CERN Accelerator School

26 February 2009 - Divonne

Superconducting Magnets for the LHC

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CERN – TE department

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

Applied Superconductivity

- ✓ **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**
- ✓ 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

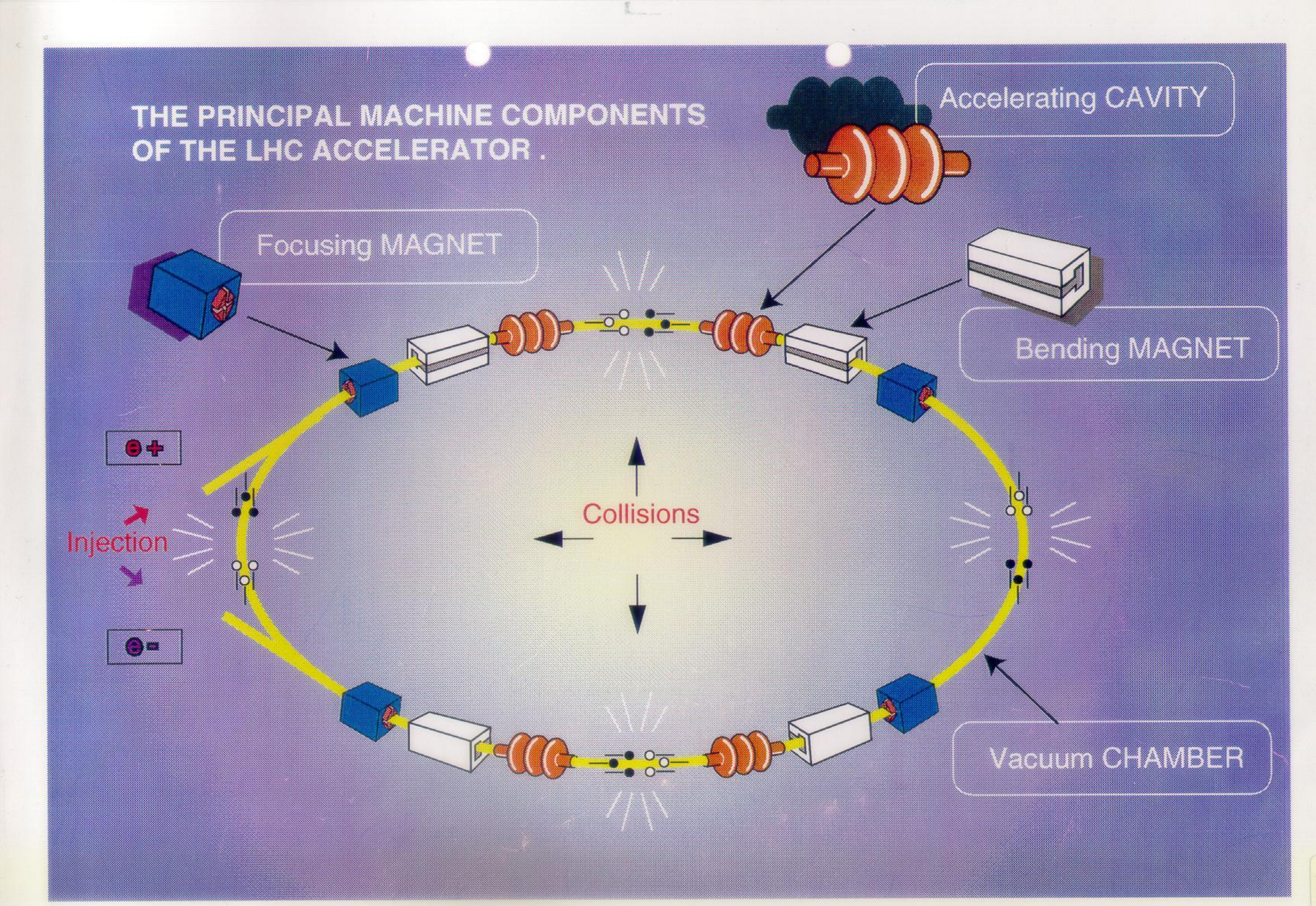
- 1999 : Ph. Lebrun - Superfluid Helium
- 2000 : L. Rossi - Superconducting Magnets
- 2002 : D. Larbalestier - Superconducting Materials

CAS School on SC and cryogenics for accelerator and detectors, Erice 2002, Report CERN 2003-

Content

- Accelerators and magnet shape
- Accelerator Magnets : basic design, magnet types
- The heart: superconductors (and superconductivity)
- Mechanical structure
- Making it suitable for LHC: Field Quality
- Alignment issues
- Snapshot at construction in Industry
- Quench and stability

Circular accelerator: magnet festival



E ≅ 0.3 B R

Tev, T, km

LHC:

18 km MB

2.5 km MQ

2 km of other Quads

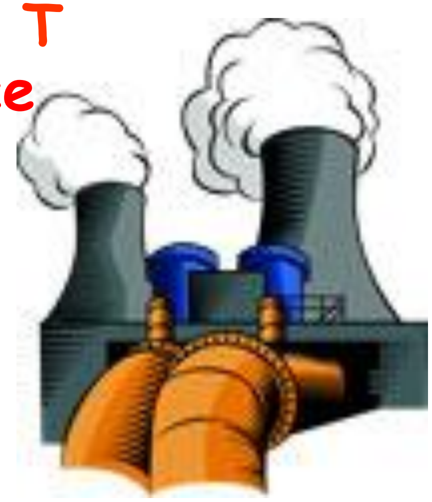
> 8000 Sc Magnets!!!

Rationale for using SC

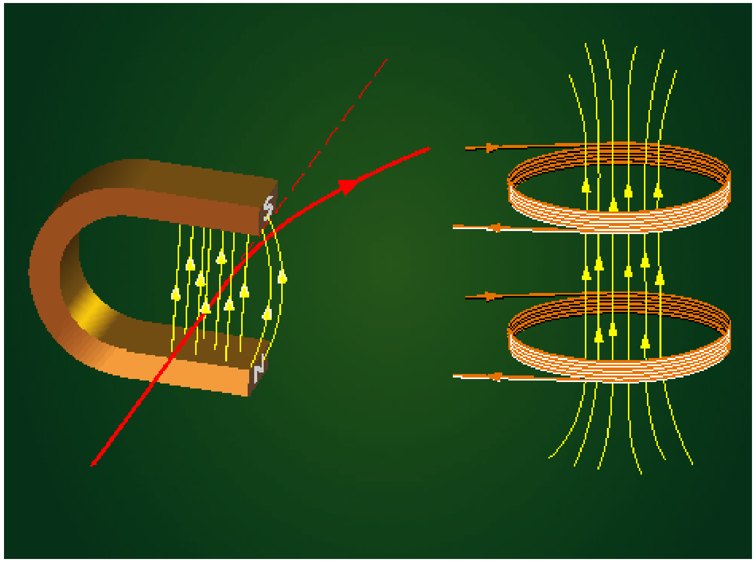
- The LHC has a circumference of 26.7 km, out of which some 20 km of main superconducting magnets operating at 8.3 T. Cryogenics will consume about 40 MW electrical power from the grid.

If the LHC were not superconducting:

- If it used resistive magnets operating at 1.8 T (limited by iron saturation), the circumference would have to be about 100 km, and the electrical consumption 900 MW (a good-size nuclear power plant), leading to prohibitive capital and operation costs.

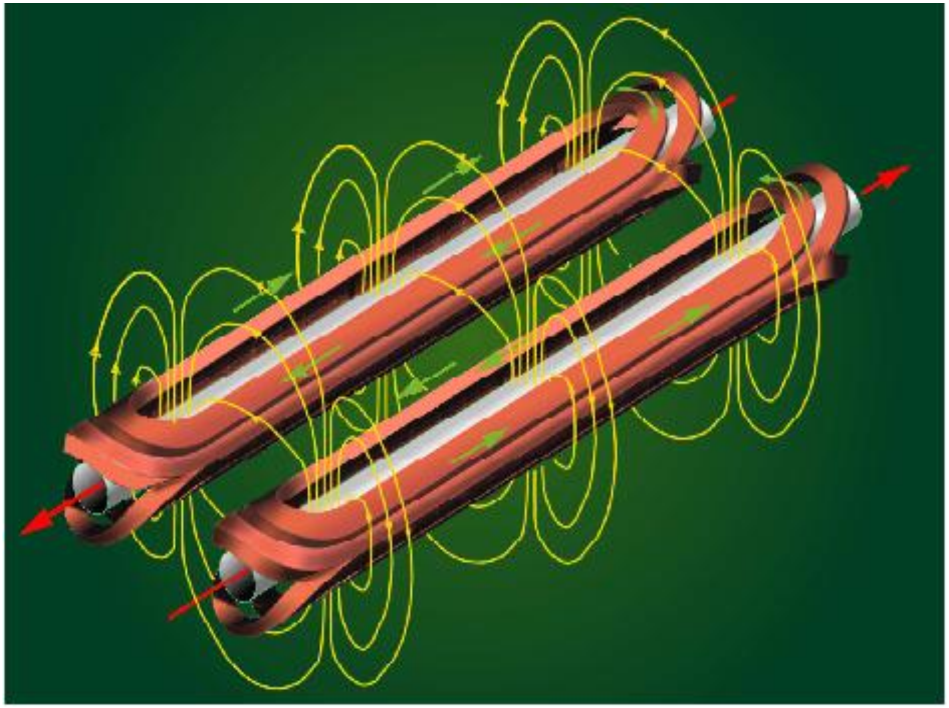


Accelerators and Magnet Shape

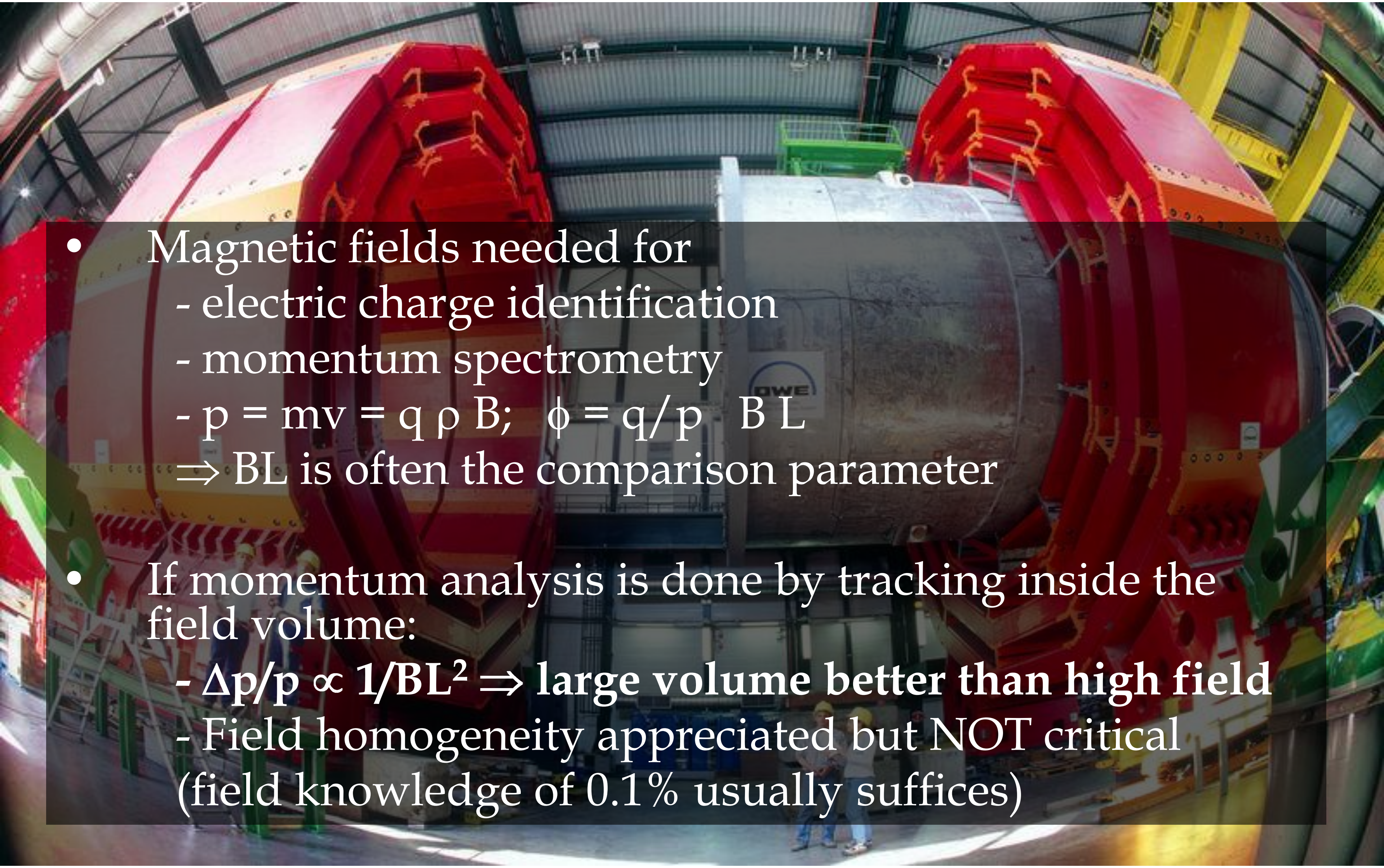


- The cost and the difficulties scales as the amount of the stored energy: Vol $\times B^2/2\mu_0$
- Rush for high field
  $\Rightarrow$ small volume of field

- Thin field tubes that follow the particle trajectories
- Dipole to bend
- Quadrupoles to focus
- Sextupoles and Octupoles
- Correctors (from Dip to Decap)
- Correctors are mostly local



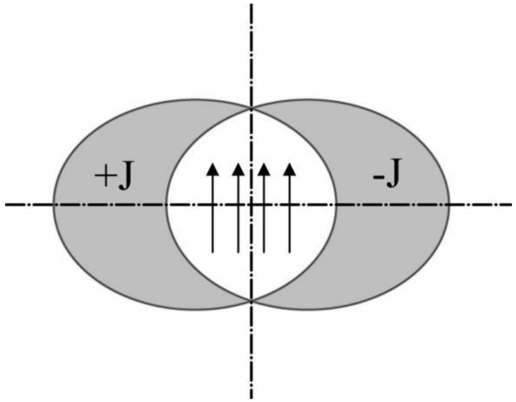
Detector Magnets

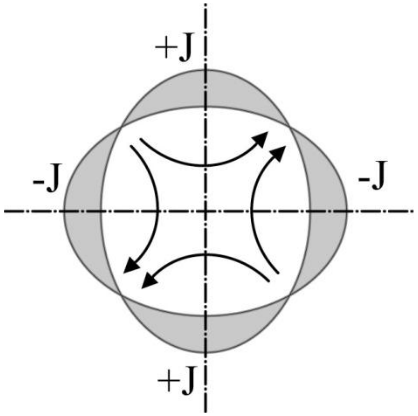


- Magnetic fields needed for
  - electric charge identification
  - momentum spectrometry
  - $p = mv = q \rho B$; $\phi = q/p \; B L$
  - $\Rightarrow$ BL is often the comparison parameter

- If momentum analysis is done by tracking inside the field volume:
  - **$\Delta p/p \propto 1/BL^2 \Rightarrow$ large volume better than high field**
  - Field homogeneity appreciated but NOT critical (field knowledge of 0.1% usually suffices)

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:

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

d = coil thickness

a, b, ellipses parameter

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

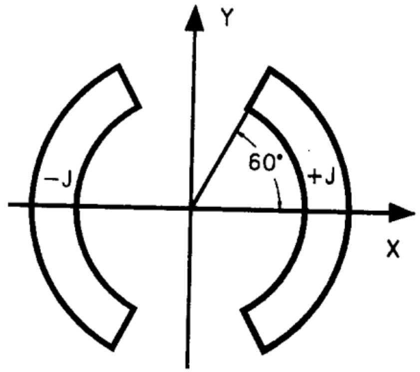
$$B_x = \frac{\mu_0 J (a-b)}{a+b} y$$

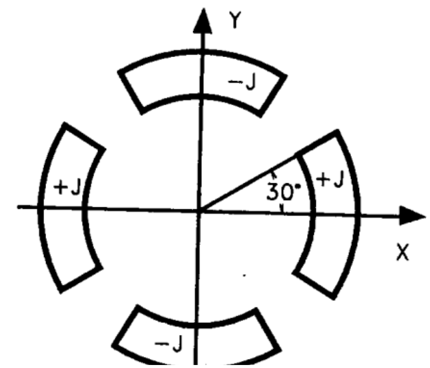
$$B_y = \frac{\mu_0 J (a-b)}{a+b} x$$

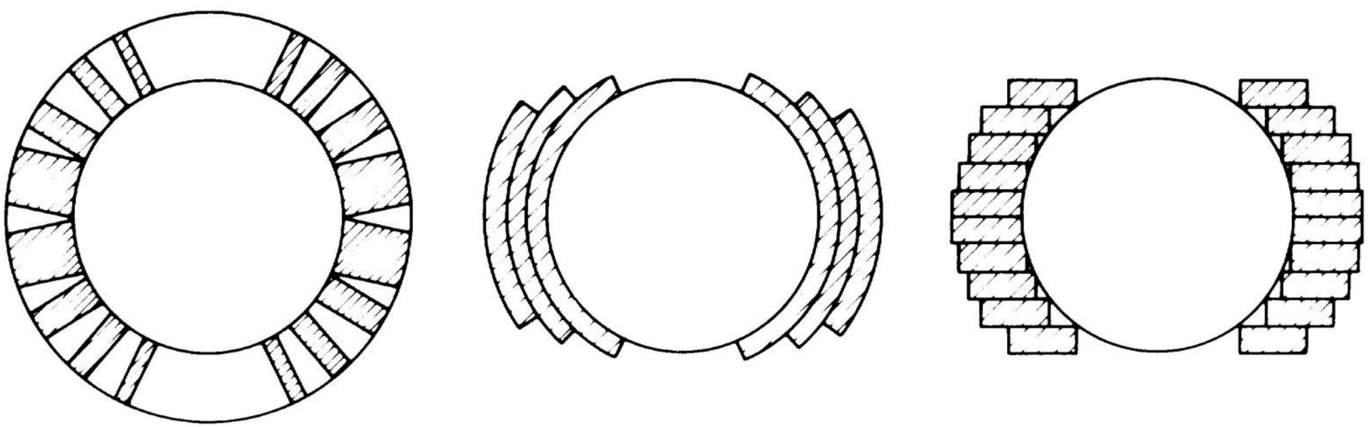
In practice the above current distributions are approximate, so the field contains also higher order harmonics (see later).
It can be shown that if the cos(nθ) is approximate by step function, there is a "magic" angle that makes nil the first higher order harmonics.

Accelerator Magnets Basic Design - II

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







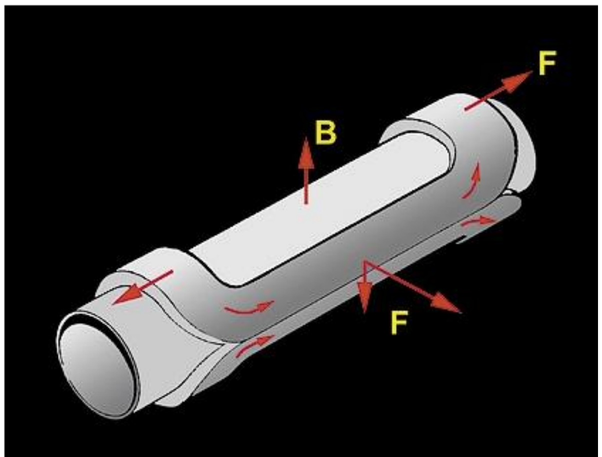
Approximation of cosθ with coil blocks (left) and multiple shells (centre) and of intersecting ellipses (from Wilson book).

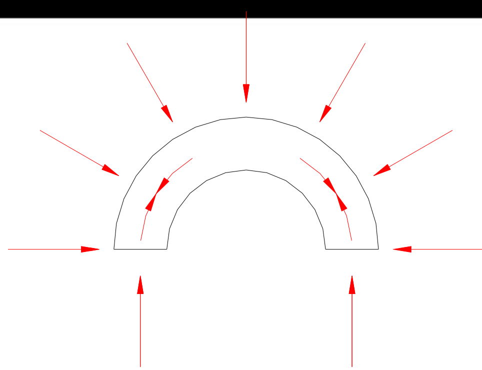
DEVIATION FROM PERFECT FIELD: 10^{-4} (0.01%) that is taken as the **unit**.

Accelerator Magnets Basic Design - IV

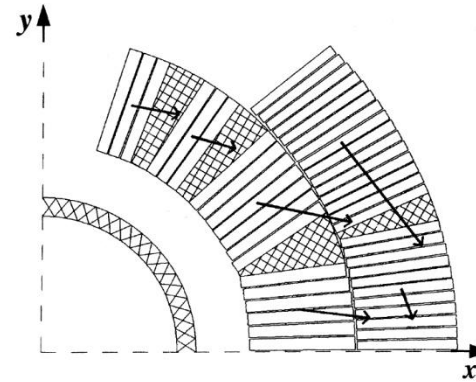
$J_{overall} \approx 500\ A/mm^2$! e.m. forces are not kept by conductors but tend to torn apart the winding.

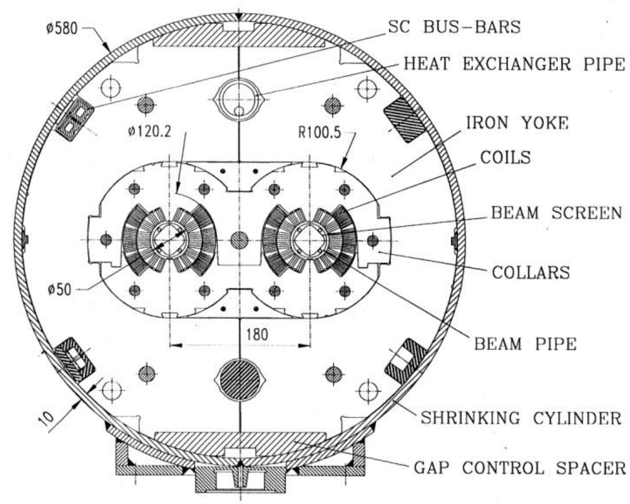
Principle

- 



Reality

- 



e.m. forces

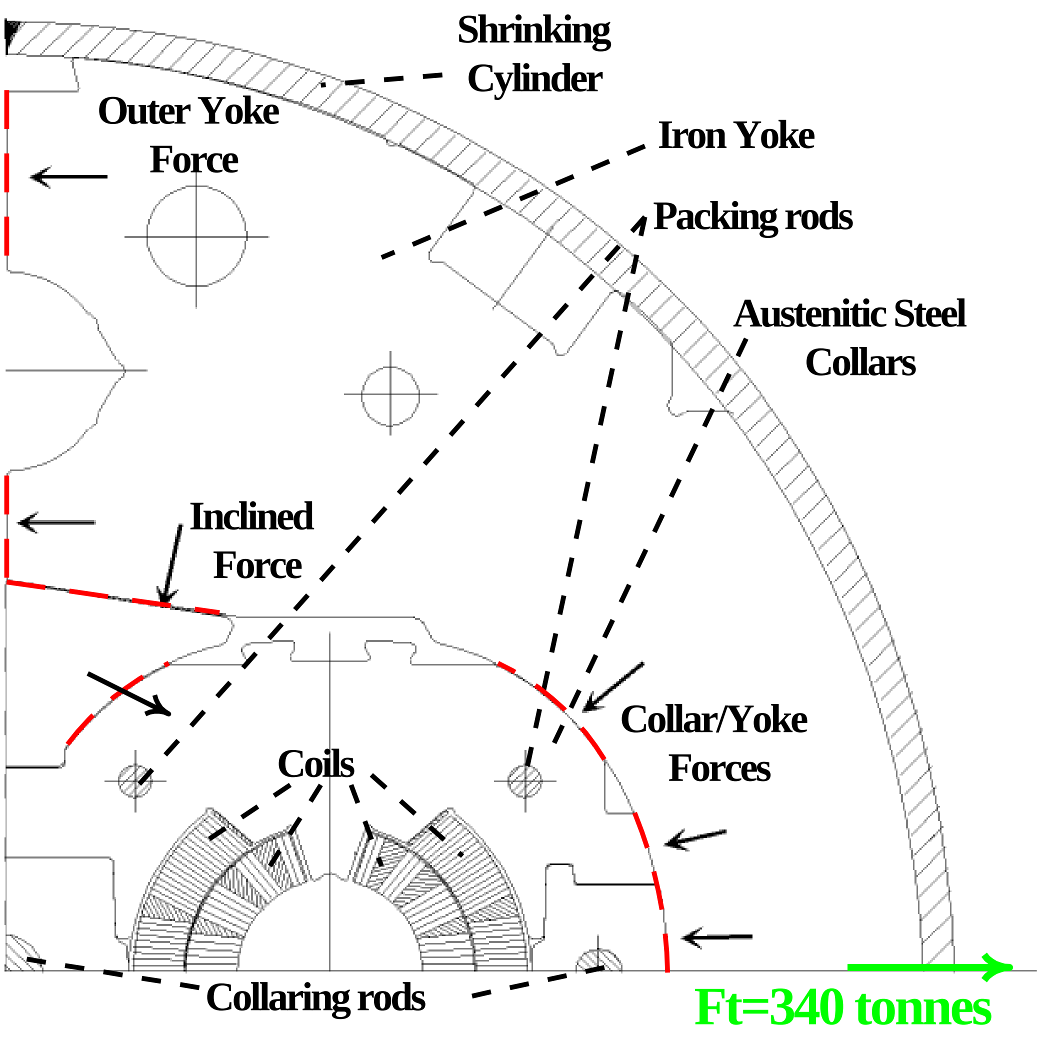
NOT SELF-SUPPORTING

How to contain them

More difficult in twin magnets!

coil-collars-cylinder structure

- The approach chosen by LHC is to have a design where most of the force can be taken by collars
- Then to have a vertical gap almost closed at RT and the outer skin welded such as to have a strong prestress
- Part of this is lost during cool-down but there is enough to assure azimuthal prestress of the coil up to 9 T and to have at least radial contact radial between collar and yoke
- The choice of stainless steel has released the tolerances on the skin stress: ideal 150 ± 15 MPa We can live even if all tolerance goes in the too low or too high direction.



LHC DIPOLE

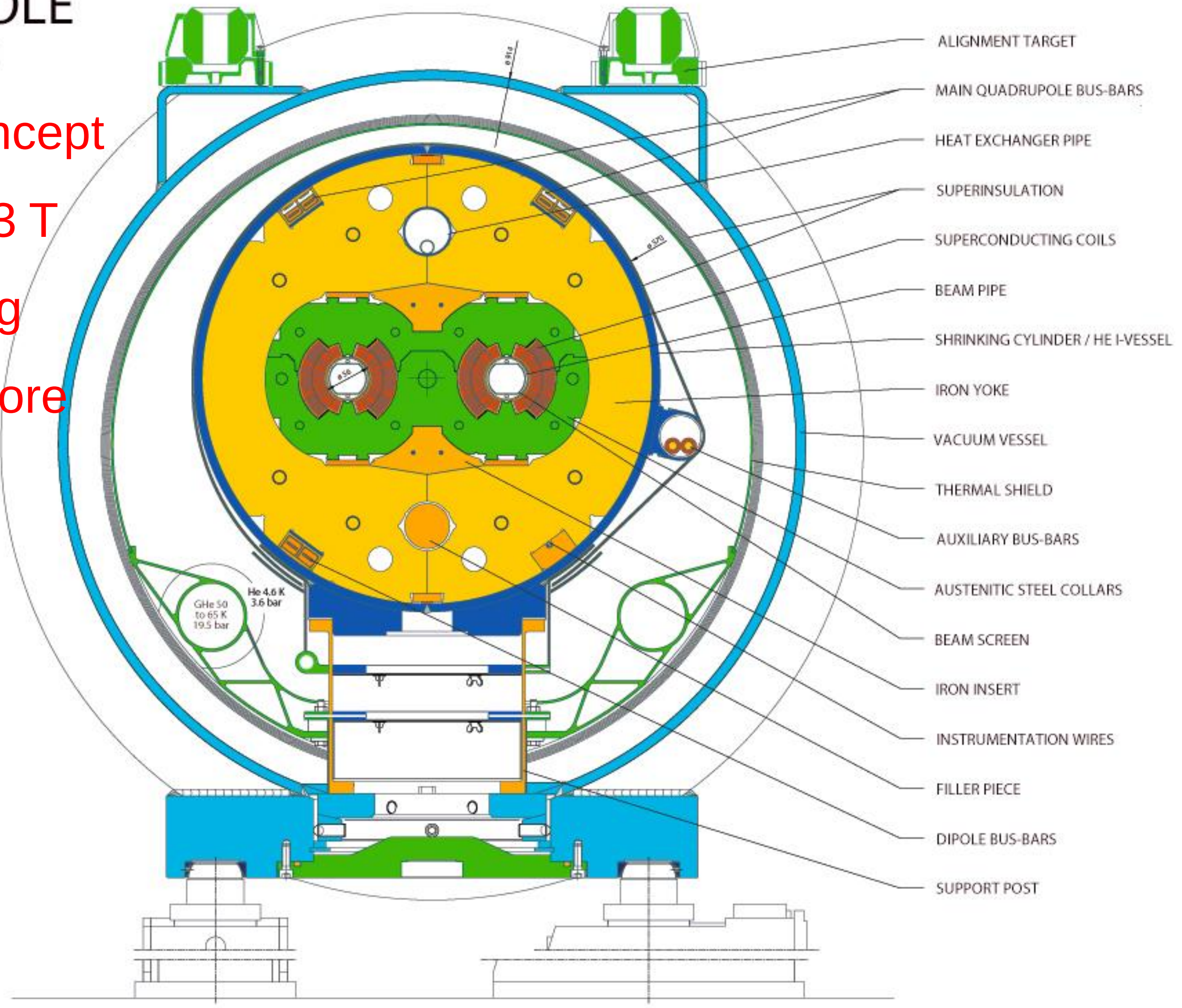
CROSS SECTION

Twin Concept

1.9 K, 8.3 T

15 m long

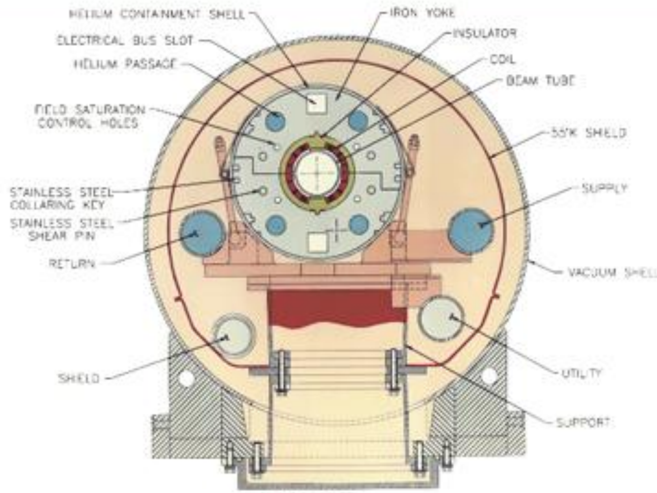
56 mm bore



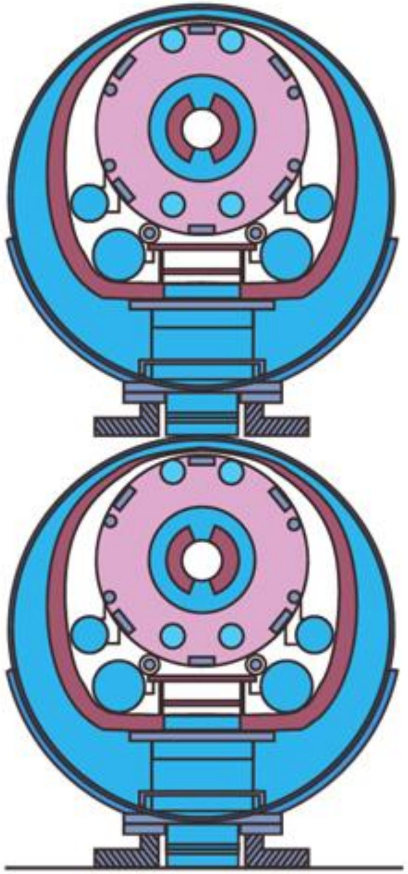
CERN AC/DI/MM — 06-2001

DIPOLE MAGNETS

HERA
B = 4.7 T
BORE : 75 mm

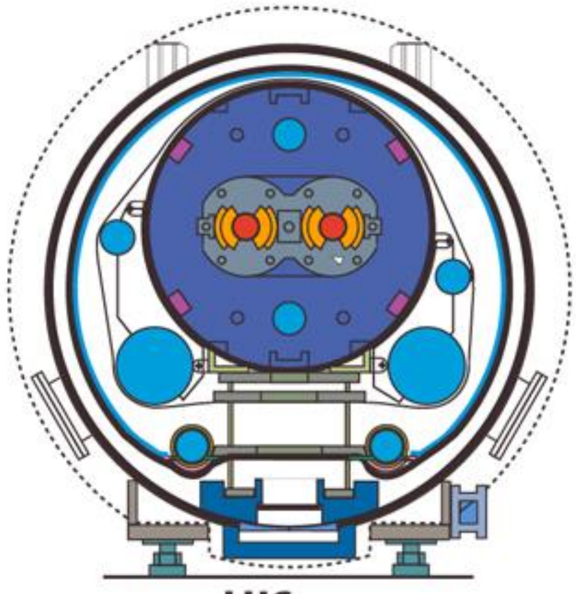


RHIC
B = 3.5 T
Bore : 80 mm



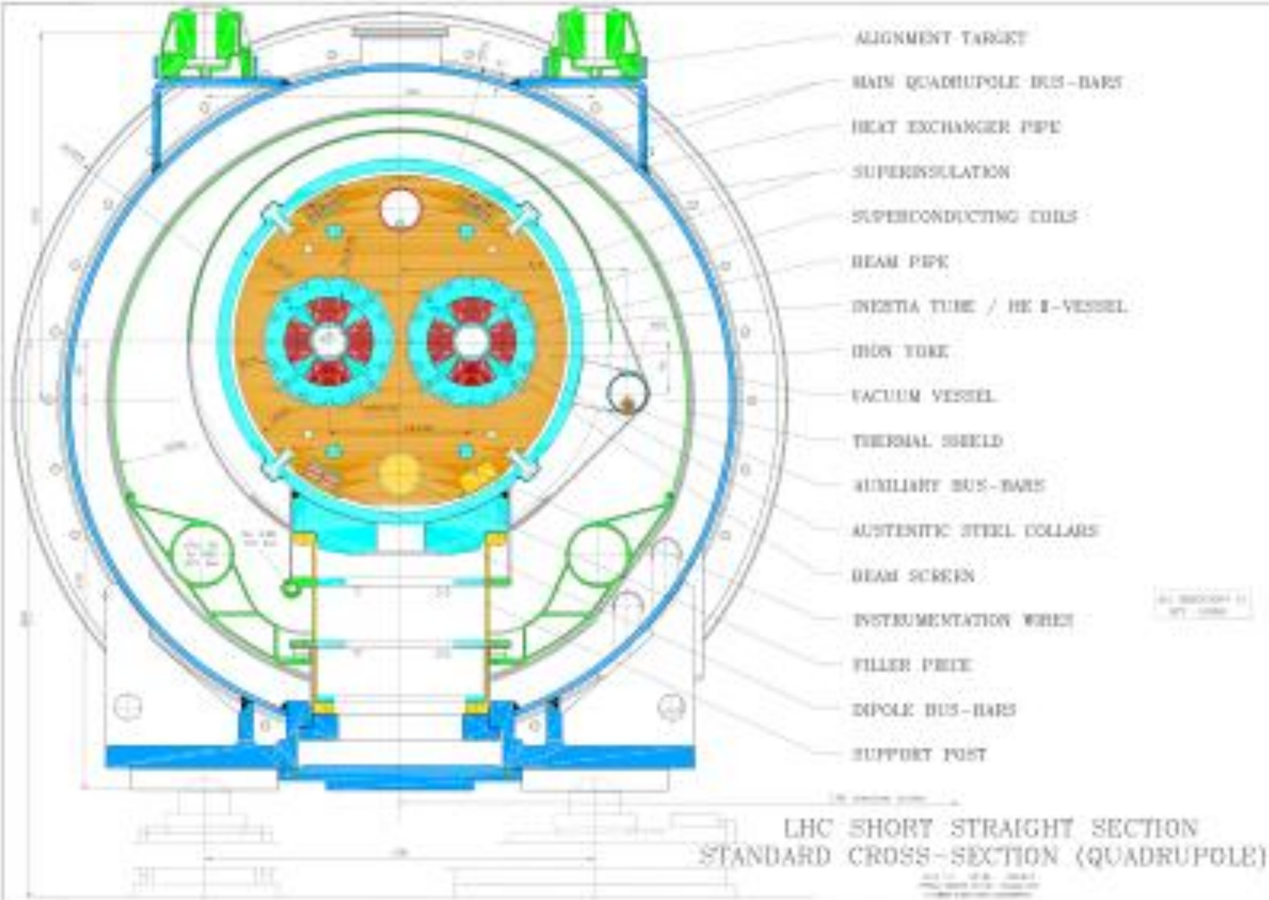
SSC
B = 6.6 T
Bore : 50-50 mm

TEVATRON
B = 4.5 T
Bore : 76 mm



LHC
B = 8.3 T
Bore : 56 mm

CERN AC - HE 109 RHIC 2001/09/20

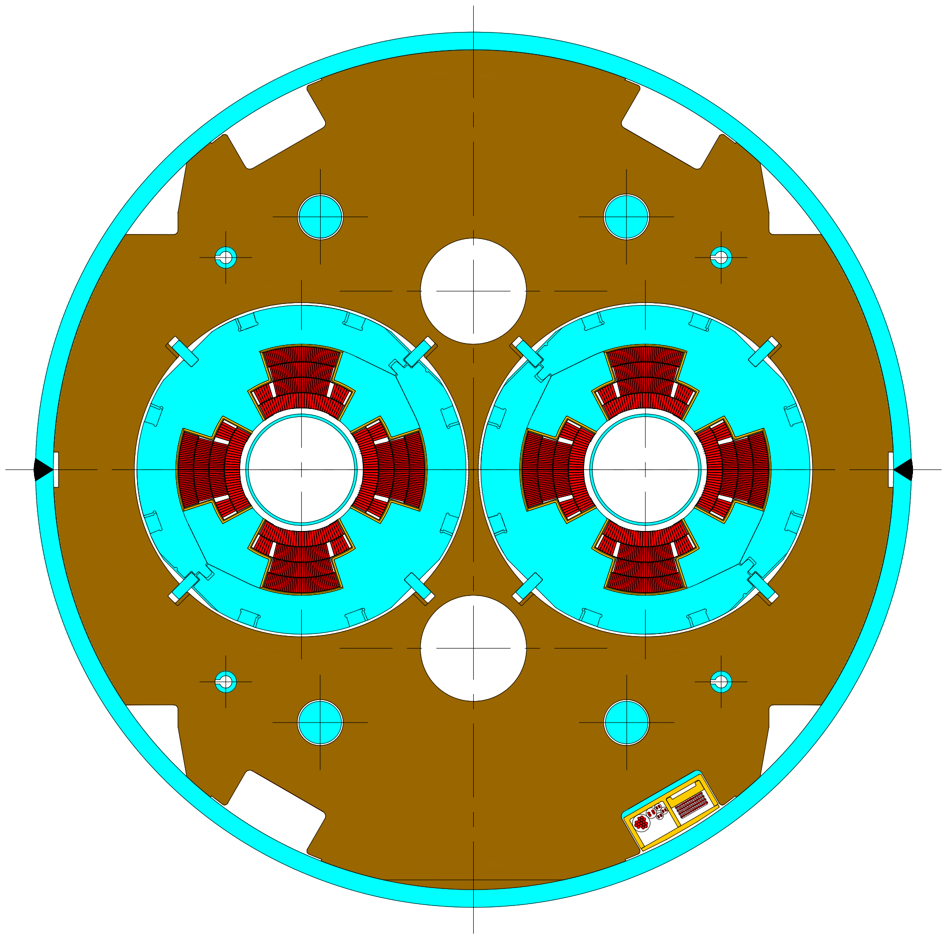


MQ
Main Quad

CERN- CEA collaboration

- Cu-NbTi cable @ 1.9 K. G_{op} = 223 T/m
- e.m. forces kept by collars only (iron is a mere flux return yoke)
- **Two-in-one concept (two apertures are de-coupled both magnetically and mechanically).**
- 3.5 m long, coil ap.56 mm, straight, alignment given by inertia tube
- Correctors are fixed on the inertia tube

MQY wide aperture quadrupole



70 mm ID coil

G = 160 T/m at 4.5 K

I = 3620 A

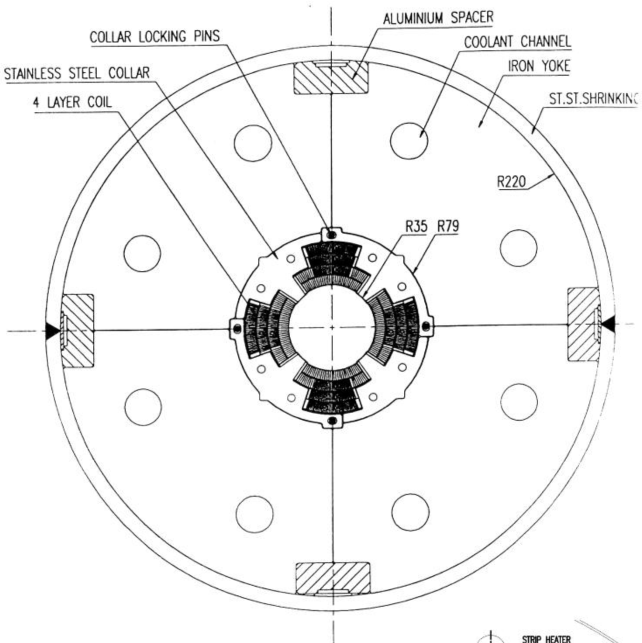
E = 141 kJ/m/aperture

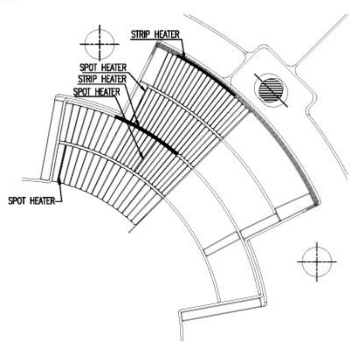
L_{mag} = 3.4

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

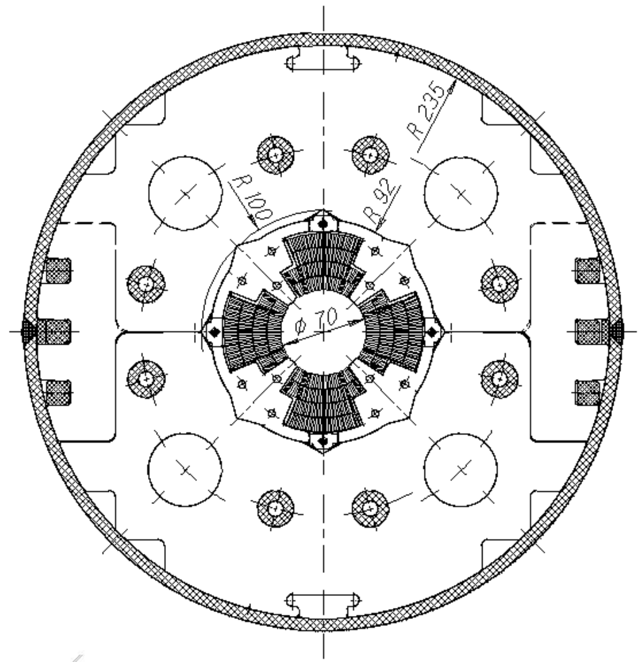
Three 70 mm quadrupoles developed for the LHC IRs

CERN-Oxford Inst.
(MQY)

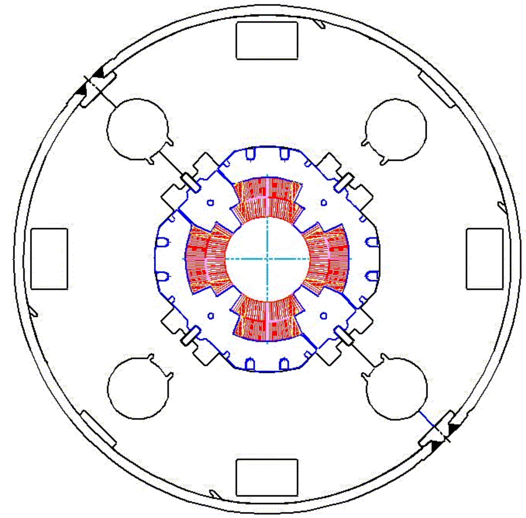


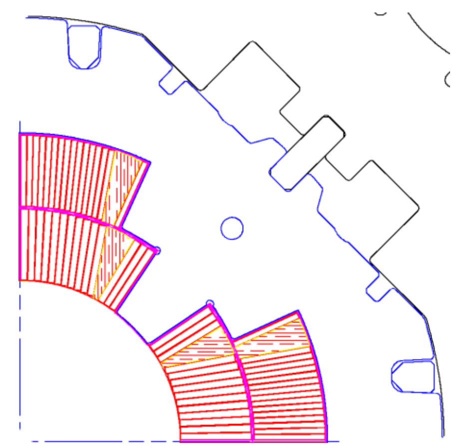


KEK
(MQXA)

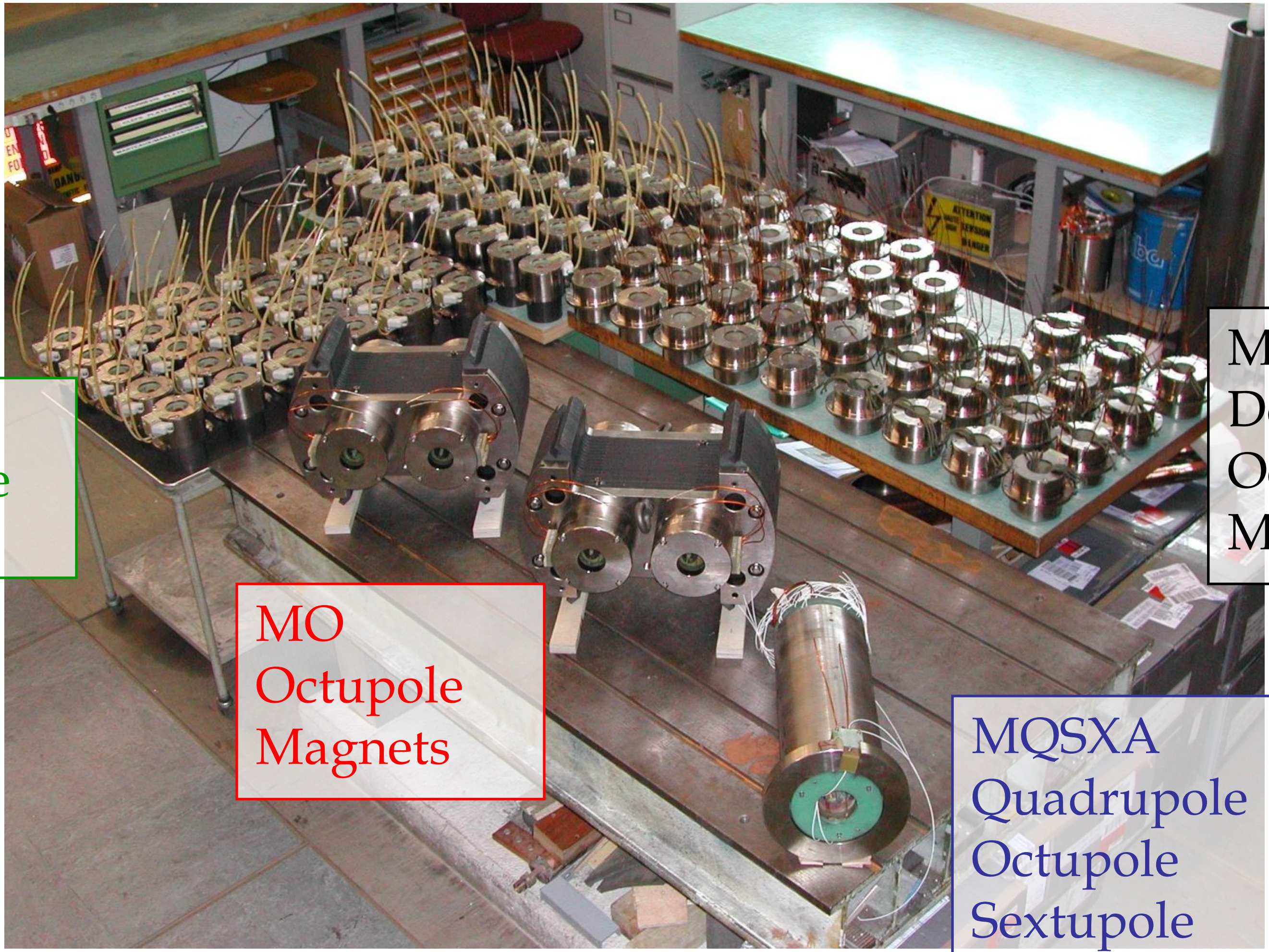


Fermilab
(MQXB)



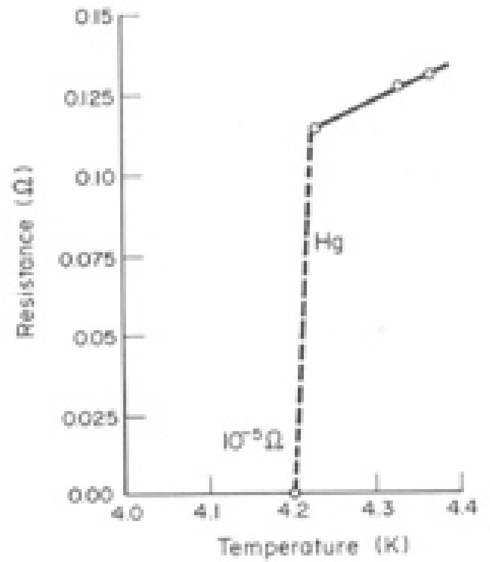


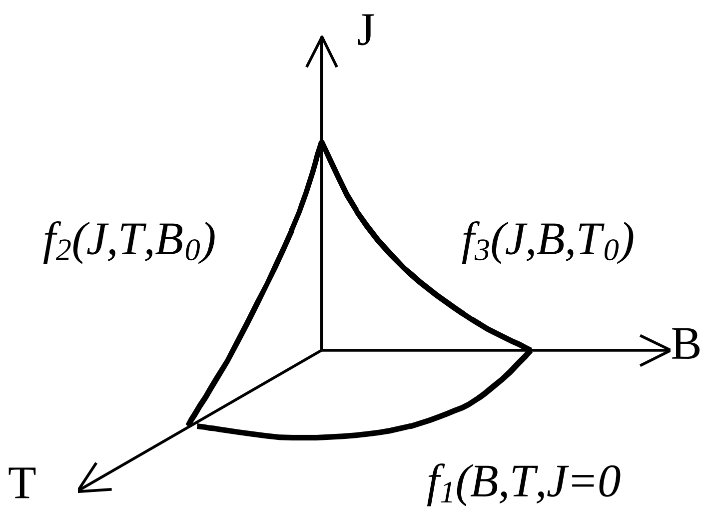
The zoo of the 6000 SC corrector magnets



Superconductivity

- Zero resistance !!
- But at low temperature
- And within certain limit of field and current
- Concept of critical surface

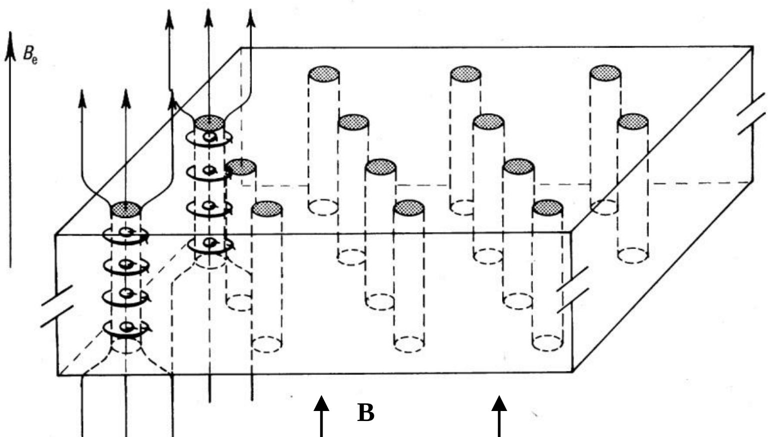


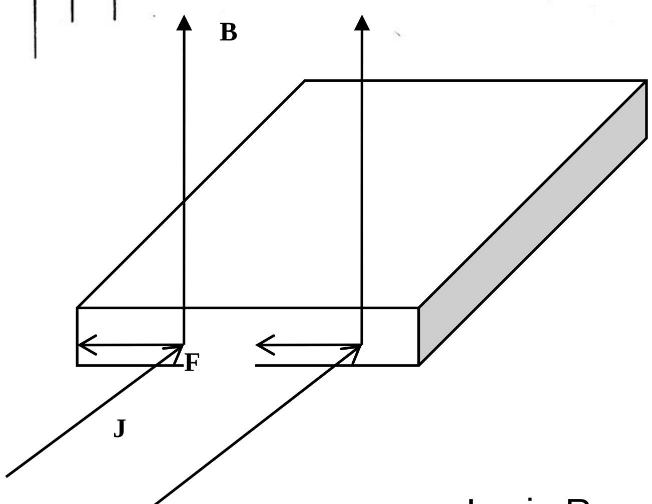


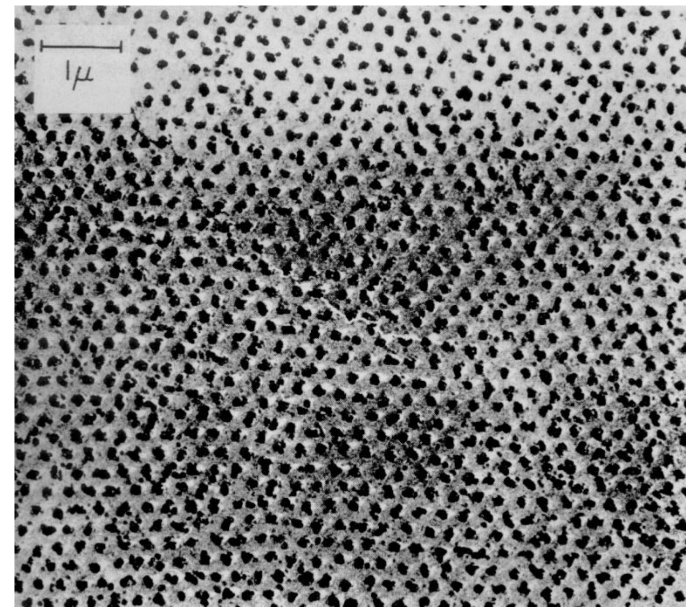
Who provide the current: type II superconductors

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

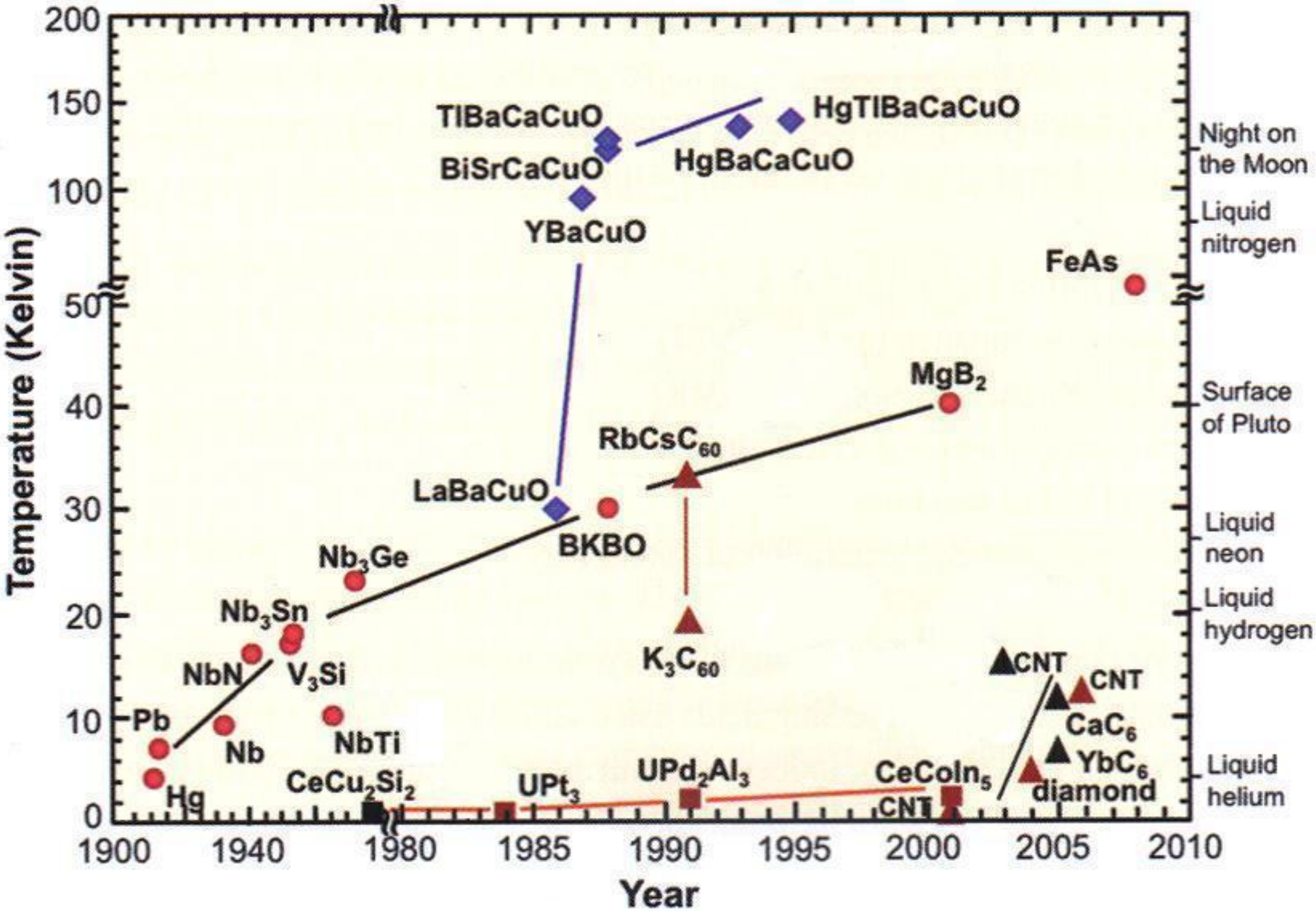
Practical Materials

Long journey from material discovery to magnet application

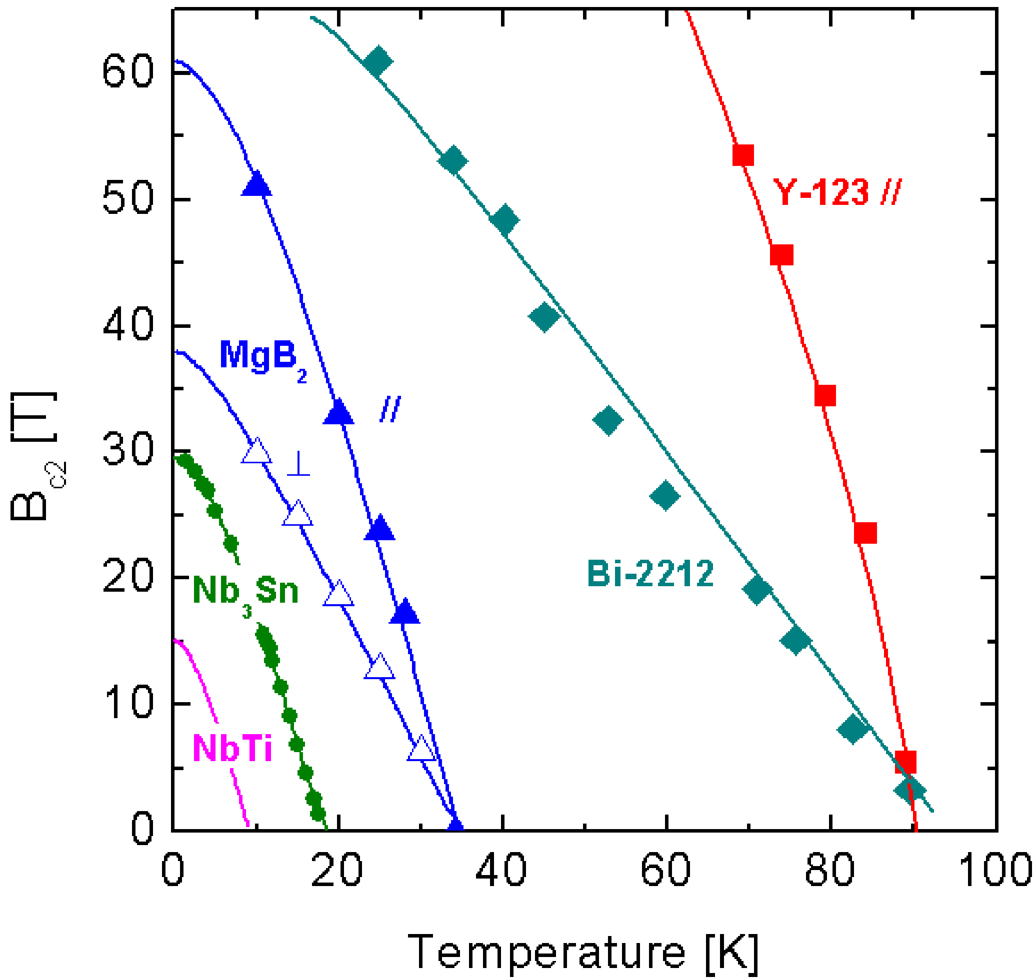
From science to technology

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

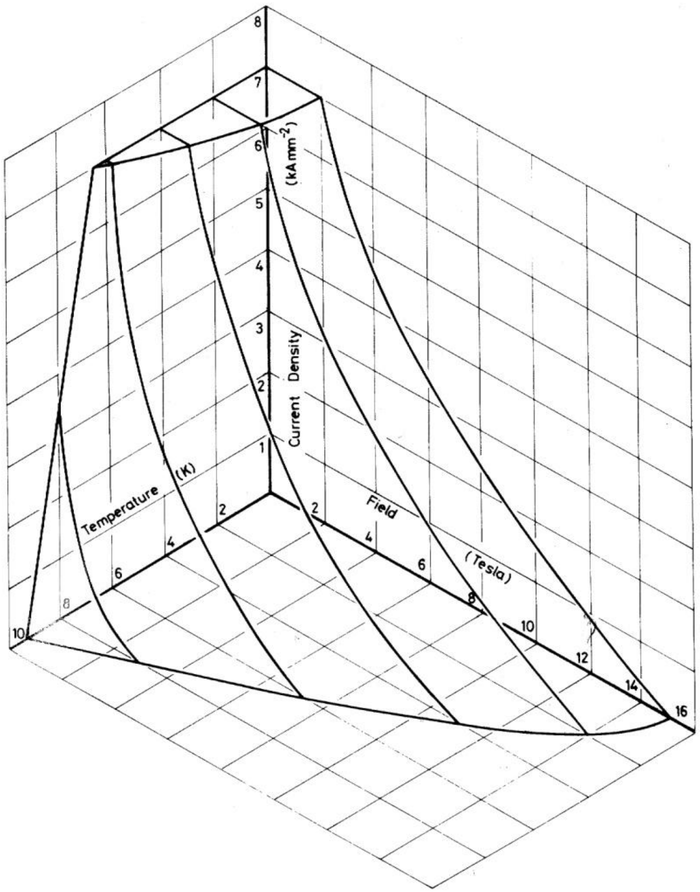
Tc vs year


Temperature (Kelvin)
Year
TlBaCaCuO
BiSrCaCuO
HgTlBaCaCuO
HgBaCaCuO
YBaCuO
FeAs
MgB$_2$
RbCsC$_{60}$
LaBaCuO
BKBO
Nb$_3$Ge
Nb$_3$Sn
NbN
V$_3$Si
K$_3$C$_{60}$
Pb
Nb
NbTi
Hg
CeCu$_2$Si$_2$
UPt$_3$
UPd$_2$Al$_3$
CeCoIn$_5$
CNT
CNT
CaC$_6$
YbC$_6$
diamond
CNT
Night on the Moon
Liquid nitrogen
Surface of Pluto
Liquid neon
Liquid hydrogen
Liquid helium
200
150
100
50
40
30
20
10
0
1900
1940
1980
1985
1990
1995
2000
2005
2010

Critical field vs temperature (zero current)

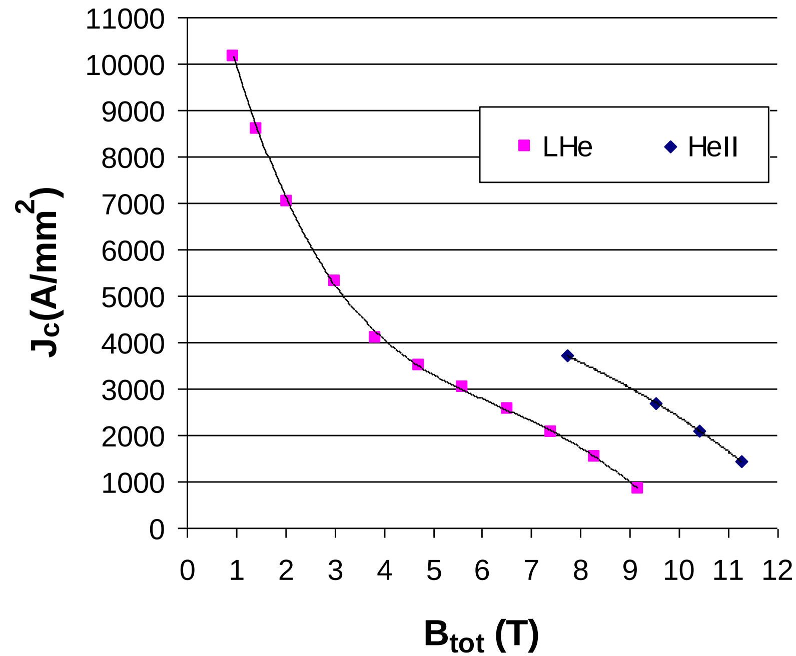


Niobium-Titanium



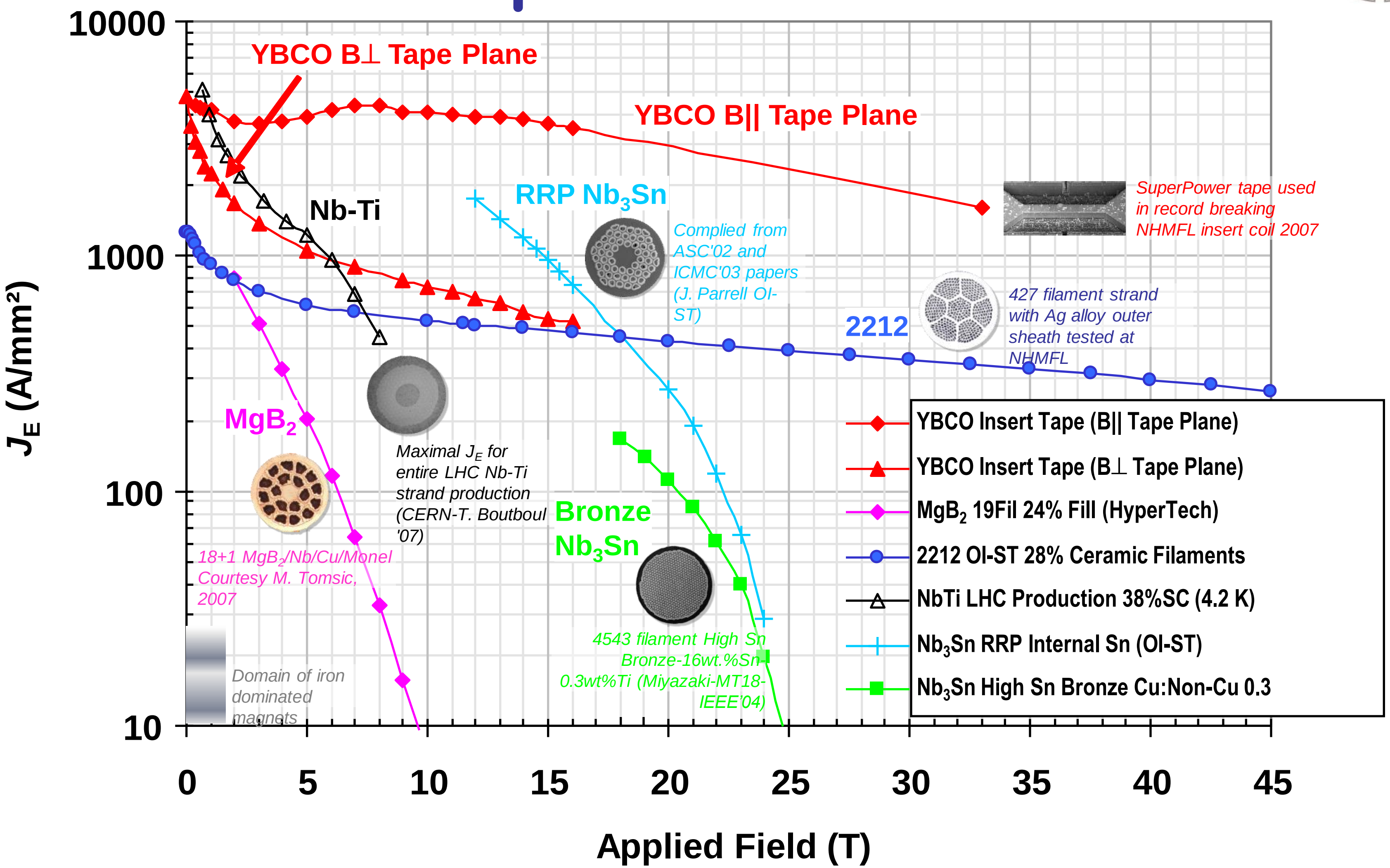
Critical surface of NbTi (from Wilson textbook)

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)

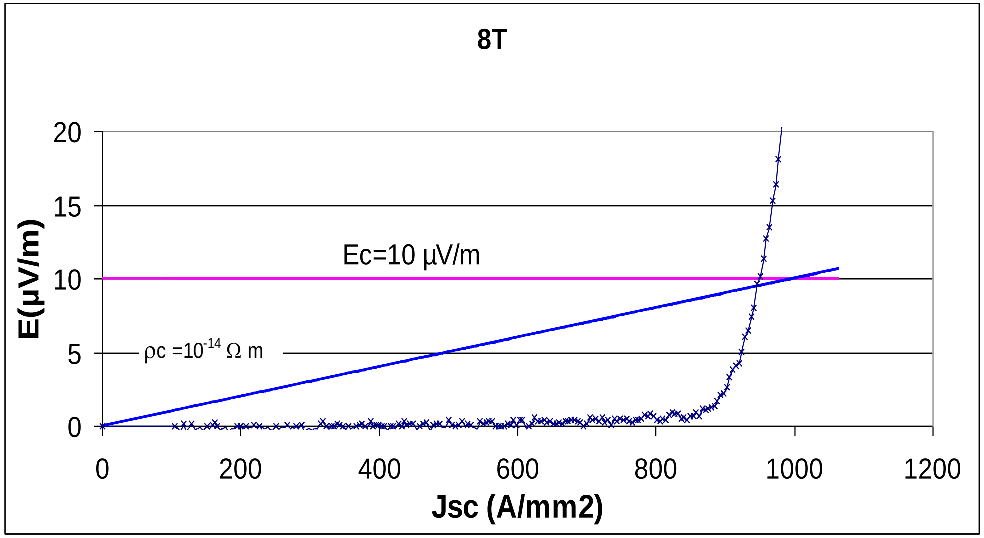
Je vs field for all practical superconductor

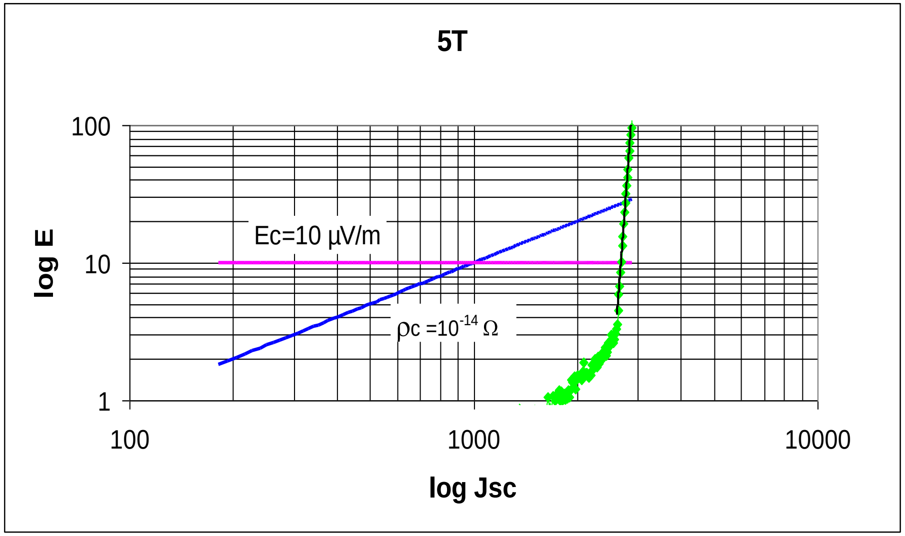


E-J curve

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 $\rho_c = 10^{-14}\ \Omega$m.
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.

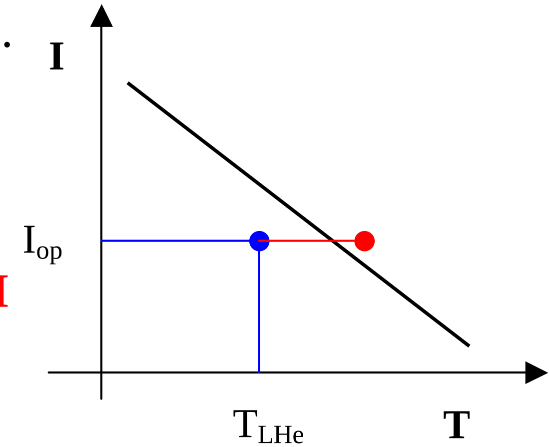




Superconductors are not stable!

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

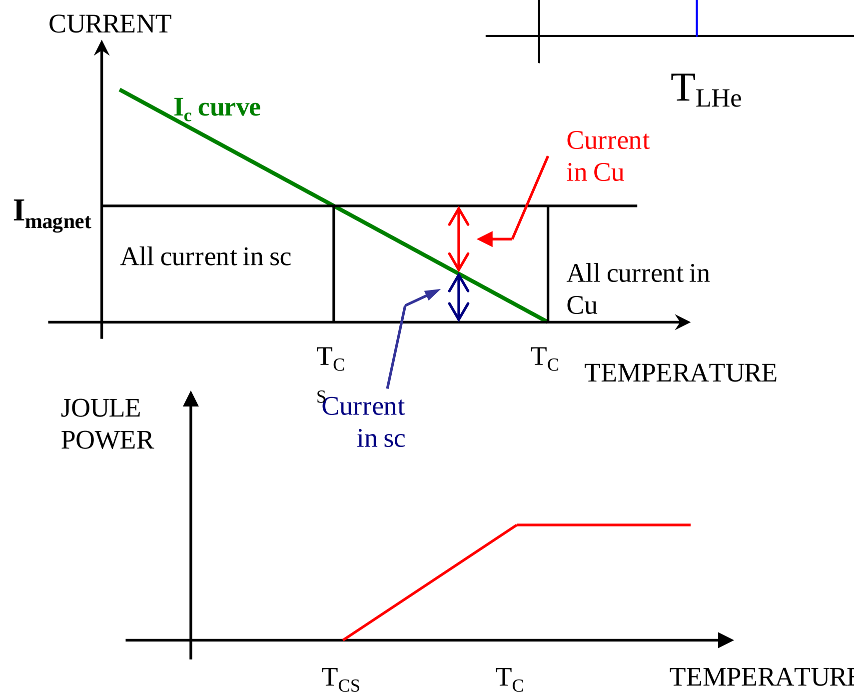
Heat capacity drops at low temperature ($T \ll T_{Debey}$) :
$C \propto T^3 \Rightarrow \Delta T = \Delta E/\gamma C$. So even small ΔE generates sensible ΔT
$\Rightarrow$ operating point of the magnet beyond critical surface **$\Rightarrow$ QUENCH**



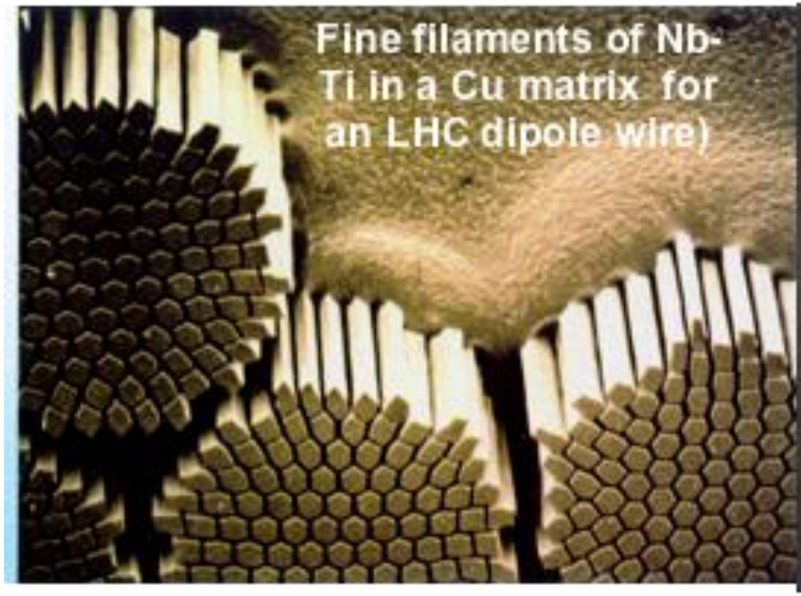
Electrodynamic stability: intimate contact between the superconductor and a good conductivity material.

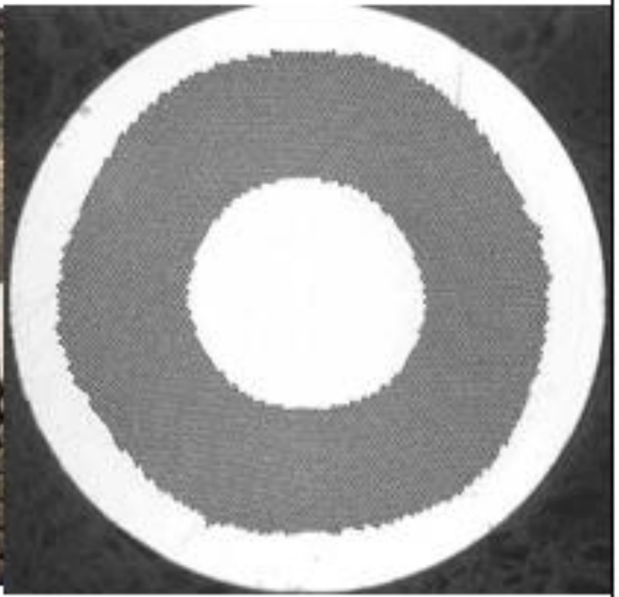
Adiabatic (or intrinsic)stability: to cure the flux rearrangement that generates heat

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!

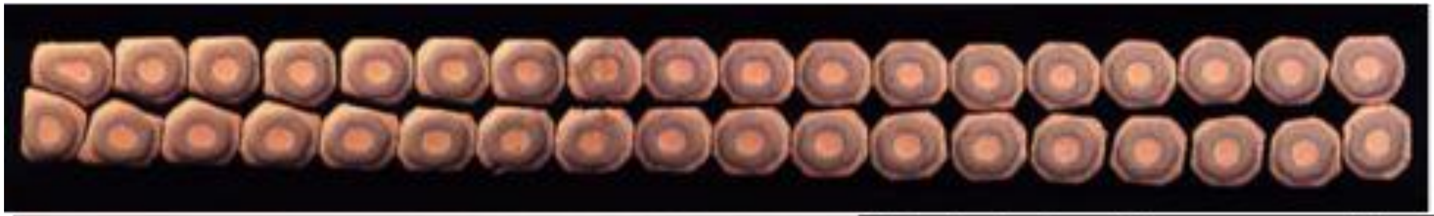


Superconductor of LHC





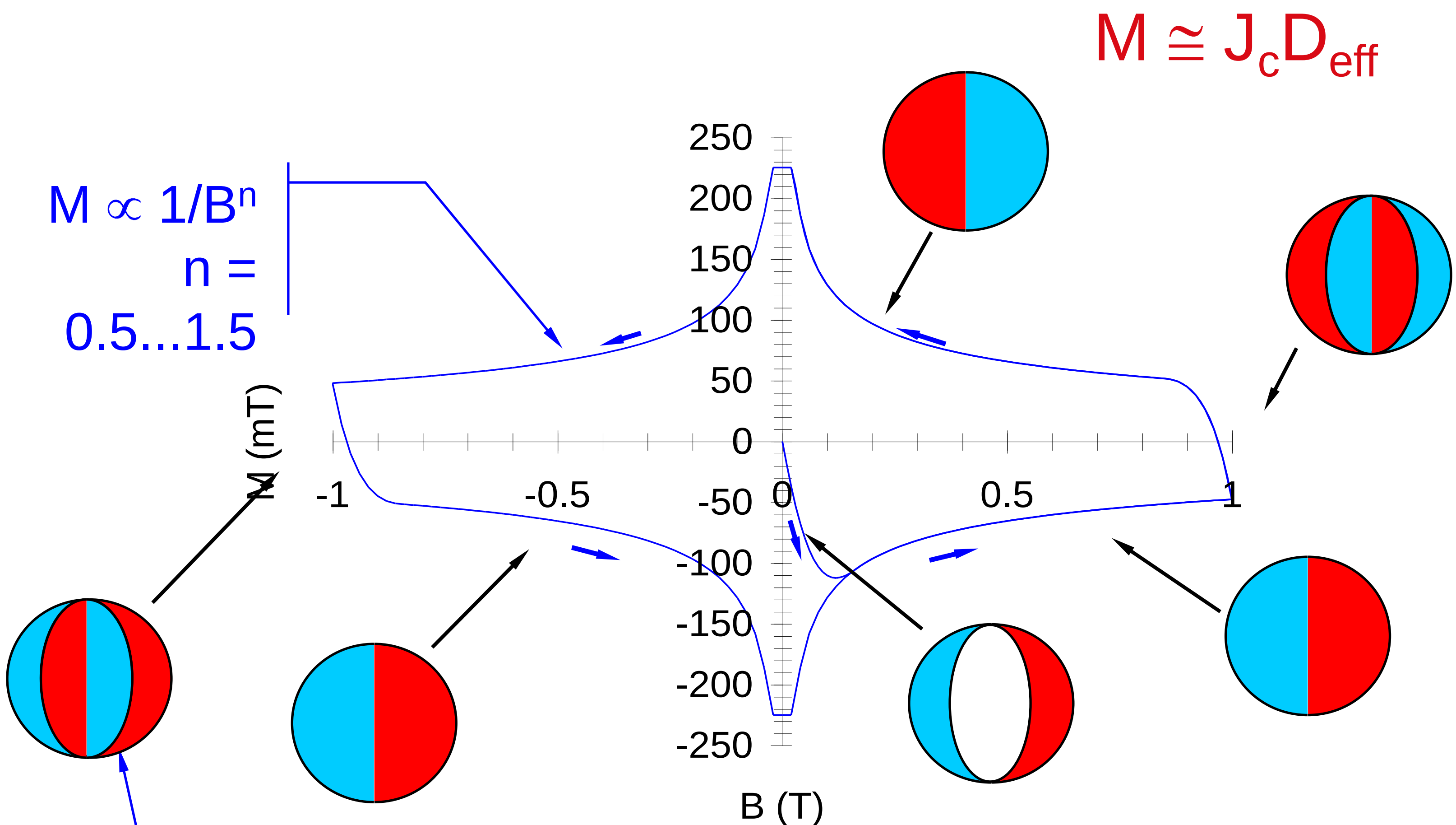
Full cross section of a Cu/Nb-Ti wire (1.06 mm dia.) for an LHC dipole, 6000 filaments of 7 μm dia.



Rurtherford cables, composed by the wire shown above.
View of the flat side (at right), with one end etched to show the Nb-Ti filaments. View of the cross section at the top

Magnetization and fine filaments

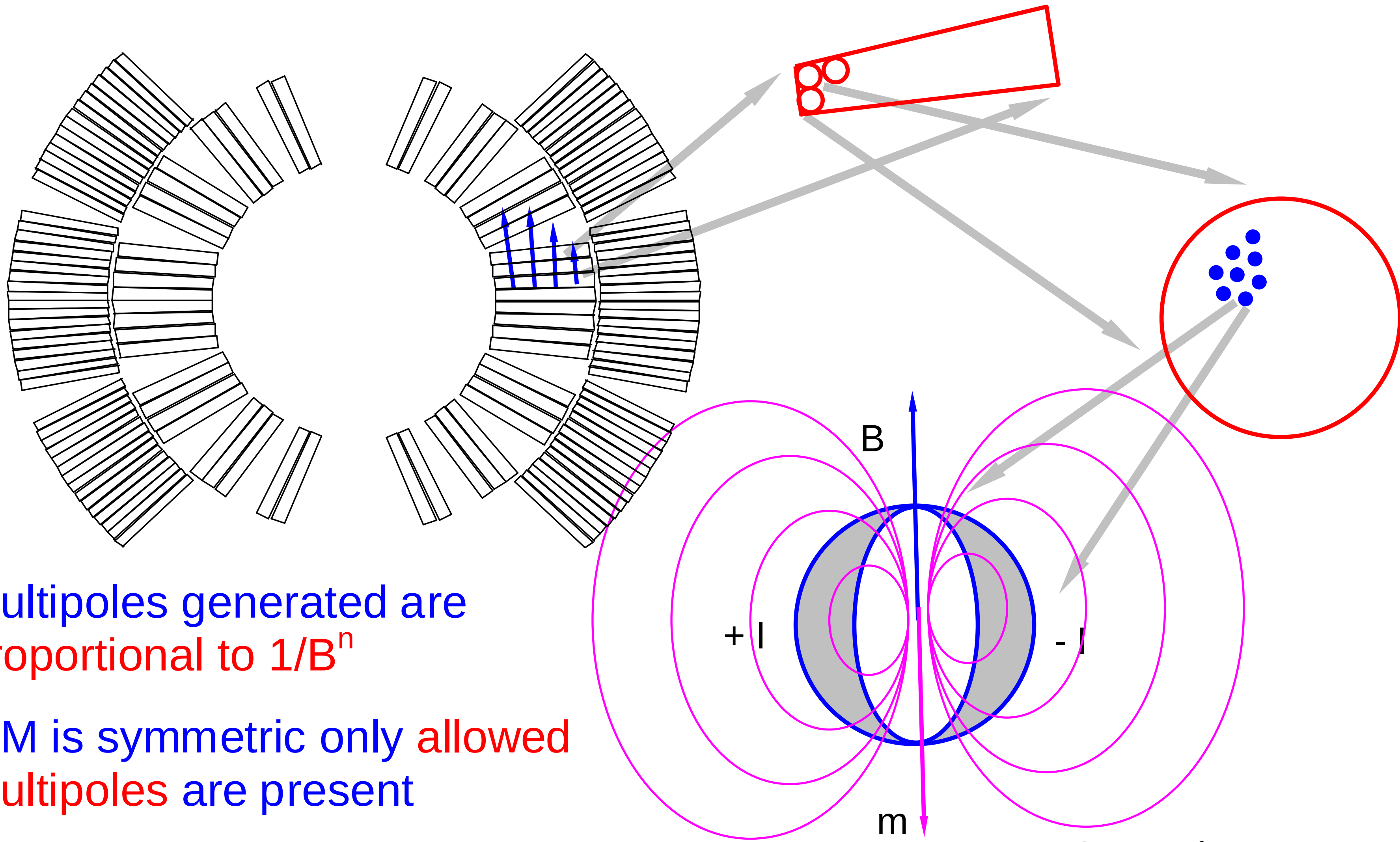
$M \cong J_c D_{eff}$



shielding current layer in a superconducting filament (persistent currents)

Courtesy of L. Bottura

Effect of magnetization

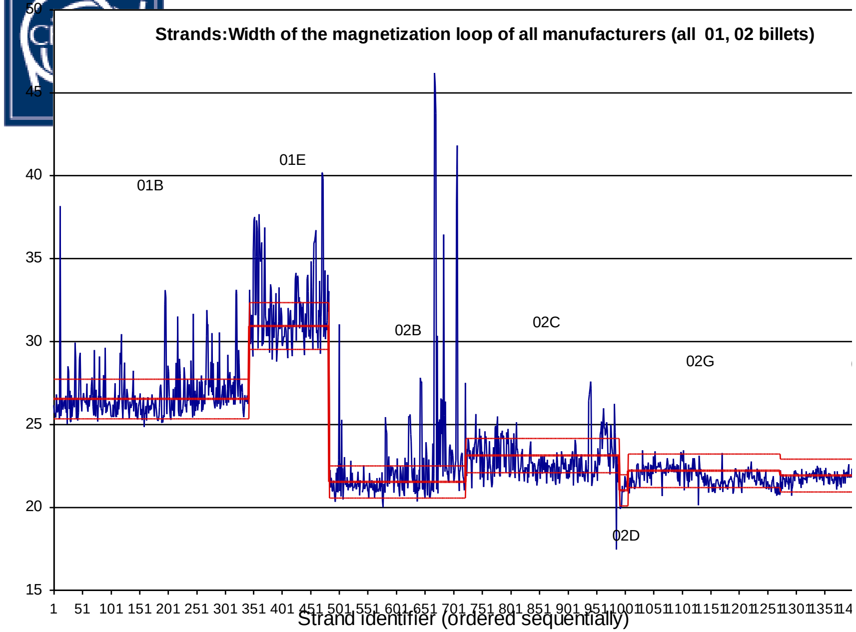


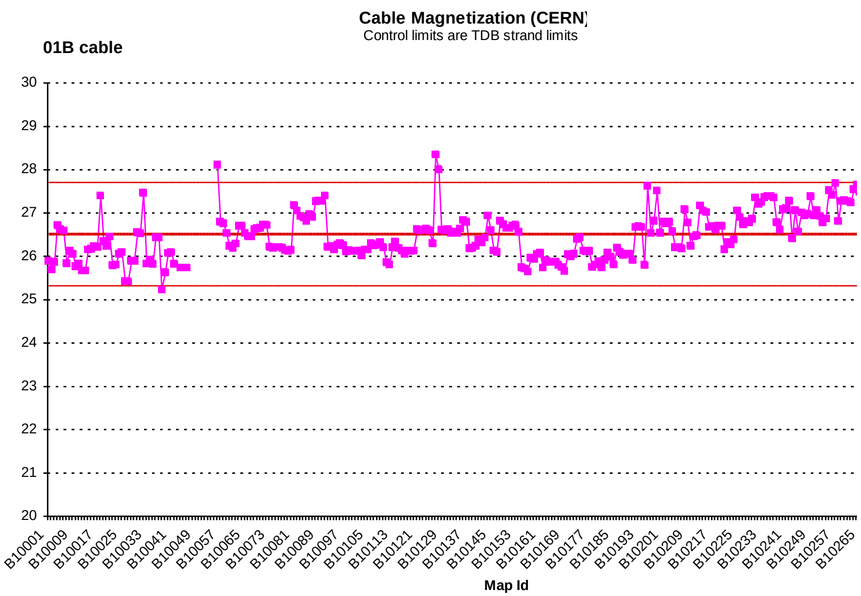
Multipoles generated are proportional to $1/B^n$

If M is symmetric only allowed multipoles are present

Courtesy of L. Bottura

Magnetization for LHC NbTi





Courtesy of S. LeNaour

Due to field imperfection generated by M:

Rejection of conductor

Limit in the dynamic range of the magnets

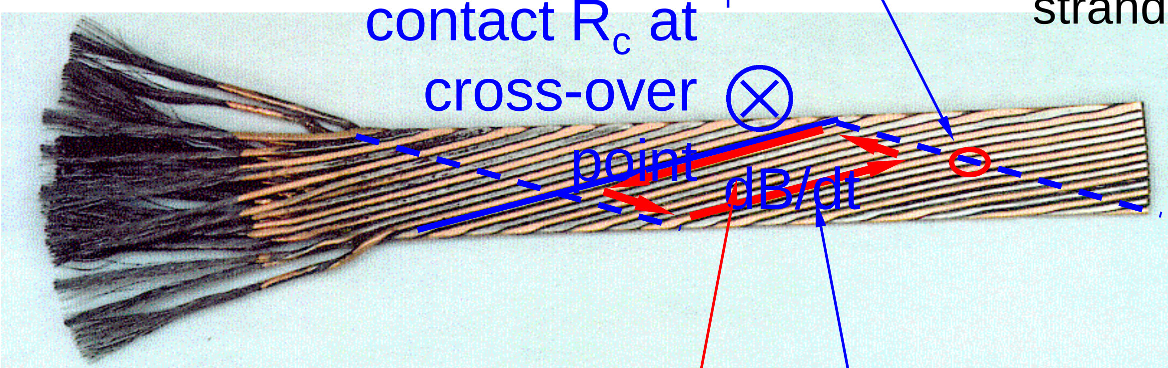
In LHC D_{fil}= 6-7 μm

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

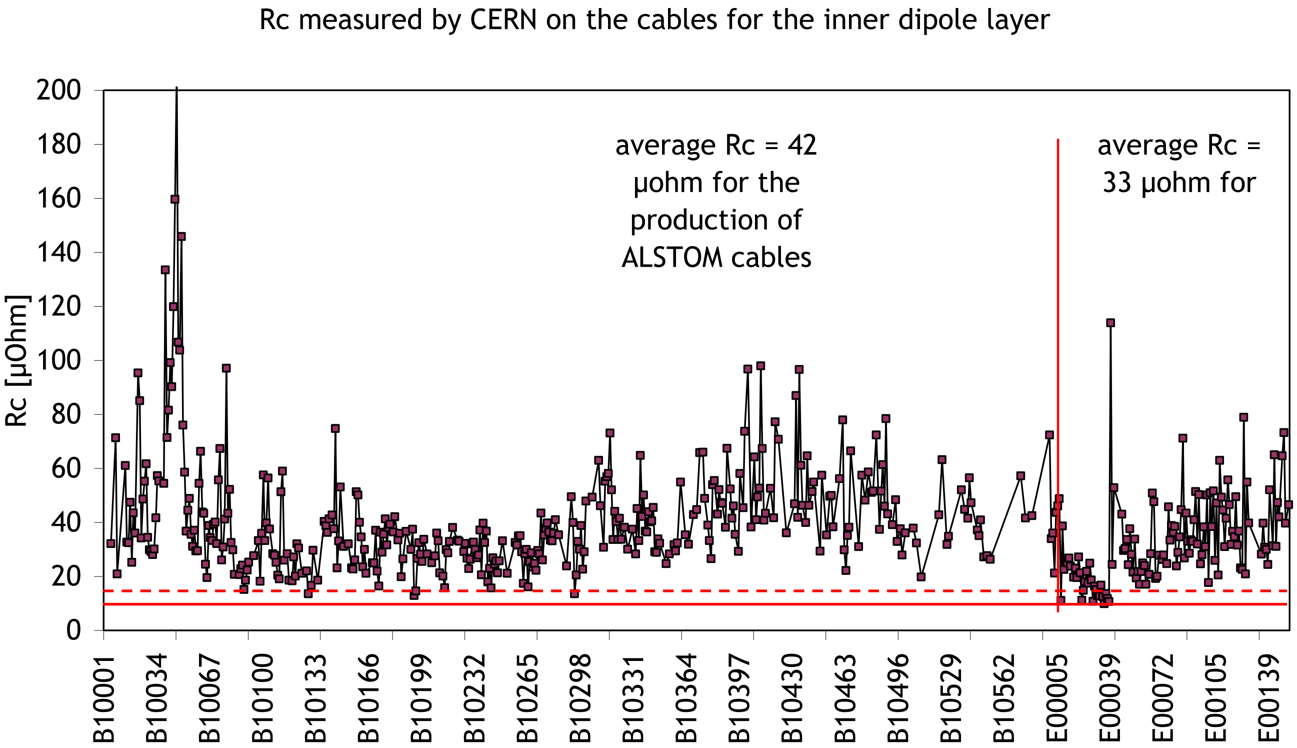
BUT field changes over a period !

Ends problems

Junctions

BICC

Controlling the contact resistance



CERN has developed the controlled oxidation method

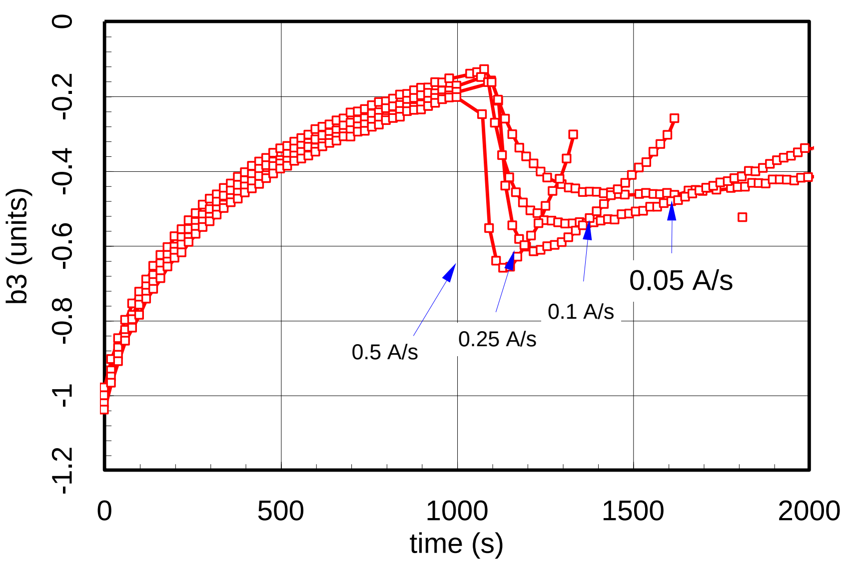
Coating wire with 0.3-0.5 of SnAg then H.T. cable in air

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

Snap-back phenomena



•during the injection platform of an LHC dipole, the sextupole error term **integrated over the magnet length** decays with a time constant of ~ 1000sec.

•when the ramp is started, the error term 'snaps back' to its earlier value

•it is difficult to find a time constant of 1000 seconds in any of the usual coupling modes

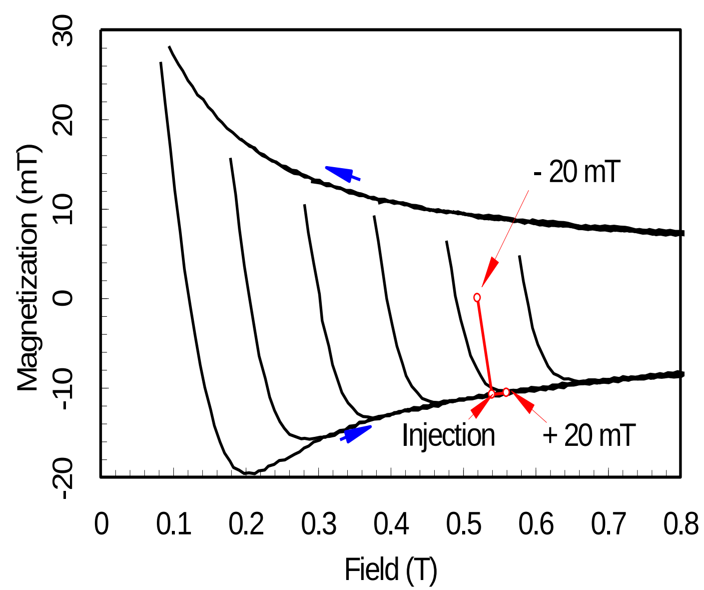
•BICCs produce a field component which alternates ± 20 mT along the magnet

•imagine the hysteresis curve of NbTi filaments subjected to this oscillation

•a 20 mT increase produces very little change in filament magnetization

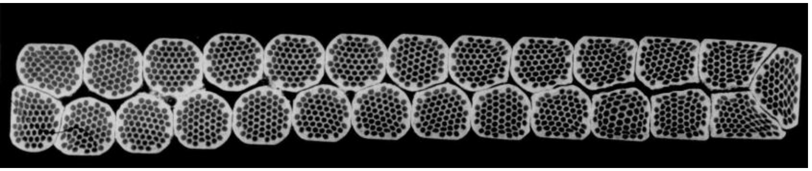
•a 20 mT decrease produces a large change in filament magnetization

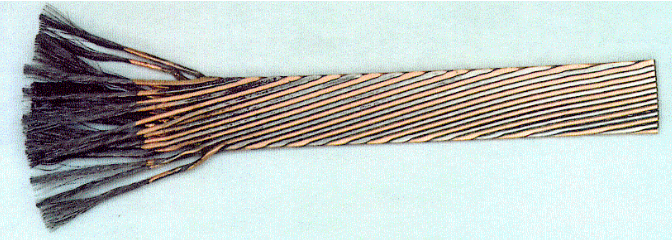
•thus the hysteresis curve acts as a 'rectifier' enabling the oscillating BICCs to produce a dc level

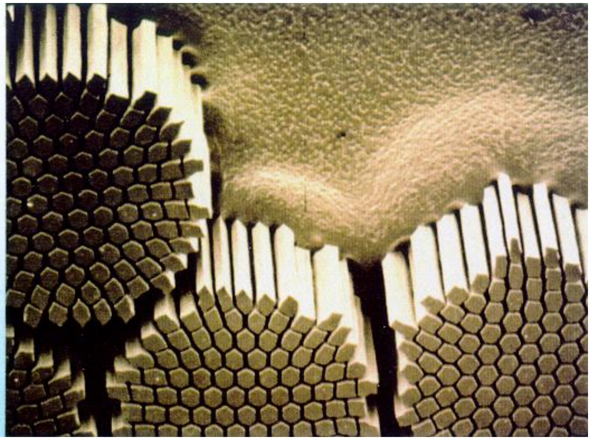


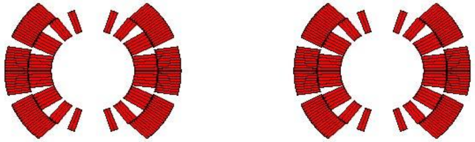
After Rob Wolf

LHC MB X-sect: conductor (Rutherford cable)









Conductor position optimization:

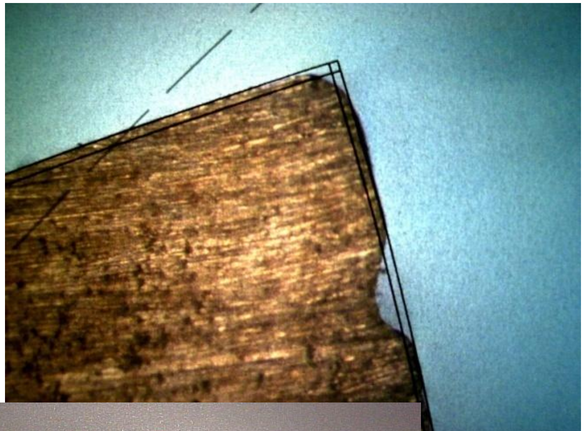
Control of harmonics
Balance of margin among blocks

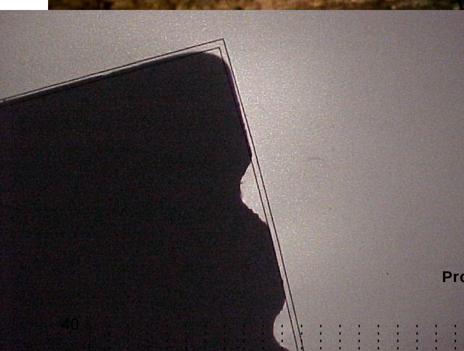
Stable against inevitable errors

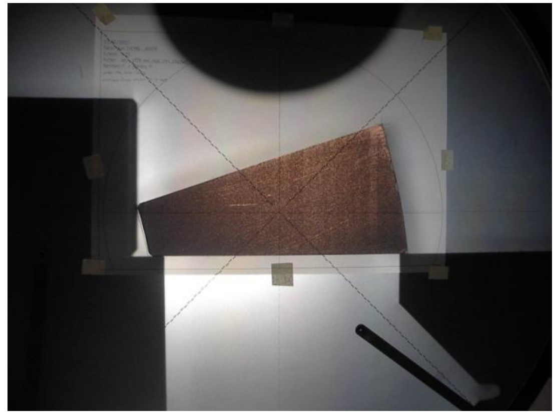
Minimum shear among conductors

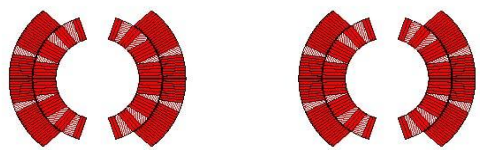
Balance between T margin of inner/outer

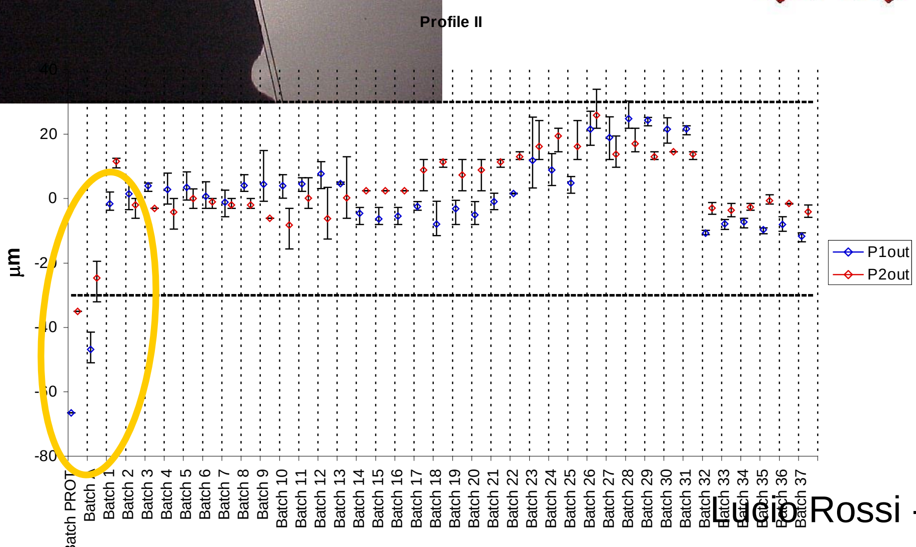
LHC MB X-sect: copper wedges











Cu Spacer

Precise at ±20 µm

Used to steer production

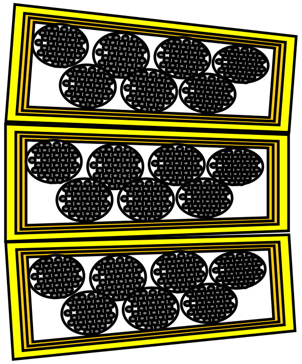
Change of Cu wedge 0.2-0.5 mm of inner wedges in July 2001 (3 CM, 15 CC).

Effect in 2002.

~35 CM old Xsect.

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

Rutherford Cables Insulation

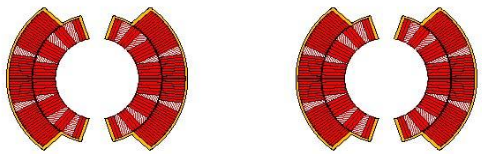


-2 layers of Apical 200 AV insulation

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

Ground isolation

Four layers 125AH



Polyimmide insulation

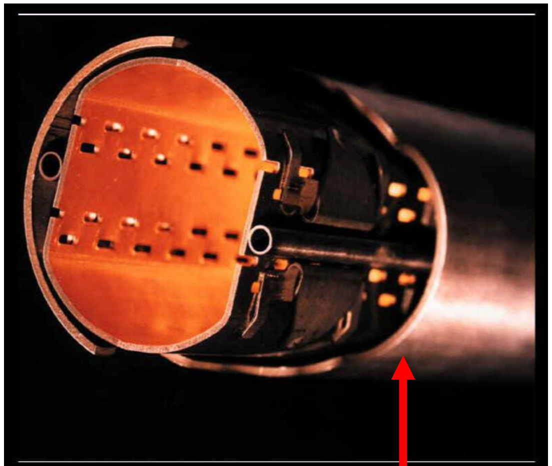
Around cable and around coils

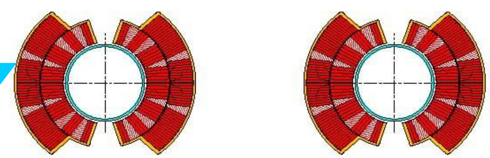
Important elements are dimensions, ±3% of thickness, and creep (Apical creeps less than kapton)

Inter layer

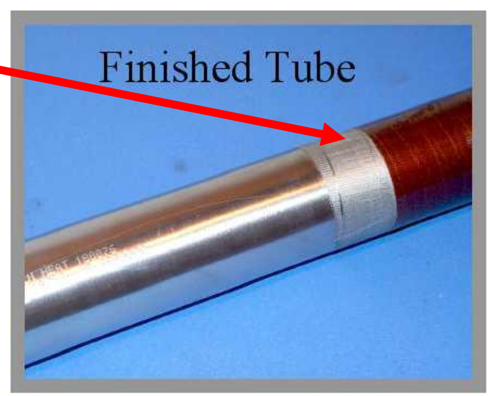
To allow HEII to flow

LHC MB X-sect: insulated CBT





CBT



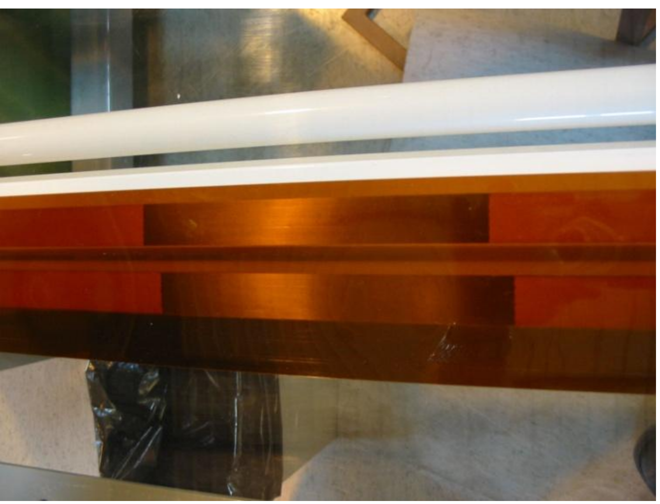
Cold bore tube

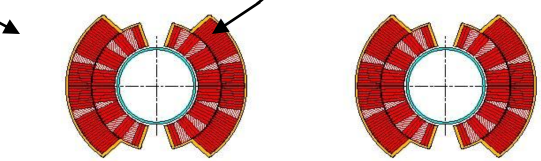
StSt tubes

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

LHC MB X-sect: Quench Heater



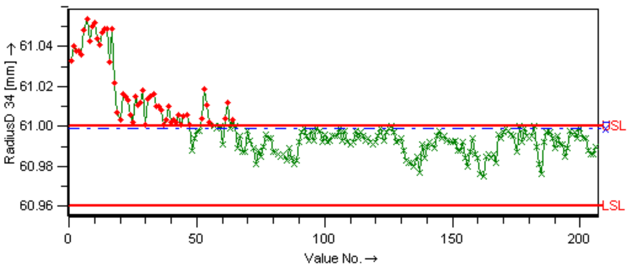


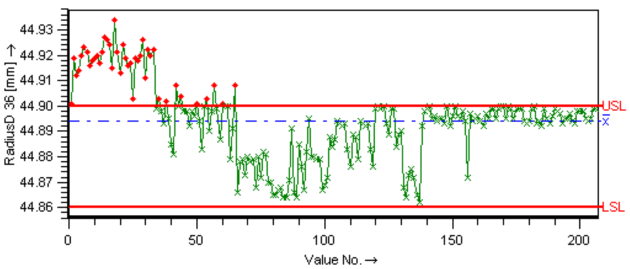
Strips of stainless steels partially coated with copper to adjust resistance

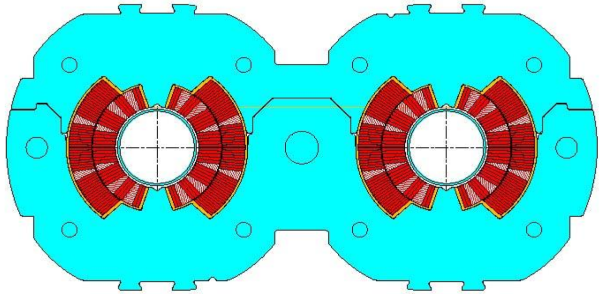
Encapsulated like a sandwich in two foils of 75 μm of polyimide

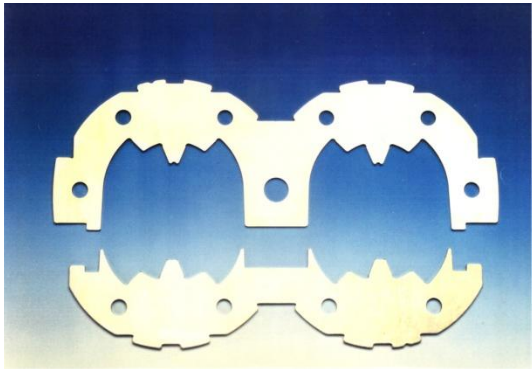
Fired by current pulse, heat must diffuse from strip to coils in 20-50 ms !!

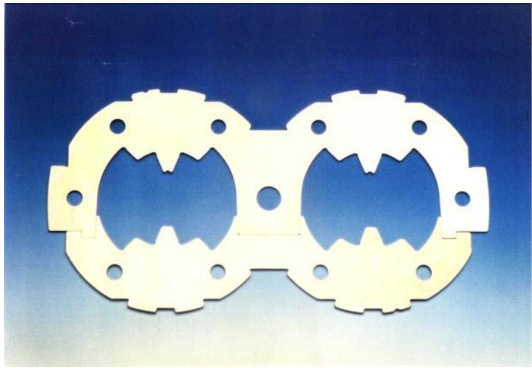
LHC MB X-sect: Collars







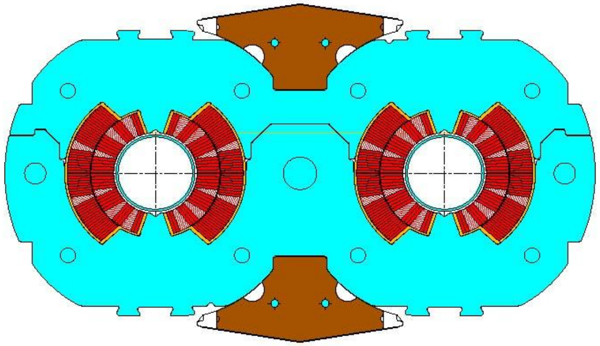




Collars and collaring are the main controllers of the final coil shape

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

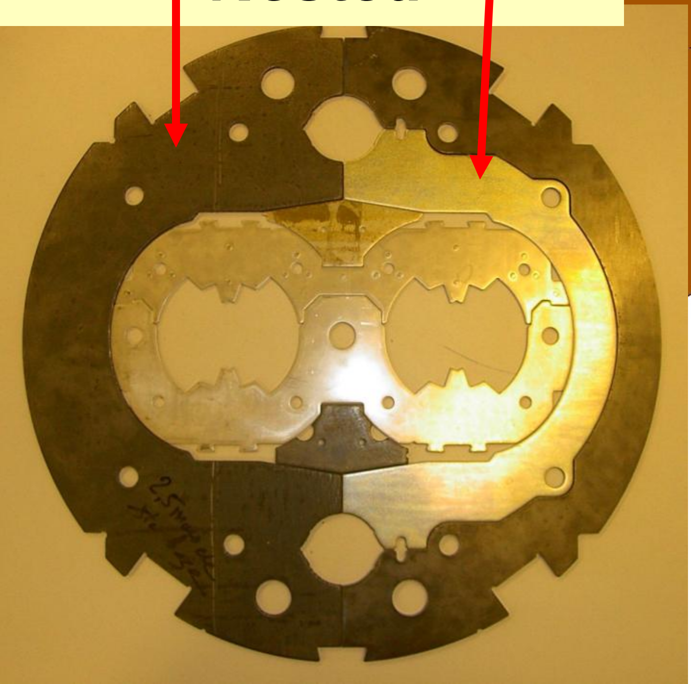
LHC MB X-sect: yoke laminations

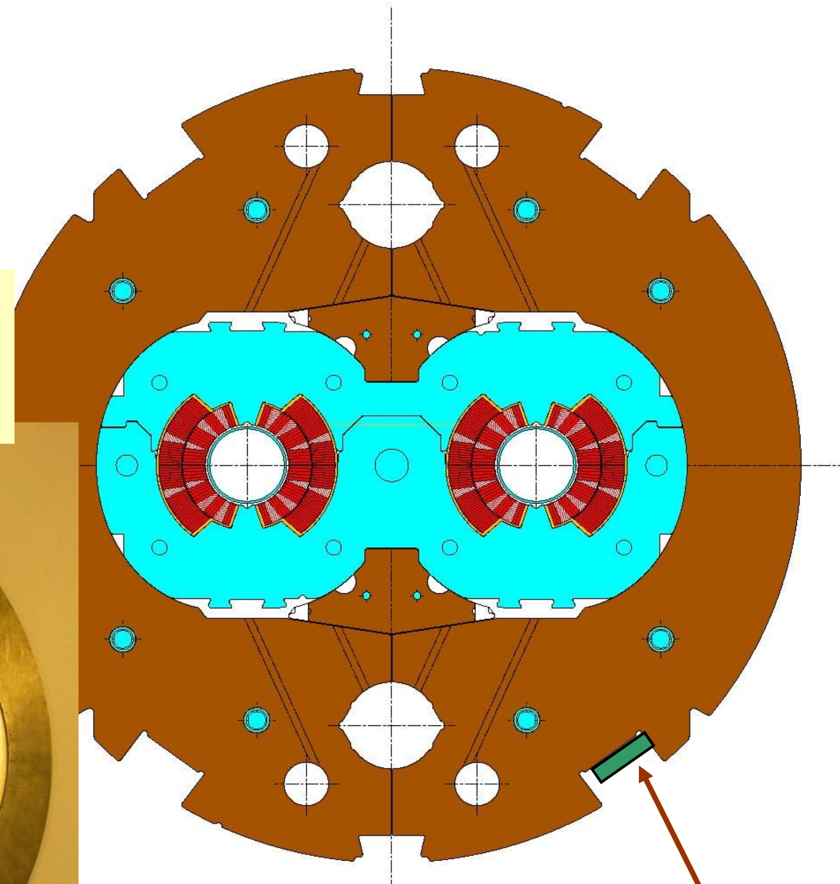
One supplier for the steel 45,000 tons

Precise vertical gap

Regular

Nested





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

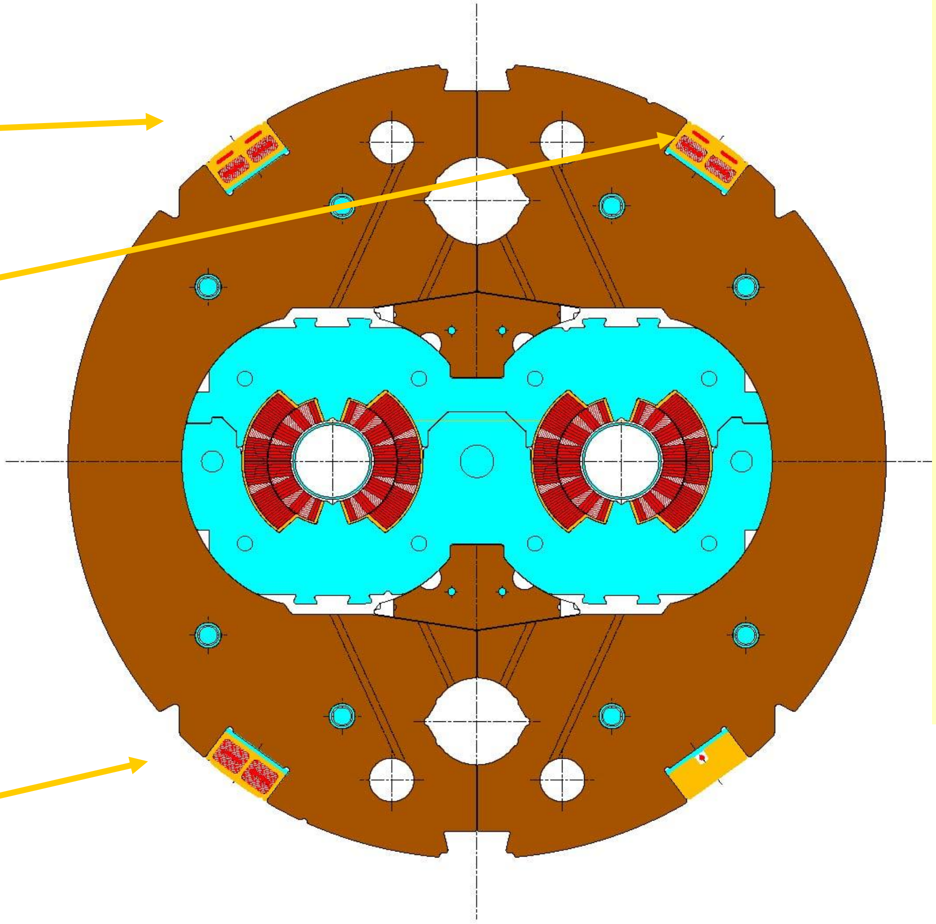
Bus Bars

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

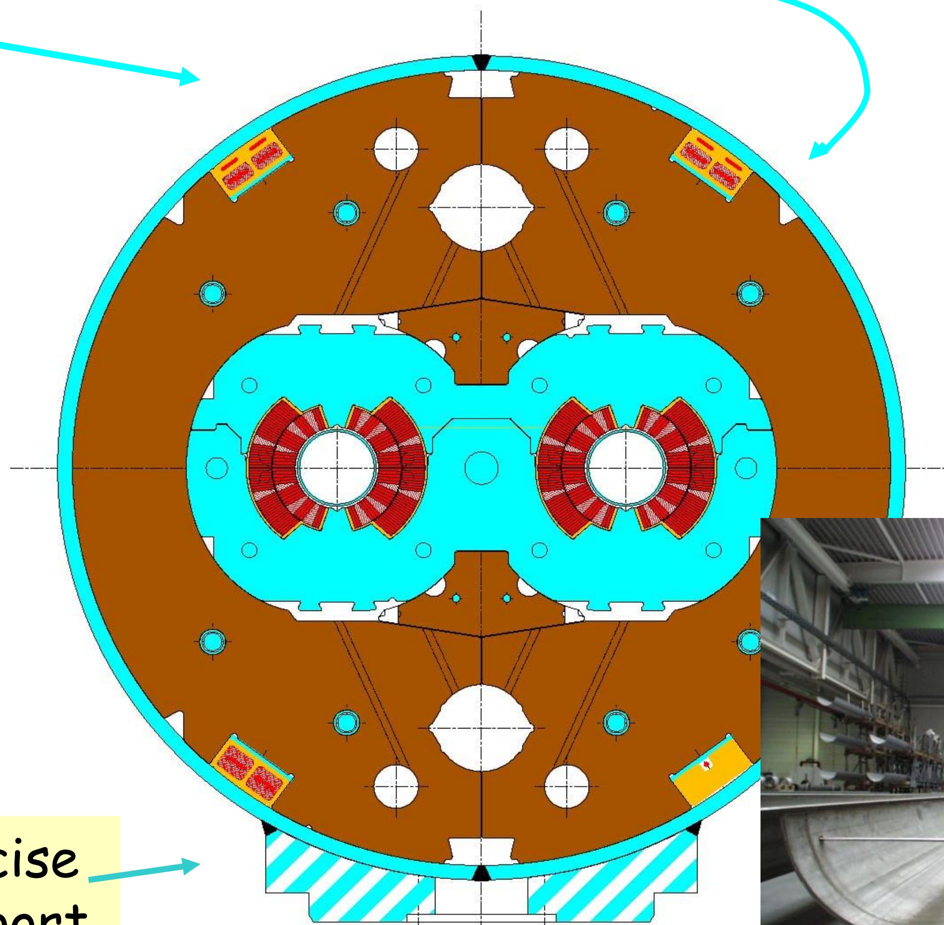
-SC 02 cables

-Polyimmide foils and tapes

LHC MB X-sect: Shrinking cylinder and support

Two half shells, welded on the magnet

Many difficulties

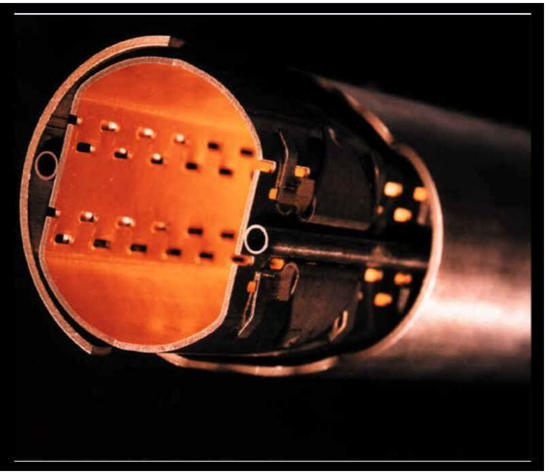


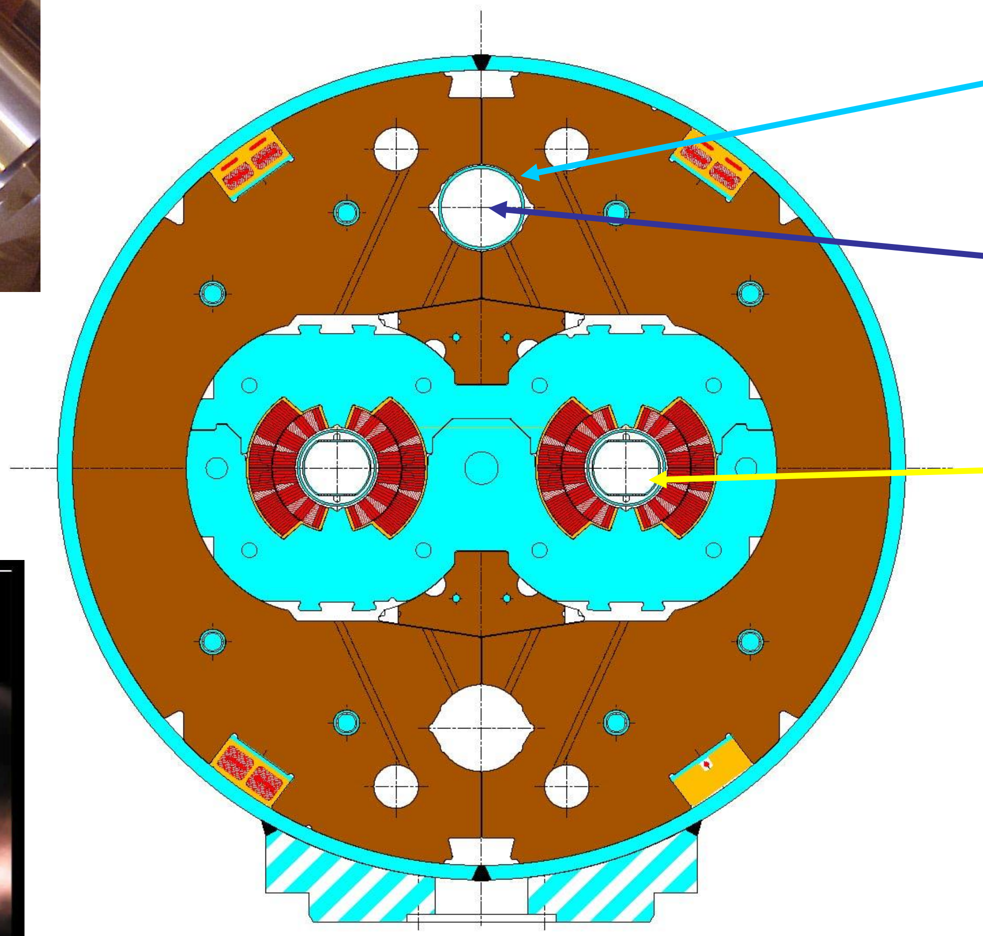
Precise support

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

To c ure this we went to sorting

LHC MB X-sect: beam screen and HXT





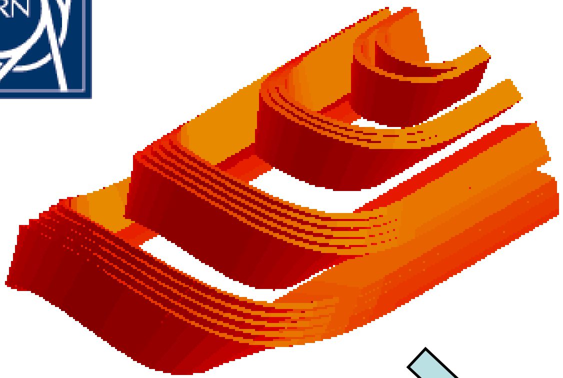
Copper Heat Exchange Tubes

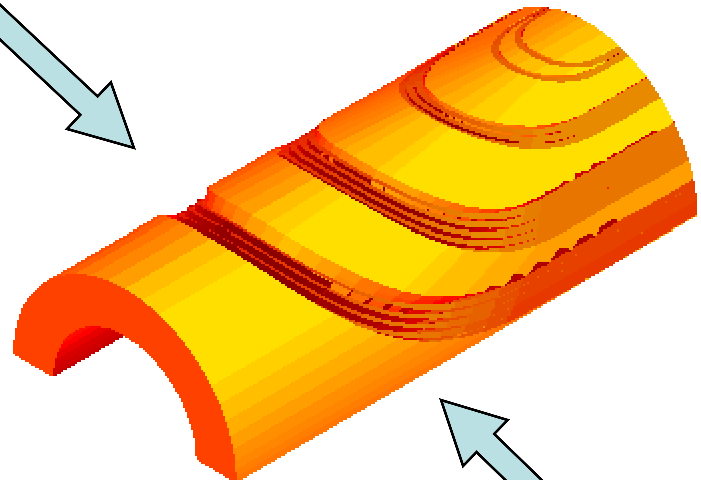
HEII satur.

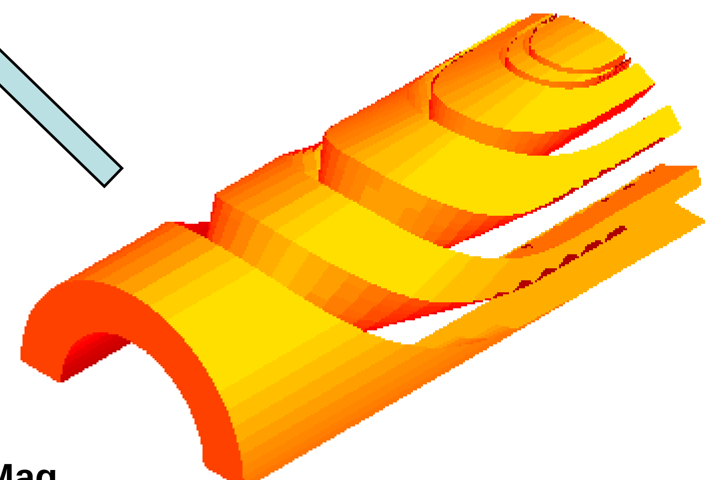
Beam Screen

Inserted at CERN just before insertion in the tunnel

3D
Inner layer lyre side





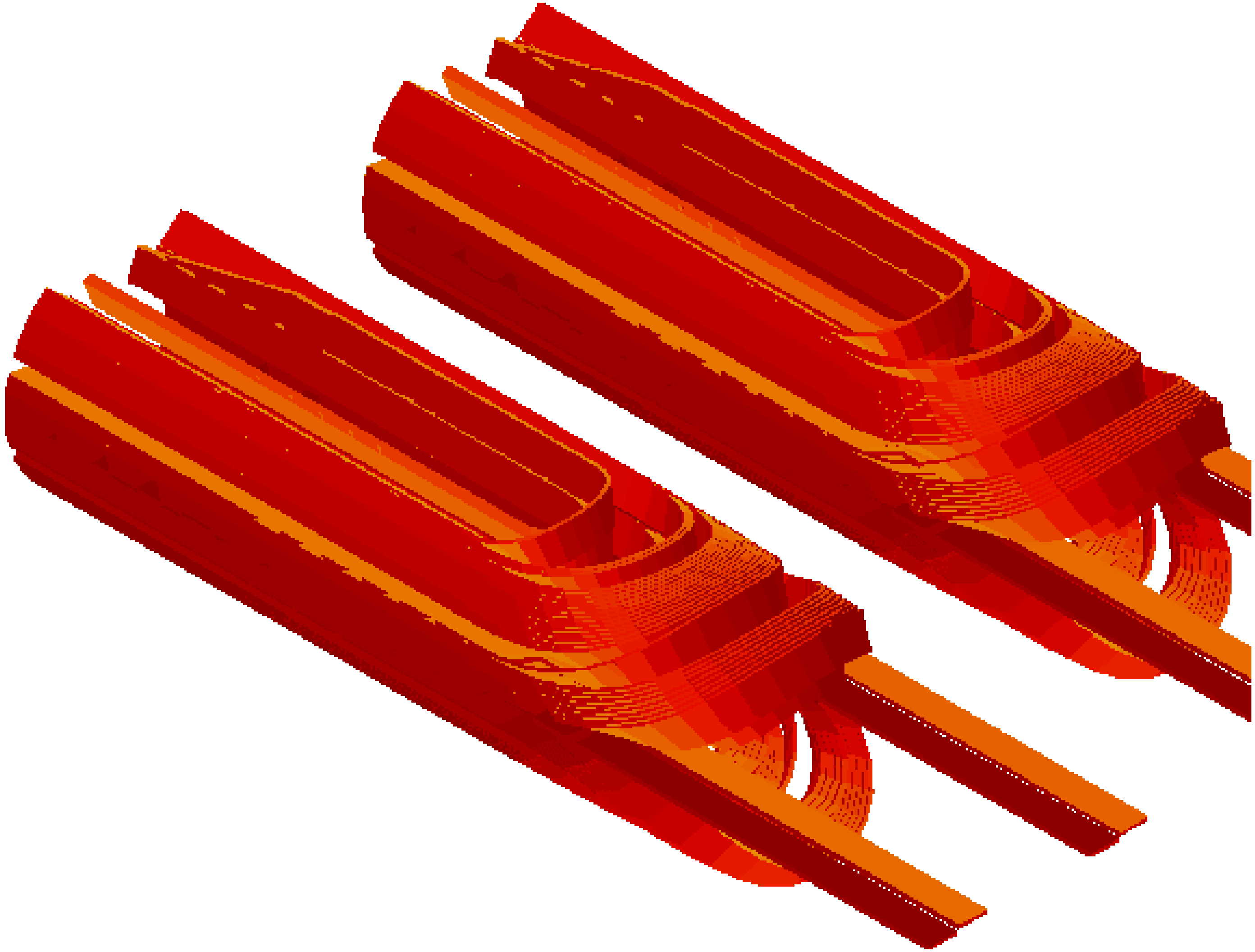


End Spacers: critical for Quench

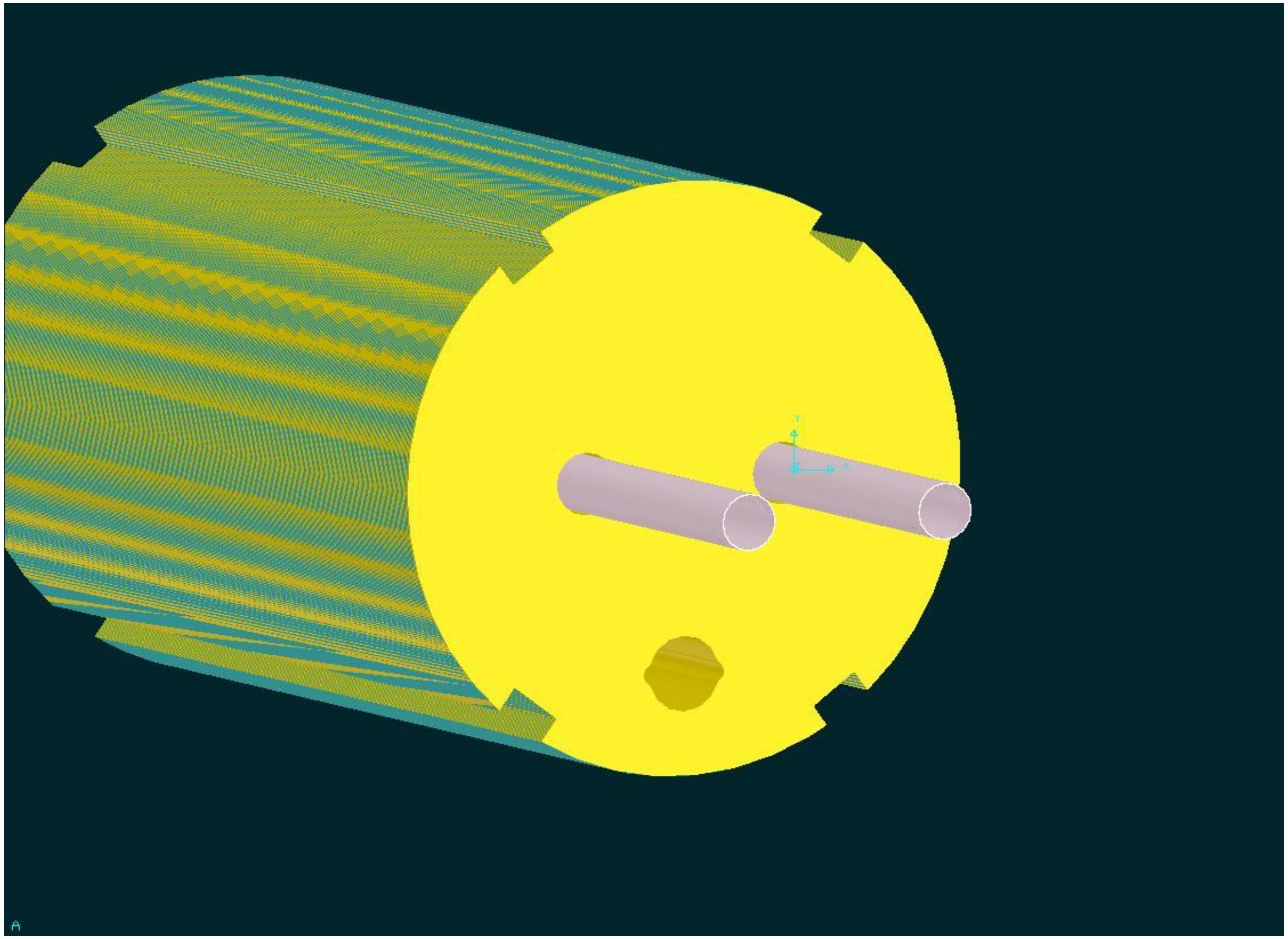
Two slightly different design (in cable profile)

Only pre-series (4-5 suppliers can do)

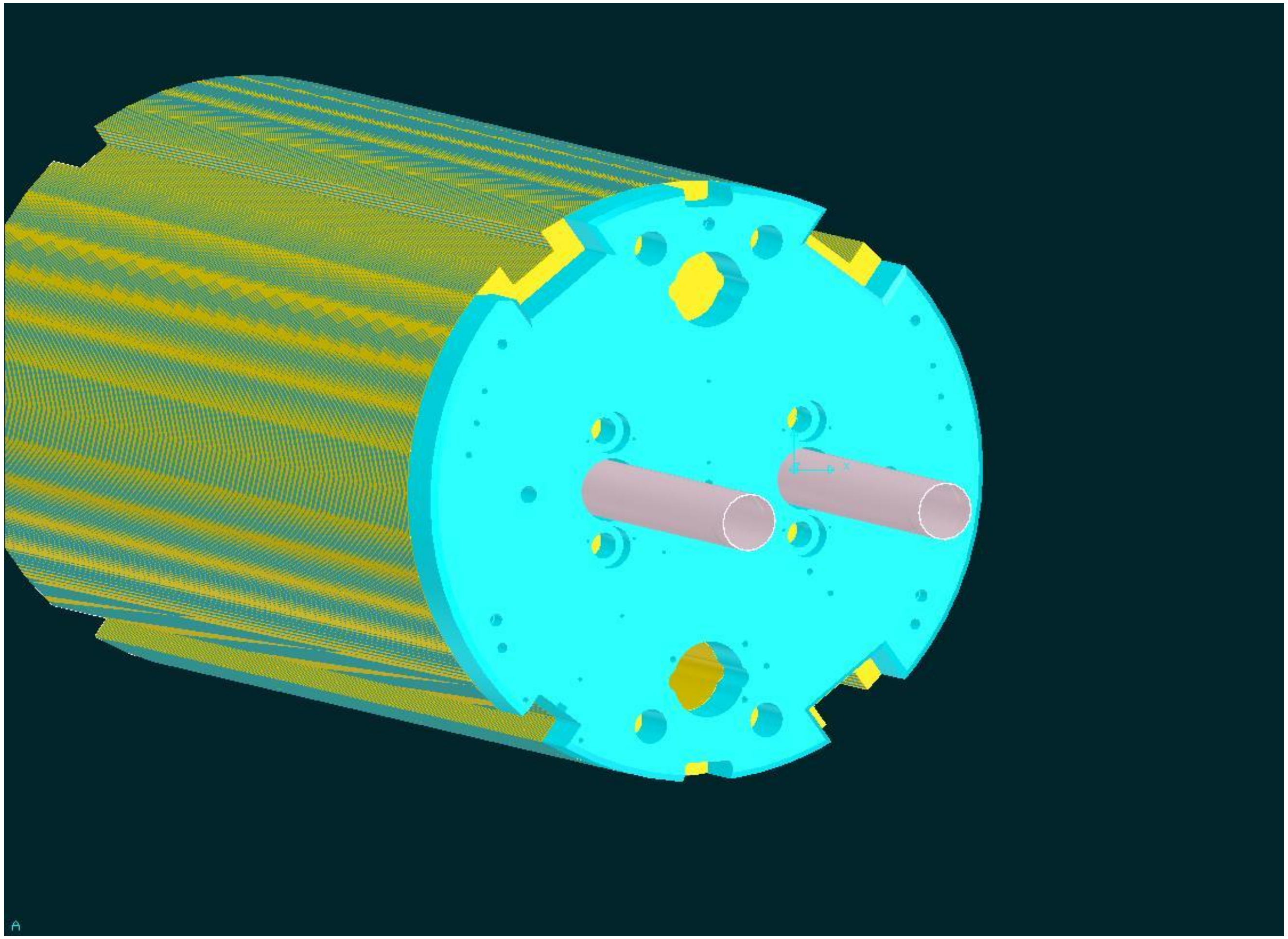
3D
Connection side 3



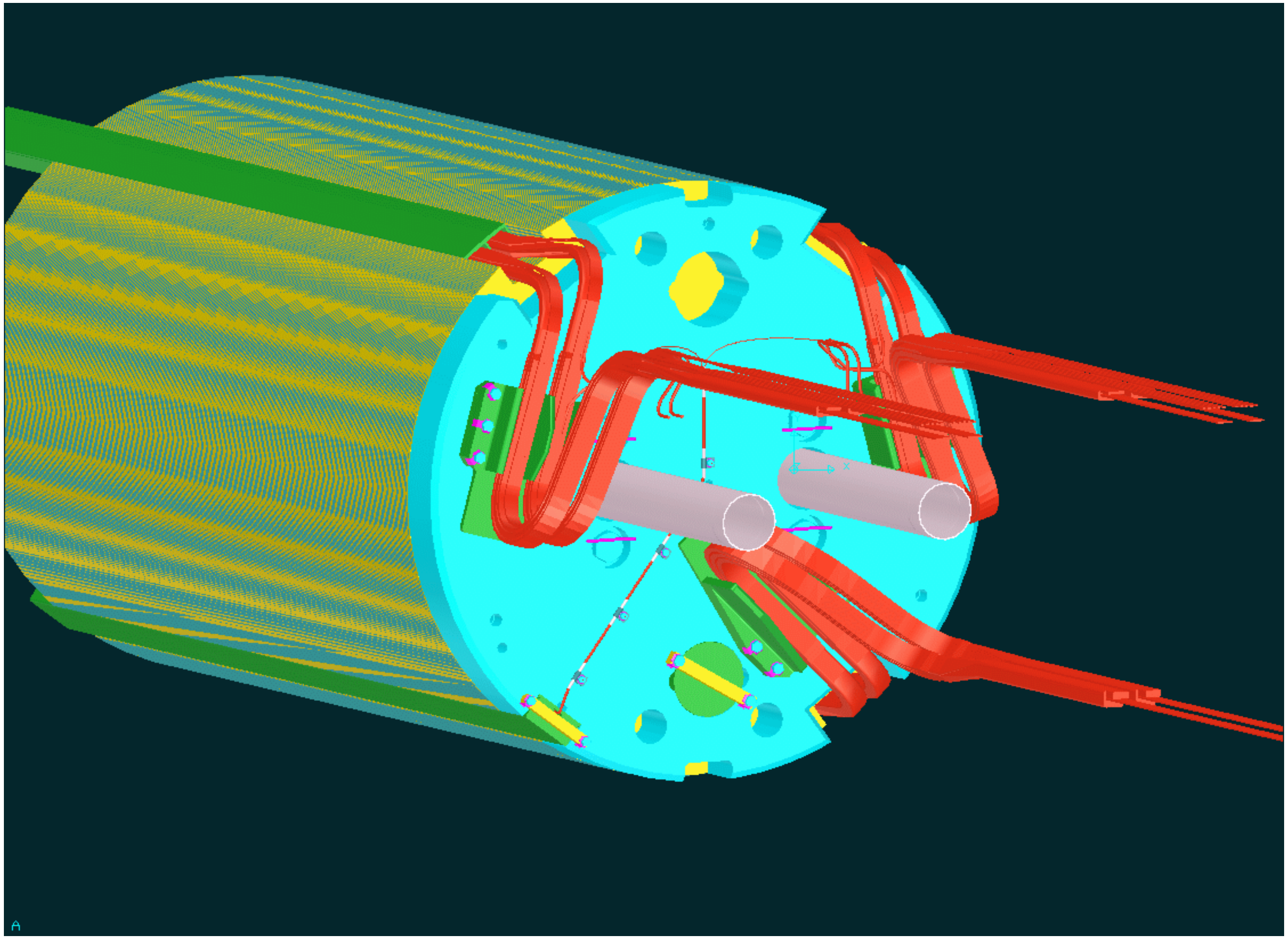
LHC MB - end part
CBTs and Yoke



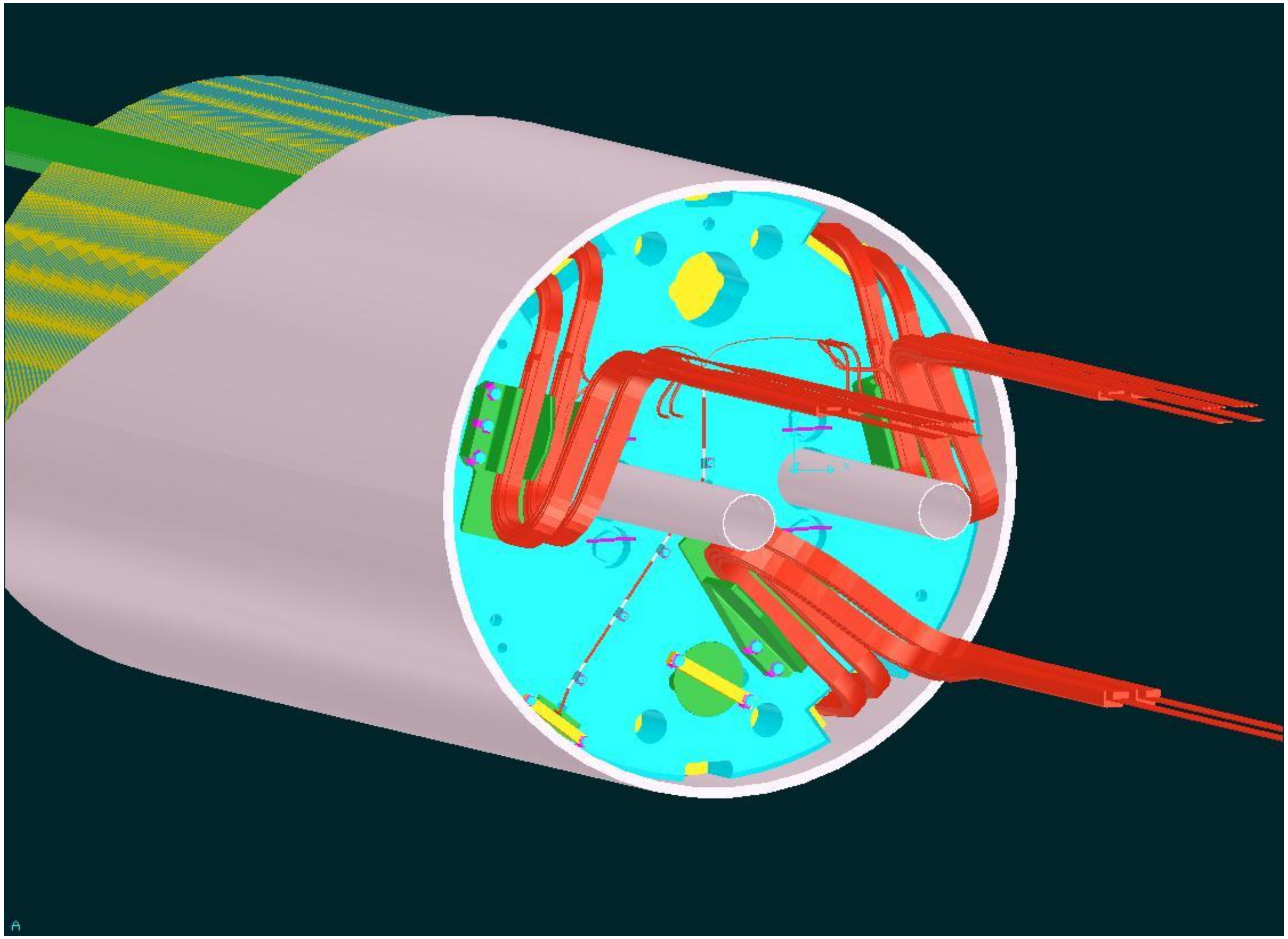
LHC MB -end part
end plate



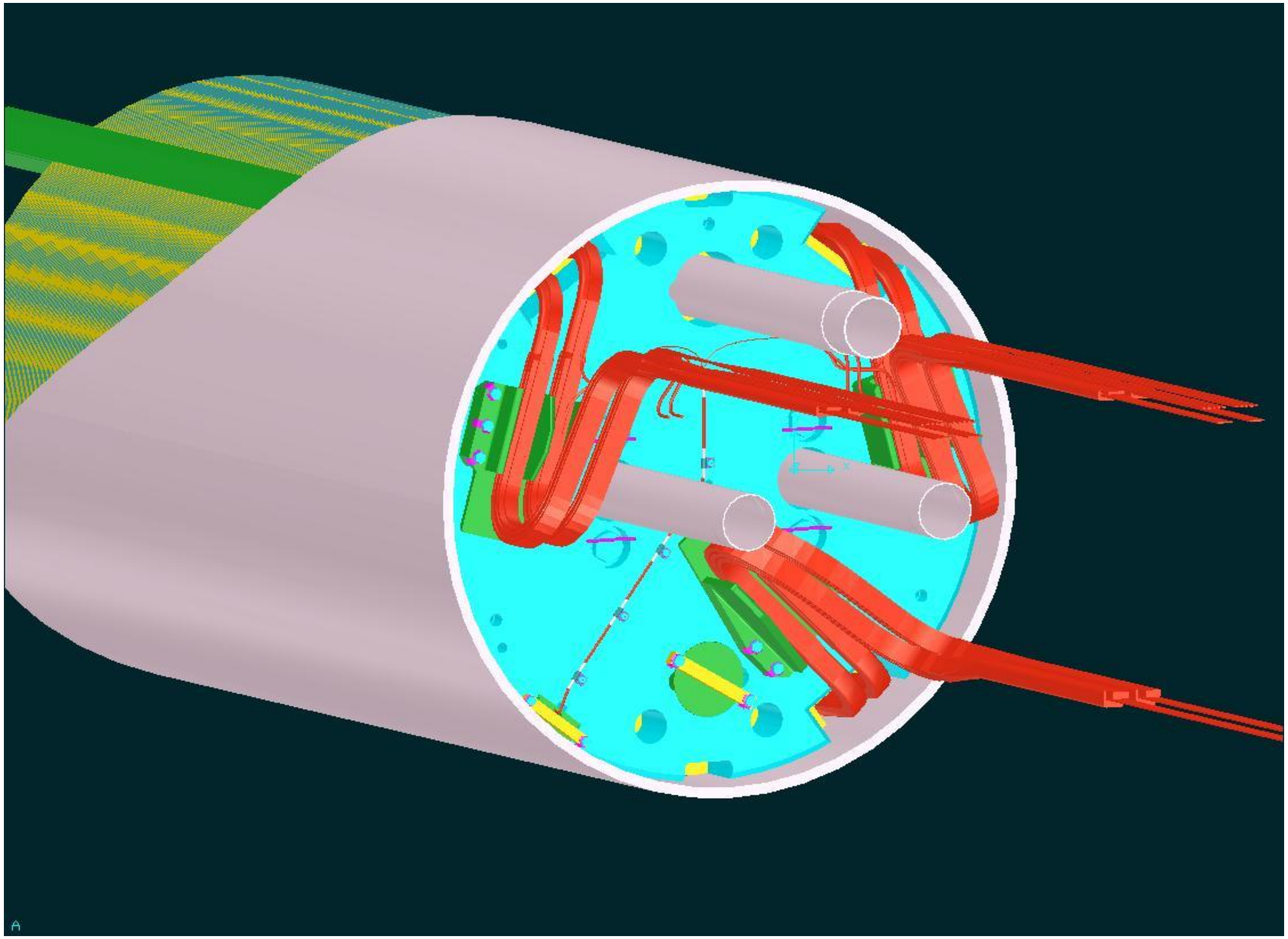
LHC MB-end part
Bus Bars postioning



LHC MB -end part Shrinking cyilinder



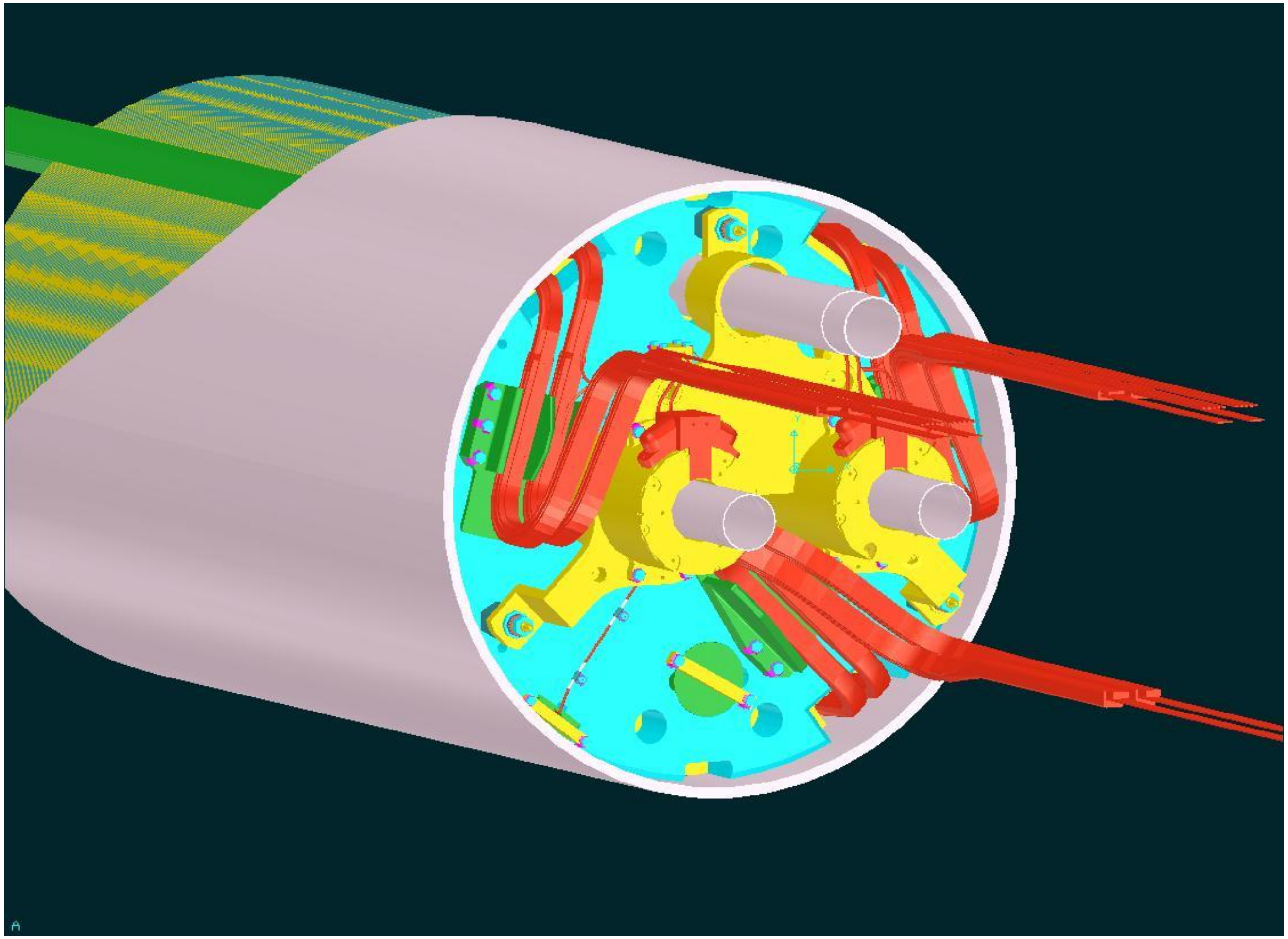
LHC Main Dipole -end part
Cu HXT



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

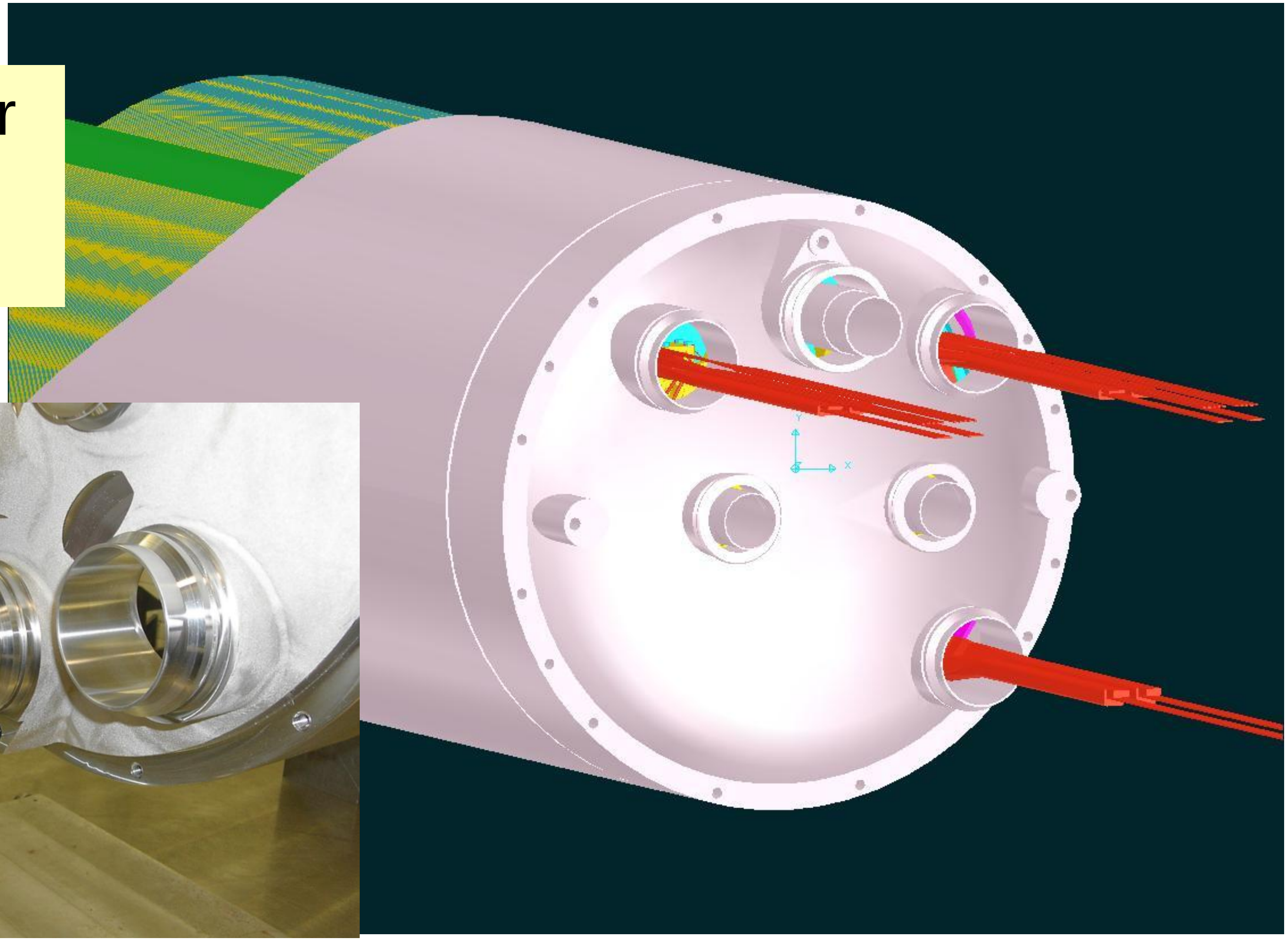
Assembly in CMAs is purely mechanical

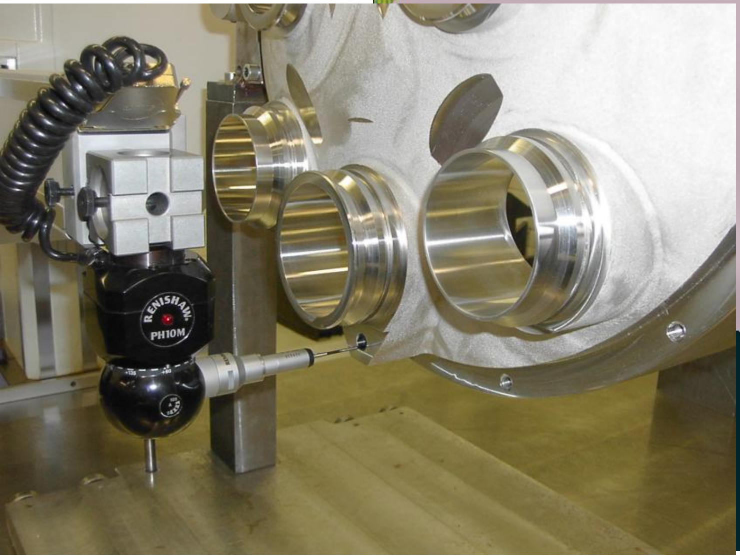
(tolerances of B axis wrt mech. frame given by supplier



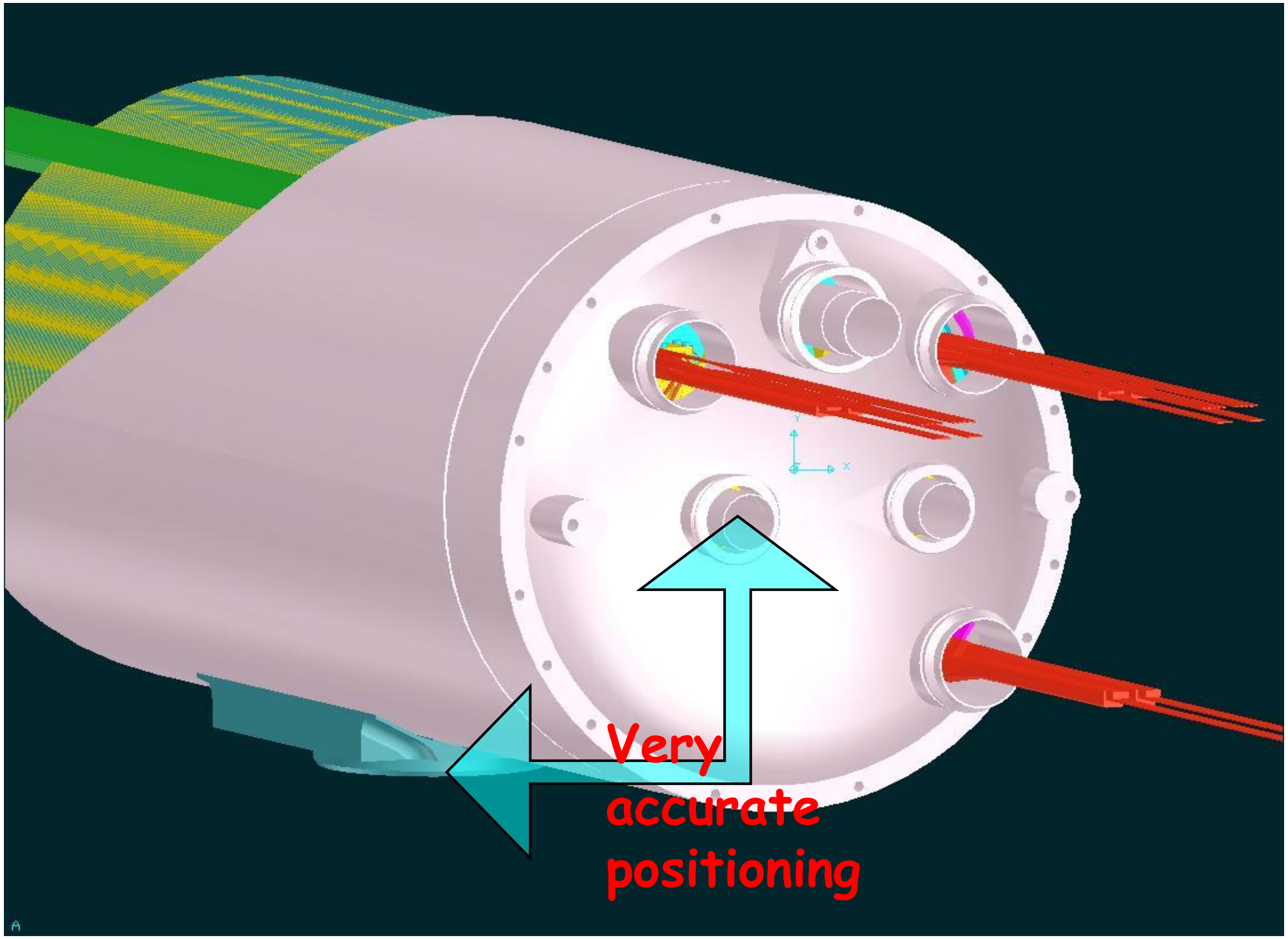
LHC Main Dipole -end part
End covers

One supplier
Powder
technology

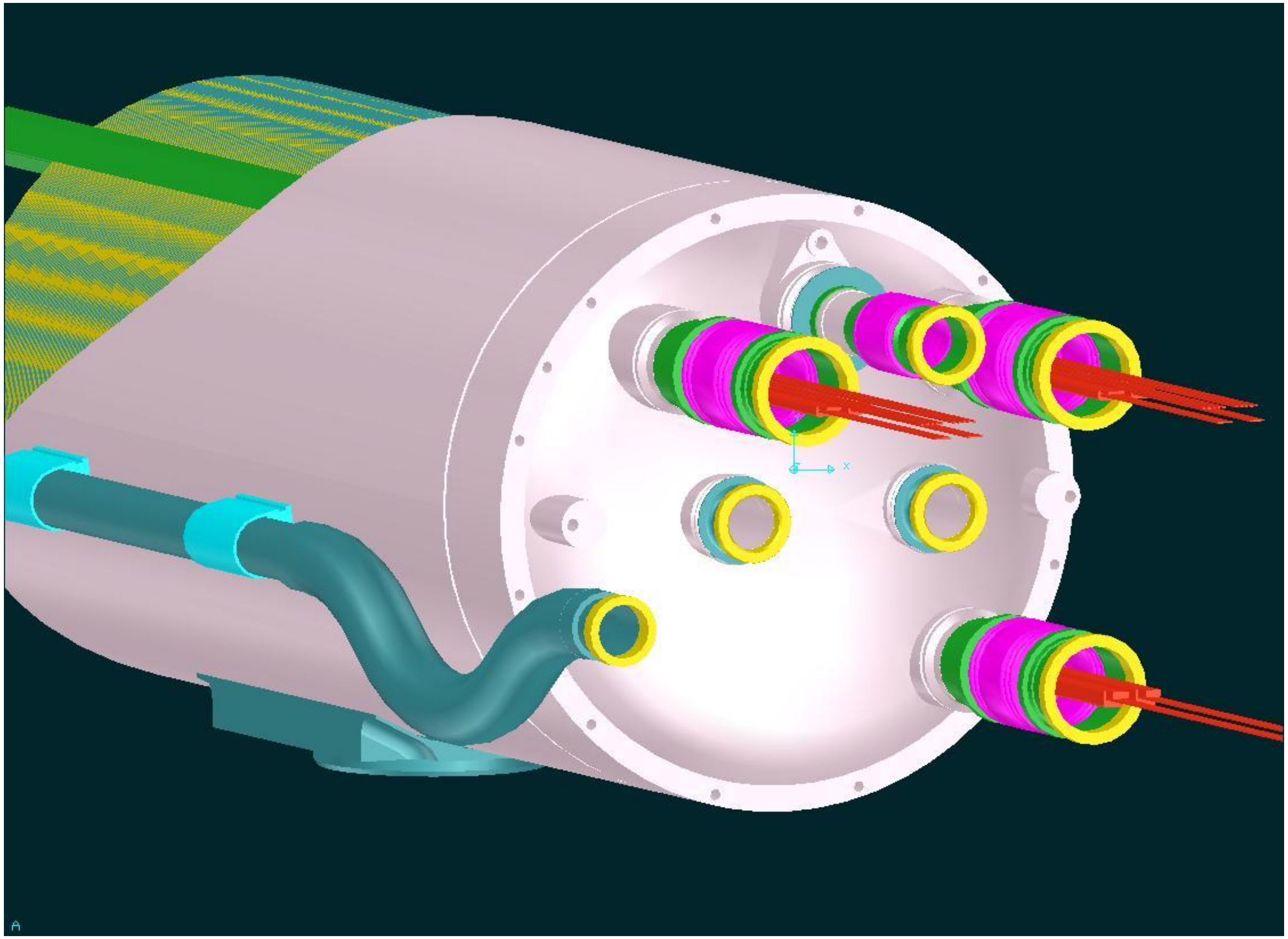




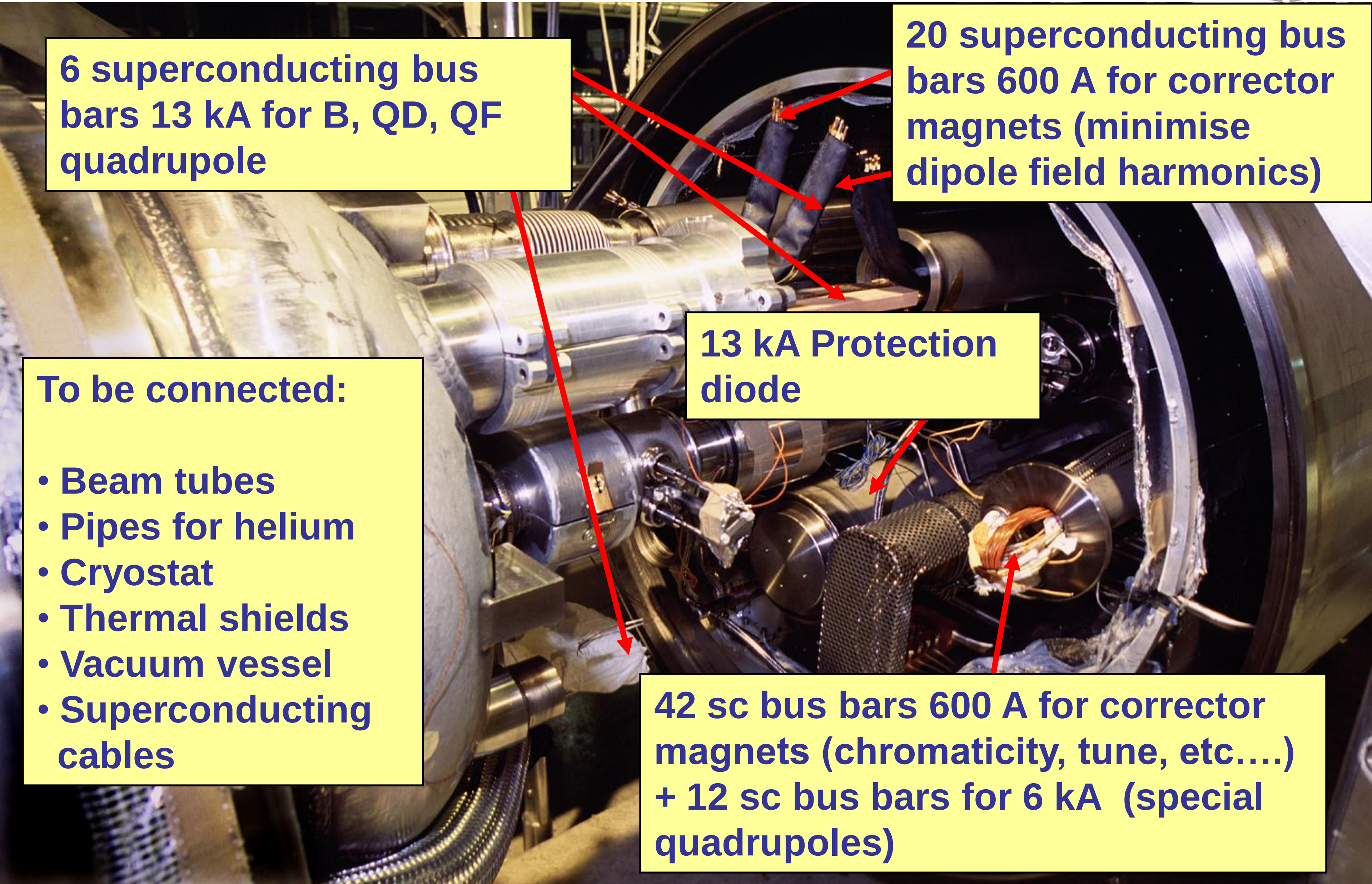
LHC Main Dipole -end part « Cold foot »



LHC Main Dipole -end part
Bellows and N-line

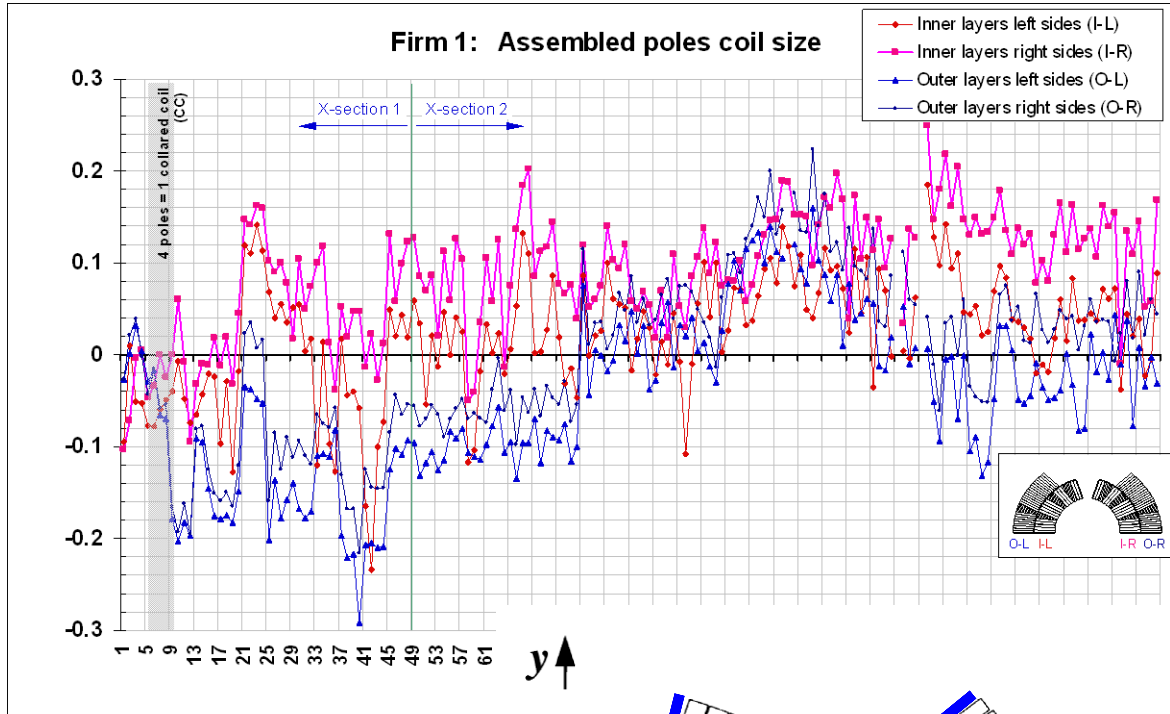


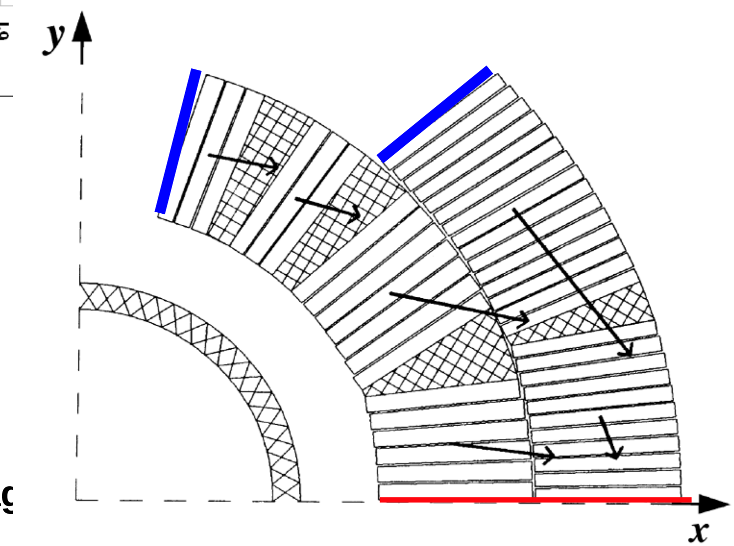
Interconnection between two superconducting magnets



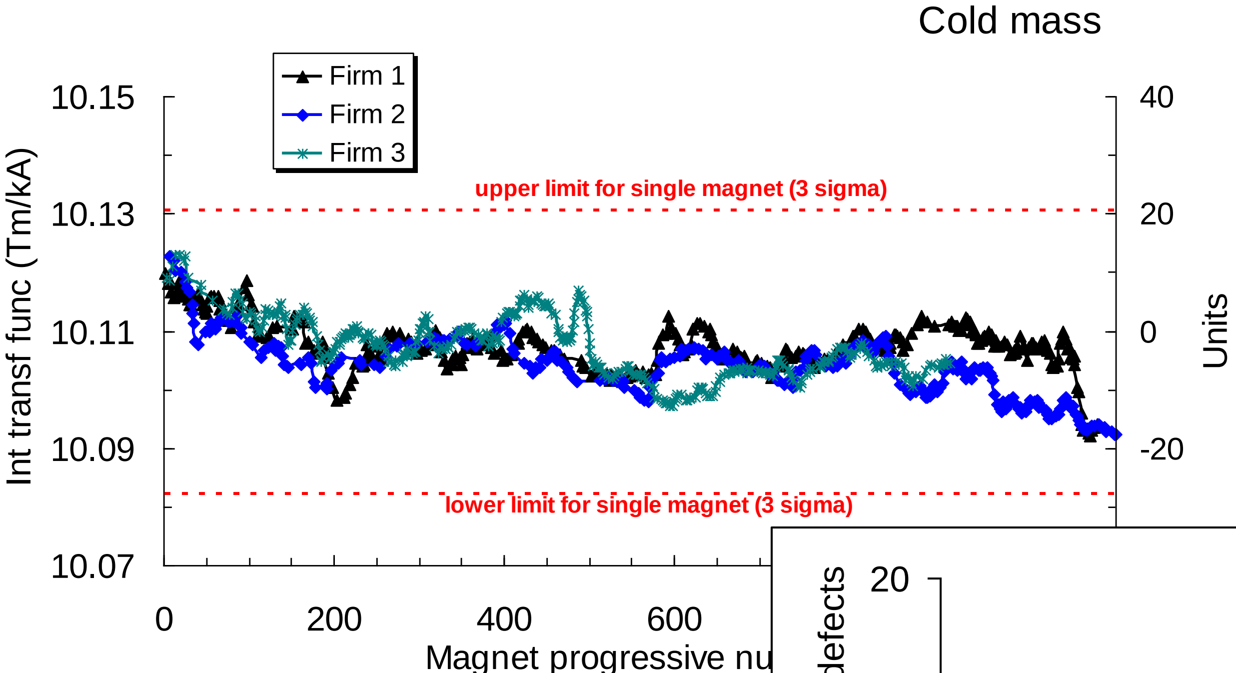
Critical Process
Winding-Curing-Coil formation

- 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





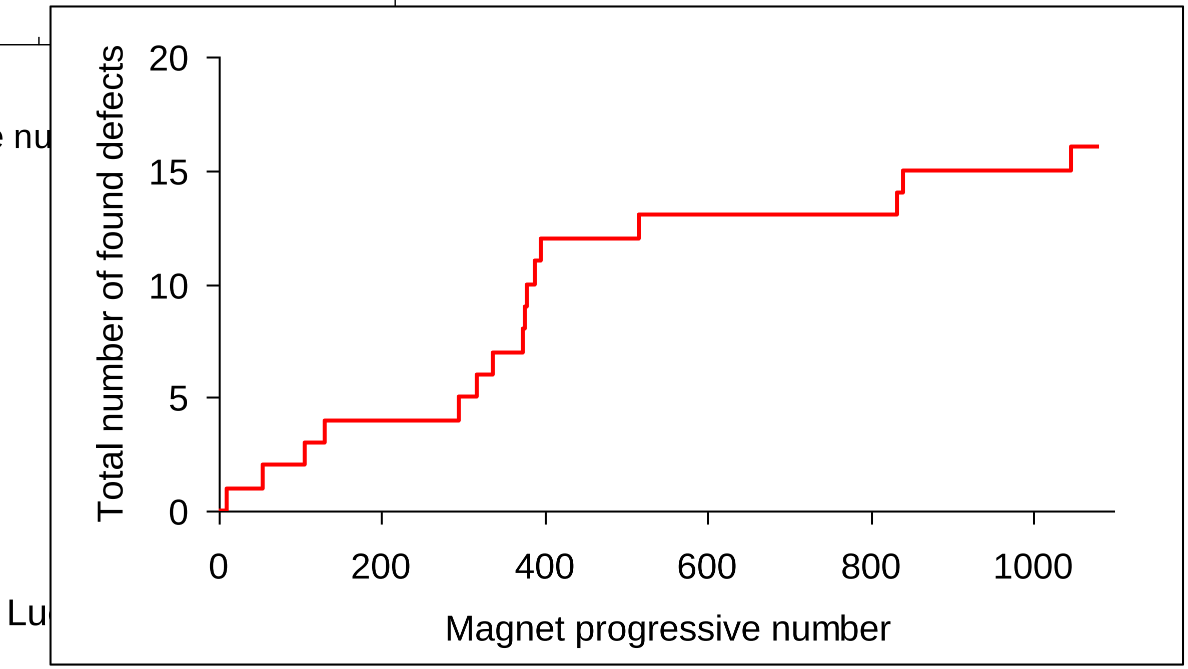
Steering production (and check assembly) Field Measurements - CERN supply



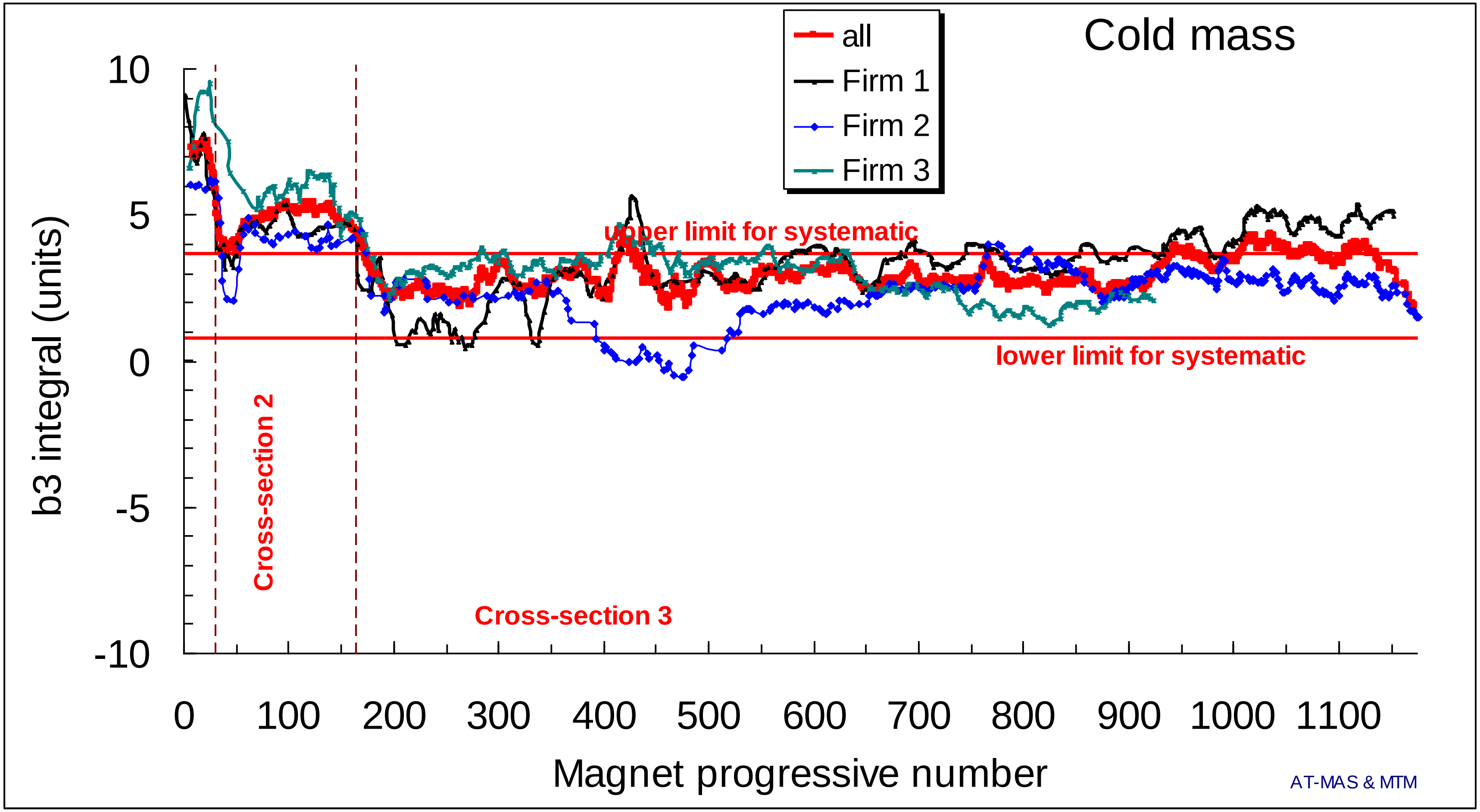
Introduced first to steer the FQ toward beam dynamics targets. Note the uniformity among different manufacturers

It has also helped to detect a number of defects.

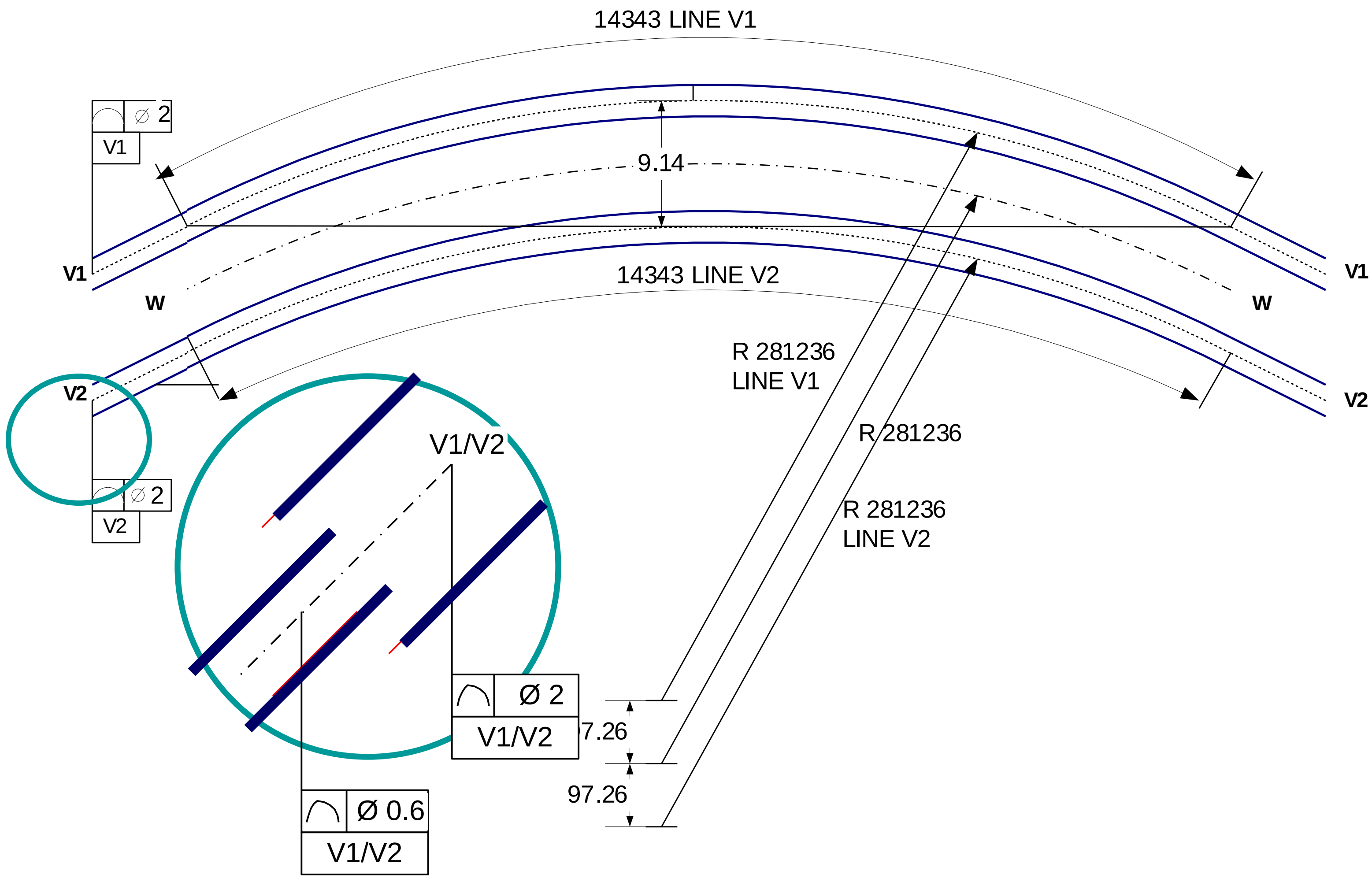
It has also been used to detect subtle electrical shorts



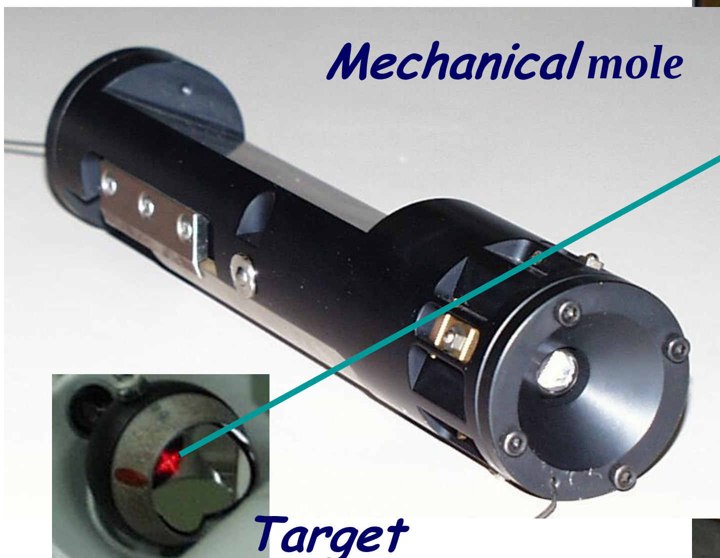
Stering production with actions

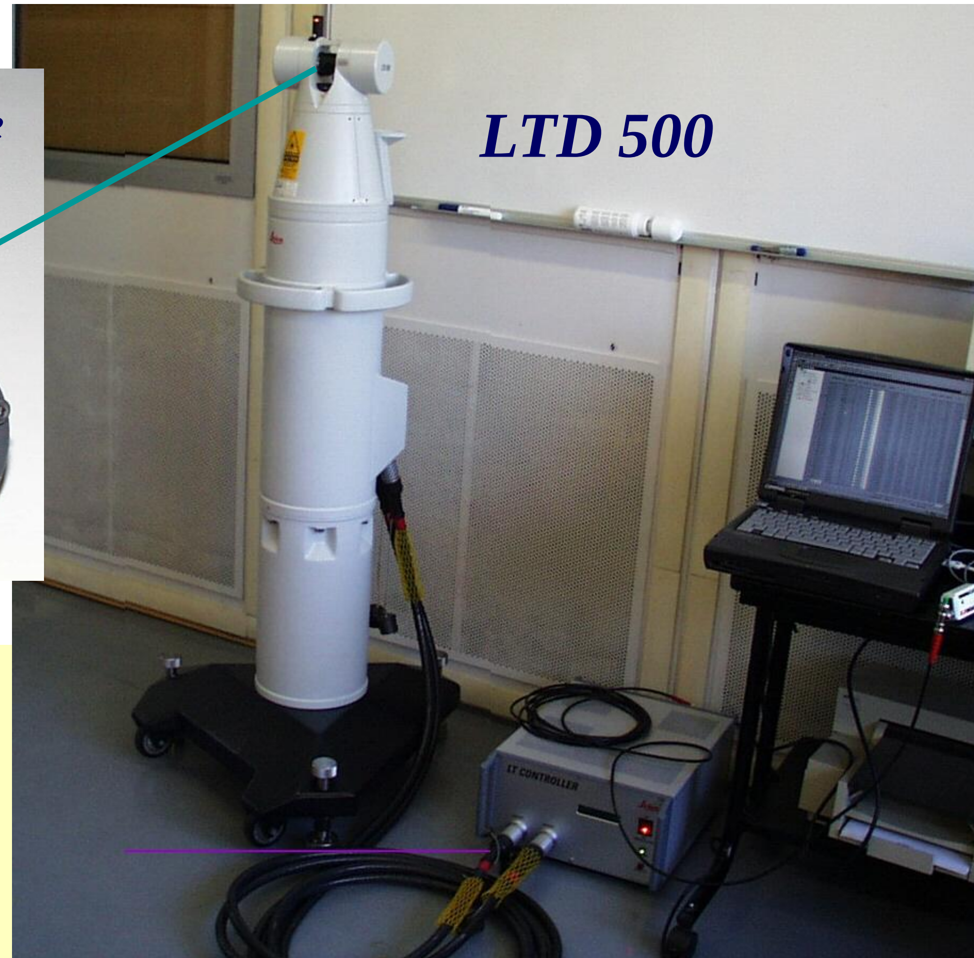


3 D: curvature measurements End tolerances



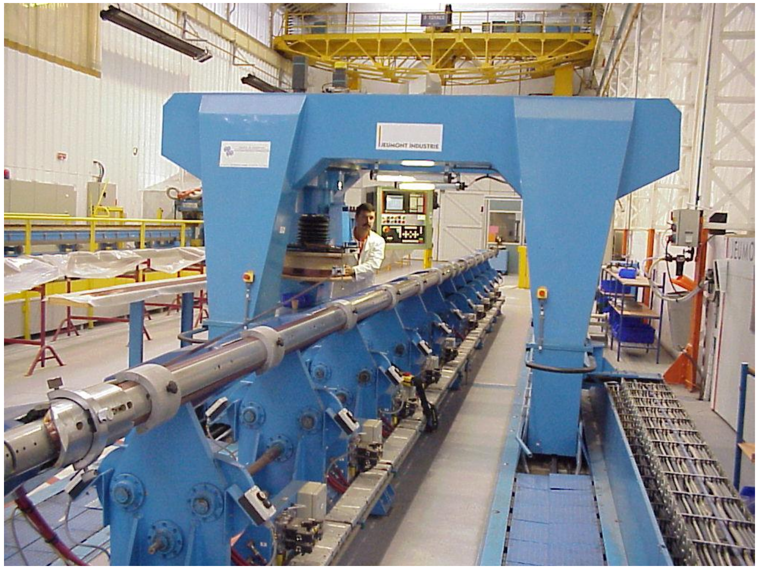
Measuring Instruments : Laser tracker (Leica) and moles



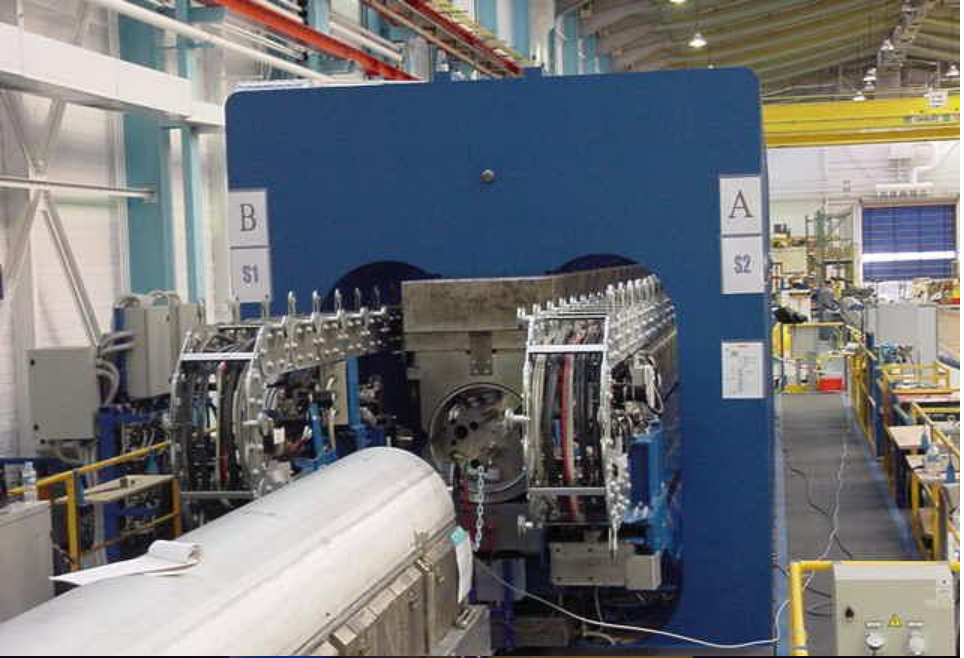


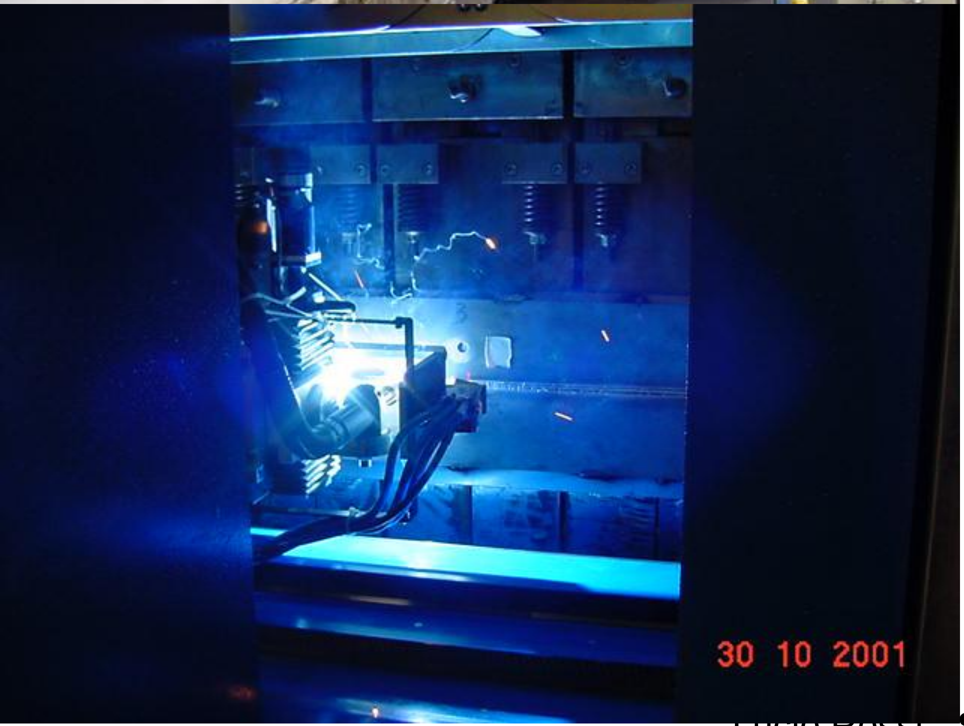
Accuracy: 10ppm at 2σ
on static target
BUT 0.2 mm when
changing position

Snapshot at industry



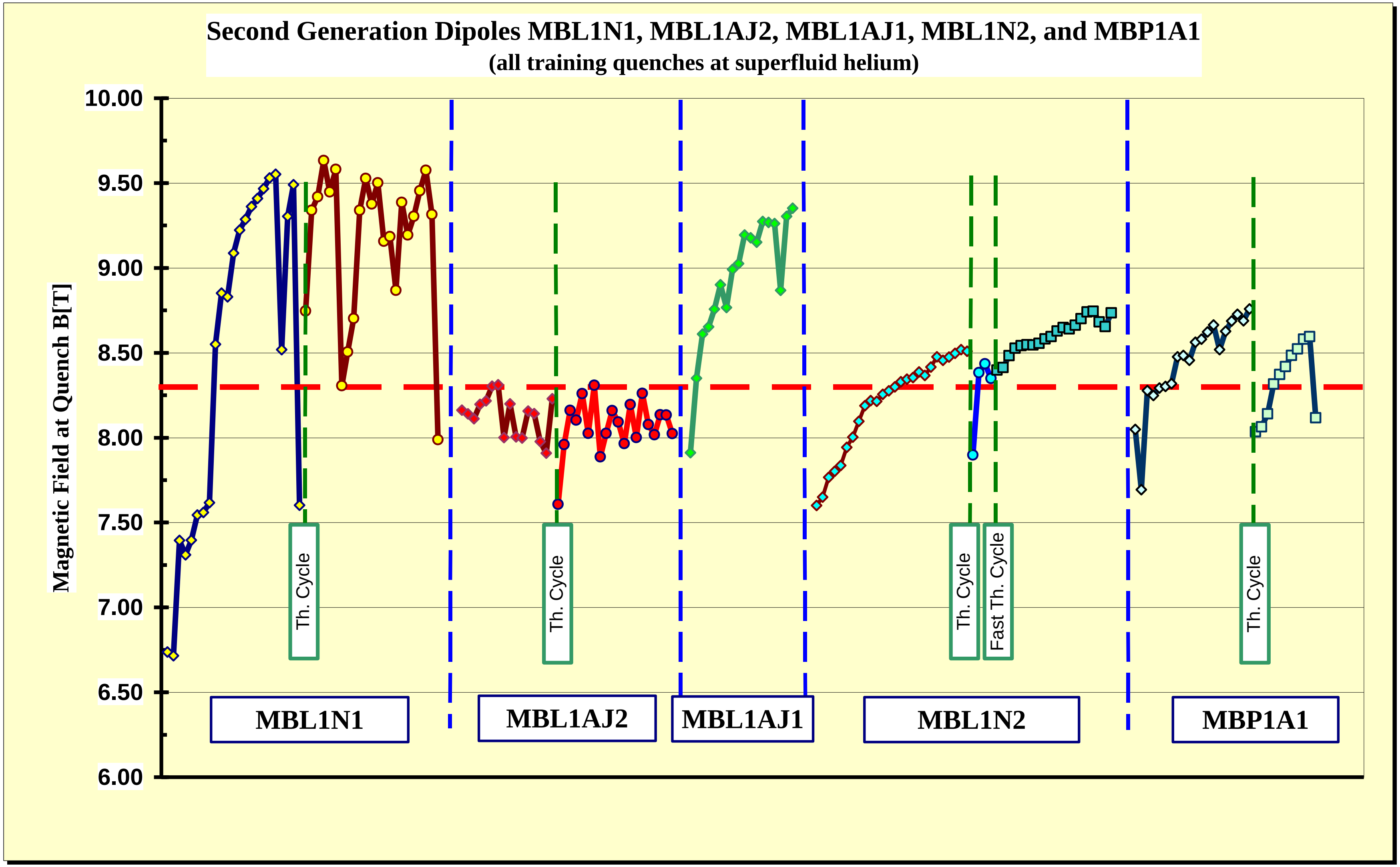
The longitudinal welding





- 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 !!!

Magnet performance and Training Curve



The spectrum of disturbances

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 ⇒ 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 !)

The spectrum of disturbances - II

Transient Distributed/Point Perturbances

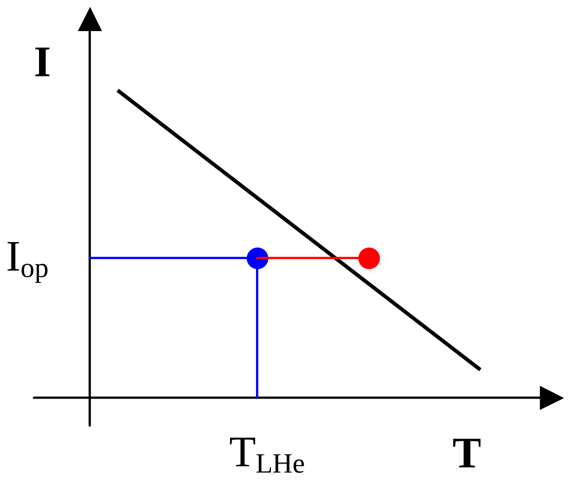
- Flux jumps. This effect is cured almost definitely for NbTi. Effects could be seen on NbSn with very high current density and very large effective filament diameter. This effect can be detected at low field, during current ramp.
- **Mechanical origin: movements, friction, sudden release of elastic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

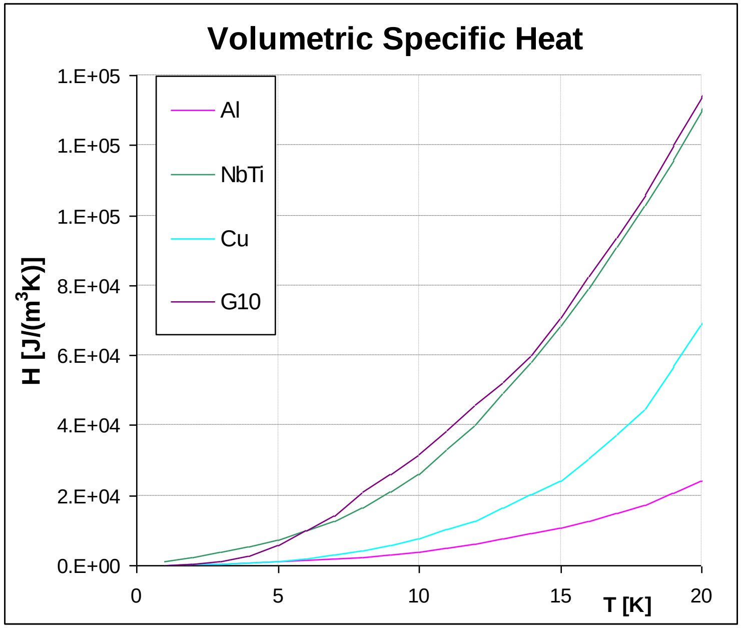
Basically these last two mechanism are now understood, in principle, and acoustic emission experiments did prove it almost visually.

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.)

Temperature and enthalpy margins

The main 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 $\Delta T \approx 1\text{-}2$ K



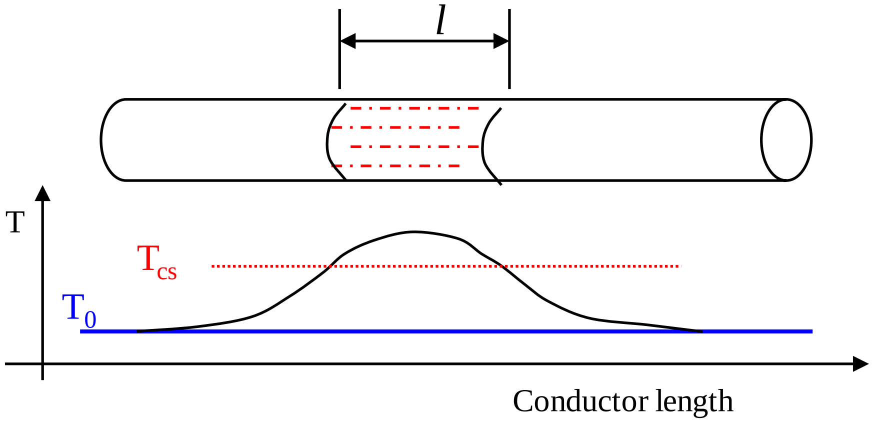


Point Disturbances : MPZ

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:

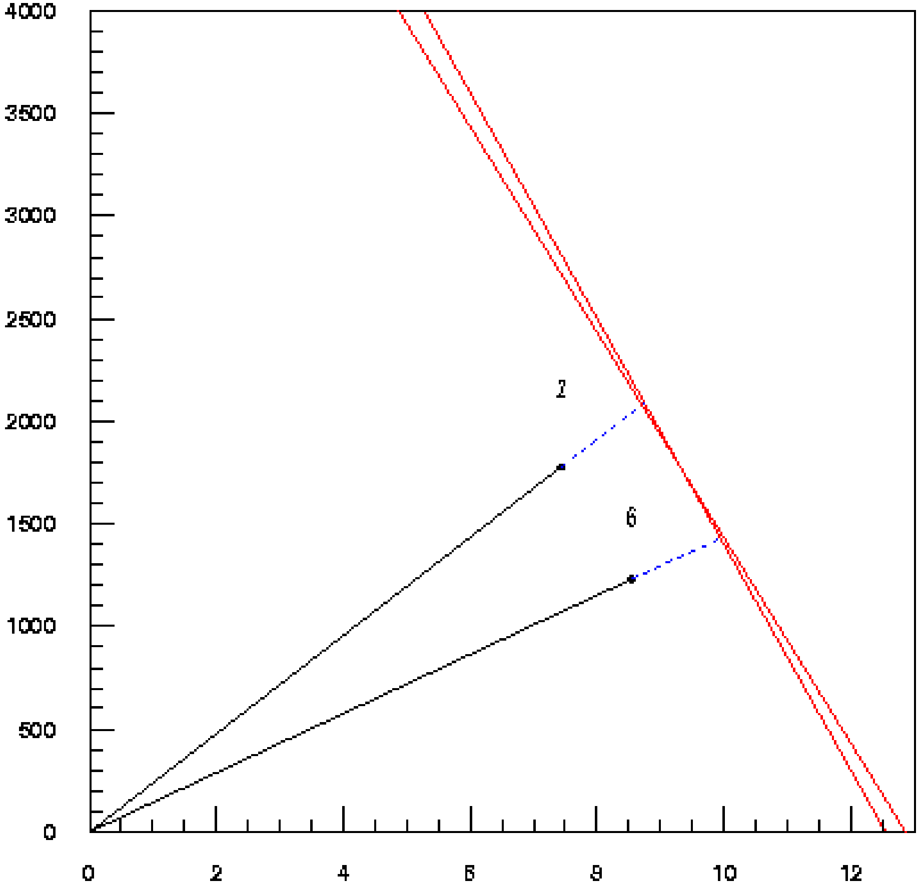
$$l = \frac{2k(T_{cs} - T_{op})}{\rho J_c^2}$$

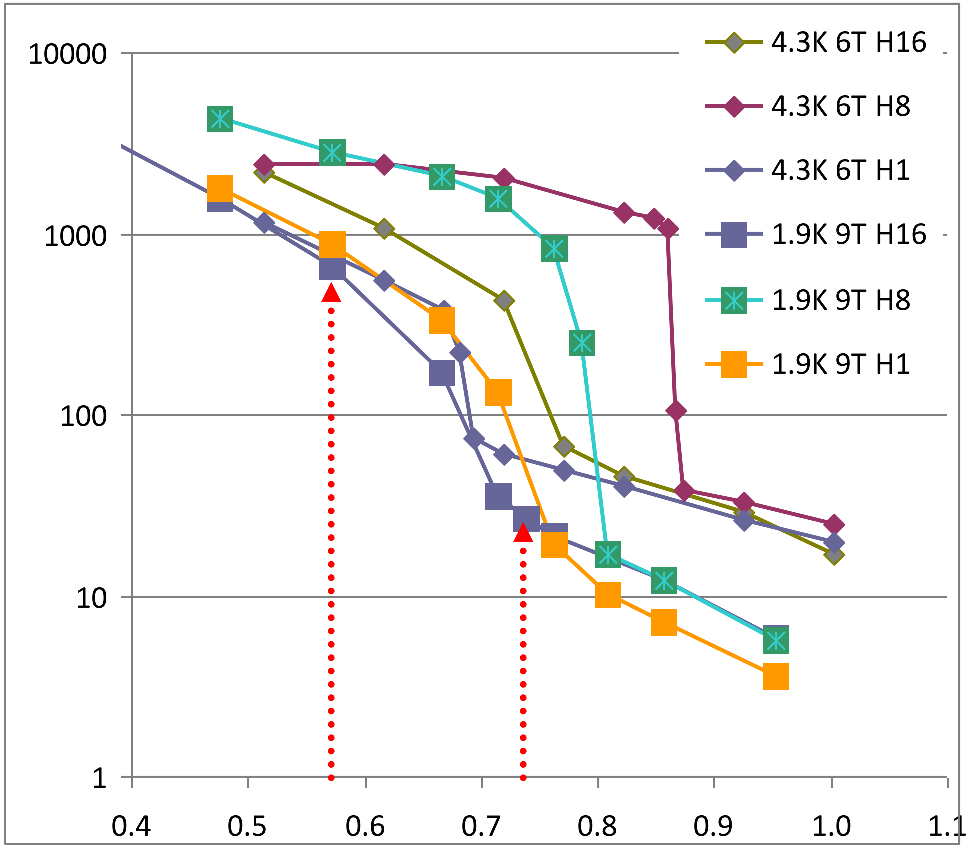


If there is no stabiliser, only NbTi, we see that $l \cong 1\ \mu m \Rightarrow \Delta H \sim 1$ nJ only !!

Stability of LHC

If there is no stabiliser, only NbTi, we see that $l \cong 1\ \mu m \Rightarrow \Delta H \sim 1$ nJ only !!
If each strand hehaved as single wire, $\Delta H \sim 1\text{-}10\ \mu J$





PROTECTION

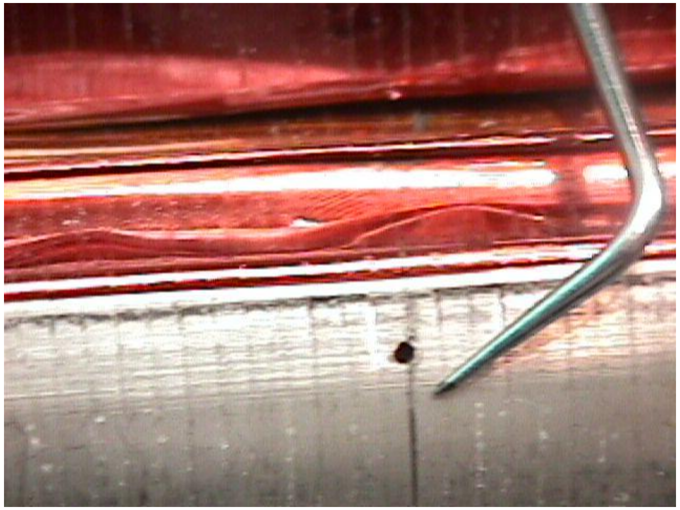
A superconducting magnet, whatever the stability margin, **it will quench**. And magnet integrity has to be preserved.

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

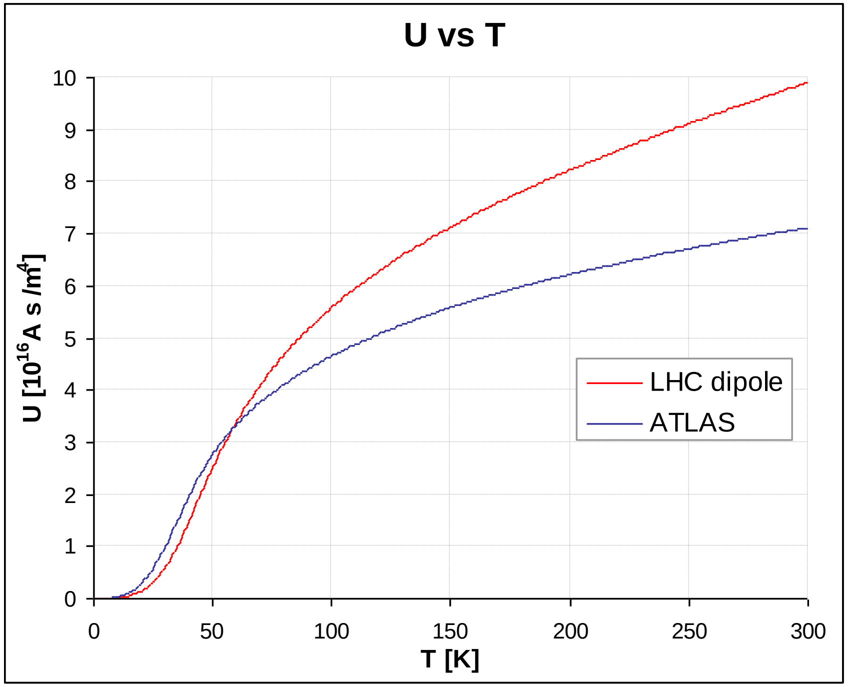
The function U(T) is a computable a priori, based only on material properties. If the magnet is discharged on an external –dumping- resistors, R_D, $T_d = 0.5 \cdot L_{mag}/R_D$.

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

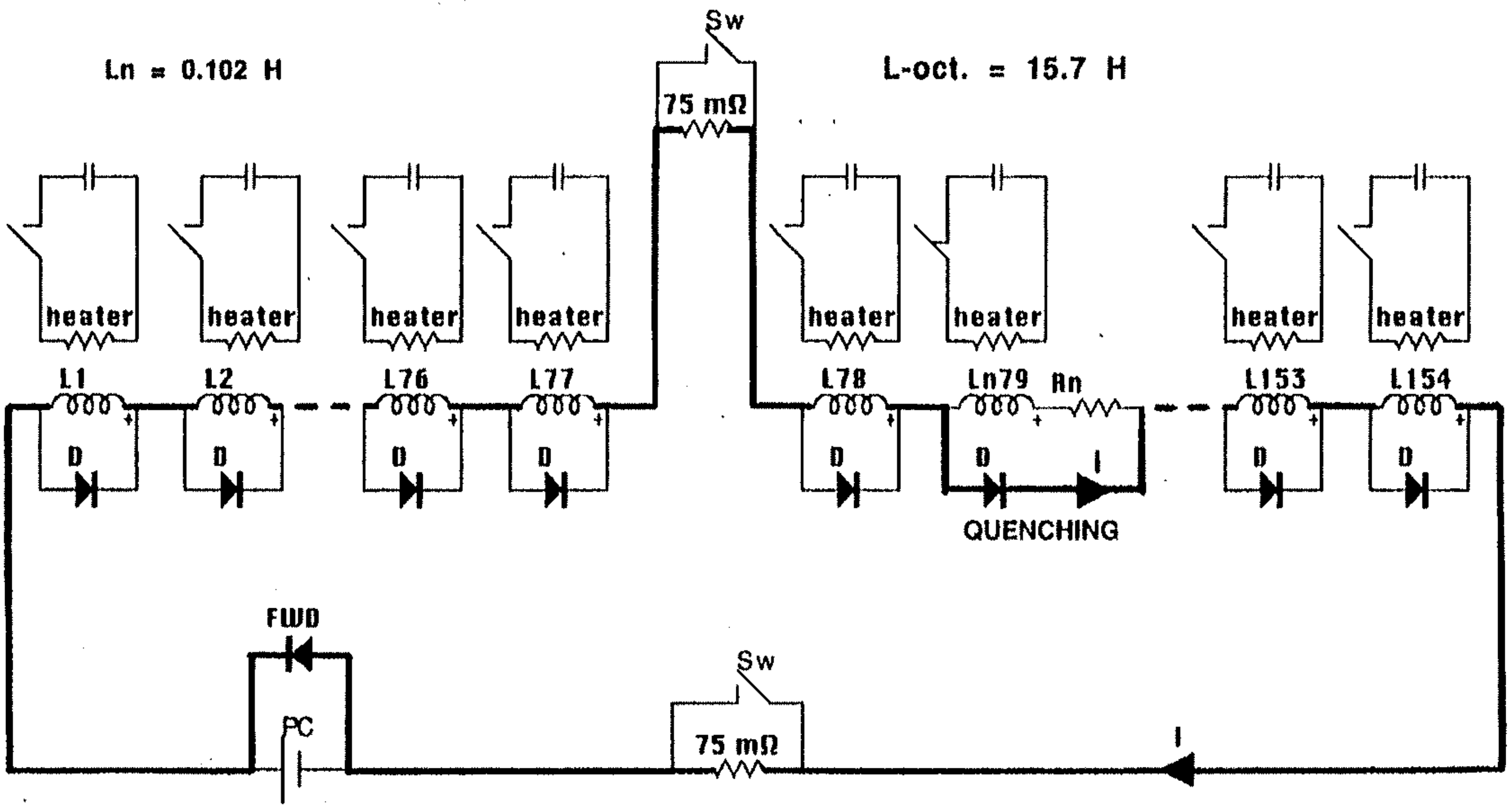
1**) Heater : activated in 20 ms !!**

2) Benefit of quench-back

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

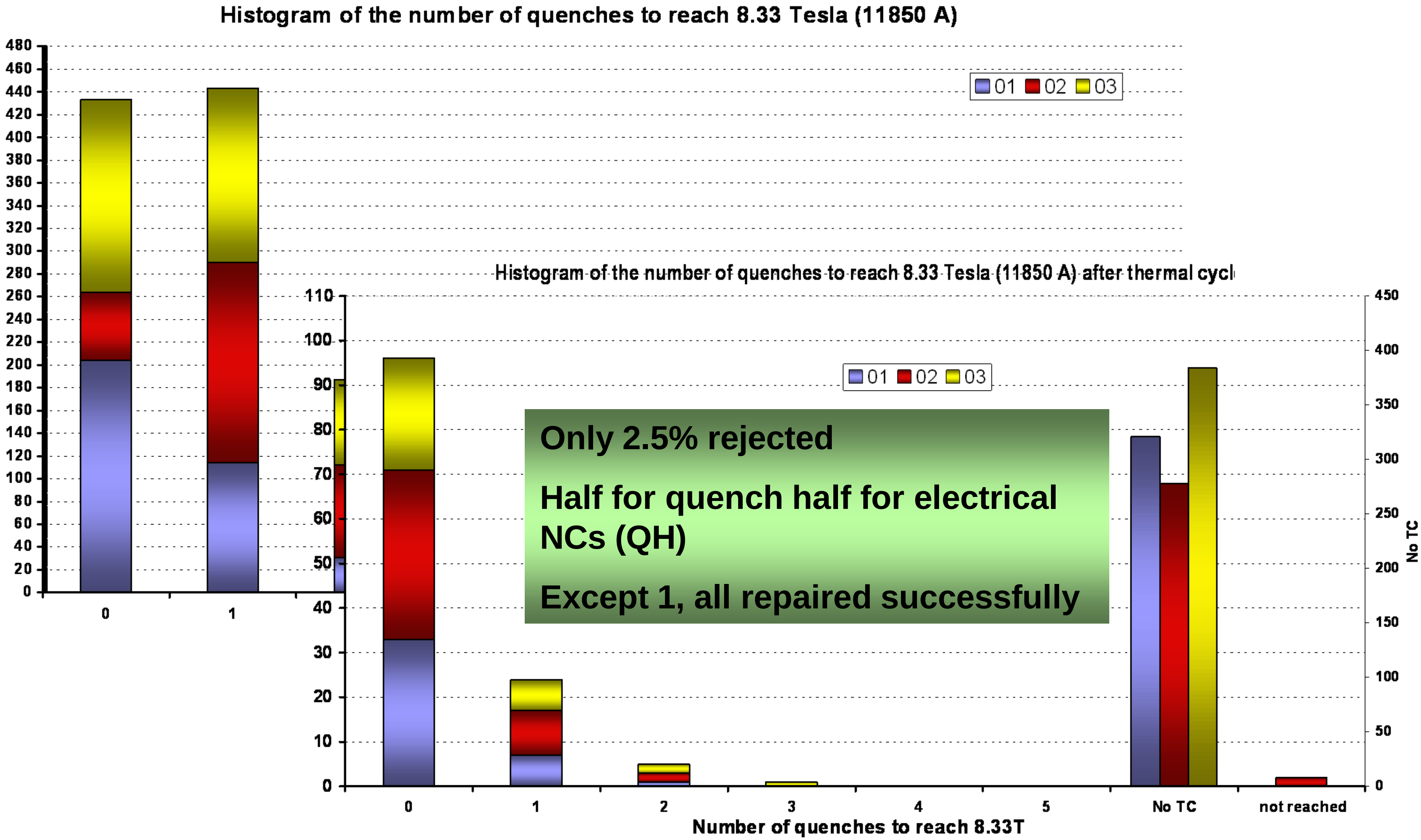


Protection scheme for a dipole string



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

Quench statistics (single magnet test)



Only 2.5% rejected

Half for quench half for electrical NCs (QH)

Except 1, all repaired successfully

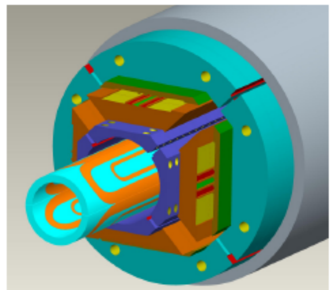
Future for SC magnets ?
No new LHC at view but…

LARP

Next Step: 120 mm Quadrupoles

Completed:
- *Cable optimization & test winding (LBNL)*
- *Coil cross-section and end design (FNAL)*
- *Winding/curing tooling design (LBNL)*

In progress:
- *Reaction/potting tooling design (BNL)*
- *Coil parts procurements (FNAL)*
- *Support structure design (LBNL)*



Plans:
- *Test 1 m models (HQ) in 2009-10, 4 m models (QA) in 2011-12*
- *Aiming at full qualification based on Phase 1 upgrade requirements*
- *Conductor-limited gradient is about twice the Phase 1 requirement*
- *Will provide performance reference for Phase 2 upgrade design*

9th ICFA Seminar, October 28-31, 2008 | R&D for High Field Magnets | GianLuca Sabbi, LBNL

LHC luminosity upgrade
Larger and higher gradiend quadrupoles…
Higher field dipoles

FAIR project at GSI

SIS100 – superferric fast cycled 2.1 T
SIS300 – 4.5 T 0.1 Hz cycled magnets