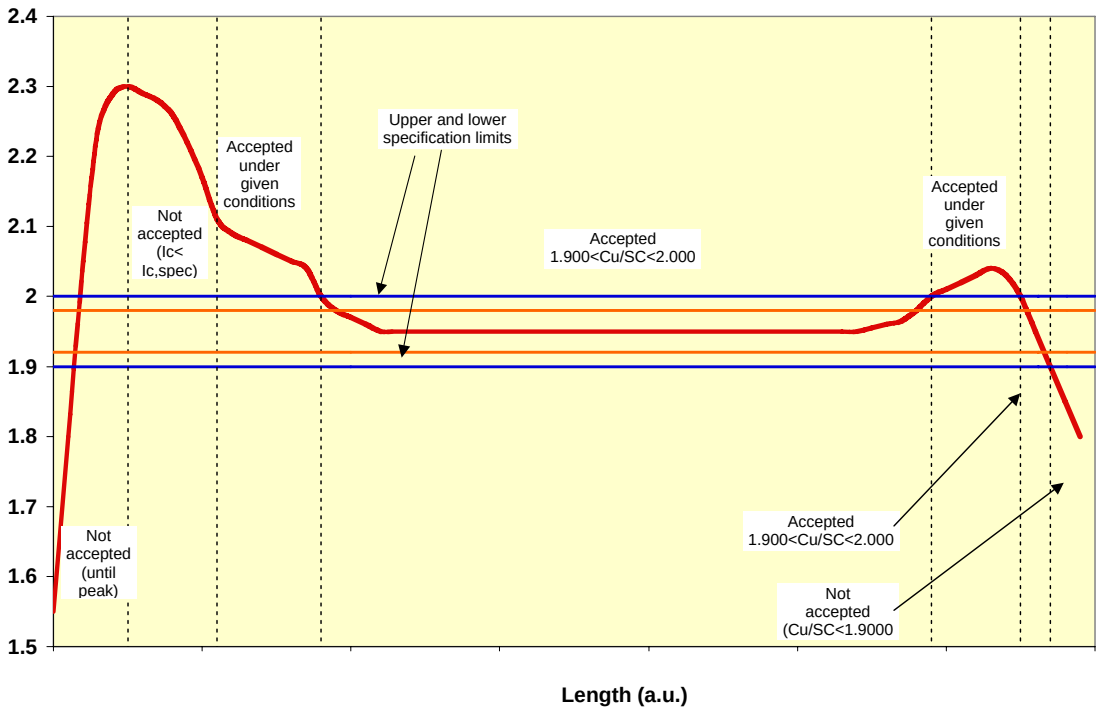
$J_c \approx$1-2 kA/mm^2

J_{stab} same order

Trigger protection in ms time (for a big plant is not trivial !)

Unbalance between coils and magnets due to Cu variation

$\Rightarrow$ Dangerous internal voltages

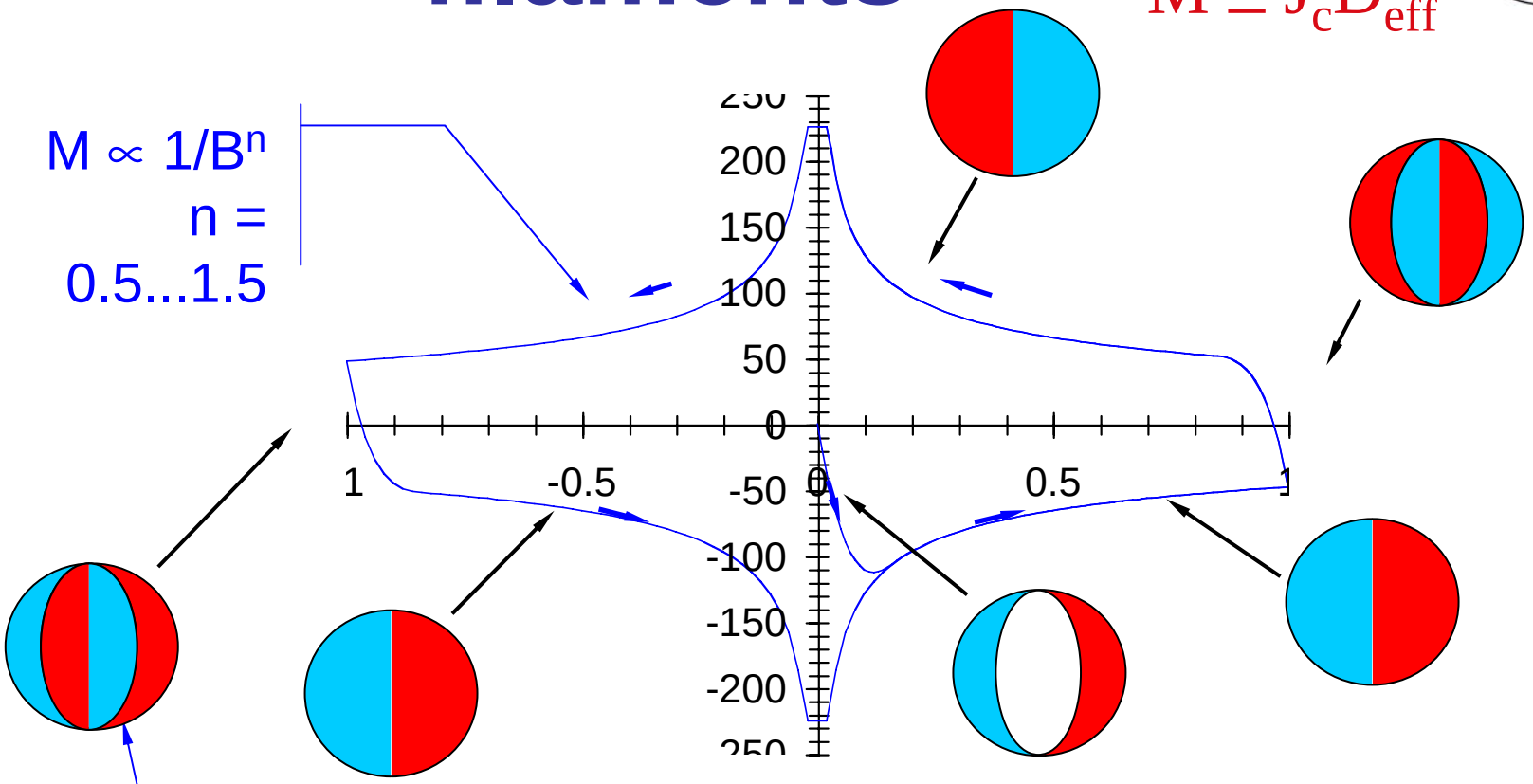


Courtesy of D. Leroy

Important point: Cu/Sc is always cost sensitive

Magnetization and fine filaments

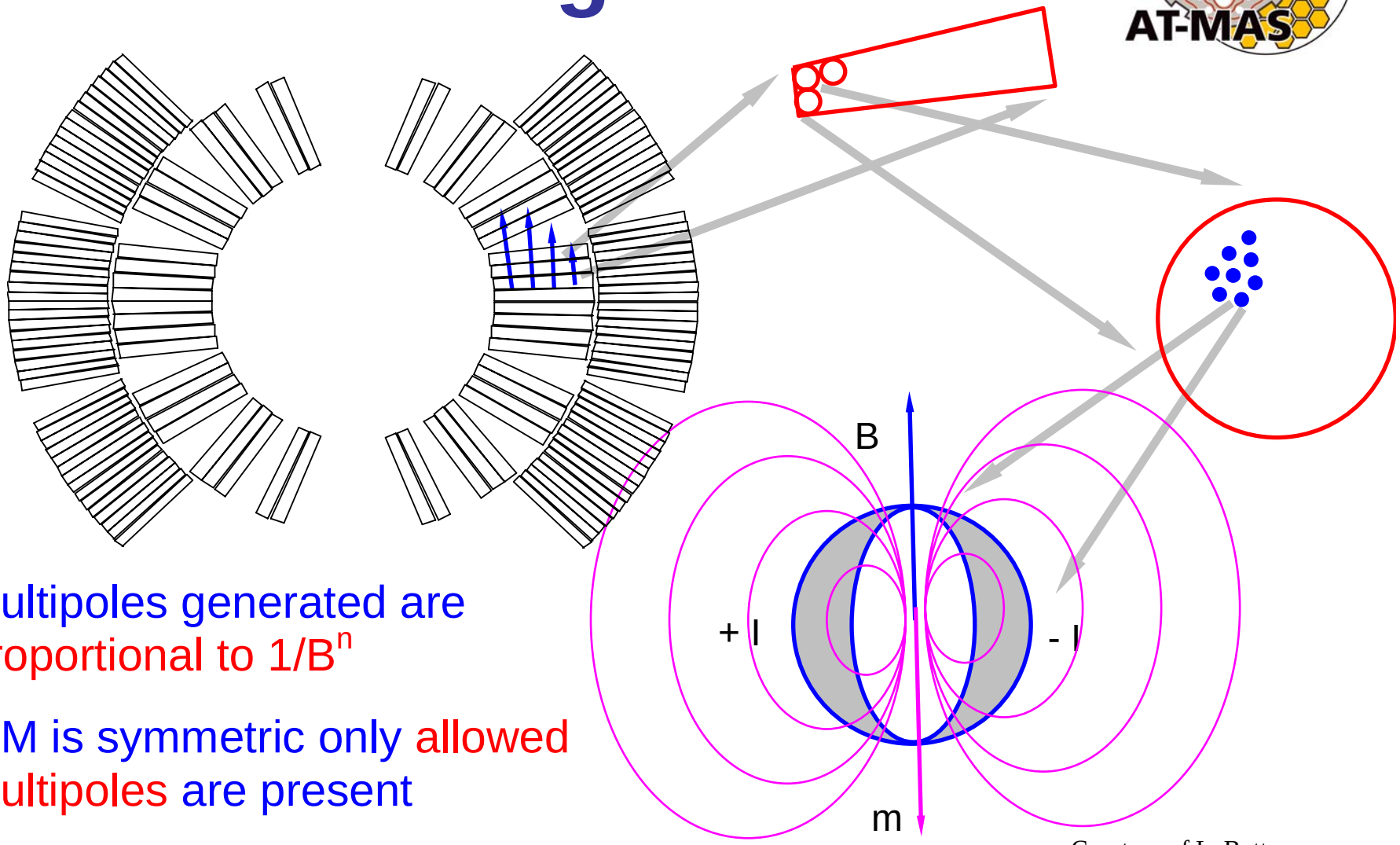
$M \cong J_c D_{eff}$



shielding current layer in a superconducting filament (persistent currents)

Courtesy of L. Bottura

Effect of magnetization

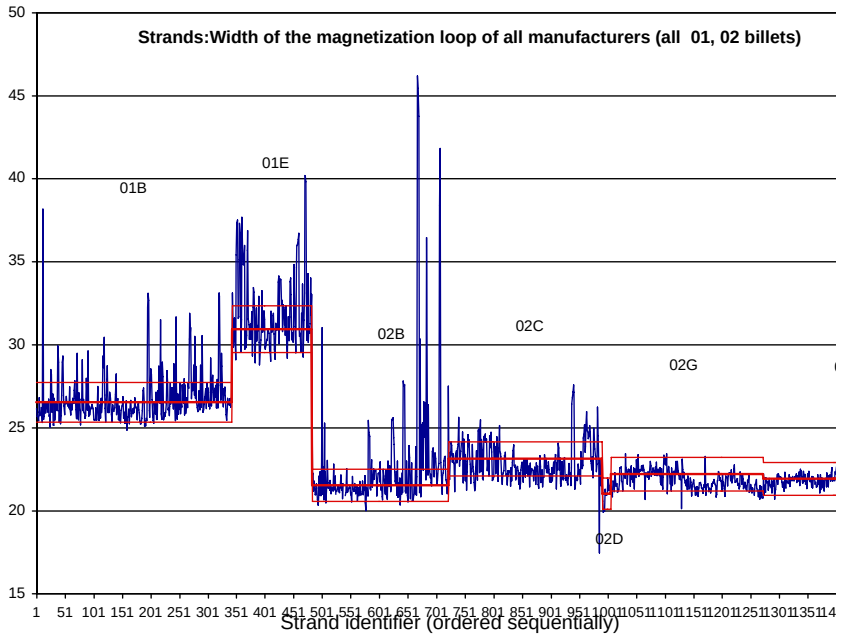


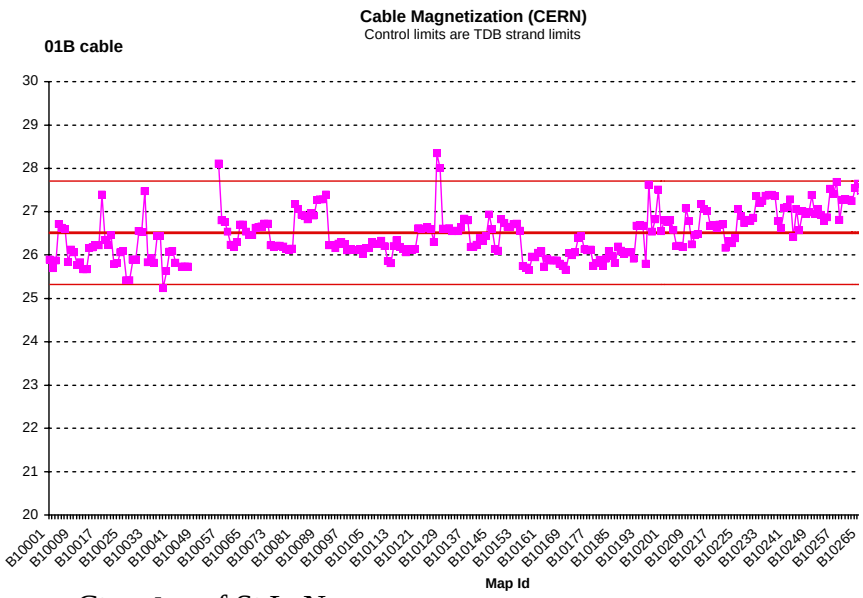
Multipoles generated are proportional to $1/B^n$

If M is symmetric only allowed multipoles are present

Courtesy of L. Bottura

Magnetization for LHC NbTi





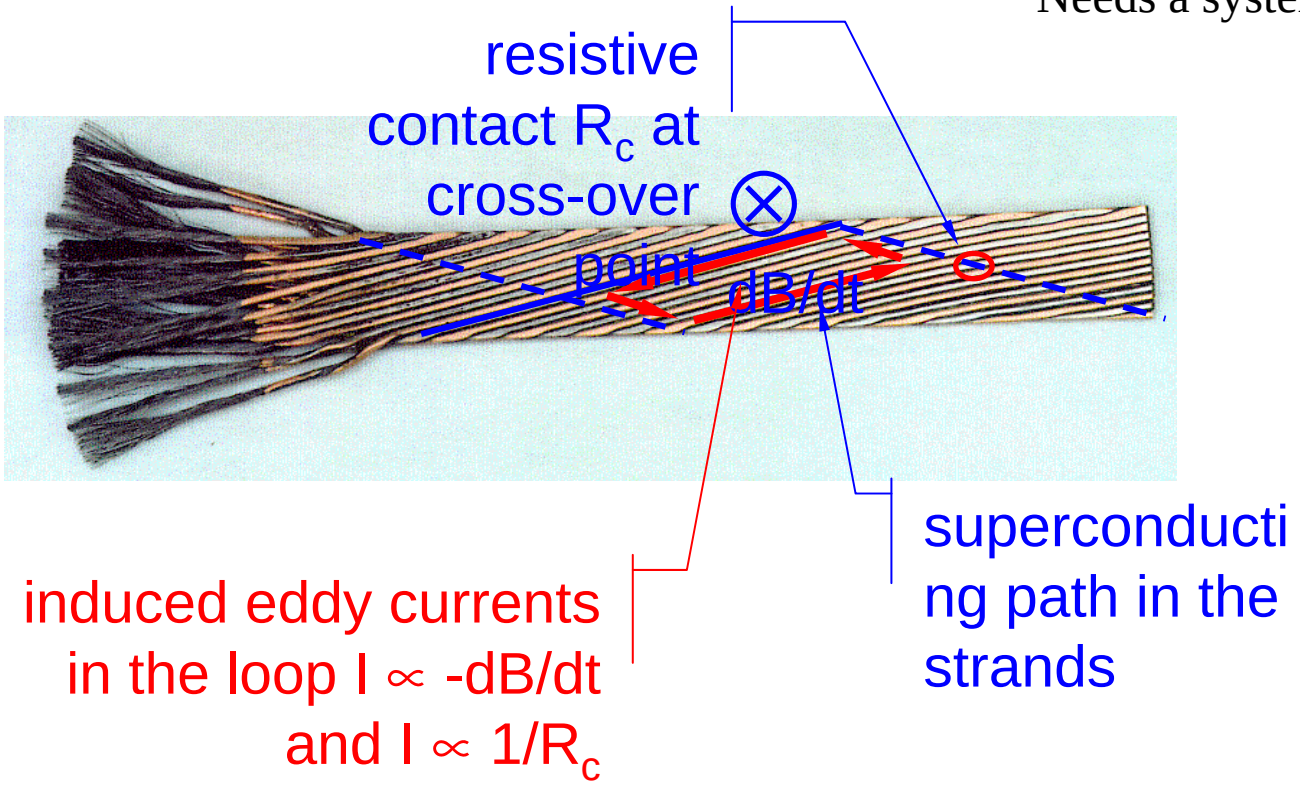
Due to field imperfection generated by M:

Rejection of conductor

Limit in the dynamic range of the magnets

In LHC D_{fil}= 6-7 μm

Rutherford cable



Needs for 10-20 kA cable for protection

Needs very high packing factor: 90% !!

Needs a system simple that keep strands

The strand are fully transposed

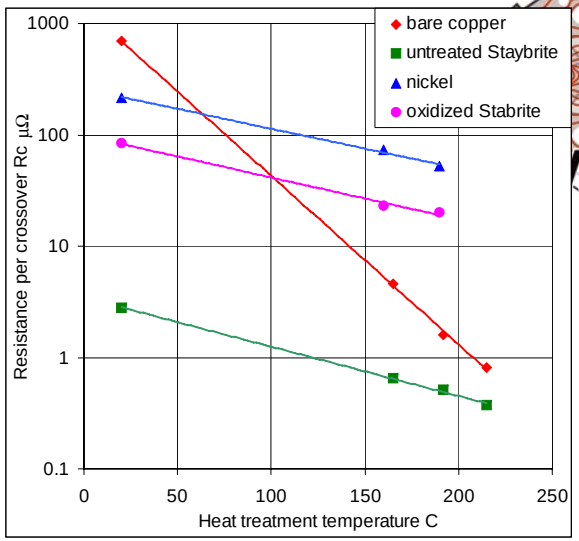
BUT field changes over a period !

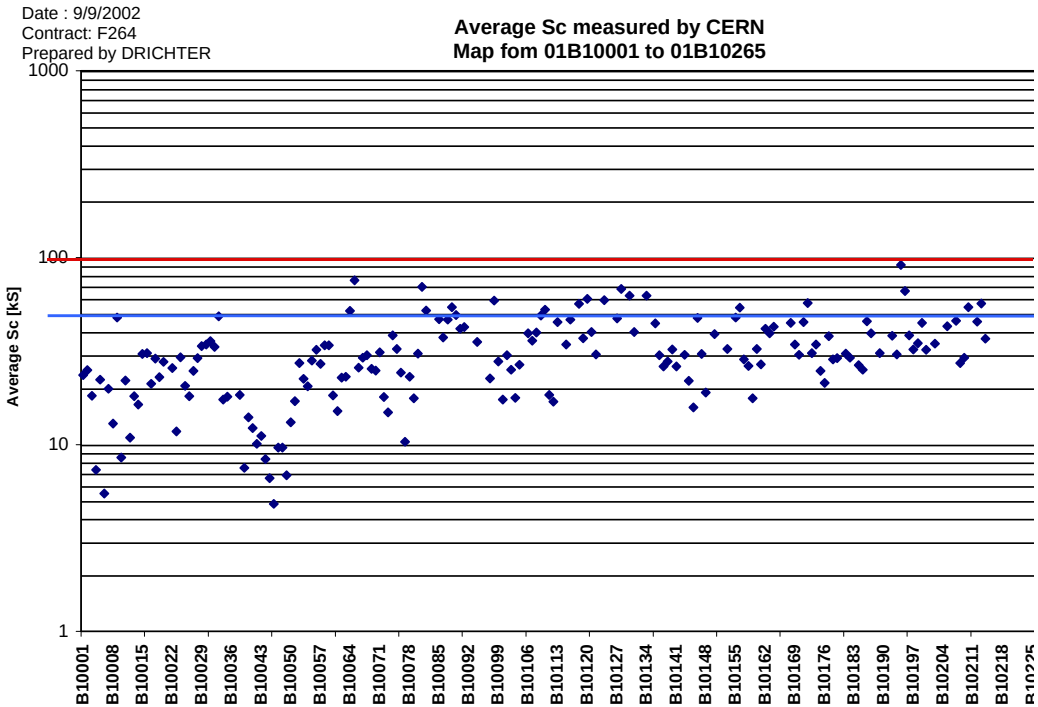
Ends problems

Junctions

BICC

Controlling the contact resistance





CERN has developed the controlled oxidation method

Coating wire with 0.3-0.5 of SnAg then H.T. cable in air

What are the acceptable limits ?

Too low (< 15-20) gives field errors (ad He consumption

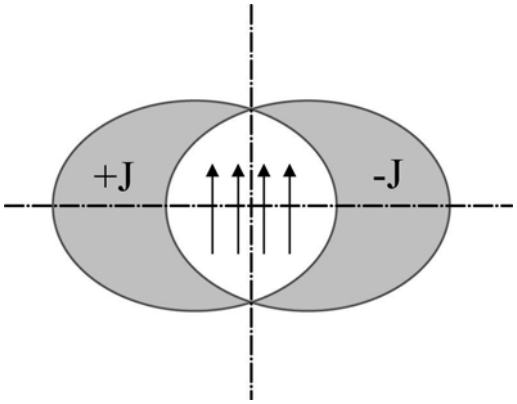
Too high (>100-200) may raise instability or current distribution

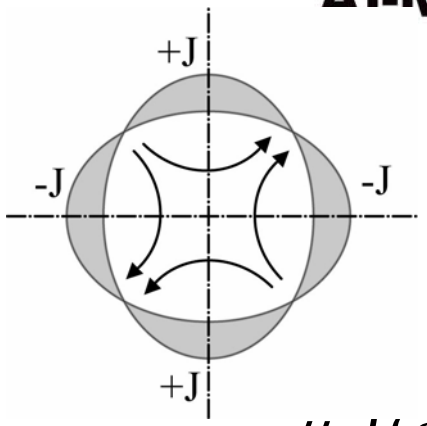
Courtesy of D. Ritcher

Accelerator Magnets
Basic Design - I

Intersecting ellipses generate uniform field.

Two intersecting ellipses, rotated of 90°, generate a perfect quadrupole fields:.





All these configurations follow:
$J_s = J\cdot\cos(\theta)$, $J_s = J\cdot d\cdot\cos(2\theta)$, …

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

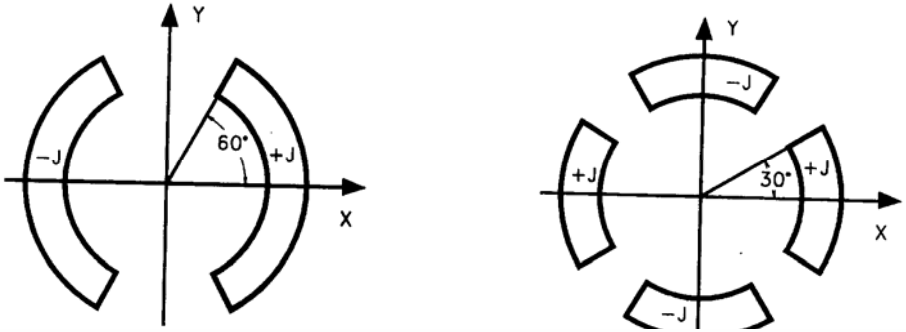
$$B_x = \frac{\mu_0 J (a-b)}{a+b} y$$

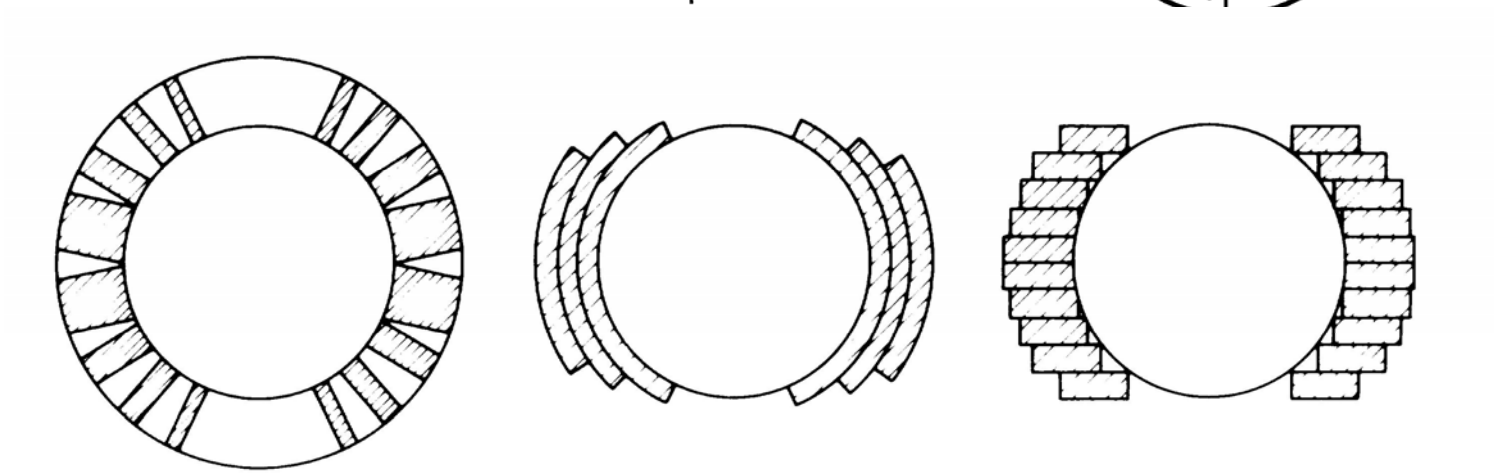
$$B_y = \frac{\mu_0 J (a-b)}{a+b} x$$

In practice the above current distributions are approximate, so the field contains also higher order harmonics (see later).
It can be shown that if the cos(nθ) is approximate by step function, there is a "magic" angle that makes nil the first higher order harmonics.

Accelerator Magnets
Basic Design - II

Uniform shell current density with cut to nul the first higher order harmonic.



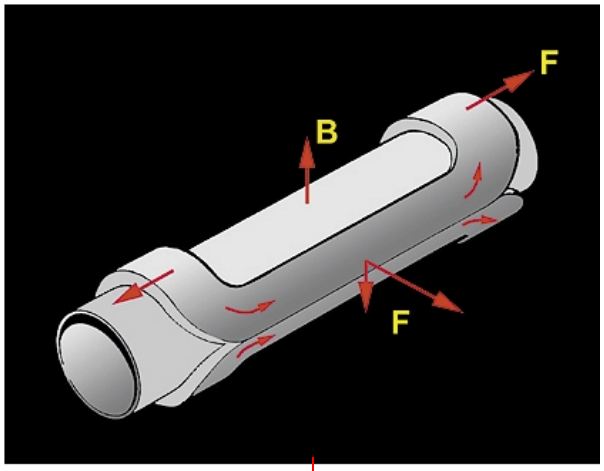


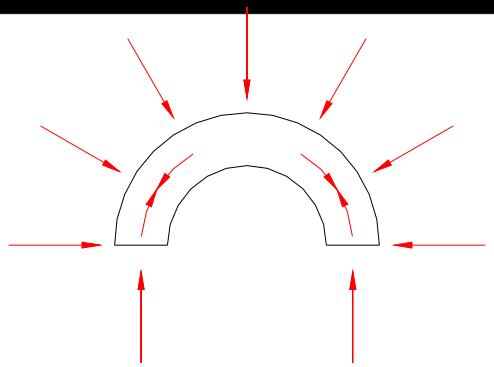
Approximation of cosθ with coil blocks (left) and multiple shells (centre) and of intersecting ellipses (from Wilson book).

Accelerator Magnets: Basic Design - III

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

Principle





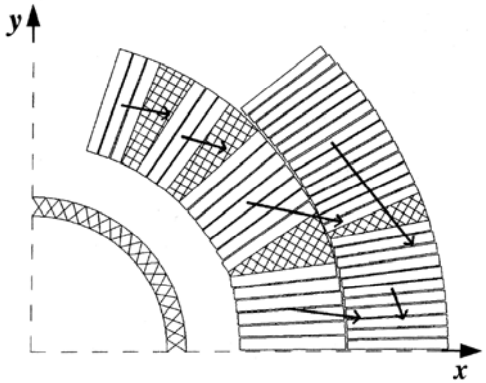
e.m. forces

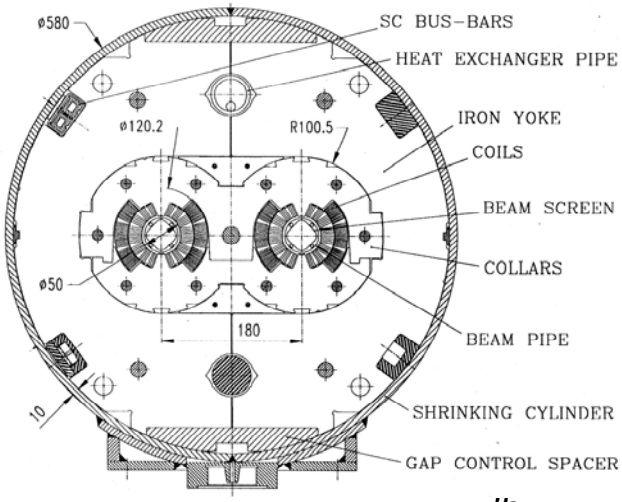
NOT SELF-SUPPORTING

How to contain them

More difficult in twin magnets!

Reality

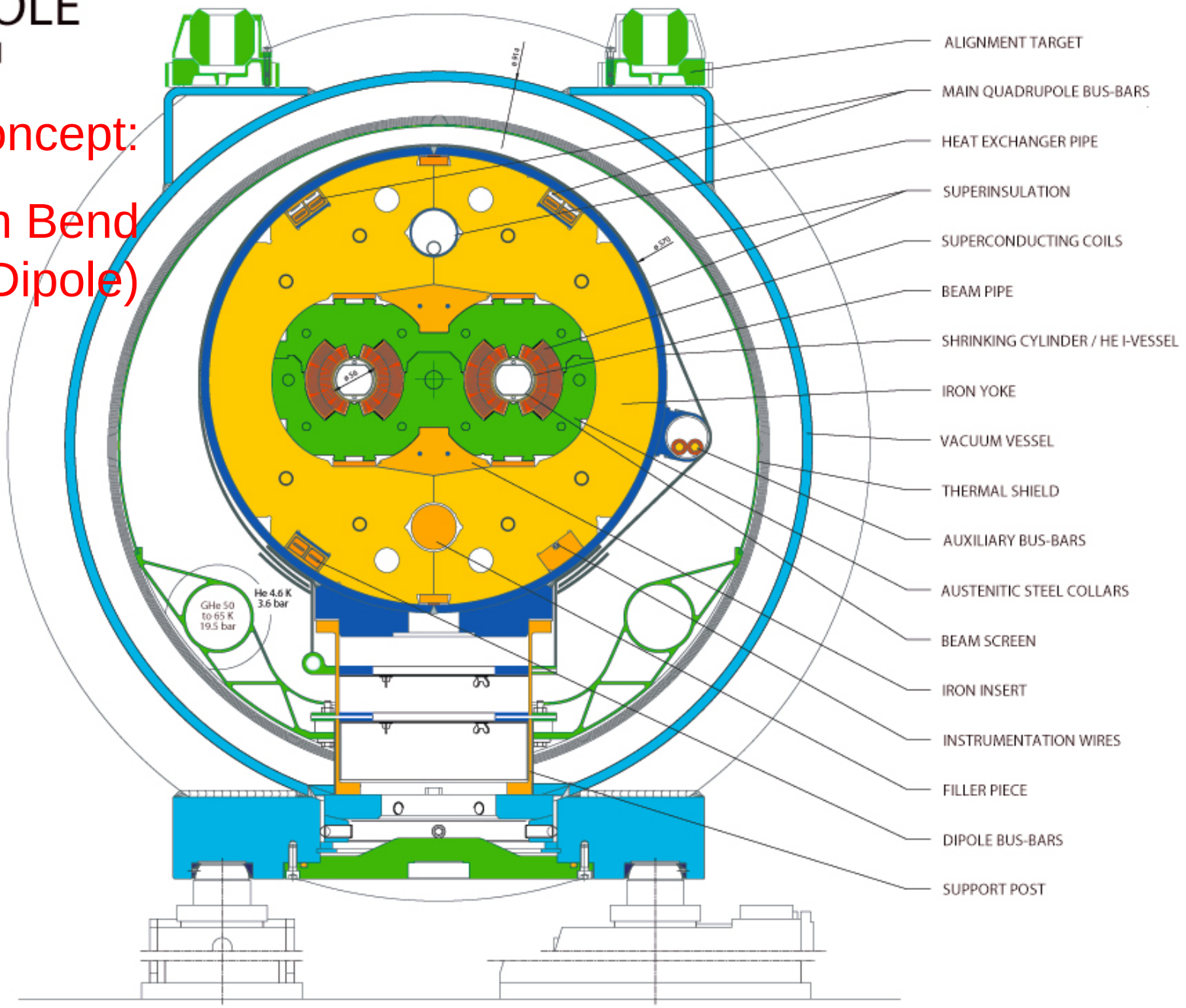




LHC DIPOLE
CROSS SECTION

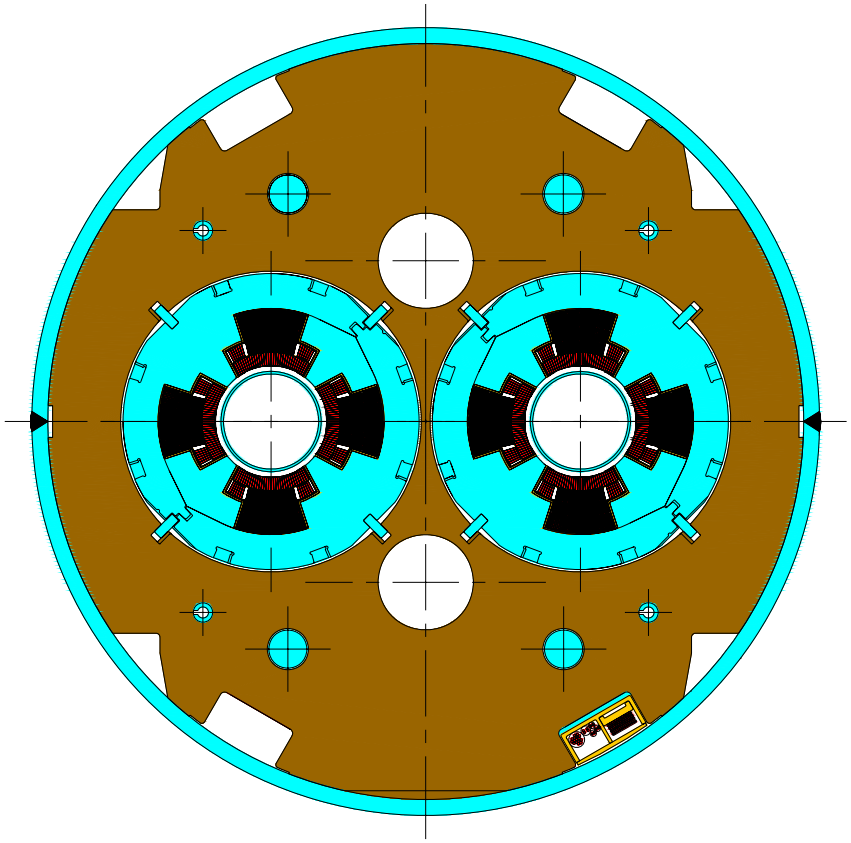
Twin Concept:

MB Main Bend
(Dipole)



CERN AC/DI/MM — 06-2001

MQY wide aperture quadrupole

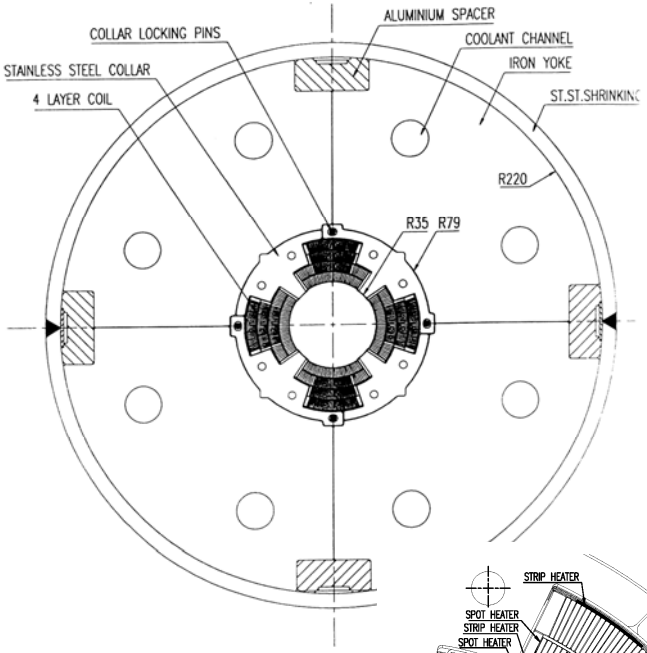


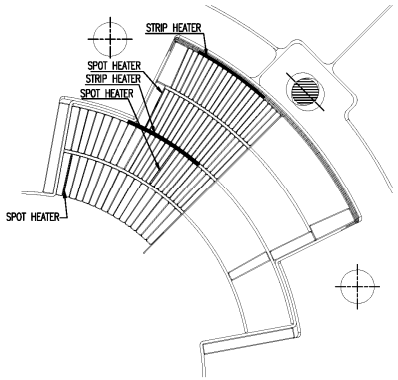
70 mm ID coil
G = 160 T/m at 4.5 K
I = 3620 A
E = 141 kJ/m/aperture
L_{mag} = 3.4

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

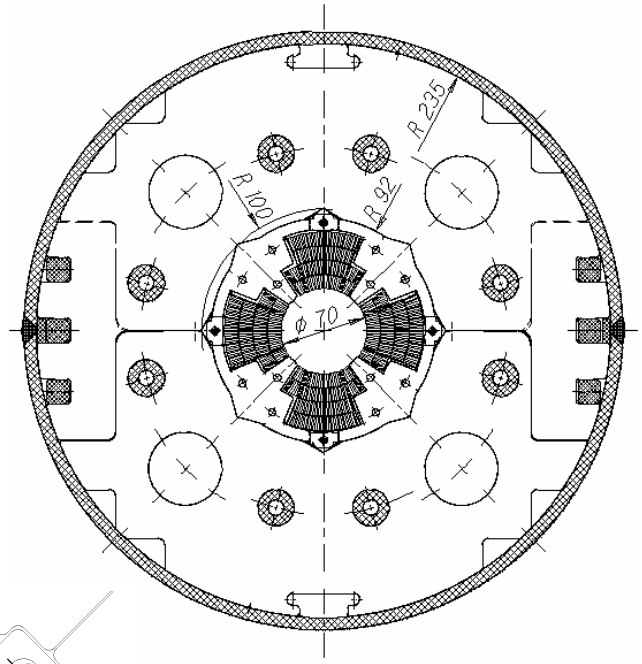
Three 70 mm quadrupoles developed for the LHC IRs

CERN-Oxford Inst. (MQY)

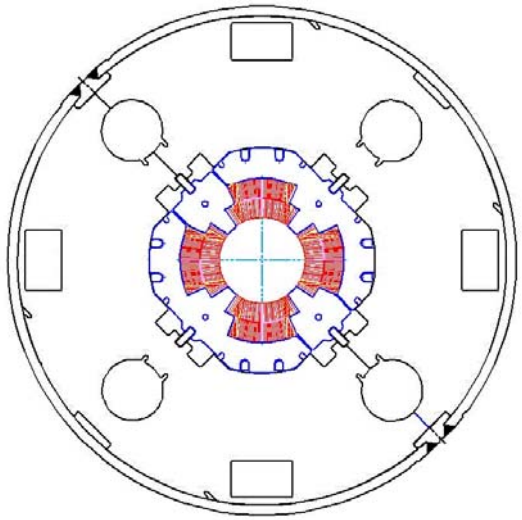


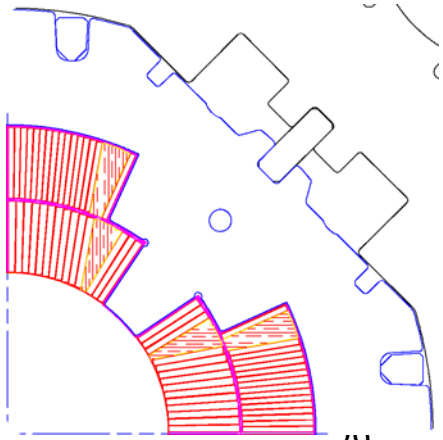


KEK (MQXA)

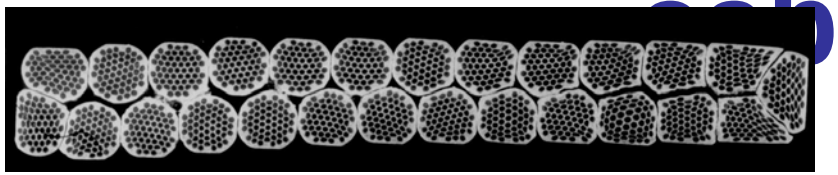


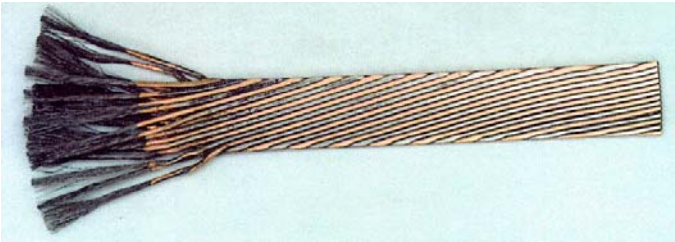
Fermilab (MQXB)

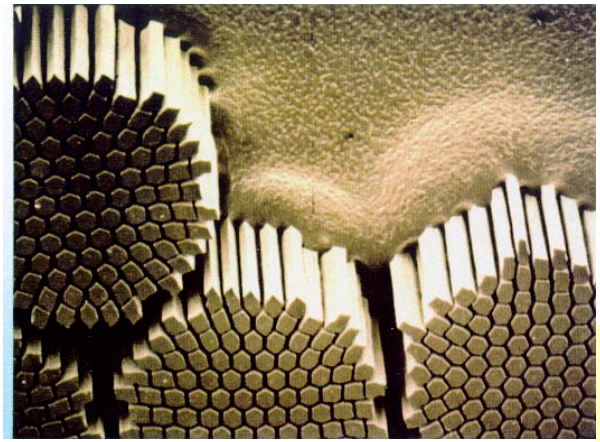


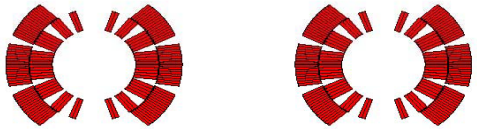


LHC MB X-sect: conductor (Rutherford cable)









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

Conductor position optimization:

Control of harmonics
Balance of margin among blocks

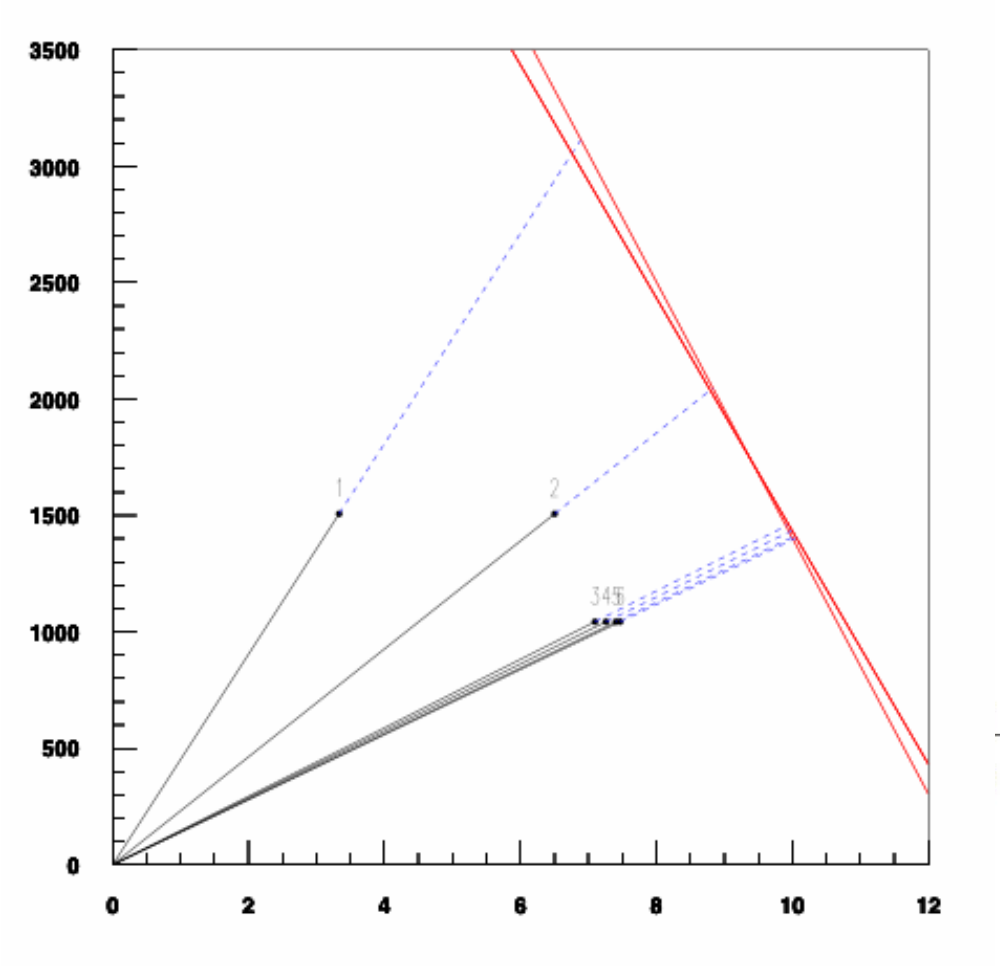
Stable against inevitable errors

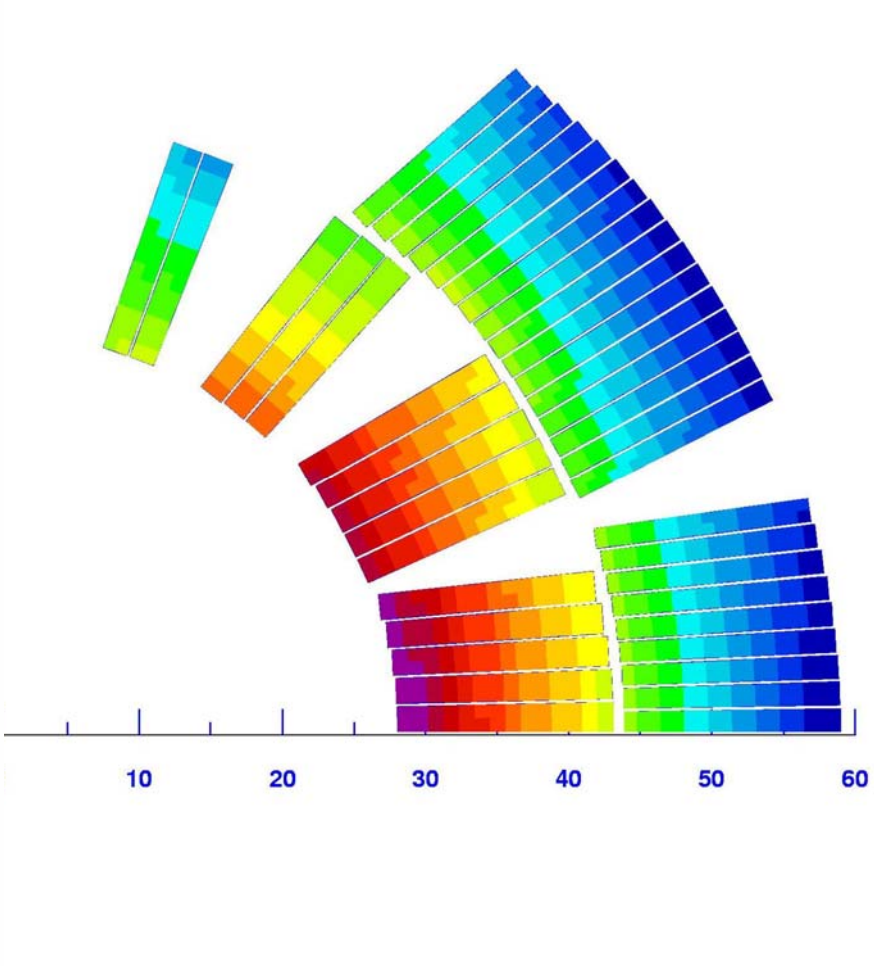
Minimum shear among conductors

Balance between T margin of inner/outer

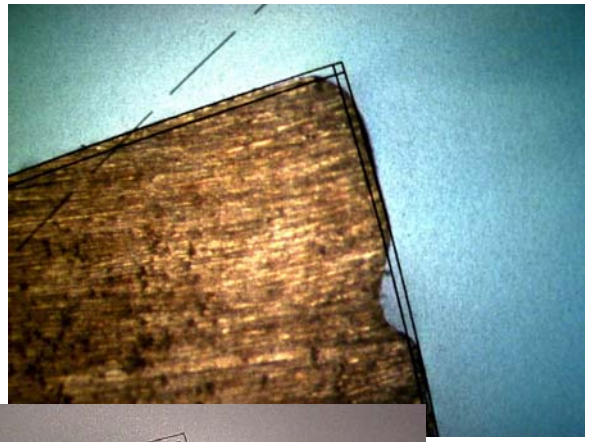
No quench anymore in straight part

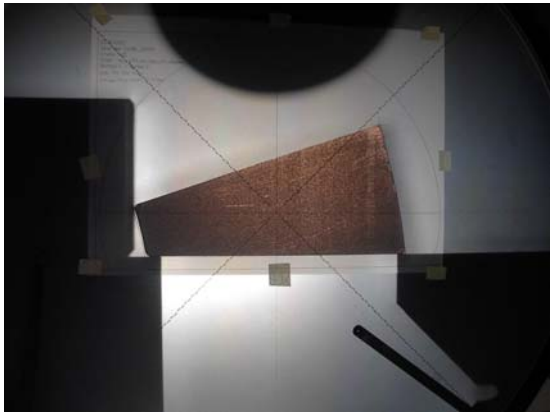
The basic relation: B vs I

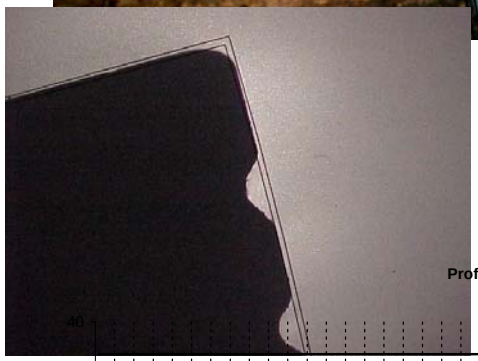


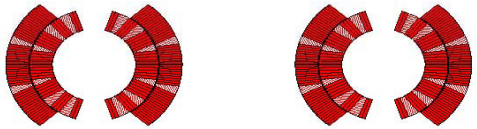


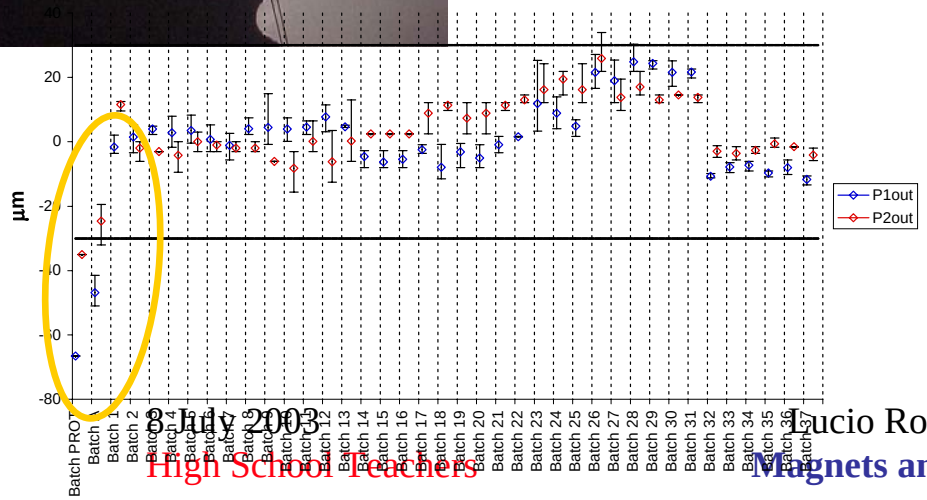
LHC MB X-sect: Cu wedges











Precise at ±20 µm

Used to steer production toward correct Field Quality

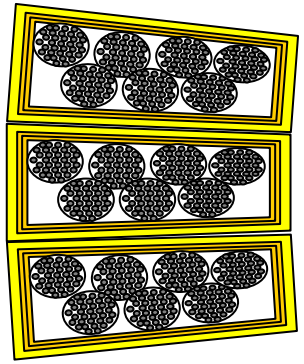
In LHC we have changed them during production.

Effect in 2002.

~35 CM old Xsect.

LHC MB X-sect: Insulation and 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

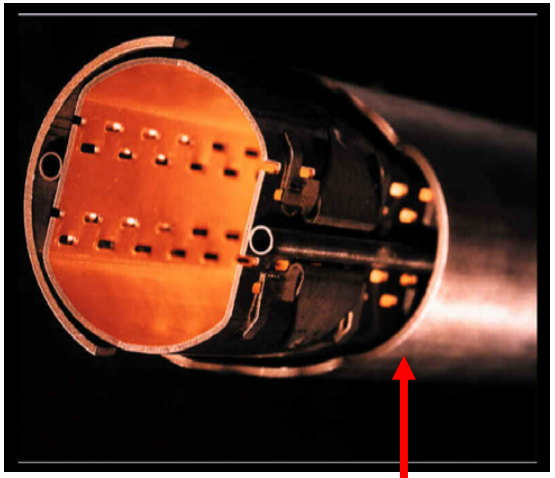
Polyimmide insulation

Around cable and around coils

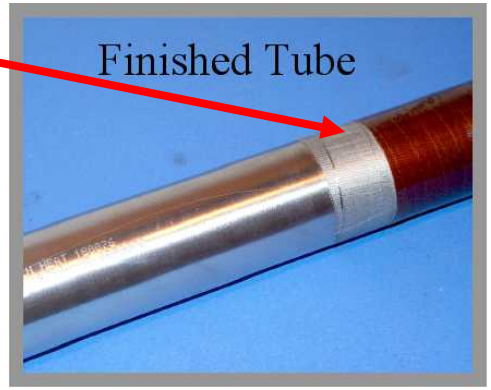
Important elements are dimensions, ±3% of thickness, and creep (Apical creeps less than kapton)

Inter layer
To allow HEII to flow

LHC MB X-sect: insulated CBT



CBT



Cold bore tube

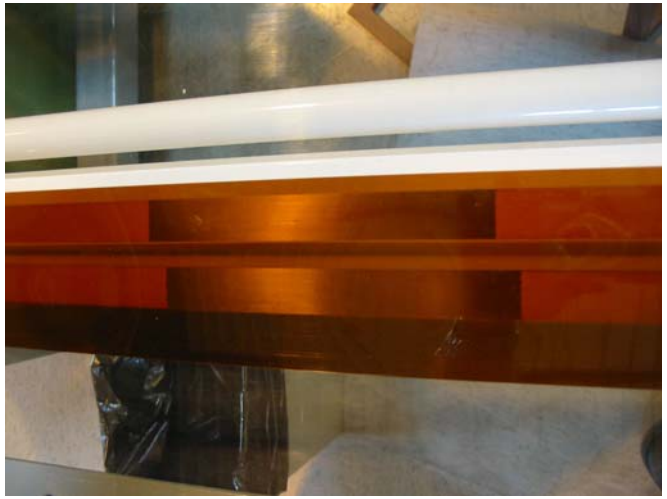
StSt tubes: one supplier

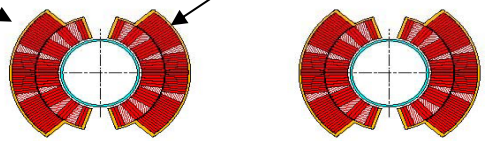
Tubes at CERN

⇒Insulation (line installed in bldg 927)
Special Insulation technique > 20 kV

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

LHC MB X-sect: Quench Heater





These strips has to be fired in 10 ms if a quench happens!

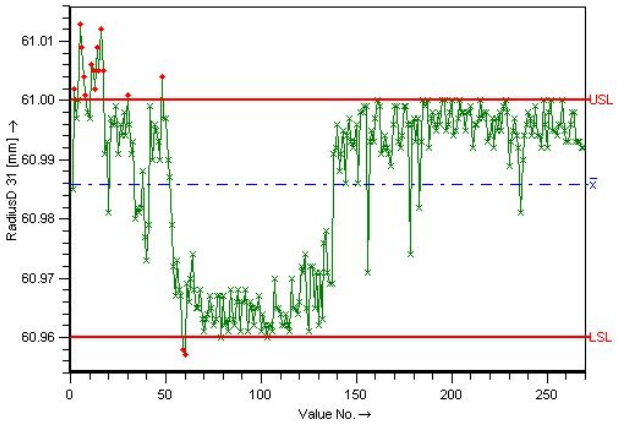
They get hot and heat diffuse from strip to coils in about 20-40 ms

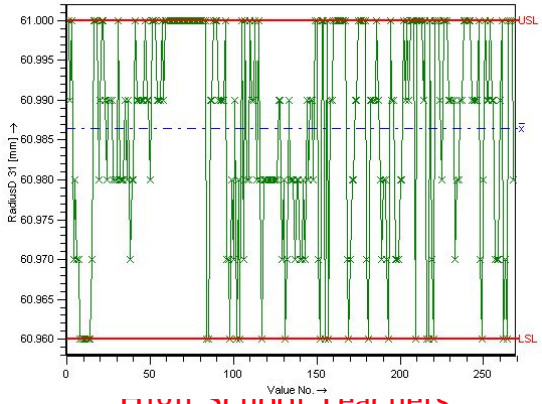
It's one of the main delicate element (metallic strip under strong stress, the foils must be thin to favor heat diffusion)

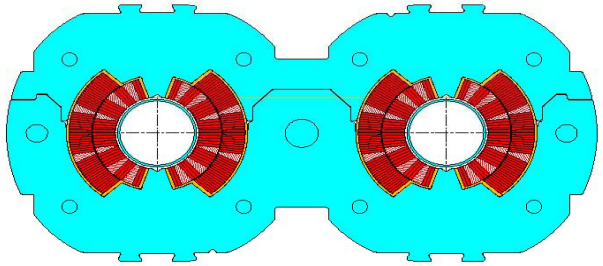
LHC MB X-sect: Collars

One of the key element of a magnet:

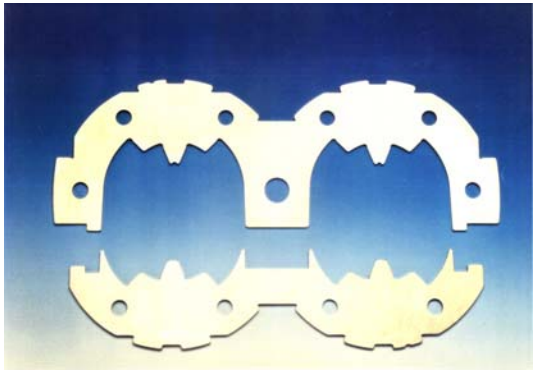
It controls prestress (mechanic) and Field Quality

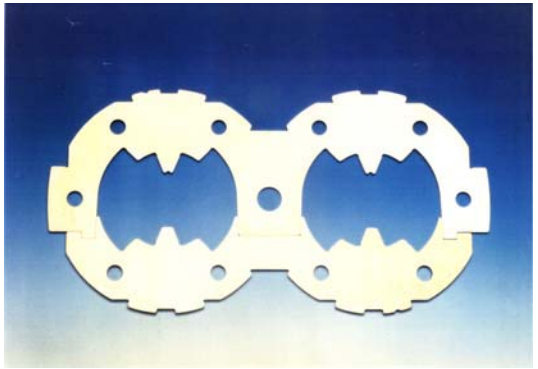






Collars and collaring are the main controllers of the final coil shape

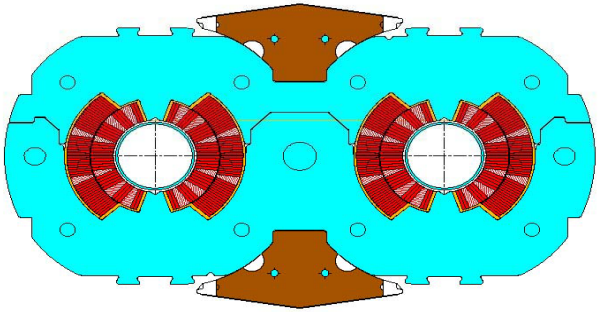




LHC MB X-sect: magnetic insert

The iron Insert

Punched together with the yoke lamination



Introduced to ease the mechanical assembly

It serves for FQ

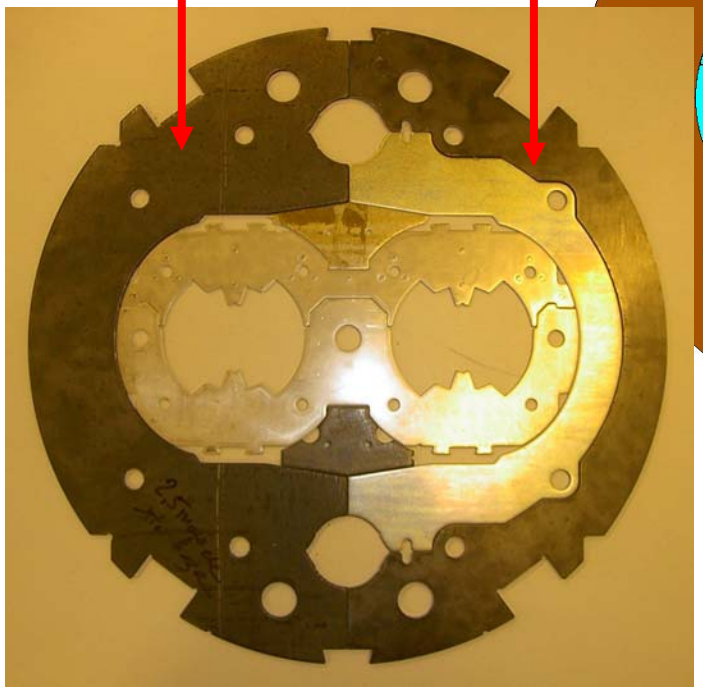
By tapering we cured unwanted quadrupole and octupole components

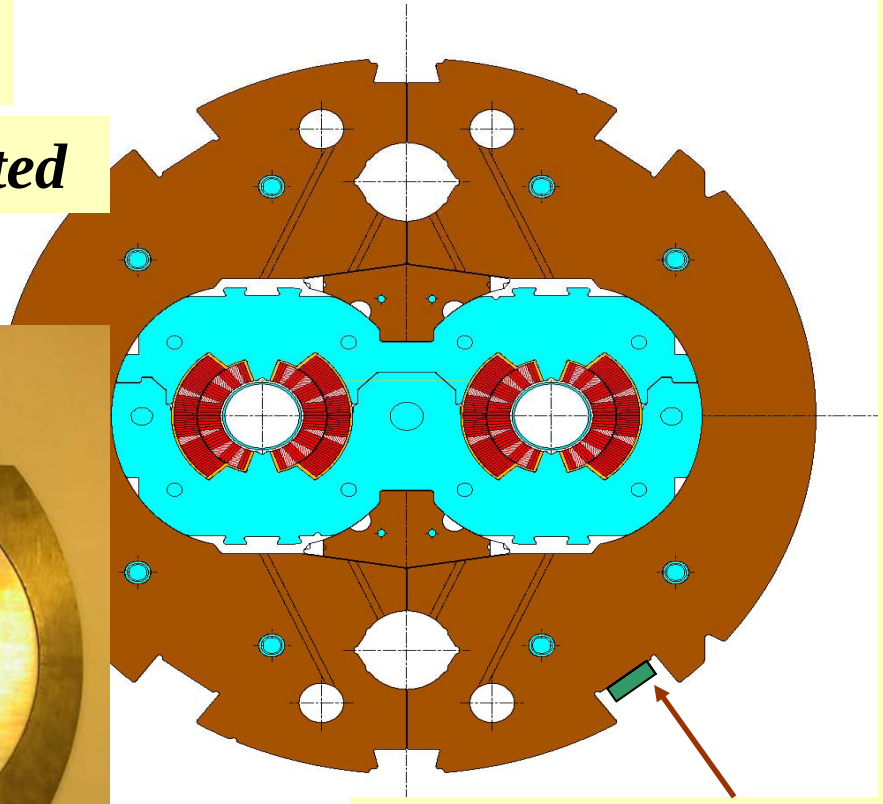
LHC MB X-sect: yoke laminations

One supplier for the steel 45,000 tons

Precise vertical gap

Regular ***Nested***





Temperature probe

The iron yoke:

Stray field

15% field increase (but big gain in protection)

If saturates affect FQ (sextupole)

Trim of magnetic length

LHC MB X-sect: Bus Bars & fillers

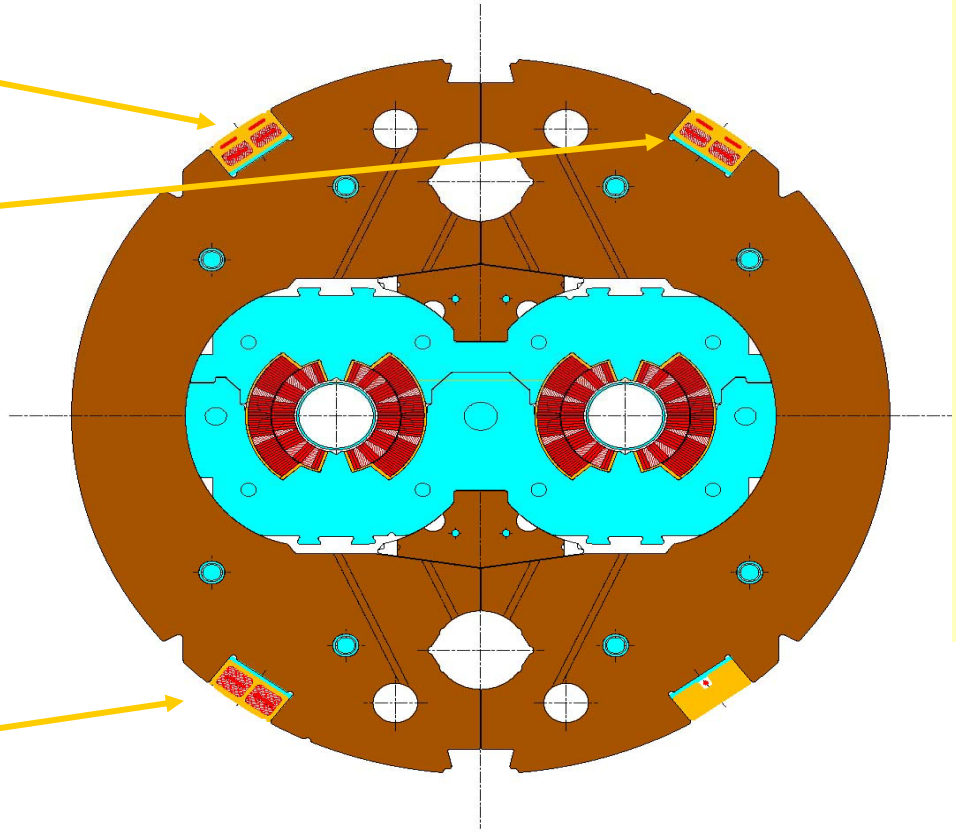
Bus Bars

Quad BB Focusing

Quad BB Defocusing

Corrector circuit bus bars on top of Quad BB

Dipole circuit BB



160 km of main BusBars!!

We provide:

-technology

-SC 02 cables

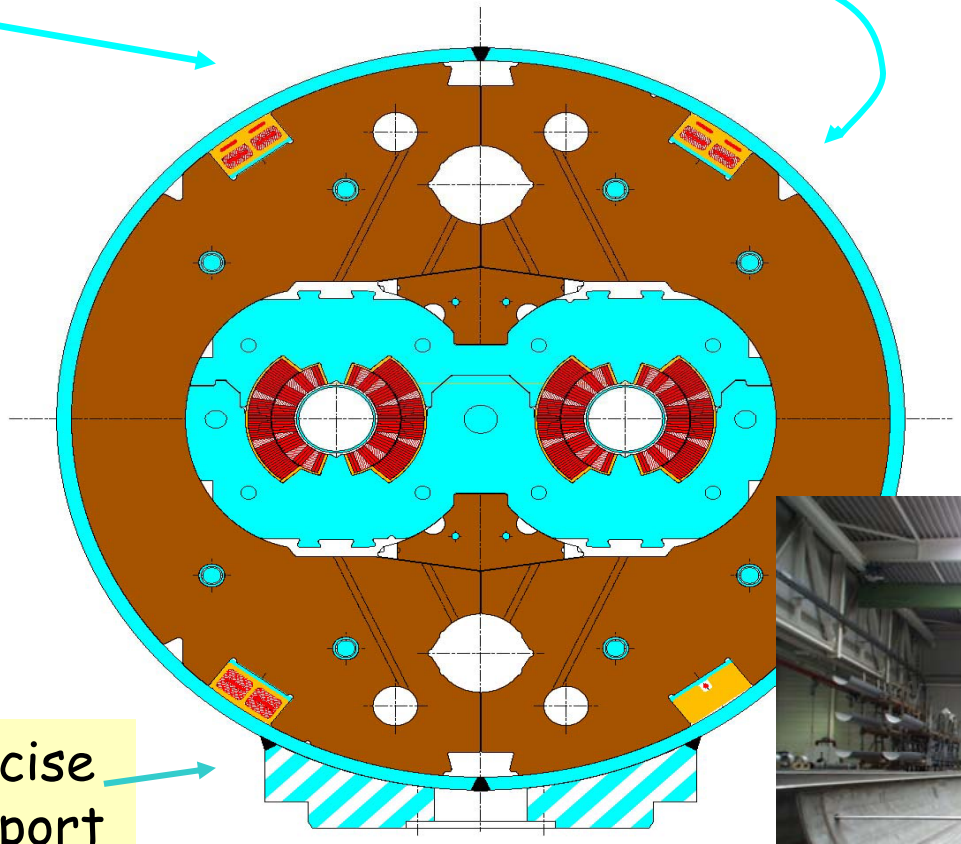
-Polyimmide foils and tapes

LHC MB X-sect: Shrinking cylinder and support

Two half shells, welded on the magnet

Many difficulties

End opening

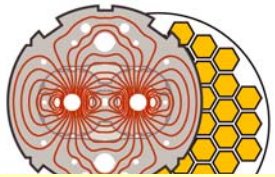


Precise support

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

So far not one shell in tolerance.

LHC MB X-sect: Copper HXT



Saturated low pressure HEII

Cu tubes (bare)

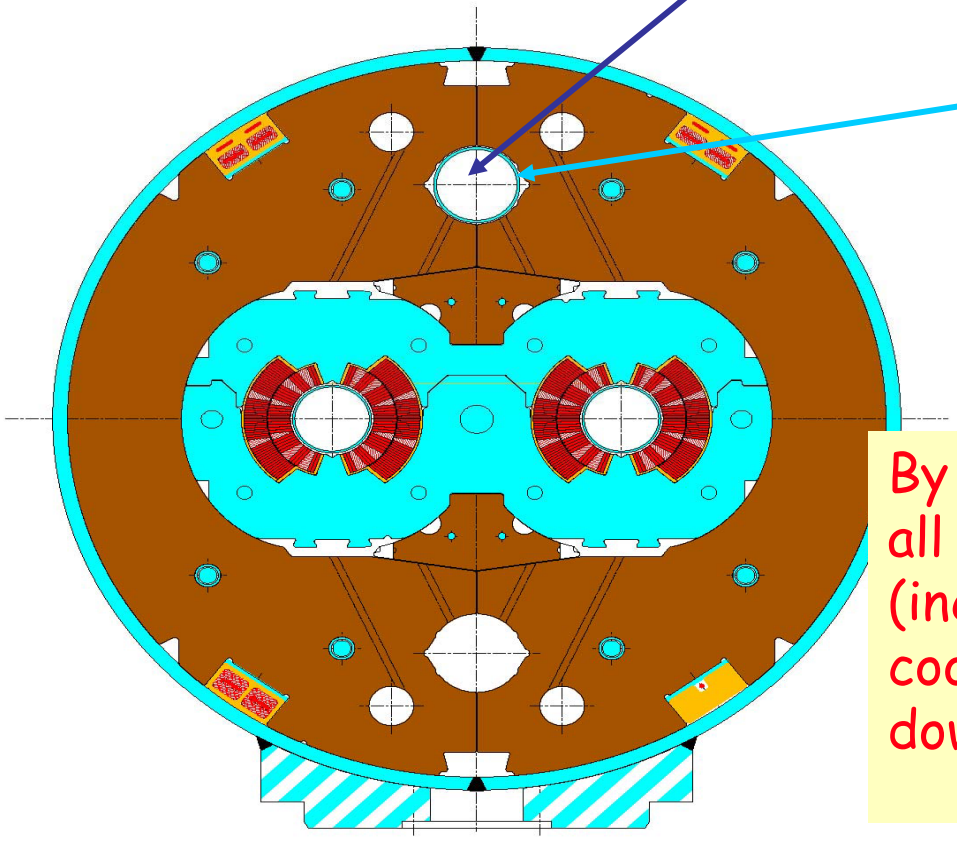
Then all working at CERN

-machining

-vacuum brazing

- e-beam welding

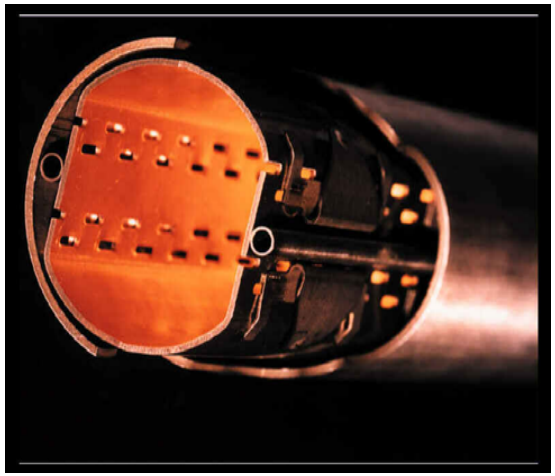
-Cleaning

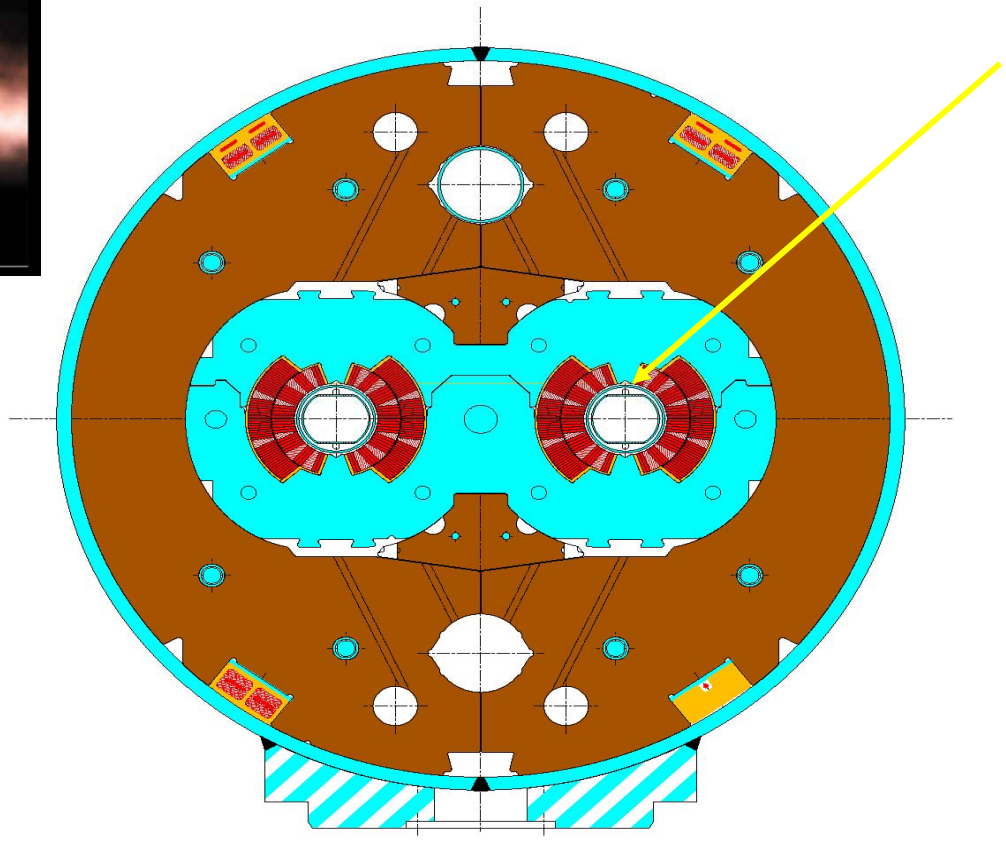


Copper Heat Exchange Tubes

By heat exchange, all He inside voids (included coils!), are cooled from 4.2 K down to 1.9 K

LHC MB X-sect: beam screen

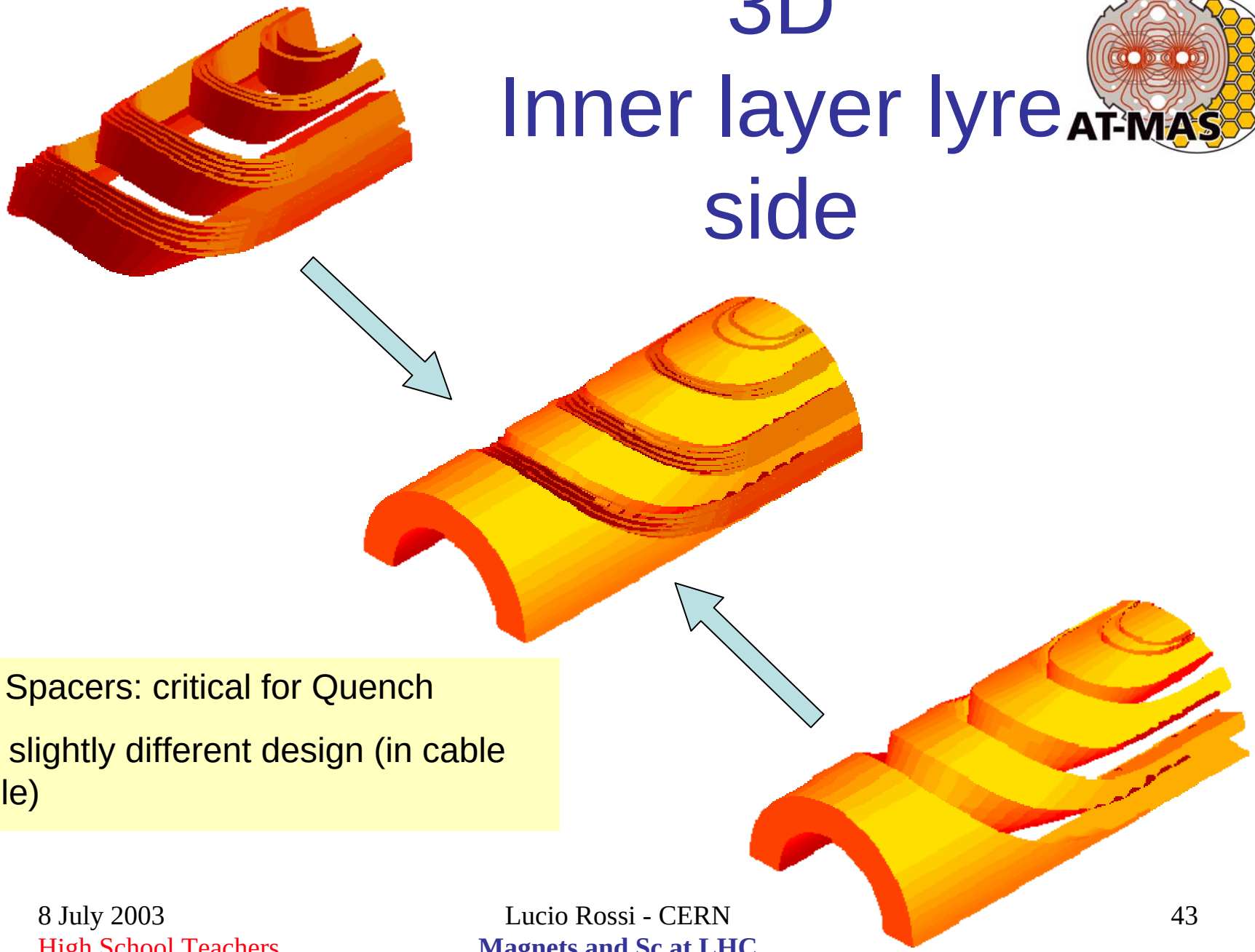




Beam Screen

Inserted at CERN just before insertion in the tunnel

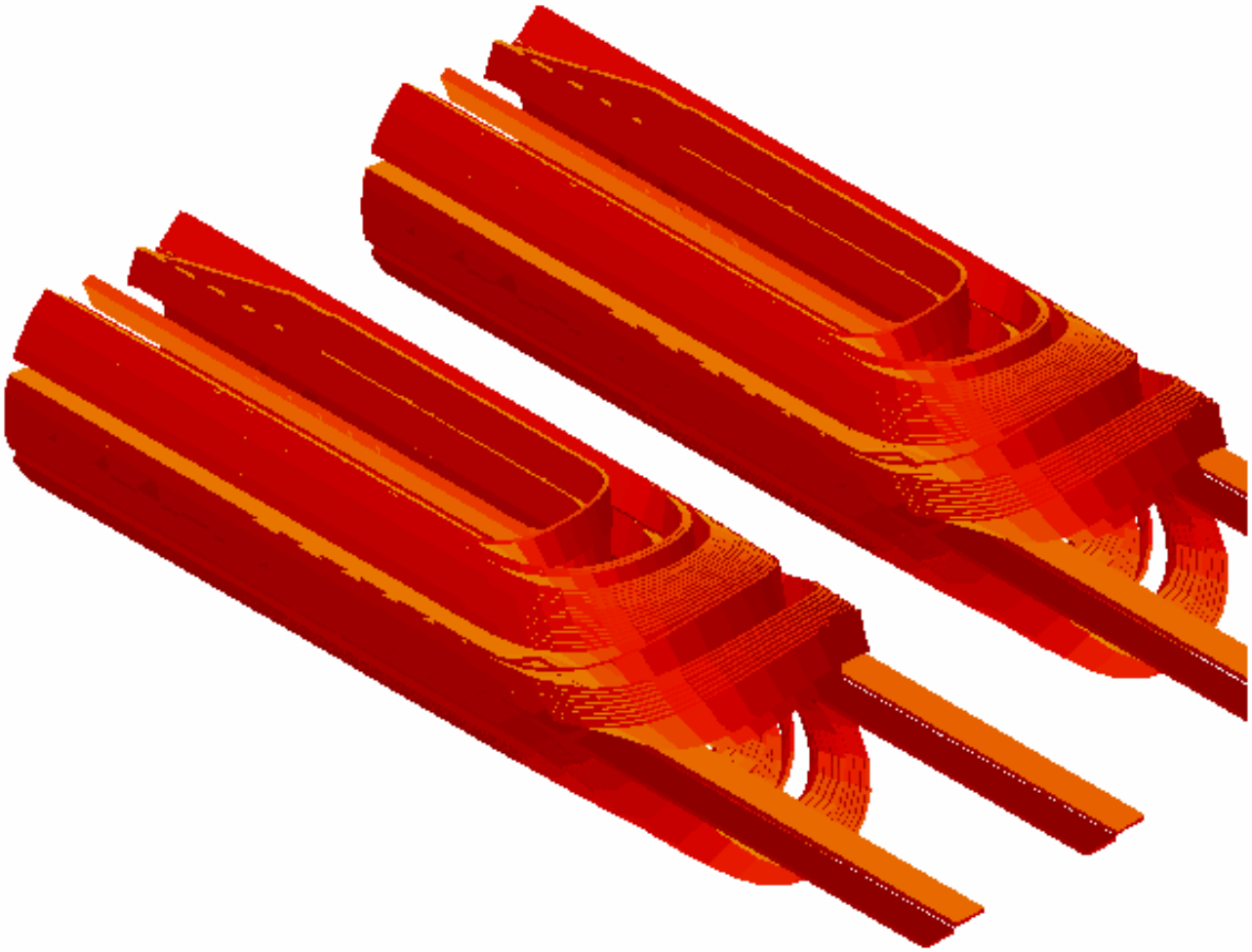
3D Inner layer lyre side



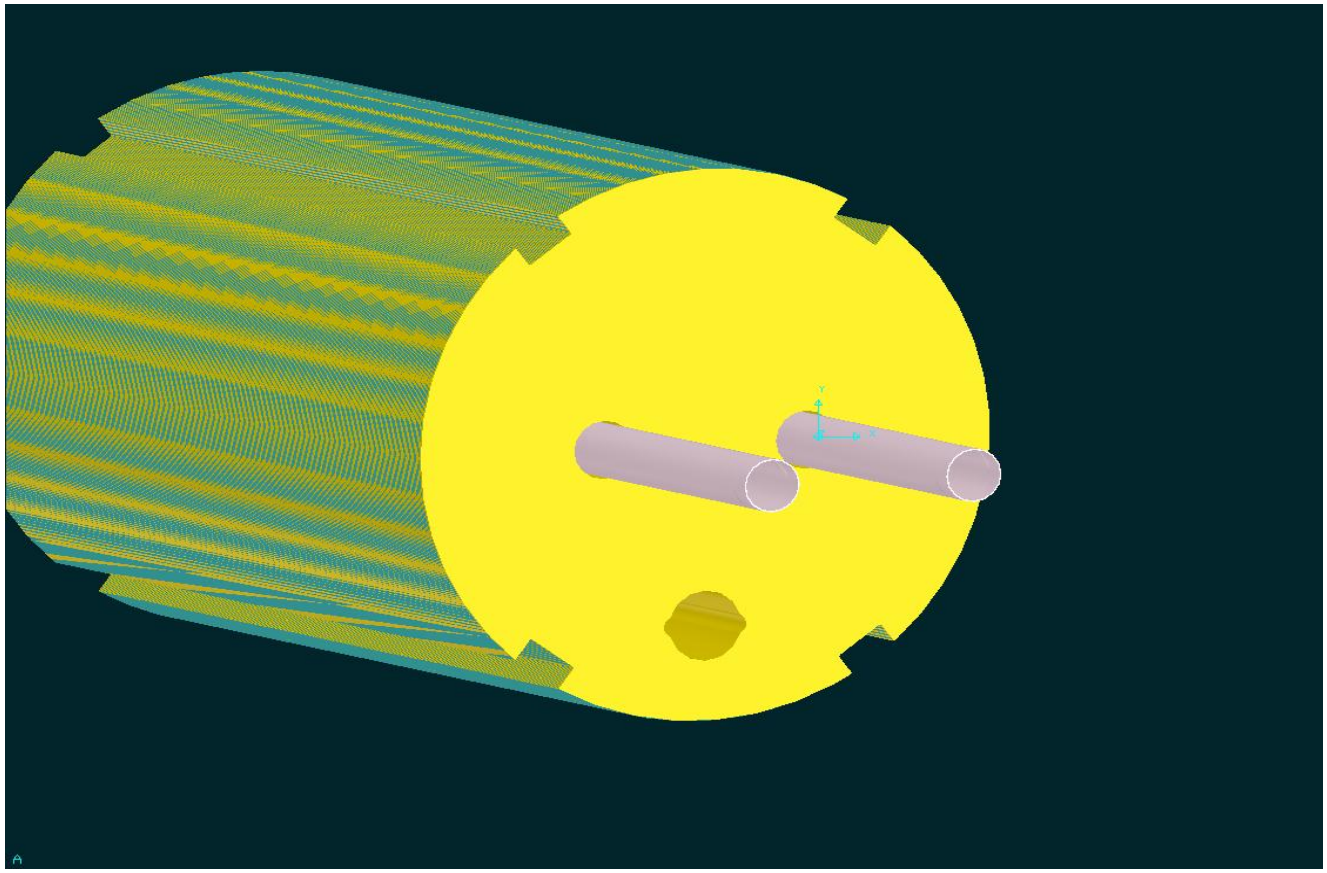
End Spacers: critical for Quench

Two slightly different design (in cable profile)

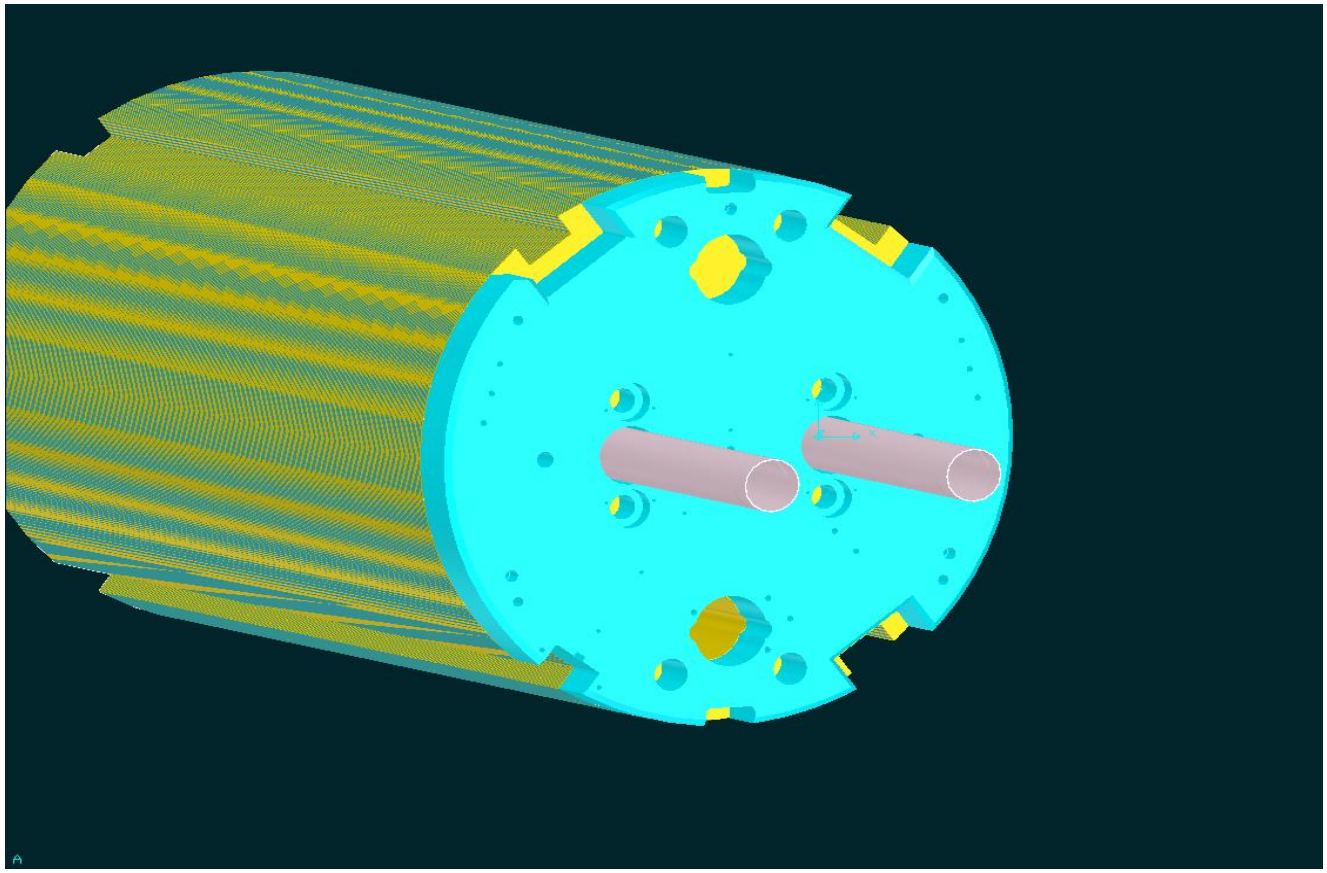
3D
Connection side 3



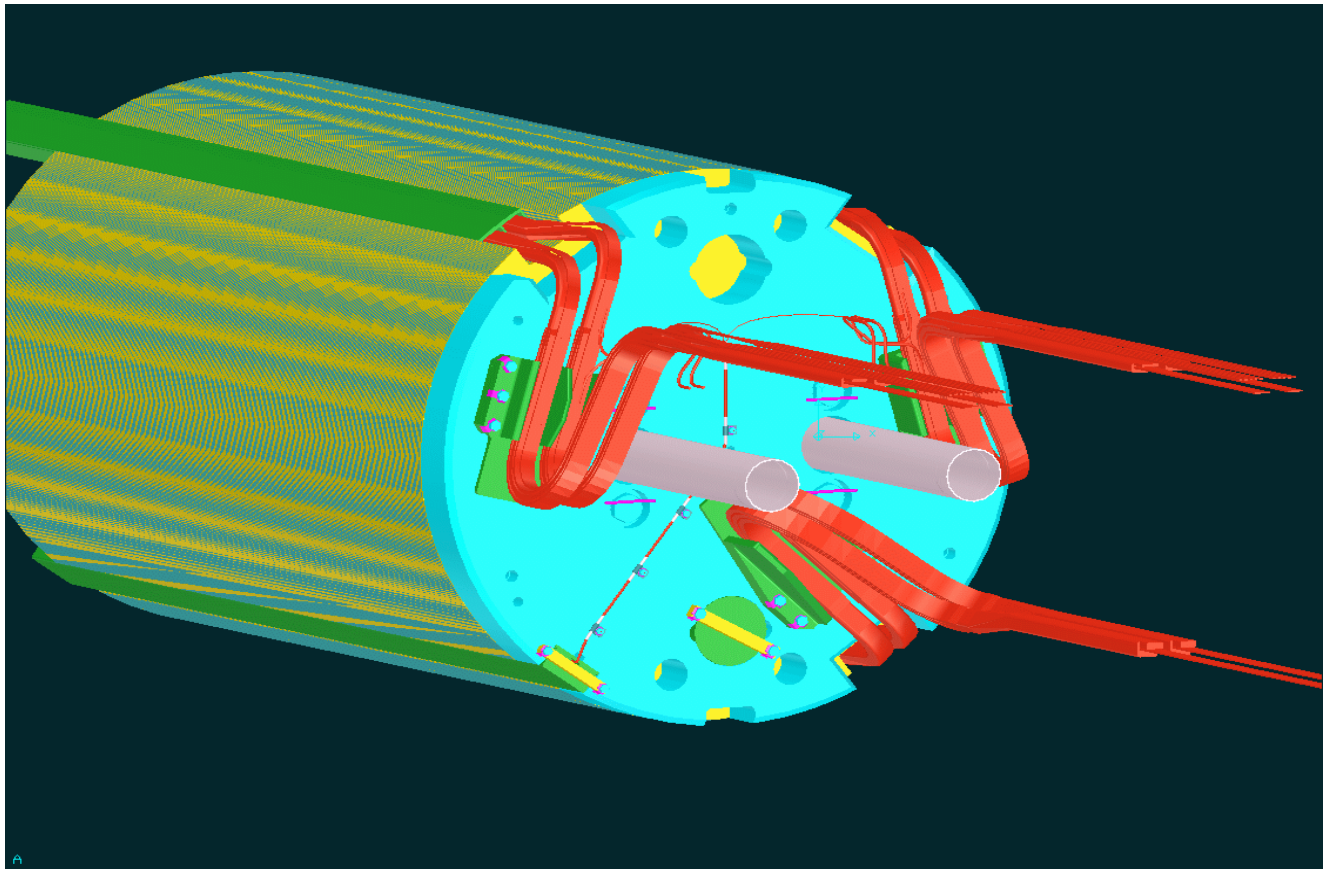
LHC MB - end part CBTs and Yoke



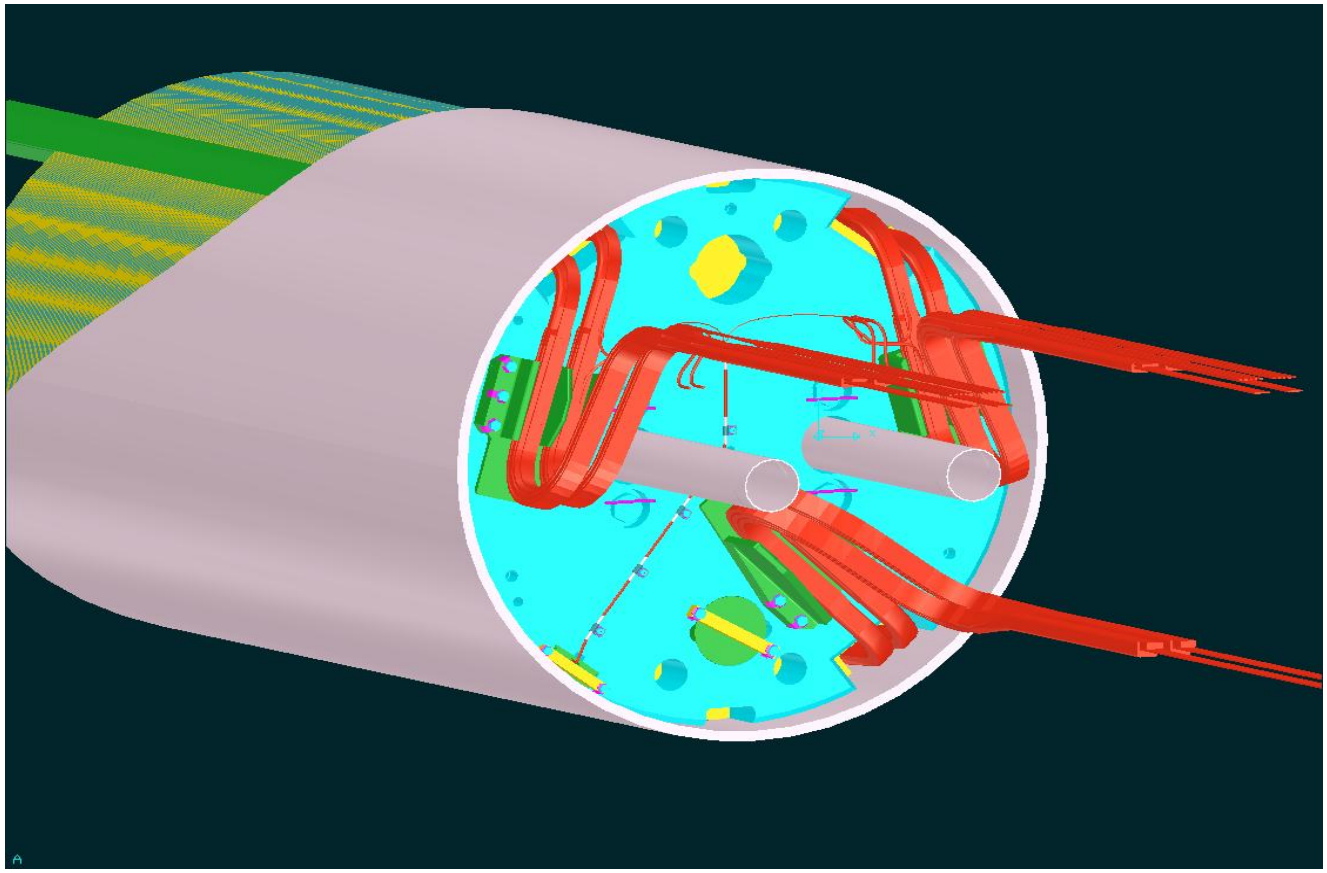
LHC MB -end part end plate



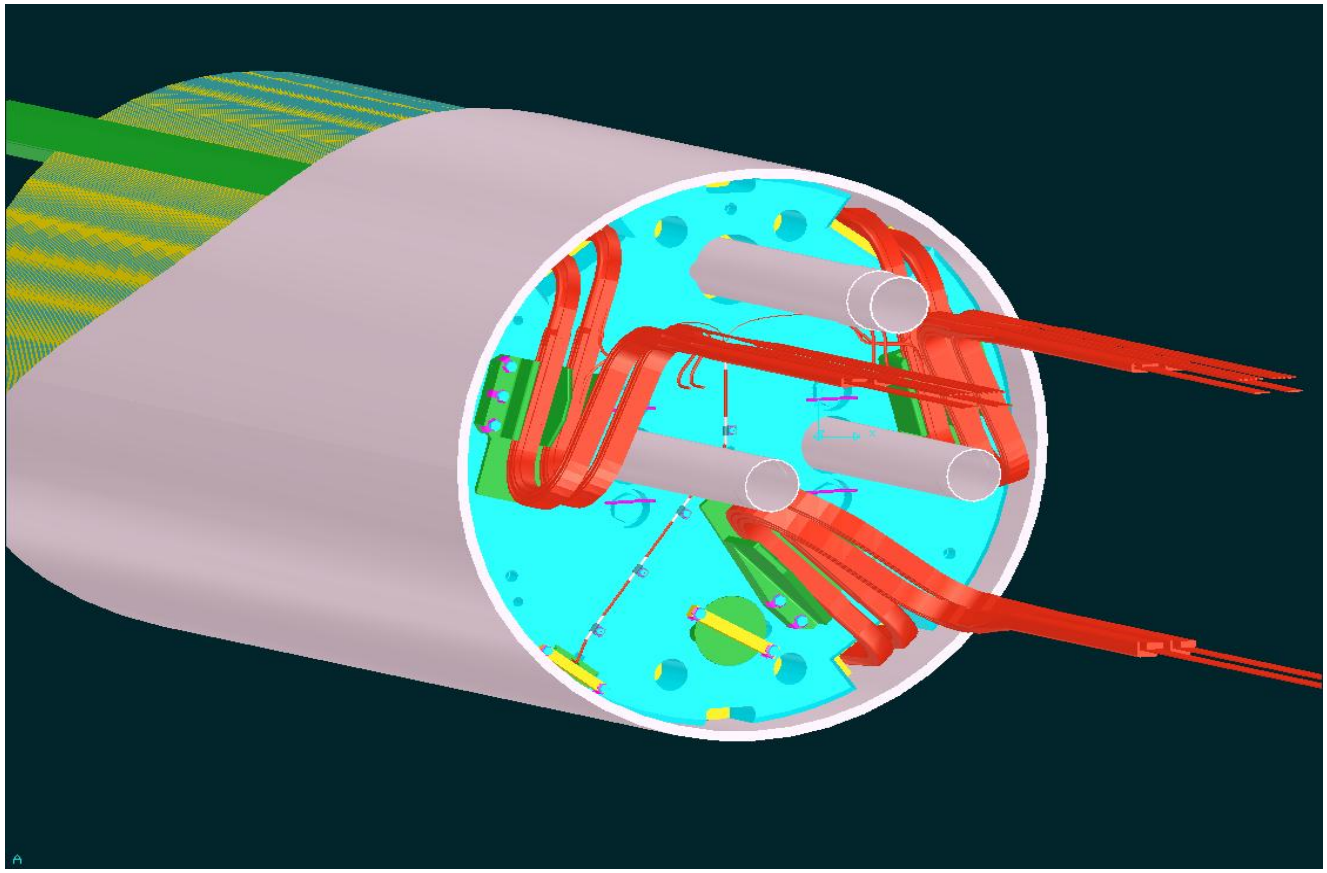
LHC MB-end part
Bus Bars postioning



LHC MB -end part Shrinking cyilinder



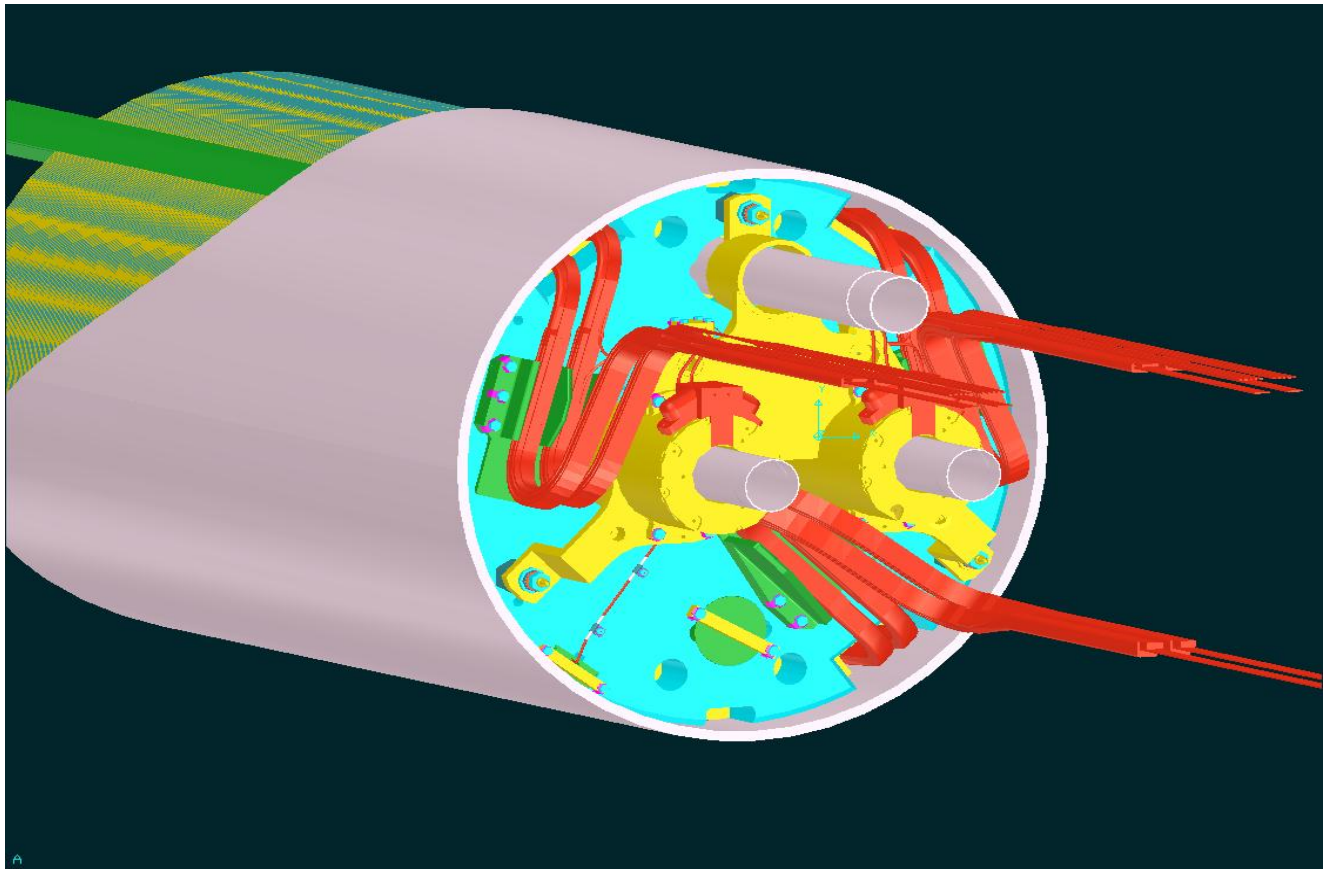
LHC Main Dipole -end part Cu HXT



Corrector Magnets (spool pieces)

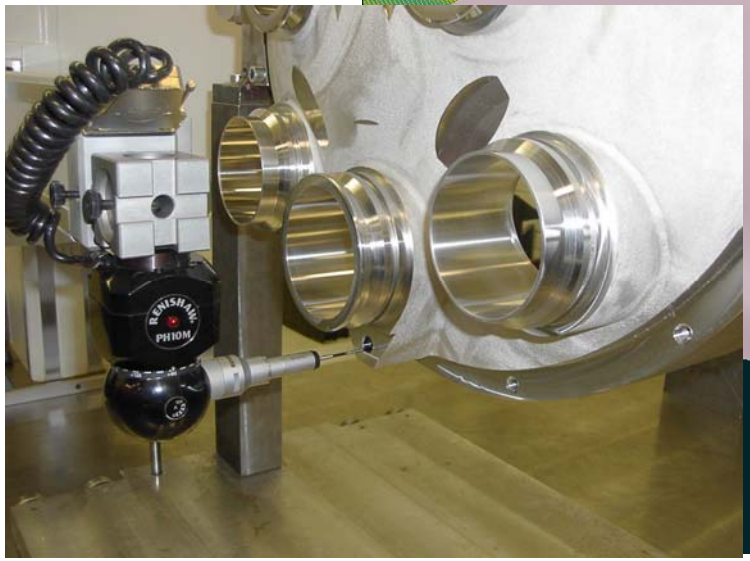
Assembly in CMAs is purely mechanical

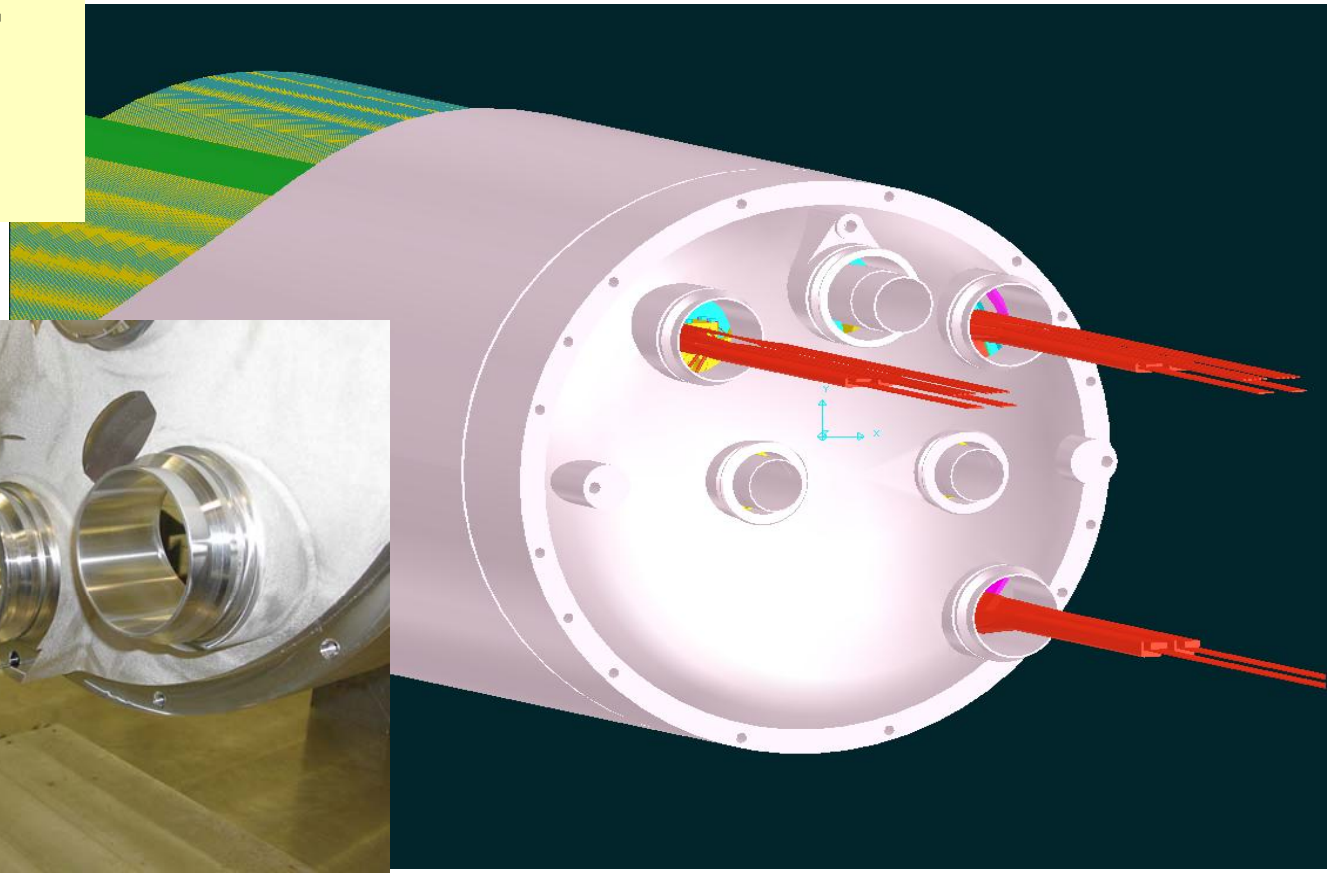
(tolerances of B axis wrt mech. frame given by supplier



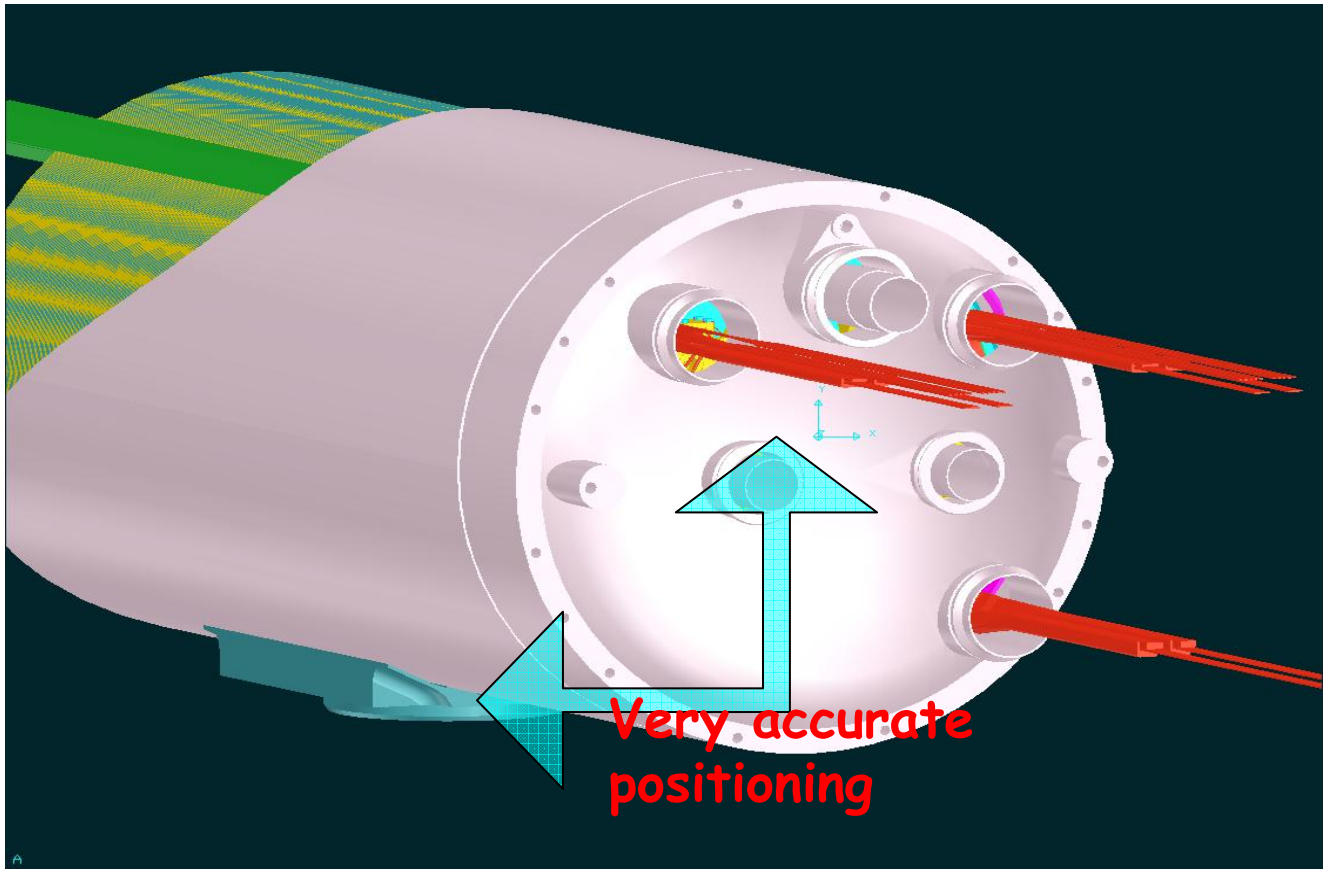
LHC Main Dipole -end part
End covers

One supplier
Powder
technology

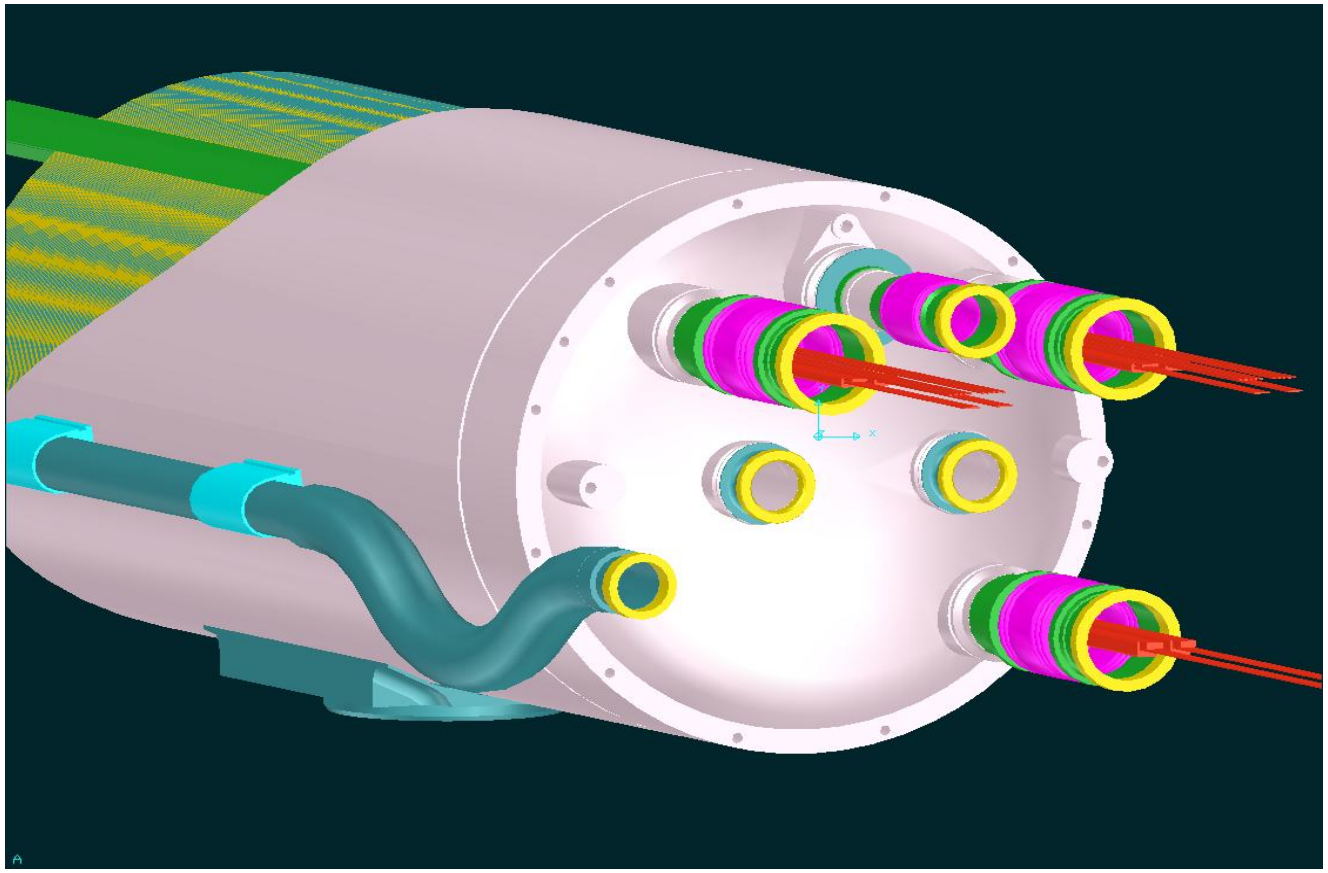




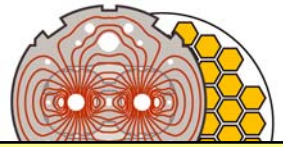
LHC Main Dipole -end part: « Cold foot »

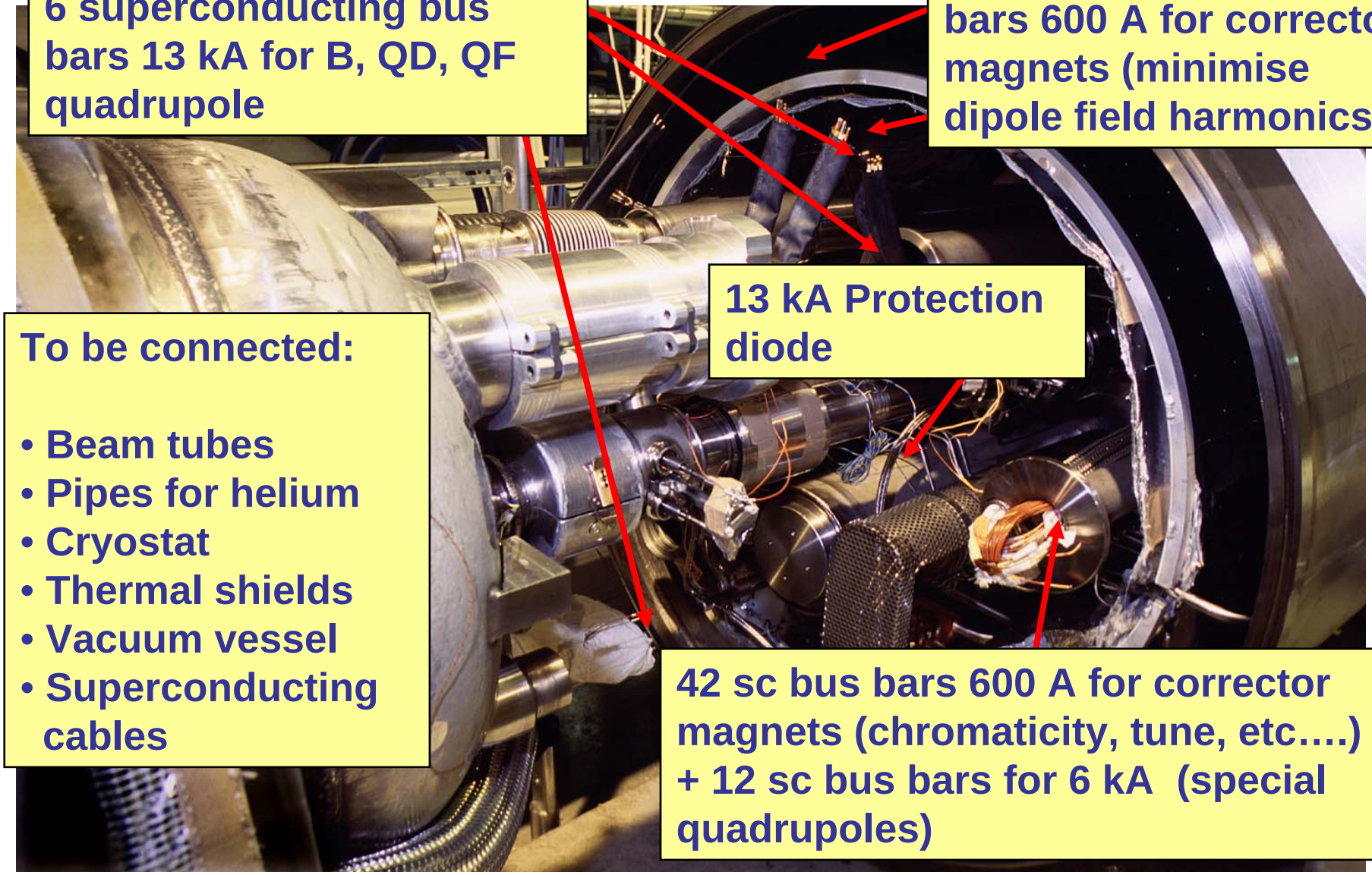


LHC Main Dipole -end part Bellows and N-line



Interconnection between two SC magnets





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

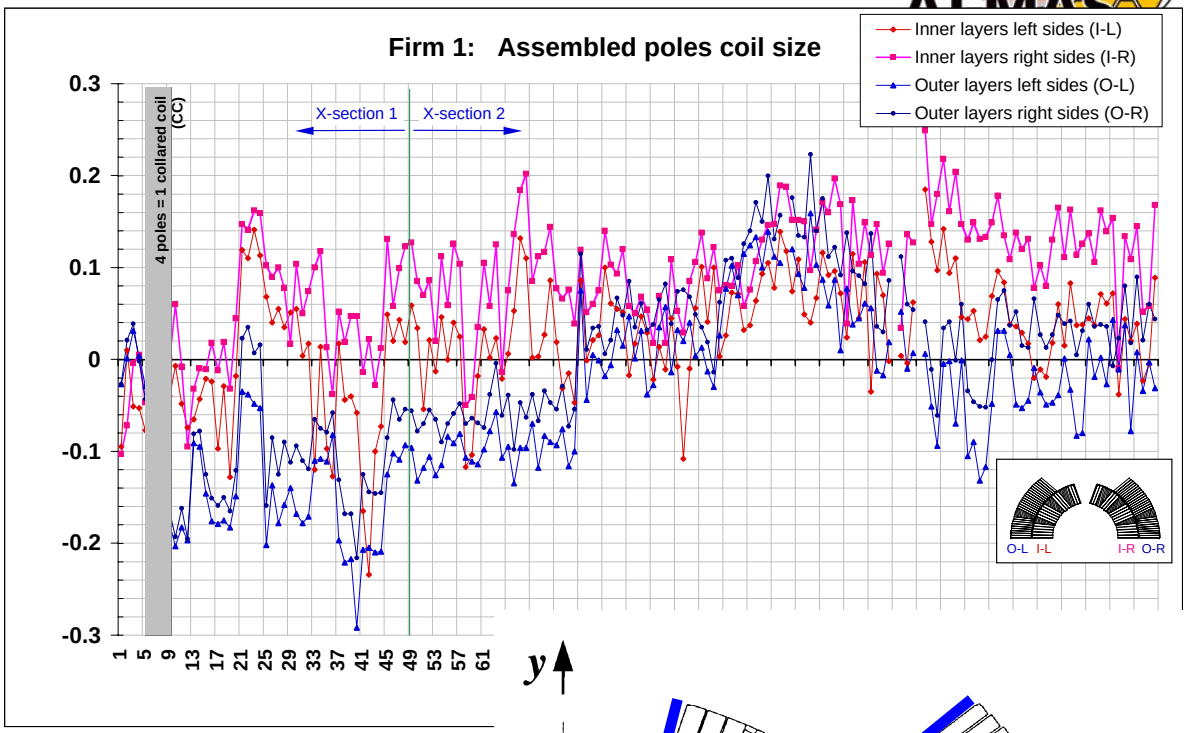
To be connected:

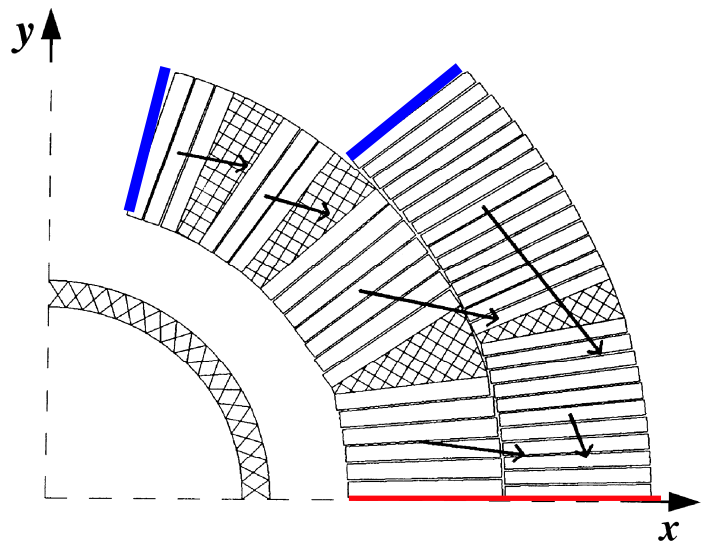
- Beam tubes
- Pipes for helium
- Cryostat
- Thermal shields
- Vacuum vessel
- Superconducting cables

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

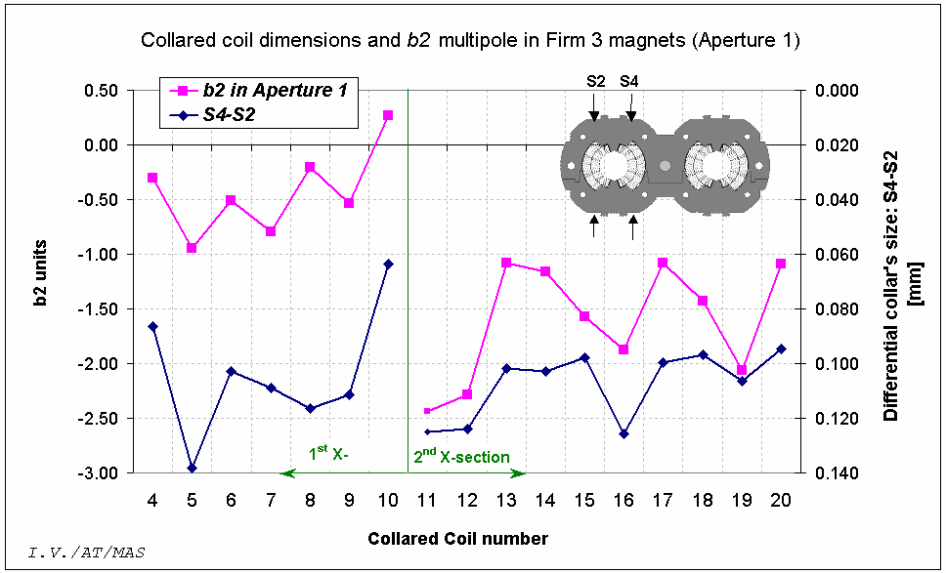
Critical Process
Winding-Curing-Coil

- Coils are cured under press
- Then measured all along 15 m
- Then collared with shims
- Shims influence also prestress and then coil movements (quench)
- Shift of radius of tens of micron as well deformation can easily drive harmonics out of tolerance

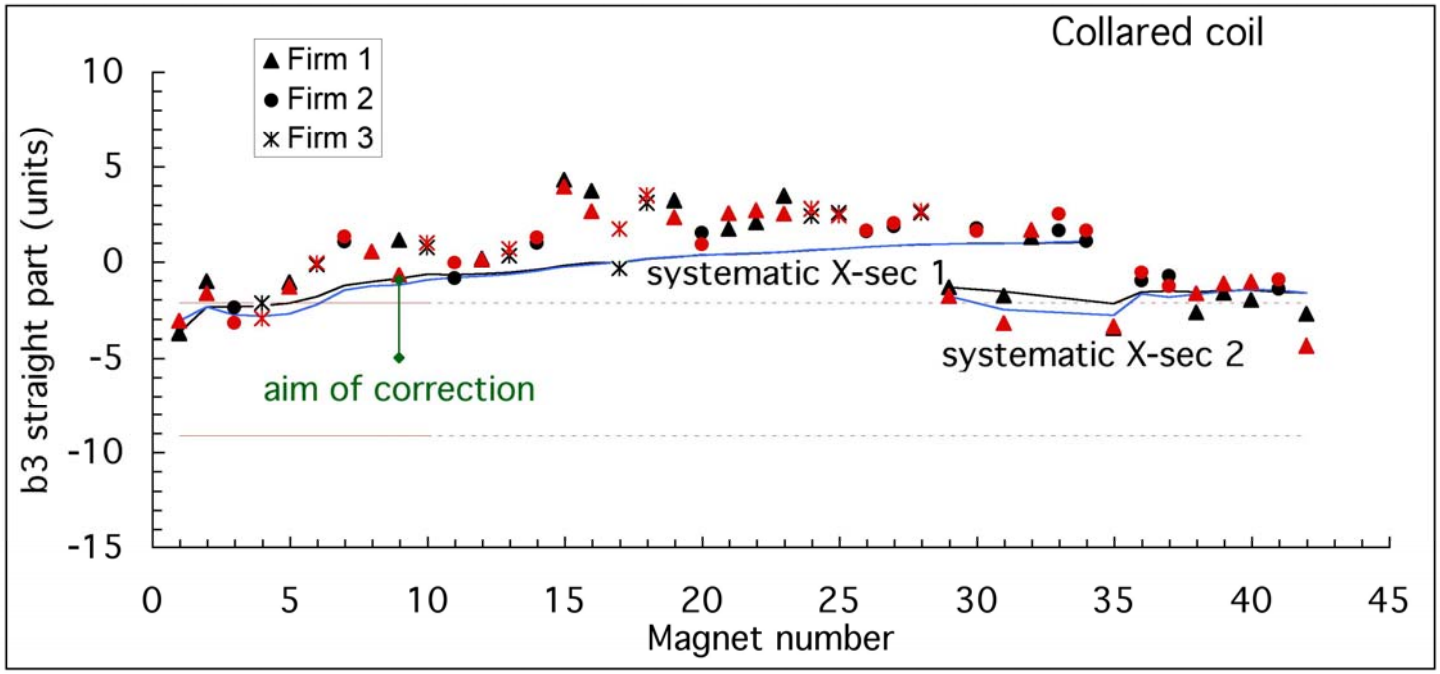




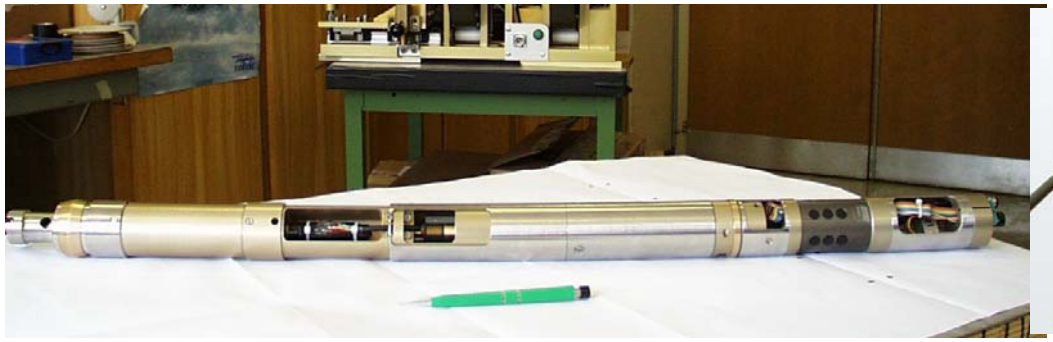
Courtesy of I.Vanenkov and C. Vollinger



Steering production (and check errors) through Field Measurements

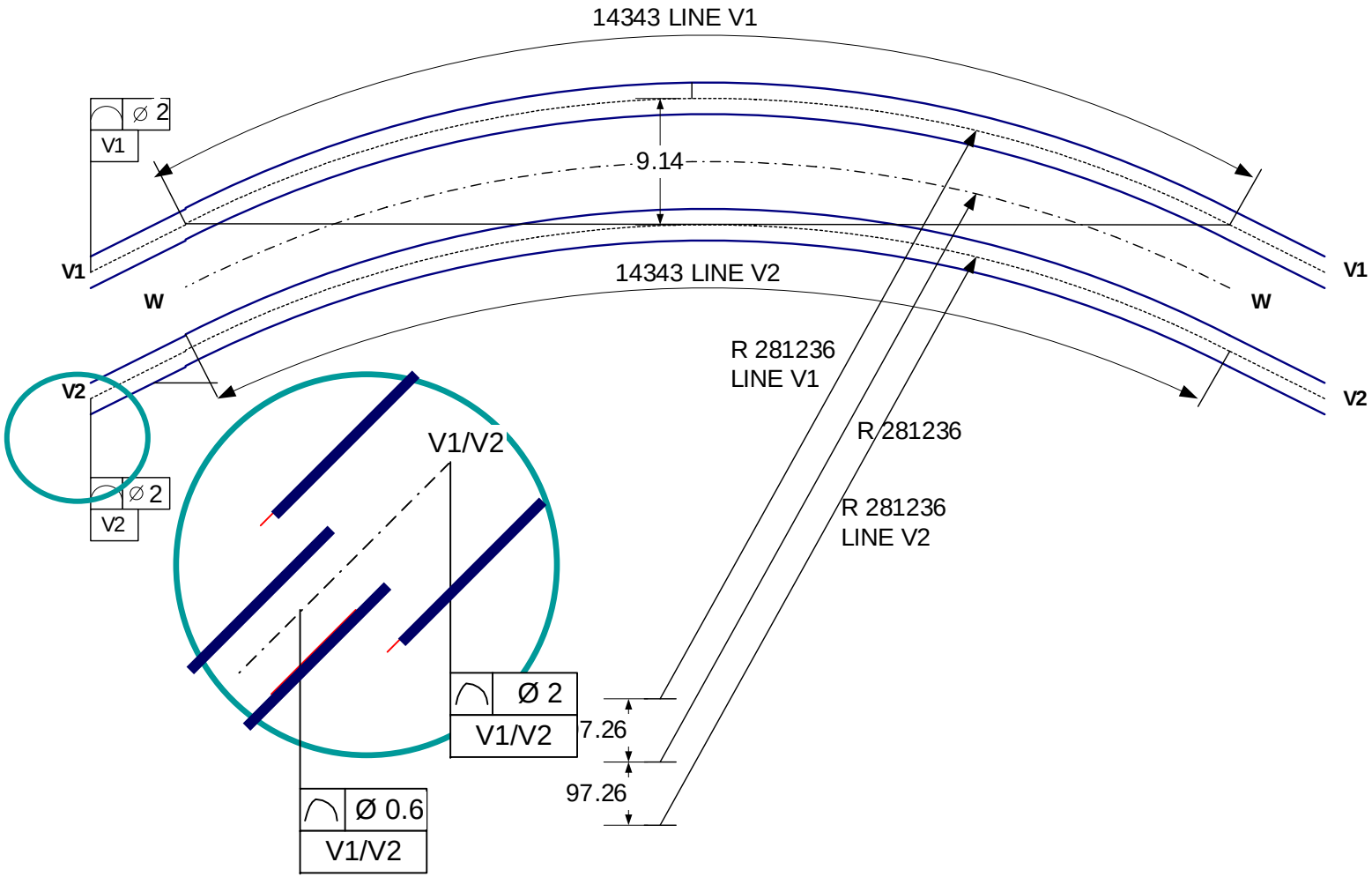


To get it right we need model that predict position and deformation at the level of 10-20 micron

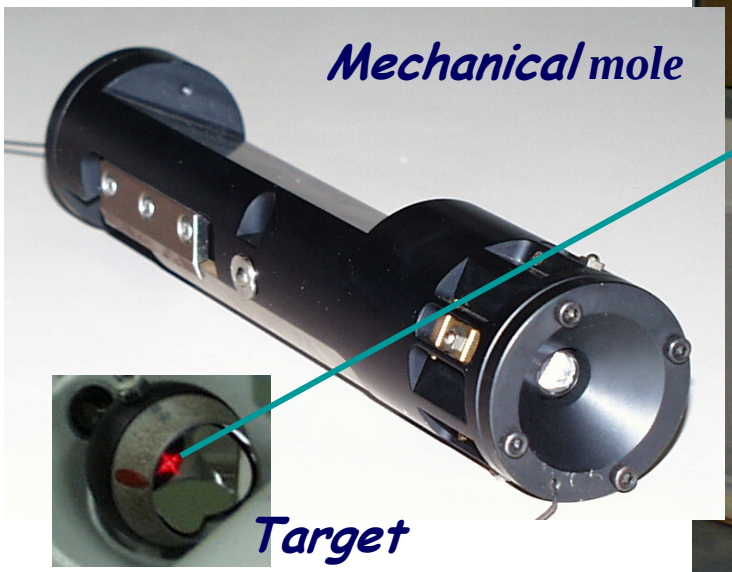


Also MQ

3 D. curvature measurements End tolerances



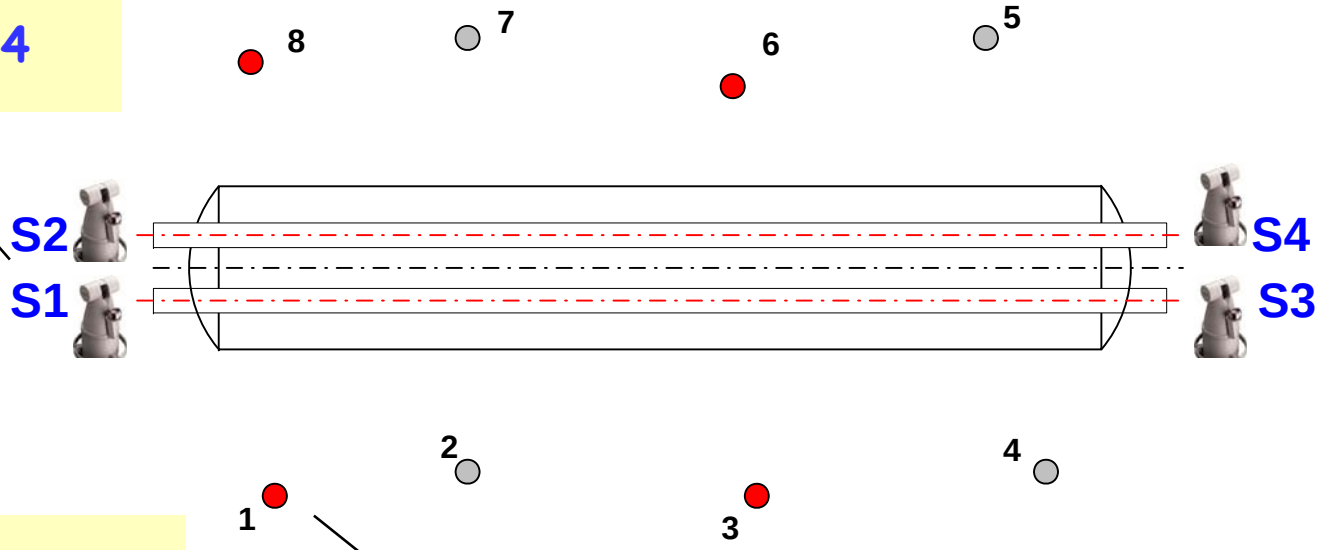
Laser tracker (Leica)to achieve geometry



Accuracy:10ppm at 2σ
on static target
BUT 0.2 mm when
changing position

Measuring method at Industry

Measuring stations position
S1,S2,S3,S4

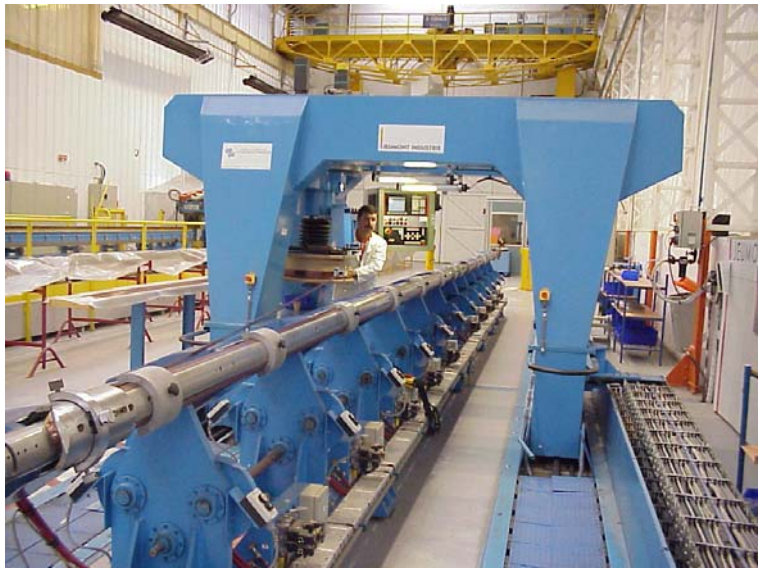


Necessary for curvature but also for assembly (but may be over-used)

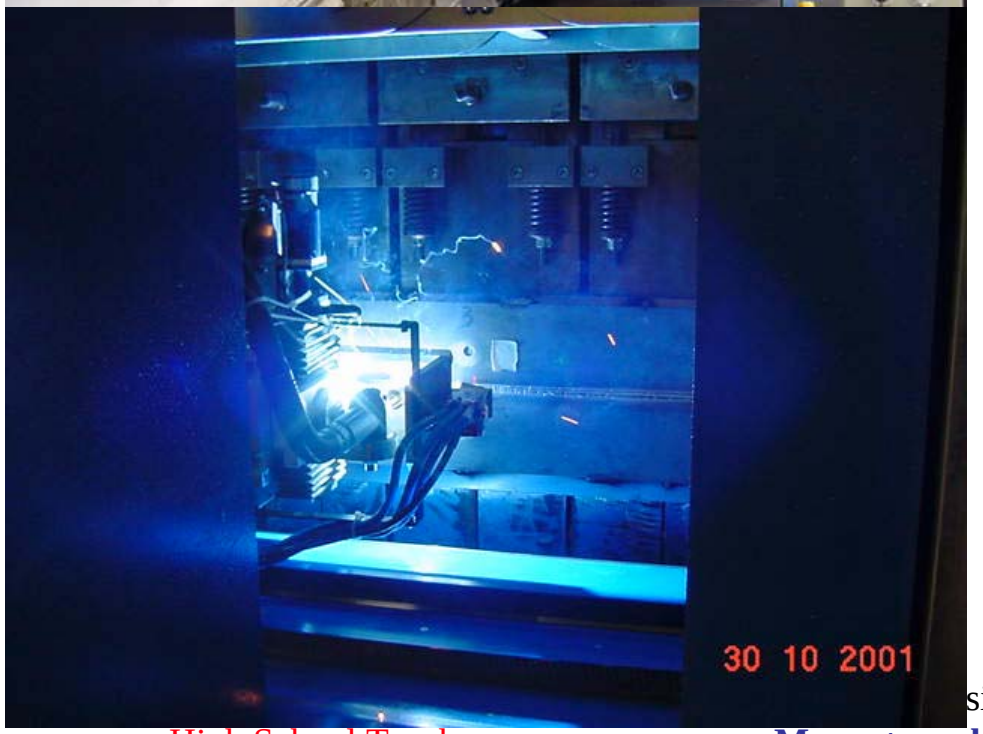
Network points distributed around the cold mass

1,2…8

Snapshot at industry



The longitudinal welding

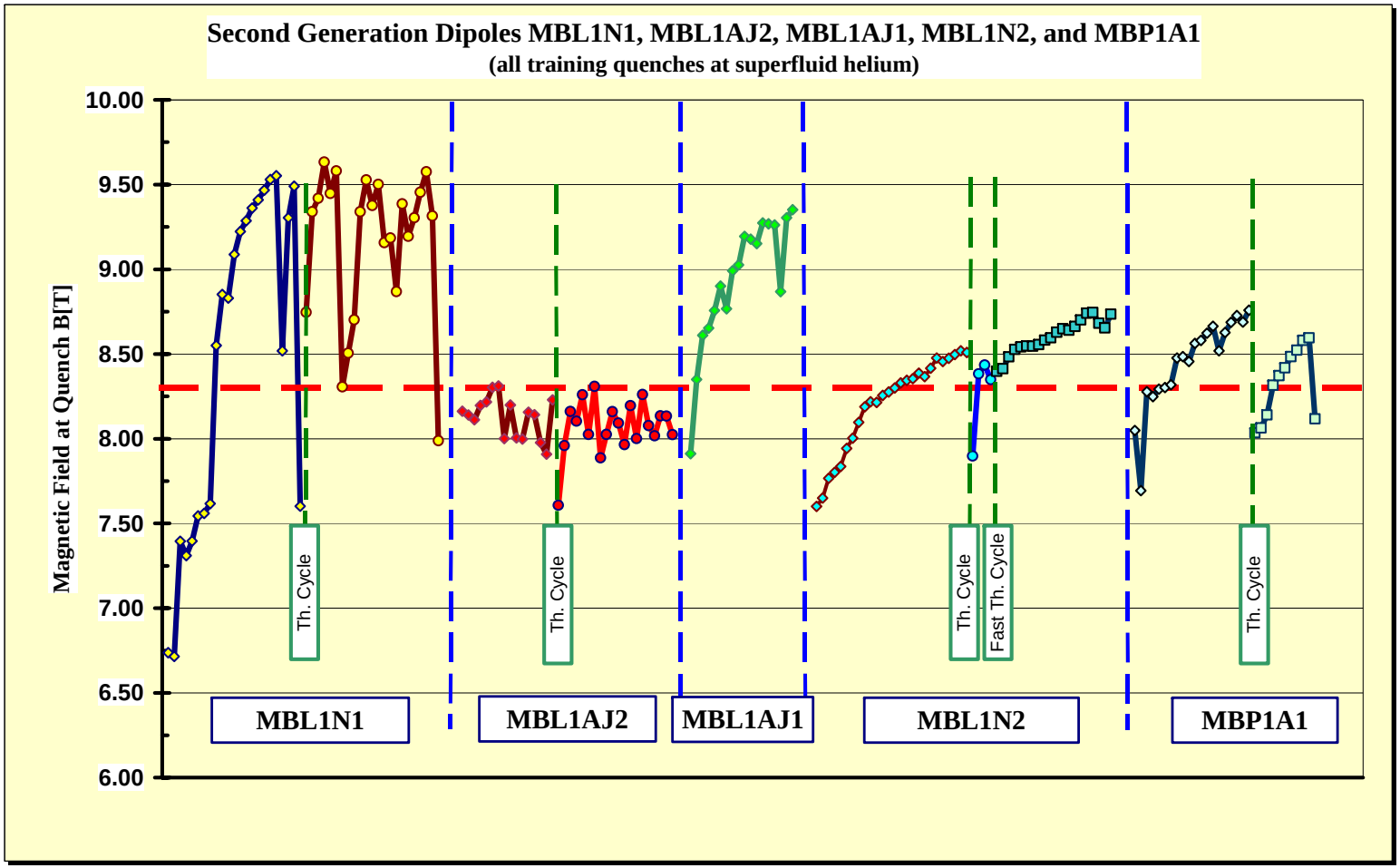


- Pre-developed at CERN
- Installed directly CMAs
- Two weldings synchronized
- Root welding STT: high quality very sophisticated control, a world *PRIMA* for this conditions and austenitic steel
- Problem on the press, now almost over : still quality of welding
- Each CM leak tested 26 bar !!!

Logistic and QA: the dark side of the work

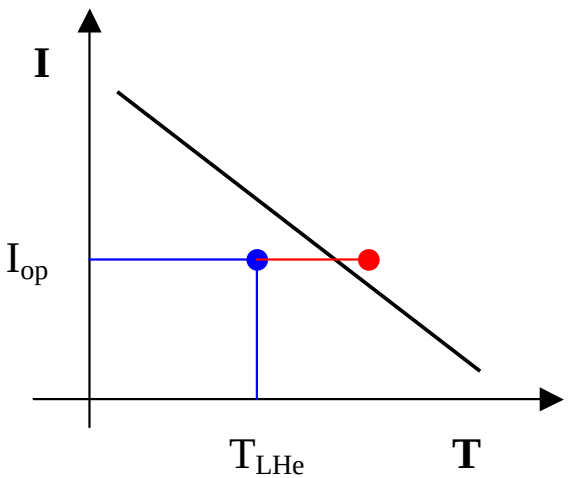
- We'll put some 50,000 tons in the tunnel
- We'll move some 150,000 tons around Europe, in four years.
  ~10000 TIR, ⇒ 10 TIR/days in average! ⇒ *Paperwork !*
- Timing! Example of low carbon iron (yoke)
- QA : The MTF Manufacturing Test Folder
  Full description of the magnets: some 500 entry !
  Based on ABS. It assures the full and permanent traceability
  Contains also all NC and components CoC

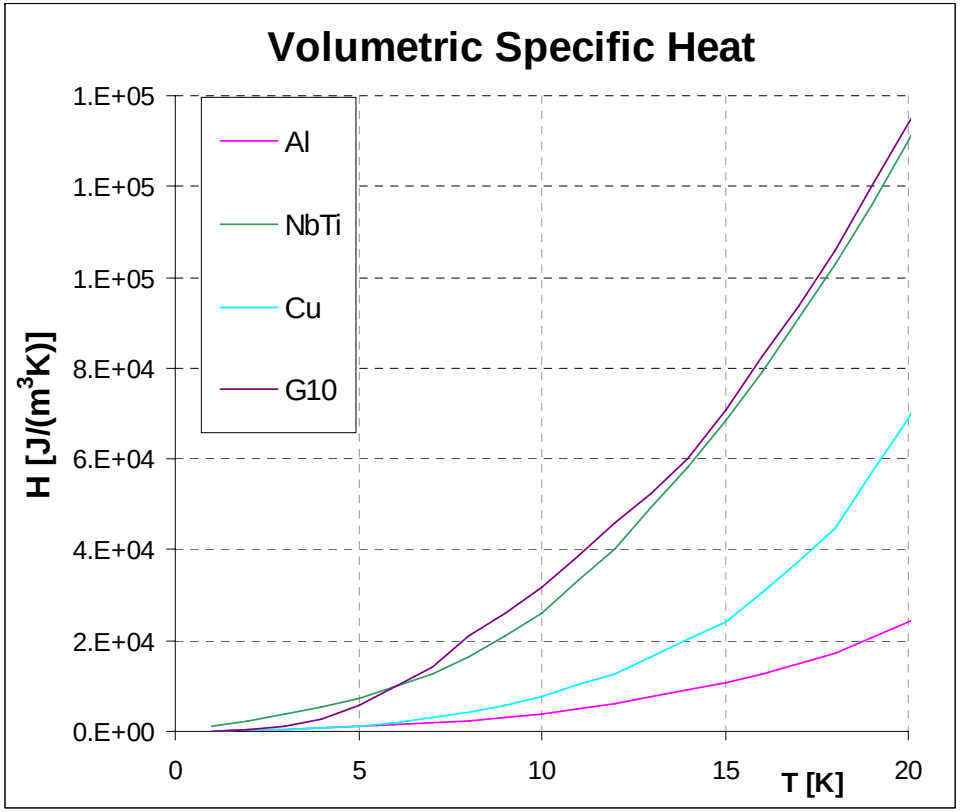
Magnet performance and Training Curve



Temperature and enthalpy margins

The first action to take is to have a reasonable energy margin, larger than the expected energy release, to make unlikely to pass the critical surface: but the specific heat of solids are pretty low near LHe and we can rely only on $\Delta T \approx$ 1-2 K



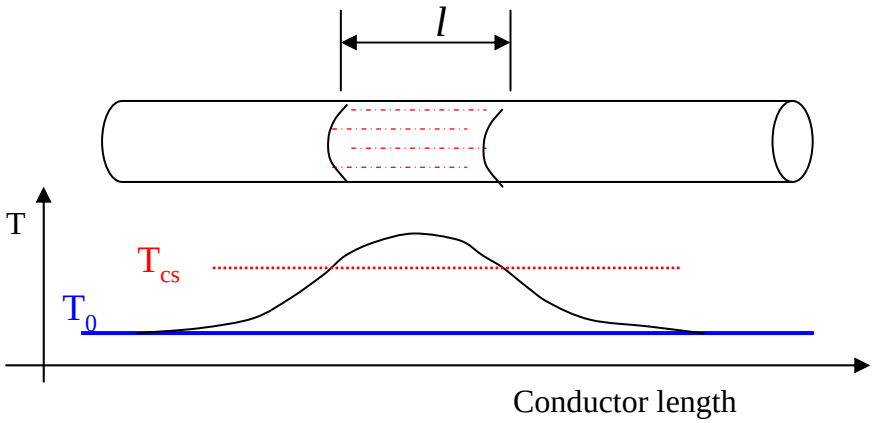


Point Disturbances : MPZ

Energy density is not the only criterion, since most of the perturbations are localized.

MPZ : the Minimum Propagating Zone
with a simple balance between power dissipated in the normal zone and heat conducted along the cable we found:

$$l = \frac{2k(T_{cs} - T_{op})}{\rho J_c^2}$$



If there is no stabiliser, only NbTi, we see that $l \cong 1\ \mu m \Rightarrow \Delta H \sim 1$ nJ only !!

Clearly a stabiliser is needed, with good conductivities, both thermal and electric : $k\,\rho = L_o T$
Heat is conducted away also the transverse direction, i.e. through insulation

If the normal zone created by the perturbation is larger, there is the thermal runaway: **quench.**

PROTECTION

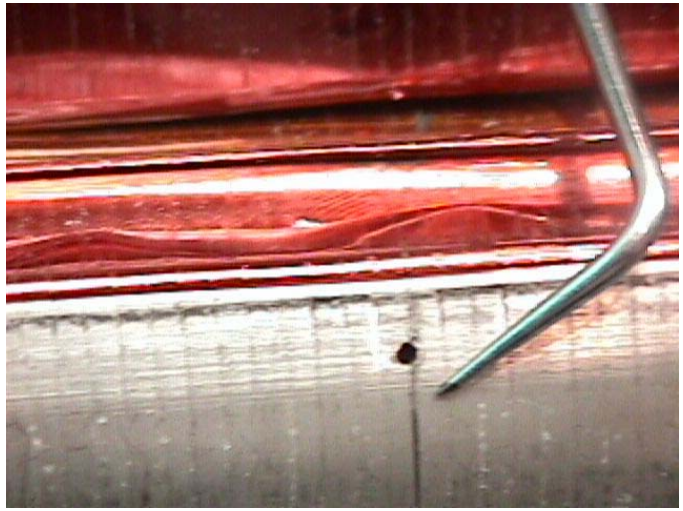
A superconducting magnet, whatever the stability margin, **it will quench**. And magnet integrity has to be preserved.

When working at current density like in the LHC dipoles, where dissipation per unit volume following a quench is $\rho\ J_{Cu}^2 \cong 6\ 10^{-10}\ \Omega m\ 10^{18}\ A/m^2 = 600\ MW/m^3$

Excessive voltage rise ⇒ insulation breakdown.

Temperature growth ⇒ melting or serious trouble to insulators and conductor

Temperature gradients ⇒ excessive stress with subsequent de-training.



Impressive damage caused by a short circuit developed during a quench in a LHC dipole protype

Hot Spot Temperature

Let's suppose that heat is coming only by Joule effect and conduction is not significant

$$J^2(t)\rho(T)dt = \gamma C(T)dT \qquad \int_0^{\infty} J^2(t)dt = \int_{T_{op}}^{T_m} \frac{\gamma C(T)}{\rho(T)} dT \qquad J_0^2 T_d = U(T_m)$$

MIITs

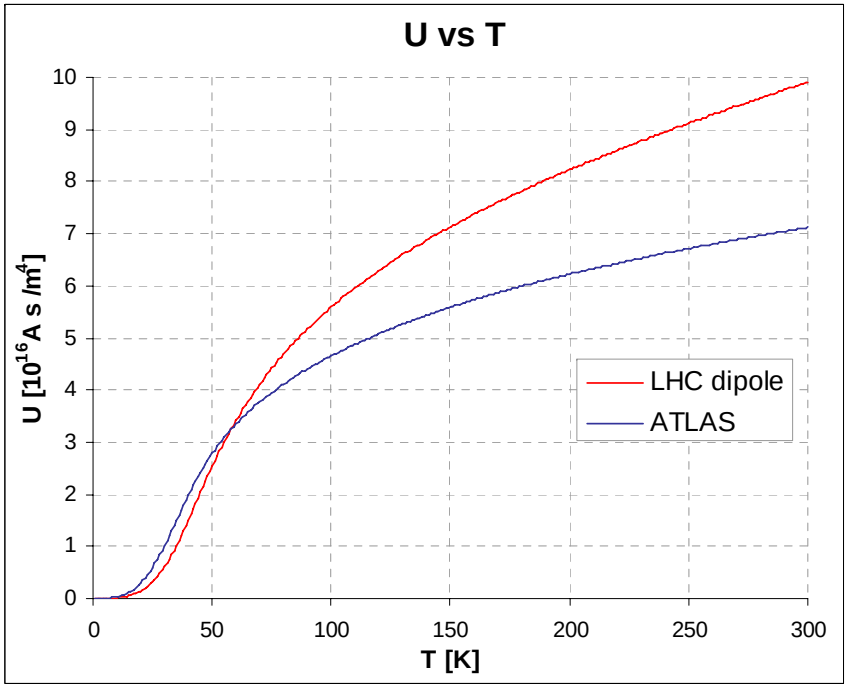
The function U(T) is a computable a priori, based only on material properties. If the magnet is discharged on an external –dumping- resistors, R_D, $T_d = 0.5 \cdot L_{mag}/R_D$.

The goal is to speed up the quench propagation by any means, to avoid too high hot spots:

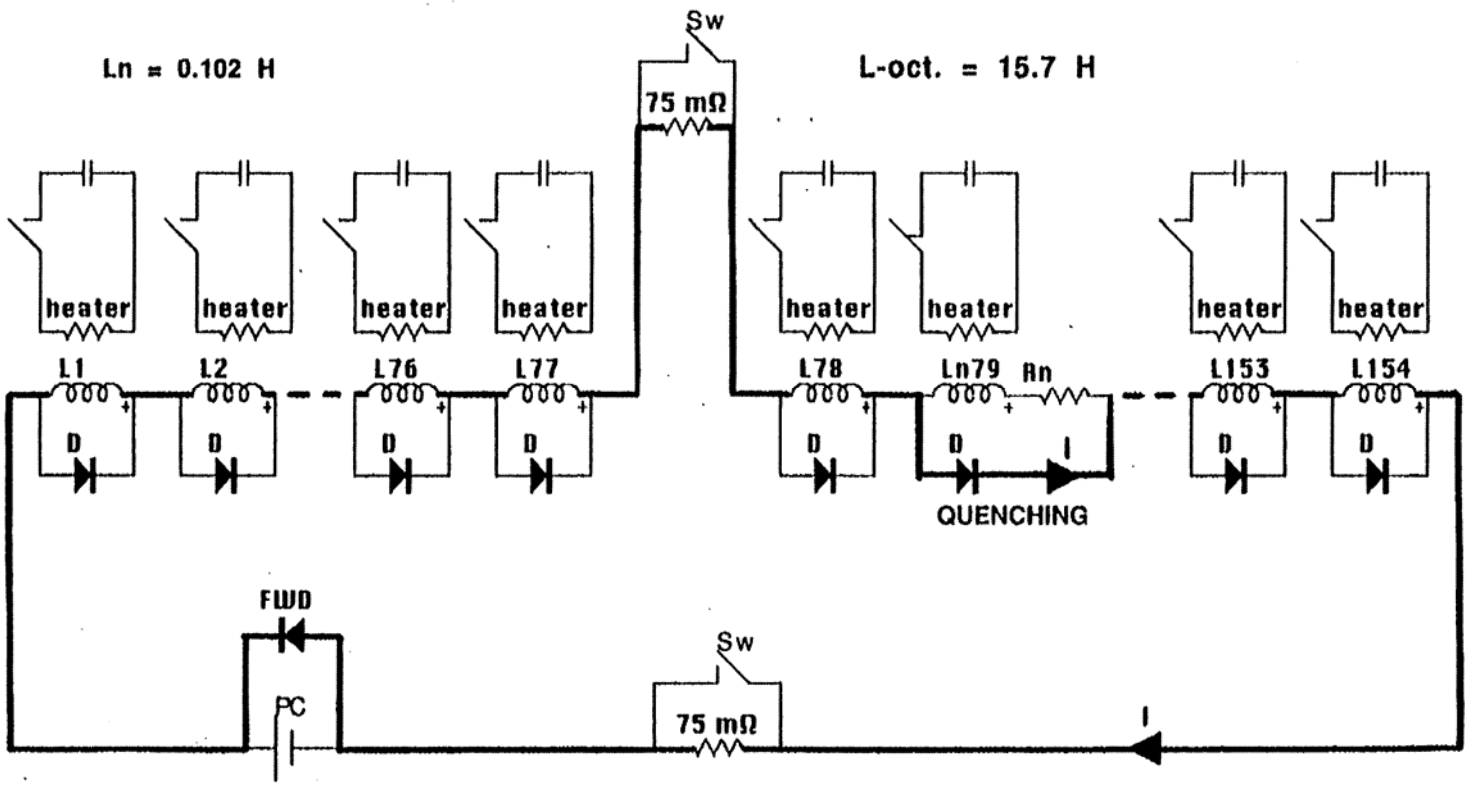
1) **Heater : activated in 20 ms !!**

2) Benefit of quench-back

This goes against having LHe inside the coils (i.e. is against stability)!

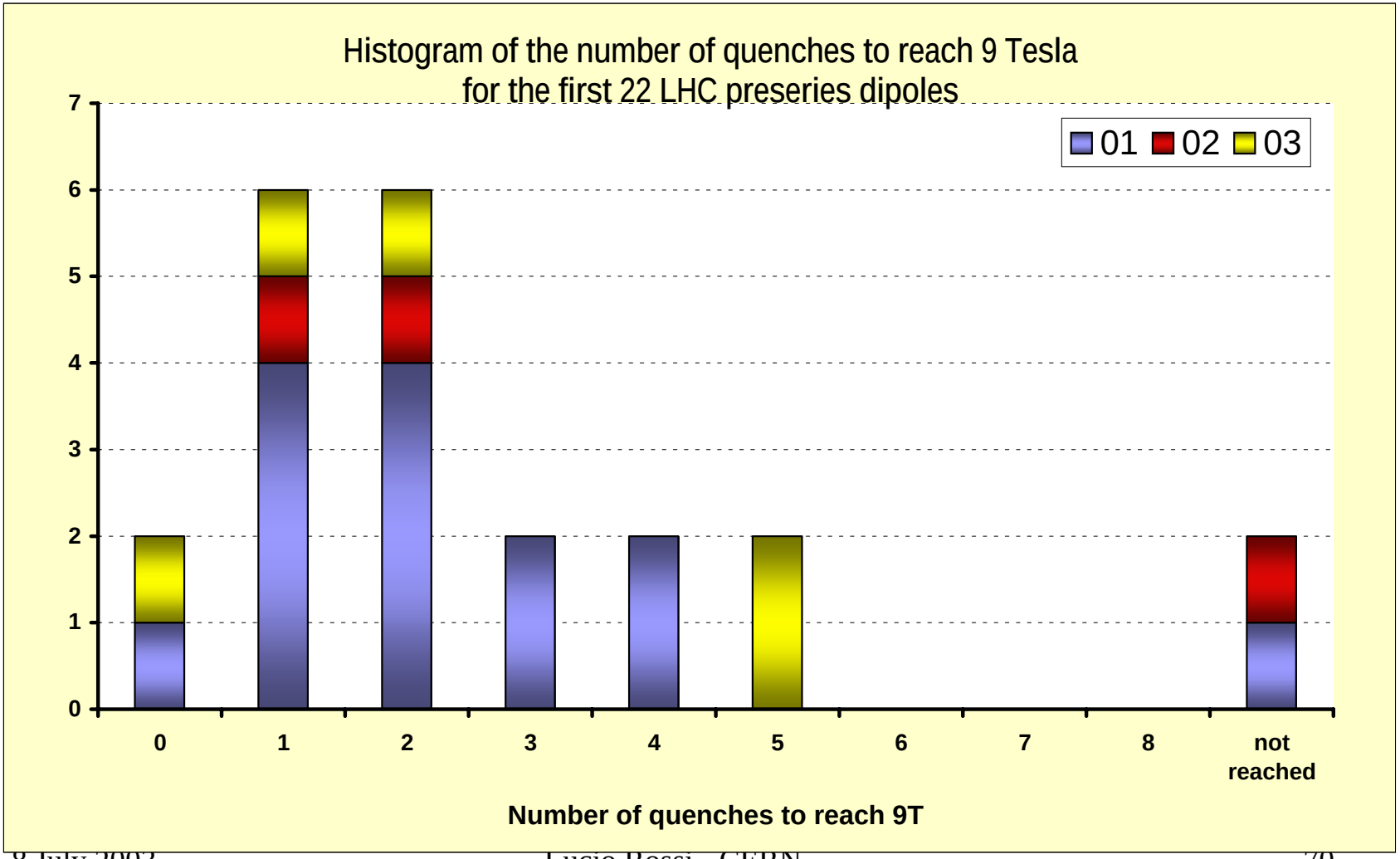


Protection scheme for a dipole string

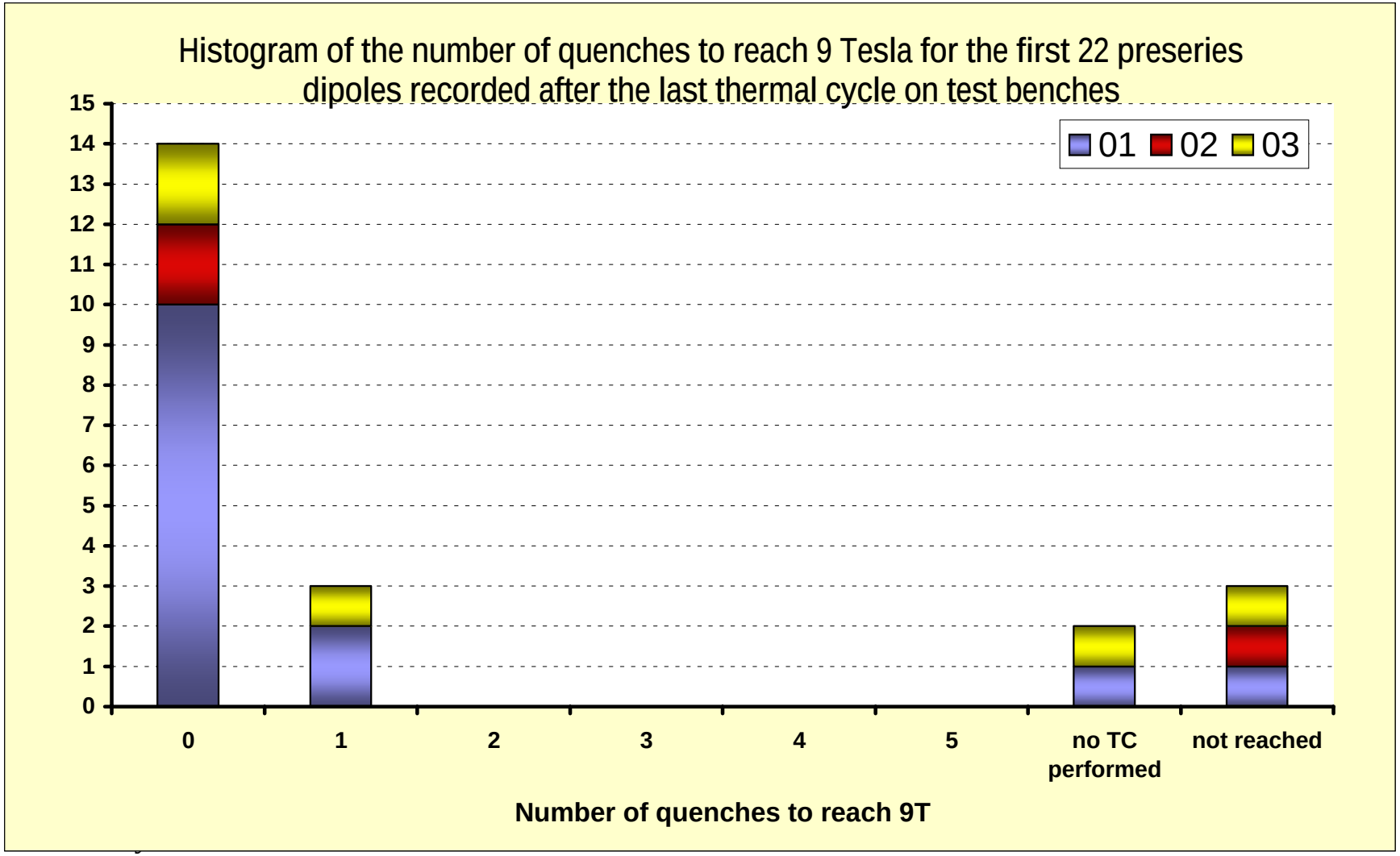


LHC protection scheme (courtesy of F. Rodriguez Mateos , CERN)

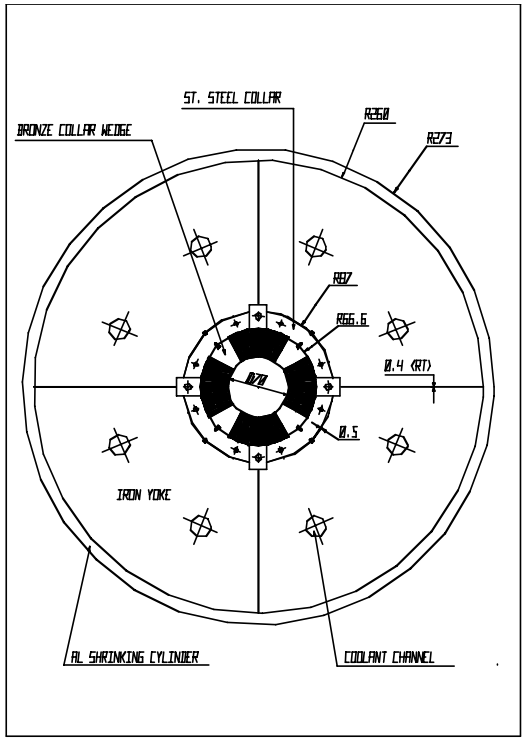
Quench today : first cool down

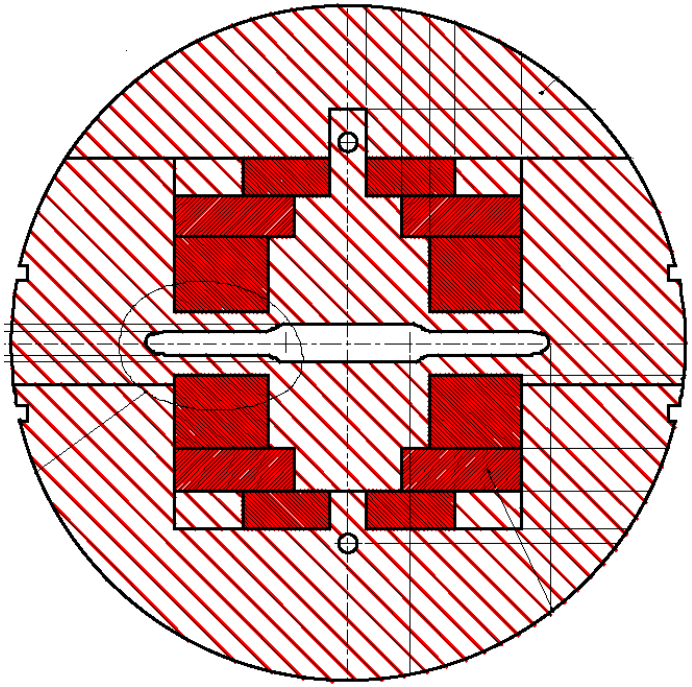


The ultimate proof for accelerators:memory



What's after LHC ?
Luminosity upgrade

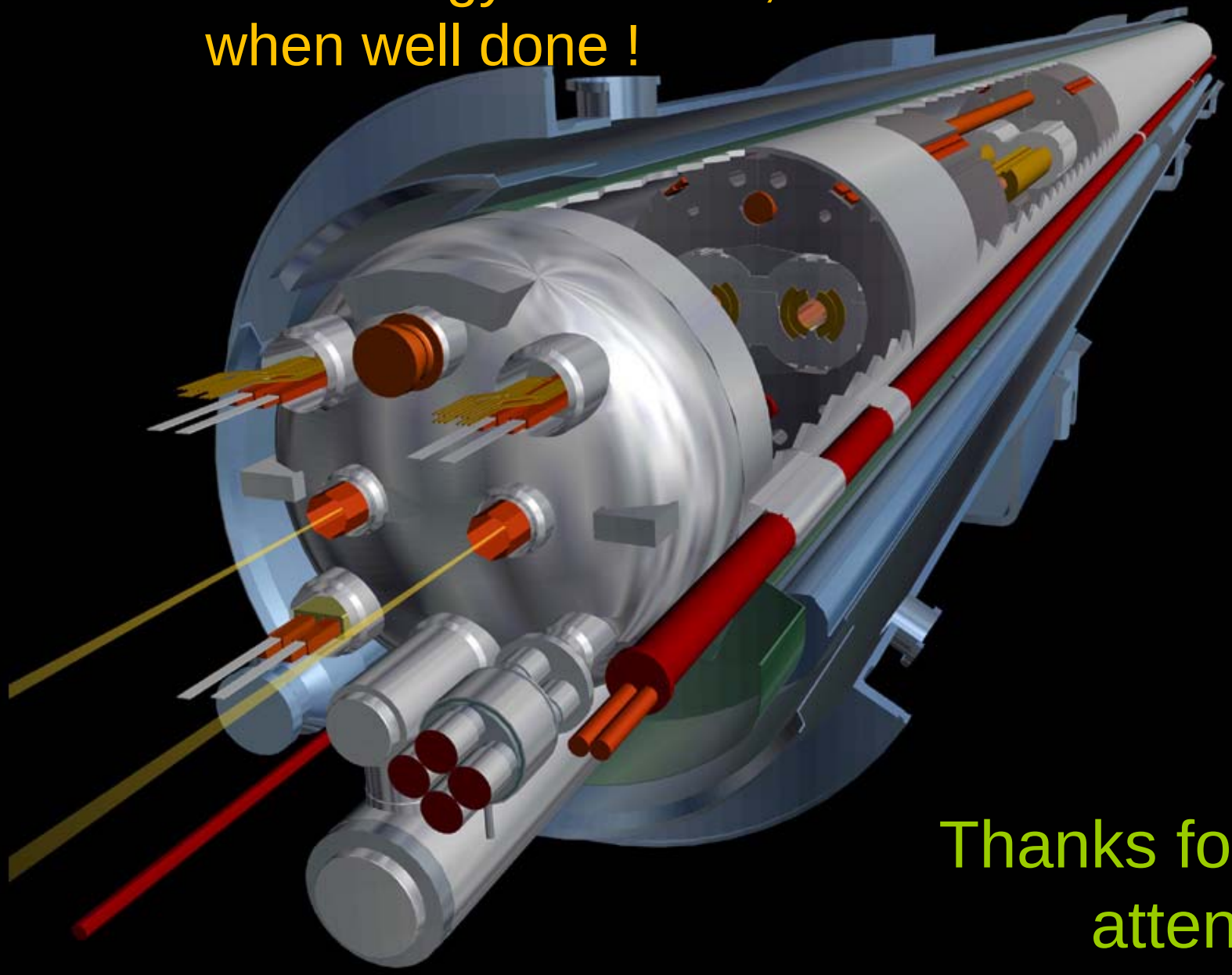




An then ? After 2015 ?
A possible energy upgrade!
With new typed of magnets

QuickTime™ and a Graphics decompressor are needed to see this picture.

Technology: beautiful,
when well done !



Thanks for the attention!