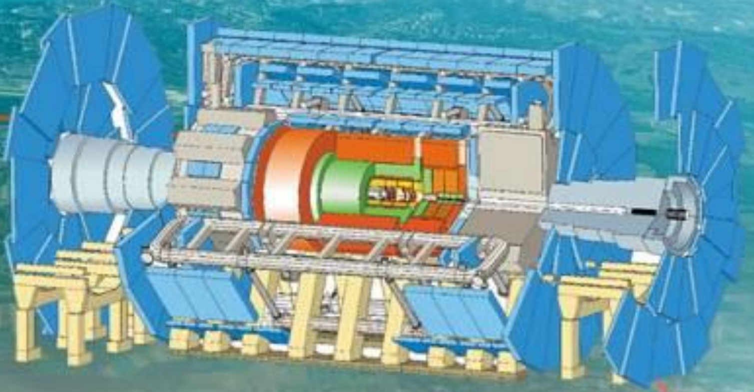
# *Superconducting Detector Magnet Structures*

***Herman ten Kate***



Content: 1. Concepts
2. Superconductors
3. Design CMS solenoid
4. Making ATLAS Magnets
5. Future Collider Detector

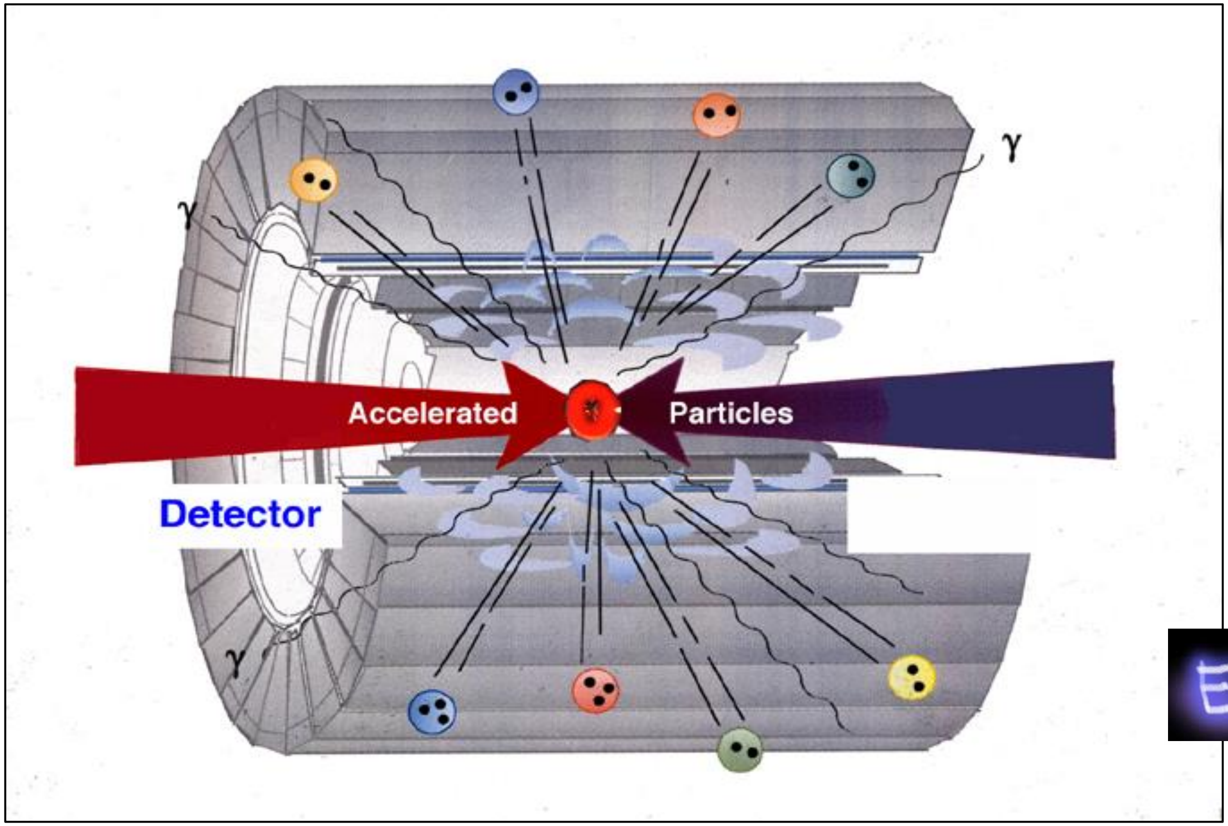
**CERN Accelerator School**
**Sint-Michielsgestel, Netherlands, June 14, 2024**

# 1. Concept: $E = mc^2$

How to discover new (elementary) particles?

✓ **$E = mc^2$**, produce particles in a spot of energy and seek in the escaping particles

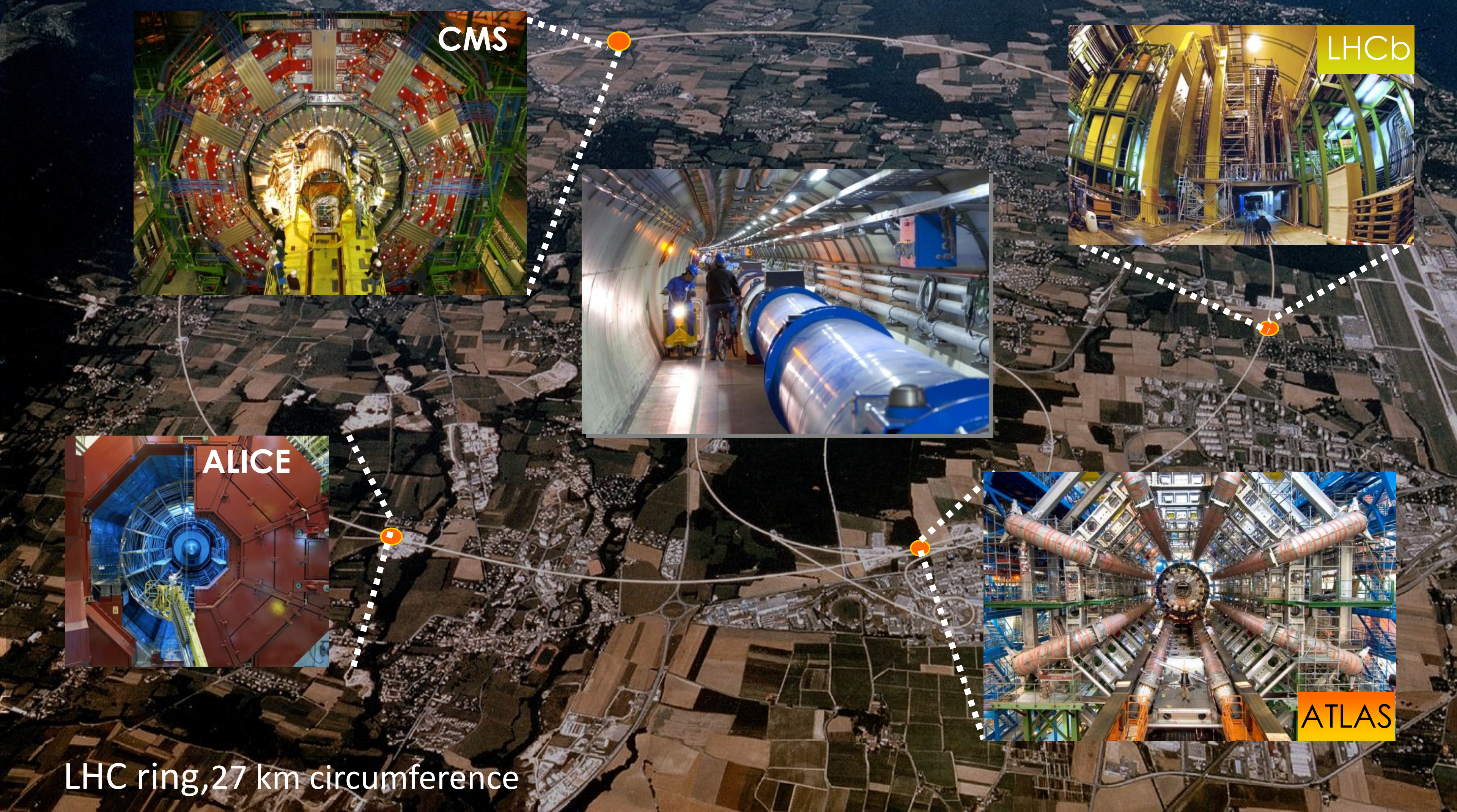
We need **E**, an energy production device (**accelerator-collider**), and an experiment to look at the shower of particles produced (**detector**).



$E=mc^2$

# Example: the Large Hadron circular Collider

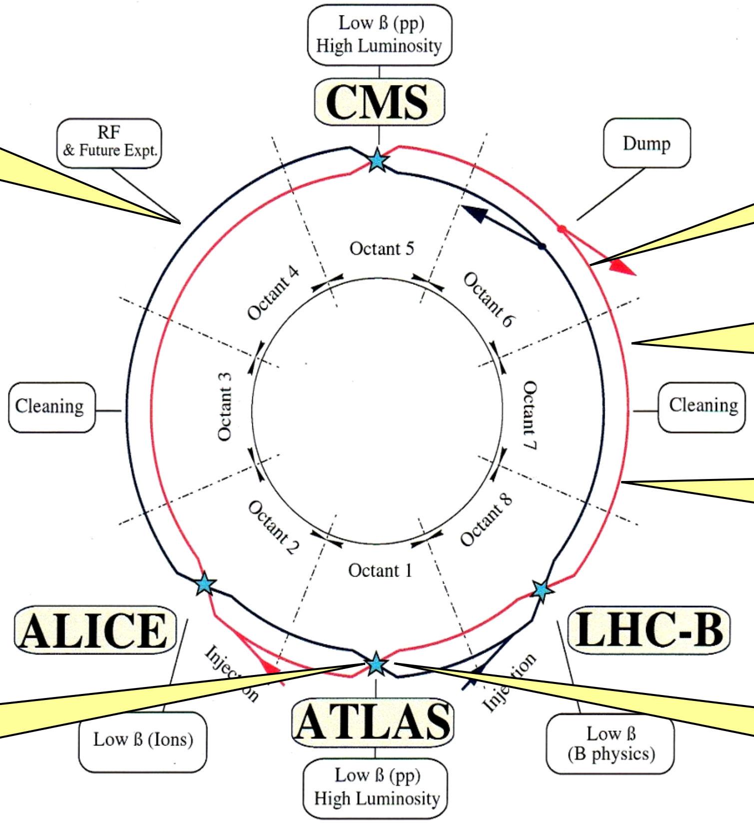
*Exploring the energy frontier between up to 14 TeV using proton-proton & Pb-Pb collisions*



LHC ring,27 km circumference

# *HE Physics and Superconductivity*

**LHC** (and many other accelerators) can not be realized without extensive use of Superconductivity and High-Quality Magnets



**Nb/Cu cavities for acceleration**

**1232 dipoles magnets for bending**

**386 quadrupole magnets for focusing**

**~7000 Correction magnets**

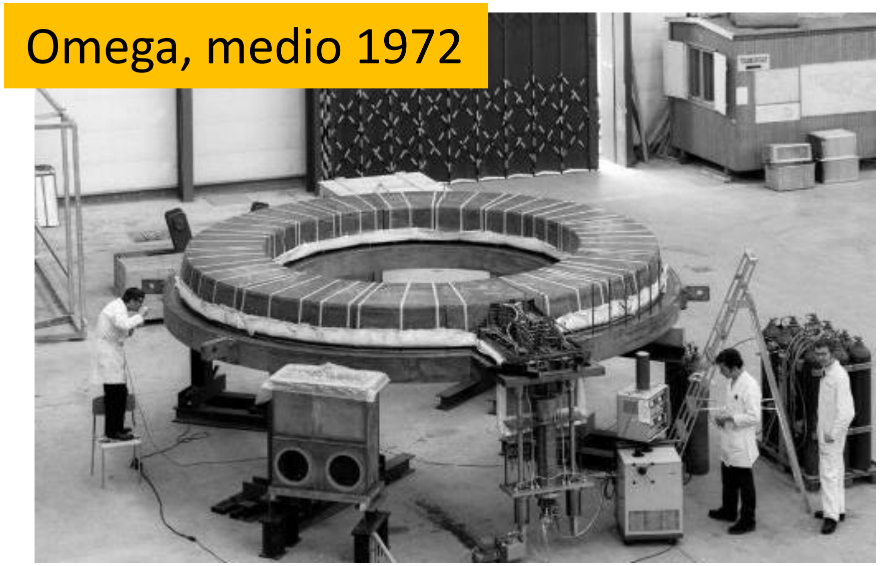
**ATLAS and CMS detector magnets**

**Insertion and Final Focusing magnets**

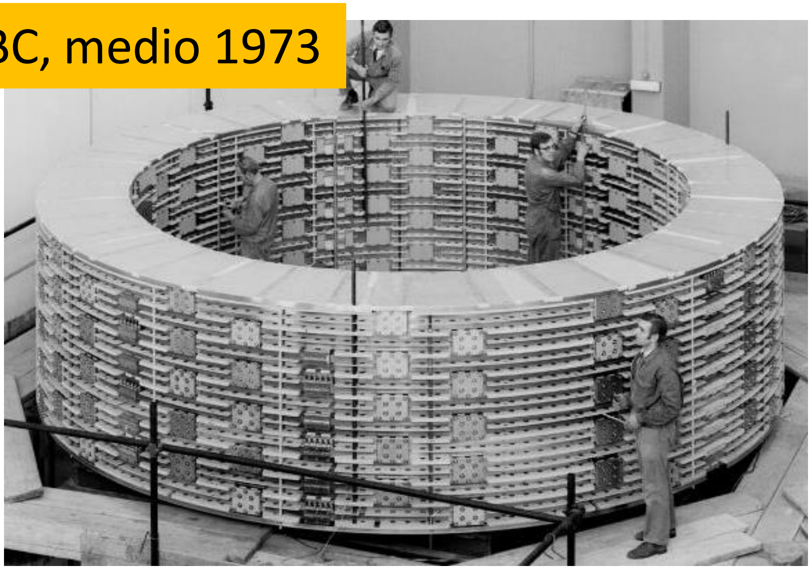
**No Higgs (and much more) without Superconductivity !**

# Large HEP Detector Magnets of the past...

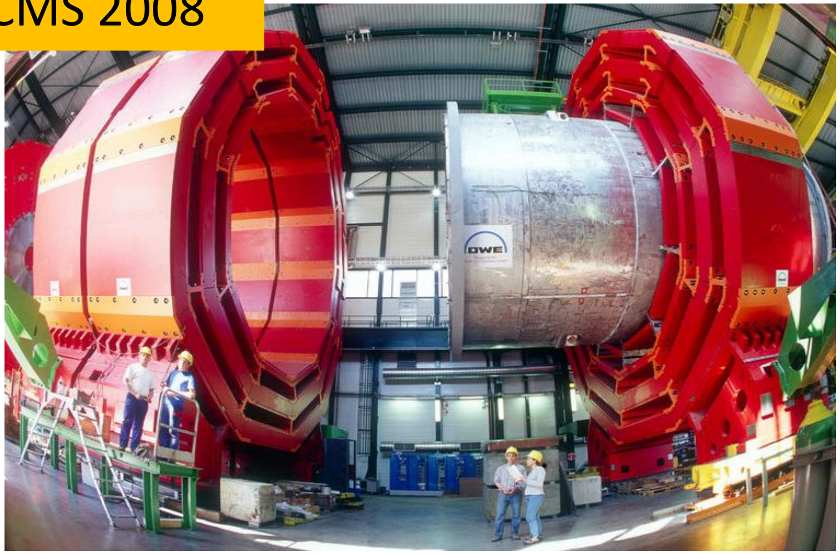
Omega, medio 1972



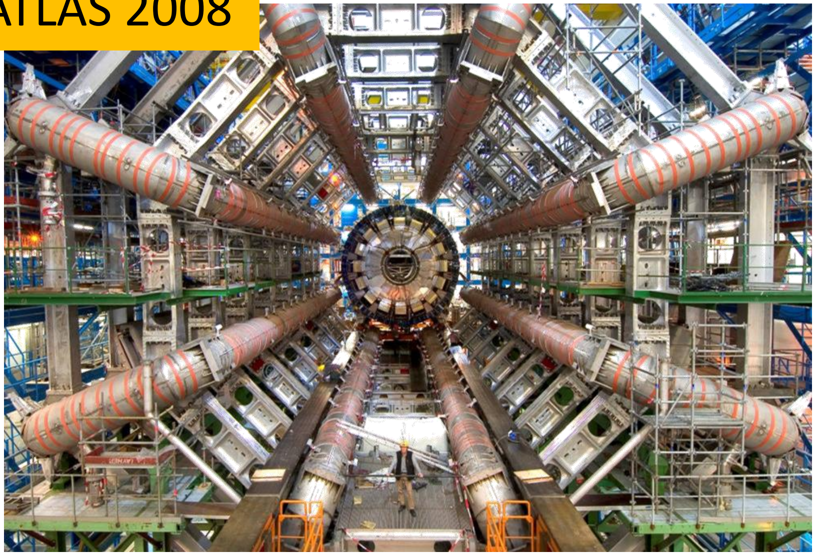
BEBC, medio 1973



CMS 2008



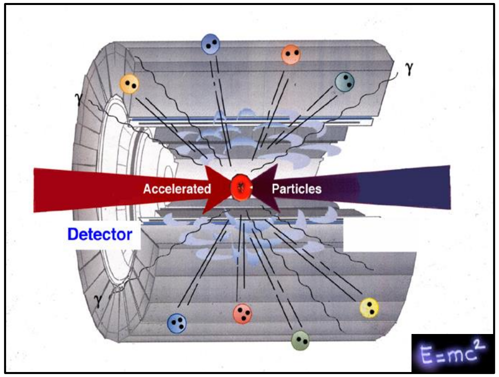
ATLAS 2008



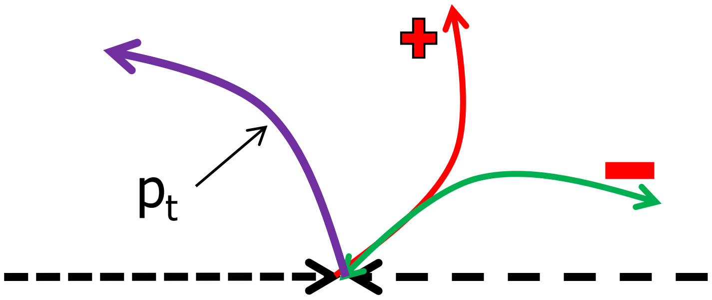
# Concept: why magnetic field in detectors

How to analyze the shower of particles ? We need:

- Track reconstruction
- Energy measurement (in calorimeters)
- Charge identification in magnetic field
- Momentum measurement in magnetic field.

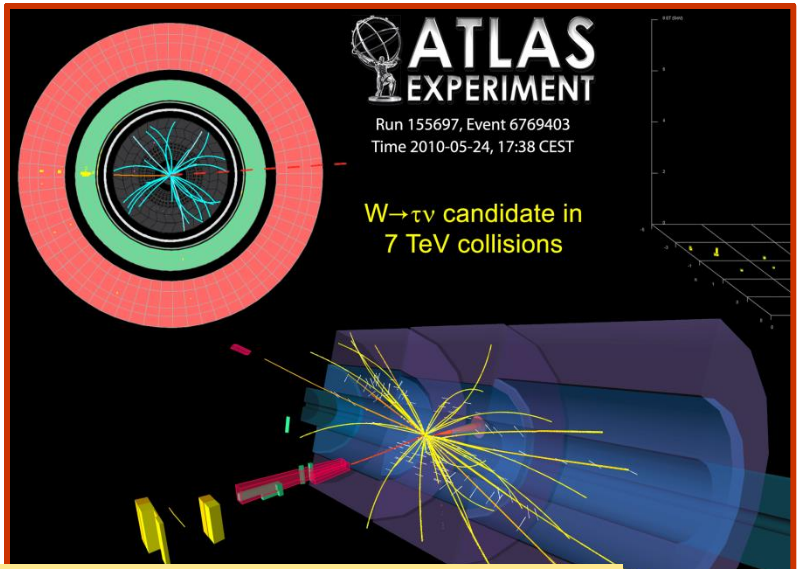


A detector magnet is in fact a “magnetic separator”.



Information yield:

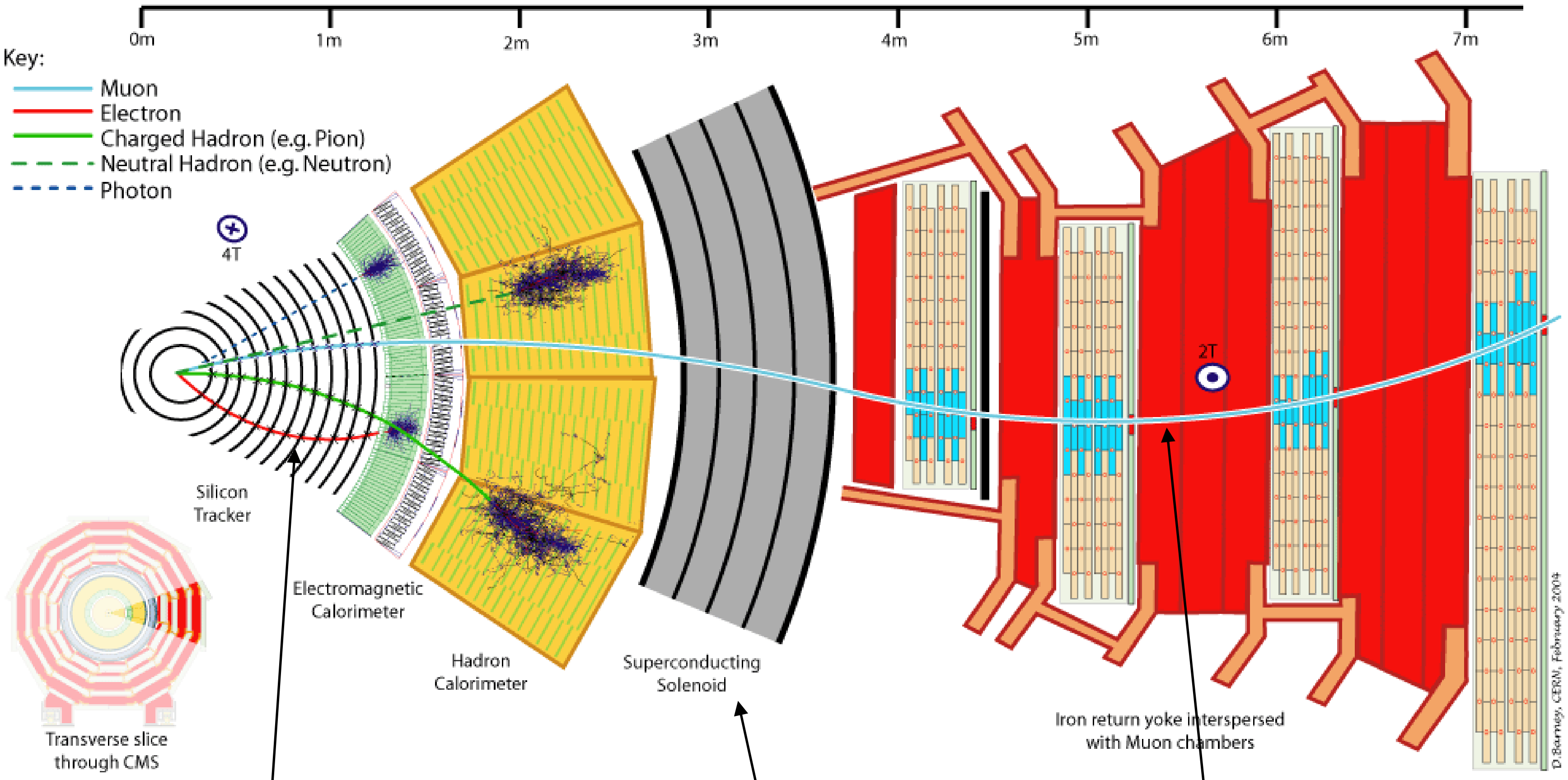
- left turn => positively charged particle
- right turn => negatively charged particle
- curvature => momentum.



Tracks in ATLAS inner detector in 2 T

# Concept: charged particle tracking

Example: tracking in the CMS Solenoid and iron return yoke



Curved particle tracks due to **solenoid field**

3.5 T **solenoid**

Curved muon tracks due to field in **iron yoke**

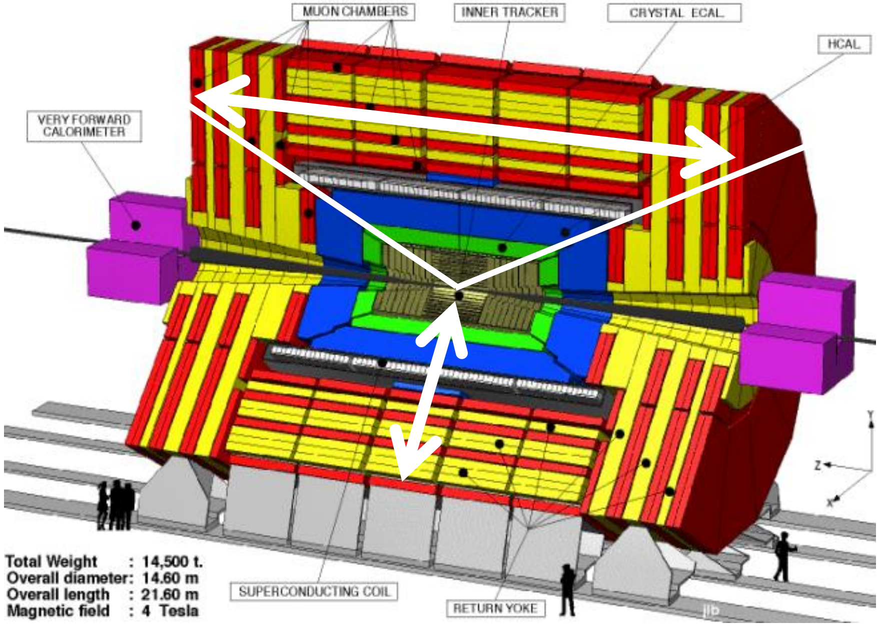
# Concept: sizing the detector

**What determines the size of a generic “4$\pi$“ detector and its magnetic field?**

## Radial thickness

Is the summation of:

+ tracking length inner detector
+ thickness of the solenoid
+ radial build of the calorimeters
+ tracking length
+ thickness of shielding iron yoke



Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

## Axial length

Is the summation of:

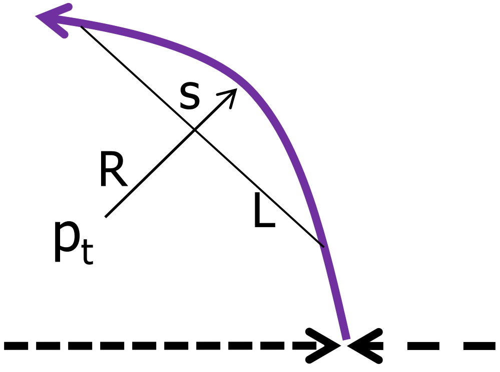
+ “catch angle” in forward directions sizing the length of the solenoid
+ thickness of iron shielding.

# Concept: sizing detector magnet

**What counts is momentum resolution!**

A particle with charge q and momentum $p_t$ traveling through B is bent by Lorentz force

$$F = q\,(E + v\ x\ B) \qquad (E \cong 0)$$



In the transverse direction, radius R, sagitta s:

$$s = {}^{L}/_{8R} = {}^{qBL^2}/_{8p_t}$$

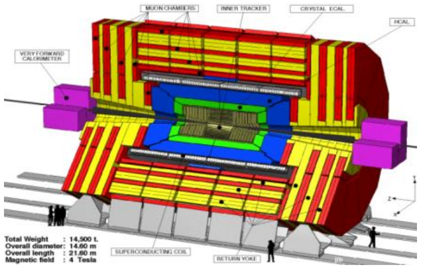
and momentum resolution

$$\partial p_t/p_t = {}^{p_t}/_{0.3BL^2}$$

| $p_t$ (GeV/c) | s [mm] @ B=1T, L=1m |
|---|---|
| 1000 | 0.037 |
| 100 | 0.37 |
| 10 | 3.7 |
| 1 | 37 |

- Keeping at minimum the resolution for higher collision energies, so higher momenta, requires to scale up the detector up with $BL^2$ !
- 10 times more energy → 2xB and $\sqrt{5}$=2.4x tracking length, say diameter
- And the axial length grows accordingly!
- **Thus: detector magnets scale in size with collision energy!**

# Concept: more requirements



(1) **Momentum resolution** → sufficient $BL^2$

(2) **For physics we need B, not the magnet** (!),

though a rewarding challenge for magnet engineers!

→ **Minimum thickness of coils to minimize particle scattering**
(especially when the calorimeters are put outside the central solenoid!)

→ **Material?: in general, all Al, low density, when inside the calorimeters**

(3) **Hermetically closed detector catching all particles**

→ Minimum lost sphere for magnet services and supporting structures.

(4) **Full integration of magnets with detectors interleaved and supported**

(5) **Always working to avoid loss of data**

→ Requiring high operational margins in terms of temperature and current

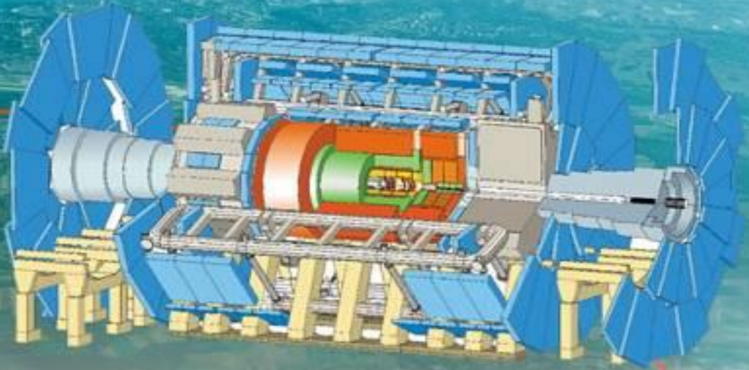
(6) **Unique and not replaceable** (can not really be repaired)

→ Very robust design with large margins and high level of redundancy

(7) **And low cost as well** !

→ **Use NbTi superconductor at 4.5 K**

# 2. Superconductors for Detector Magnets



Practical superconductors

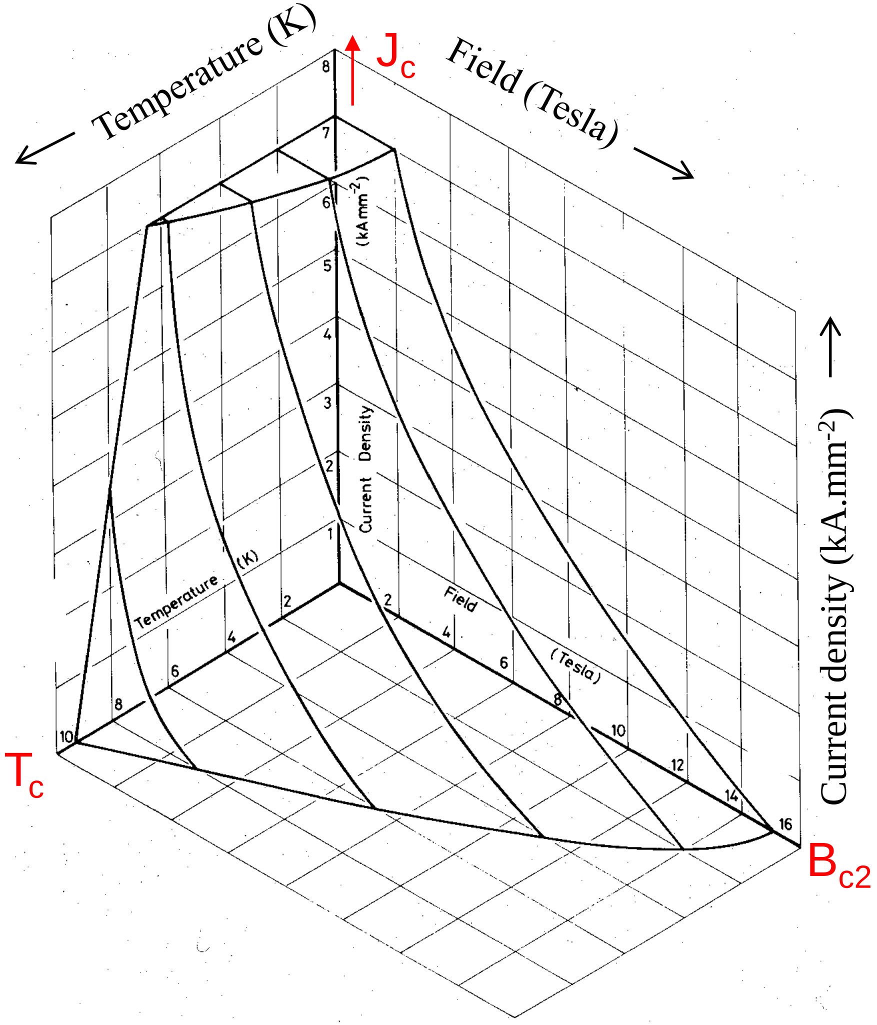
Basic properties

Stability requirements

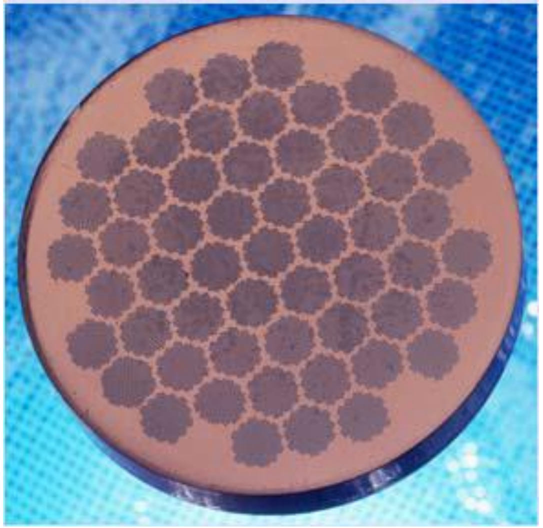
Minimum Propagation Zone

High Currents and Cables

# *Practical Conductor - NbTi*



**Cubic alloy, isotropic**



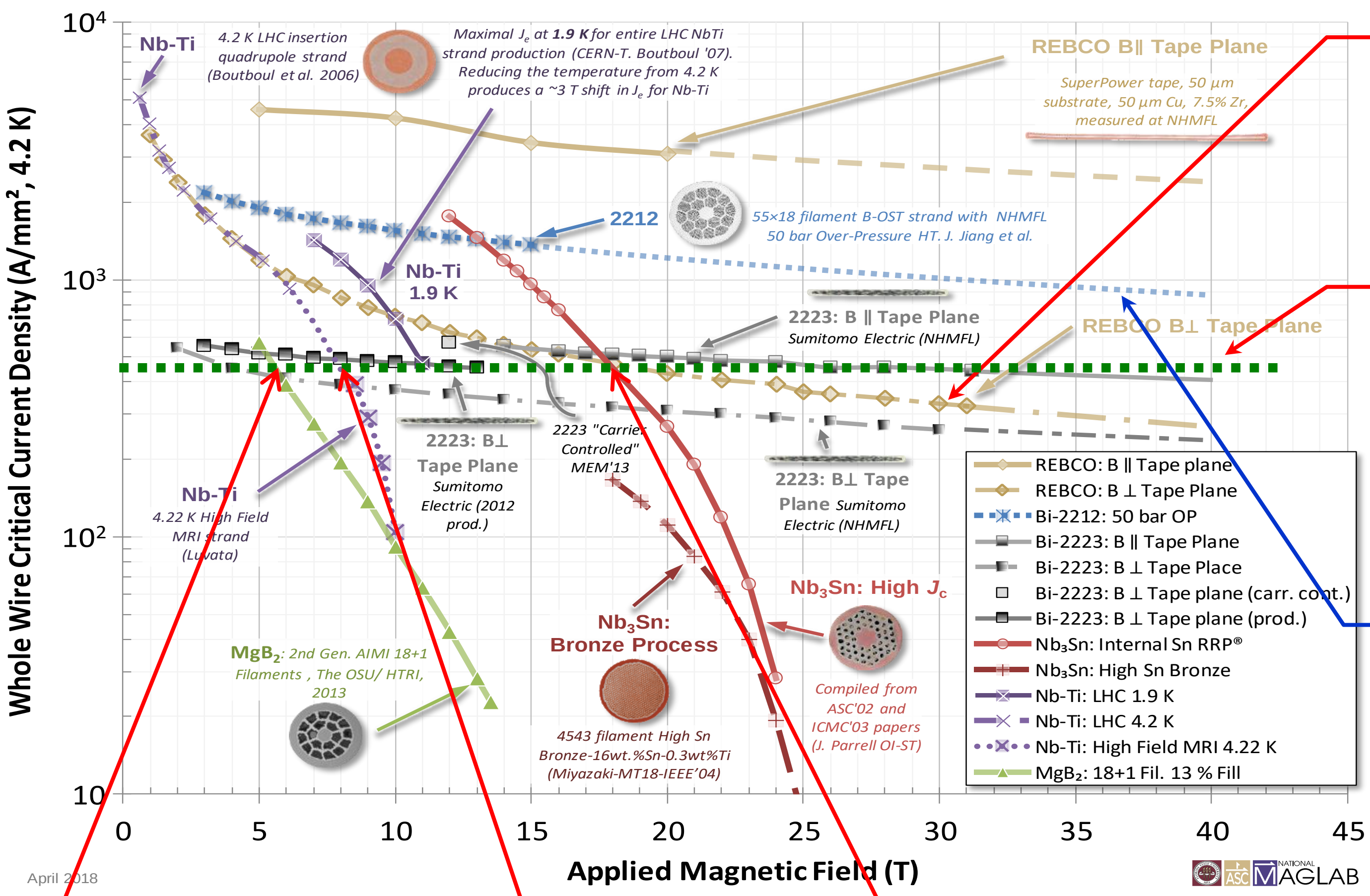
*0.7 < wire diameter < 1.3 mm*

Tc : 9.3 K

$Bc_2$ : 13 T

Very well developed
~1 € / kA m

# Practical Superconductors for Magnets



***ReBCO*** **in a magnet, not in // field !**

Minimum practical current density

**Bi2211** may do better than Y123 when anisotropy is considered

**$MgB_2$** not for high field magnets but niche market 1 - 5 T, 4-20 K

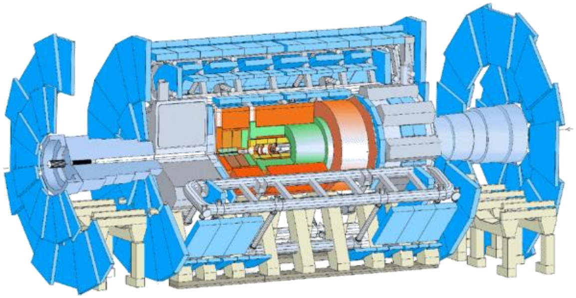
**NbTi**
for high field up to 9 T and 4 K and 11 T, 1.8 K

**$Nb_3Sn$**
for any magnet of 9-20 T

**Bi2212 or *Re*BCO**
for DC magnets of 17 -40 T provided cost comes down drastically

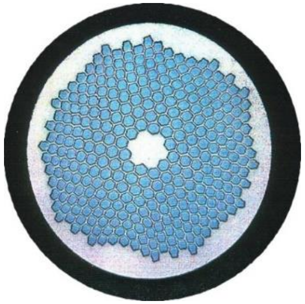
# Example: Superconductors in ATLAS Detector

**Barrel Toroid Conductor: 65 kA at 5 T**



- 1.25 mm diameter NbTi/Cu strand, 2900 A/mm$^2$ at 5 T
- 40 strands Rutherford cable, ~1700 A / strand
- Co-extruded with high purity Al (RRR>1500)
- Intermetallic bonding Cu-Al is required

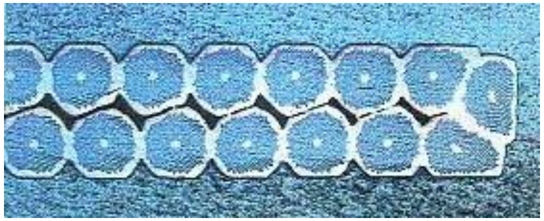
- size 57 x 12 mm$^2$
- 56 km made
- Production by 2 suppliers



*1.25 mm diameter*

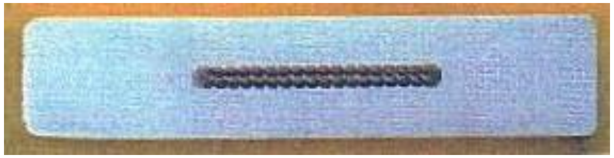
**End Cap Toroid Conductor**, size 41 x 12 mm$^2$,

- 26 km made



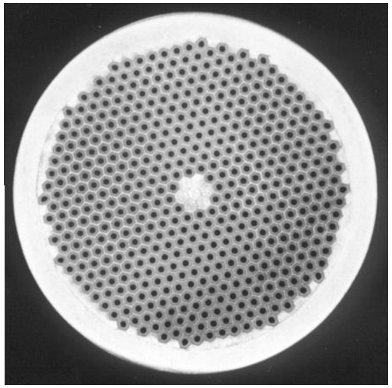
**Central Solenoid Conductor**, size 30 x 4.3 mm$^2$

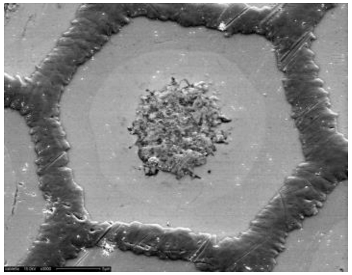
- 9 km made  (Ni/Zn doped Al for higher Y-stress)



*57 x 12 mm$^2$*

# Adiabatic Filament Stability: $d_{fil}$





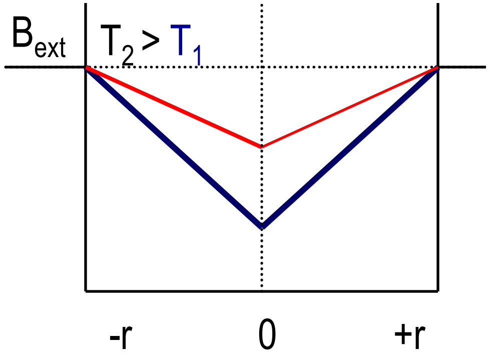
Field penetration in filaments, **the Critical State Model**

- In the filament magnetic energy is stored.
- When disturbed, the heat must be taken up by the enthalpy of the filament.
- A disturbance ΔT1 will cause a –ΔJc, so flux motion, leading to E, this leading to heat and so again a ΔT2.
- When ΔT2 > ΔT1, the process will accelerate and the flux profile collapses.
- Based on simple slab model, the adiabatic stability criterion is found:

$$\boxed{d_{fil} \cdot J_c < \{ 3\, c\, (T_c - T_o) / \mu_o \}^{1/2}}$$

**So we see a maximum filament thickness for a given current density, to guarantee stability.**

- For NbTi, $c = 5600$ J/m$^3$; $T_c(5\ T) = 7.2$ K, $T_o = 4.2$ K and $J_c = 3000$ A/mm$^2$, we find **$d_{fil} < 70$ μm.**



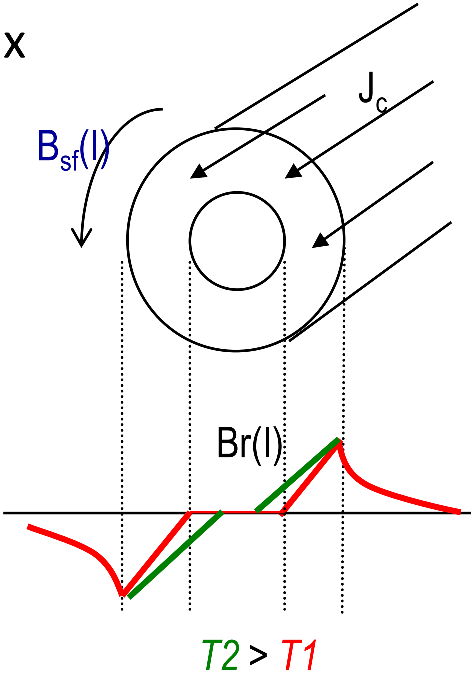
# *Adiabatic Wire Self field Stability: $D_{wire}$*

Filaments are coupled by self field

- Adiabatic filament stability requires fine filaments in a matrix
- Following the CSM, we see the magnetic field penetration profile disturbed by a ΔT
- Field profile has to change, field penetrates deeper, causing heat, taken up by enthalpy up to a certain limit
- Assuming $\eta$=sc/total ratio and current density $\eta J$
- We find for the adiabatic self-field criterion:

$$\boxed{D_{wire}.\eta J < \{ 4\, c\, (T_c - T_o)/\mu_o \}^{1/2}\ f\,(I/I_c)}$$

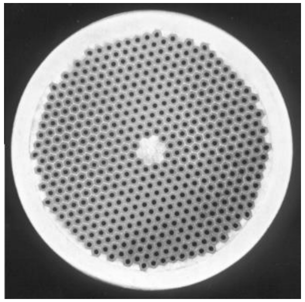
where $f\,(I/I_c) = 1/(-0.5 \ln(I) - 3/8 + i^2/6 - i^4/8)$



**We find a maximum wire diameter for a given Jc and $I/I_c$**

**Commonly used $0.7 < D_{wire} < 1.3$ mm in cables.**

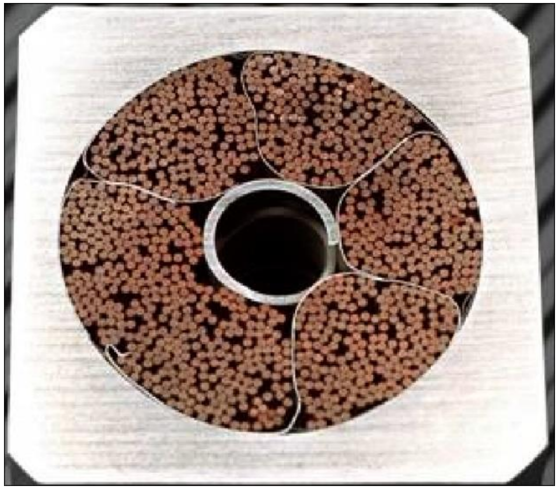
**Thus: we need cables!**



# Self-field Stability: Cable examples

### ITER cable for central solenoid

- 65 kA at 13.5 T, ≈ 1152 $Nb_3Sn$ wires parallel in a twisted multi-stage cable.
- Cable layout with 5 stages: 1x3x4x4x4x6.
- Wire 0.81 mm, filaments 4 µm.
- The strands take all positions in the cable to guarantee equal current sharing.



*~1152 wires ITER $Nb_3Sn$ cable*

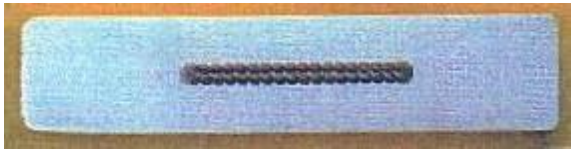
### LHC type $Nb_3Sn$ Rutherford cable

- 33 stands single stage twisted.
- 13 kA at 11 T.

*33 wires LHC-type $Nb_3Sn$ cable*

### ATLAS Detector Magnet conductor

- Al stabilized 40 strands Rutherford cable.
- 65 kA at 5 T.



*40 strands ATLAS BT cable*

# Temperature jumps, low heat capacity

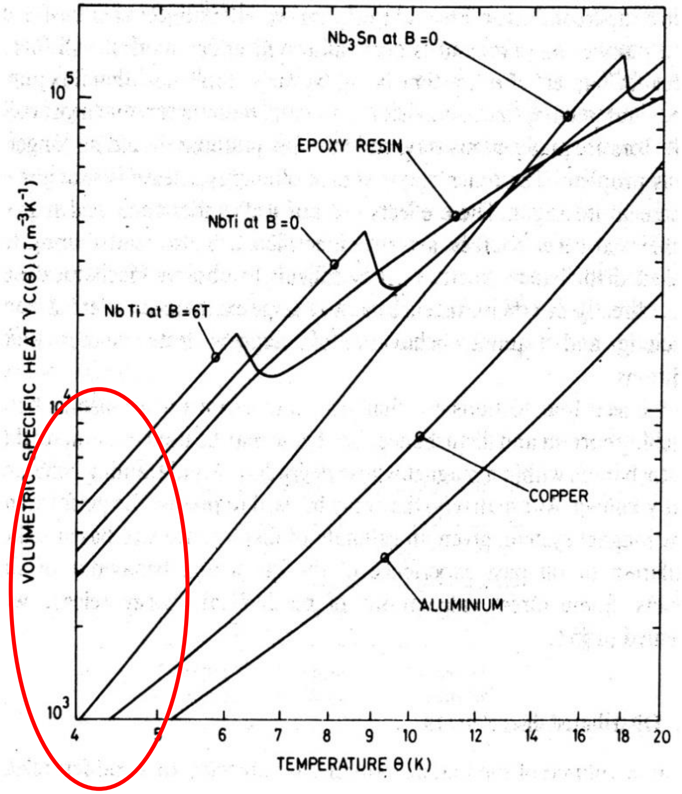
**Why is release of heat so critical at 4 K ?**

- Heat capacity is strongly T-dependent
- Copper-NbTi composite:

  $C_p(T) = \eta((6.8/\eta + 43.8)T^3 + (97.4 + 69.8\,B)T)$

  $\mu J/mm^3K$, at 5 T and 40% NbTi in a Cu matrix:
- 2.5 $\mu J/mm^3K$ at 4.2 K and
- 0.5 $\mu J/mm^3K$ at 1.9 K !
- 2.5 $\mu J/mm$ corresponds to a movement in

  a 1 mm wire at 5 T, 500 A of 1 $\mu m$ only!



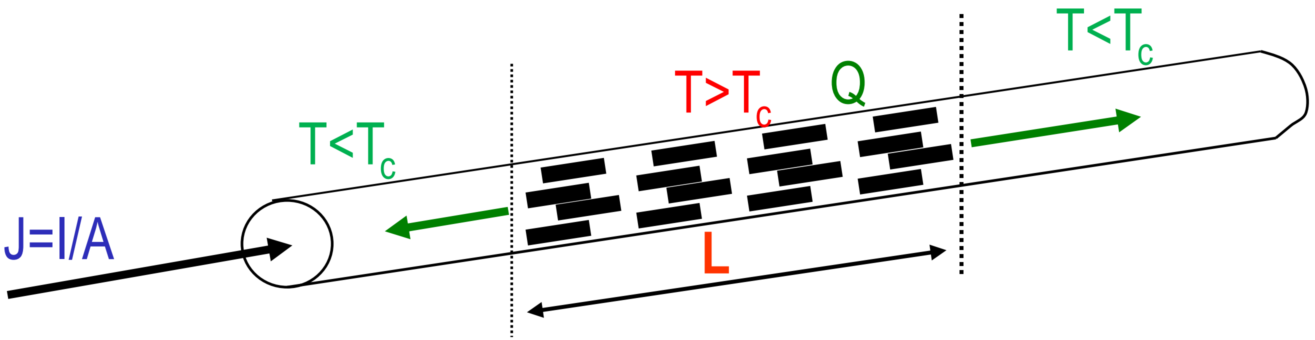
**Heat release of $\mu J/mm^3$ has to be avoided, otherwise magnet will quench**

- avoid friction and slip-stick by introducing low friction sliding (Kapton films wrapped around wires and cables).
- avoid any displacement, vacuum impregnation of coils.
- avoid resin cracks, avoid local stress concentrations at bonded surfaces.

# Point disturbance, MPZ

**Minimum Propagation Zone** (1-d case)

- How large must the distortion be to get a quench ?
- Consider a wire with current I, heat removal Q along the wire and central zone in normal state (simple, one dimensional case)



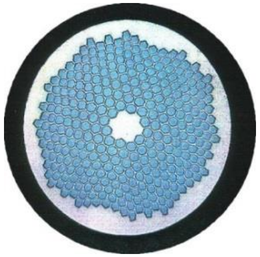
Look for length **L** where heat produced is equal to heat removed:

$$\rho\, J^2\, A\, L \approx 2\, \lambda\, A\, (T_c - T_{bath}) / L$$

$$\boxed{L = \{\, 2\, \lambda\, (T_c - T_{bath}) / \rho J^2 \,\}^{1/2} = \text{MPZ}}$$

**Propagation occurs when L > MPZ and recovery when L < MPZ !**

# Minimum Propagation Zone, MPZ



Examples of MPZ in a various wires

- In a bare NbTi wire or filament:
  take 5 T; 3000 A/mm$^2$; $\rho$= 6x10$^{-7}$ $\Omega$m; $\lambda$= 0.1 W/mK; $T_c$= 7 K
  and we find MPZ of **0.3 $\mu$m** only, pure NbTi can not be used!
- NbTi with CuNi matrix would give MPZ of **3 $\mu$m** and 0.1 $\mu$J !
- Such wire is extremely sensitive to any heat pulse

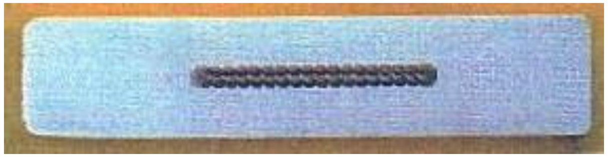
**Remedy**: **reduce $\rho$ by using copper matrix** (3x10$^{-10}$ $\Omega$m, factor 2000 !)
and **increase $\lambda$ by using copper** (> 200 W/mK, factor 2000 again !)

We see how wonderful copper (or Al) is, without copper no sc magnets !

✓ factor 2000 improvement, from $\mu$m to **few mm** and $\mu$J range

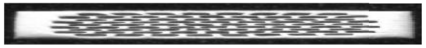
✓ for a typical LHC cable we get **about 15 mm**

✓ and in the ATLAS conductor (600 mm$^2$ pure Al and 20 kA) we get about **500 mm** !



# Request for: high current conductors

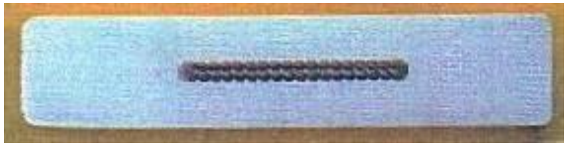
**200 A HTS tape?**



≈ 4 x 0.1 mm²

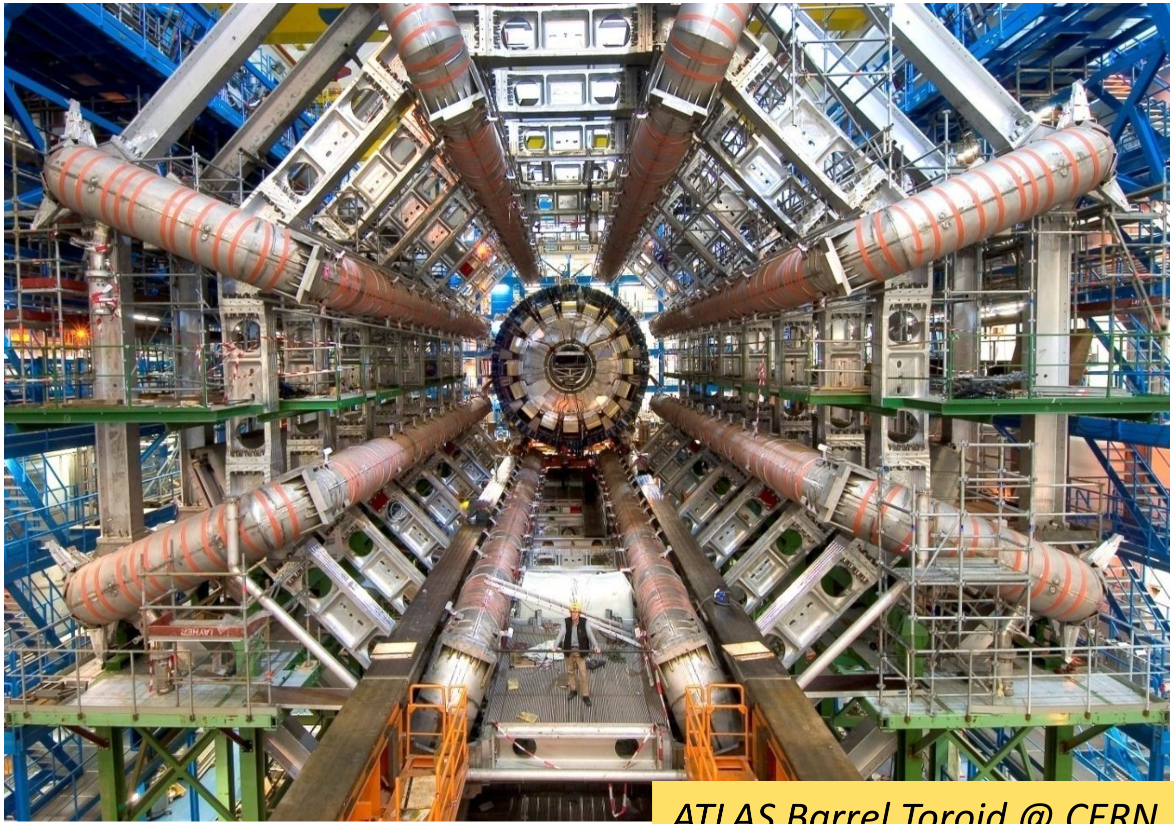
Single: **No!**
Cabled: may be, but
to be developed

**65000 A@5T Al-NbTi/Cu?**



≈ 57 x 12 mm²

**Yes!**

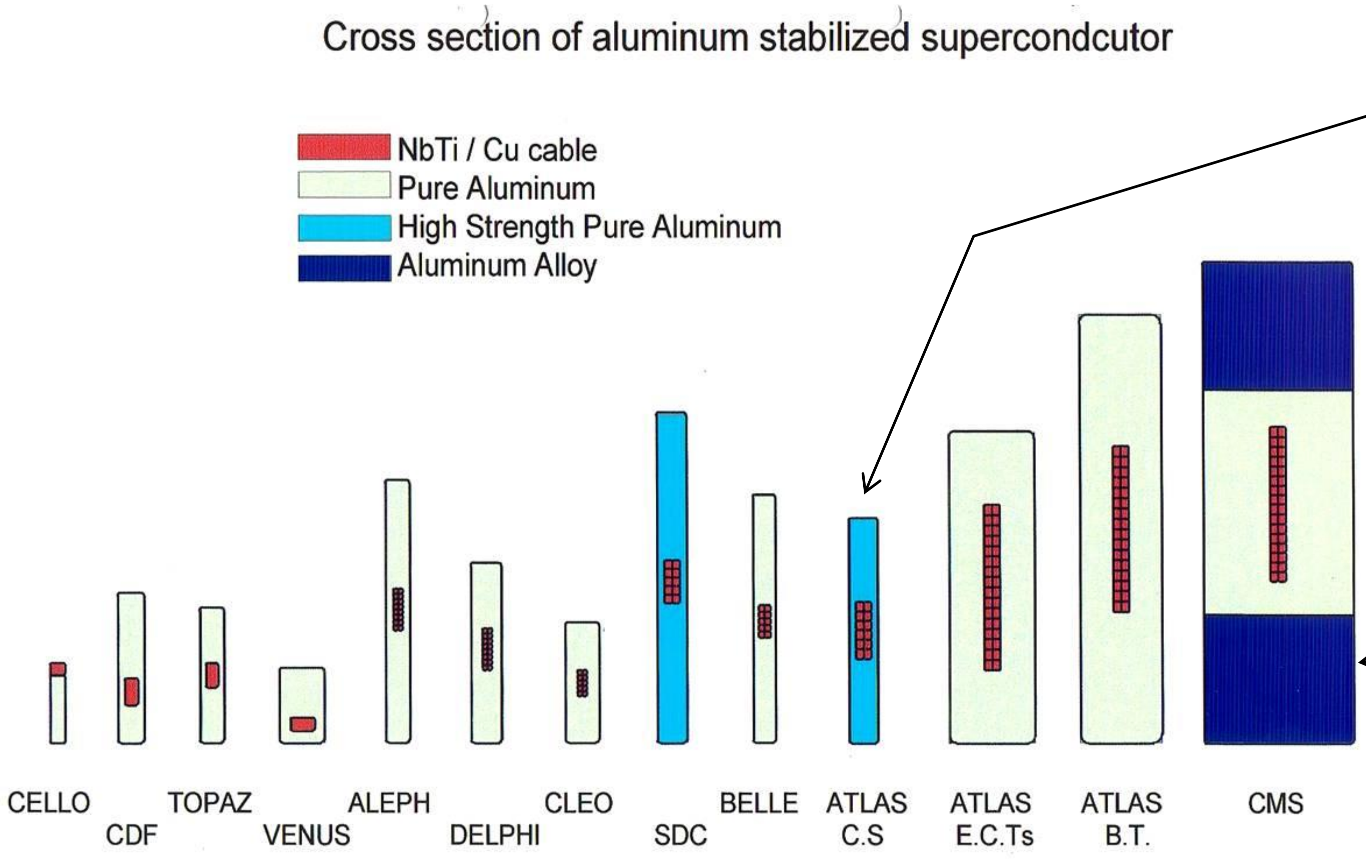


*ATLAS Barrel Toroid @ CERN*

- ✓ One can not build large scale magnets from single wires or tapes.
- ✓ **We need superconductors that can be cabled and survive a quench!**

# *Novel Detector Magnet Superconductors*

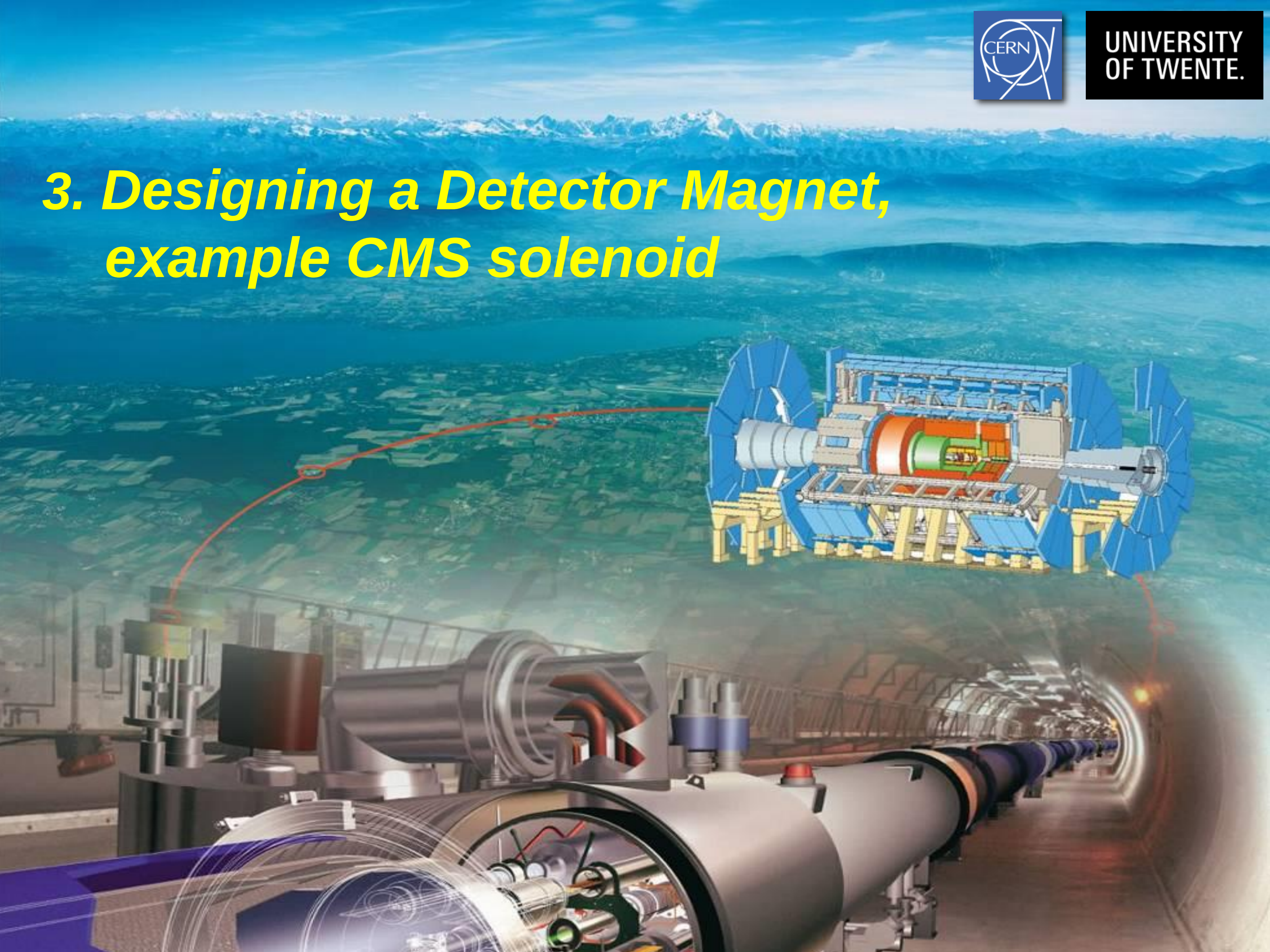
- For the next generation detector magnets, conductors are further developed and reinforced, more stored energy, larger size.



ATLAS CS type, Ni/Zn doped Al

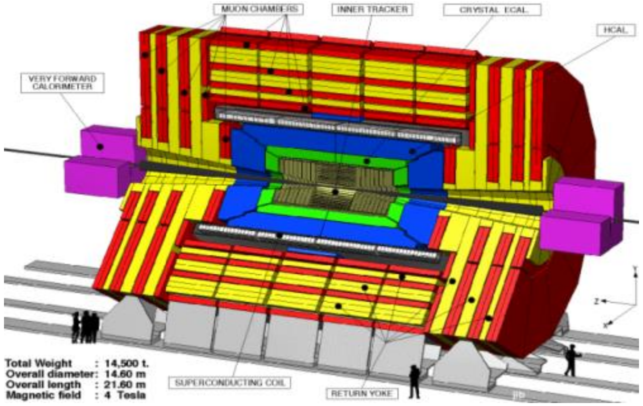
CMS type, reinforcement bars

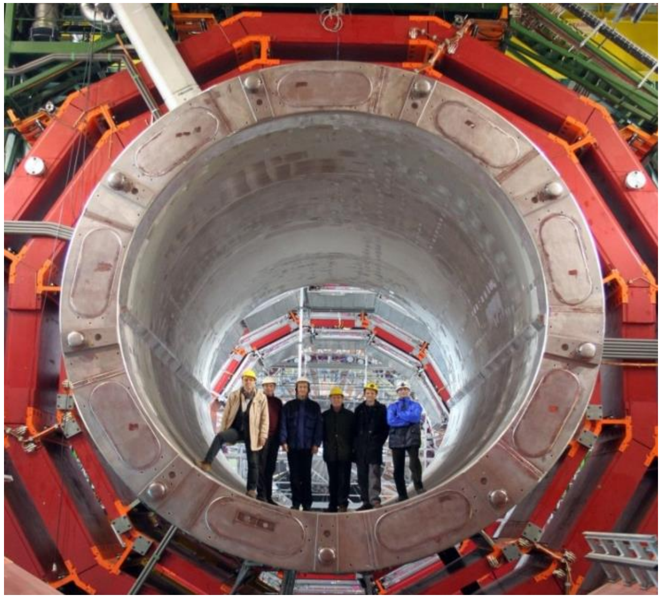
# 3. Designing a Detector Magnet, example CMS solenoid



# Design steps: Example CMS solenoid

- Magnetic field calculation
- Effect of the iron yoke
- Magnetic stored energy
- Lorentz forces in the coils
- Hoop stress
- Choosing current vs self-inductance
- Conductor dimensions and layers
- Conductor details
- Stabilizer, Cu or Al





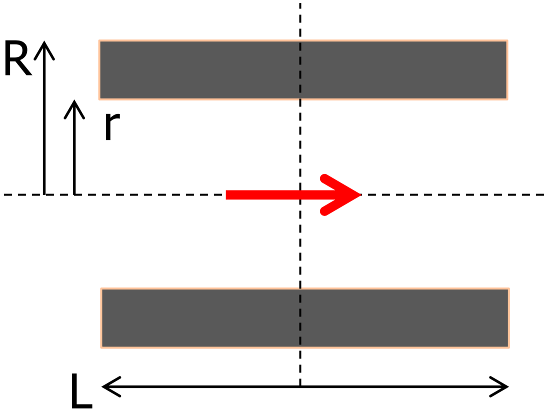
# Design steps: Magnetic field, no iron

**Field calculation without iron yoke:**

Current density: $J = {}^{NI}/_{L(b-a)}$

Field $B_o = Jr\mu_o\beta \left\{\frac{\alpha+\sqrt{(\alpha^2+\beta^2)}}{1+\sqrt{1+\beta^2)}}\right\}$

$B_o = \mu_o nI$ for $\beta \rightarrow \infty$

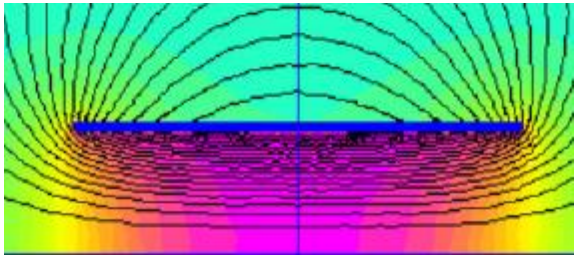


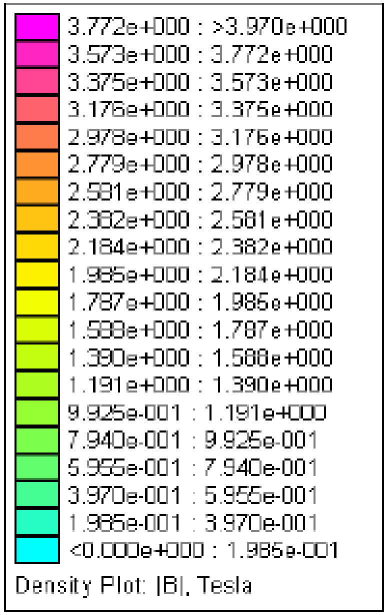
$\alpha = R/r$
$\beta = L/2r$

N turns
I current
n= N/L

- With real CMS magnet sizes:

  r = 3200 mm; R = 3418 mm
  L = 12500 mm
  N = 2180; I = 19500 A





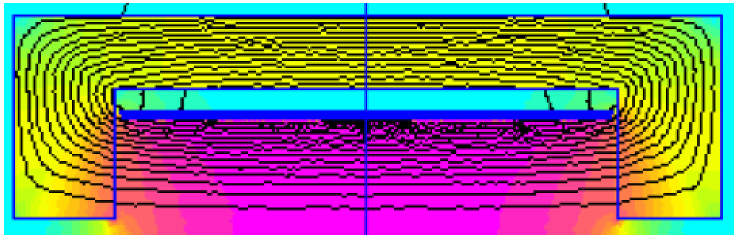
- We find: $B_o(\alpha,\beta) = 3.77\ T$ (88% of infinite)
  $B_o(\beta = \infty) = 4.27\ T$

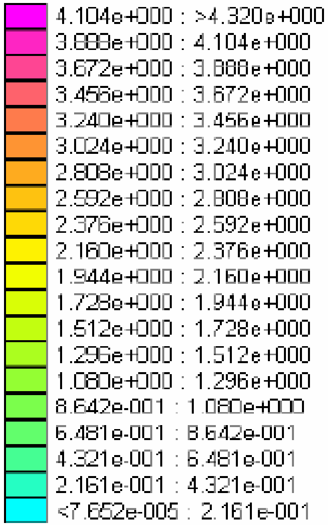
- With a FEM code we find 3.77 T as well.

# Design steps: Magnetic field, with iron

Accurate analytical formulae do not exist, a calculation with a FEM code is needed (OPERA-3D, ANSYS, COMSOL).

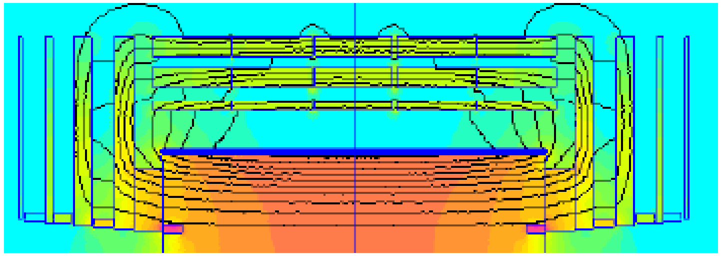
- Simple solid magnetic yoke:
- $B_o = 4.17$ T (98% of infinite).

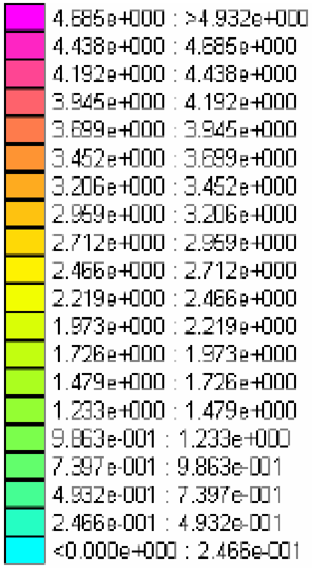




Iron is a magnetic mirror, the coil becomes almost infinite.

- Real iron with gaps for detectors:
- $B_o = 4.0$ T in center
- 4.6 T in conductor.





Stored energy:

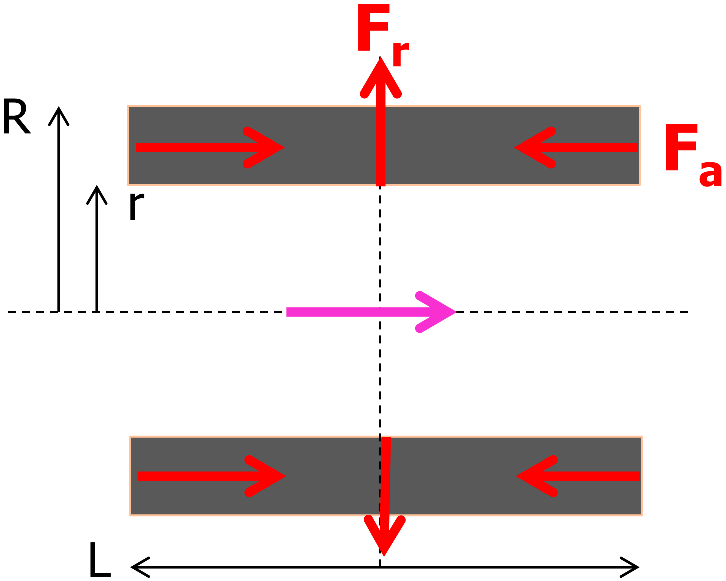
- FEM calculation yields: $\frac{1}{2\mu_o} \int B^2(r,z)dV = 2.6\ GJ$
- Simple approximation: $\frac{1}{2\mu_o} B^2\ \mathrm{V} = 2.46\ \mathrm{GJ},\quad \mathrm{V} = \text{bore volume}$

# Design steps: Magnetic forces

Lorentz forces due to B and J cause axial compressive forces and radial forces causing hoop stress:

$$\bar{F} = \int (\bar{J} \ x \ \bar{B}) dV$$

- Radial field causes axial force $F_a$
- Axial field causes radial forces $F_r$
- In fact the solenoid wants to blow up into a ball shape



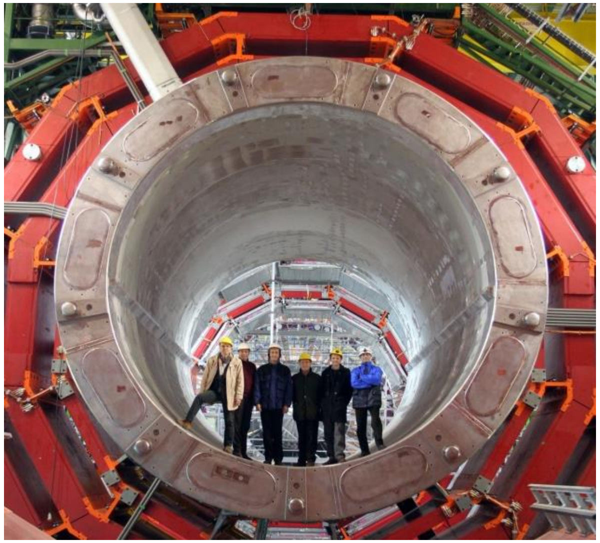
For CMS: $F_a$ = +1.66 GN,

$F_r$ = -140 MN (14 kt)

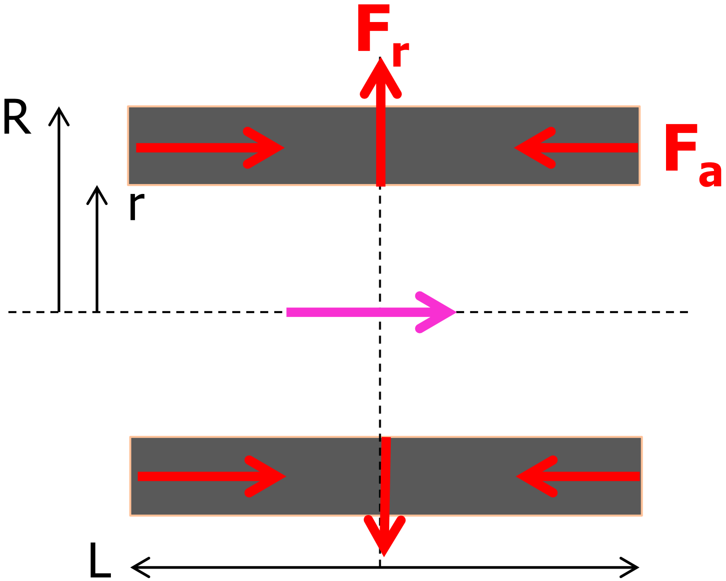
The "Ball" Pressure ≈ $F_r$/surface = 6.6 MPa

- Magnetic pressure = $B^2/2\mu_o = 6.4 \ MPa$

  or 64 atm.



# Design steps: Hoop stress, coil thickness



The radial pressure is reacted in the cylinder with thickness t (windings + extra material) by the hoop stress:

$$\sigma_{hoop} = {}^{a\,P_r}/_{t}$$

To be respected design rule:

$$\sigma_{hoop,max} = {}^{2}/_{3}\;\rho_{yield}$$

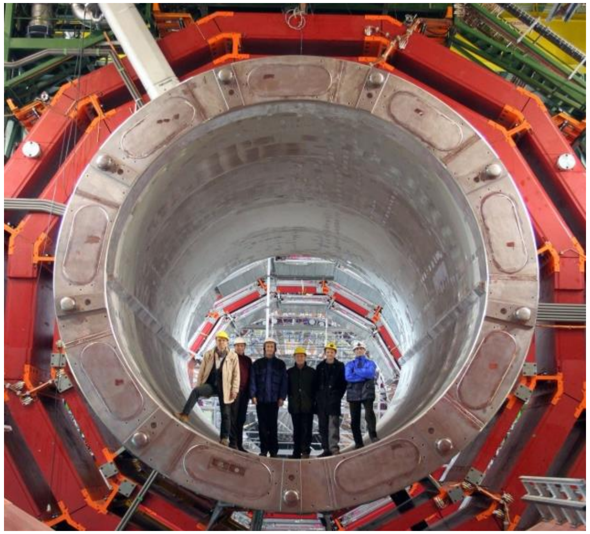
Structural coil thickness:

$$t = {}^{3\,r\,P_r}/_{2\,\rho_{yield}} = 320\;mm\;,$$

using 100 MPa annealed Al5083, or

*t = 190 mm* , based on special 170 MPa
Al5083-H321.

- ✓ **So we need some 190 - 320 mm thick structural special Al alloy on top of the soft conductor to withstand the radial forces in a safe way.**

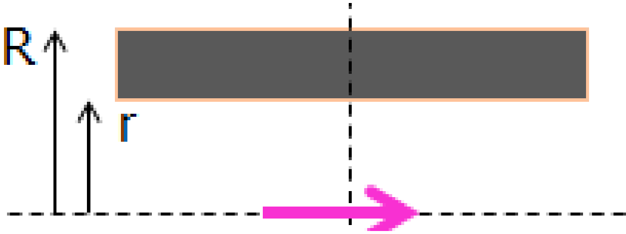


# Design steps: Current vs self-inductance

Self-inductance $L_c$ and current I are linked through the stored energy:

$$E = \frac{L_c\, I^2}{2} = \frac{1}{2\mu_o} \int B^2\, dV \approx \frac{1}{2\mu_o} B_o{}^2\, V, \;\; and \quad L_c = \mu_o N^2 \pi\, r^2 2/L$$

- **Current I must be high for protection reasons, say 20 kA**
- **Then $L_c$ ≈ 14 H and for N follows N ≈ 2100.**
- Adaptation to conductor & coil dimensions leads to 19.5 kA / 2180 turns.
- The coil has 42.5 $10^6$ ampere-turns.



In the windings section of

≈ 320 mm x 12500 mm we have to put in place:

- 2180 turns of superconducting cable with 19.5 kA
- extra stabilizing and quench protection material around the cable
- conductor insulation
- structural reinforcement for handling the hoop stress
- an outer support cylinder for integrity and conduction cooling supply.

# Design steps: Conductor size and layers

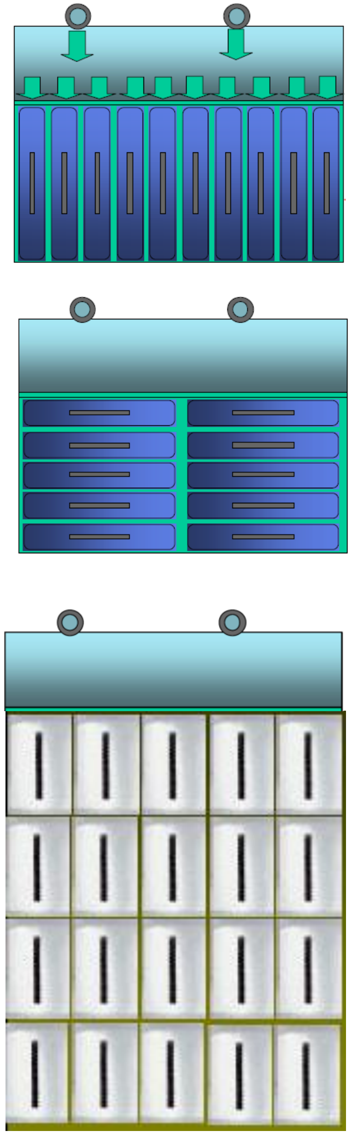
4 T is made with 2180 turns and 19.5 kA current, but:

How many layers is wise?

- Coil winding section is 12500 mm x 263 mm,
- n layers x conductor height = 263 mm
- Use 1 (easy), or even number of layers: 2, 4 or 6
- 1 or 2 layers requires a too thin conductor to be wound on its small edge.
- Then 4 layers is best, few layers only and acceptable conductor size of 66 x 23 mm$^2$, 6 layers would mean 44 x 34, almost square.

There is a thermal argument as well:

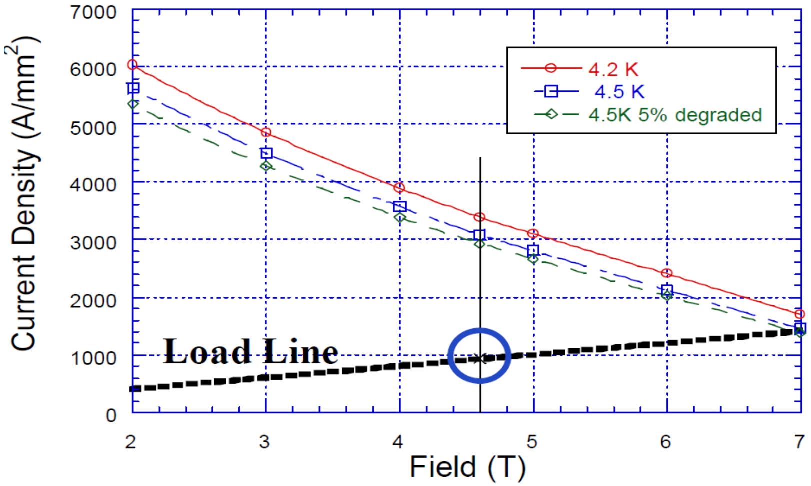
- **winding on small-edge gives less layers, so less thick insulation (resin, glass, polyimide) between the superconductor (NbTi) and the heat sink (cooling pipe), thus a smaller temperature gradient.**



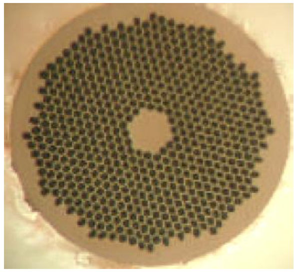
# Design steps: Superconductor needed

The coil runs at 19.5 kA with a peak field of 4.6 T at 4.5 K:

- Critical current density at 4.6 T/4.5 K including 5% cabling degradation is 3000 A/mm$^2$.
- We need margin so we run at 33% of the critical current, at 1000 A/mm$^2$.

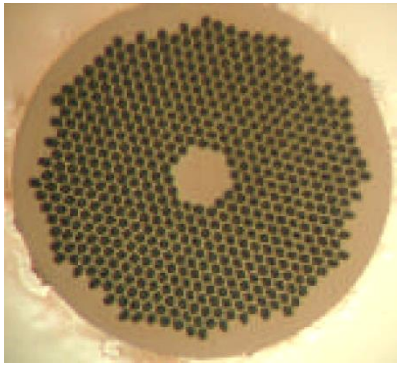


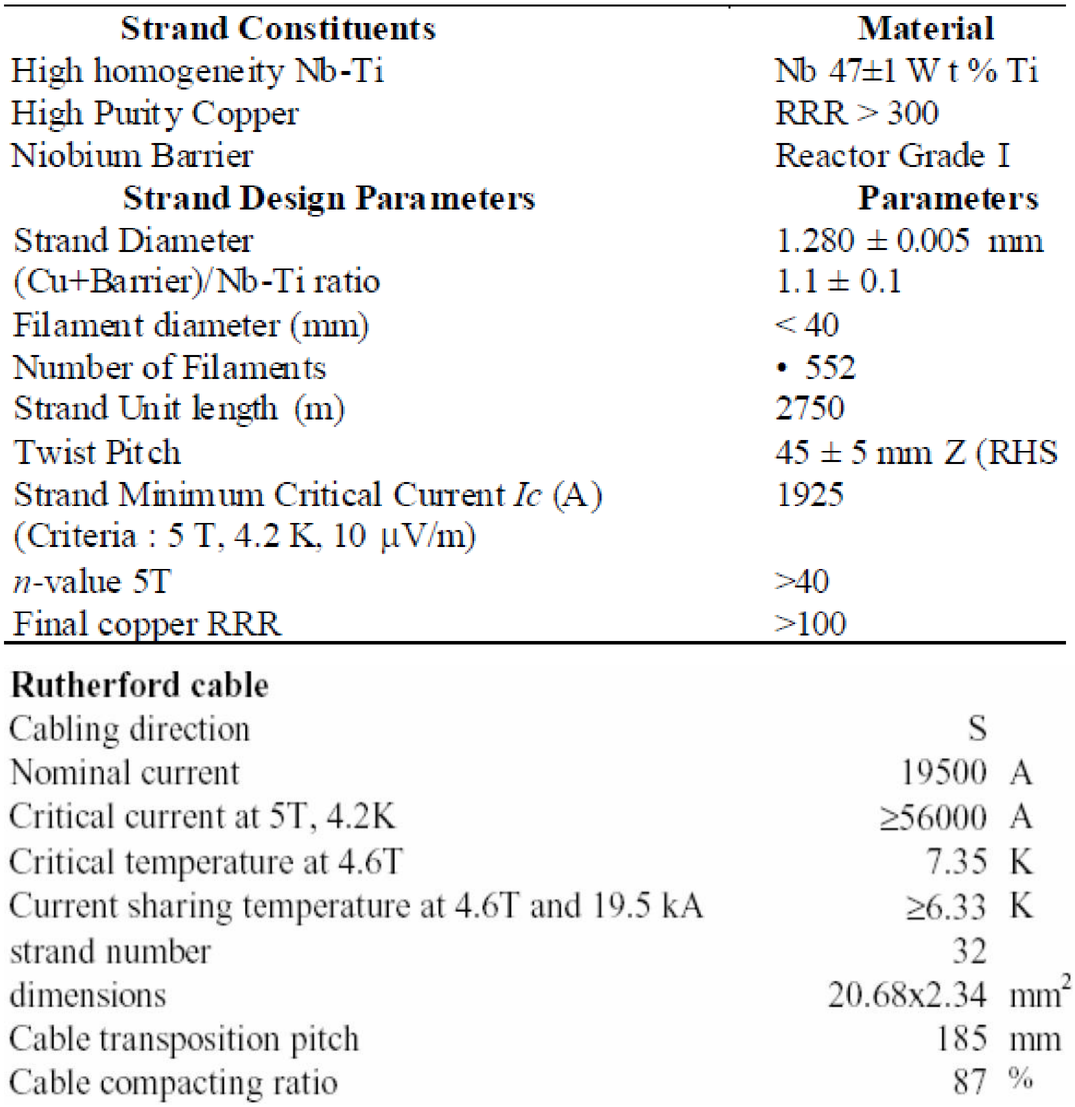
- 19500 A and 1000 A/mm$^2$, → need 19.5 A/mm$^2$ superconductor per turn in the cable
- Self-field stability → wire diameter <1.28 mm
- A minimum Cu/sc ratio is 1:1/1 → Asc= 0.61 mm$^2$
- Number of strands in the cable is then 19.5/0.61 = 32
- Filament size? Adiabatic filament stability requires <40 µm
- The filament section is 0.00126 mm$^2$ → we need ≥484 filaments
- Twist pitches of strand and cable can be standard giving a good cable stability as needed for the cable/Al co-extrusion process
- Thus Ls=25 mm and Lc= 185 mm and twist directions SZ.



# Design steps: Wire & Cable specification

Following these arguments the cable specification is now as follows:



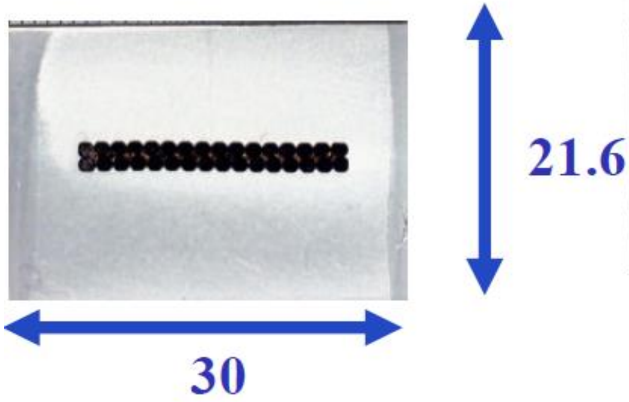


| Strand Constituents | Material |
|---|---|
| High homogeneity Nb-Ti | Nb 47±1 Wt % Ti |
| High Purity Copper | RRR > 300 |
| Niobium Barrier | Reactor Grade I |
| **Strand Design Parameters** | **Parameters** |
| Strand Diameter | 1.280 ± 0.005 mm |
| (Cu+Barrier)/Nb-Ti ratio | 1.1 ± 0.1 |
| Filament diameter (mm) | < 40 |
| Number of Filaments | • 552 |
| Strand Unit length (m) | 2750 |
| Twist Pitch | 45 ± 5 mm Z (RHS |
| Strand Minimum Critical Current *Ic* (A)<br>(Criteria : 5 T, 4.2 K, 10 μV/m) | 1925 |
| *n*-value 5T | >40 |
| Final copper RRR | >100 |

| **Rutherford cable** | | |
|---|---|---|
| Cabling direction | S | |
| Nominal current | 19500 | A |
| Critical current at 5T, 4.2K | ≥56000 | A |
| Critical temperature at 4.6T | 7.35 | K |
| Current sharing temperature at 4.6T and 19.5 kA | ≥6.33 | K |
| strand number | 32 | |
| dimensions | 20.68x2.34 | $mm^2$ |
| Cable transposition pitch | 185 | mm |
| Cable compacting ratio | 87 | % |

# Design steps: Cable - Al co-extrusion

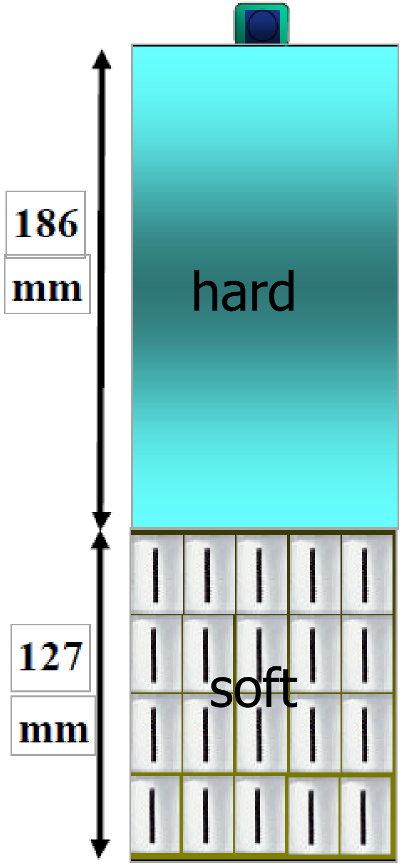
The cable is co-extruded with high purity Al (RRR>1500)



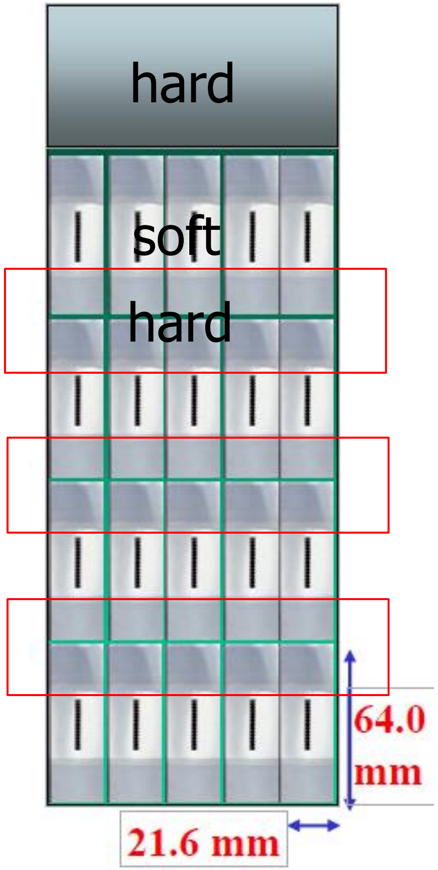
# *Coil windings: radial build-up*

Now we have: 4 layers of a soft conductor Al/NbTi/Cu, 127 mm thick and a thick support cylinder of 186 mm.

- Is this thermally and mechanically an optimal design? No !

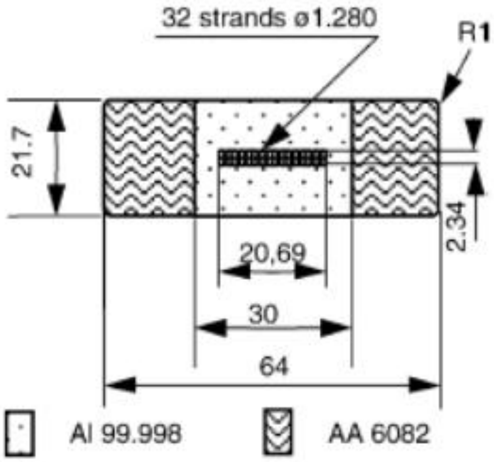


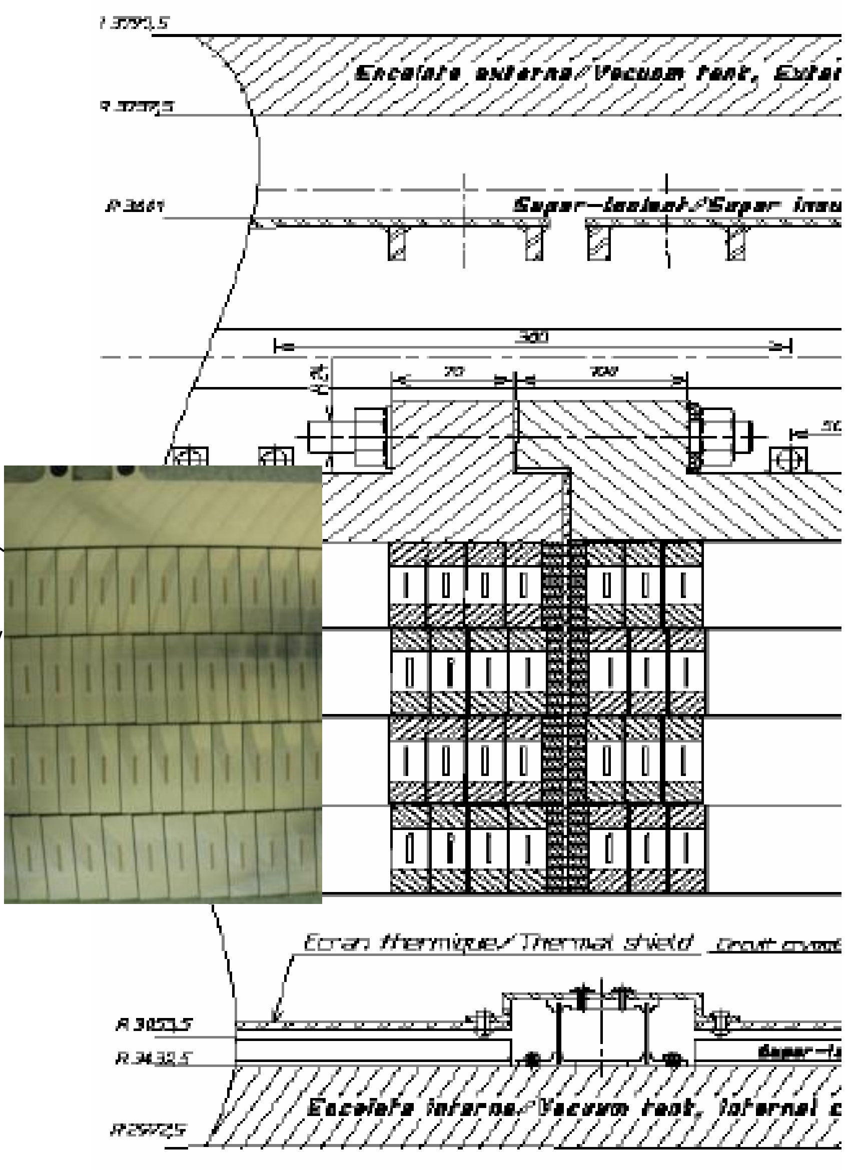
- High shear stress at interface
- In the 4 layers , axial forces up to 1400 MN gives 55 MPa in the pure Al >> 20 MPa, not possible.
- Soft 4 layers of 127mm +186mm gives 22 MPa, is acceptable but strain and shear stress is not uniform.
- A much better solution is to mix soft Al stabilizer and harder Al-alloy support.
- Cure: slice up the thick support cylinder and redistribute it as reinforcement bars on the conductor, creating force bridges in the winding pack in axial direction.



# *Real coil: final solution for CMS*

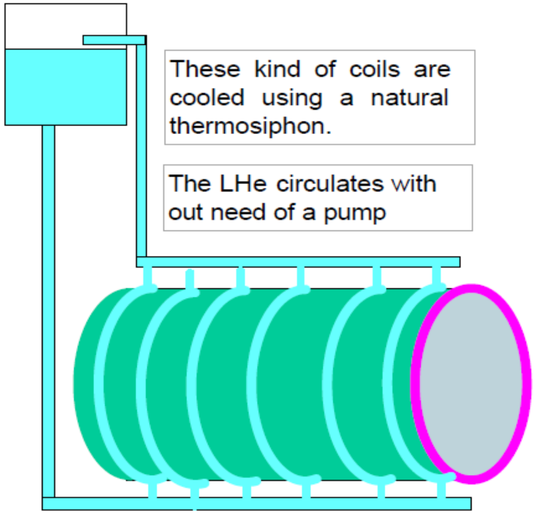
- Conductor: soft Al-NbTi with NbTi cable reinforced with Al 6082 bars connected by electron beam welding
- New yield stress is about 250 MPa!





# Making of CMS Solenoid: support cylinder

- The CMS magnet cold mass was made in 5 units mostly at ASG – Genua, transported to CERN for on-surface assembly and then insertion as a whole in the CMS cavern.



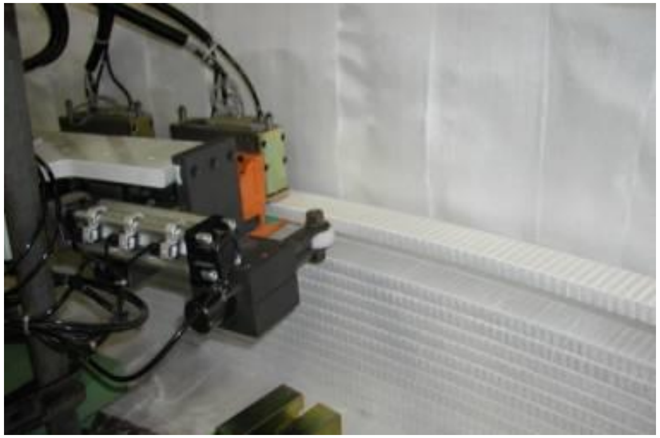
These kind of coils are cooled using a natural thermosiphon.

The LHe circulates with out need of a pump

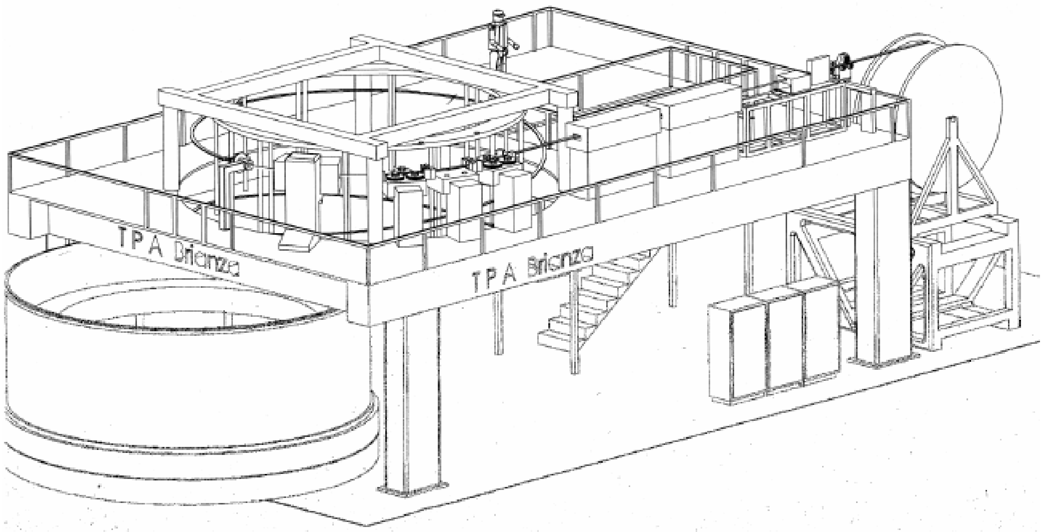
Support cylinder manufacturing, 5 units

Thermal siphon cooling layout, pipework welded to the cylinder

# Making of CMS Solenoid: coil winding



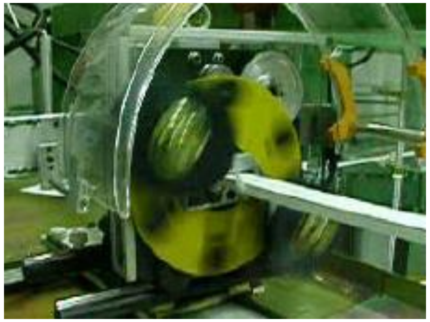
Bend conductor pressed against cylinder



Dedicated coil winding machine allowing winding inside the support cylinder (6.2 m diameter)

Conductor spiral leading into cylinder

Conductor bending



Taping insulation on conductor

# Making of CMS Solenoid: vac impregnation

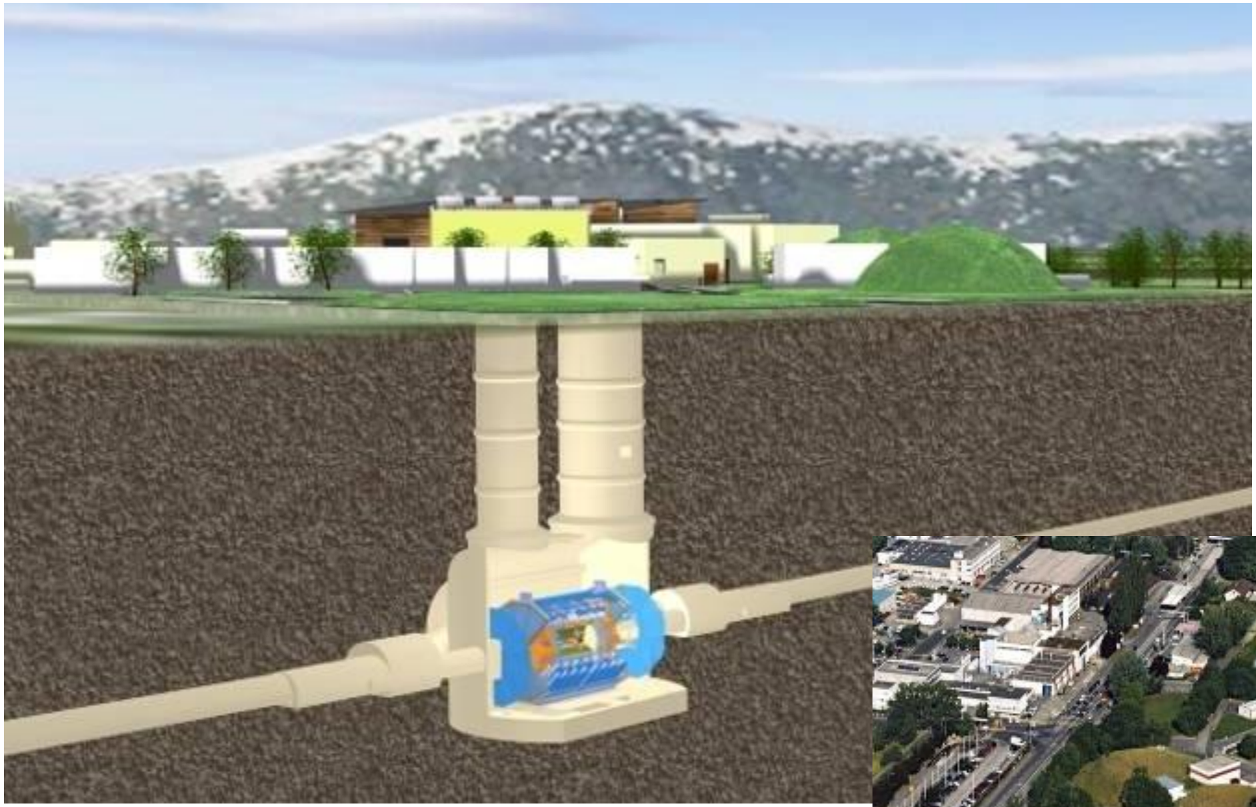
Vacuum impregnation tools,
resin curing, result:
Clear transparent resin

# Making of CMS Solenoid: assembly on site

Modules transport, stacking, integration in cryostat and finished coil ready for insertion in cavern. READY !

# 4. Making ATLAS magnets……

# ATLAS on surface & underground



- Underground cavern at - 90 m.
- 2 shafts give access to a 50,000 $m^3$ cavern for the detector.

Cavern length = 55 m
width = 32 m
height = 35 m.

# ATLAS superconducting magnet system

## 1 Barrel Toroid, 2 End Cap Toroids and 1 Central Solenoid

4 magnets make 2 T in inner detector (solenoid) & ~1 T in muon detectors (toroids)

20 m diameter x 25 m long

8300 $m^3$ volume with field

170 t superconductor

700 t cold mass

1320 t magnets

7000 t detector

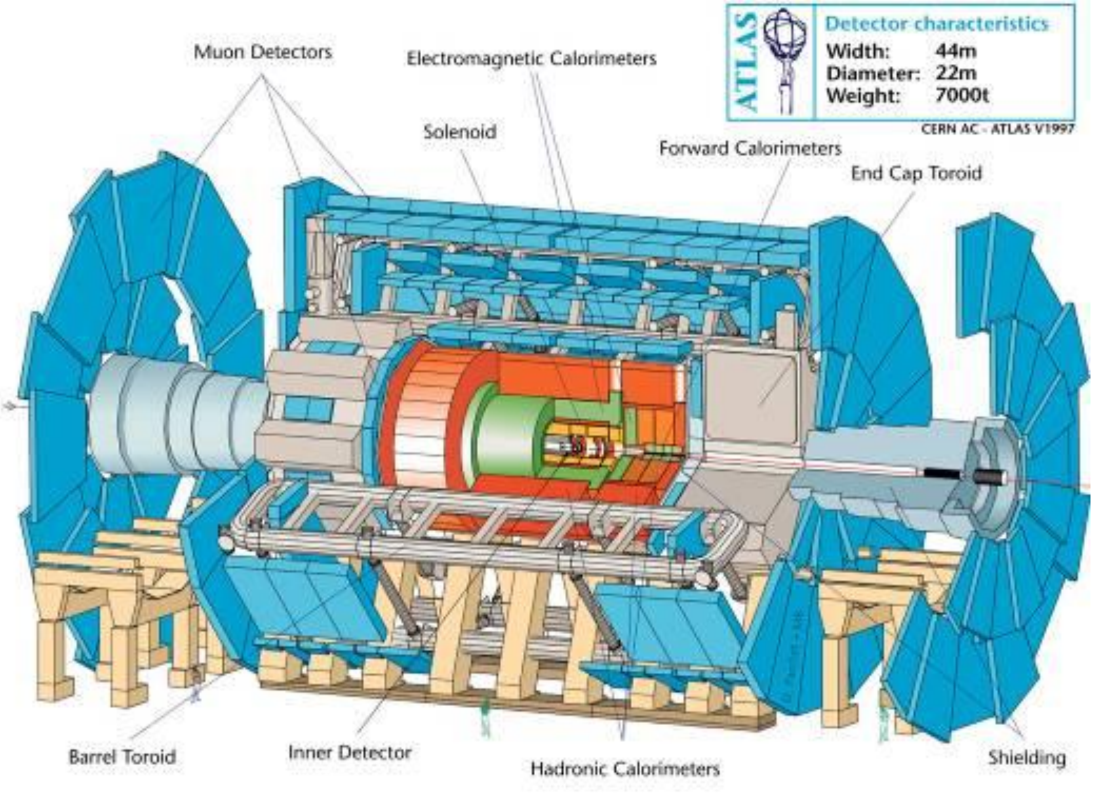
90 km superconductor

20.5 kA at 4.1 T

1.6 GJ stored energy

4.7 K conduction cooled

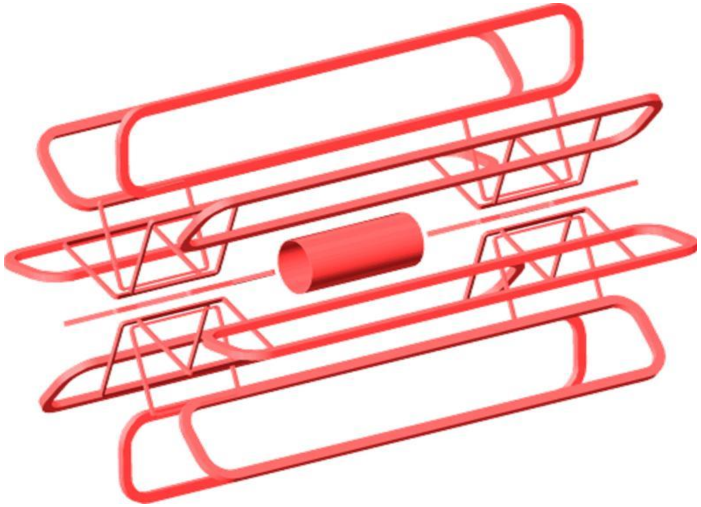
9 yrs of construction 98-07

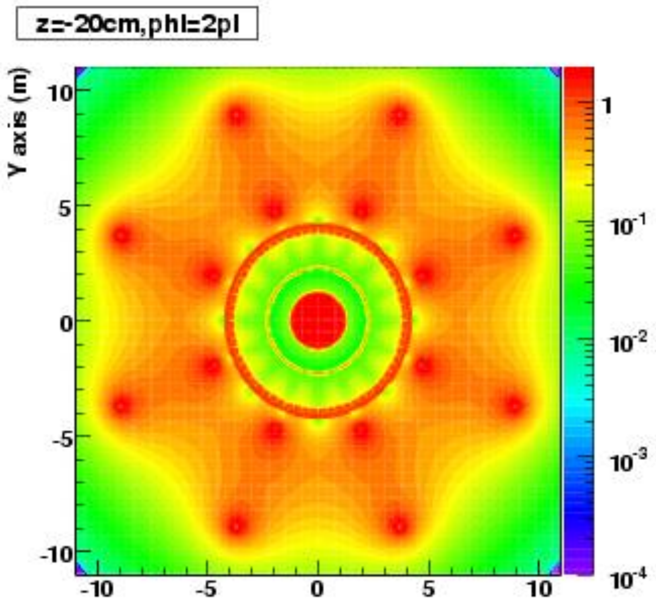


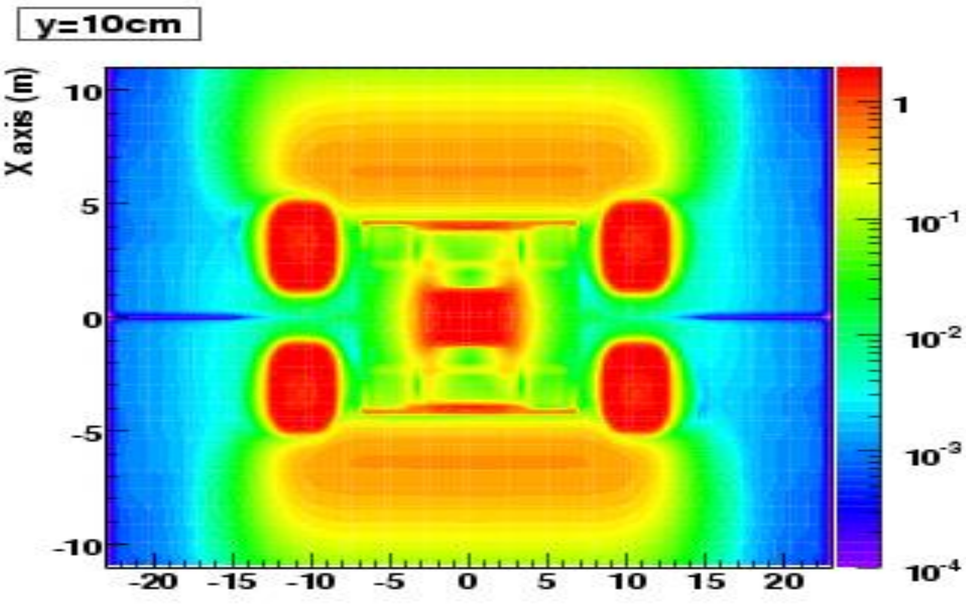
**So far, the largest trio of toroids ever built**

# Magnetic field configuration

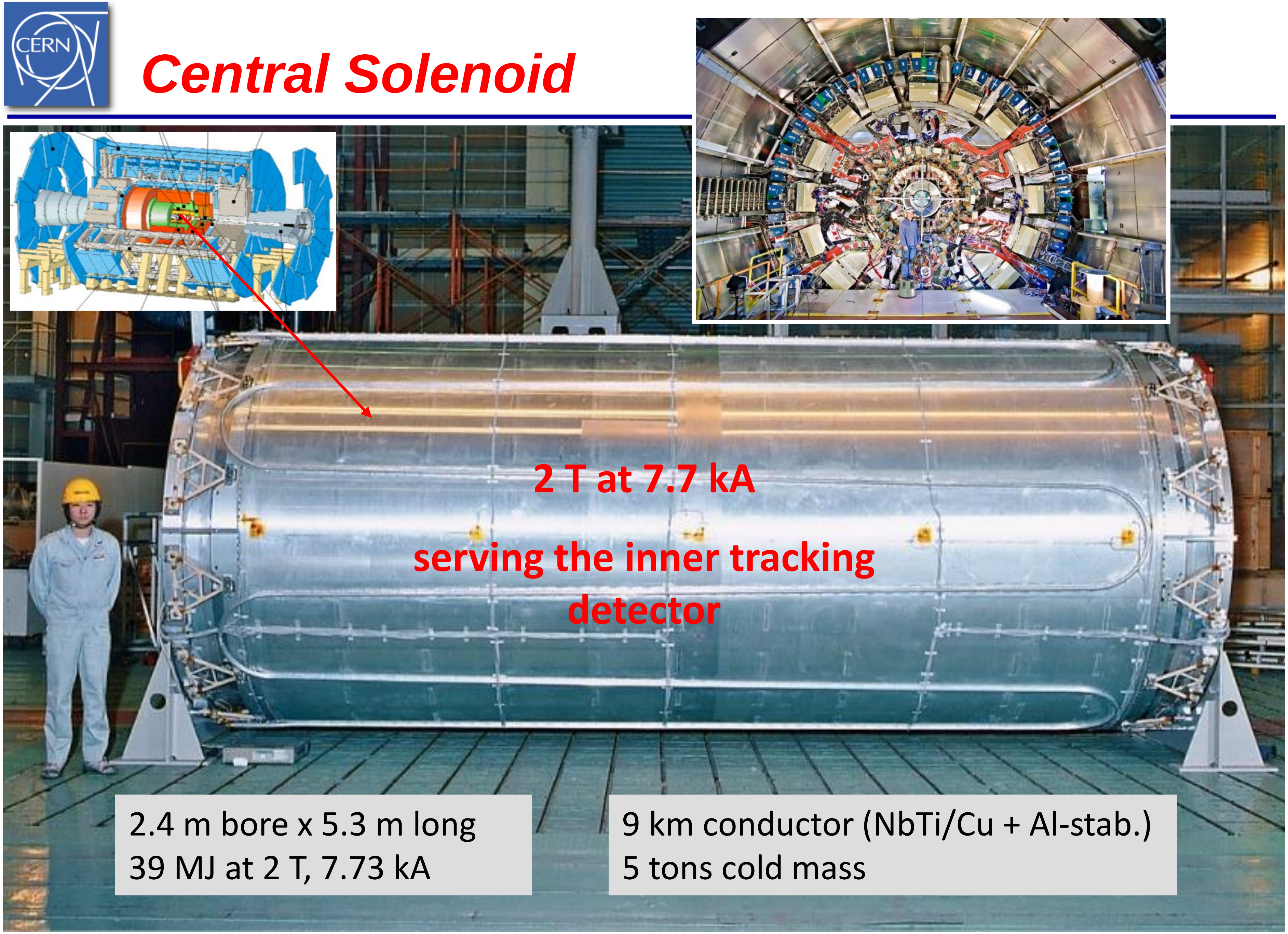
- 2 T in Solenoid closed via return yoke
  2.6 T peak in windings
- ≈ 0.8 T average in Barrel Toroid torus
  3.9 T peak in windings
- ≈ 1.3 T average in End Cap Toroid
  4.1 T peak in windings







# Central Solenoid



2 T at 7.7 kA

serving the inner tracking detector

2.4 m bore x 5.3 m long
39 MJ at 2 T, 7.73 kA

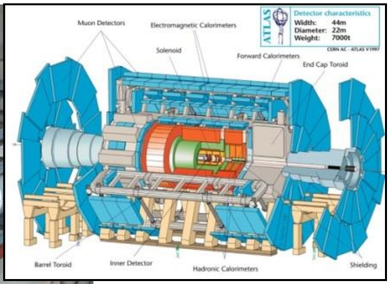
9 km conductor (NbTi/Cu + Al-stab.)
5 tons cold mass

# ATLAS: Barrel Toroid manufacturing

56 km superconductor

16 double pancakes

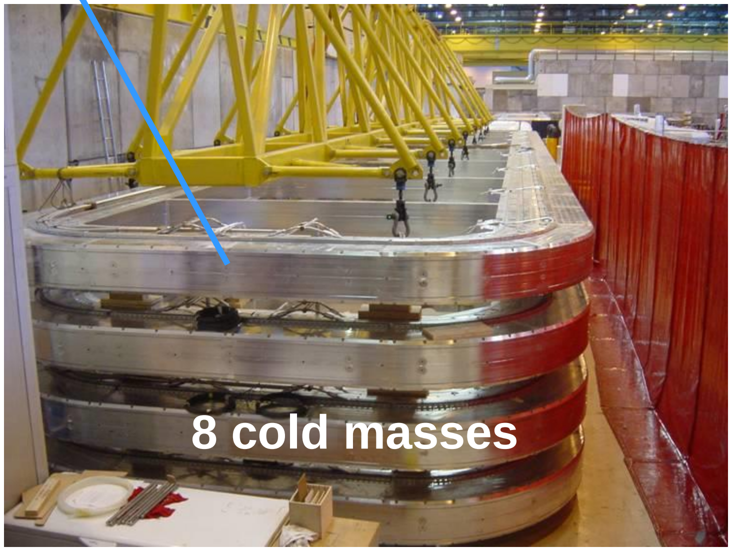
8 vacuum vessels



instrumented

8 coil casings

cold mass integration

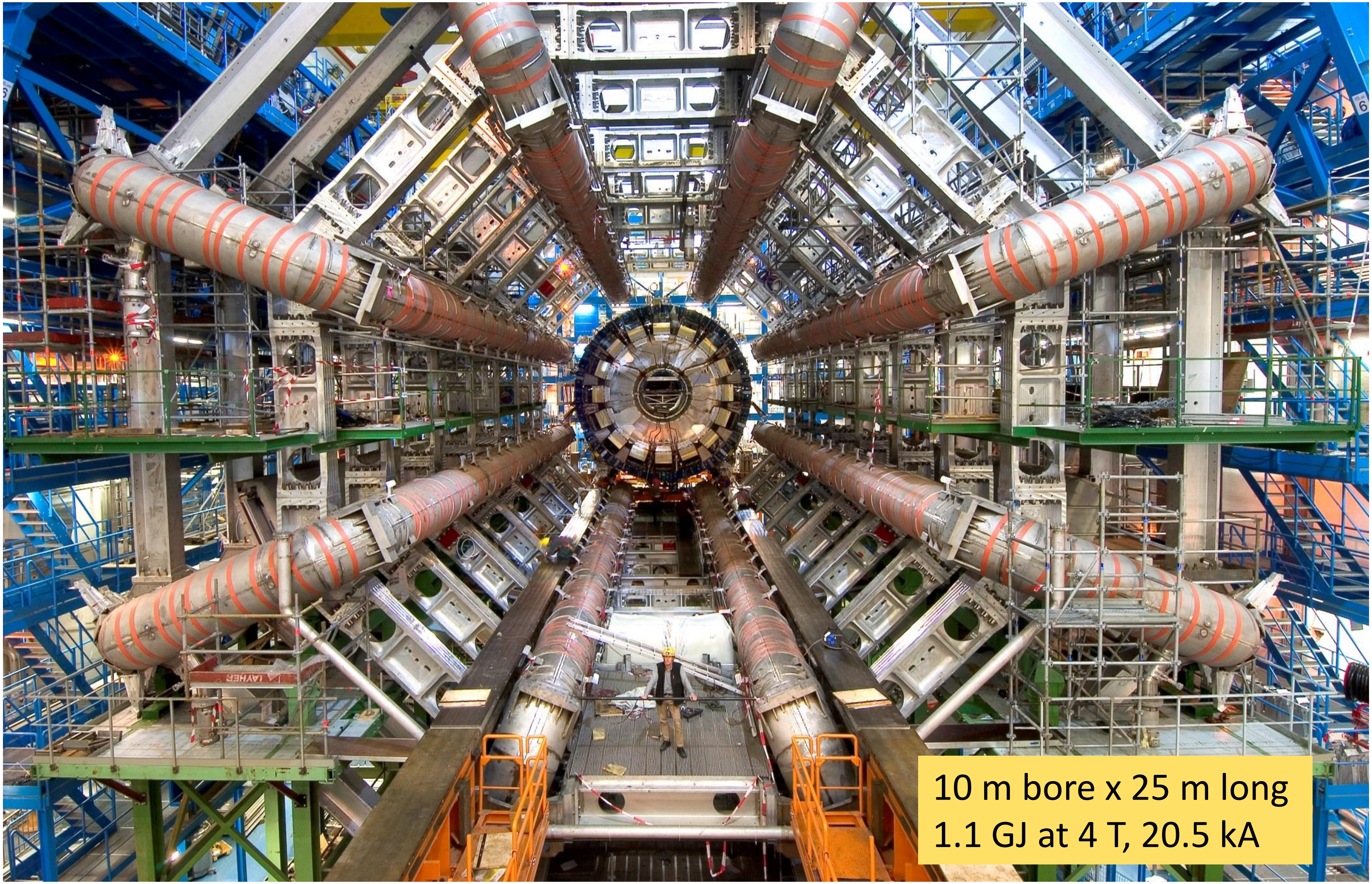


8 cold masses

# ATLAS: Barrel Toroid assembly

- Transport, decent, reception
- Complex but safe manipulations
- Lowering using 2 lifting frames
- Hydraulic winch with load capacity 190 t

# ATLAS: Barrel Toroid in cavern (November 2005)

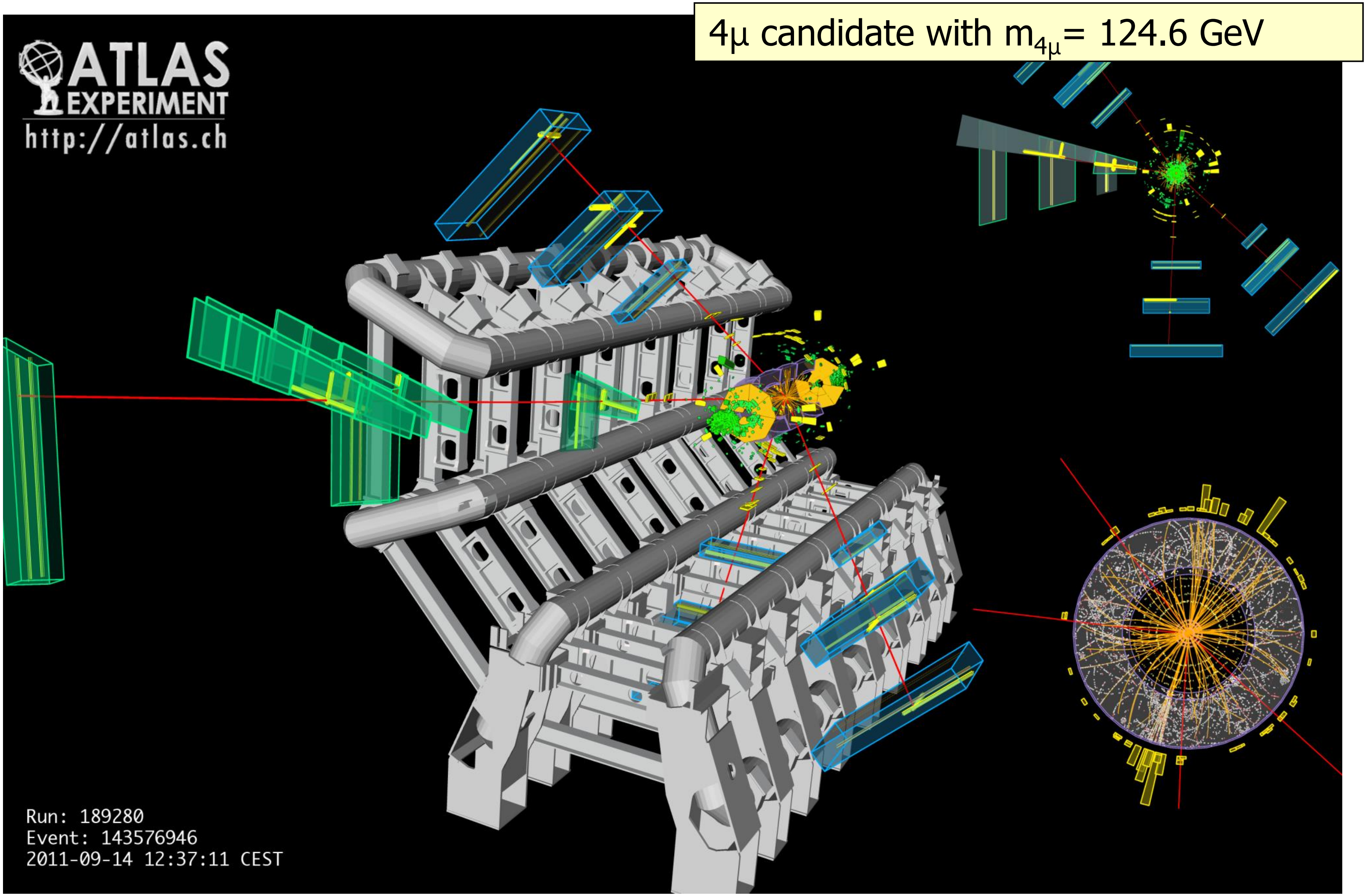


10 m bore x 25 m long
1.1 GJ at 4 T, 20.5 kA

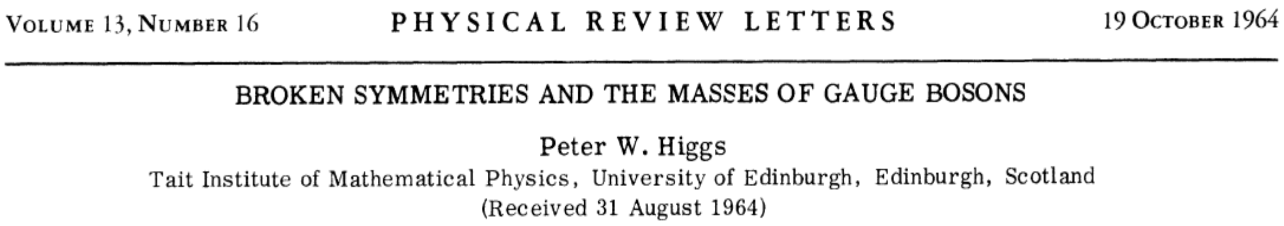
# *Higgs events*

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (4e, 4μ, 2e2μ)

4μ candidate with $m_{4\mu}$= 124.6 GeV



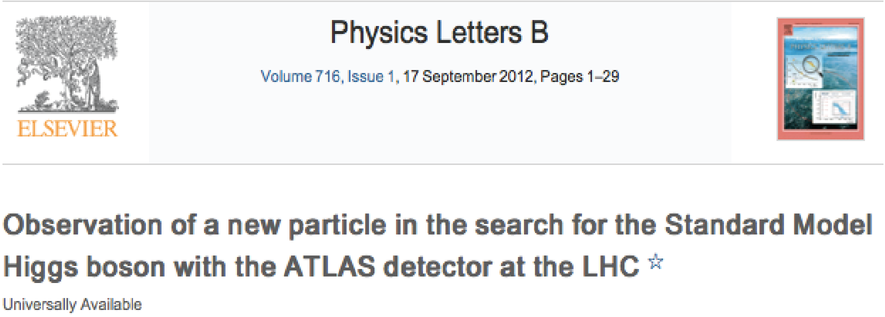
# It takes time……. Mr Higgs



Volume 13, Number 16 PHYSICAL REVIEW LETTERS 19 October 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)



Physics Letters B

Volume 716, Issue 1, 17 September 2012, Pages 1–29

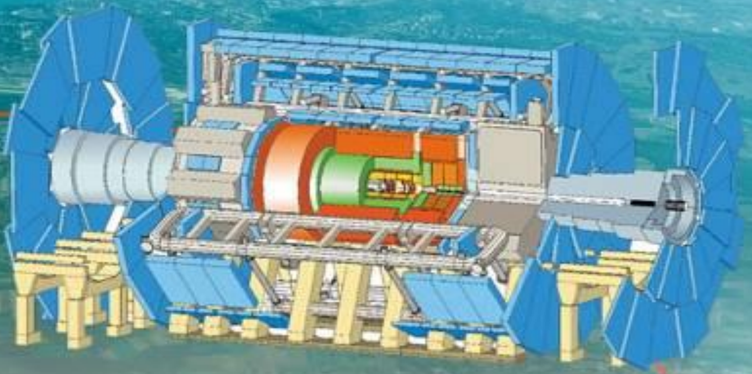
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

Universally Available

***"I certainly had no idea it would happen in my lifetime at the beginning, more than 40 years ago.***
***I think it shows amazing dedication by the young people involved with these colossal collaborations to persist in this way, on what is a really a very difficult task.***
***I congratulate them."***

**Peter Higgs, July 4th, 2012**

# 5. Detector Magnets for a 100 TeV p-p collider



**Future Circular Collider study**

**Design drivers**

**Example Baseline Detector for FCC-hh**

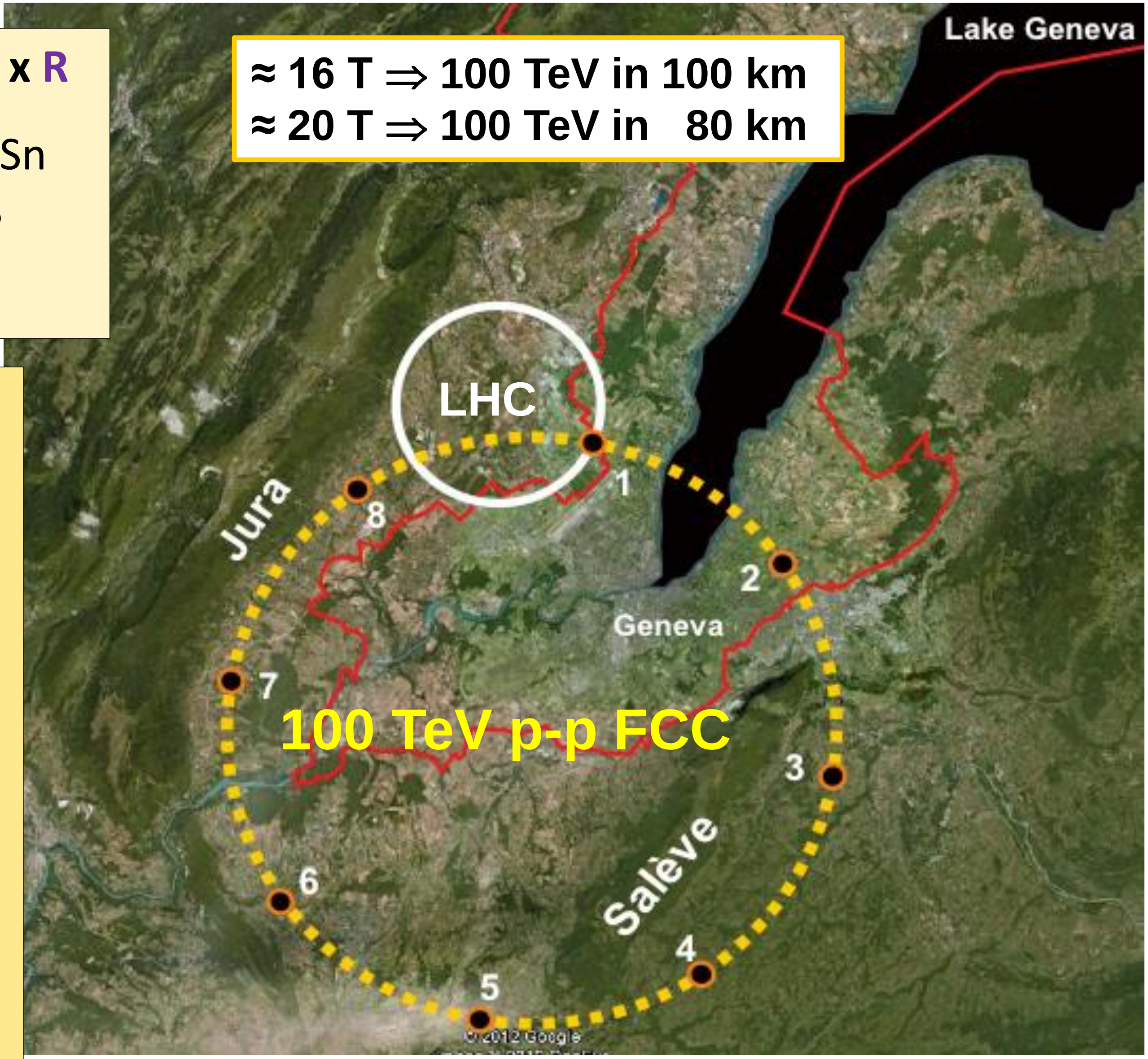
# Options for increasing colliding energy

**Collision energy = 0.6 x B x R**

**B:** 1.8 x from NbTi to $Nb_3Sn$
**B:** 2.4 x from NbTi to HTS
**R:** 4-5 x more magnets

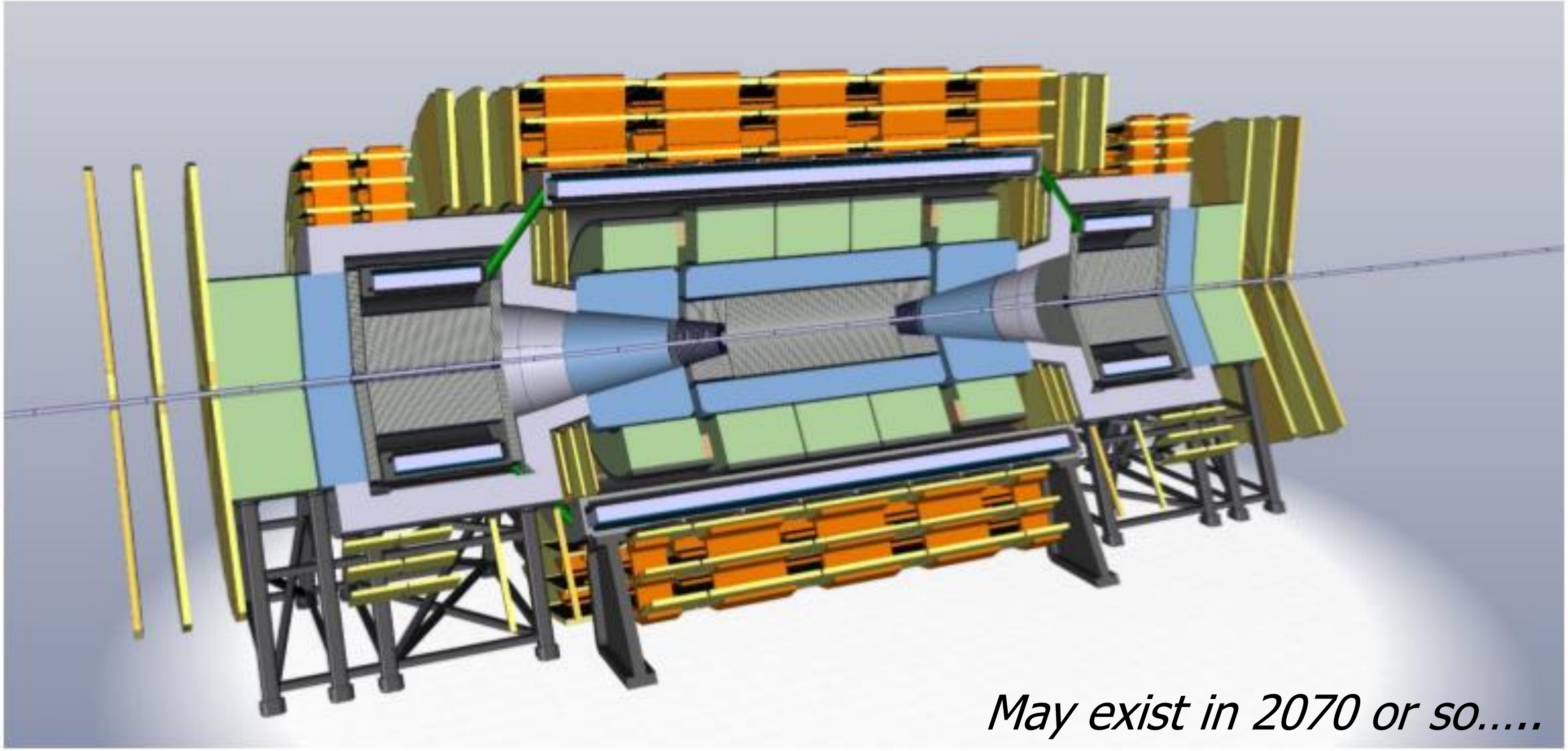
- New 80-100 km tunnel in Geneva area
- pp-collider defining the size
- e+e- collider may come first
- Option p-e collider
- CERN-hosted study with international collaboration

≈ 16 T ⇒ 100 TeV in 100 km
≈ 20 T ⇒ 100 TeV in 80 km



# Baseline Detector 4T/10m-20m + 2 side Solenoids

100TeV pp collisions, $L_{peak} = 3\times10^{35}\ cm^{-2}s^{-1}$, $L_{int} = 3/30\ ab^{-1}$
25ns/5ns bunchcrossing, pileup 1000/200 per bunchcrossing



*May exist in 2070 or so…..*

4T, 10m free bore unshielded solenoid, two 4T unshielded forward solenoids, precision spectroscopy and ECAL up to eta=4, Tracking and Calo up to eta=6

***Now you know a bit about detector magnets & its materials….***

***This concludes the course…***