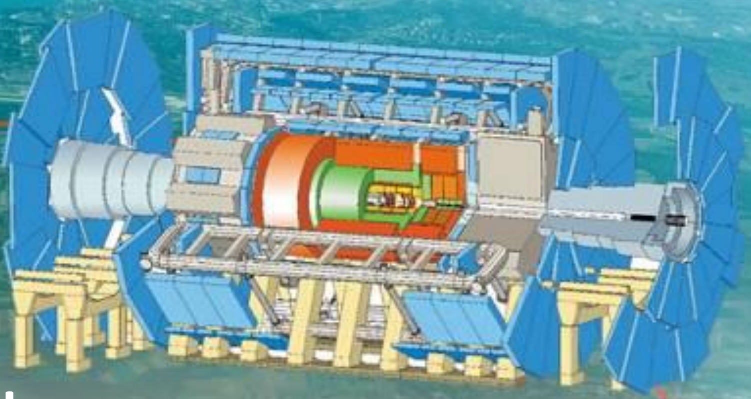
Superconducting Detector Magnets

Herman ten Kate



Content: 1. Concepts
2. Superconductors
3. Design of the CMS solenoid
4. The making of ATLAS
5. Future Collider Detector
6. Exercises

ESIPAP School

Archamps, Feb 28, 2022

Course schedule, goal and fun….

UNIVERSITY OF TWENTE.

COURSE 2

WEEK 7

		28 Feb. Monday	1 March Tuesday	2 March Wednesday	3 March Thursday	4 March Friday
PRE-REQUISITE VIDEOS	Videos 1	**Magnets for Particle Detectors** Herman Ten Kate	**LIVE** **9:00 - 12:00** **Lab Training Session:** ??	**Additive Printing** Marc Krauth	**LIVE** **9:00 - 12:00** **Lab Training Session: Alpha particle pulse measurement in diamond detectors** Mahfoud Yamouni	**The Ariane Odyssey, from Ariane 1 to Ariane 6** Isabelle Rongier ASL & Jan Droz CNES
	Videos 2	**Magnets for Particle Detectors** Herman Ten Kate		**Additive Printing** Marc Krauth		
	Videos 3	**Magnets for Particle Detectors** Herman Ten Kate				
13:30 - 14:00	Q&A LIVE	**Magnets for Particle Detectors** Herman Ten Kate	**LIVE** **13:30 - 16:45** **Ahead Lab : detection of extensive air cosmic showers** François Montanet	**LIVE** **13:30 - 16:45 Project Management** Thijs Wijnands	**LIVE** **13:30 - 16:45 Project Management** Thijs Wijnands	
14:00 - 15:15	Tutorial 1 LIVE	**14:00 - 15:30** **EXAMINATION** **DT**				**14:00 - 15:30** **EXAMINATION** **MPD**
15:30 - 16:45	Tutorial 2 LIVE	**16:00 - 17:30** **EXAMINATION** **SPE**				**16:00 - 17:30** **EXAMINATION** **Multi Field**

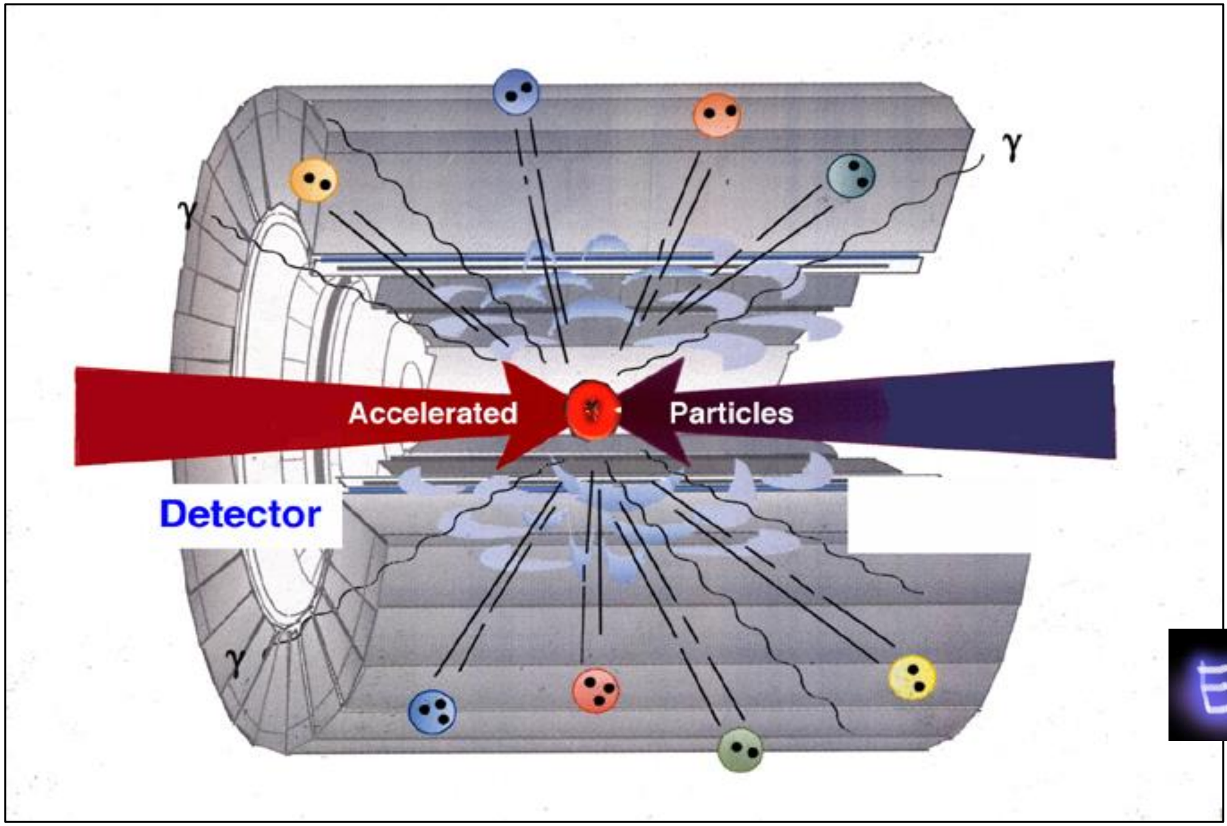
- Content: 3 videos + Q&A session + examination
- Goal: qualitative understanding of superconducting detector magnets
- Enjoy…………………………and hopefully appreciate sc magnet technology!

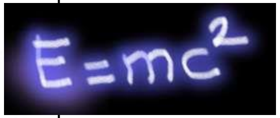
1. Concept: E = mc²

How to discover new (elementary) particles?

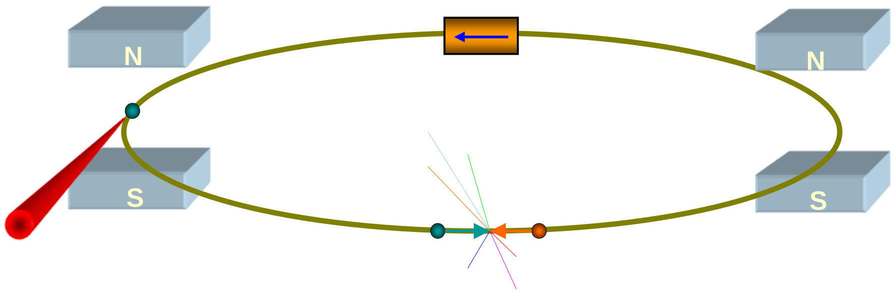
✓ **$E = mc^2$**, produce particles in a spot of energy and seek in the escaping particles

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





Concept: Colliders, Circular vs. Linear



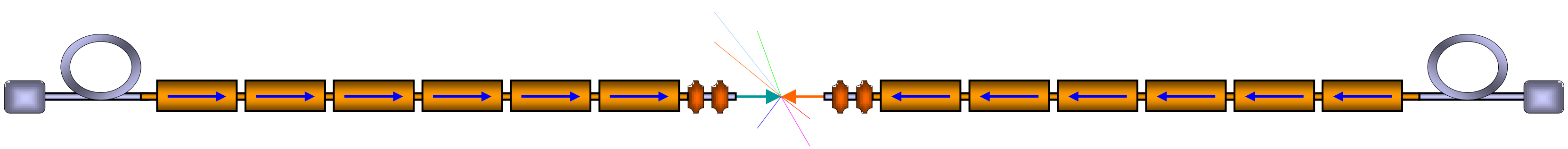
Collision energy

$$E_{TeV} \cong 0.6\, B_T\, R_{km}$$

9 T & 4.6 km → 14 TeV

Circular Collider:

- Many magnets & few cavities, need higher magnetic field for a smaller ring
- High energy but growing synchrotron radiation losses ($\propto E^4/R$)
- High luminosity by a high bunch repetition rate
- Main bill is for the cryogenics for running the compressors to get 4 K.

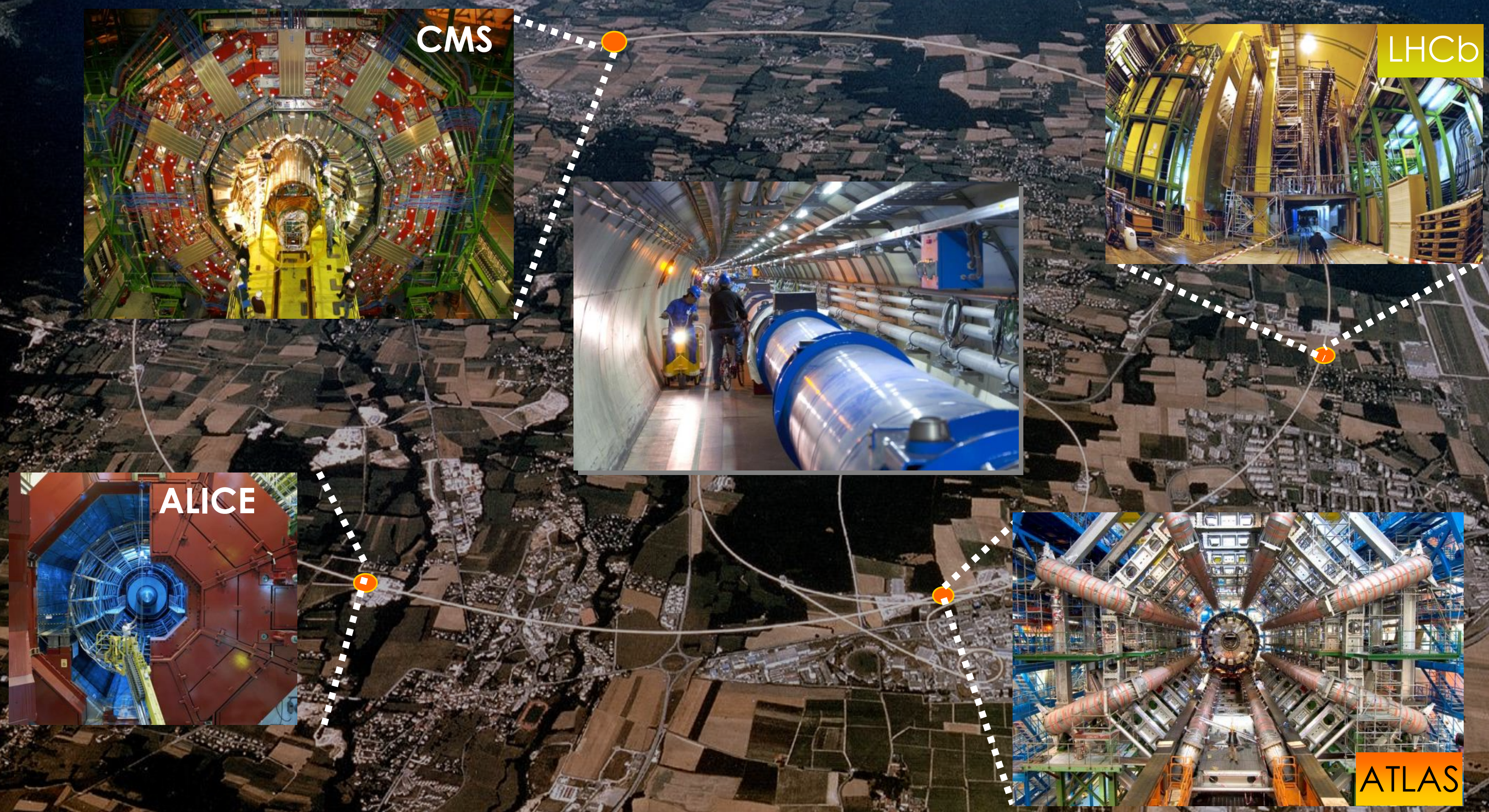


Linear Collider:

- Few magnets but nearly all cavities, need efficient RF power production
- A higher gradient will give a shorter machine
- Single shot, requiring a very small cross-section for high luminosity
- Main bill Is for the RF power.

Example: the Large Hadron circular Collider

Exploring the energy frontier between up to 13-14 TeV using
proton-proton & Pb-Pb collisions



LHC ring,27 km circumference

HE Physics and Superconductivity

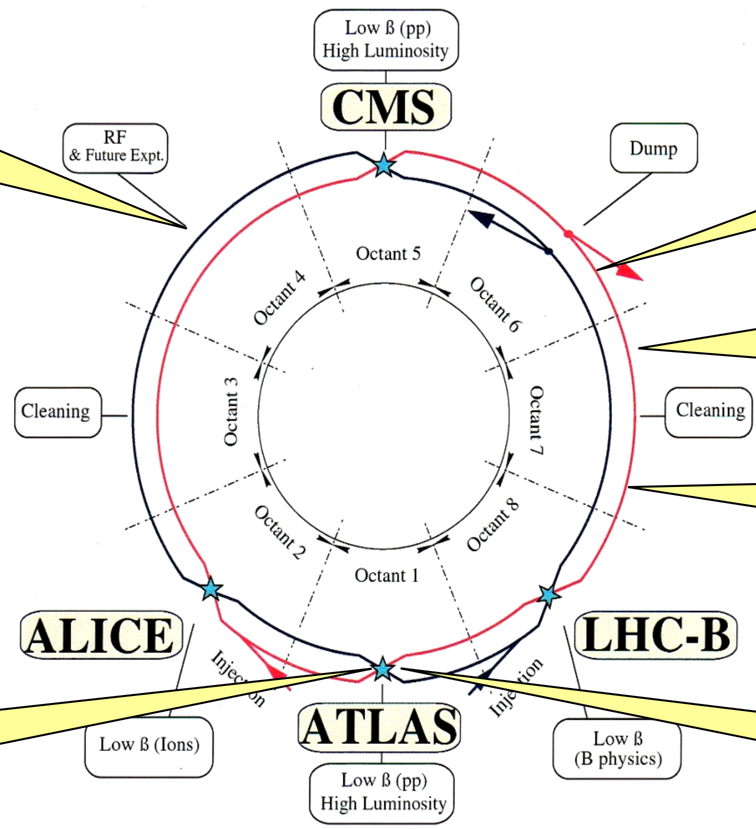
LHC (and many other accelerators) can not be realized without extensive use of Superconductivity and High Quality Magnets

Nb/Cu cavities for acceleration

1232 dipoles magnets for bending

386 quadrupole magnets for focusing

~7000 Correction magnets



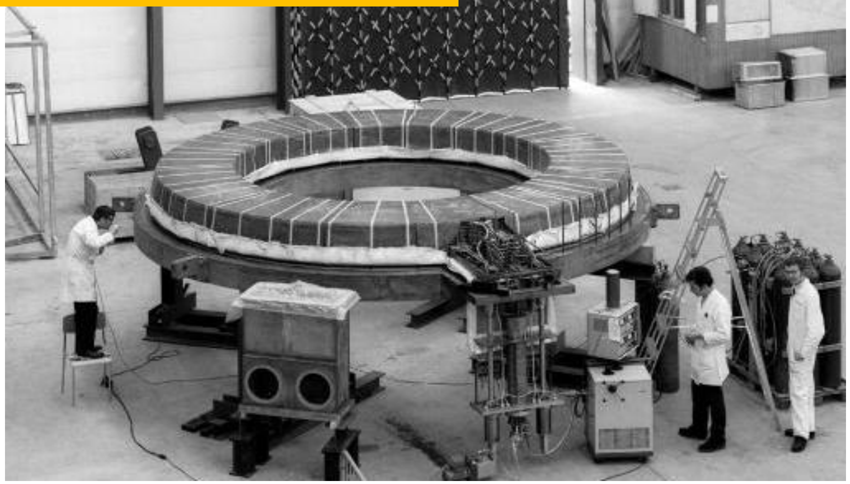
ATLAS and CMS detector magnets

Insertion and Final Focusing magnets

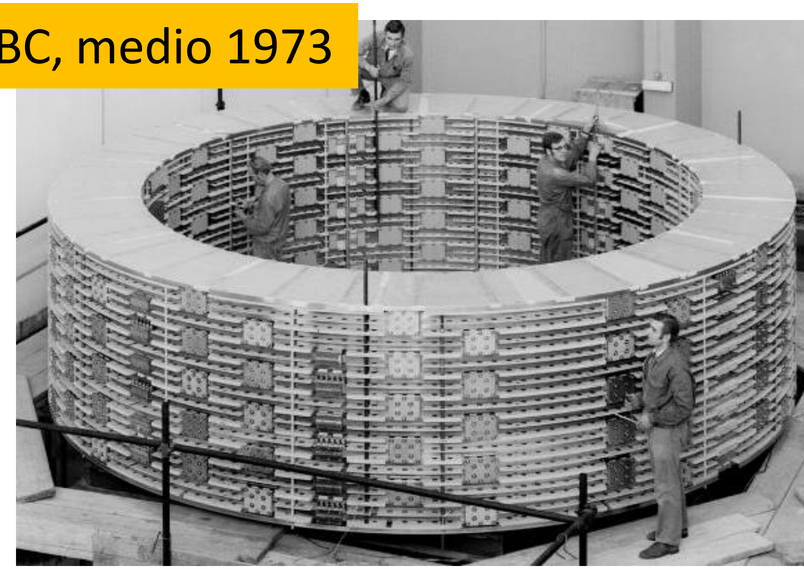
No Higgs without Superconductivity !

Large HEP Detector Magnets of the past…

Omega, medio 1972

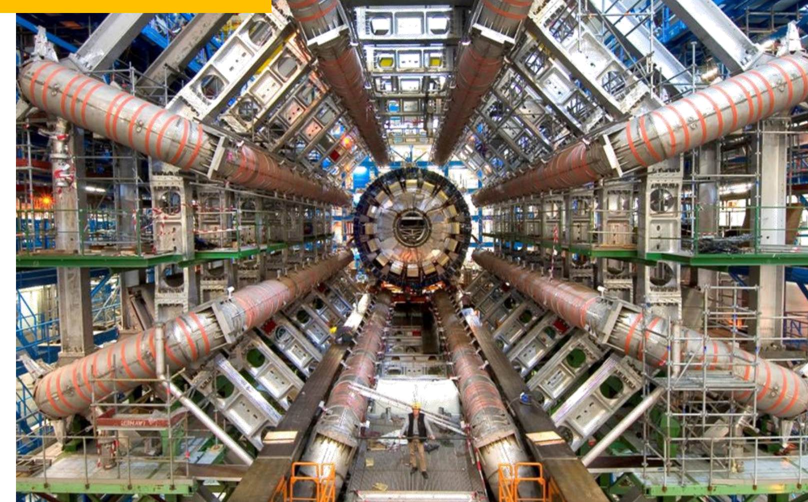


BEBC, medio 1973



CMS 2008

ATLAS 2008

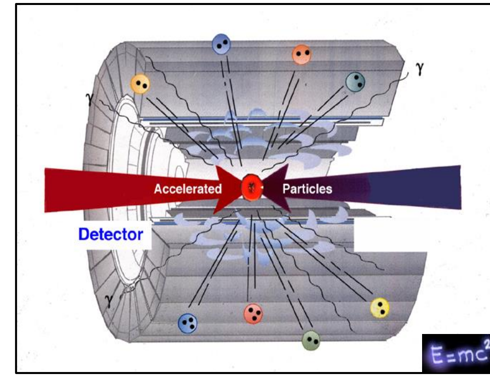


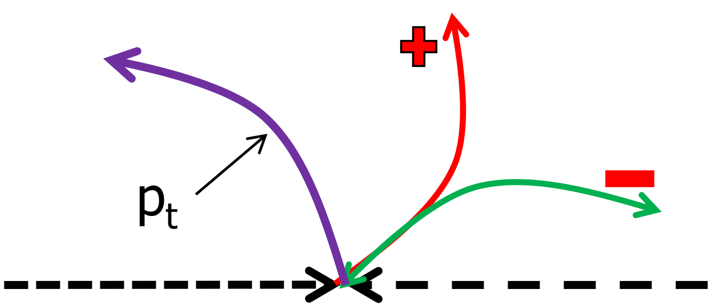
Concept: why magnetic field in detectors

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.

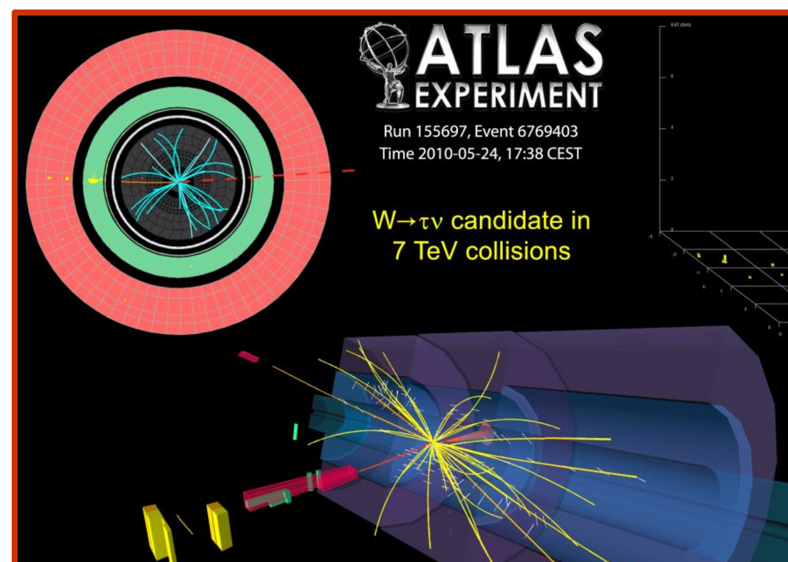
A detector magnet is in fact a "magnetic separator".





Information yield:

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



Tracks in ATLAS inner detector in 2 T

Concept: sizing the detector

What determines the size of a generic “4π“ detector and its magnetic field?

Radial thickness

is the summation of:

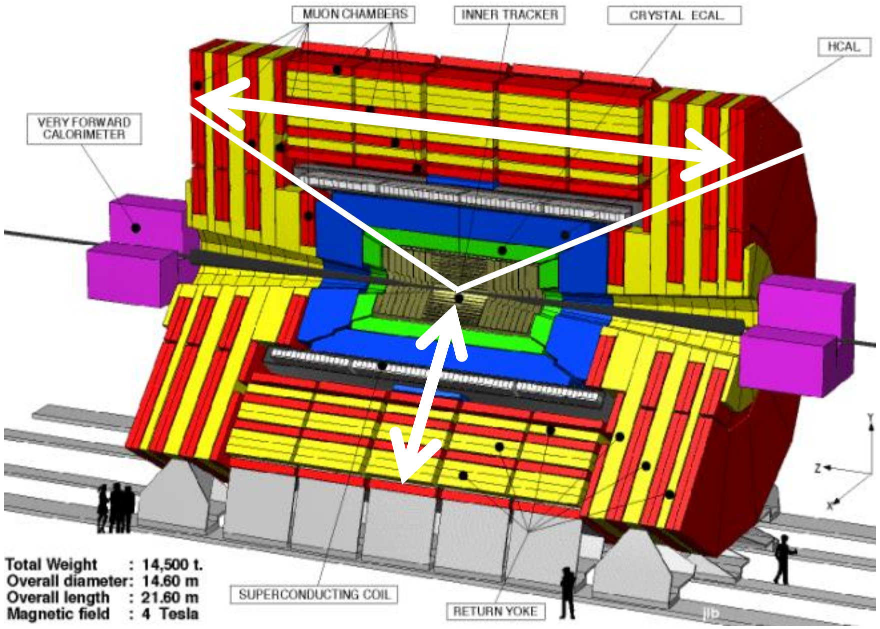
+ tracking length inner detector

+ thickness of the solenoid

+ radial build of the calorimeters

+ tracking length

+ thickness of shielding iron yoke



Axial length

is the summation of:

+ “catch angle” in forward directions sizing the length of the solenoid

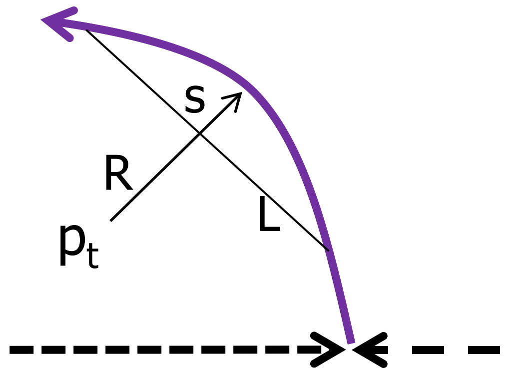
+ thickness of iron shielding.

Concept: sizing the detector

What counts is momentum resolution!

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

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



In the transverse direction, radius R, sagitta s:

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

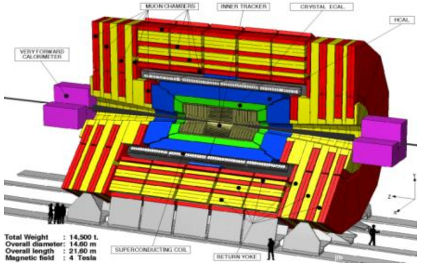
and momentum resolution

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

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: detectors scale in size with the 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

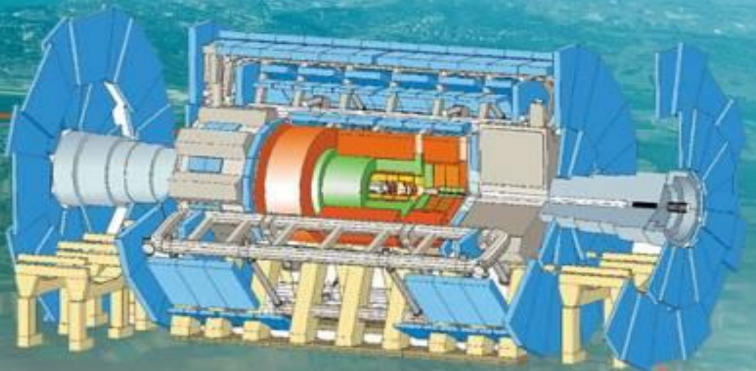
(6) **Unique and not replaceable** (can not really be repaired)

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

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

→ Use NbTi superconductor at 4.5 K

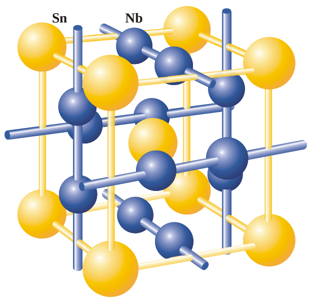
2. Superconductors for Detector Magnets



- Practical superconductors
- Basic properties
- Stability requirements
- Minimum Propagation Zone
- High Currents and Cables

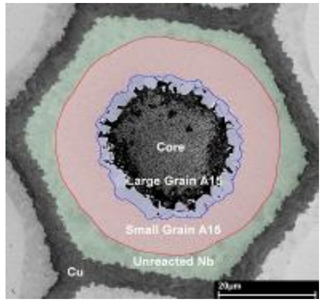
From Material to Magnets

Lattice



50 nm

Filament



20 µm

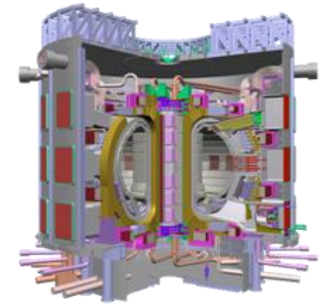
Wire

1 mm

Cable/conductor

50 mm

Magnet



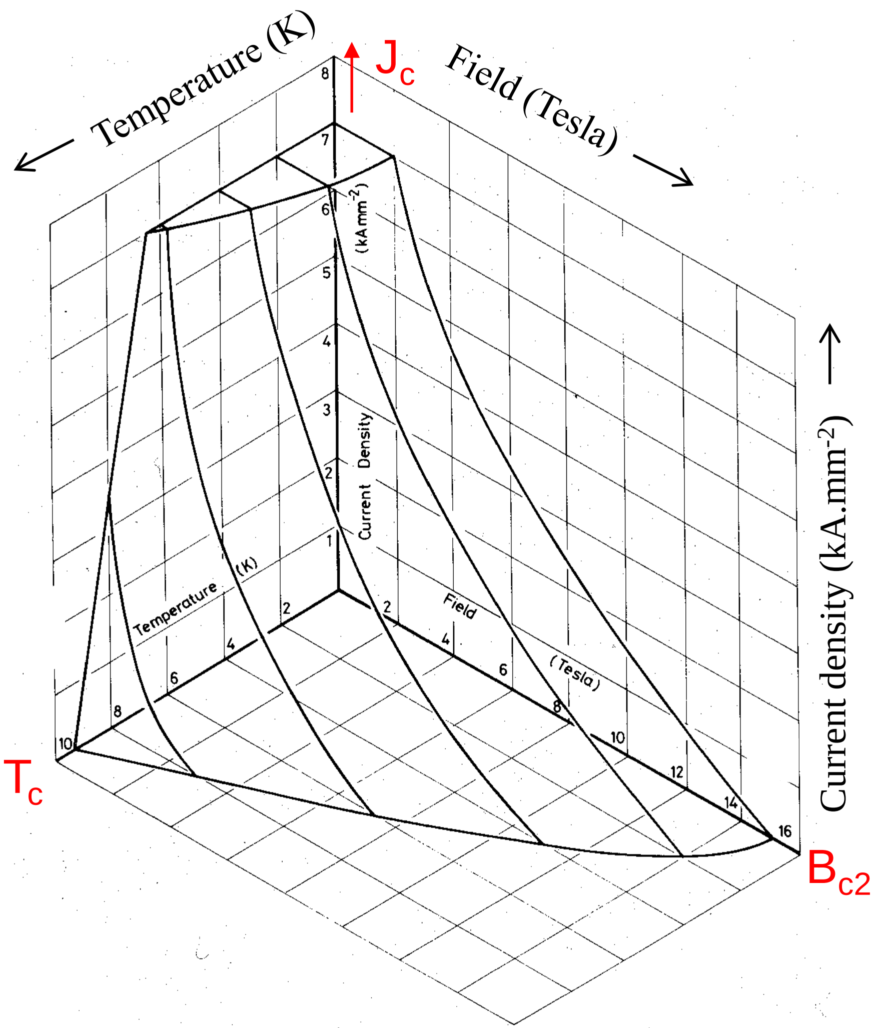
35 meter

How to make performing multi-kA conductors that guarantee the magnet not to quench or degrade ?

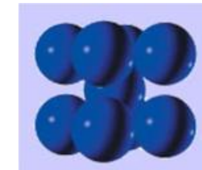
→ **We need to understand and control the entire chain**

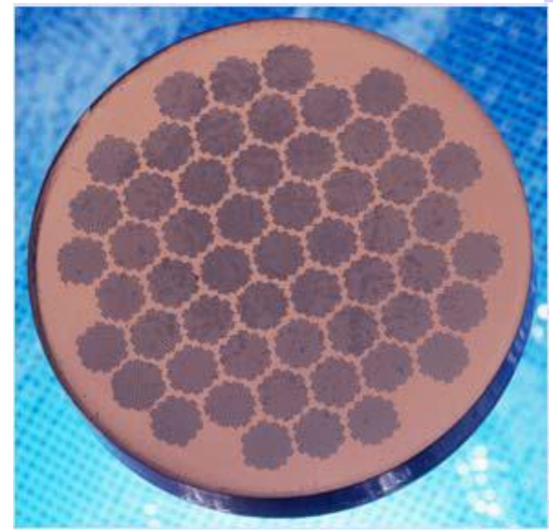
- An under developed area of research, but essential to avoid surprises and degraded magnet performance
- Striking examples exist of missing understanding putting large projects at risk.

Practical Conductors, NbTi



Cubic alloy, isotropic



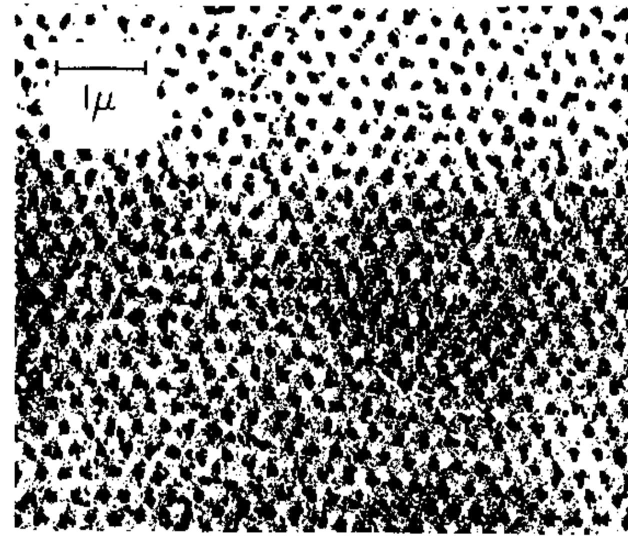


0.7 < wire diameter < 1.3 mm

Tc : 9.3 K
Bc_2 : 13 T

Very well developed
~1 € / kA m

Critical properties of Type II Superconductors



Critical Temperature T_c:

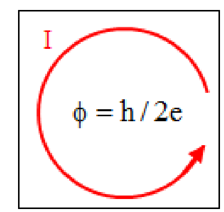
$$3.5\, k_B\, T_c = 2\,\Delta(0)$$

k_B is Boltzmann's constant, Δ(0) is the *energy gap* (binding energy of Cooper pairs) at T= 0.

Upper critical field B_{c2}:

Flux is penetrating a type II superconductor through flux lines, a "tube" in the material in normal state enclosing the flux quantum

$$\phi_o = \frac{h}{2e} = 2\times10^{-15} Weber$$



h = Planck's constant, e = electronic charge

Critical temperature & upper critical field are linked:

$$B_{c2} = 3.1\times10^{3}\ \gamma\ \rho_n\ T_c$$

where ρ_n is the normal state resistivity

! Best superconductors are best resistors when in normal state!

T_c and B_{c2} are intrinsic material properties!

Critical Current Density

Flux lines consist of resistive cores with shielding super-currents circulating around them.

Spacing between flux lines:

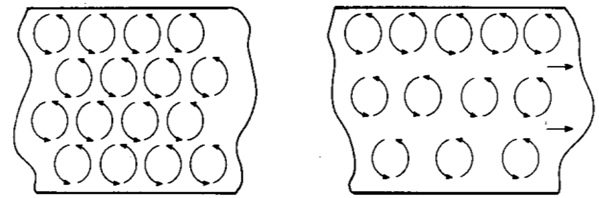
$$d = \left\{ \frac{2}{\sqrt{3}} \frac{\phi_o}{B} \right\}^{\frac{1}{2}} = 22nm \quad at\ 5T$$

A uniform distribution of flux lines gives no net current, so $J_c = 0$,

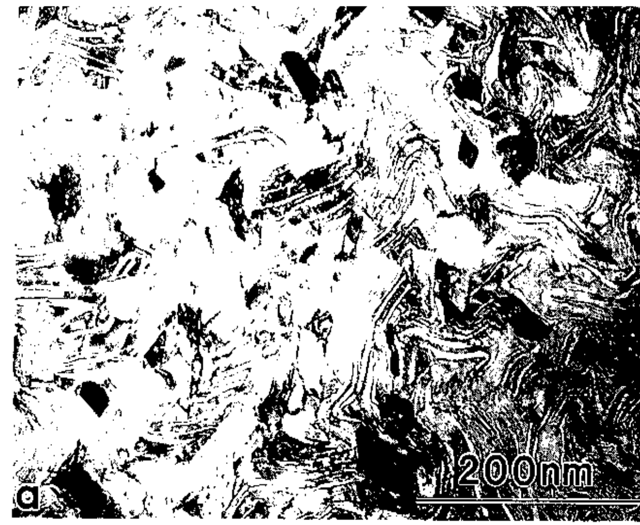
but a gradient produces a net current density:

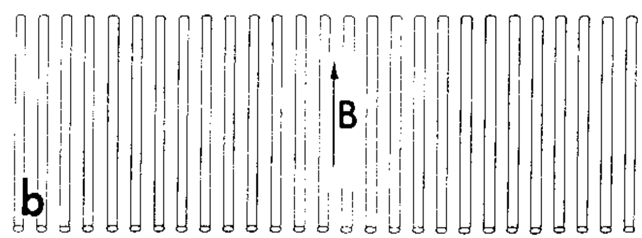
$$\nabla x B = \mu_o J = \mu_o J_c$$

- Gradients are introduced by in-homogeneities in the material, like dislocations, precipitates
- Process is known as **flux pinning**
- Flux pinning is an irreversible process leading to AC losses



precipitates of α Ti in NbTi





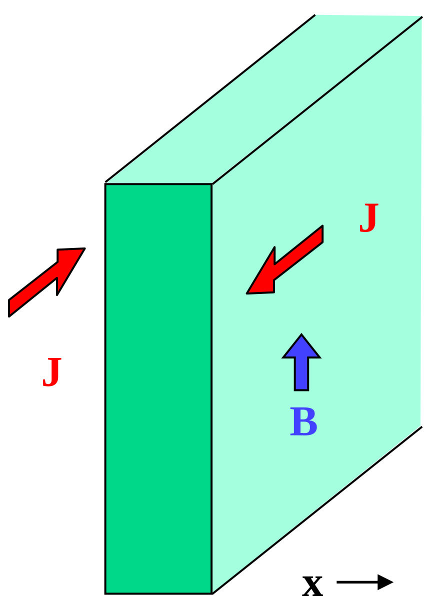
Flux lines lattice at 5 T, same scale.

Critical Current and the Critical State Model

When a superconductor is subjected to a changing magnetic field, screening currents are induced.

Screening currents are in addition to the transport current, which comes from the power supply.

They are like eddy currents but, there is no resistance, they don't decay.



Usual model is a superconducting slab in a changing magnetic field B_y

- assume it is infinitely long in the *z* and *y* directions - simplifies to a 1d-problem
- dB/dt induces an electric field E which causes screening currents to flow at critical current density J_c

Critical state model or Bean model:

- in a 1d infinite slab geometry, Maxwell's equation says

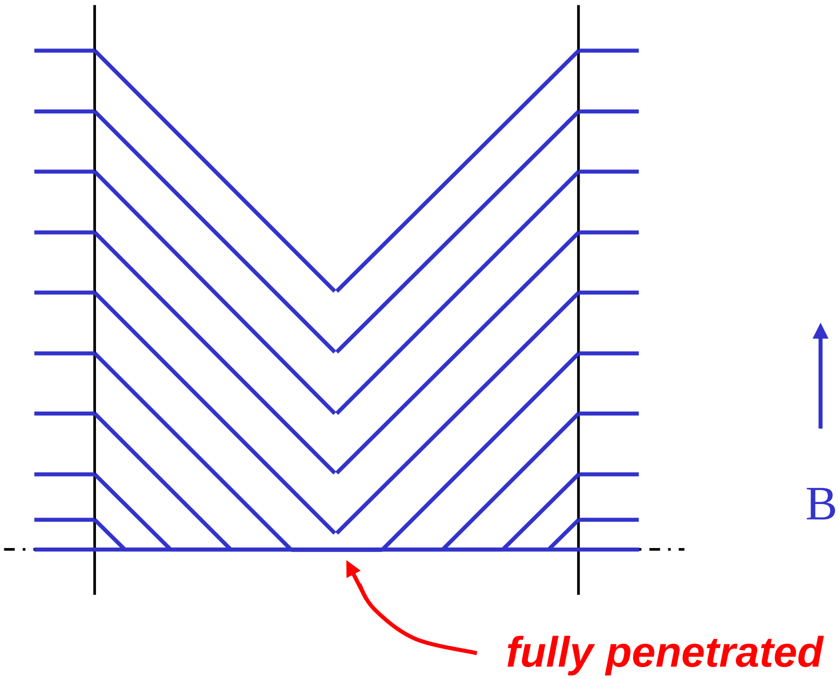
$$\frac{\partial B_y}{\partial x} = -\mu_o J_z = \mu_o J_c$$

A uniform J_c means a constant field gradient inside the superconductor.

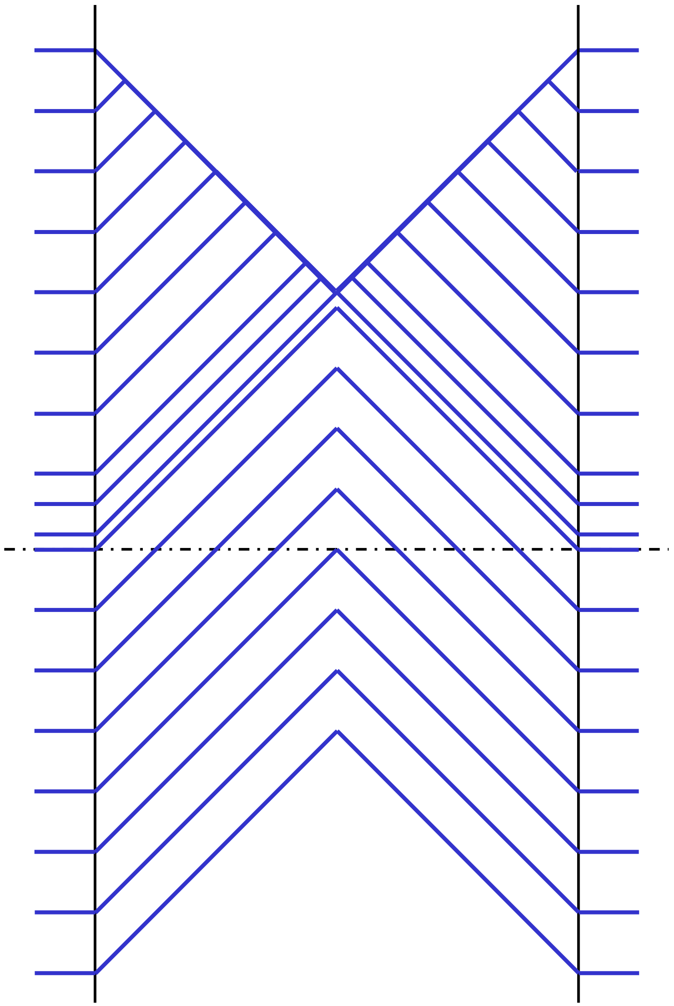
Everywhere in the superconductor the current density is either J_c or zero.

Flux penetration process (Critical State Model)

plot field profile across the slab

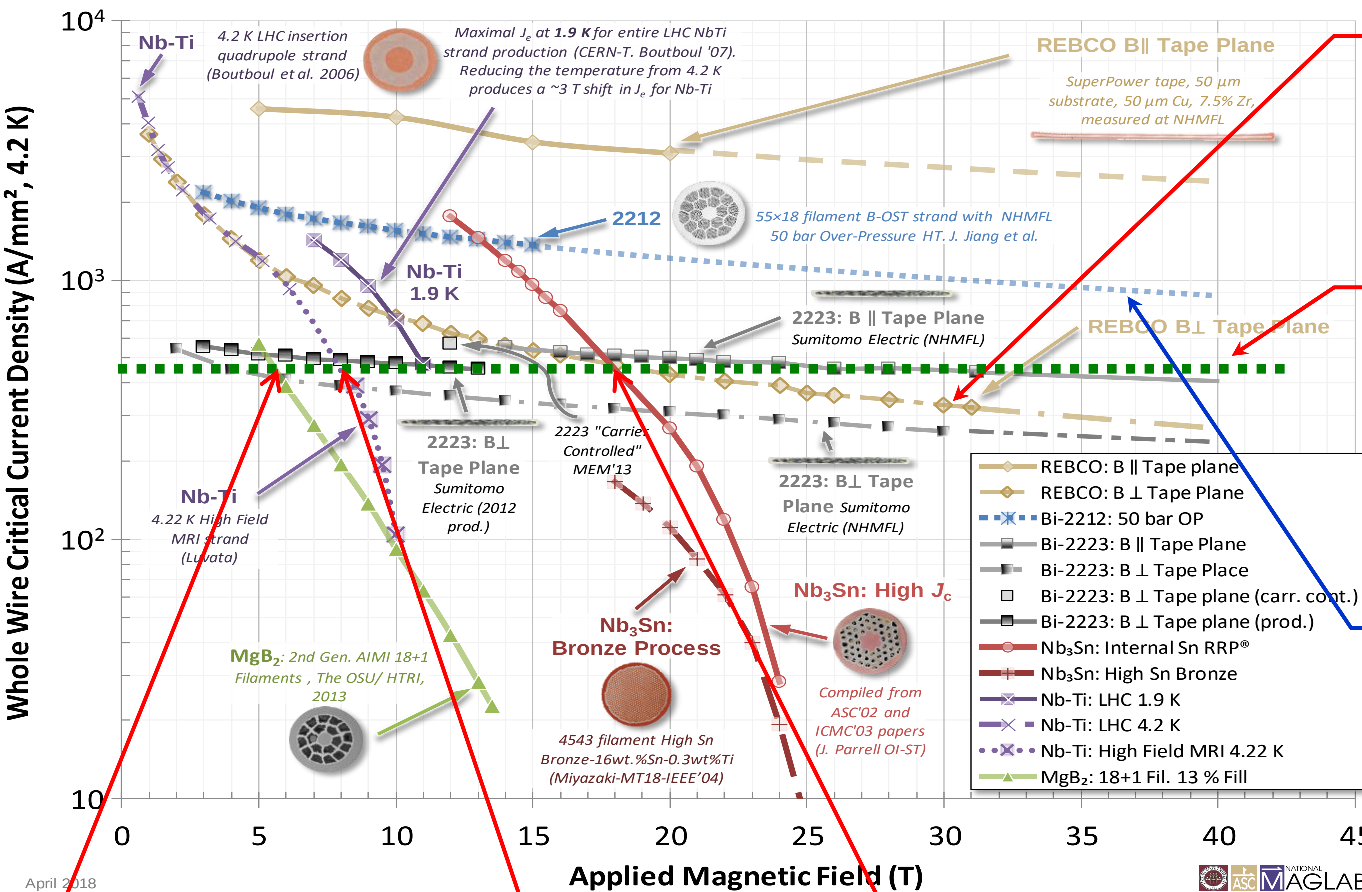


field increasing from zero



field decreasing through zero

Practical Superconductors for Magnets



***ReBCO*, Y123** 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 *ReBCO*
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

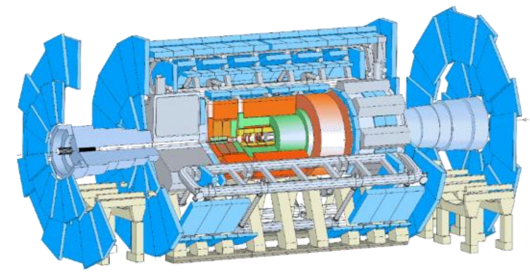
- size 57 x 12 mm^2
- 56 km made
- Production by 2 suppliers

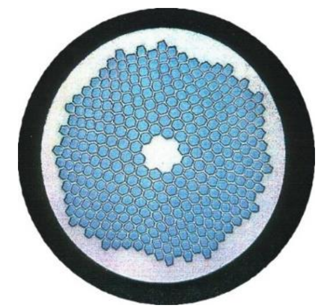
For the End Cap Toroids, size 41 x 12 mm^2,

- 26 km made

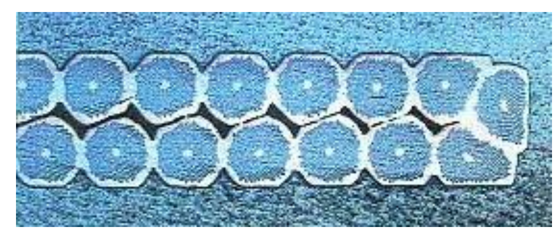
For the Central Solenoid, size 30 x 4.3 mm^2

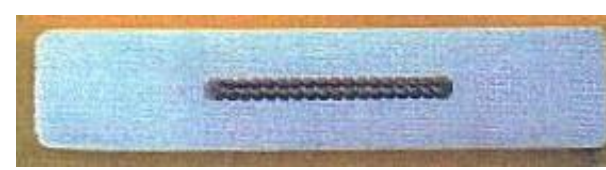
- 9 km made (Ni/Zn doped Al for higher Y-stress)





1.25 mm diameter





57 x 12 mm^2

Coils and Superconducting Windings

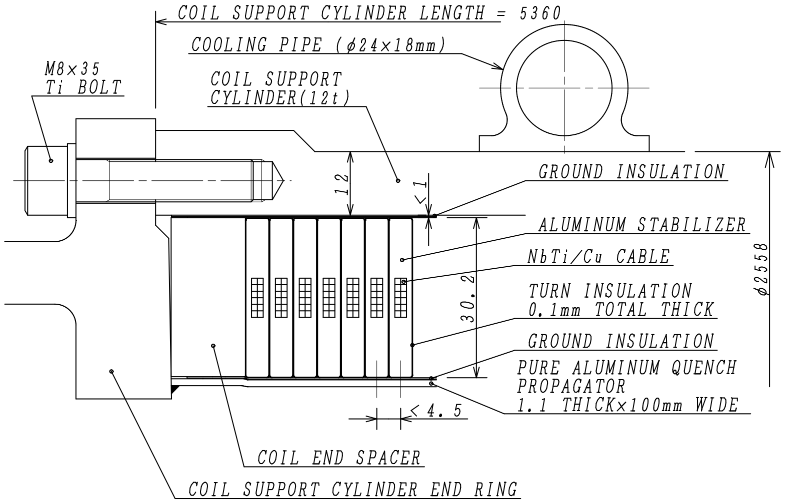
As argued before, we need:

- 1 - 5 T, so we use NbTi
- thin and transparent, so we use Al
- simple cooling and robust mechanics.

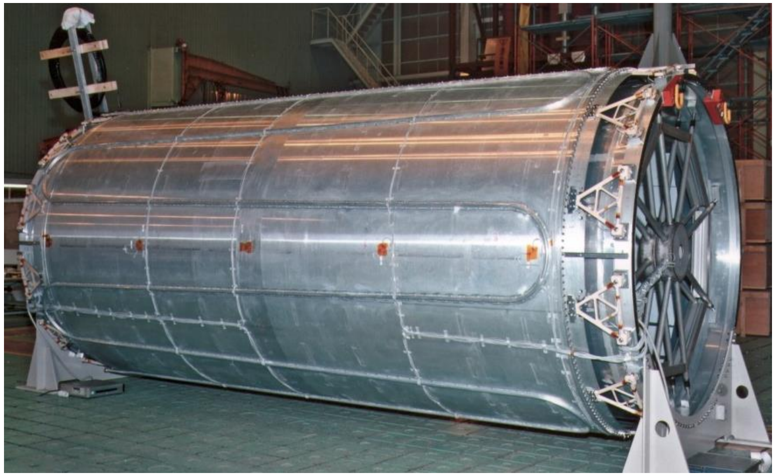
This caused an evolution of detector magnet designs since some 40 years.

We see:

- Al stabilized Rutherford cables made from NbTi/Cu strands.
- 1-4 layer coils, often wound inside a supporting cylinder taking the hoop stress.
- Conduction cooled by thermo-siphon or forced He flow cooling at 4.5 K through Al tubes on the support cylinder.

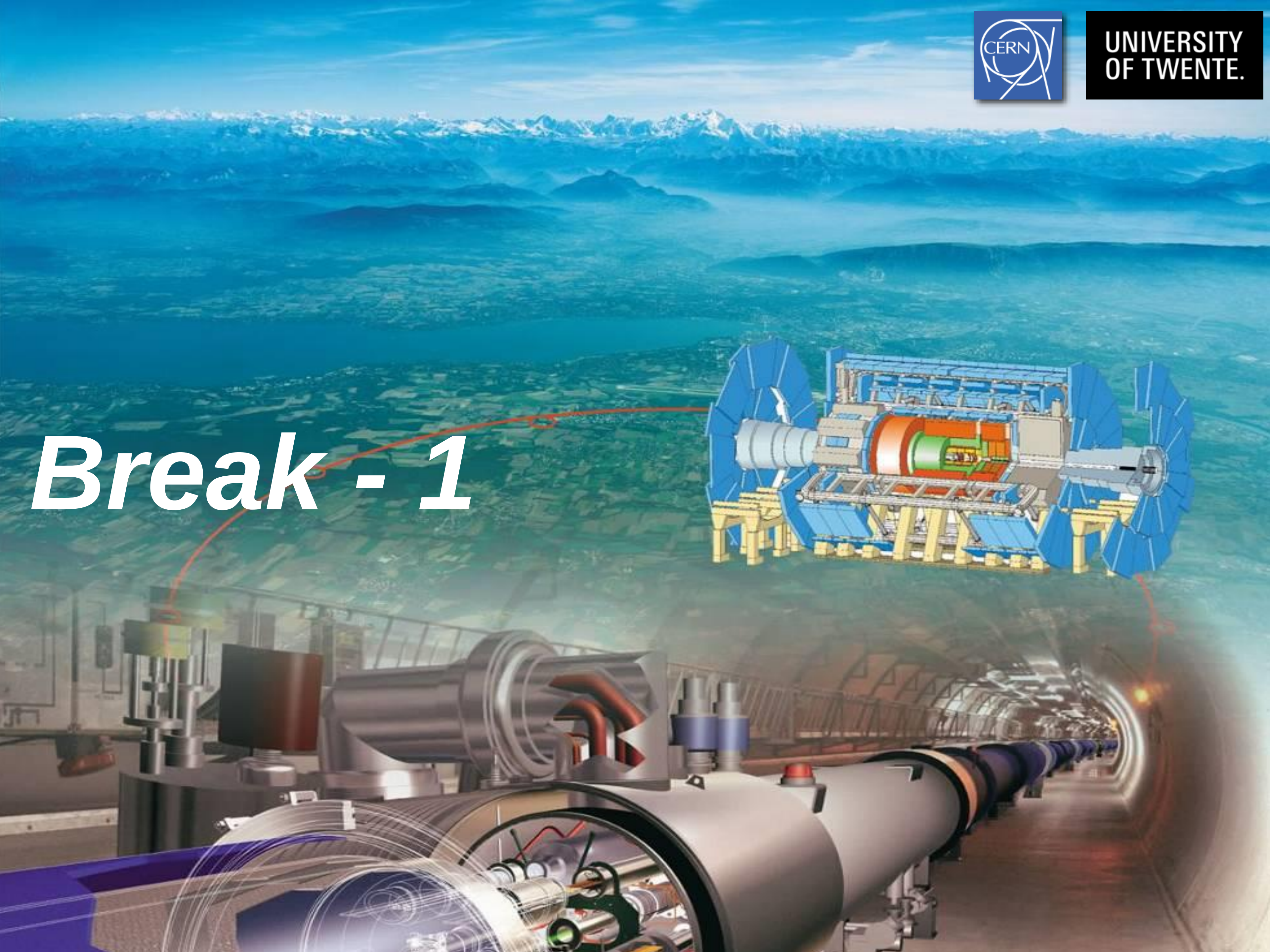


Typical coil windings (ATLAS solenoid)



ATLAS Solenoid 2.5 T

Break - 1

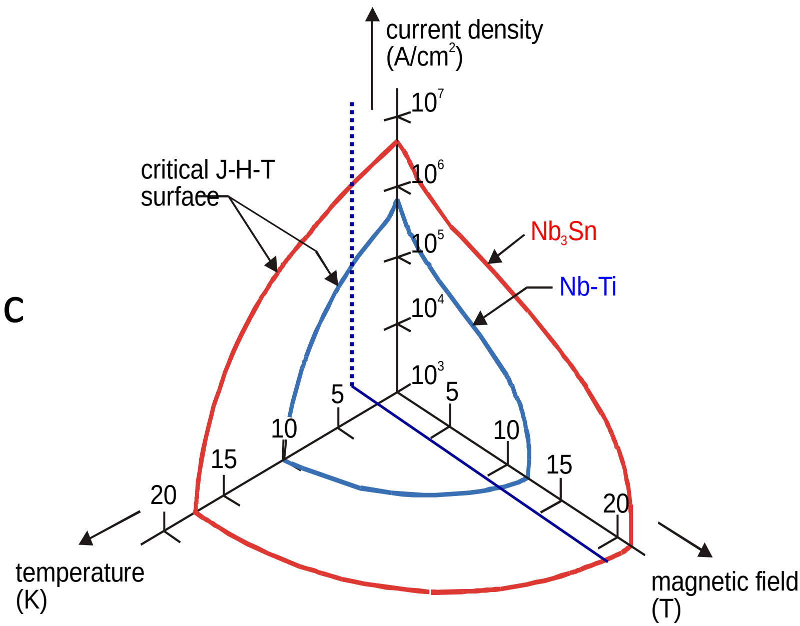


Video - 2

Critical temperature, field dependency

Superconducting Phase (J_c vs. B and T).

For maintaining the superconducting state, the conductor must operate below the critical surface determined by critical current, magnetic field and temperature.



For **NbTi** the critical area is bounded by:

$T_c(B=0) = 9.2$ K and $B_{c2}(T=0) = 14.5$ T

$$B_{c2}(T) = B_{c2}(0)\,\{1 - (T/9.2)^{1.7}\}$$

$B_{c2}(4.2\text{ K}) = 10.7$ T

$$T_c(B) = T_c(0)\,\{1 - (B/14.5)\}^{0.59}$$

$T_c(5\text{ T}) = 7.16$ K

Similar relations are found for Nb_3Sn and BSCCO and ReBCO superconductors

Temperature margin, T_{cs}

When a transport current flows, the onset of resistance is

is further reduced from T_c to T_{cs}, **the current sharing temperature**

$$T_{cs}(B,I) = T_b + (T_c(B) - T_b)\,(1 - I/I_c)$$

$T_{cs}(5\ \text{T}, \tfrac{1}{2} I_c\ \text{A}) = 5.7$ K only!

- **So we lost a lot of margin from 9.2 K --> 7.2 K --> 5.7 K versus 4.5 K.**
- **At 4.4 K, at 50% I_c and 5 T there is only 1.2 K margin !**
- At 75% of I_c we get 0.7 K, so we never can operate very near to I_c !
- Following $\Delta T = Q / c(T)$,

  release of energy (heat) from various sources will cause a temperature rise and thus the superconducting state is very seriously in danger.
- The heat that can be absorbed without reaching T_{cs} is the enthalpy difference $\Delta H = \int c(T)\,dT$ between T_{cs} and T_o .

Adiabatic Filament Stability, d_{fil}

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

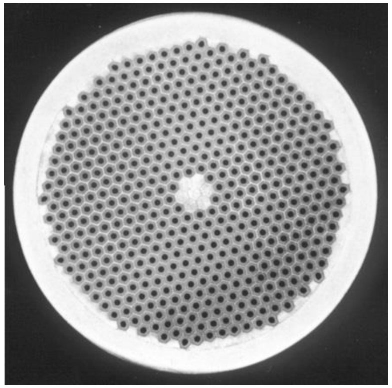
- In the filament magnetic energy is stored.
- When disturbed, the heat must be taken up by the enthalpy of the filament.
- A disturbance ΔT1 will cause a –ΔJc, so flux motion, leading to E, this leading to heat and so again a ΔT2.
- When ΔT2 > ΔT1, the process will accelerate and the flux profile collapses.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

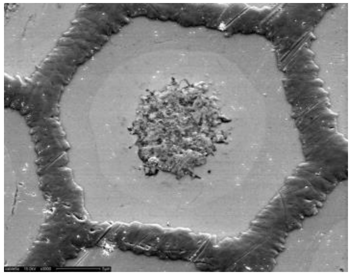
$$d_{fil} \cdot J_c < \{ 3\, c\, (T_c - T_o) / \mu_o \}^{1/2}$$

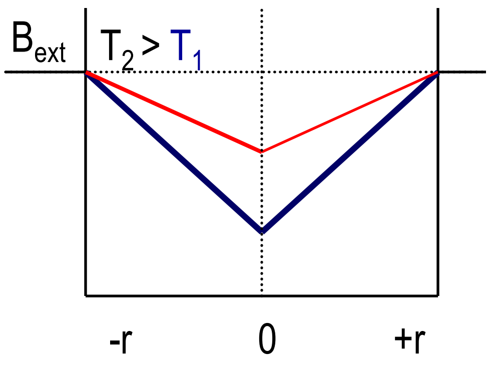
So we see a maximum filament thickness for a given current density, to guarantee stability.

- For NbTi, $c = 5600\ \mathrm{J/m^3}$; $T_c(5\ \mathrm{T}) = 7.2\ \mathrm{K}$, $T_o = 4.2\ \mathrm{K}$

  and $J_c = 3000\ \mathrm{A/mm^2}$, we find **$d_{fil} < 70\ \mu m$.**







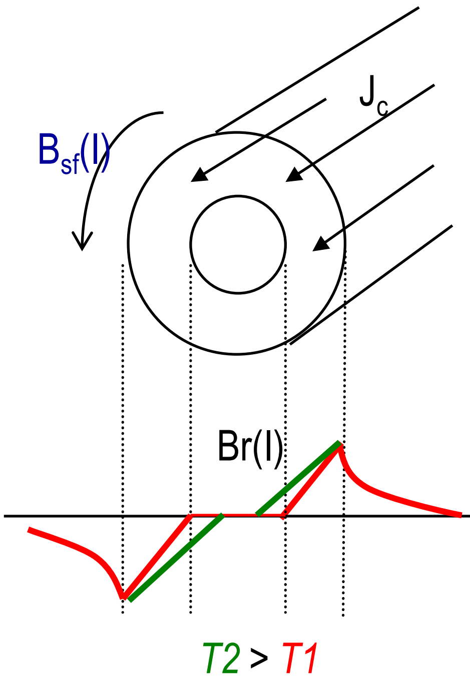
Adiabatic Wire Self field Stability, D_{wire}

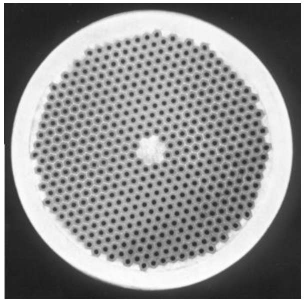
Filaments are coupled by self field

- Adiabatic filament stability requires fine filaments in a matrix
- These can be de-coupled for transverse fields by twisting
- But they are still fully coupled by the self-field
- Following the CSM, we see the 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 η=sc/total ratio and current density ηJ
- We find for the adiabatic self-field criterion:

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

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





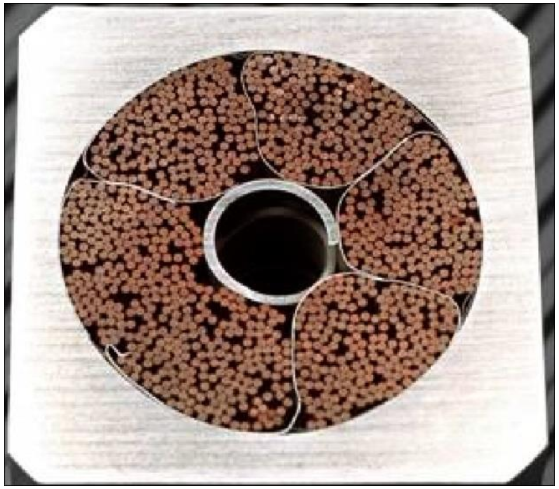
Thus there is a maximum wire diameter for a given Jc and I/I_c

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

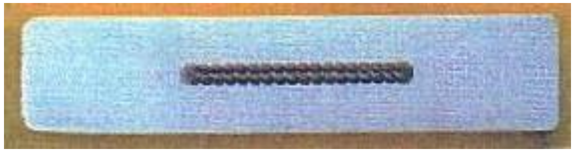
LHC type Nb_3Sn Rutherford cable

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

33 wires LHC-type Nb_3Sn cable

ATLAS Detector Magnet cable

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



40 strands ATLAS BT cable

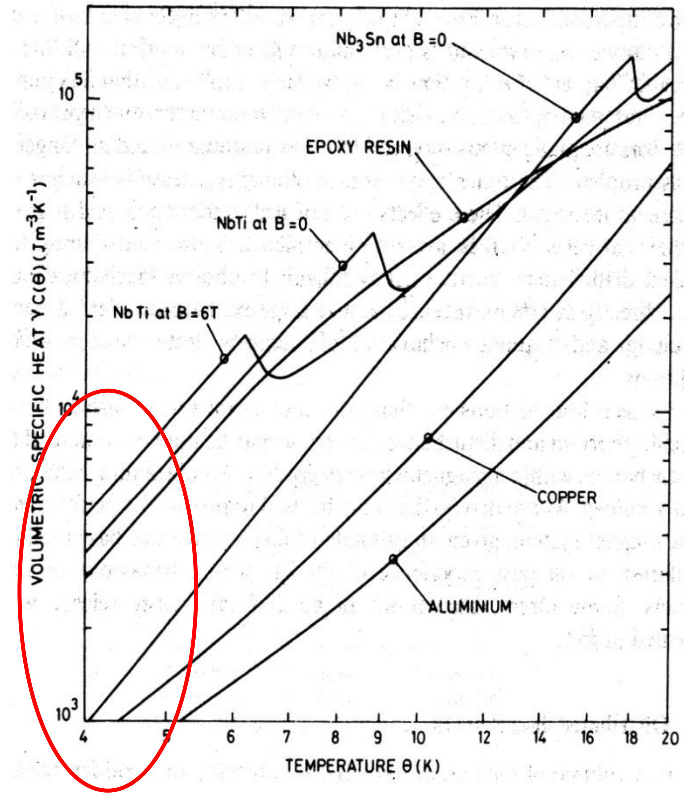
Temperature jumps, low heat capacity

Why is release of heat so critical at 4 K ?

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

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

  $\mu J/mm^3K$, 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 μm only!



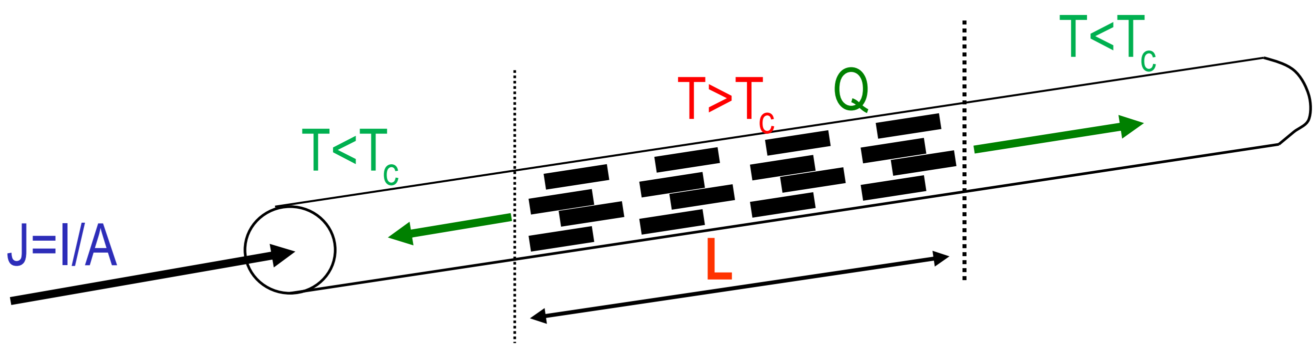
Heat release of $\mu J/mm^3$ has to be avoided, otherwise magnet will quench

- 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:

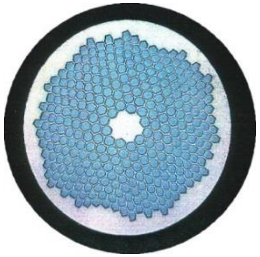
$$\rho J^2 A L \approx 2 \lambda A (T_c - T_{bath}) / L$$

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

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; ρ= 6x10^{-7} Ωm; λ= 0.1 W/mK; T_c= 7 K
  and we find MPZ of **0.3 μm** only, pure NbTi can not be used!
- NbTi with CuNi matrix would give MPZ of **3 μm** and 0.1 μJ !
- Such wire is extremely sensitive to any heat pulse

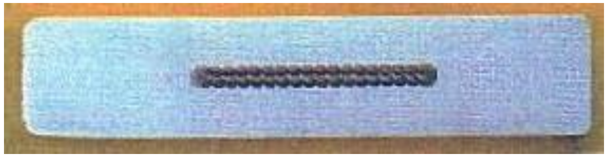
Remedy: **reduce ρ by using copper matrix** (3x10^{-10} Ωm, factor 2000 !)
and **increase λ by using copper** (> 200 W/mK, factor 2000 again !)

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

✓ factor 2000 improvement, from μm to **few mm** and μJ 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** !

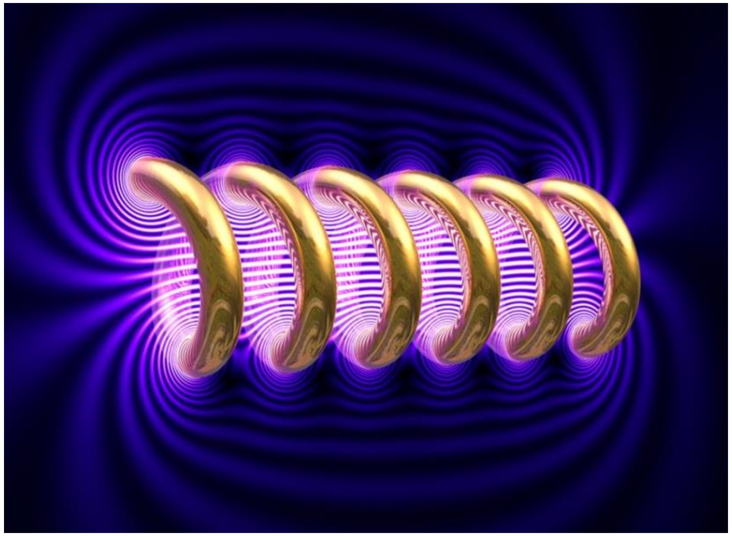


Why magnets need High Current & Cables

Magnetic field and stored energy

$B \propto N.I$ $E \propto B^2.Volume$

Inductance $L \propto N^2$



- Need safe survival from a quench
- Energy dump within short time before conductor burns out

→ **Thus low N, high current I !**

Also we wish to limit the voltage V_d to the sub or low kV-range, with usual current densities this leads to 10-100 kA.

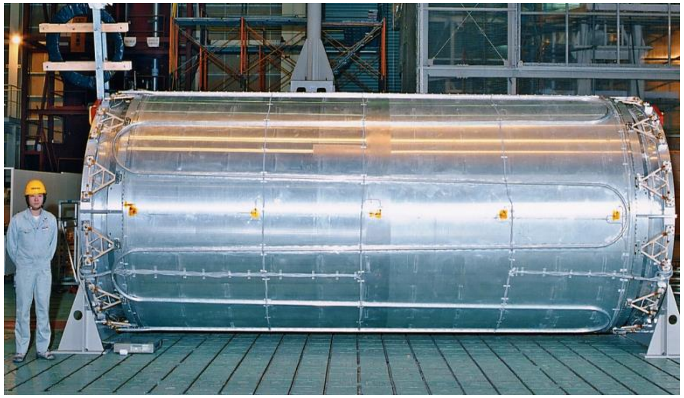
→ **Given common strand currents of 100 to 500 A, we need for large scale magnets multi-strand cables with 20-1000 strands!**

No escape!

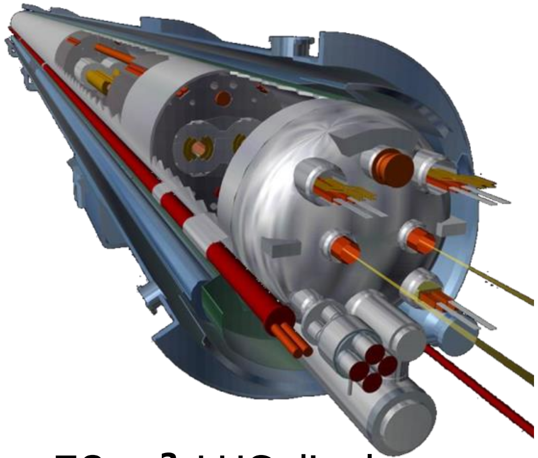
Scaling: $I_{safe} \propto J \times B^2 \times Volume$

0.0001 m³ HF insert
200 A

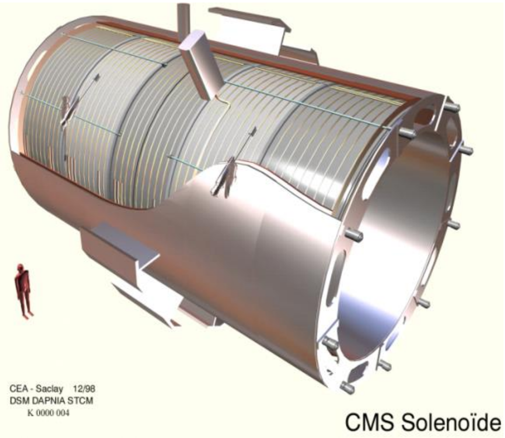
2 m³ MRI magnet
200-800 A @ 1-3 T, ~10 MJ



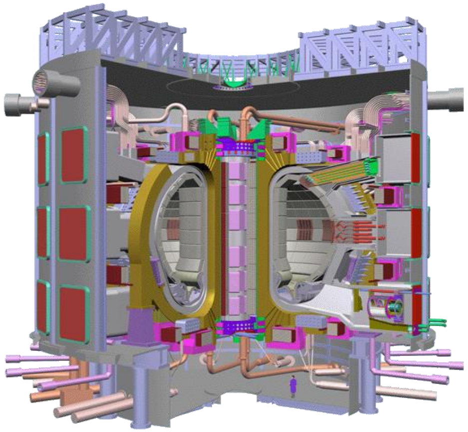
25 m³ ATLAS solenoid
8 kA @ 2T, 40 MJ



50 m³ LHC dipole
12 kA



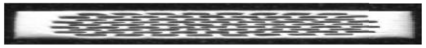
400 m³ HEF detector magnet
20 kA @ 4 T, 2.6 GJ



1000 m³ ITER magnets
40-70 kA @ 10-13T, 50 GJ

Request for: high current conductors

200 A HTS tape?



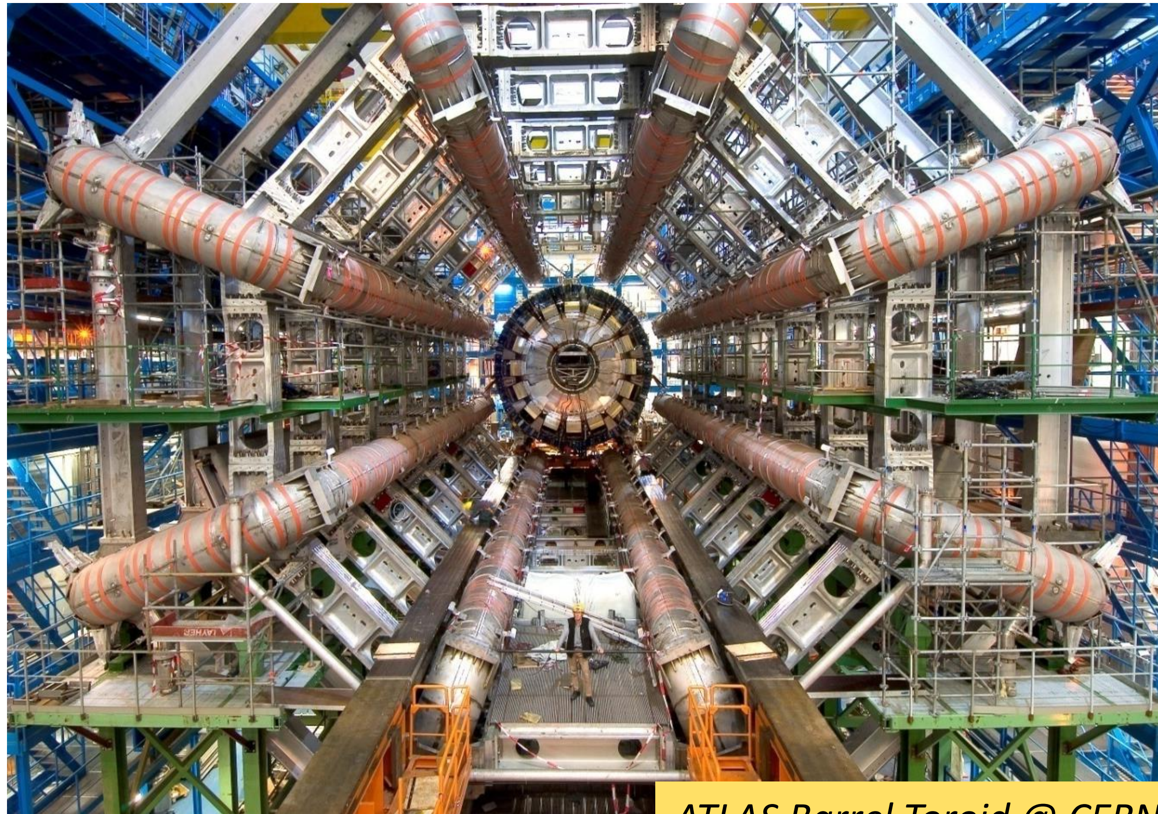
≈ 4 x 0.1 mm²

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

65000 A@5T Al-NbTi/Cu?

≈ 57 x 12 mm²

Yes!

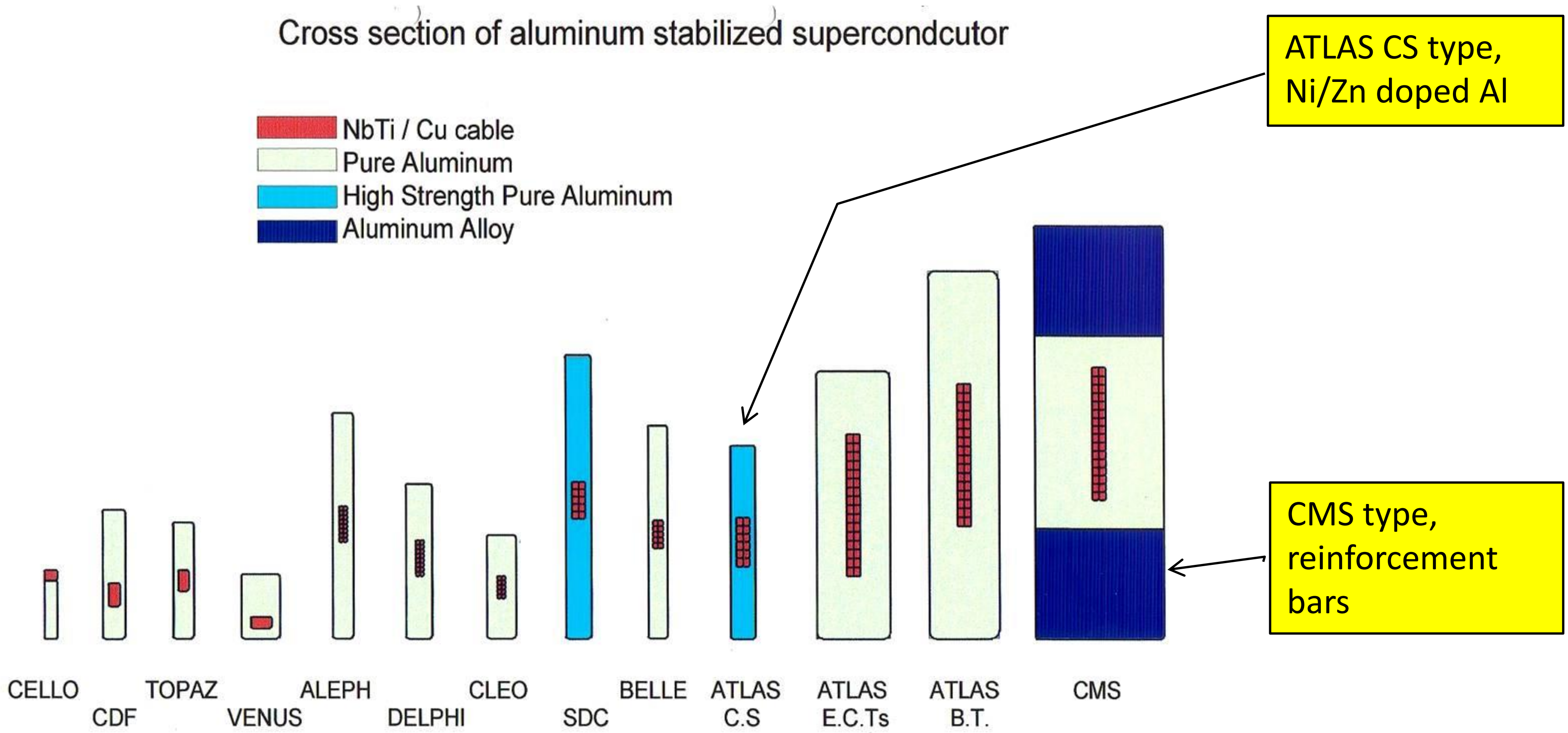


ATLAS Barrel Toroid @ CERN

- ✓ 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

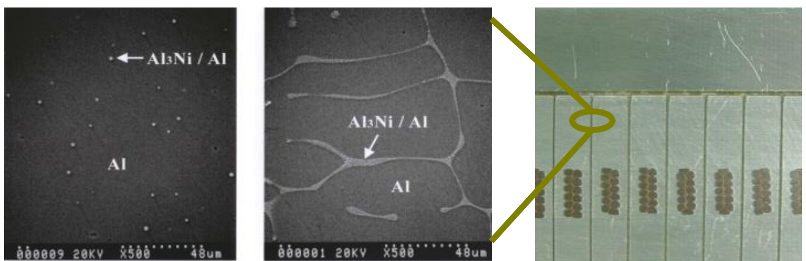
- For the next generation detector magnets, conductors are further developed and reinforced, more stored energy, larger size.



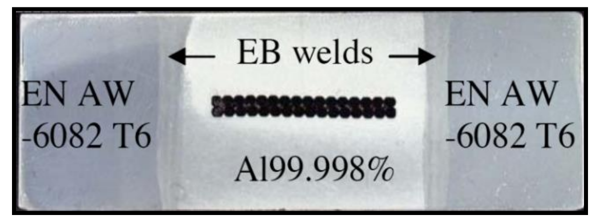
Reinforcing Al-stabilized conductors

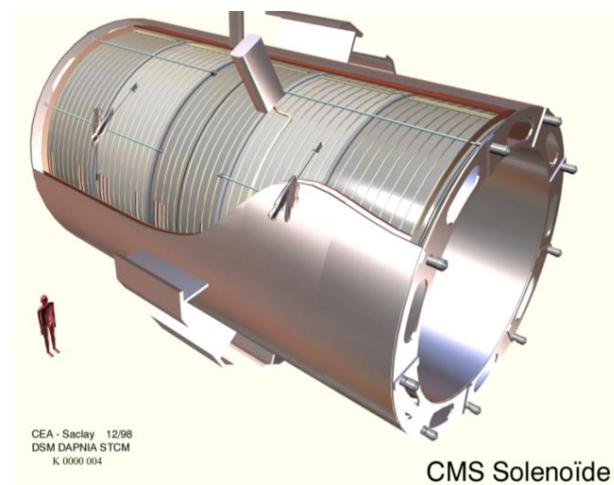
- Option 1
  Ni or Zn - doped Aluminum.
- Used in the ATLAS Solenoid, mechanical reinforcement while keeping quench stability.

- Option 2
  Reinforce with Al-alloy side bars, EB- welded to the Al and NbTi/Cu co-extruded conductor.
- Doable but expensive.



a) Al-0.1wt%Ni Alloy   b) Al-0.5wt%Ni Alloy



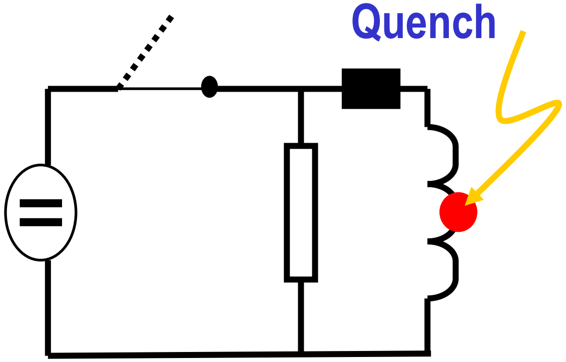


Stored Energy to dump

The energy stored in a magnet is

$W_L = ½ L I^2$ [J] $= ½ \int BH\,dV$,

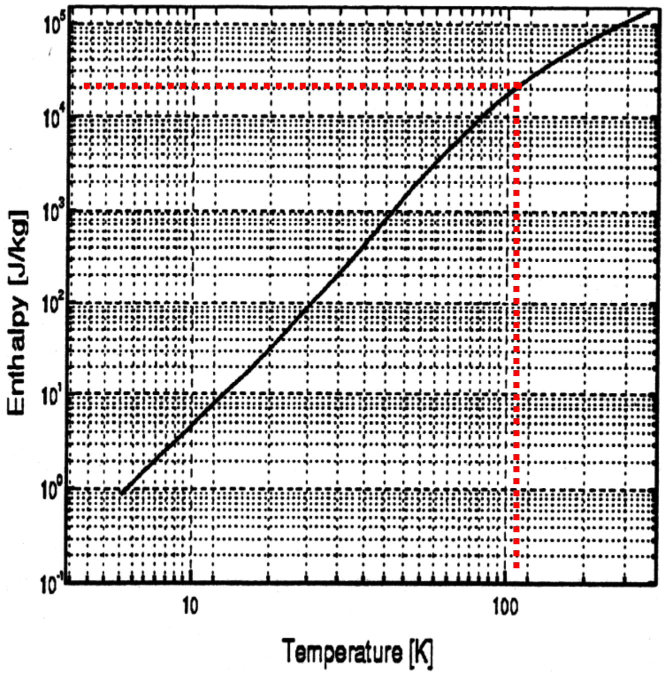
the energy density being ½ BH or $B^2/2\mu_o$.



This energy could be absorbed by the magnet cold mass assuming a safe temperature T_m.

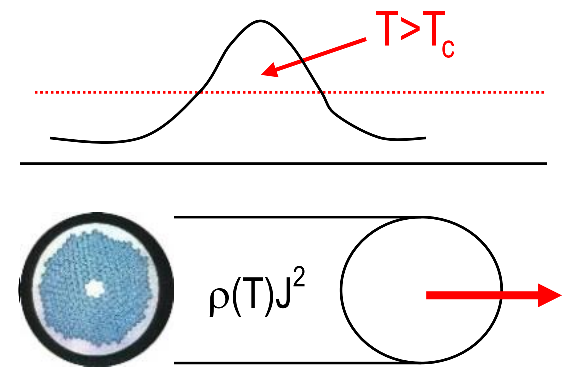
- $W_L/m = {}_o\int^{Tm} C_p(T)\,dT = H(T_m) - H(T_o=4.2)$

  $\approx H(T_m)$ since $C_p(4.2)$ is negligible.
- For 150 K, we can absorb about 20 kJ/kg cold mass provided uniformly distributed.
- Usual values for W_L/m are in the range <10 kJ/kg, so apparently no problem.
- But heat distribution must be controlling the normal zone spatial distribution and speed.



Adiabatic heating of the conductor

Temperature of the conductor?

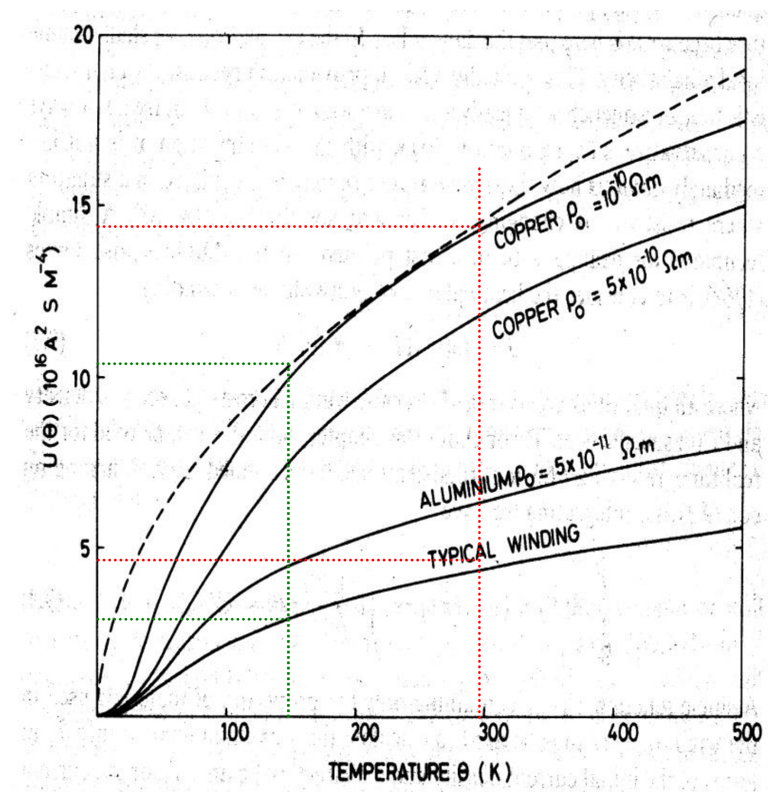


- Heating in the normal zone ρJ^2 is taken up by the conductor enthalpy:

$$\rho(T)\, J^2(t)\, dt = c(T)\, dT$$

$$\int_0^t J^2(t)\, dt = \int_4^T c(T)/\rho(T)\, dT = \text{constant} = F(T_m)$$

- **F** is the Load Integral, is a constant, calculated for the NbTi, Cu, resin mixture in the coil.
- Typical values for $F(T_m)$ are in the range 2-9 x 10^{16} for 150 K and 5-15 x 10^{16} for 300 K maximum temperature, depending on the conductor composition.



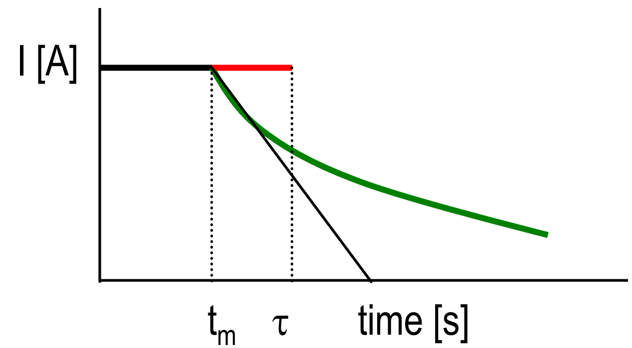
Adiabatic hot spot temperature

$$_{o}\int^{t} J^2(t)\, dt = {}_{4}\int^{T} c(T) / \rho(T)\, dT = \text{constant} = F(T_m)$$

Simple solutions exist for constant or exponential decaying currents:

Constant current:

$$J^2 t_m = F(T_m) \quad \text{-->} \quad t_m < F/J^2$$



Exponential decay:

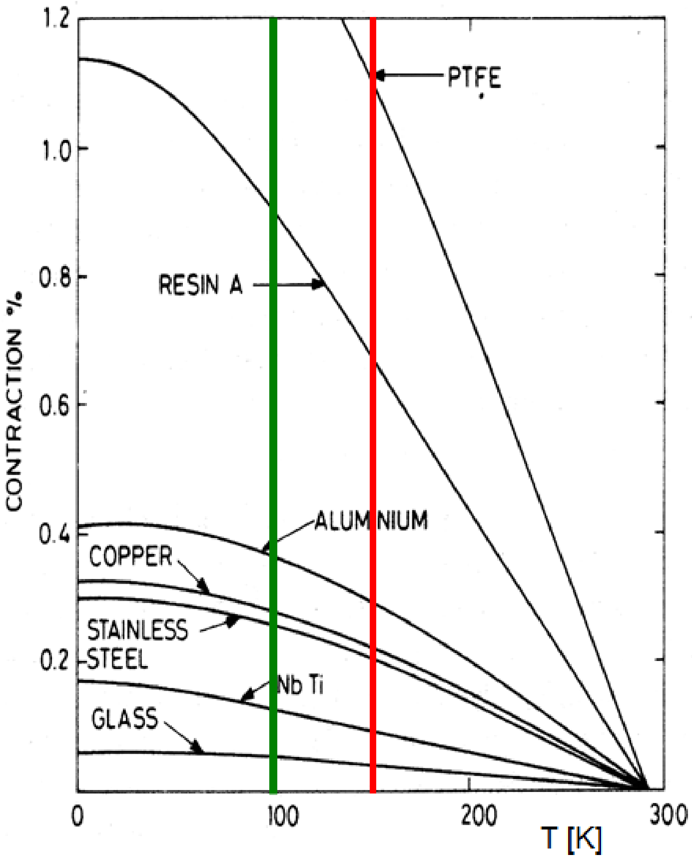
$$J^2 \tau /2 = F(T_m) \quad \text{-->} \quad \tau < 2F/J^2$$

Examples

- NbTi/Cu and CuNi matrix conductors with $J = 500$ A/mm^2
- $F(300) \propto 1/\rho$
- F(300) for Cu is ~1.4 10^{17} and ~1.4 10^{16} for CuNi (or pure NbTi)
- Maximum τ in NbTi/Cu before reaching 300 K is a 0.1-1 second
- **Maximum τ in pure NbTi or NbTi/CuNi is ~ms, so very little time to react and the conductor will burn out when used at high current density !**

Safe hot spot temperature

- > 900 K Al structures start to collapse.
- > 650 K we start to lose pinning, so J_c.
- 300 K is too high, it endangers the windings.
- Severe thermal shock due to differential thermal contractions.
- Causing resin cracking and de-bonding, and thus training or degradation.
- ✓ **A "safe" hot spot temperature is 100-150 K!**
- **Usually 100 K is taken nominally and a peak of 200-300 K for exceptional cases (failing protection systems for example).**



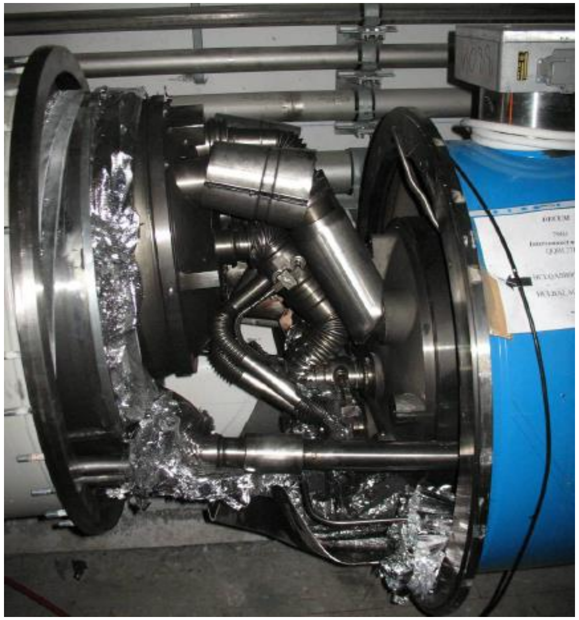
- 300 K is not an acceptable design value for a detector magnet that has to survive, operate at minimum risk and must be quench-recovered within 3-4 days.

Destructive power of uncontrolled quenches

LHC dipole of 15 m and 8.35 T stores 8 MJ, which corresponds to melting 1.5 L of copper, enough to evaporate 10cm of coil !

And we have seen in September 2008 at start of LHC what magnet quenches can do!

ATLAS detector toroids store 1.6 GJ, good for 600 L of melted copper, or equivalent to the collision energy of 100 trucks of 40 tons with speed of 100 km/h!

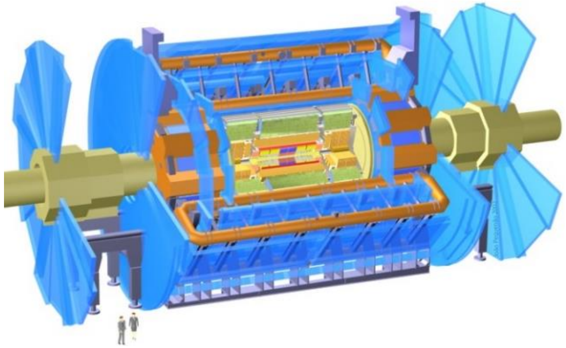


Damage at an LHC interconnect

To be safe with equipment and personnel:

- Quench Protection has to cover all possible quenches in the entire electrical circuit

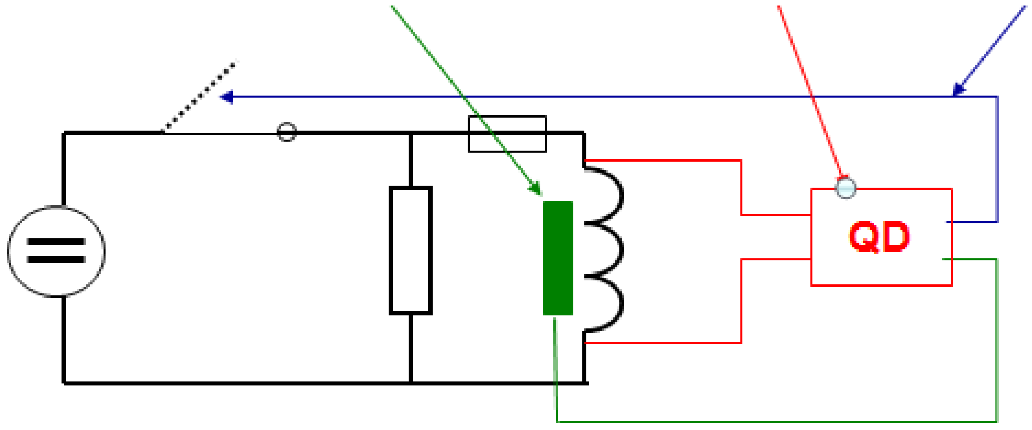
  from + terminal to – terminal on the cryostat.



Quench Detection

Quench detection circuit

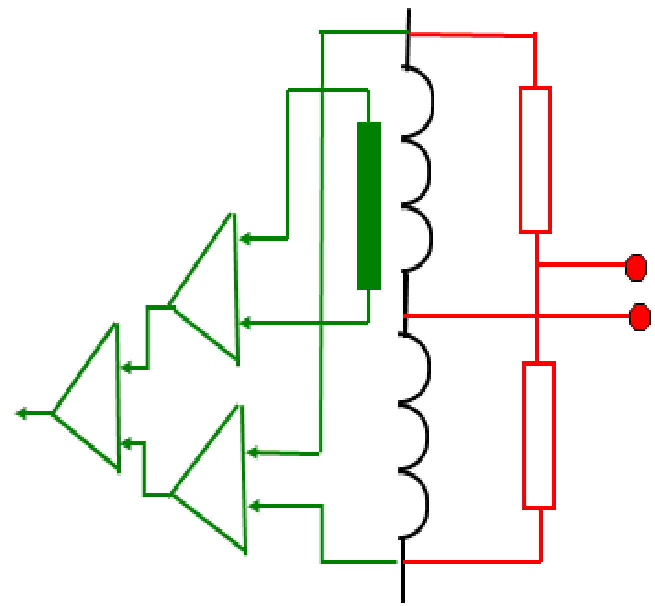
- The magnet safety system comprises the quench detectors, logics for opening switches and to supply current to the quench heaters.
- The system must be extremely reliable and power secured.
- ✓ The motto is "**keep it simple**", meaning robust and straight forward detection circuits, simple electronics, hardwired and 3-5 times redundant.
- **First the quench, a normal zone, must be detected, then switches have to be opened and quench heaters activated.**



Quench detection methods

Bridge method

- Detects the resistance in any branch of the coils, very robust, simple and proven.
- 3 sets of bridges, asymmetrically connected to see symmetric quenches.
- Commonly used for large magnets.



Voltage across coil

- Voltage across coil compensated for the inductive component. Requires differential amplifiers, more complicated, more electronics.

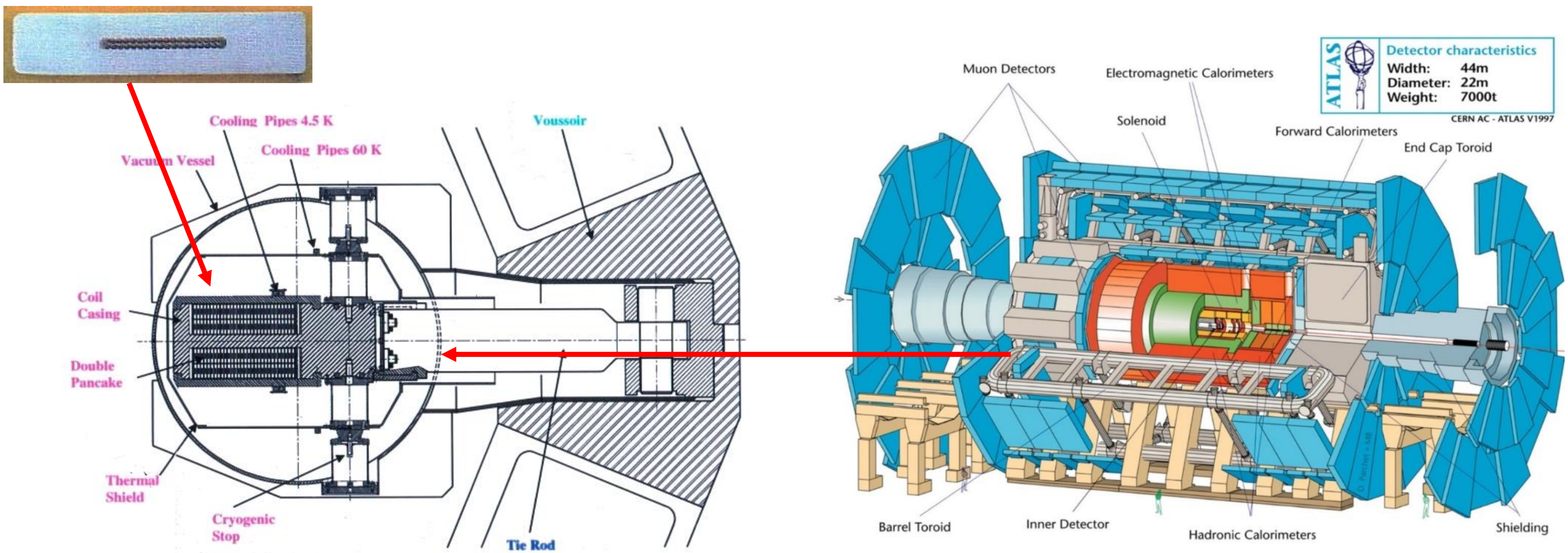
Other methods

- Temperature, pressure gages, pick-up coils, strain sensor, etc.
- Many proposed, but mostly not used.

Example ATLAS Toroids

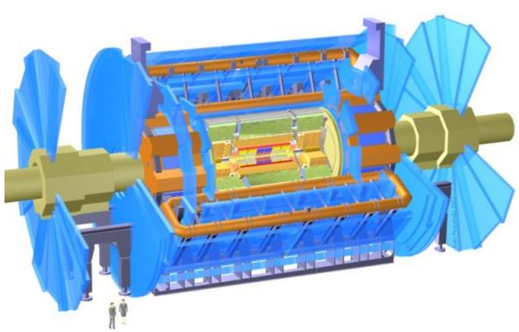
Toroid quench detection:

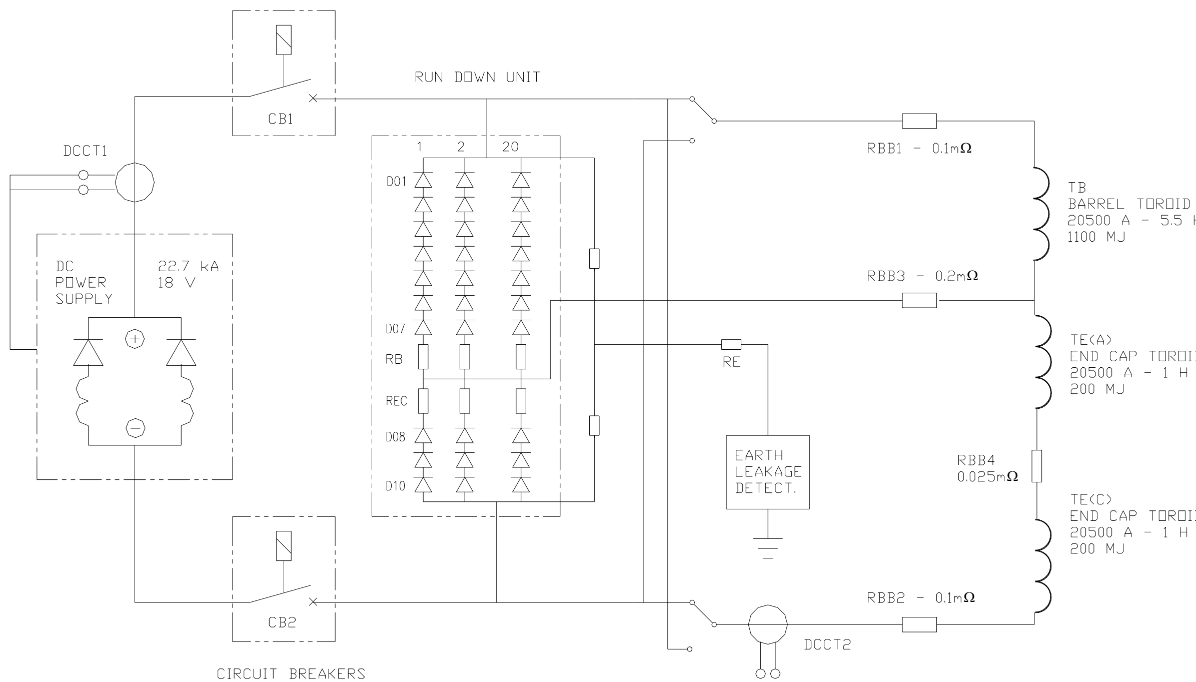
- 1.6 GJ stored energy, 20 kA current, 4 T peak field, 3 kJ/kg stored
- 3 toroids, each comprising 8 flat coils, thermally not connected
- 22 m diameter
- 5 m x 26 m long coils
- Largest toroid ever built.



Example ATLAS Toroids

- All toroid coils: 3 x 8 = 24 coils, are connected in series.
- The stored energy is dumped in the 3 toroid cold masses, voltage limited to 40 V.
- **Quench detection by 3 bridges + 3 differential units per toroid so 6 fold redundancy, heaters are fired introducing 4 normal zones in every coil, expected maximum hot spot temperature ≈ 100 K.**
- Threshold 0.3 V.
- Low pass filter 1 s.
- Fast dump in about 80 s.

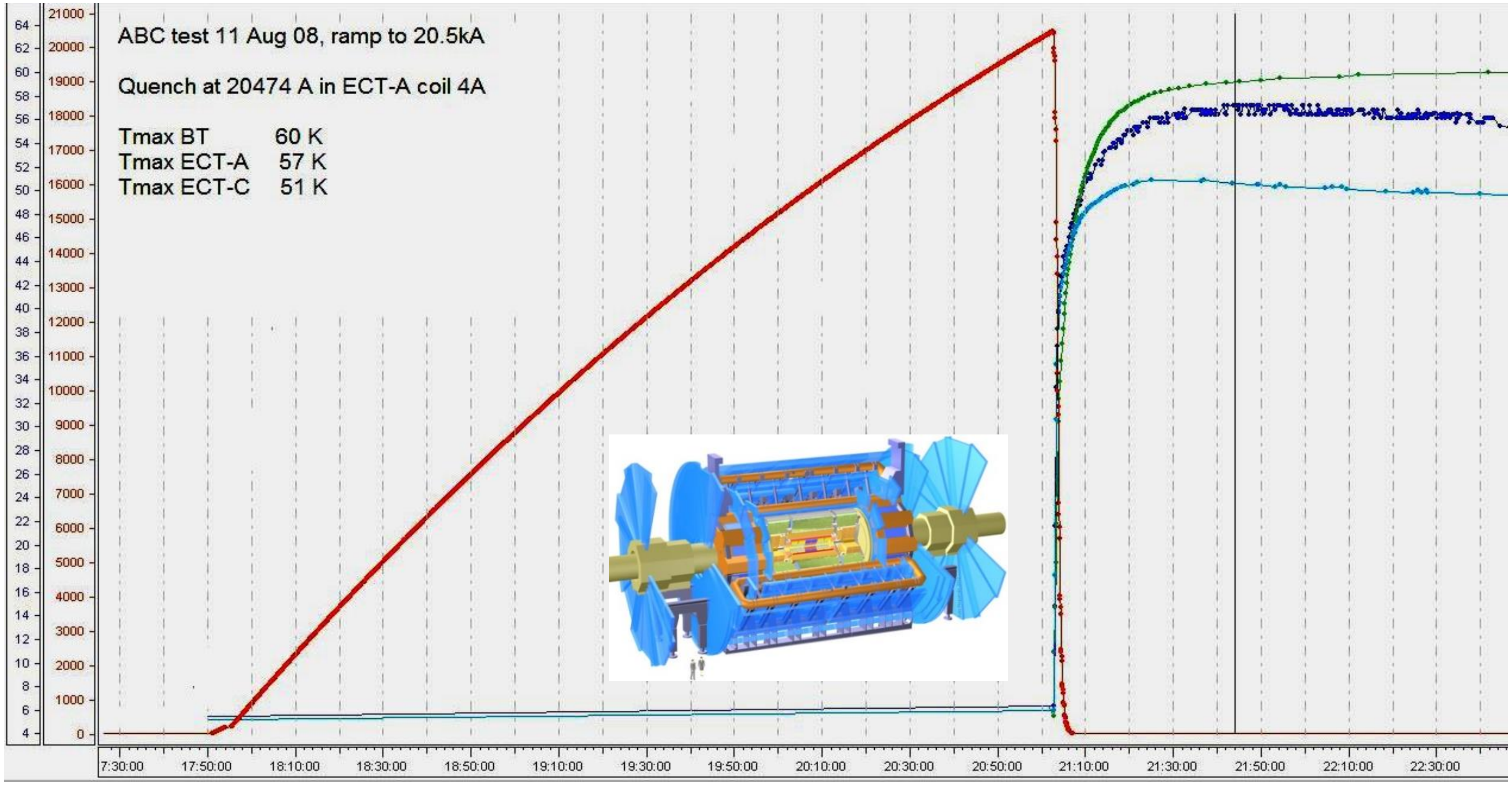




Example ATLAS Toroids

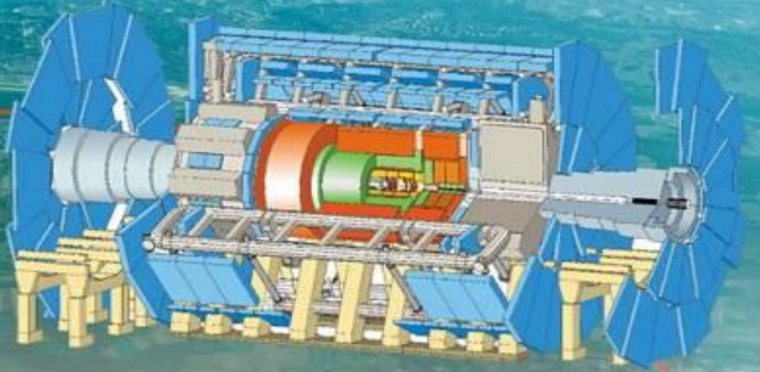
Toroid Fast Dump test result:

- Provoked quenches at 20.5 kA, heaters fired, quench is spread
- ≈ 60 K cold mass temperature at 20.5 kA, recovery in about 80 hours
- ≈ 90 K hot spot in the conductor, perfectly safe quench behavior.



Break - 2

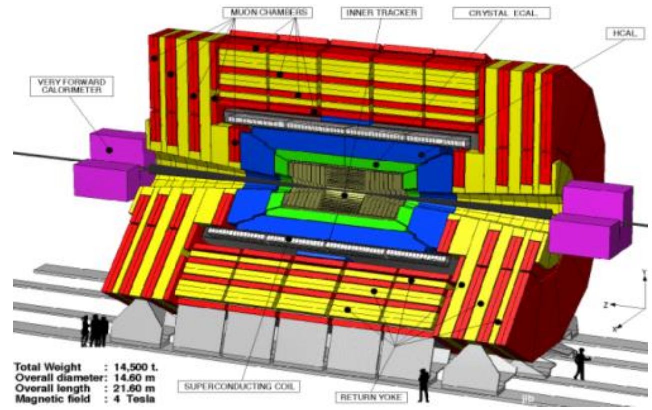
3. Designing a Detector Magnet, example CMS solenoid



Video-3

Design steps: Example CMS solenoid

1. Magnetic field calculation
2. Effect of the iron yoke
3. Magnetic stored energy
4. Lorentz forces in the coils
5. Hoop stress
6. Choosing current vs self-inductance
7. Conductor dimensions and layers
8. Conductor details
9. Stabilizer, Cu or Al



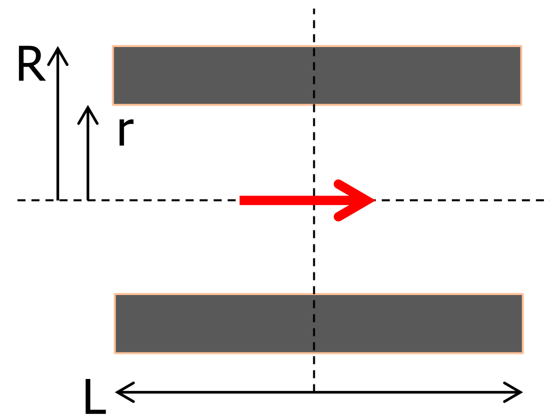
Design steps: Magnetic field, no iron

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 $\beta \rightarrow \infty$

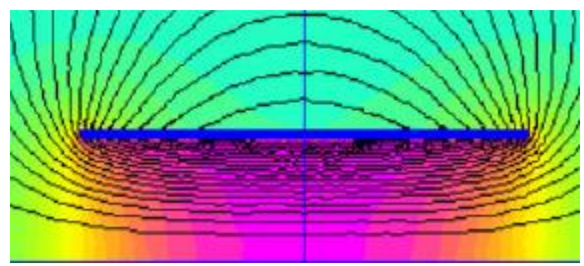


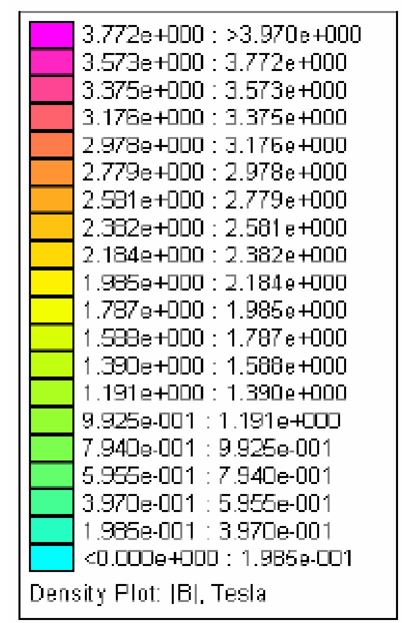
$\alpha = R/r$
$\beta = L/2r$

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





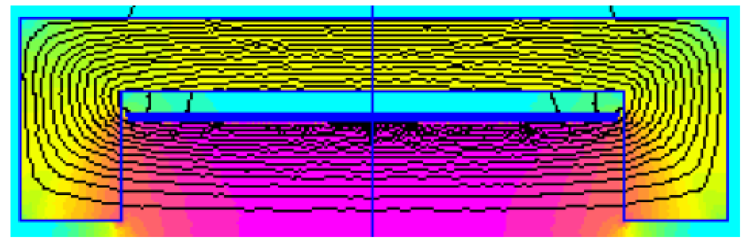
- We find: $B_o(\alpha,\beta) = 3.77\ T$ (88% of infinite)
  $B_o(\beta = \infty) = 4.27\ T$

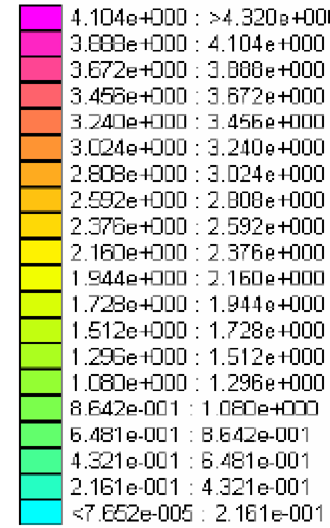
- With a FEM code we find 3.77 T as well.

Design steps: Magnetic field, with iron

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

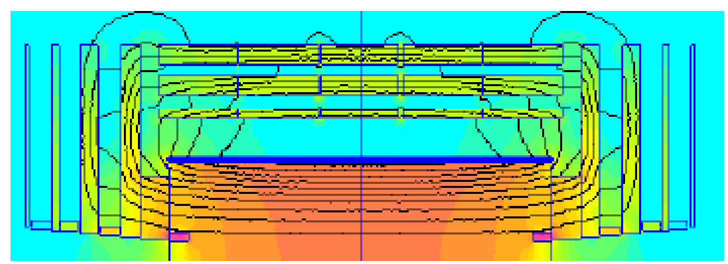
- Simple solid magnetic yoke:
- B_o = 4.17 T (98% of infinite).

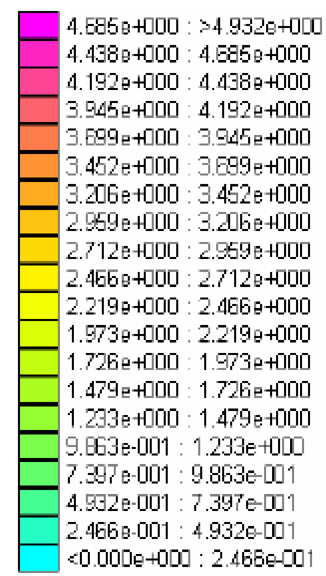




Iron is a magnetic mirror, the coil is almost infinite.

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

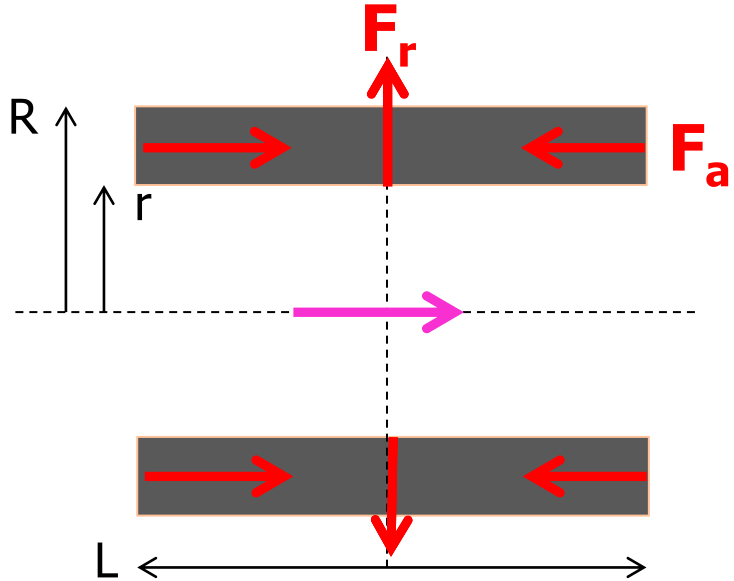




Stored energy:

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

Design steps: Magnetic forces



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

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

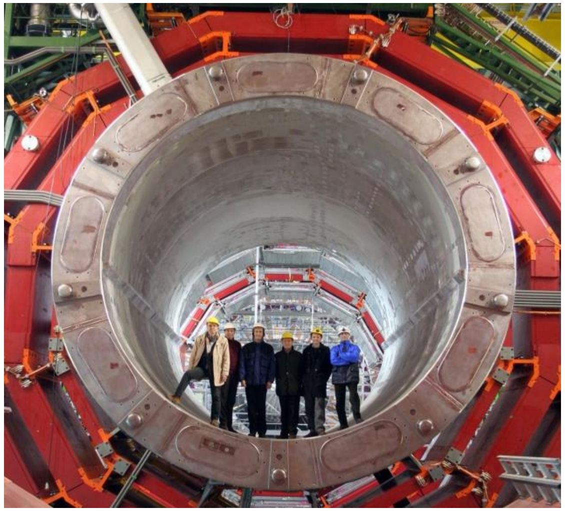
- Radial field causes axial force F_a
- Axial field causes radial forces F_r
- In fact the solenoid wants to blow up into a ball shape

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:

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

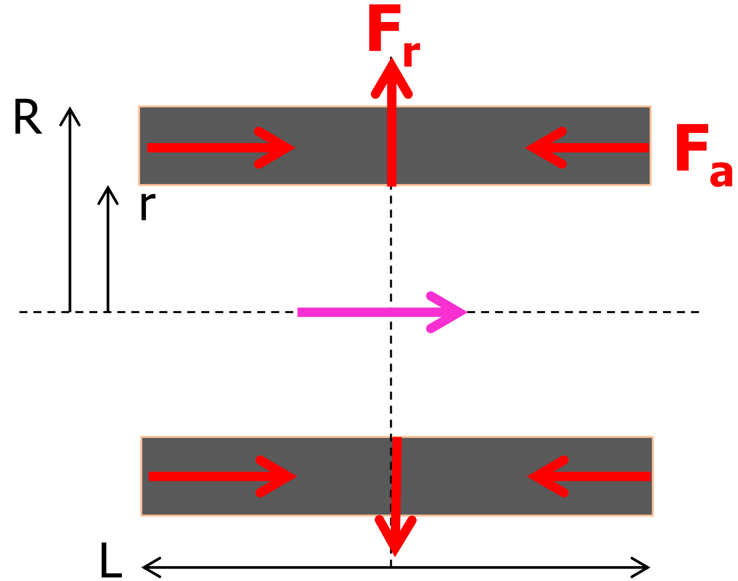
Structural coil thickness:

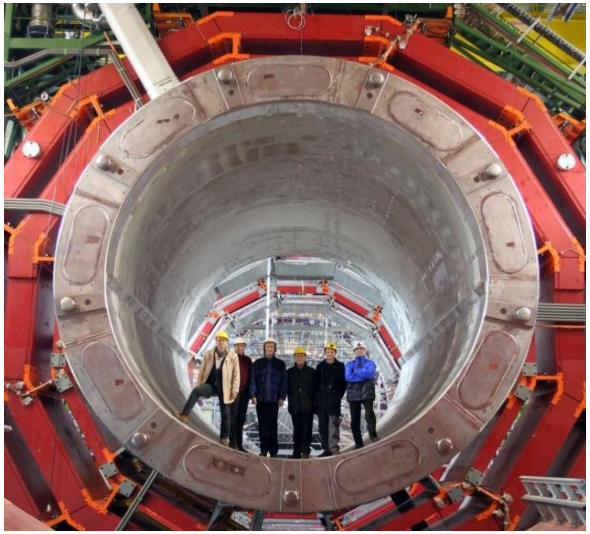
$$t = {}^{3\,r\,P_r}/_{2\,\rho_{yield}} = 320\ mm\ ,$$

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.



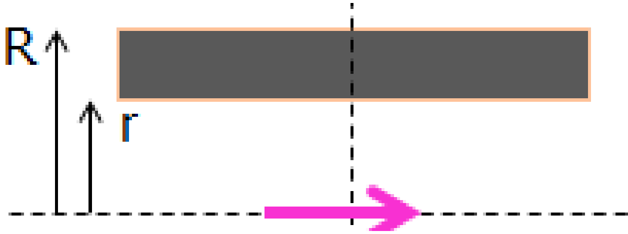


Design steps: Current vs self-inductance

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:

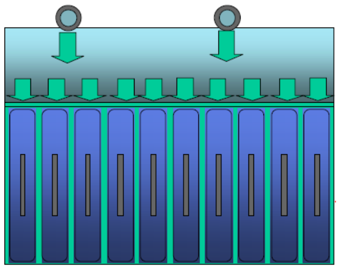
- 2180 turns of superconducting cable with 19.5 kA
- extra stabilizing and quench protection material around the cable
- conductor insulation
- structural reinforcement for handling the hoop stress
- an outer support cylinder for integrity and conduction cooling supply.

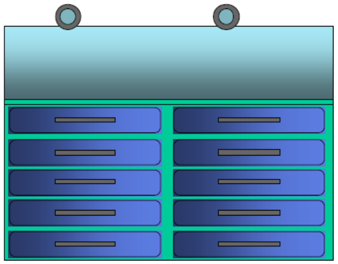
Design steps: Conductor size and layers

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.





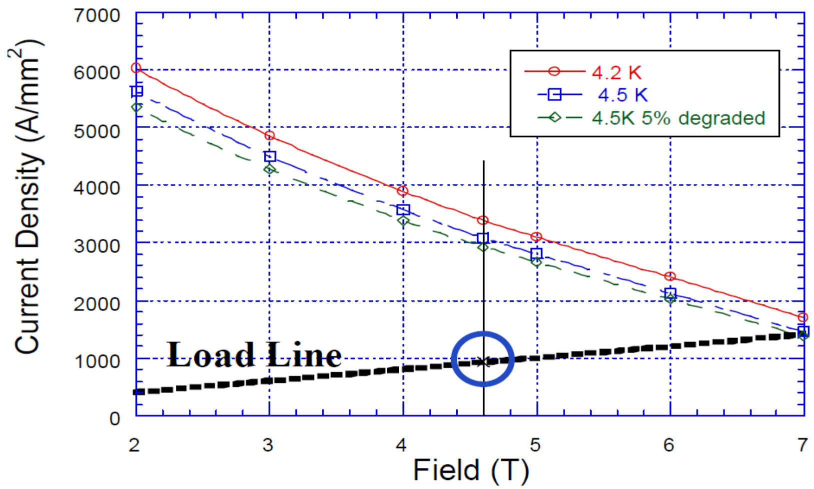
There is a thermal argument as well:

- **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.**

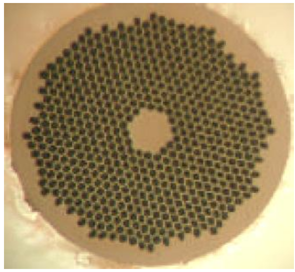
Design steps: Superconductor needed

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.

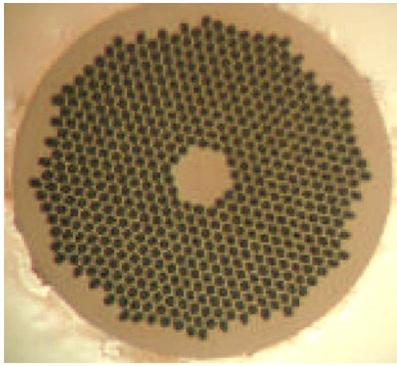


- 19500 A and 1000 A/mm^2, → need 19.5 A/mm^2 superconductor per turn in the cable
- Self-field stability → wire diameter <1.28 mm
- A minimum Cu/sc ratio is 1:1/1 → Asc= 0.61 mm^2
- Number of strands in the cable is then 19.5/0.61 = 32
- Filament size? Adiabatic filament stability requires <40 µm
- 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:

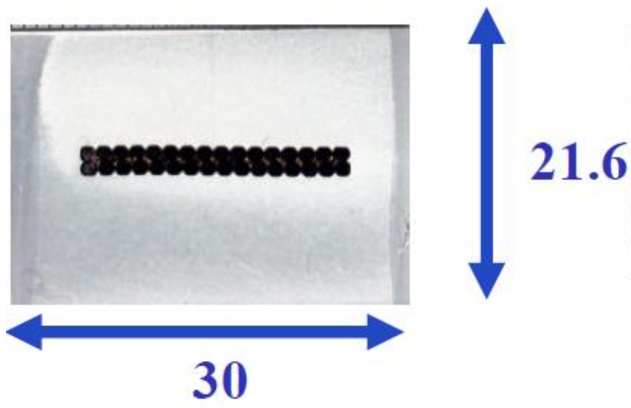


Strand Constituents	Material
High homogeneity Nb-Ti	Nb 47±1 Wt % Ti
High Purity Copper	RRR > 300
Niobium Barrier	Reactor Grade I
Strand Design Parameters	**Parameters**
Strand Diameter	1.280 ± 0.005 mm
(Cu+Barrier)/Nb-Ti ratio	1.1 ± 0.1
Filament diameter (mm)	< 40
Number of Filaments	• 552
Strand Unit length (m)	2750
Twist Pitch	45 ± 5 mm Z (RHS
Strand Minimum Critical Current *Ic* (A) (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

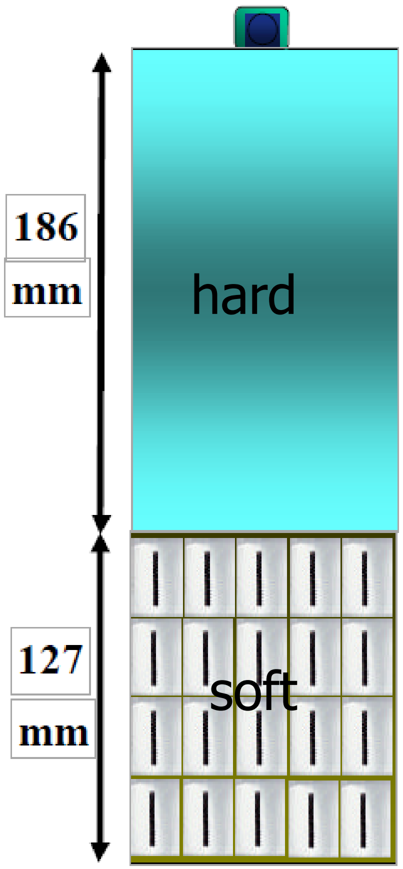
The cable is co-extruded with high purity Al (RRR>1500)



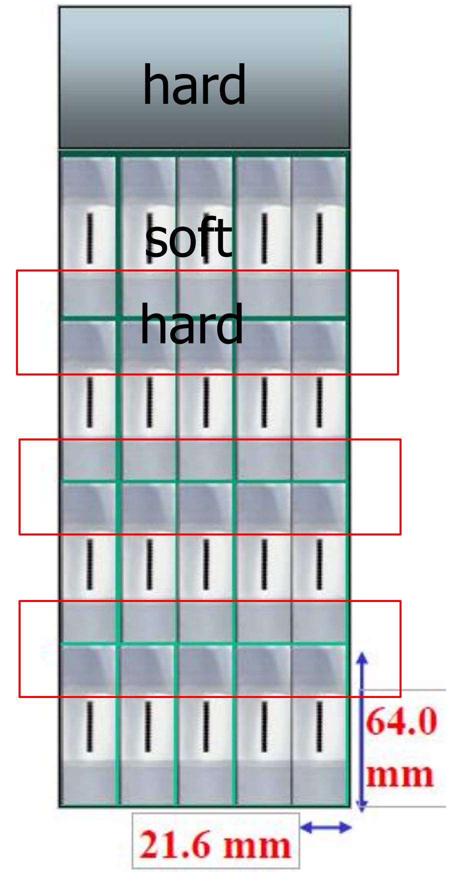
Coil windings: the build-up

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 !

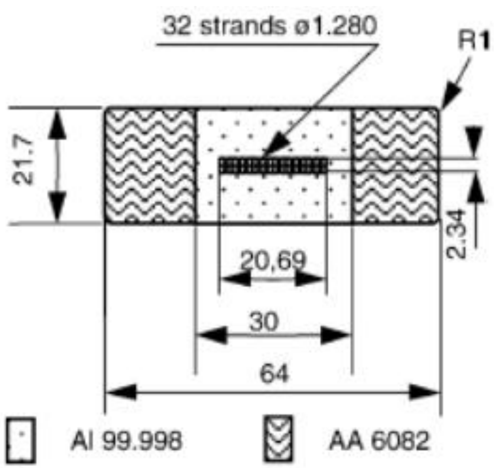


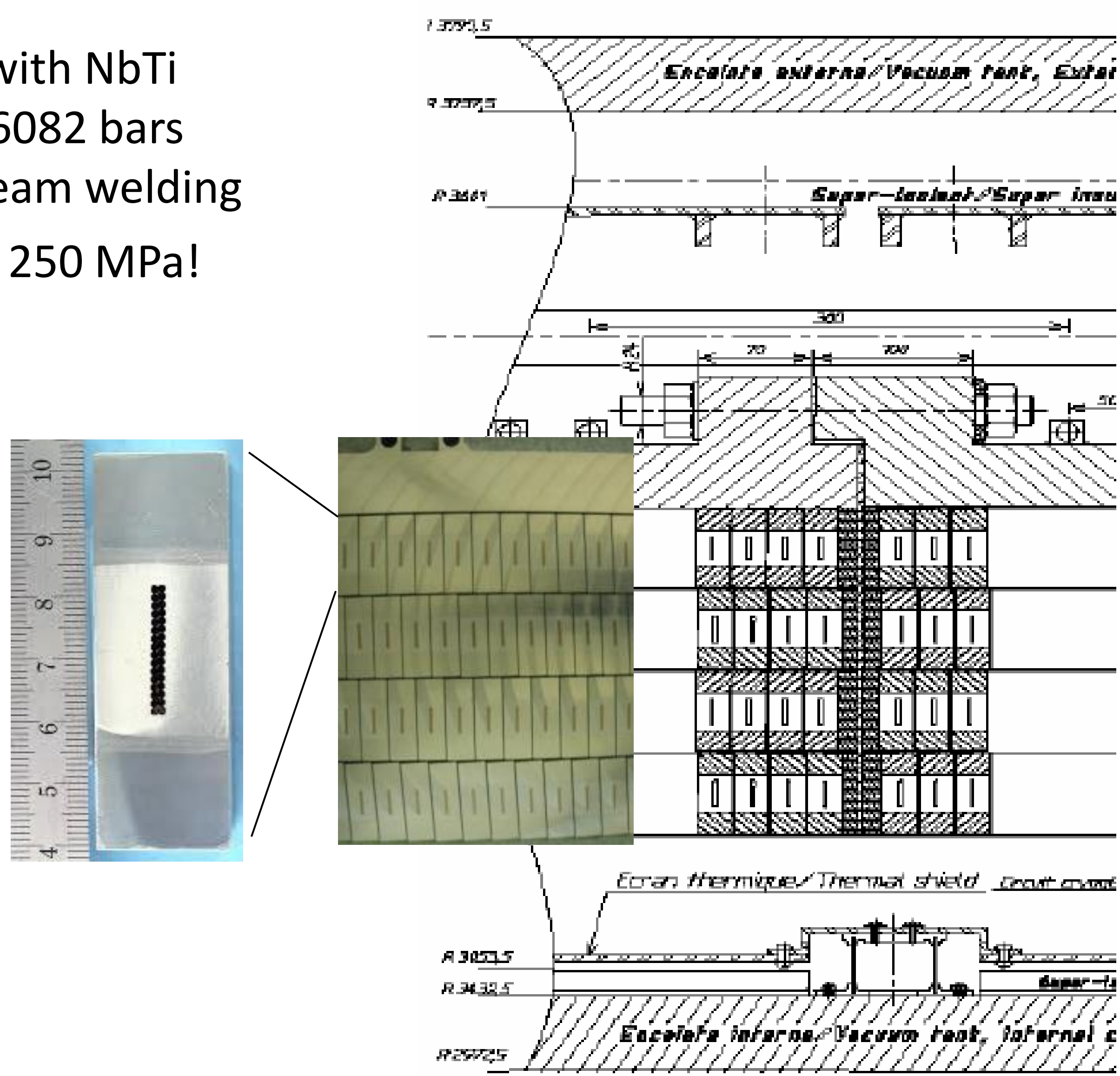
- High shear stress at interface
- In the 4 layers , axial forces up to 1400 MN gives 55 MPa in the pure Al >> 20 MPa, not possible.
- Soft 4 layers of 127mm +186mm gives 22 MPa, is acceptable but strain and shear stress is not uniform.
- A much better solution is to mix soft Al stabilizer and harder 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

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

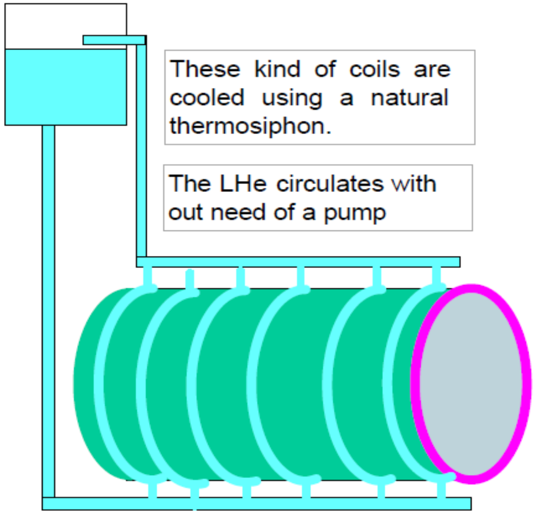




Making of CMS Solenoid: support cylinder

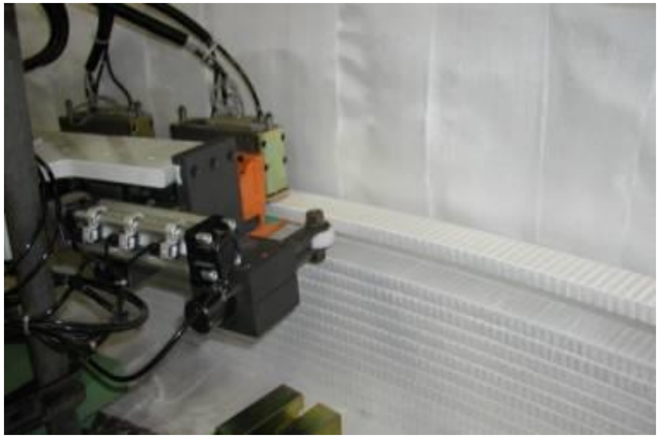
- The CMS magnet cold mass was made in 5 units mostly at ASG – Genua, transported to CERN for on-surface assembly and then insertion as a whole in the CMS cavern.

Support cylinder manufacturing, 5 units

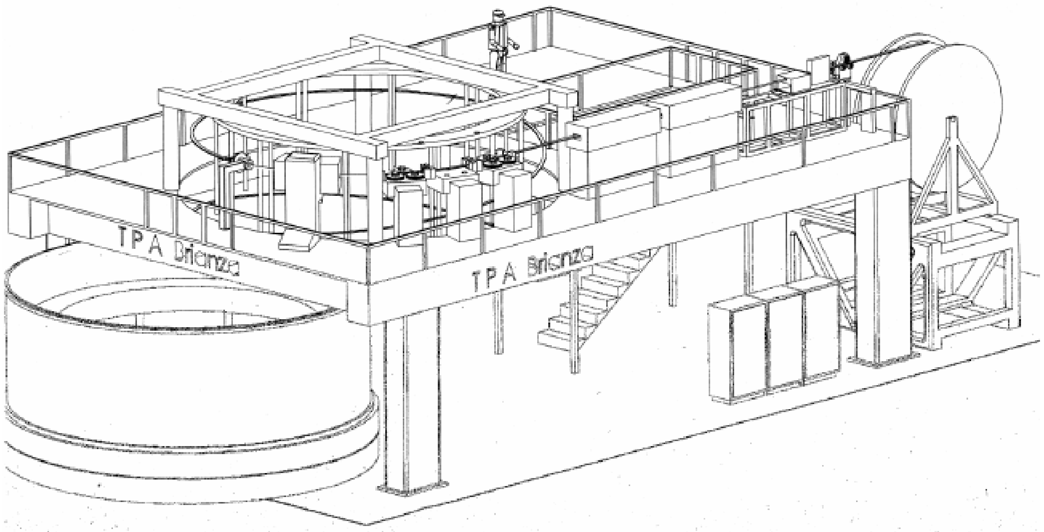


Thermal siphon cooling layout, pipework welded to the cylinder

Making of CMS Solenoid: coil winding



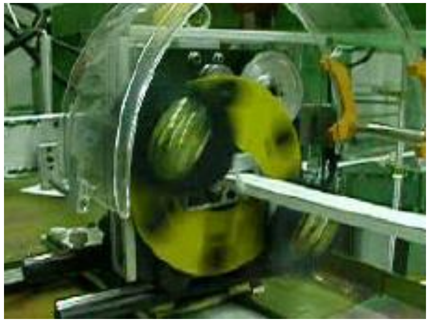
Bend conductor pressed against cylinder



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

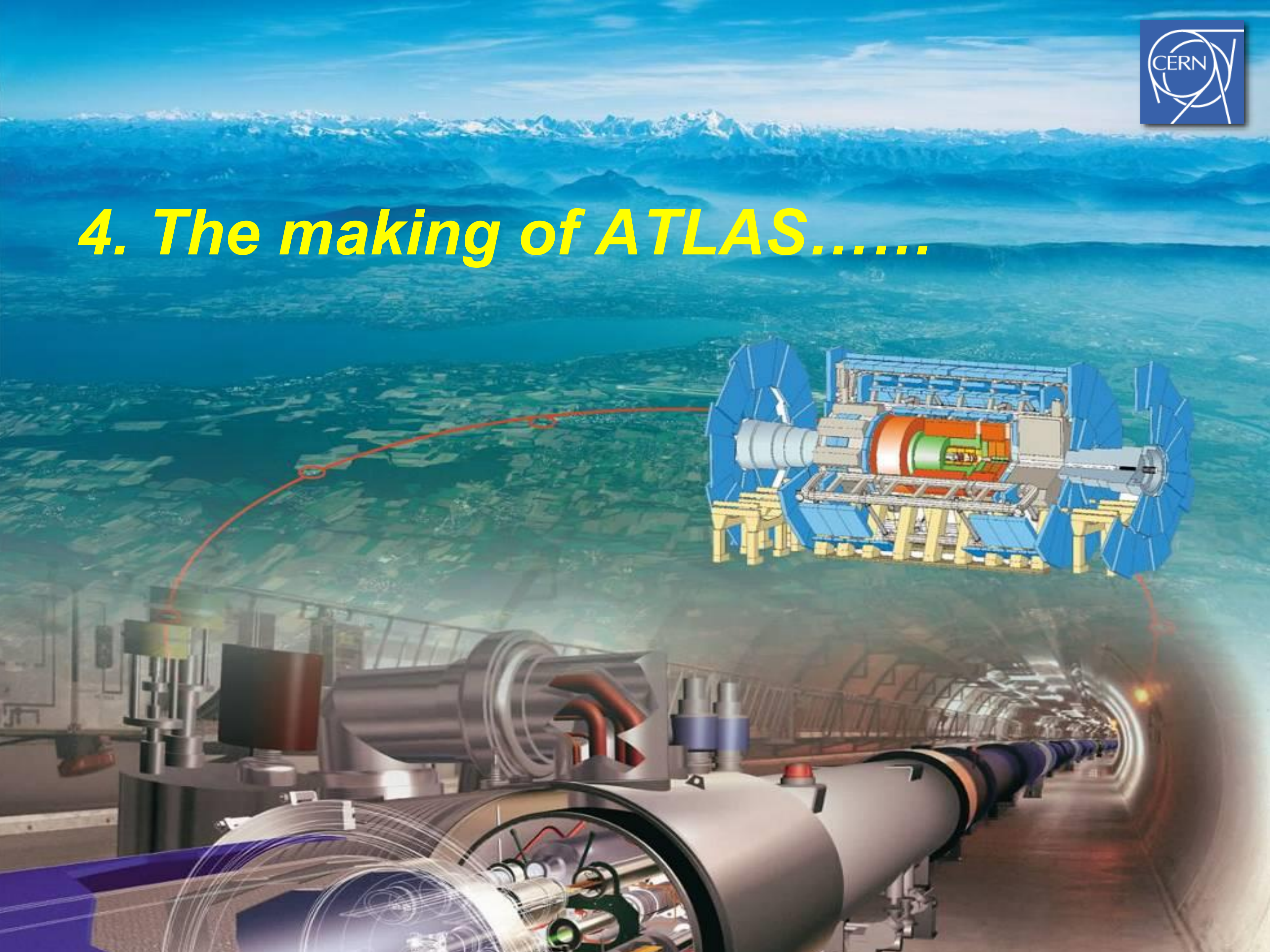
Making of CMS Solenoid: vac impregnation

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

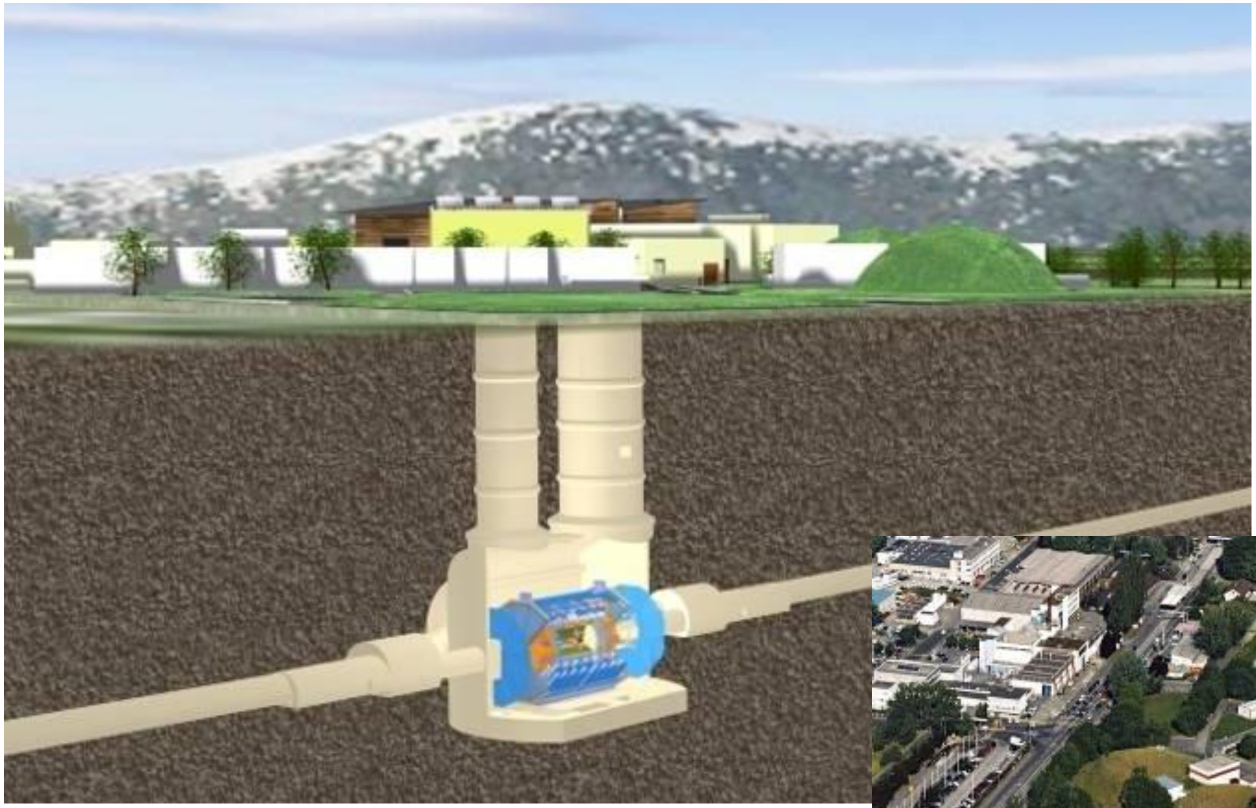
Making of CMS Solenoid: assembly on site

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

4. The making of ATLAS……



ATLAS on surface and 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 provide 2 T magnetic field for the inner detector (solenoid) and ~1 T for the muon detectors in blue (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

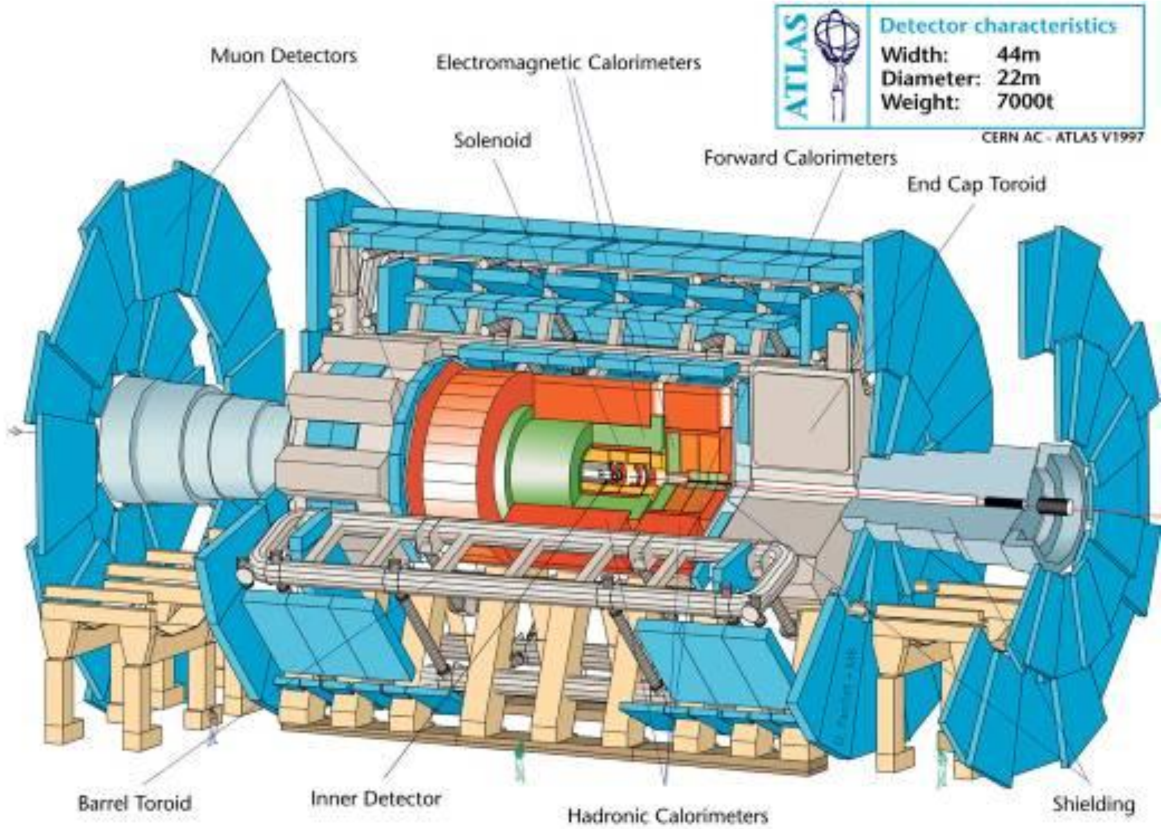
90 km superconductor

20.5 kA at 4.1 T

1.6 GJ stored energy

4.7 K conduction cooled

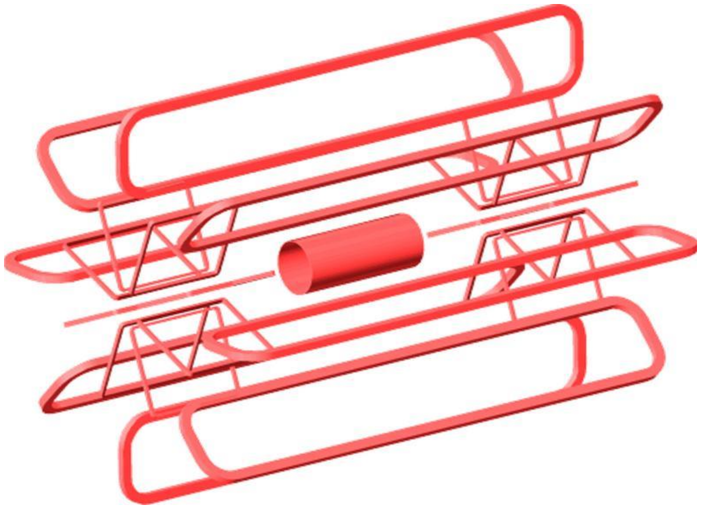
9 yrs of construction 98-07

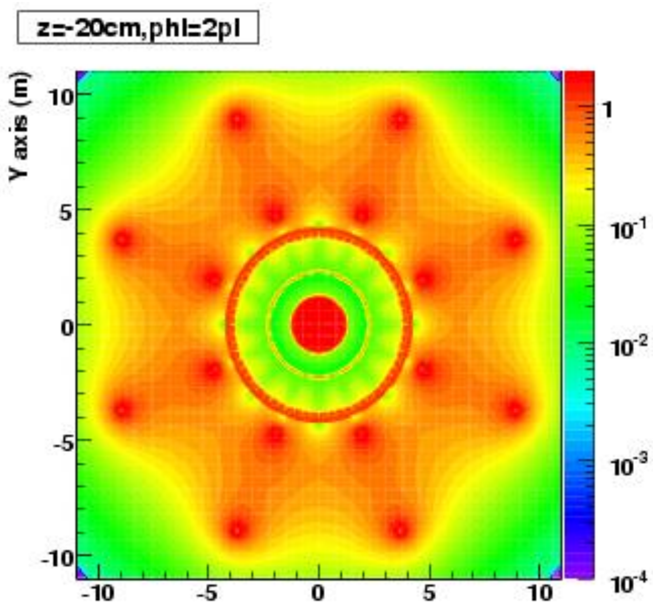


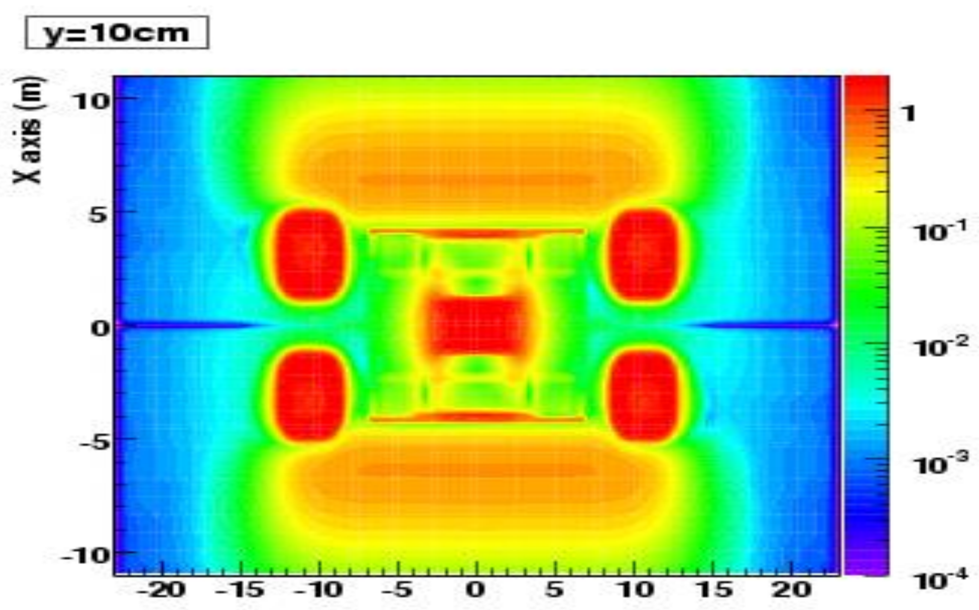
So far the largest trio of toroids ever built

Magnetic field configuration

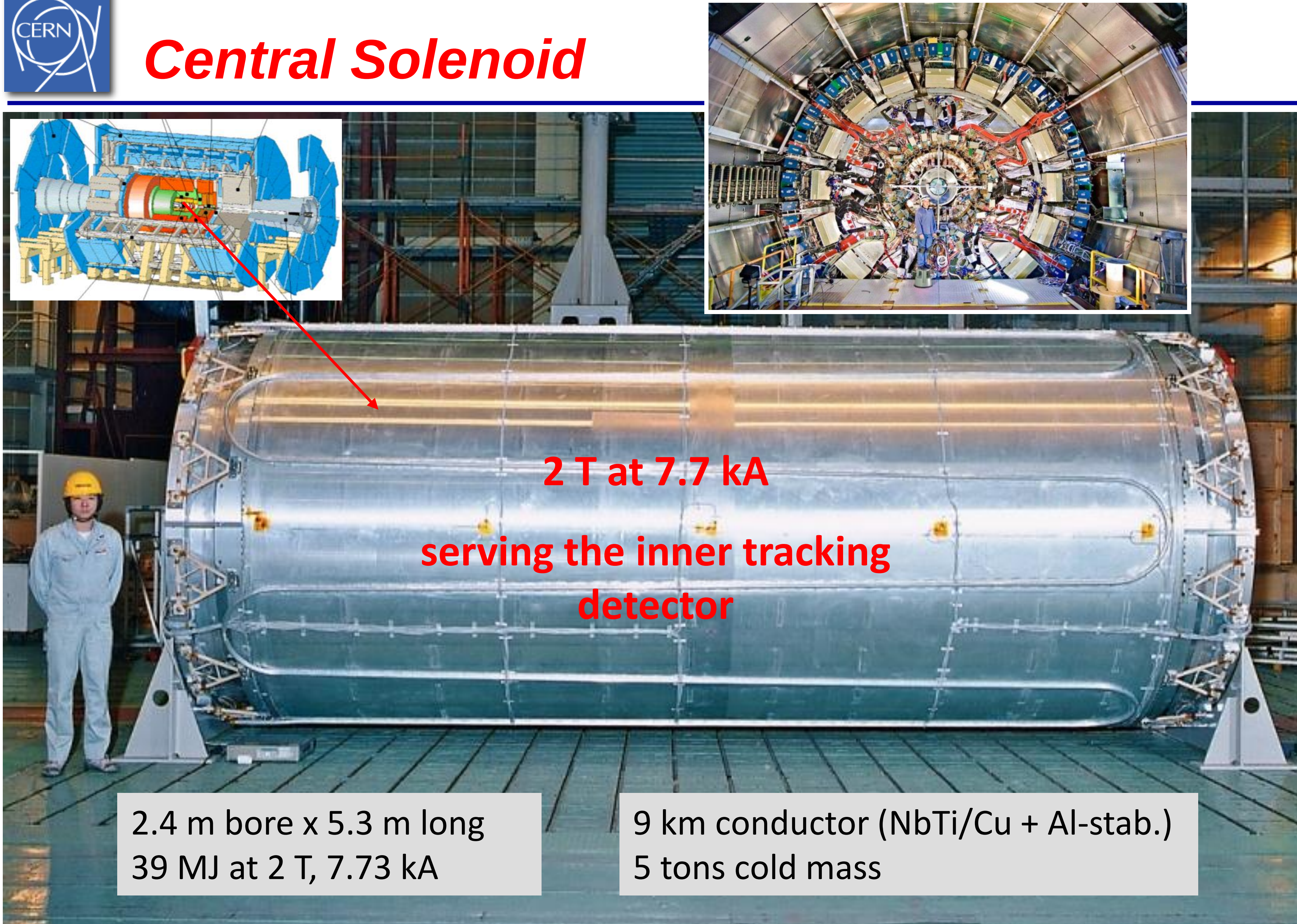
- 2 T in Solenoid closed via return yoke
  2.6 T peak in windings
- ≈ 0.8 T average in Barrel Toroid torus
  3.9 T peak in windings
- ≈ 1.3 T average in End Cap Toroid
  4.1 T peak in windings







Central Solenoid



2 T at 7.7 kA

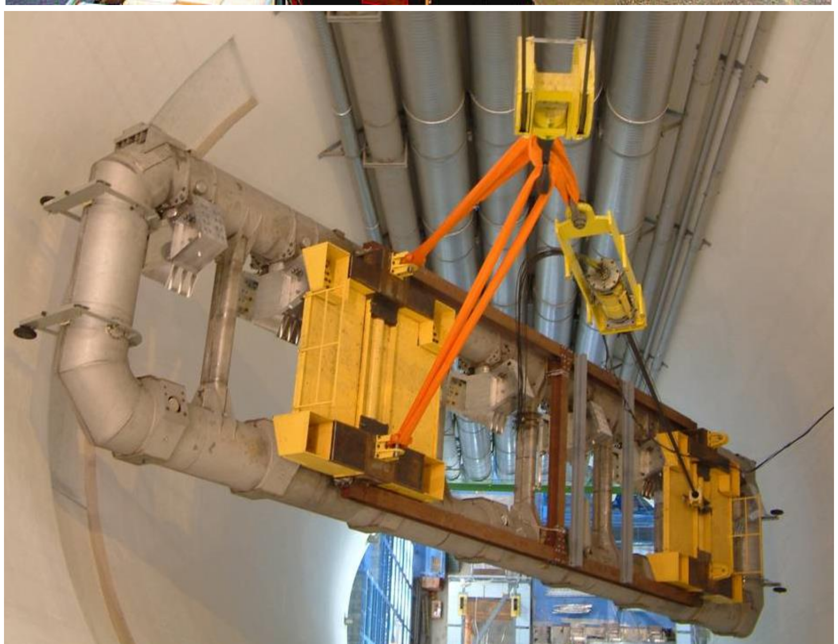
serving the inner tracking detector

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

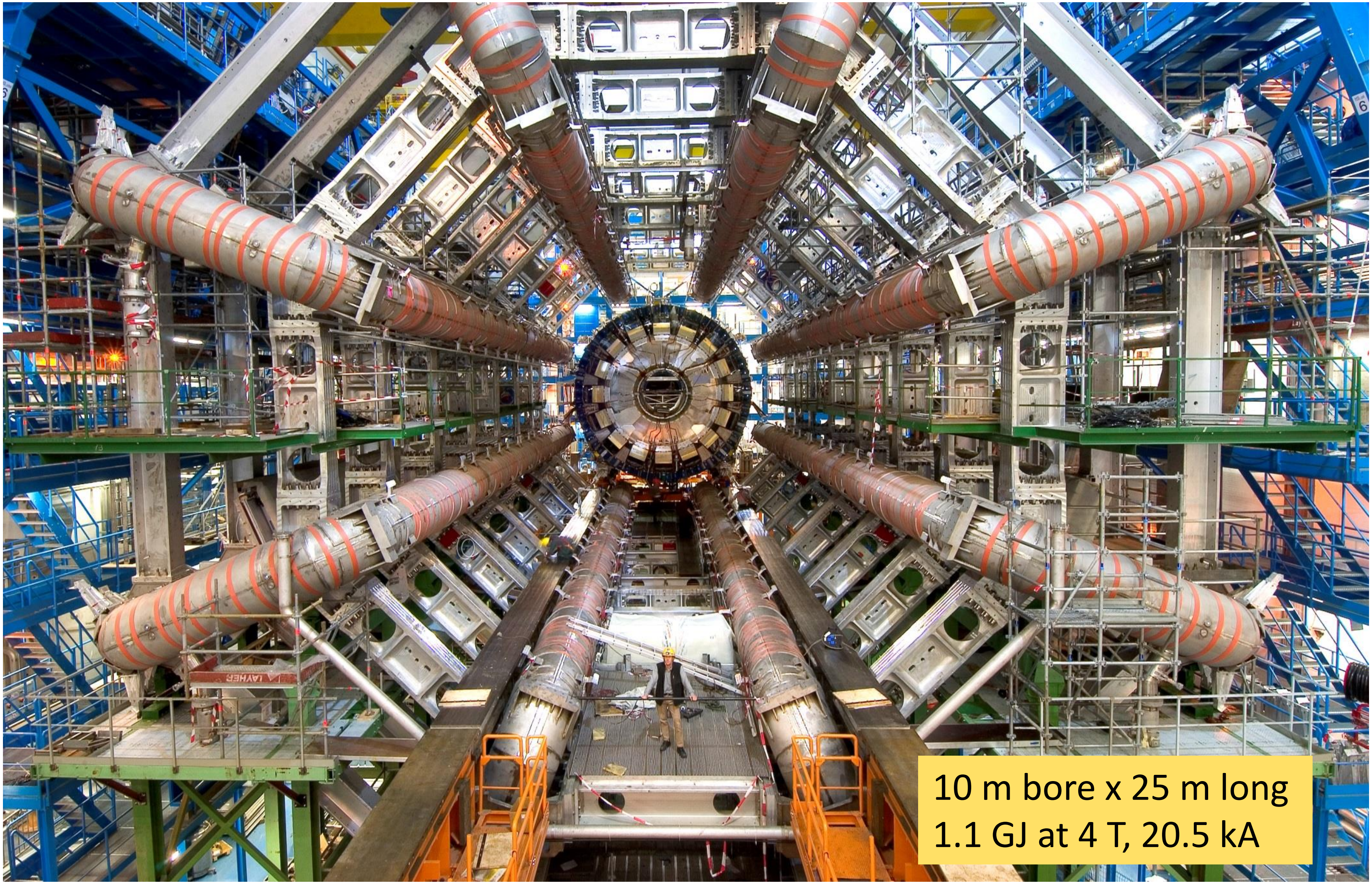
ATLAS: Barrel Toroid manufacturing

ATLAS: Start of Barrel Toroid assembly



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

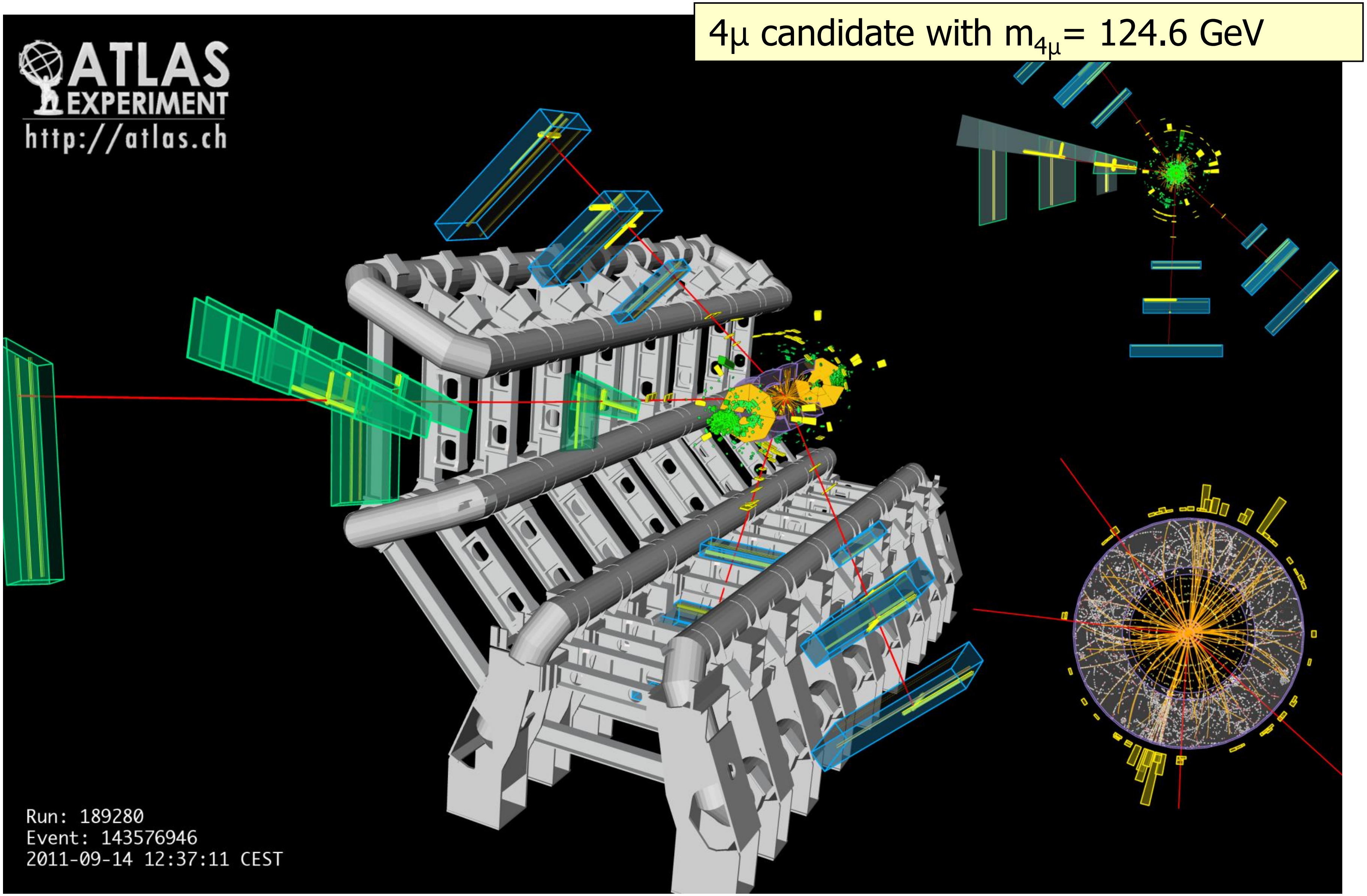
ATLAS: Barrel Toroid in cavern (Nov 05)



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)



July 4, 2012
CERN press conference

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

ELSEVIER

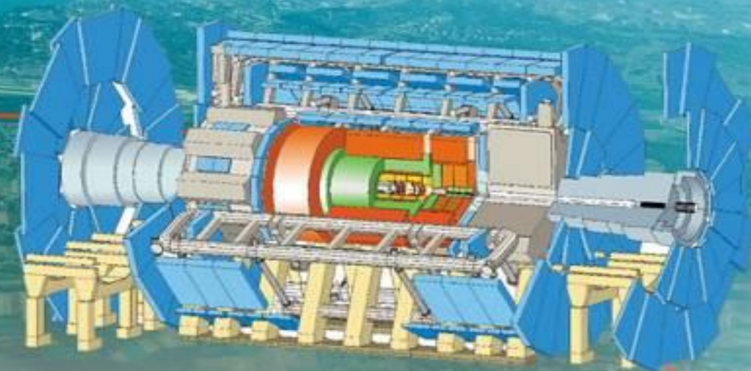
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

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

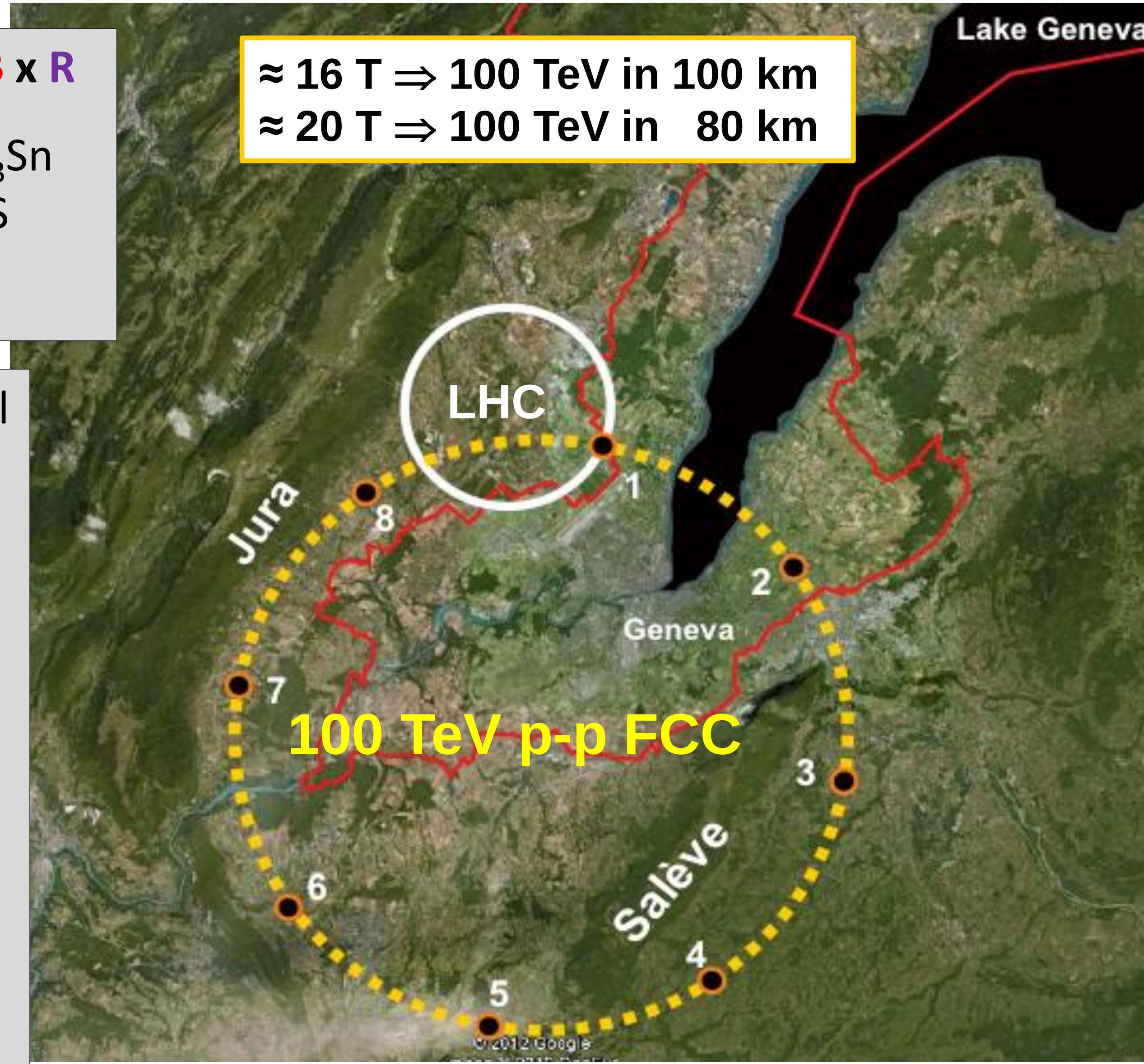
Example Baseline Detector for FCC-hh

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

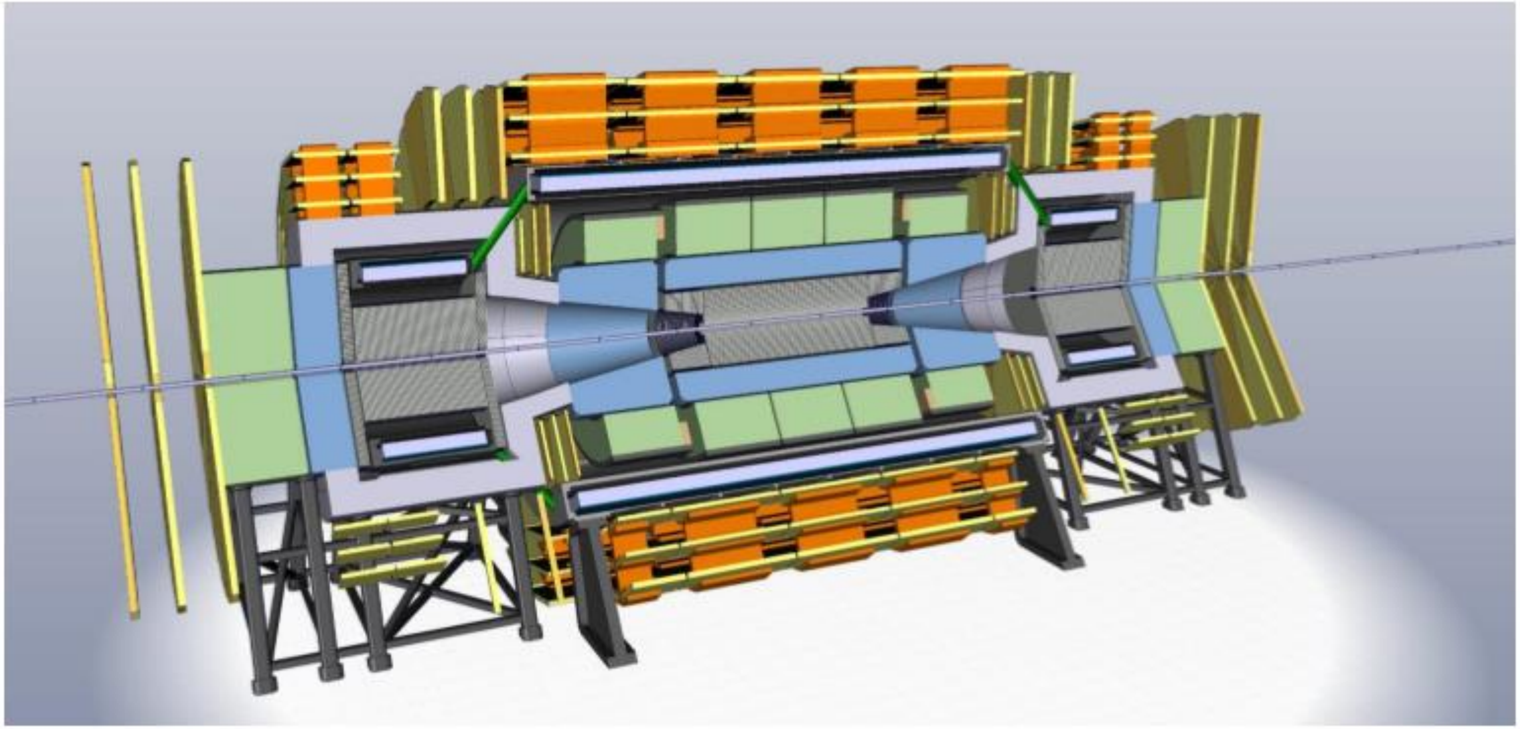
- New 80-100 km tunnel in Geneva area
- pp-collider defining the size
- e+e- collider may come first
- Option p-e collider
- CERN-hosted study with international collaboration



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

FCC-hh general purpose reference detector

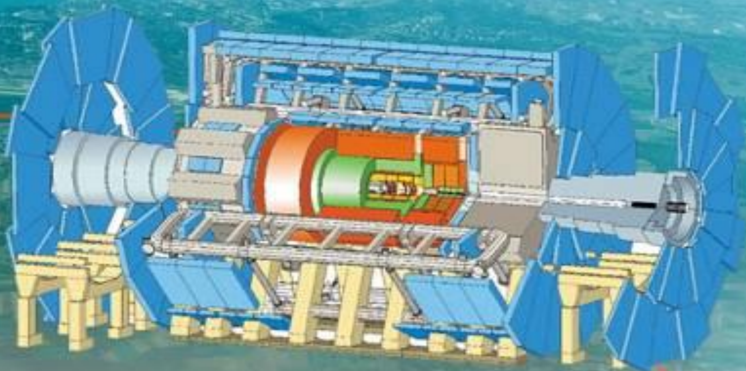
100TeV pp collisions, $L_{peak} = 3x10^{35}$ $cm^{-2}s^{-1}$, L_{int} =3/30 ab^{-1}
25ns/5ns bunchcrossing, pileup 1000/200 per bunchcrossing



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

End of video-3.

Study all this and I will test you next Monday in the Q&A session to see whether you understand the essence……



6. Exercises
“Superconductors & Magnets for Detectors”

Problem 1: Sizing a practical superconductor for a 10 T magnet

Assume you want the make a superconducting magnet of 10T with a bore of 2 m diameter and bore length of 8 m.

a) Calculate roughly the stored energy.

b) This stored energy ($0.5LI^2$) needs to be dissipated in and external resistor within 1 minute (assume linear decrease to zero) and the voltage ($V=LI/t$) is limited to 1000V.
What is the minimum safe operating current of this magnet.

c) So we need a cable, but how does it look? For a 10T magnet at 4.2K, which superconductor do we need?

d) Assume a wire with 1.0 mm diameter, critical current density 4000 A/mm^2 at 10 T and 40 % superconductor in the wire.

What is the area of superconductor in the wire?

Which current can this wire take when we assume we take a margin of 70%?

e) How many wires do I need in the cable to make 33 kA: ?

f) When we make a twisted Litze cable (3x3x3xetc.), what would be the size, the diameter of this cable?

Problem 2: Understanding the effective resistivity of a superconductor

R=0 in a superconductor when it is perfect, uniform, free of defects etc. In practice, however it is never perfect and we can take as a criterion 1 or 10 uV per meter of wire.

For MRI applications Philips Healthcare requires some 50 km of wire in one piece and perfectly connected in a persistent mode. A typical MRI magnet has 3 T in a volume of say 1 m^3 and the magnet operates at 200A.

a) What is the inductance of the magnet ?

b) What is the voltage drop across the coil with 50 km of wire operating at 1μV per meter ?

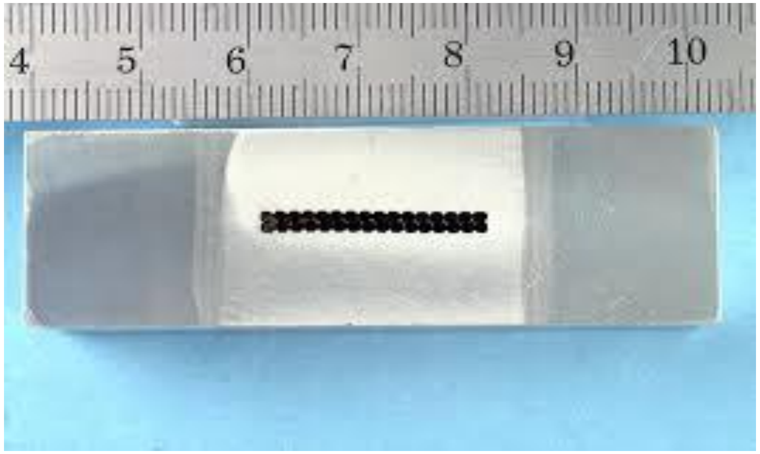
c) What is the effective resistance of the magnet ?

d) What is the current decaying time constant of the magnet ?

e) Is this a good value for an MRI magnet that should be stable in 1ppm/h ?

f) What would be the maximum resistance tolerated across the wire and the maximum voltage per meter?

Problem 3: Understanding a conductor for a Detector Magnet



Write a half page summary on what we see in this picture.
Mention all relevant issues determining the shape and internal layout of this conductor.

Problem 4: Minimum propagation zone / Minimum quench energy / Adiabatic filament stability

1. A 0.8 mm diameter superconducting wire used in the magnet of problem 1 has 40 % copper in it, and is electrically insulated with an epoxy resin, with the following properties at 4.2K and 15T:

   - Electrical resistivity : $\rho = 3\ 10^{-10}\ \Omega$ m
   - Thermal conductivity of Cu: $\lambda = 200$ W m^{-1} K^{-1}.
   - Thermal conductivity of wire insulation: $\lambda = 0.03$ W m^{-1} K^{-1}.

   The magnet is running at 4.2K with 2.6K temperature margin. Current is 187.5A at 15T.

   What's the local current density in the Cu if the winding locally becomes normal (assume all current flows in the Cu)? Using the thermal margin ΔT work out the length L of the minimum propagation zone.

2. The specific heat of Cu and Nb3Sn under the magnet working conditions are given below.

   - Specific heat copper : $c_{Cu} \approx 800$ J m^{-3} K^{-1}
   - Specific heat Nb_3Sn : $c_{Nb3Sn} \approx 11\ 000$ J m^{-3} K^{-1}

   Work out the minimum quench energy MQE, i.e. the energy required to establish a minimum propagation zone, the energy required to heat up the Minimum Propagation Zone MPZ.

European School of Instrumentation in Particle & Astroparticle Physics

Problem 4: Minimum propagation zone / Minimum quench energy / Adiabatic filament stability

3. What is the Lorentz force F_L acting on the wire in the maximum-field zone of the magnet? If the wire slips over a distance dx under influence of this Lorentz force, how big would this distance need to be for the energy released to establish a minimum propagation zone? Is this a likely disturbance?

4. Under normal operation, what's the current density in the Nb_3Sn filaments? Still using the same thermal margin ΔT, work out the maximum allowable filament diameter d_{fil} to ensure adiabatic filament stability. How many filaments must the wire minimally contain? Is this realistic?

This concludes the course……..