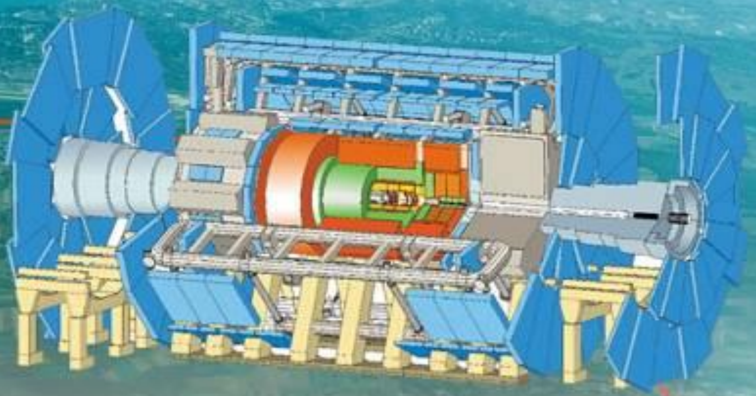
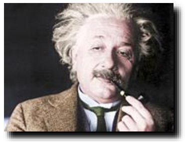
Superconducting Detector Magnets

Herman ten Kate



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

ESIPAP School
Archamps, March 12, 2018

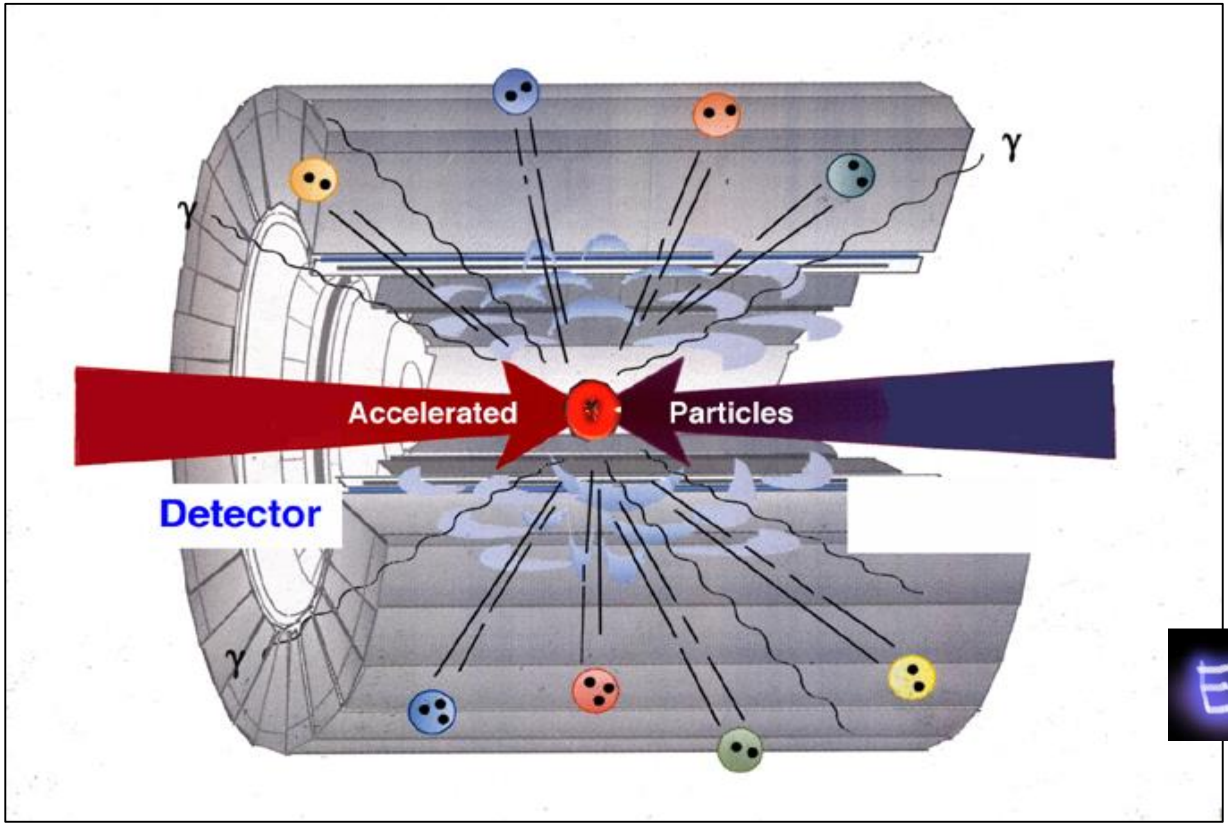


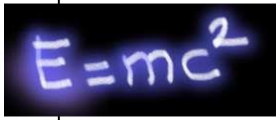
1. Concept: $E = mc^2$

How to discover new (elementary) particles?

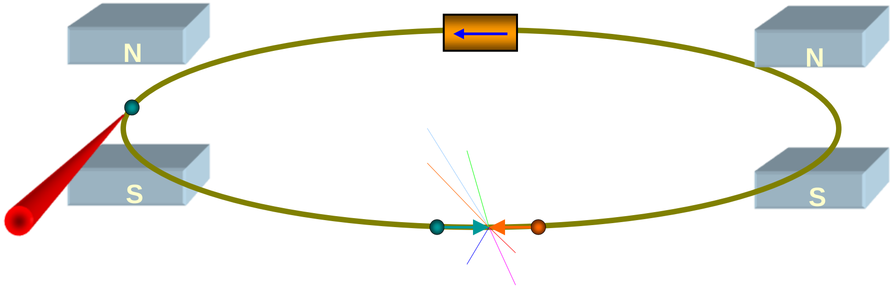
✓ **$E = mc^2$**, produce particles from a spot of energy and seek…

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





Concept: Colliders, circular vs. linear



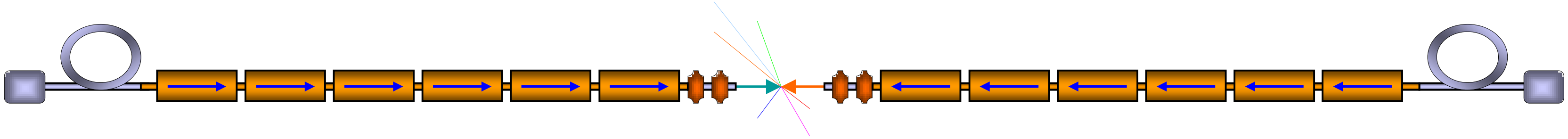
Collision energy

$E_{TeV} \cong 0.3\, B_T\, R_{km}$

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.

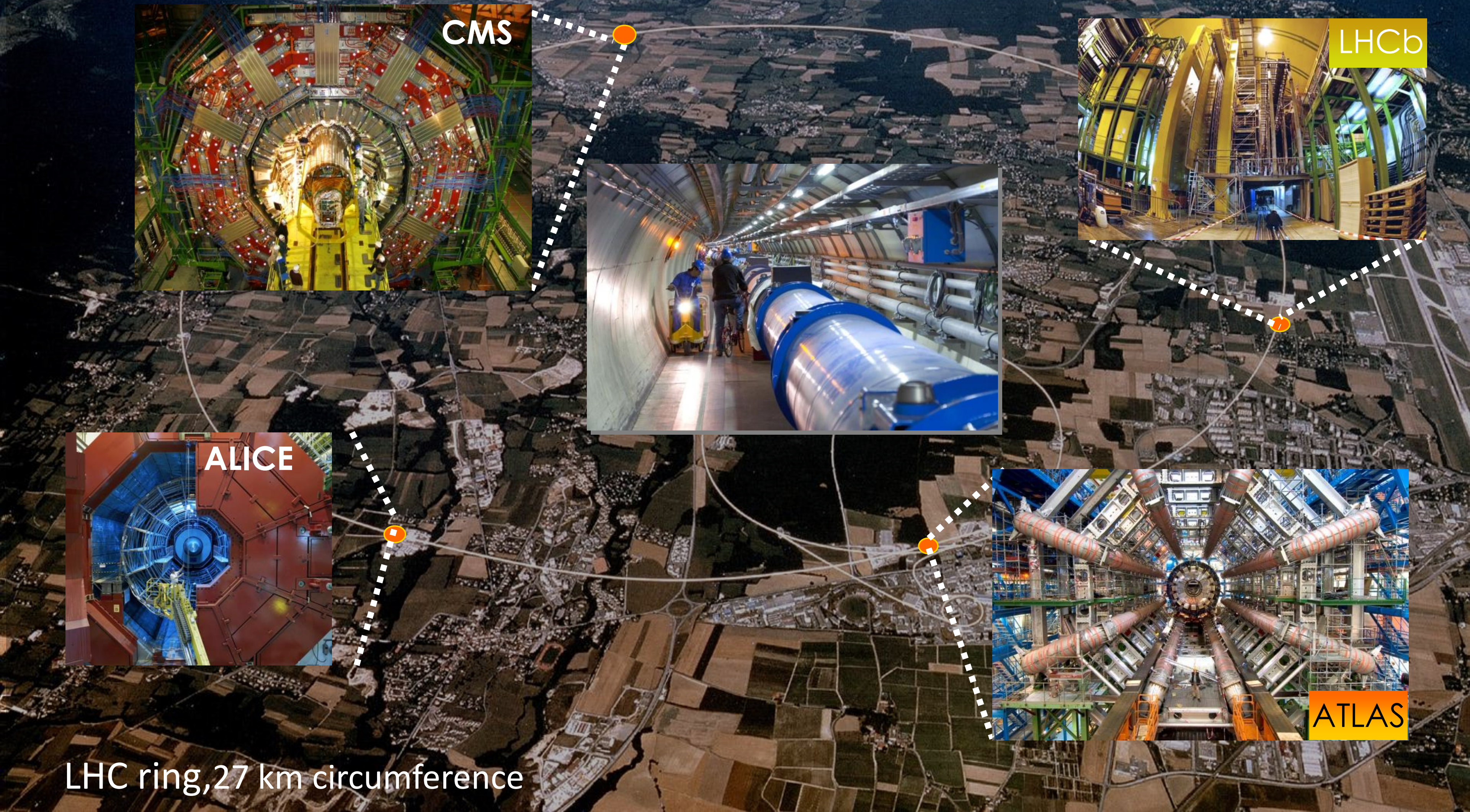


Linear Collider:

- 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: Large Hadron circular Collider

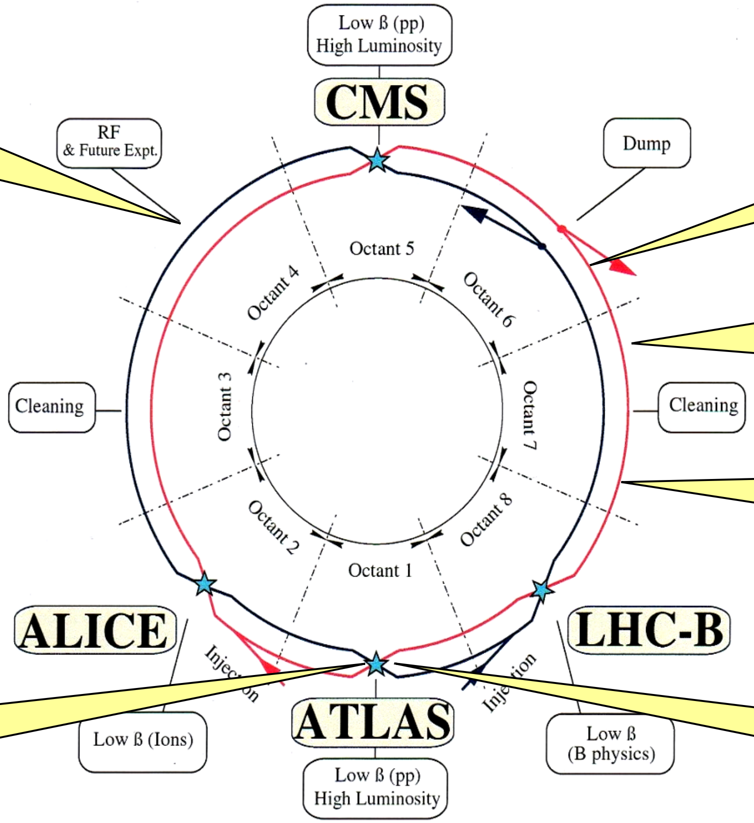
Exploring the energy frontier between up to 13-14 TeV using proton-proton & Pb-Pb collisions



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

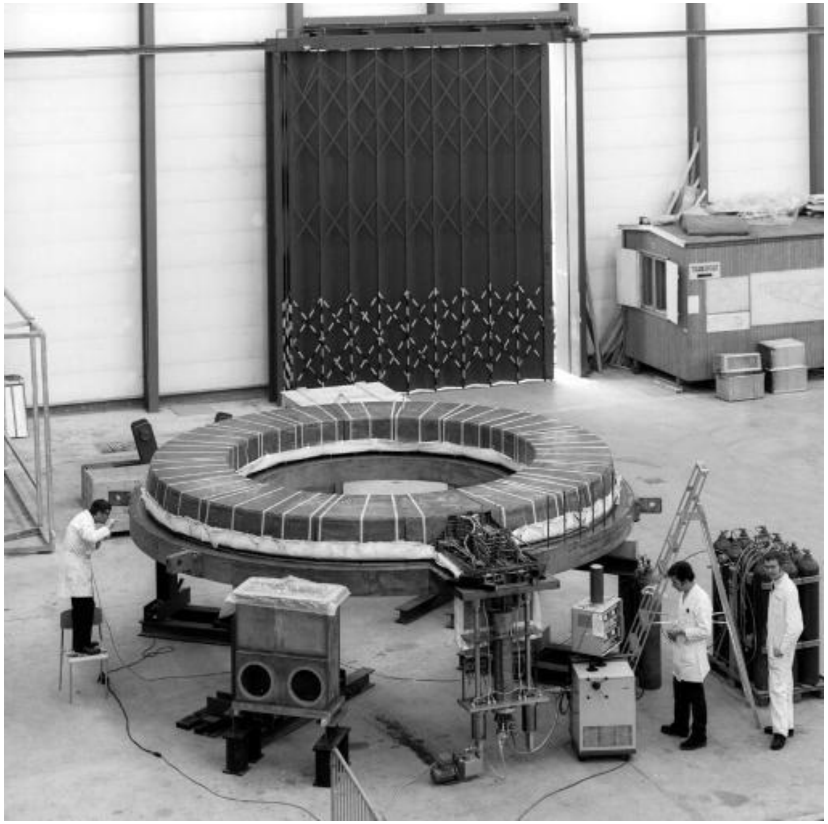
~7000 Correction magnets

ATLAS and CMS detector magnets

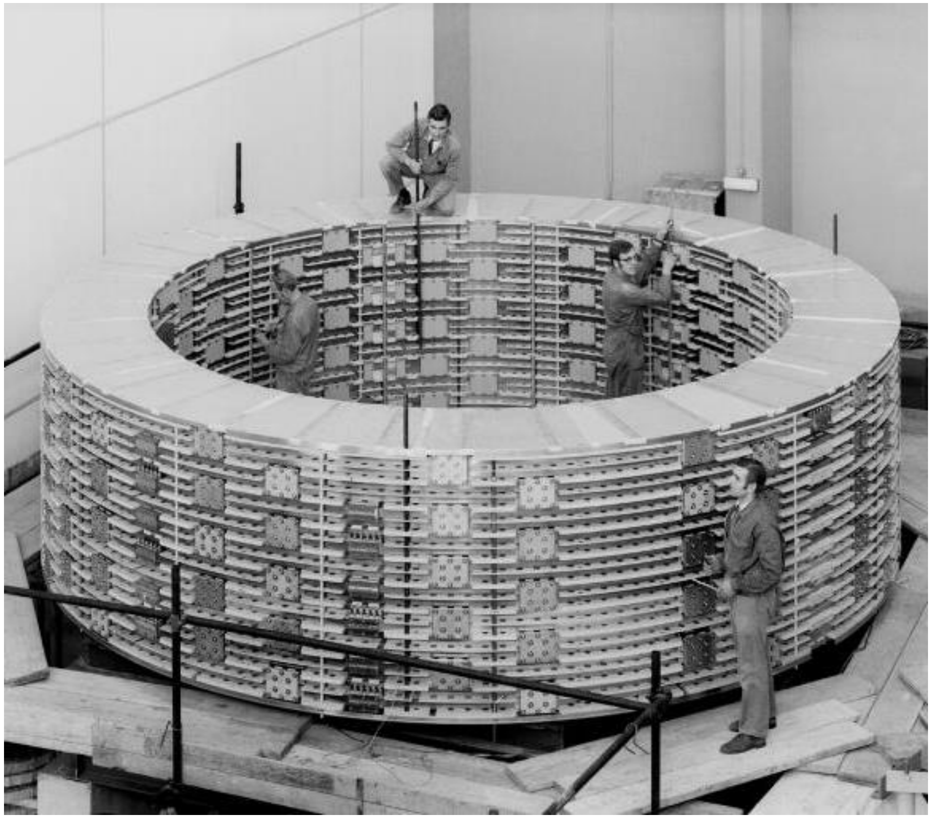
Insertion and Final Focusing magnets

No Higgs without Superconductivity !

Large HEP detector magnets of the past...

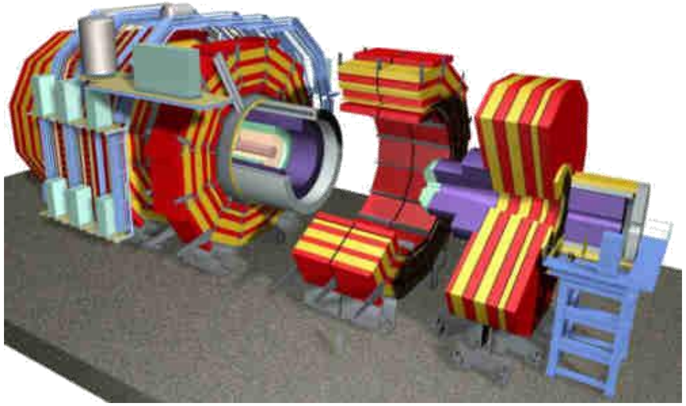


Omega, medio 1972

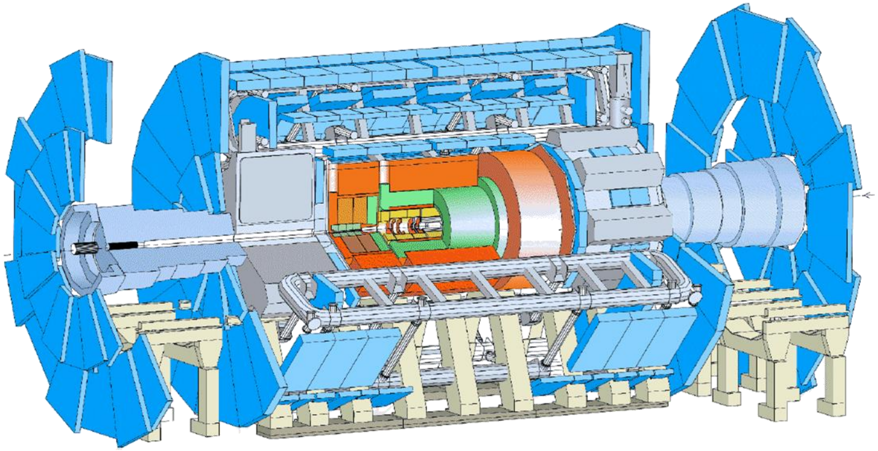


BEBC, medio 1973

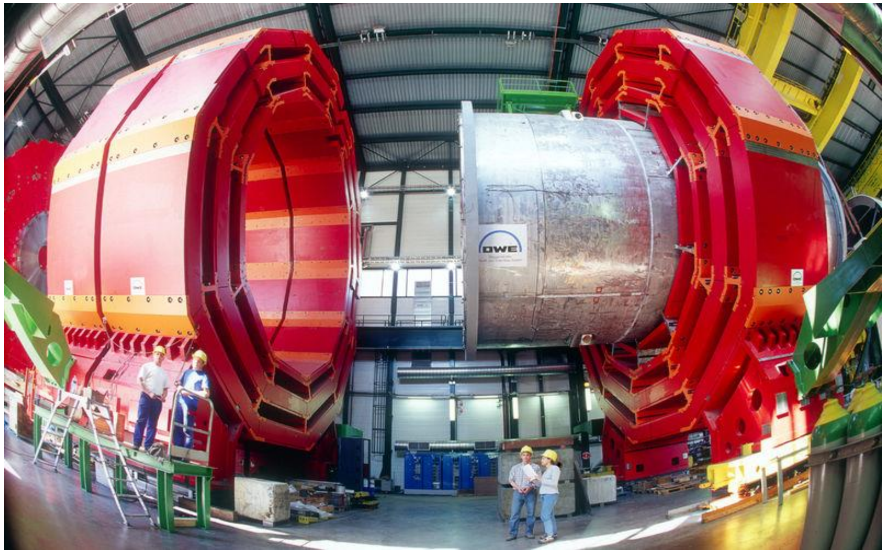
… and present detectors, CMS and ATLAS

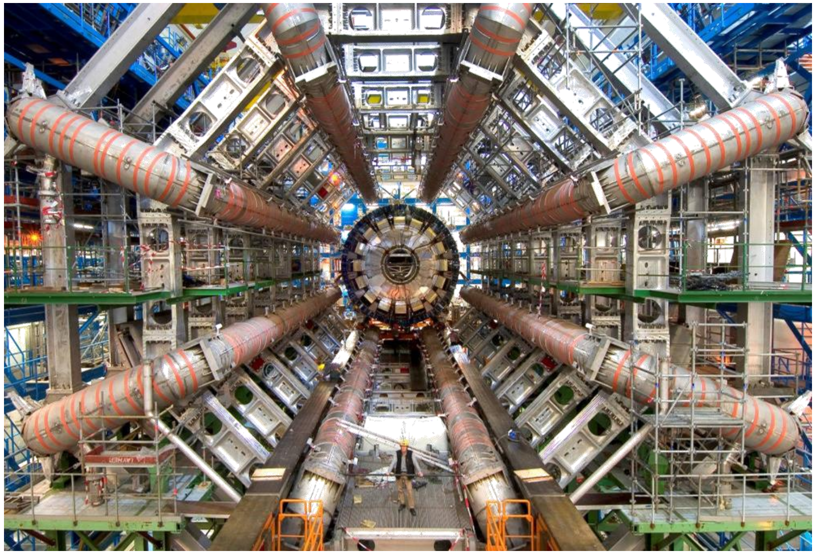


CMS (2008)



ATLAS (2008)

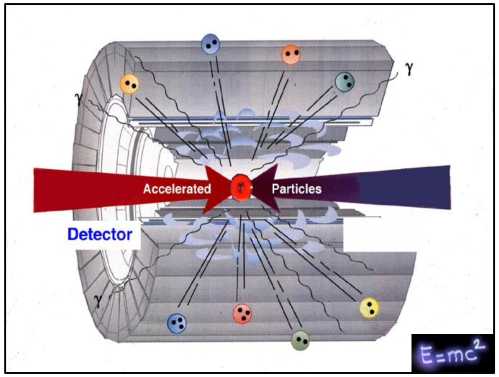




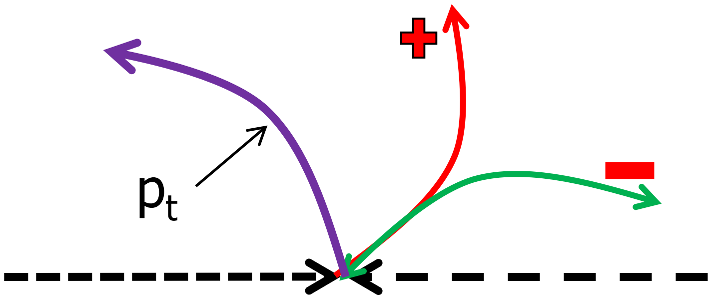
Concept: why magnetic field in detectors

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.

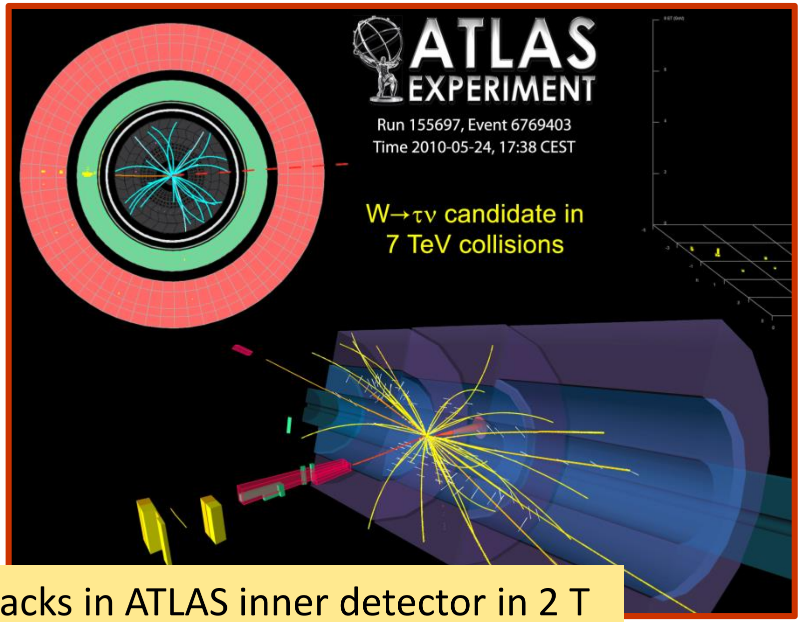


A detector magnet is in fact a "magnetic separator".



Information yield:

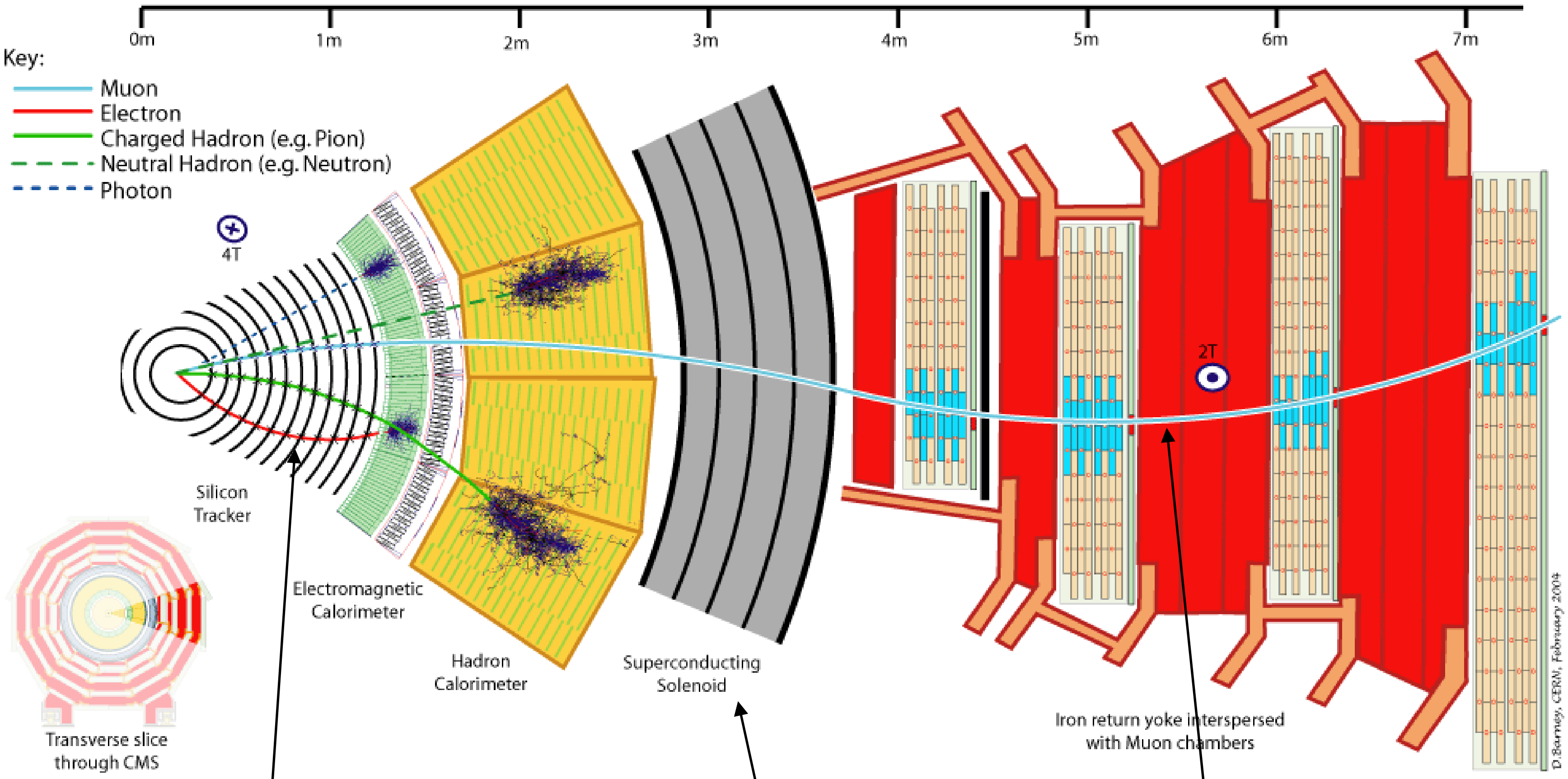
- left turn => positively charged particle
- right turn => negative particle
- curvature => momentum



Tracks in ATLAS inner detector in 2 T

Concept: charged particle tracking

Example: tracking in the CMS Solenoid and iron return yoke



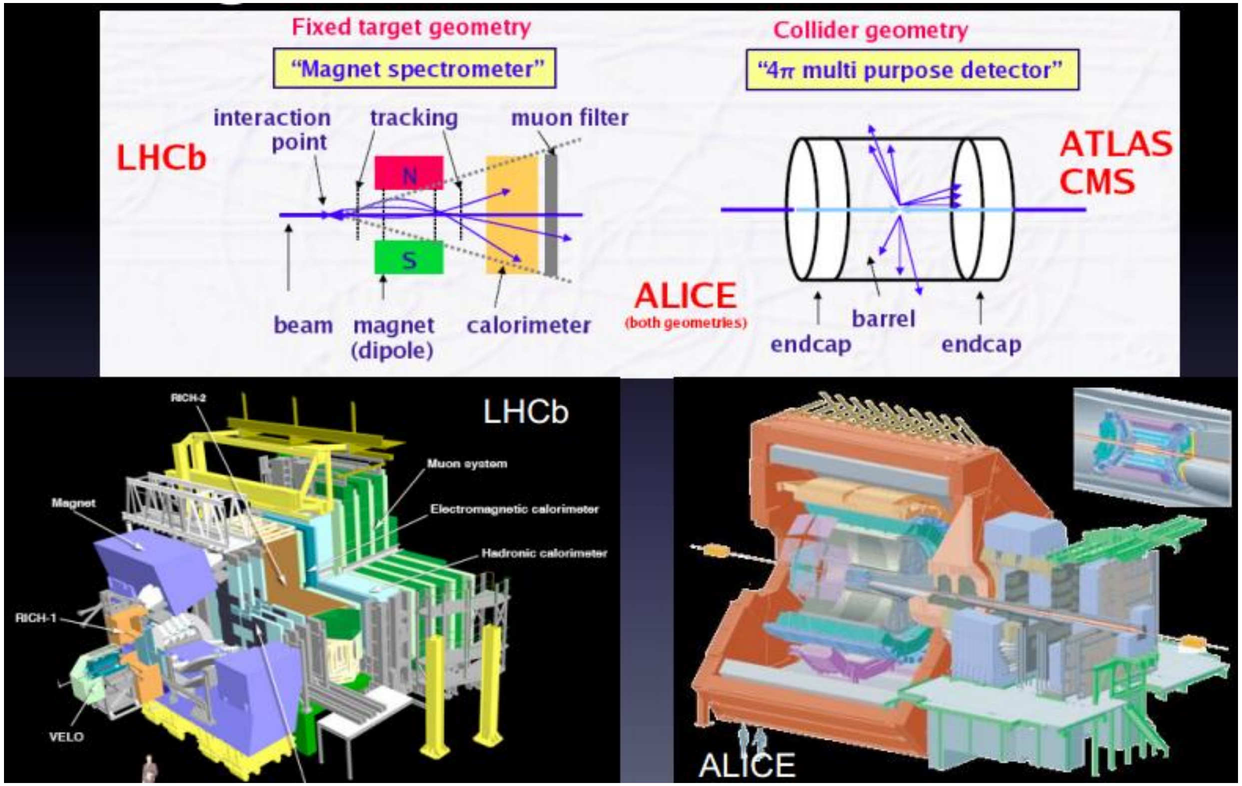
Curved particle tracks due to **solenoid field**

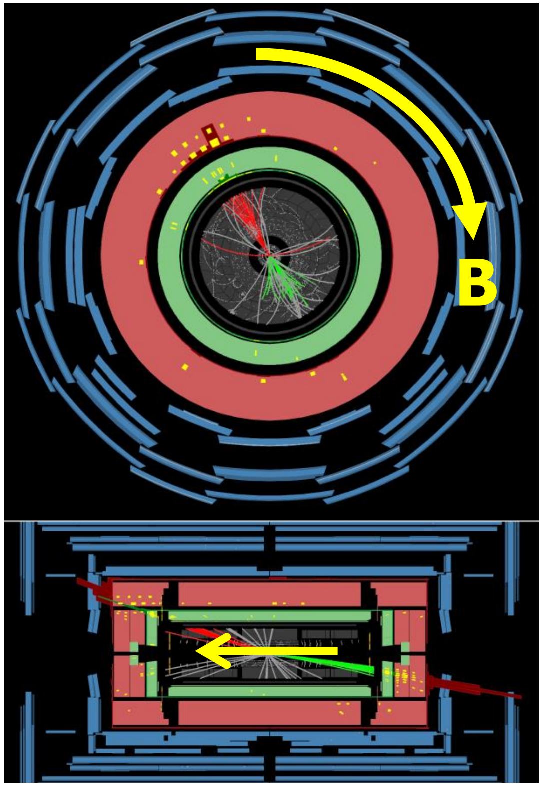
3.5 T **solenoid**

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

Concept: type of magnet used

- There are 3 principle magnet layouts for particle bending
- Choice depends on type of experiment and “4π” or single direction fixed target, or even a combination of these, all variants exist.





Dipole magnet
mainly vertical B ↑

Solenoid + yoke
mainly axial B ←

Toroid + Solenoid
Tangential + axial B

Concept: sizing the detector

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

Radial thickness

is the summation of:

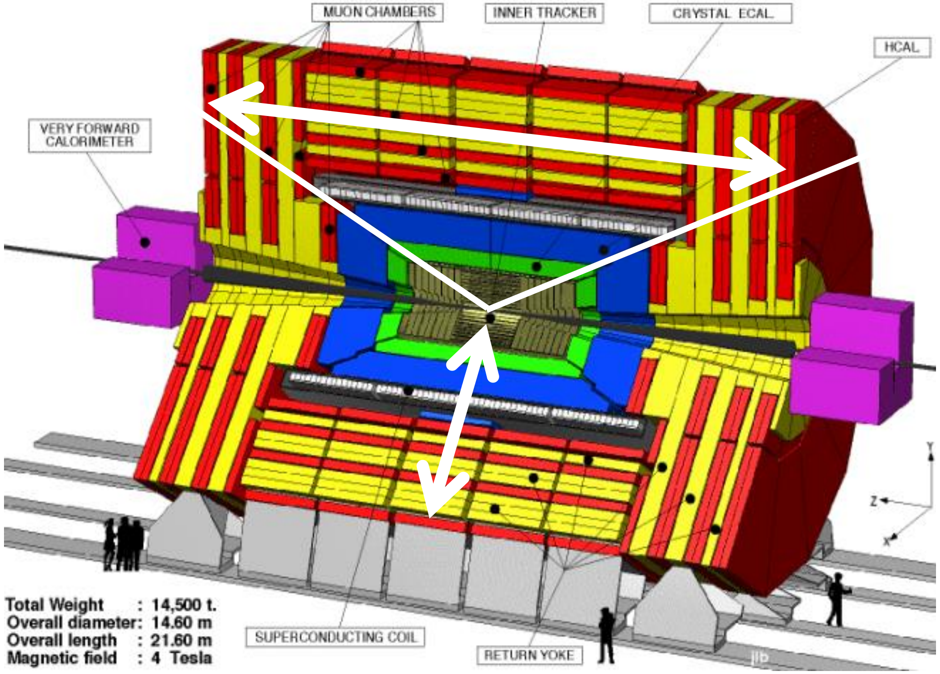
+ tracking length inner detector

+ 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

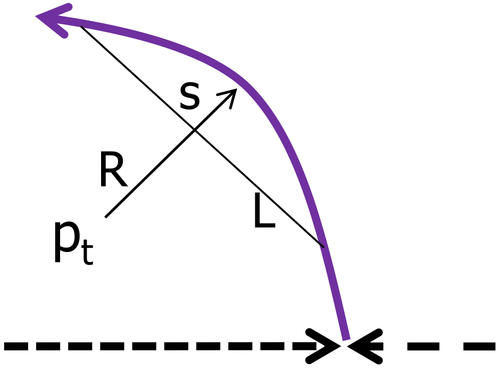
+ thickness of iron shielding.

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:

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

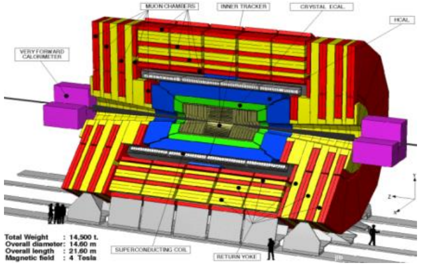
and momentum resolution

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

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 yes, low cost as well !

→ Use NbTi superconductor at 4.5 K

2. Superconductors for detector magnets

Practical superconductors

Basic properties

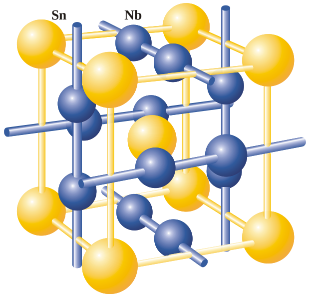
Stability requirements

Minimum Propagation Zone

High Currents and Cables

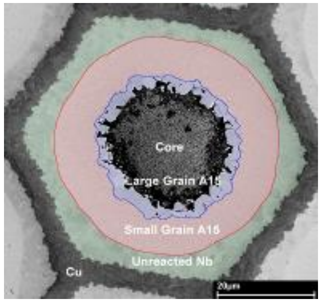
From materials to magnets

Lattice



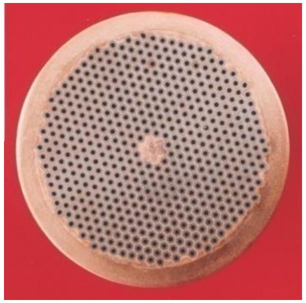
50 nm

Filament



20 µm

Wire

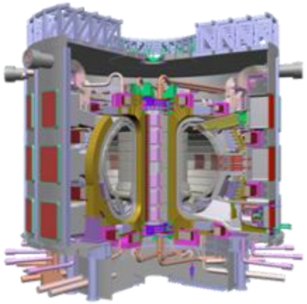


1 mm

Cable/conductor

50 mm

Magnet



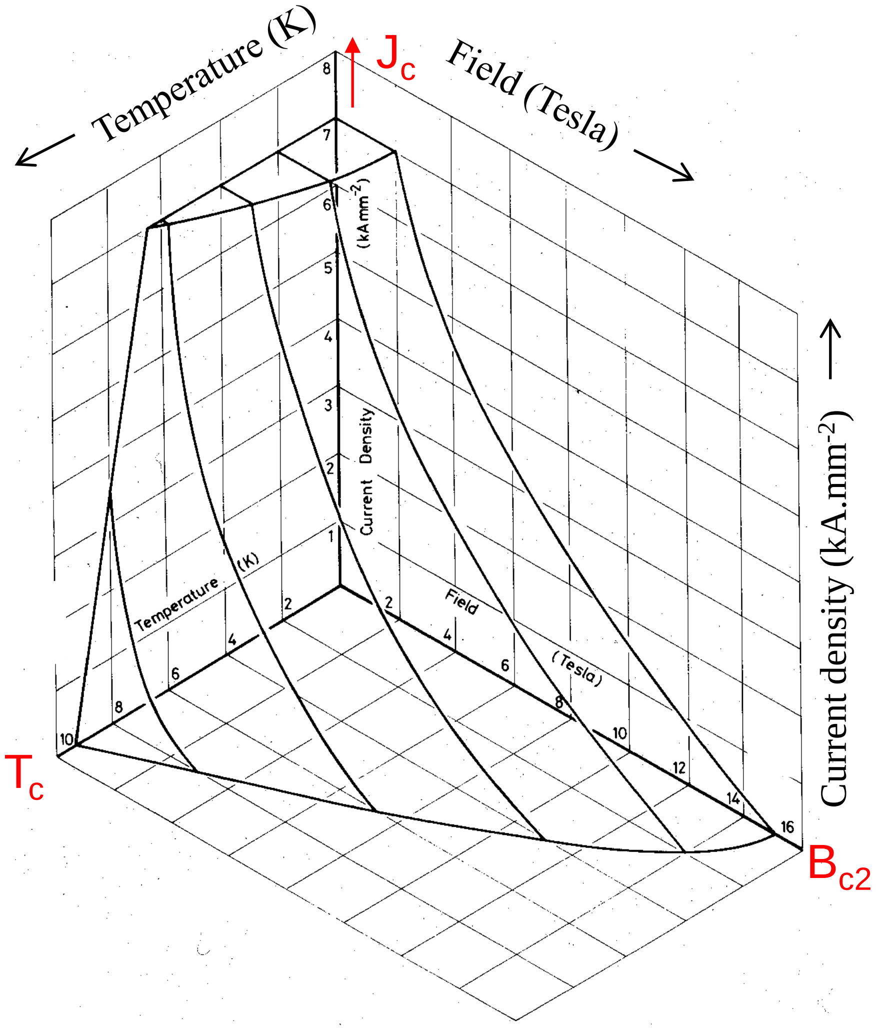
35 meter

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

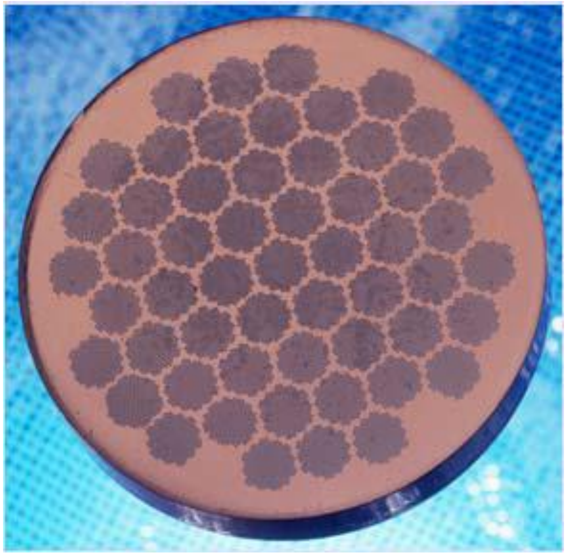
→ **We need to understand and control the entire chain**

- 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



Tc : 11 K
Bc_2 : 13 T

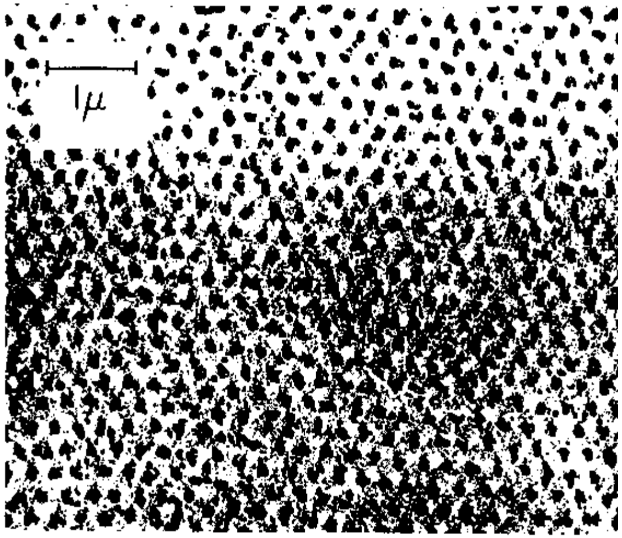
Very well developed
~1 € / kA m

Critical properties of type II superconductors

Critical Temperature T_c:

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

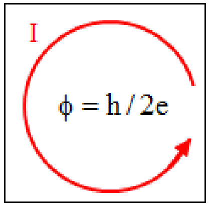
k_B is Boltzmann's constant, D(0) is the *energy gap* (binding energy of Cooper pairs) at T= 0.



Upper critical field Bc_2:

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 and upper critical field are linked

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

where r_n is the normal state resistivity

! Best superconductors are best resistors !

T_c and B_{c2} are intrinsic material properties

Critical current density

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

The spacing between flux lines:

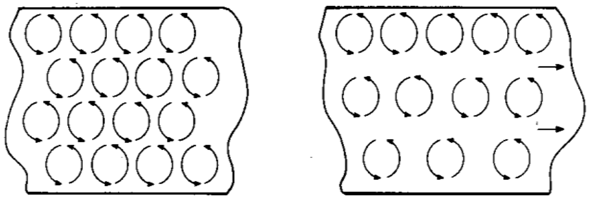
$$d = \left\{ \frac{2}{\sqrt{3}} \frac{\phi_o}{B} \right\}^{\frac{1}{2}} = 22nm \quad at\ 5T$$

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

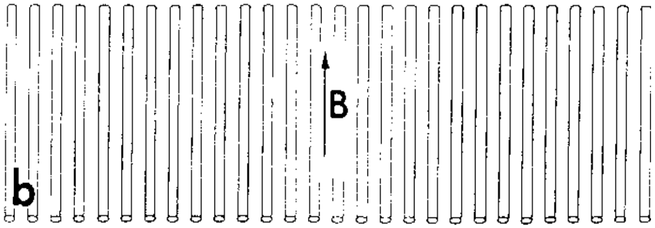
but a gradient produces a net current density:

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

- gradients are introduced by inhomogeneities in the material, like dislocations, precipitates
- process is known as flux pinning
- flux pinning is an irreversible process leading to AC losses

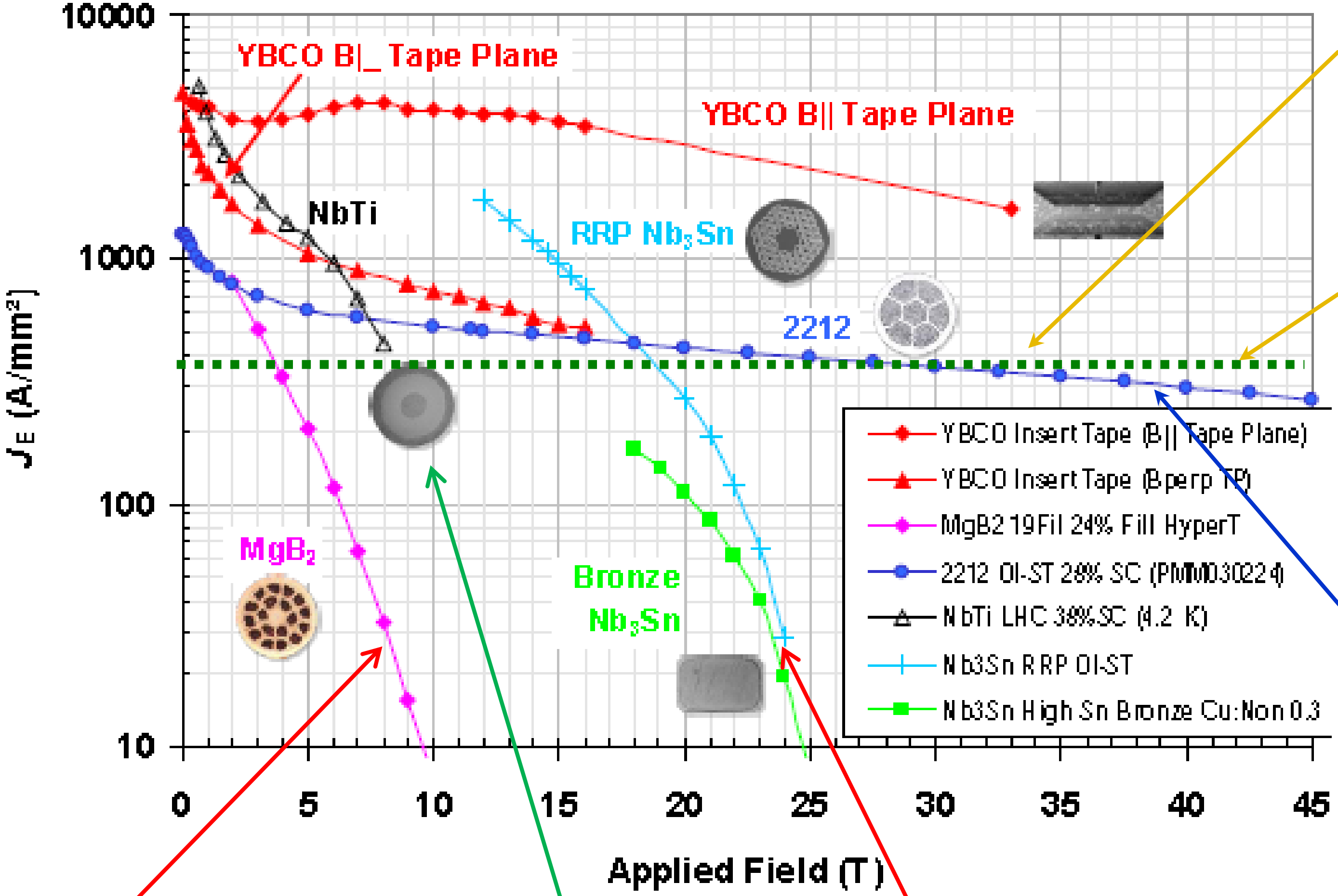


precipitates of α Ti in NbTi



Flux lines lattice at 5 T, same scale.

Superconductors for magnets



ReBCO, Y123 in a magnet, not in // field !

Minimum practical current density

B2211 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

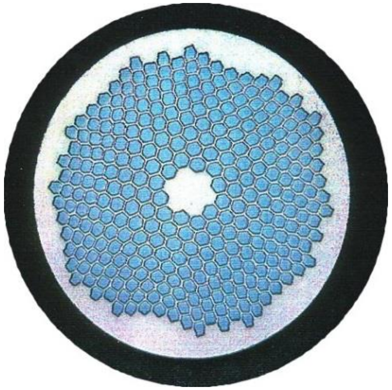
NbTi
for high field up to 9 T and 4 K and 11 T, 1.8 K

Nb$_3$Sn
for any magnet of 9-20 T

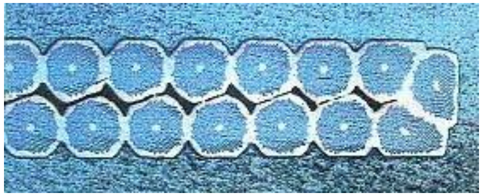
B2212 or Y123
for DC magnets of 17 -40 T provided cost comes down drastically

Example: Superconductors in ATLAS Detector

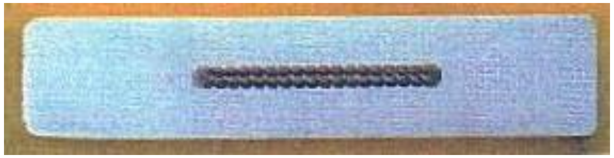
Barrel Toroid Conductor: 65 kA at 5 T



- 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)

Coils and Superconducting Windings

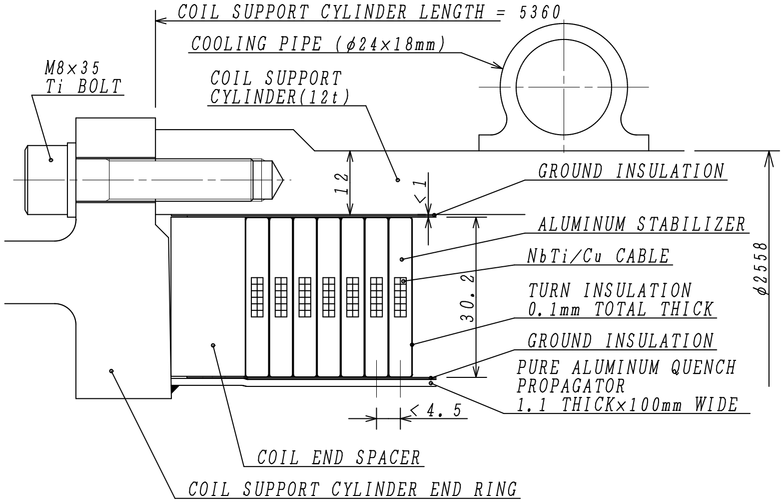
As argued before, we need:

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

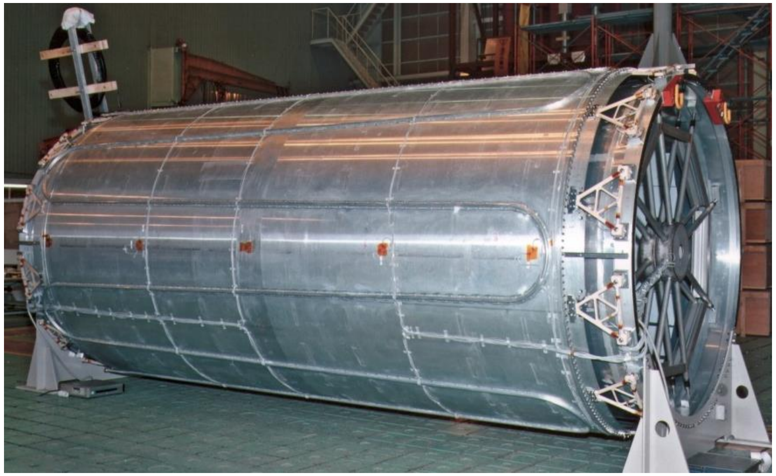
This caused an evolution of detector magnet design since some 40 yrs.

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)

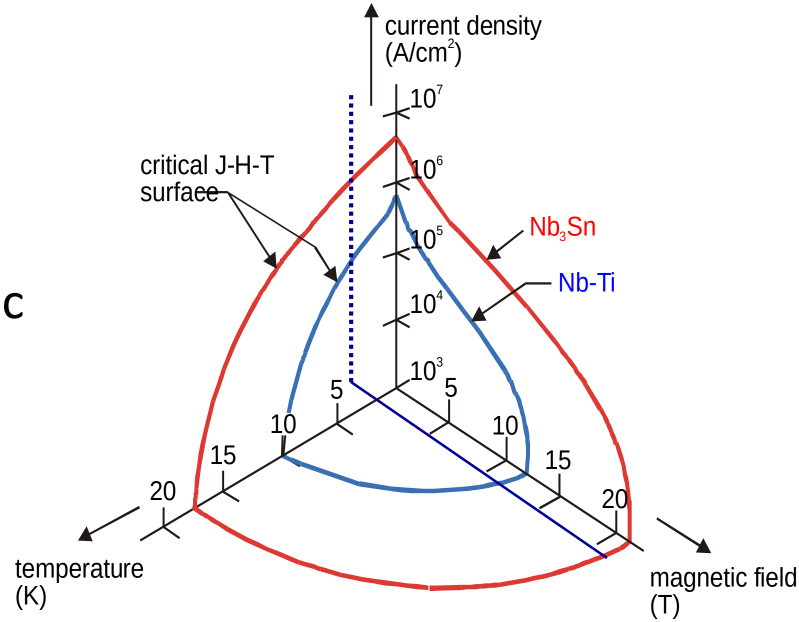


ATLAS Solenoid 2.5 T

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$_3$Sn and BSCCO 2212 and 2223.

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

$T_{cs}(B,I) = T_b + (T_c(B) – T_b)\ (1 - I/I_c)$ $T_{cs}(5\ T, I_c/2\ A) = 5.7\ K$ only!

- So we lost a lot of margin from 9.2 K → 7.2 K → 5.7 K versus 4.4 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

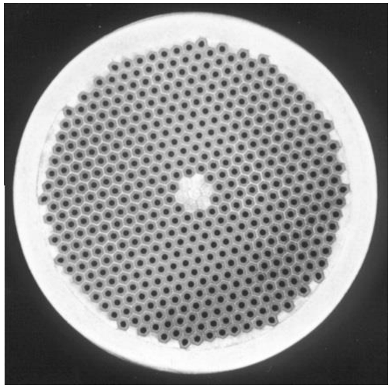
- In the filament magnetic energy is stored
- When disturbed, the heat must be taken up by the enthalpy of the filament
- A disturbance ΔT1 will cause a –ΔJc, so flux motion, leading to E, this leading to heat and so again a ΔT2
- When ΔT2 > ΔT1, the process will accelerate and the flux profile collapses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

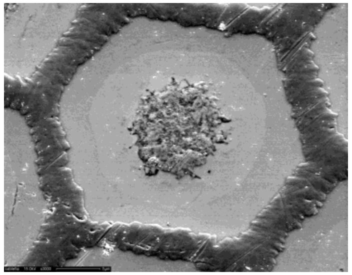
$$\boxed{d_{fil} \cdot J_c < \{ 3\, c\, (T_c - T_o) / \mu_o \}^{1/2}}$$

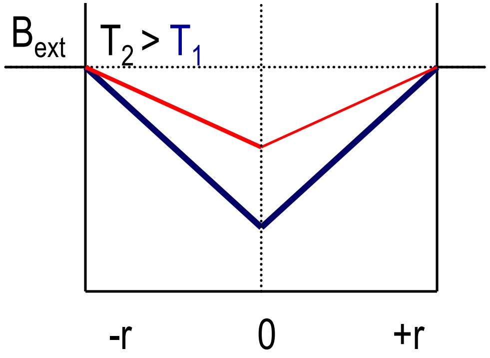
So we see a maximum filament thickness for a given current density, to guarantee stability.

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

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







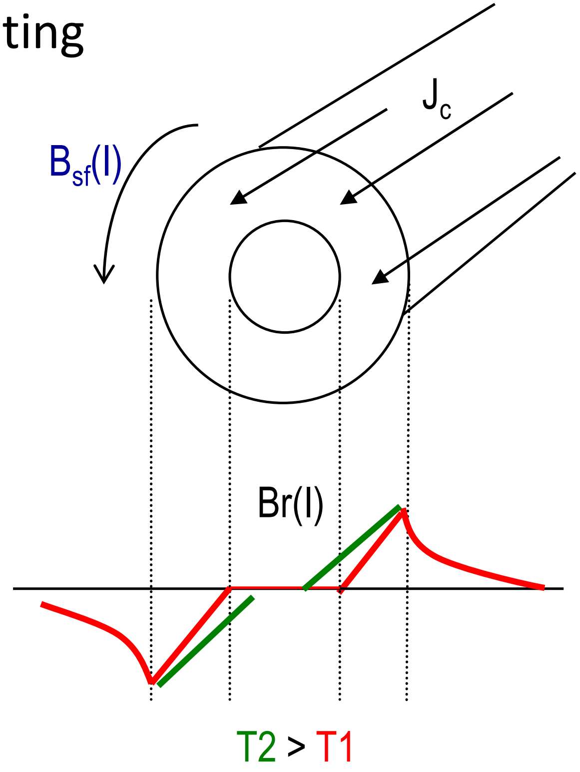
Adiabatic Wire Self field Stability, D_{wire}

Filaments coupled by self field

- Adiabatic filament stability requires fine filaments in a matrix
- These can be de-coupled for transverse fields by twisting
- But are still fully coupled by the self-field
- Again following the CSM, we see the field penetration profile disturbed by a ΔT
- Field profile has to change, penetrates deeper, causing heat dissipation taken up by the enthalpy up to a certain limit
- Assuming η=sc/total ratio and current density ηJ
- 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 $f\,(I/I_c) = 1/(-0.5 \ln(I) - 3/8 + i^2/6 - i^4/8)$

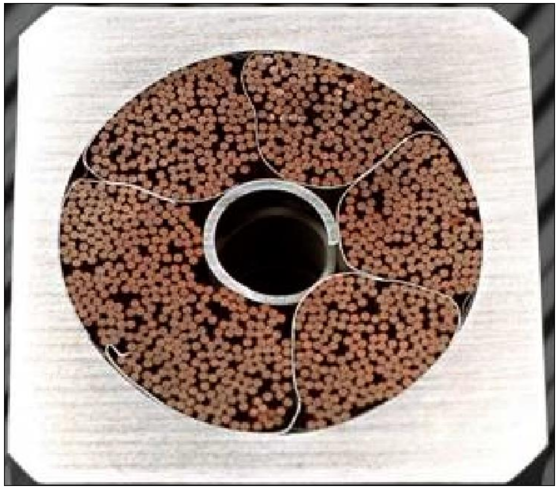


- **So we see a maximum wire diameter for a given Jc and I/I_c**
- **Commonly used $0.7 < D_{wire} < 1.3$ mm in cables.**

Self-field Stability: cable examples

ITER cable for central solenoid

- 65 kA at 13.5 T, ~1152 Nb3Sn 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 Nb3Sn cable

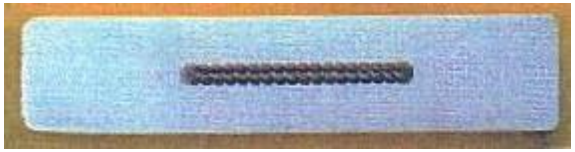
LHC type Nb3Sn Rutherford cable

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

33 wires LHC-type Nb3Sn cable

ATLAS cable

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



40 strands ATLAS BT cable

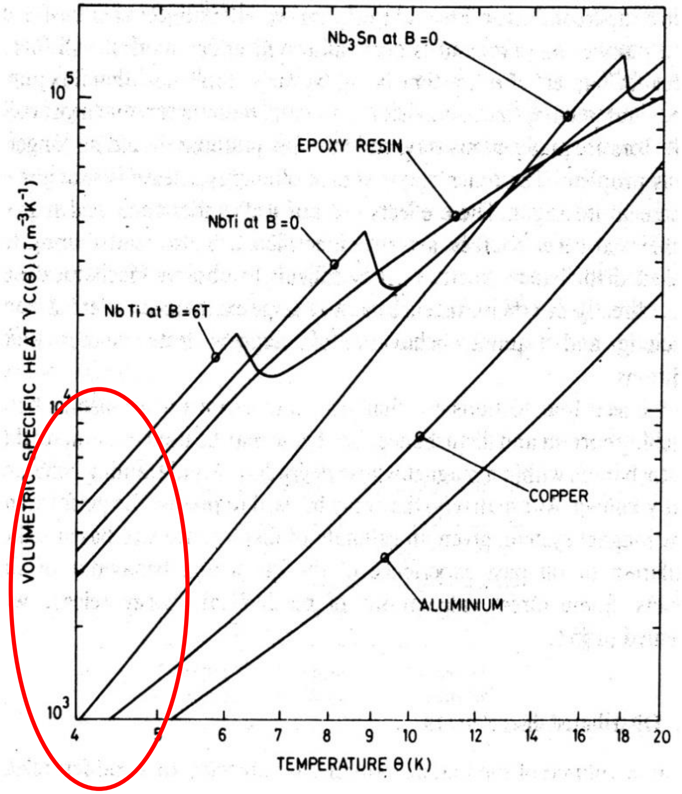
Temperature jumps, low heat capacity

Why is release of heat so critical at 4 K ?

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

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

  μJ/mm³K, at 5 T and 40% NbTi in a Cu matrix:
- 2.5 μJ/mm³K at 4.2 K and
- 0.5 μJ/mm³K at 1.9 K !
- 2.5 μJ/mm corresponds to a movement in a 1 mm wire at 5 T, 500 A of 1 μm only!



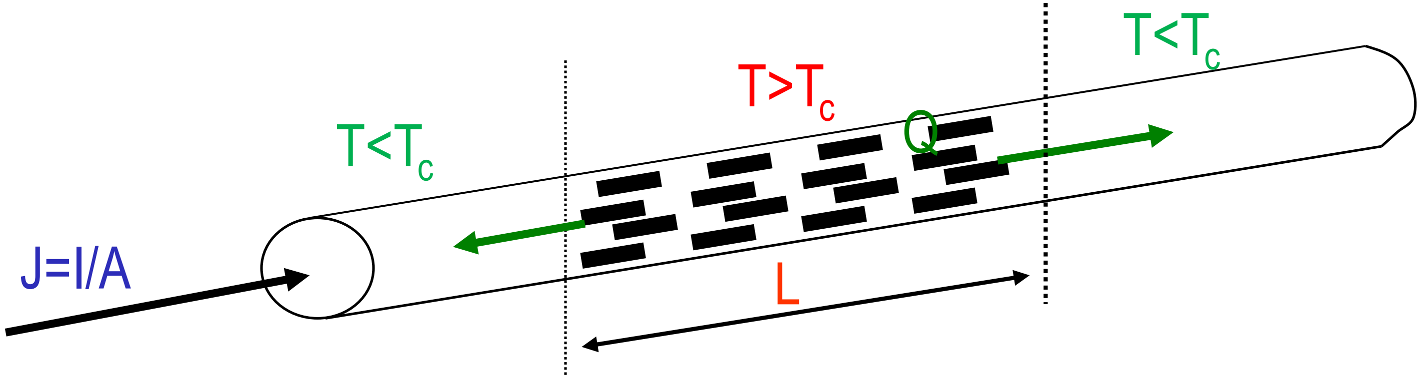
Heat release of μJ/mm³ has to be avoided, otherwise magnet will quench

- 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:

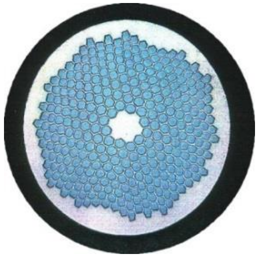
$$\rho J^2 A L \approx 2 \lambda A (T_c - T_{bath}) / L$$

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

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

Minimum Propagation Zone, MPZ

Examples of MPZ in a various wires



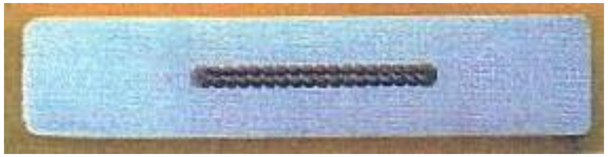
- In a bare NbTi wire or filament:
  take 5 T; 3000 A/mm^2; ρ= 6x10^{-7} Ωm; λ= 0.1 W/mK; T_c= 7 K
  and we find 0.3 μm only, pure NbTi can not be used!
- NbTi with CuNi matrix would give 3 μm and 0.1 μJ !
- Such wire is extremely sensitive to any heat pulse

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

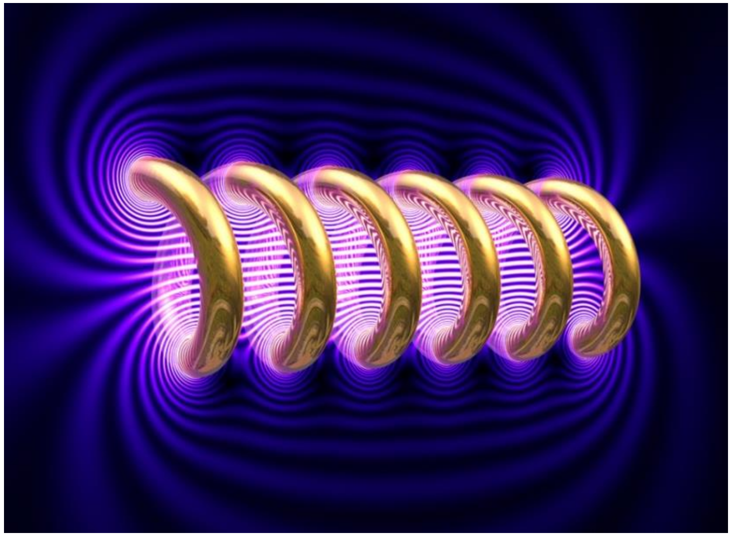
We see how wonderful copper (or Al) is, without copper no sc magnets !

- ✓ 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 $I_{safe} \propto J.E/V_d$, kV-range for V_d,
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!

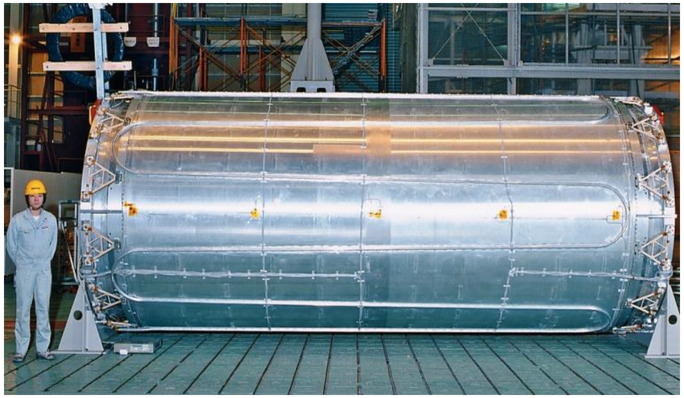
Scaling: $I_{safe} \propto J \times B^2 \times \text{Volume}$

0.0001 m^3 HF insert

200 A

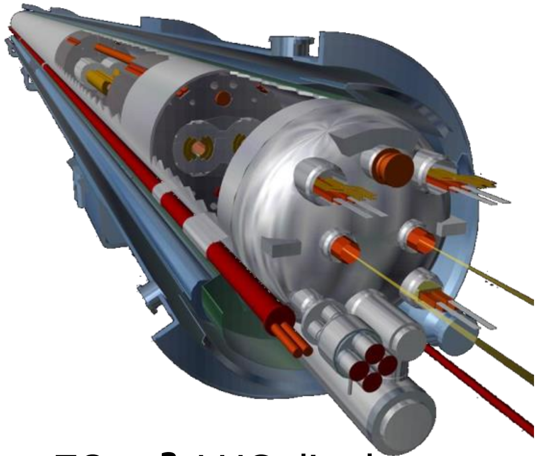
2 m^3 MRI magnet

200-800 A @ 1-3 T, ~10 MJ



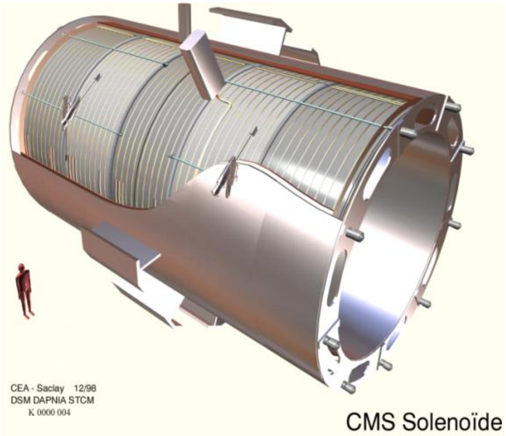
25 m^3 ATLAS solenoid

8 kA @ 2T, 40 MJ



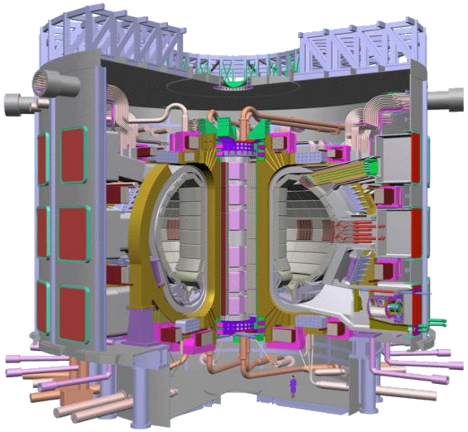
50 m^3 LHC dipole

12 kA



400 m^3 HEF detector magnet

20 kA @ 4 T, 2.6 GJ

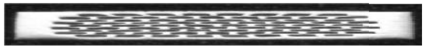


1000 m^3 ITER magnets

40-70 kA @ 10-13T, 50 GJ

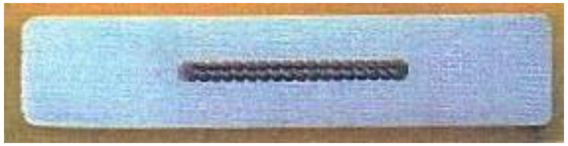
Request for: high current conductors

200 A HTS tape?

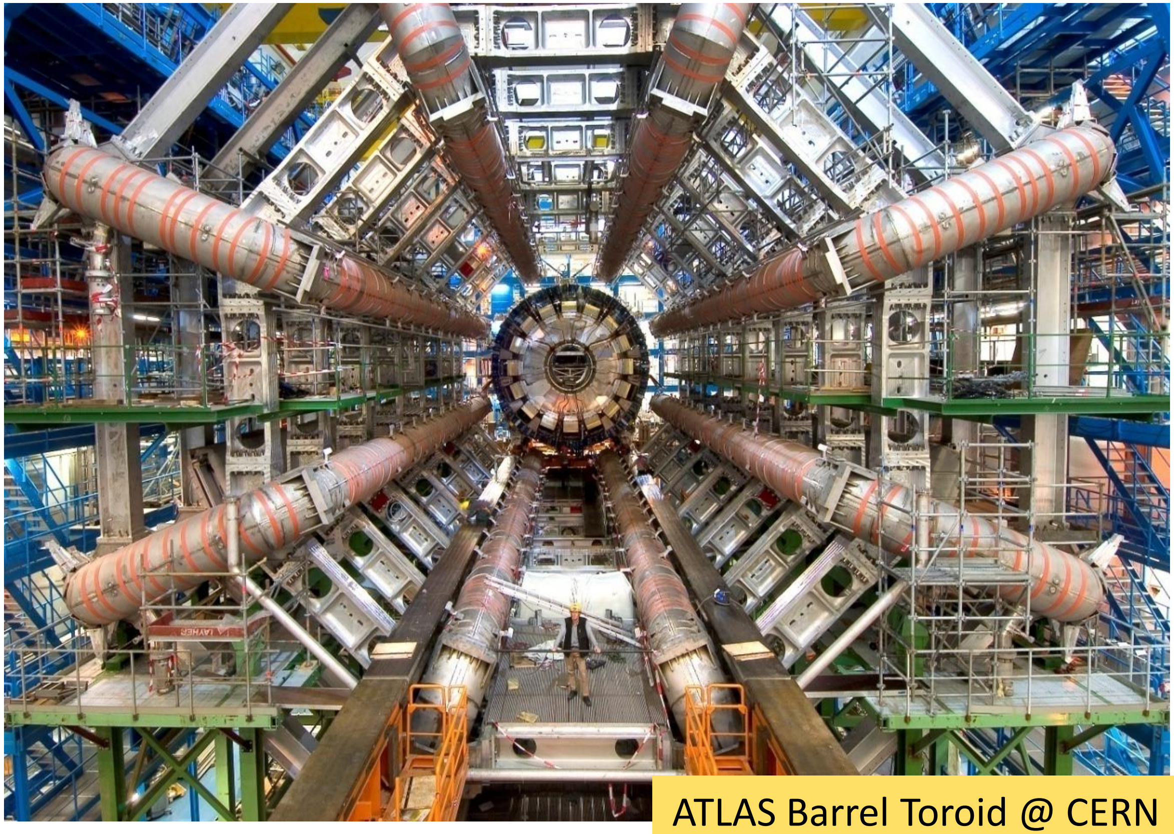


Single: No!
Cabled: may be, but
to be developed

65000 A@5T Al-NbTi/Cu?



Yes!



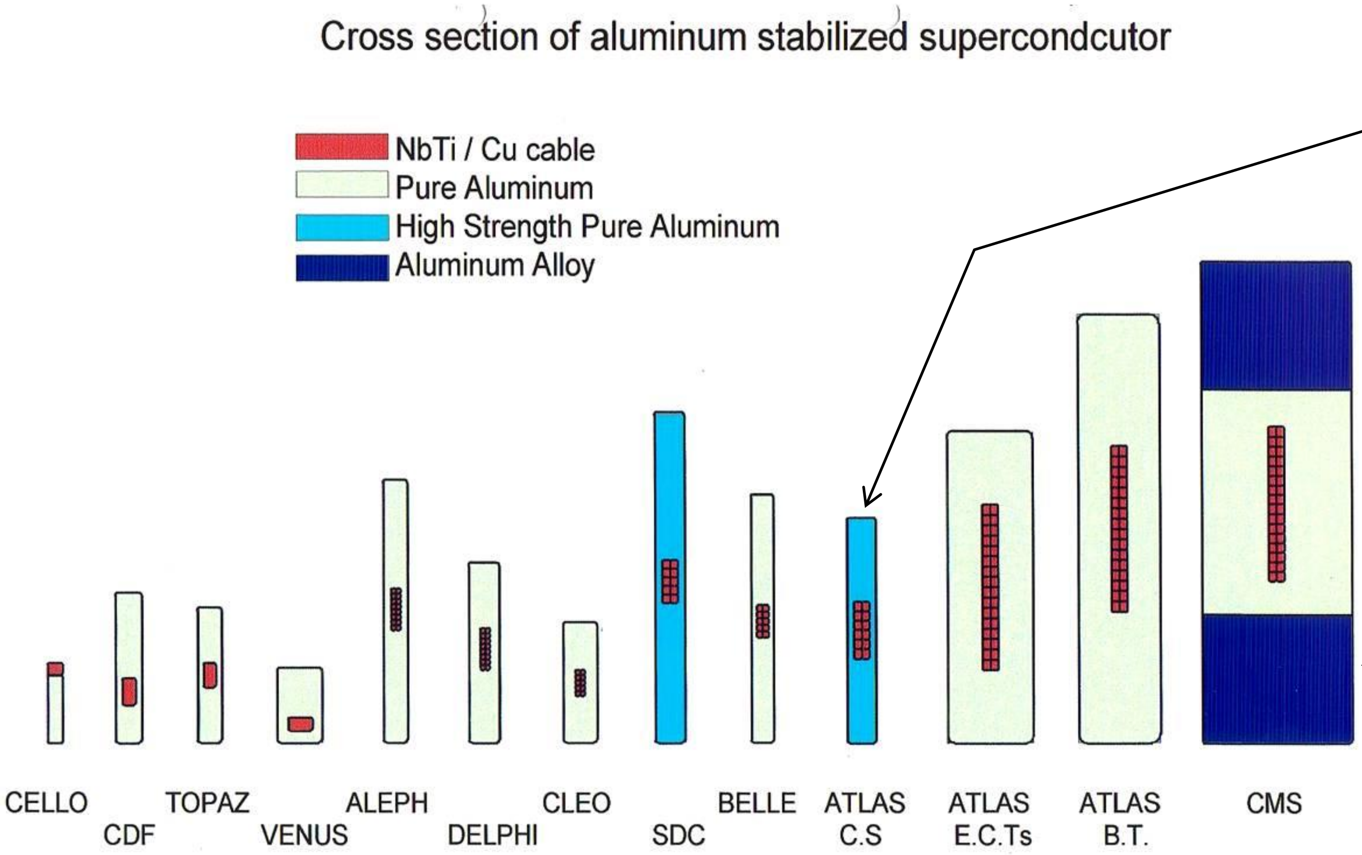
ATLAS Barrel Toroid @ CERN

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.



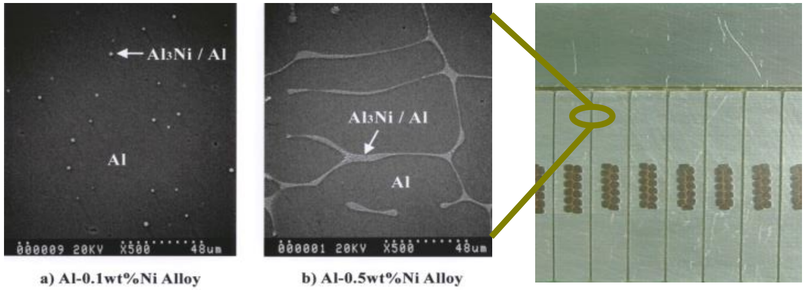
ATLAS CS type, Ni/Zn doped Al

CMS type, reinforcement bars

Re-inforcing Al-stabilized conductors

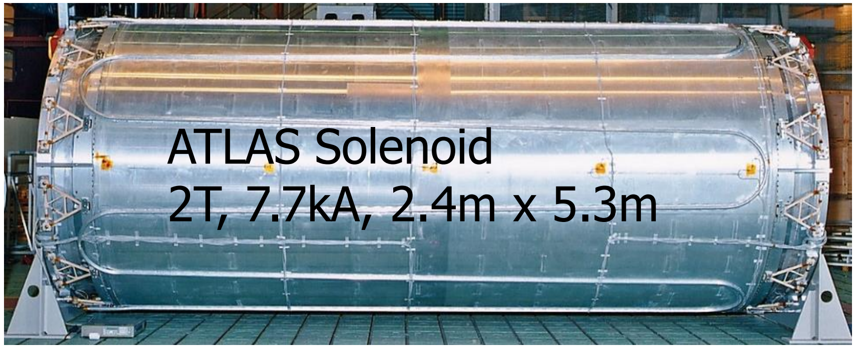
- Option 1
  Ni or Zn - doped Aluminum
- Used in the ATLAS Solenoid mechanical reinforcement while keeping quench stability.

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

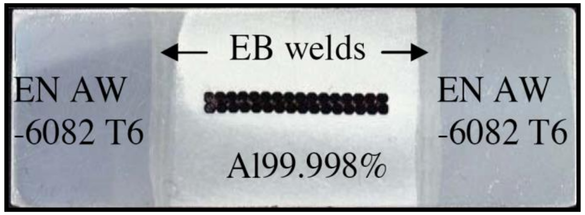


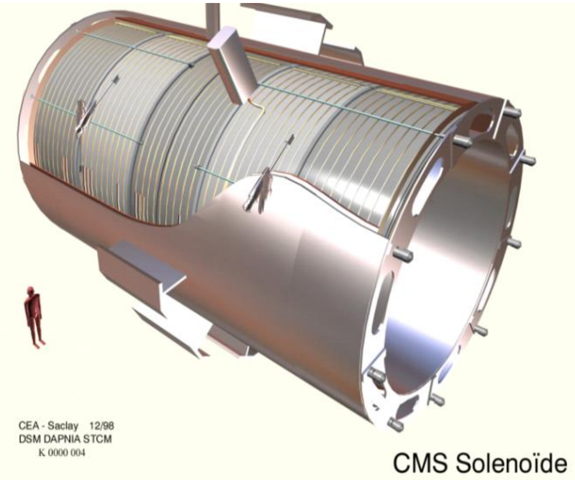
a) Al-0.1wt%Ni Alloy

b) Al-0.5wt%Ni Alloy



ATLAS Solenoid
2T, 7.7kA, 2.4m x 5.3m



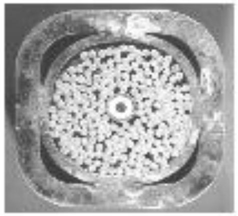


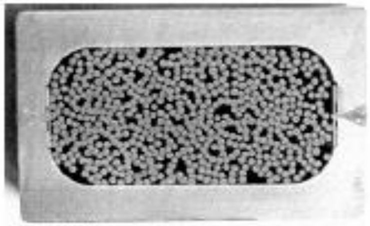
CMS Solenoïde

Alternative: use a Cable-in-Conduit

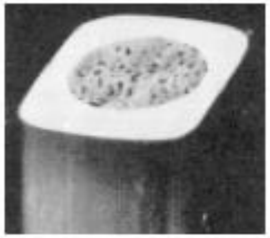
More than 25 years cable-in-conduit conductors (CICC) are in use for fusion magnets with forced flow helium maximizing heat removal and stability.


DPC-U 1988

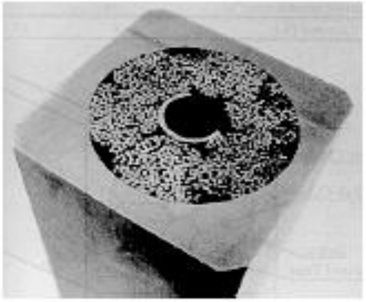

DPC-US 1989

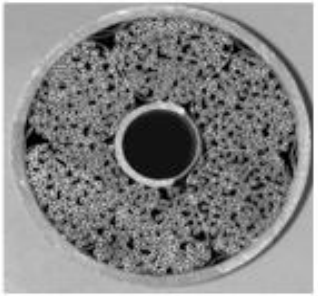

NET 1990

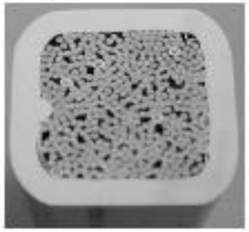

DPC-TJ 1991


W7-X 1994


LHD 1995


ITER CSMC 1998


ITER TFMC 1999


KSTAR 2000


EAST 2002

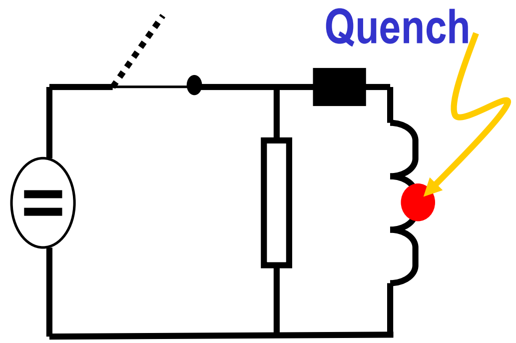
Very flexible in choosing cable size, current rating, strength and helium cooling directly on the superconductor → maximum stability

Stored energy to dump

The energy stored in a magnet is

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

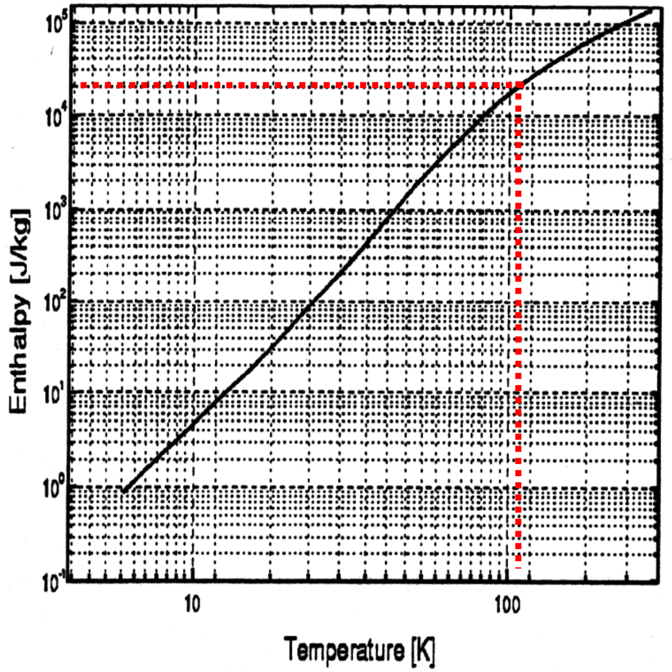
the energy density being ½ BH or $B^2/2\mu_o$



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

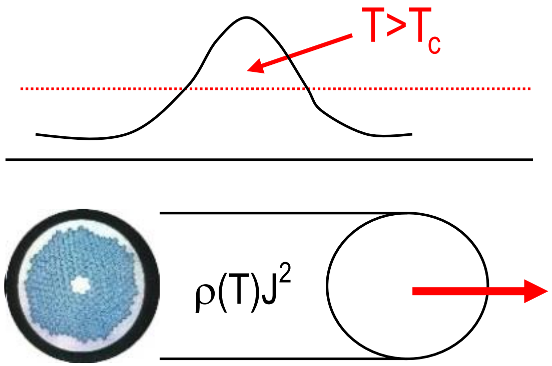
Temperature of the conductor?

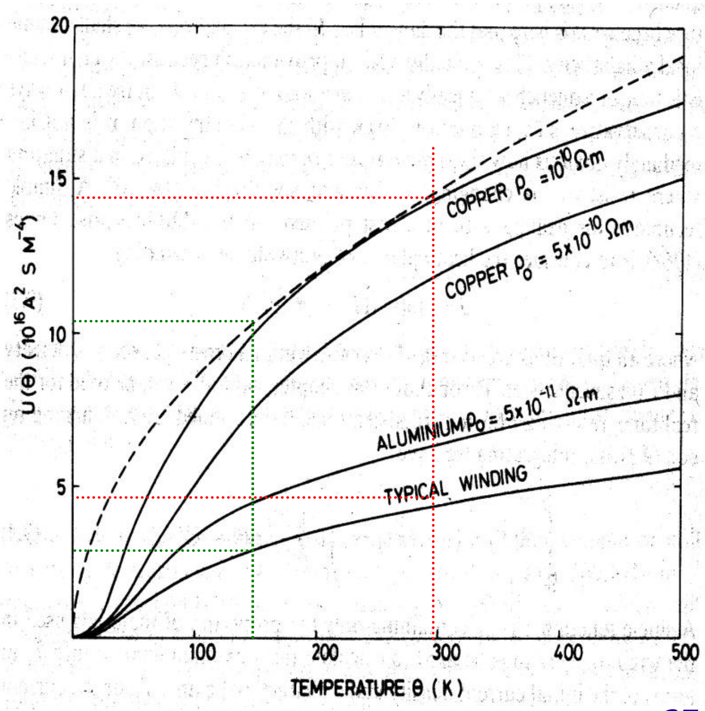
- Heating in the normal zone ρJ^2 is taken up by the conductor enthalpy:

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

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

- F is the Load Integral, used to assess transient thermal loads in devices.
- F is a constant, calculated for NbTi, Cu, resin and any mixture as a winding.
- Typical values for $F(T_m)$ are in the range 2-9x10^{16} for 150 K and 5-15 for 300 K maximum temperature depending on the conductor composition.

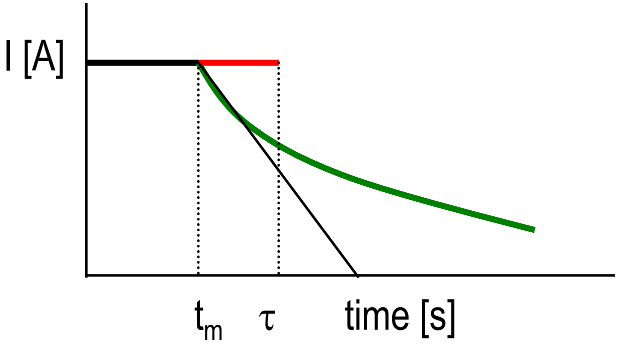




Adiabatic hot spot temperature

$$ {}_{0}\int^{t} J^2(t)\, dt = {}_{4}\int^{T} c(T) / \rho(T)\, dT = \text{constant} = F(T_m) $$

Simple solutions exist for constant or exponential decaying currents



Constant current

$$ J^2 t_m = F(T_m) \rightarrow t_m < F/J^2 $$

Exponential decay

$$ \boxed{J^2 \tau /2 = F(T_m) \rightarrow \tau < 2F/J^2} $$

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 NbTi or NbTi/CuNi is ~ms, so very little time to react and the conductor will burn out when used at high current density !

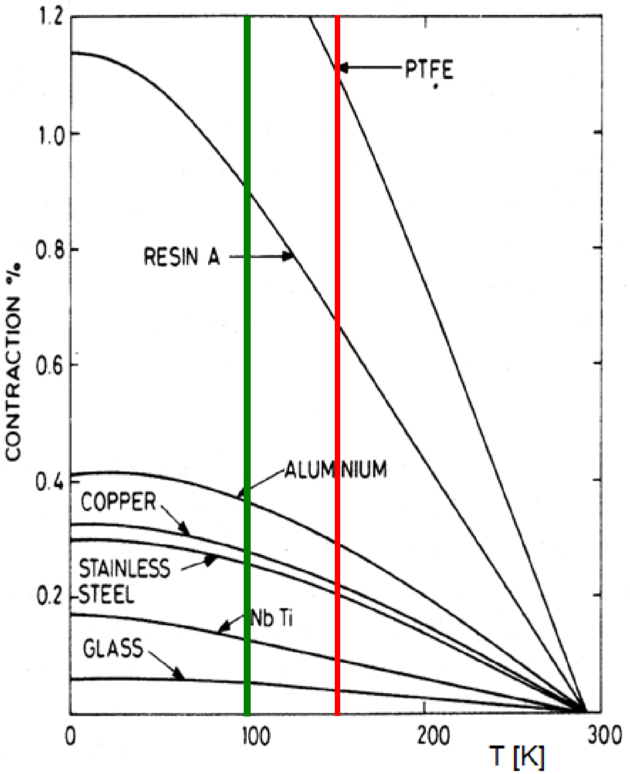
Safe hot spot temperature

Criterion for hot spot temperature

- Beyond 900 K Al structures start to collapse.
- Beyond 650 K we start to lose pinning, so J_c.
- Even 300 K is too high, as it endangers the windings.
- Severe thermal shock due to differential thermal contractions will occur.
- This may cause 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).

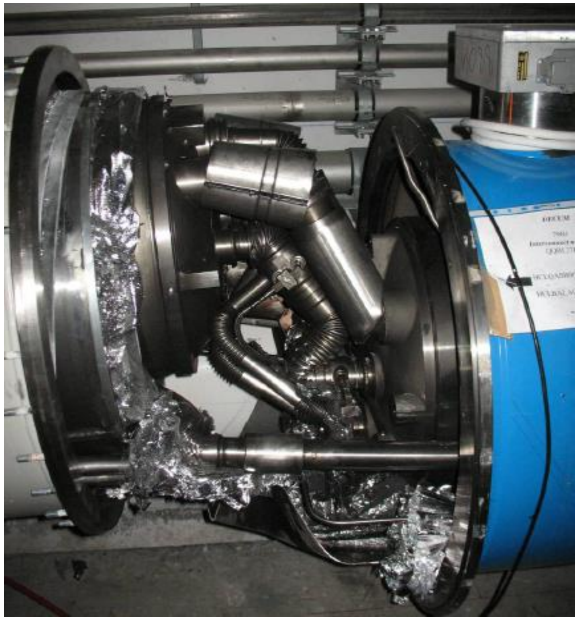


- 300 K may be acceptable for an R&D magnet, but is not an acceptable design value for a detector magnet that has to survive, operate at minimum risk and must be quench-recovered within 3-4 days.

Destructive power of uncontrolled quenches

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

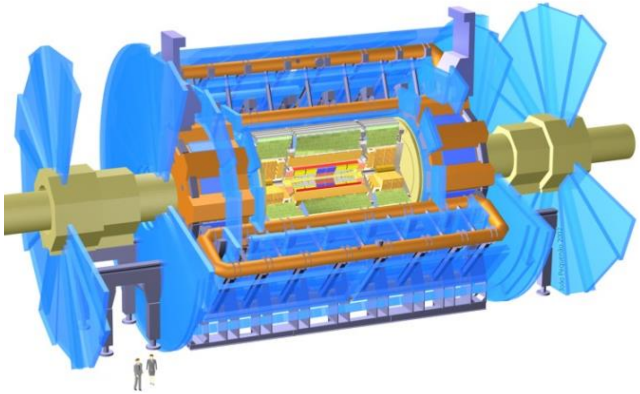
And we have seen in Sep 2008 what a few magnet quenches can do!



Damage at an LHC interconnect

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

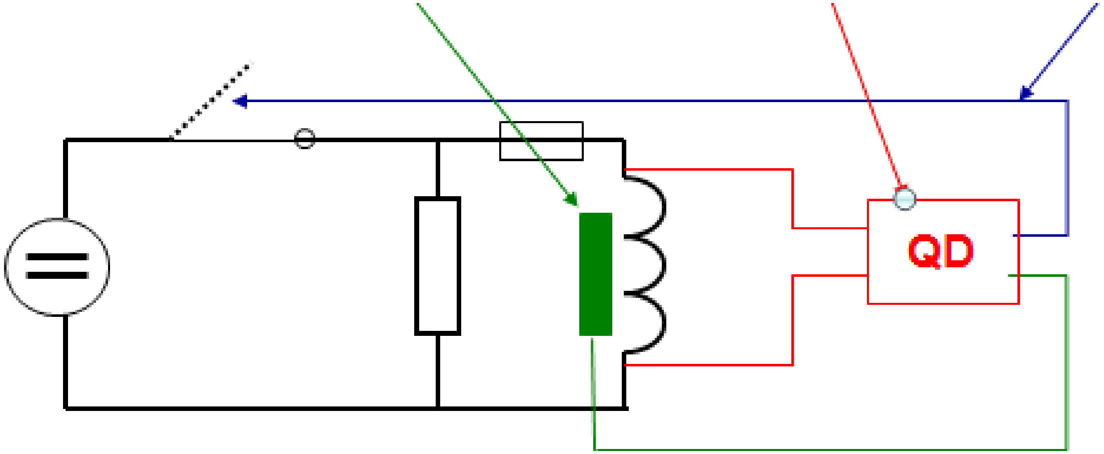
To be safe with equipment and personnel:
Quench Protection has to cover all possible quenches in the entire electrical circuit
from + to – terminal on the cryostat
(current leads & bus connections & coil).



Quench Detection

Quench detection circuit

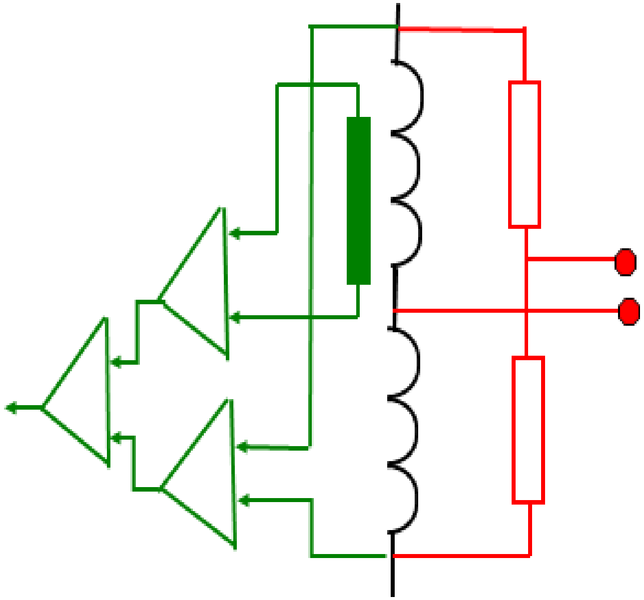
- The magnet safety system comprises the quench detectors, logics for opening switches and to supply current to the quench heaters.
- The system must be extremely reliable and power secured.
- ✓ The motto is: “keep it simple”, meaning robust and straight forward detection circuits, simple electronics, 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.

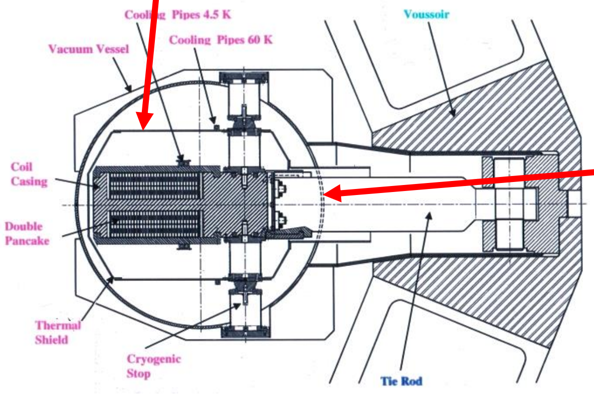
Other methods

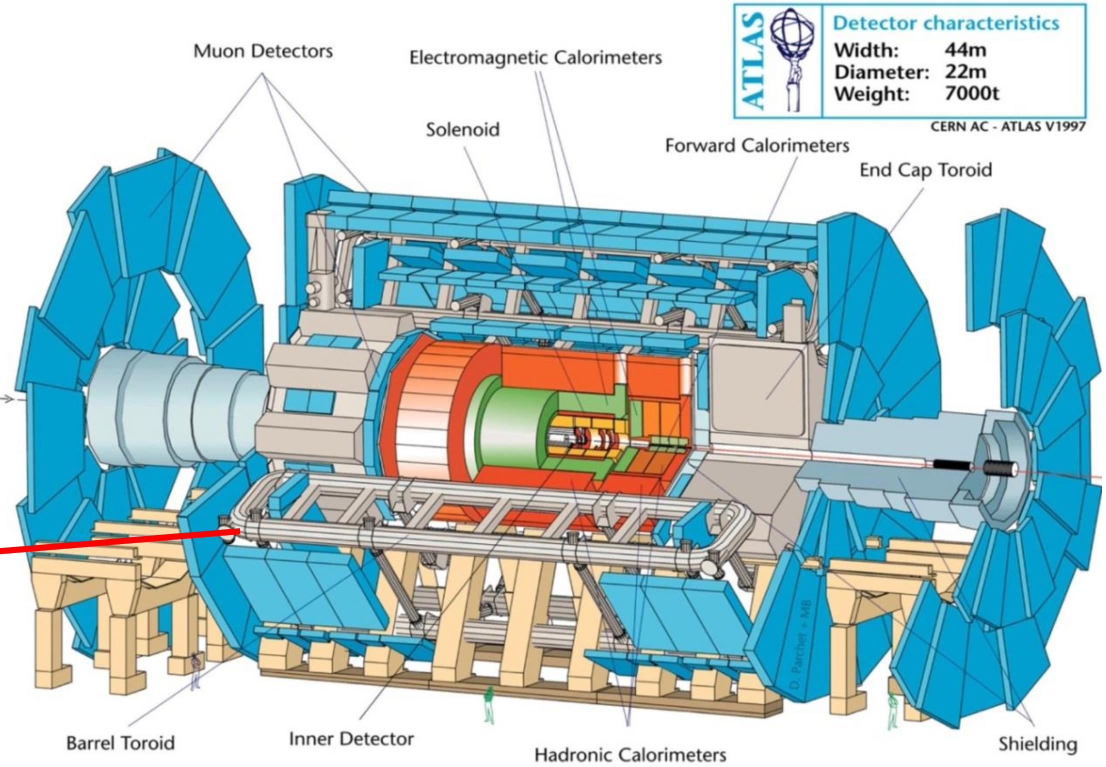
- Temperature, pressure gages, pick-up coils, strain sensor, etc.
- Many proposed, but mostly not used.

Example ATLAS Toroids

Toroids quench detection:

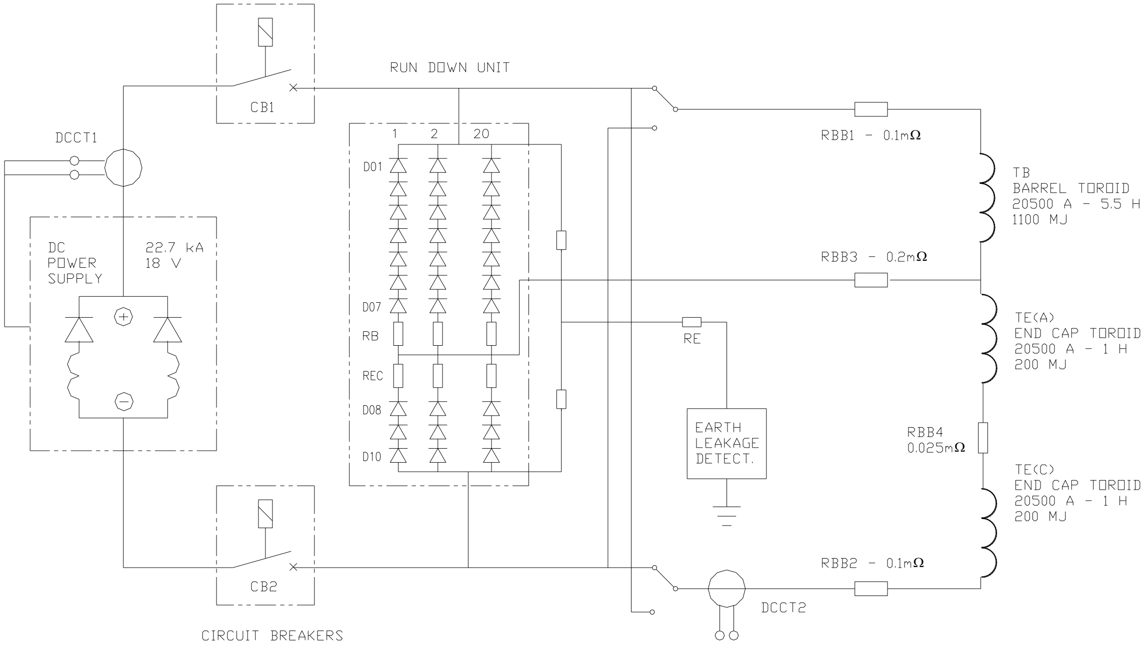
- 1.5 GJ energy, 20 kA current, 4 T peak field, 3 kJ/kg stored
- 3 toroids, each comprising 8 flat coils, thermally not connected
- 22 m diameter
- 5 m x 26 m long coils
- Largest toroid ever built.

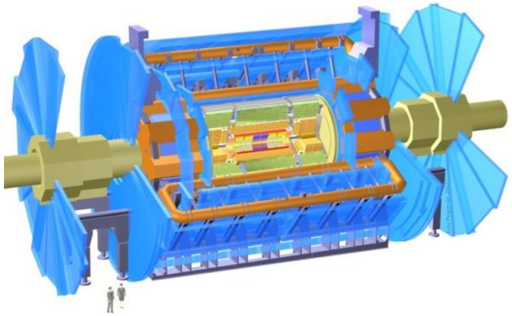




Example ATLAS Toroids

- All toroids 3 x 8 = 24 coils are connected in series.
- The energy is dumped in the 3 toroid cold masses, voltage limited to 40V.
- 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 ~100K.
- Threshold 0.3 V
- Low pass filter 1 s
- Fast dump in about 80 s.

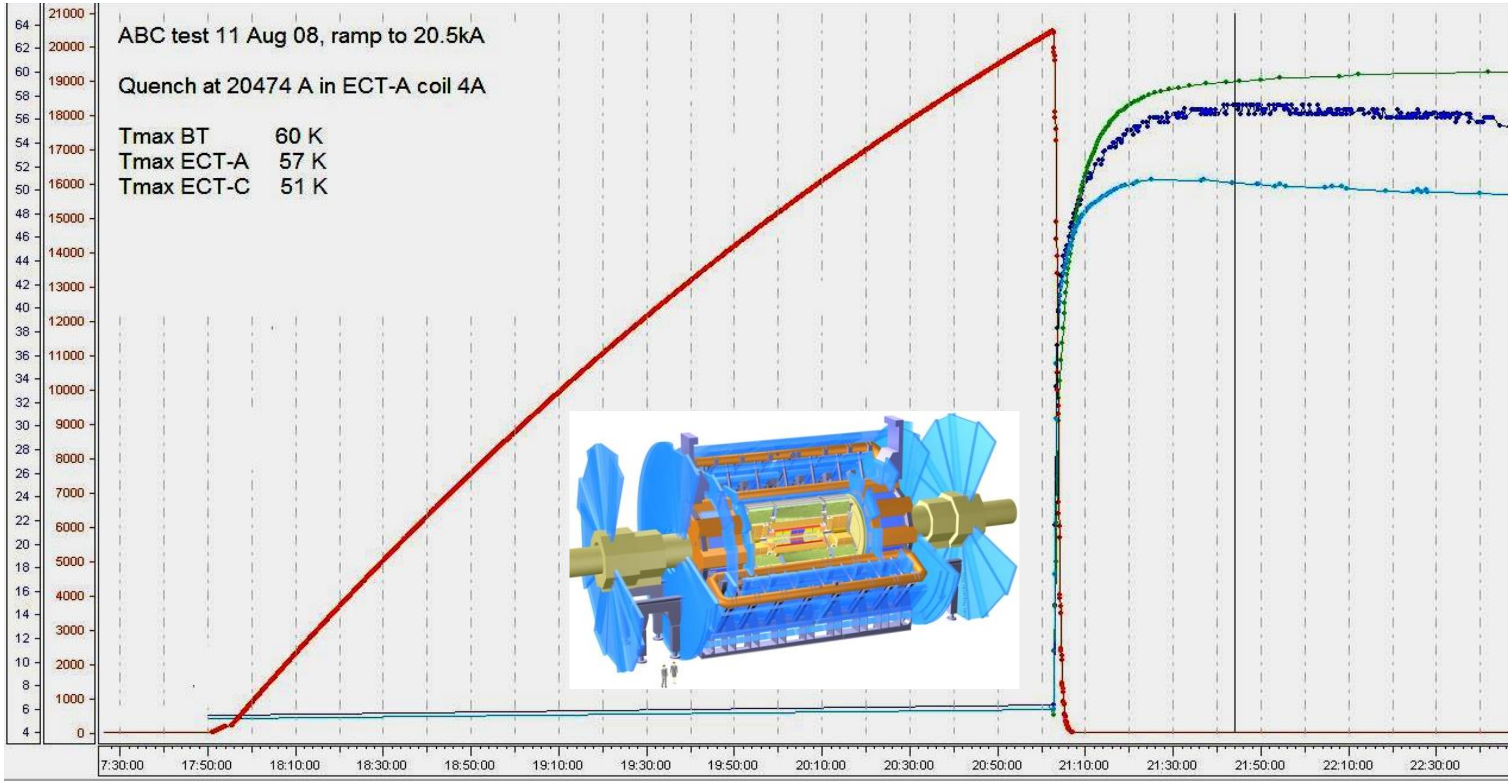




Example ATLAS Toroids

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.


ABC test 11 Aug 08, ramp to 20.5kA

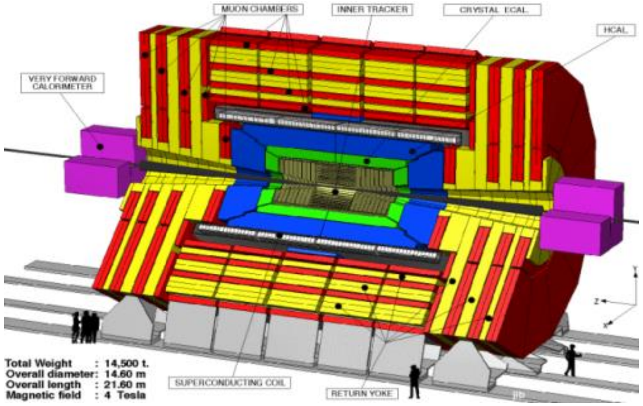
Quench at 20474 A in ECT-A coil 4A

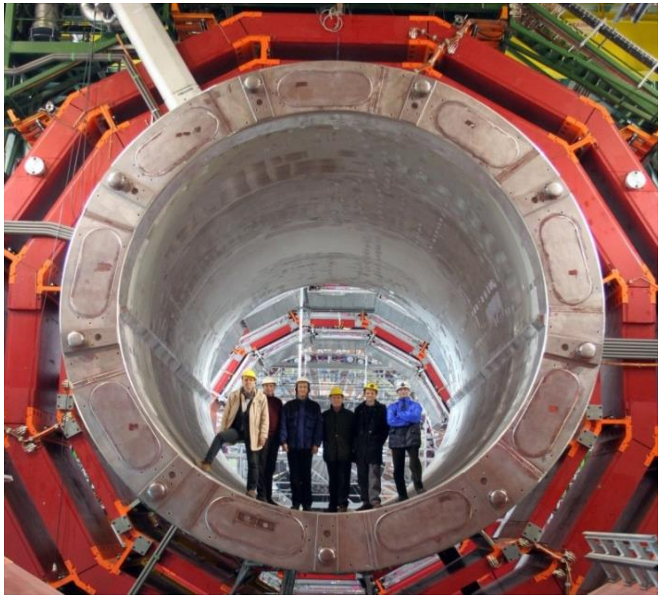
Tmax BT 60 K
Tmax ECT-A 57 K
Tmax ECT-C 51 K

3. Designing a detector magnet, example CMS solenoid

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





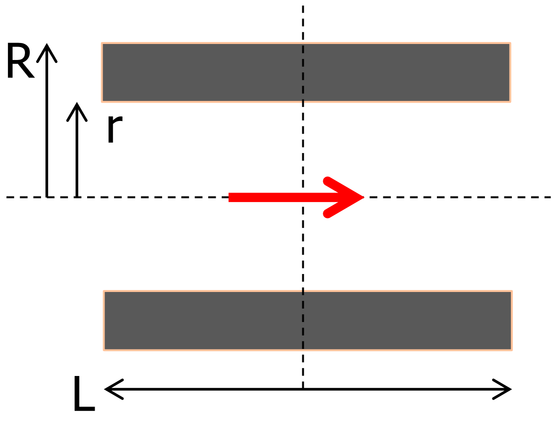
Design steps: Magnetic field, no iron

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 $\beta \rightarrow \infty$



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

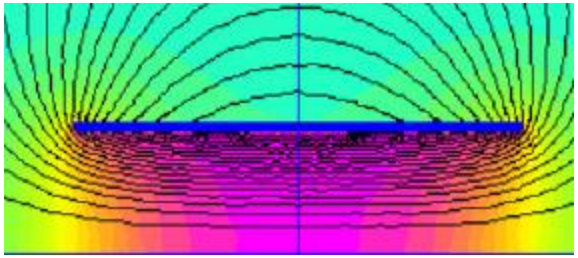
N turns
I current
n= N/L

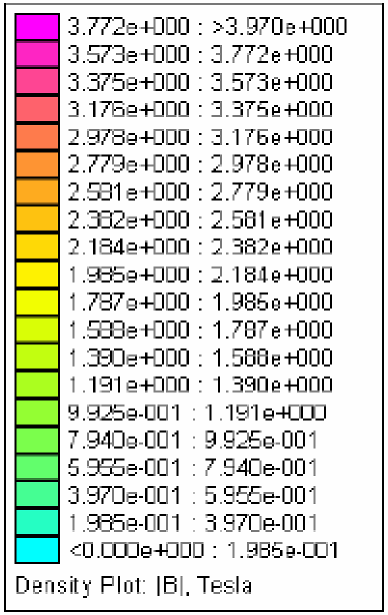
With real CMS magnet sizes:

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

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

With a FEM code we find 3.77 T as well.



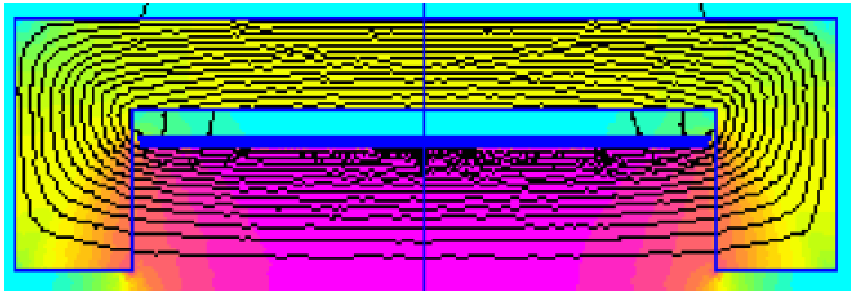


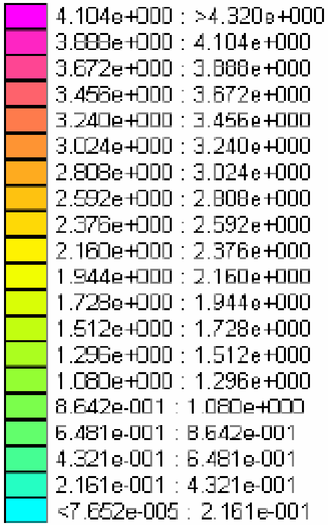
Design steps: Magnetic field, with iron

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)



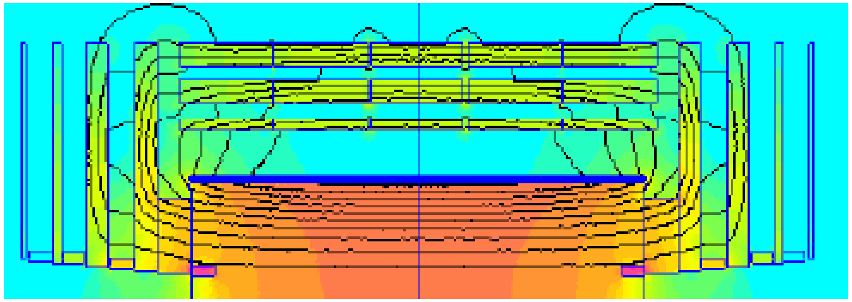


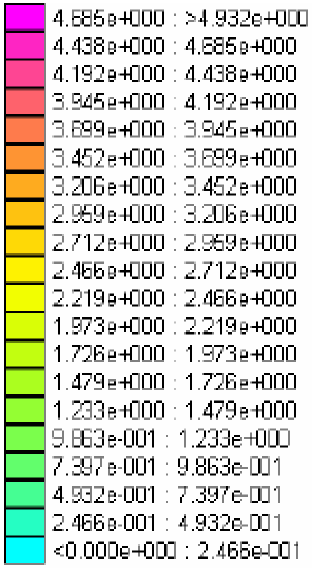
Iron is a magnetic mirror, the coil is almost infinite.

Real iron with gaps for detectors:

B_o= 4.0 T in center

4.6 T in conductor





Stored energy:

FEM calculation yields: $\frac{1}{2\mu_o}\int B^2(r,z)dV = 2.6\ GJ$

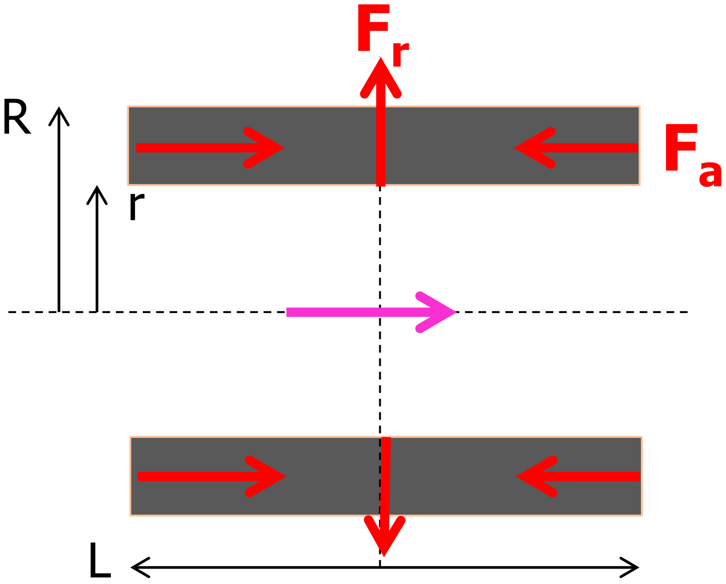
Simple approximation: $\frac{1}{2\mu_o} B^2\,\mathrm{V} = 2.46\ \mathrm{GJ},\quad \mathrm{V} = \text{bore volume}$

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

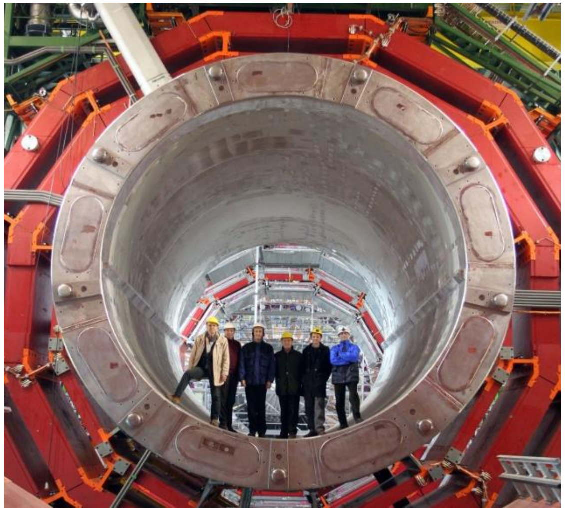


For CMS: **F_a** = +1.66 GN,

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:

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

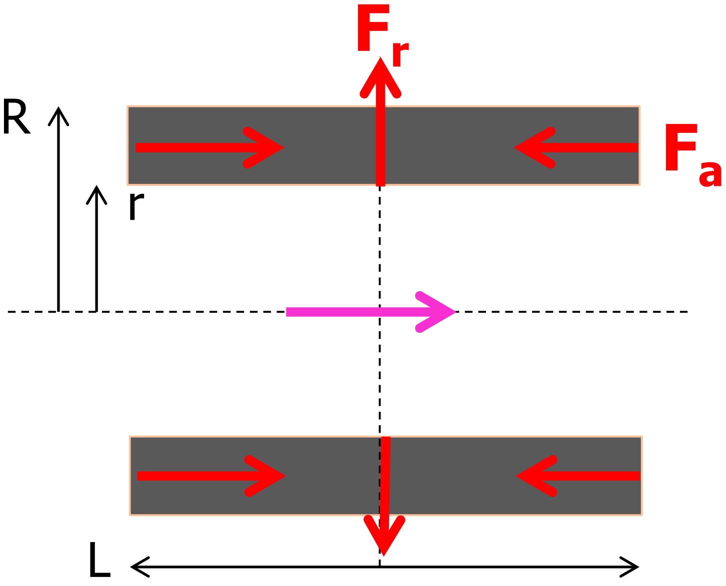
Structural coil thickness:

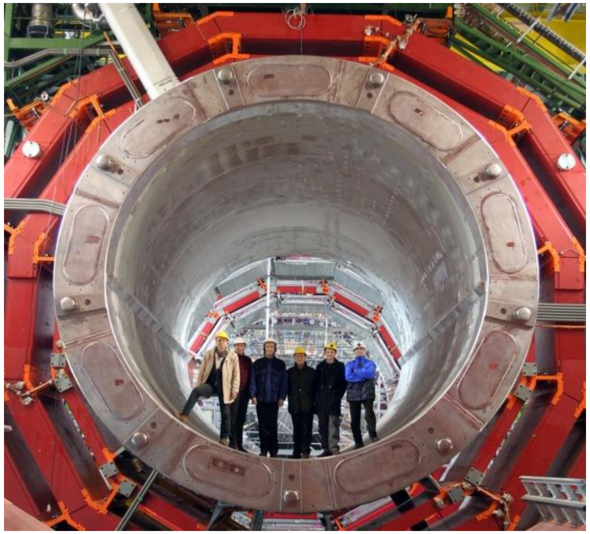
$$t = {}^{3\,r\,P_r}/_{2\,\rho_{yield}} = 320\ mm\ ,$$

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.



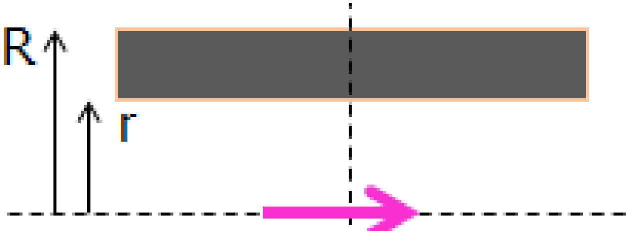


Design steps: Current vs self-inductance

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 $L_c \approx$ 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:

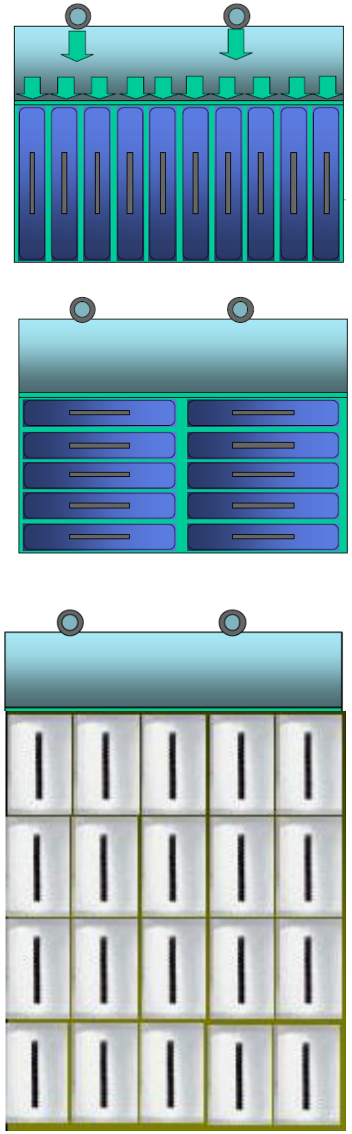
- 2180 turns of superconducting cable with 19.5 kA
- extra stabilizing and quench protection material around the cable
- conductor insulation
- structural reinforcement for handling the hoop stress
- an outer support cylinder for integrity and conduction cooling supply.

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.



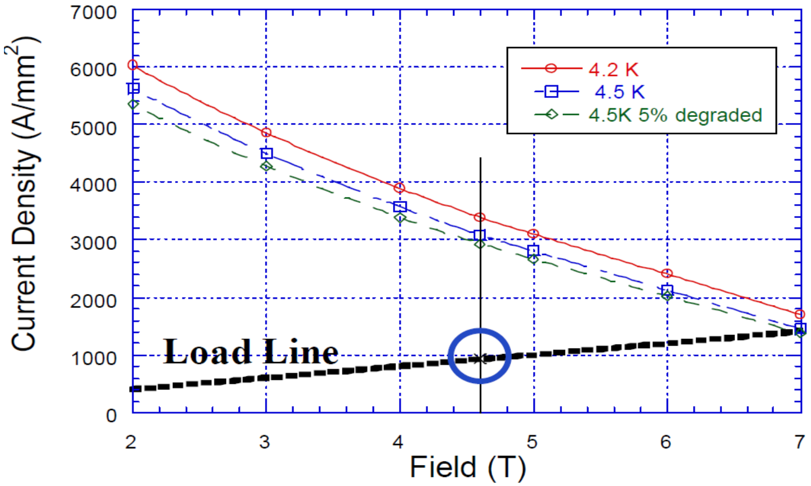
There is a thermal argument as well:

- 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 small 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:

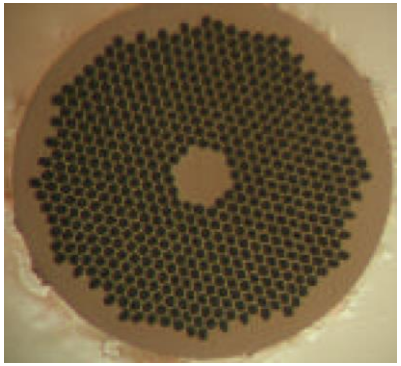
- Critical current density at 4.6 T/4.5K including 5% cabling degradation is 3000 A/mm^2.
- We need margin so we run at 1/3 of the critical current, at 1000 A/mm^2.

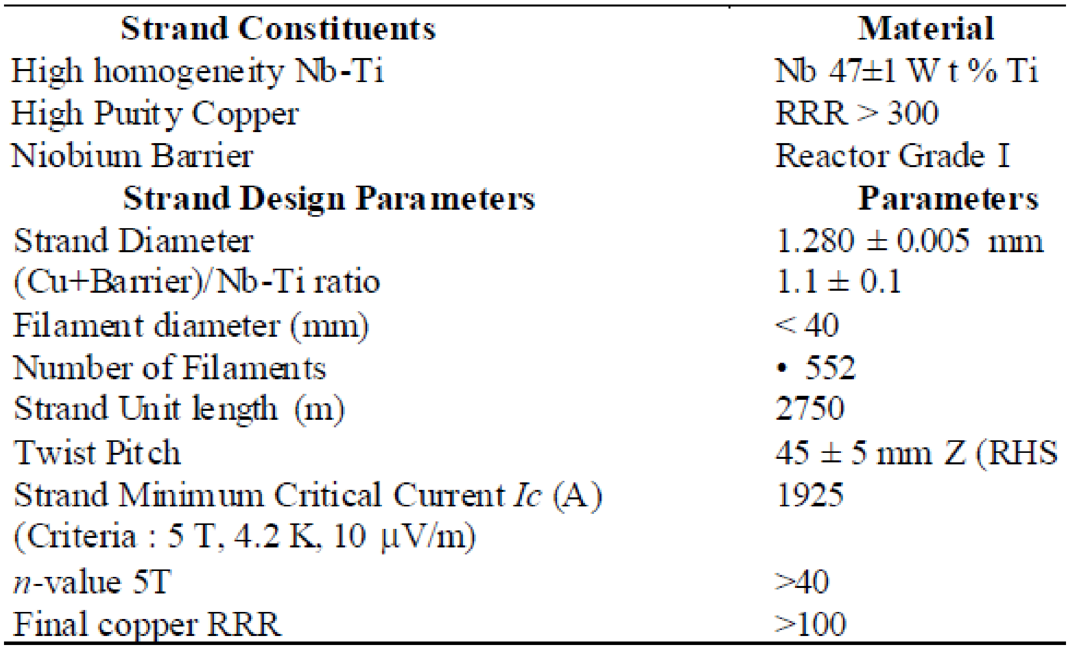


- 19500 A and 1000 A/mm^2, → need 19.5 A/mm^2 sc per turn=cable
- Self-field stability → wire diameter <1.28 mm
- A minimum Cu/sc ratio is 1:1/1 → Asc= 0.61 mm^2
- Number of strands in the cable is then 19.5/0.61 = 32.
- Filament size? Adiabatic filament stability requires <40 µm.
- The filament section is 0.00126 mm^2 → we need ≥484 filaments.
- Twist pitches on strand a cables 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.

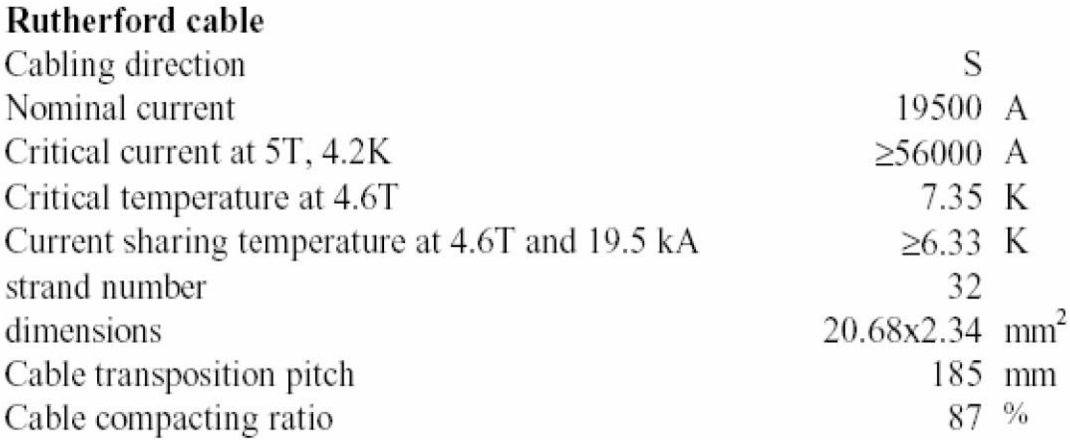
Design steps: wire & cable specification

Following these arguments the cable specification is now as follows:





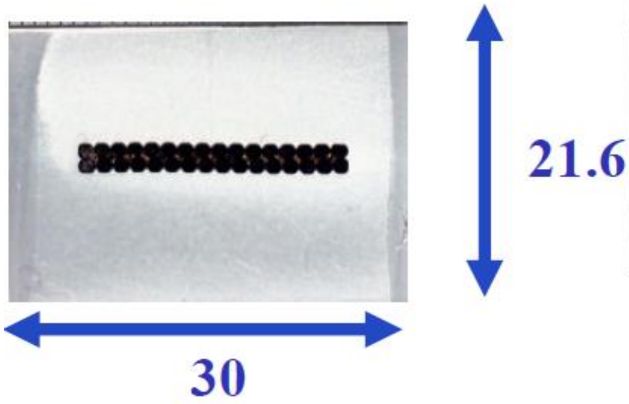
Strand Constituents	Material
High homogeneity Nb-Ti	Nb 47±1 Wt % Ti
High Purity Copper	RRR > 300
Niobium Barrier	Reactor Grade I
Strand Design Parameters	**Parameters**
Strand Diameter	1.280 ± 0.005 mm
(Cu+Barrier)/Nb-Ti ratio	1.1 ± 0.1
Filament diameter (mm)	< 40
Number of Filaments	• 552
Strand Unit 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

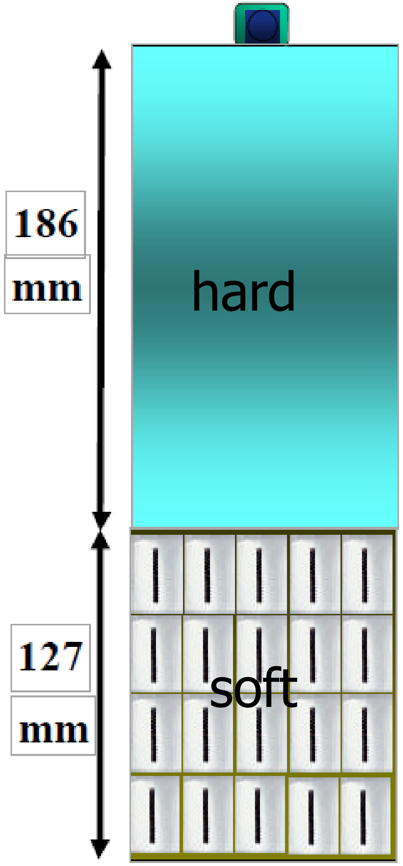
The cable is co-extruded with high purity Al (RRR>1500)



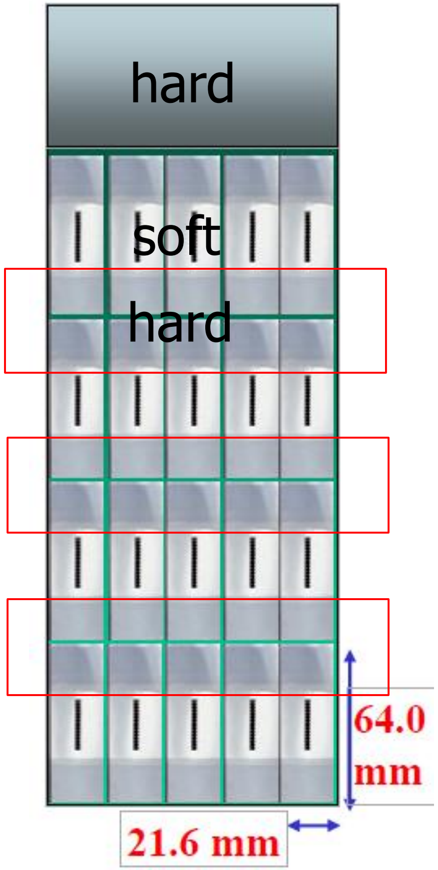
Coil windings: *build up*

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 !



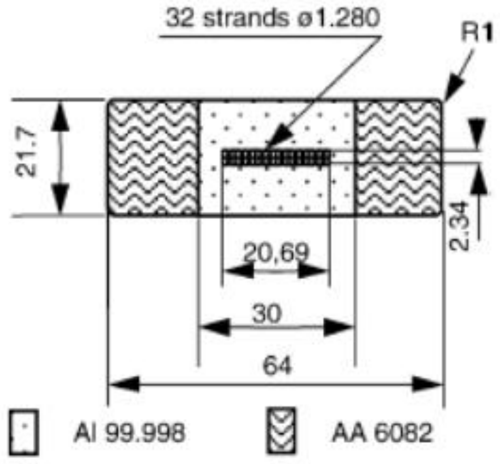
- High shear stress at interface
- In the 4 layers , axial forces up to 1400 MN gives 55 MPa in the pure Al >> 20 MPa, not possible.
- Soft 4 layers of 127mm +186mm gives 22 MPa, is acceptable but strain and shear stress is not uniform.
- A much better solution is to mix soft Al stabilizer and harder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

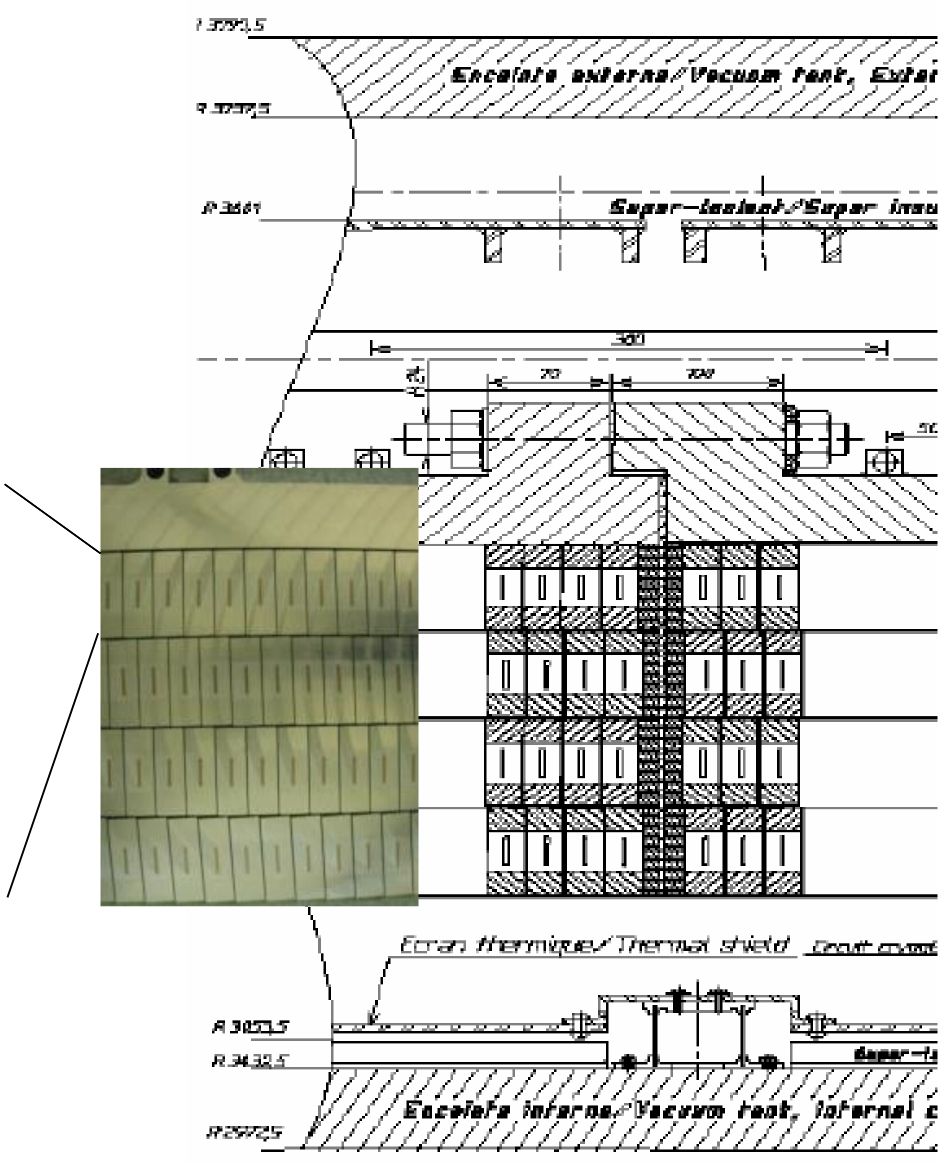


Real coil: final solution

Conductor: soft Al-NbTi with NbTi cable reinforced with Al 6082 bars connected by electron beam welding

New yield stress is about 250 MPa!

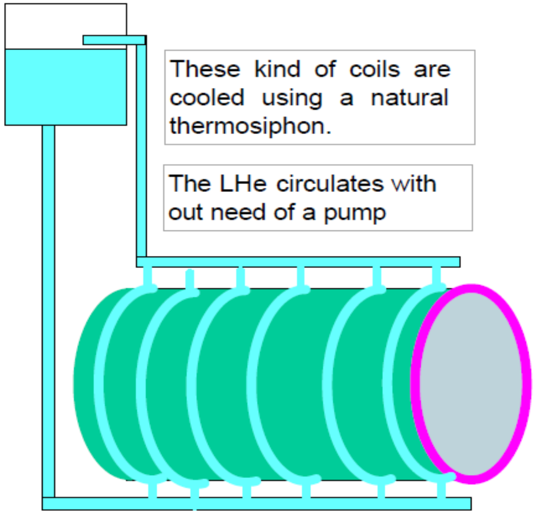




Making of CMS Solenoid: support cylinder

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

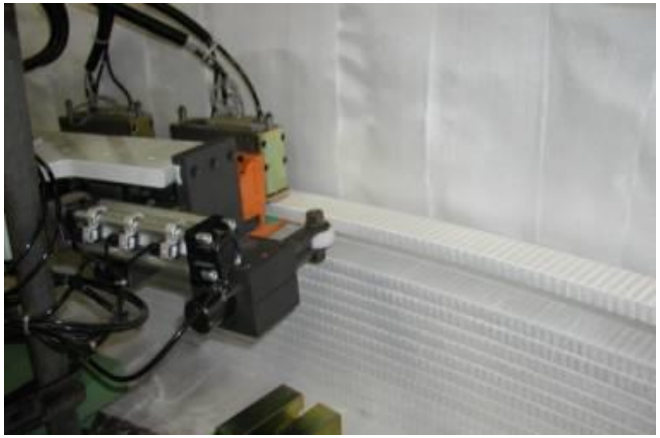


These kind of coils are cooled using a natural thermosiphon.

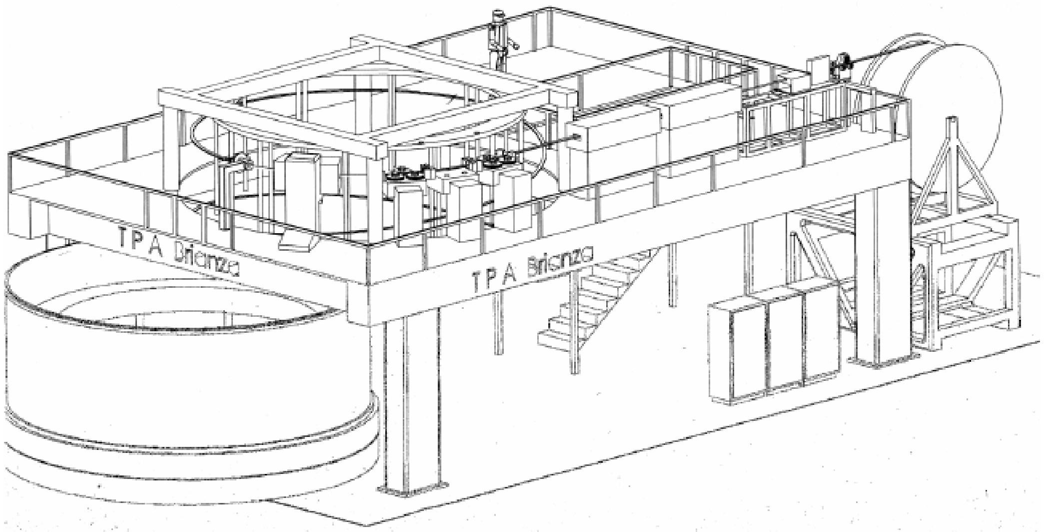
The LHe circulates with out need of a pump

Thermal siphon cooling layout, pipework welded to the cylinder

Making of CMS Solenoid: coil winding



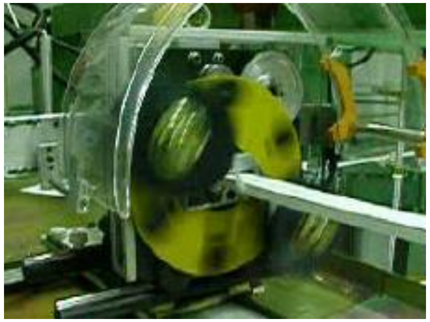
Bend conductor pressed against cylinder



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

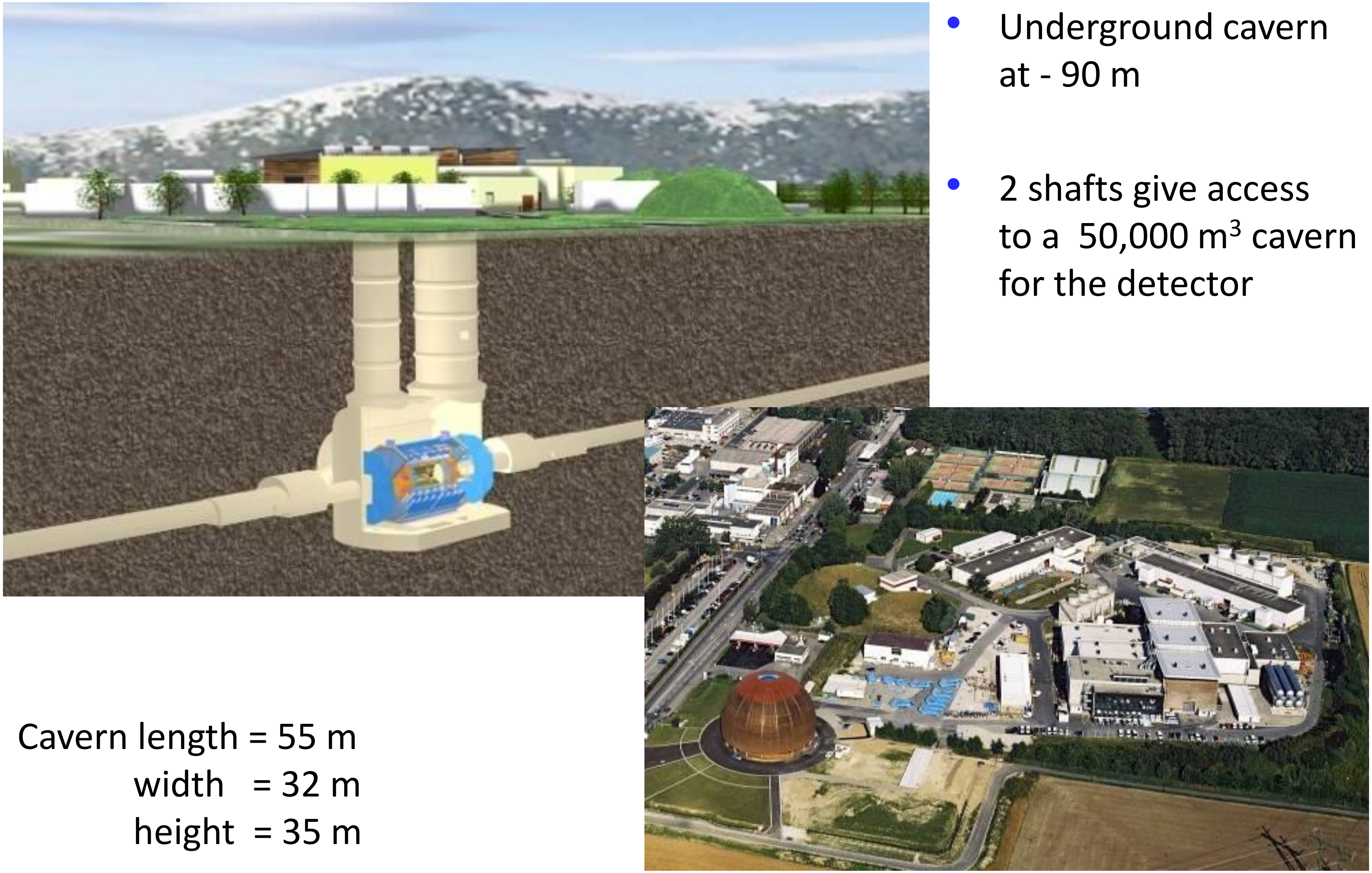
Vacuum impregnation tools,
resin curing, result:
Clear transparent resin

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 sc 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

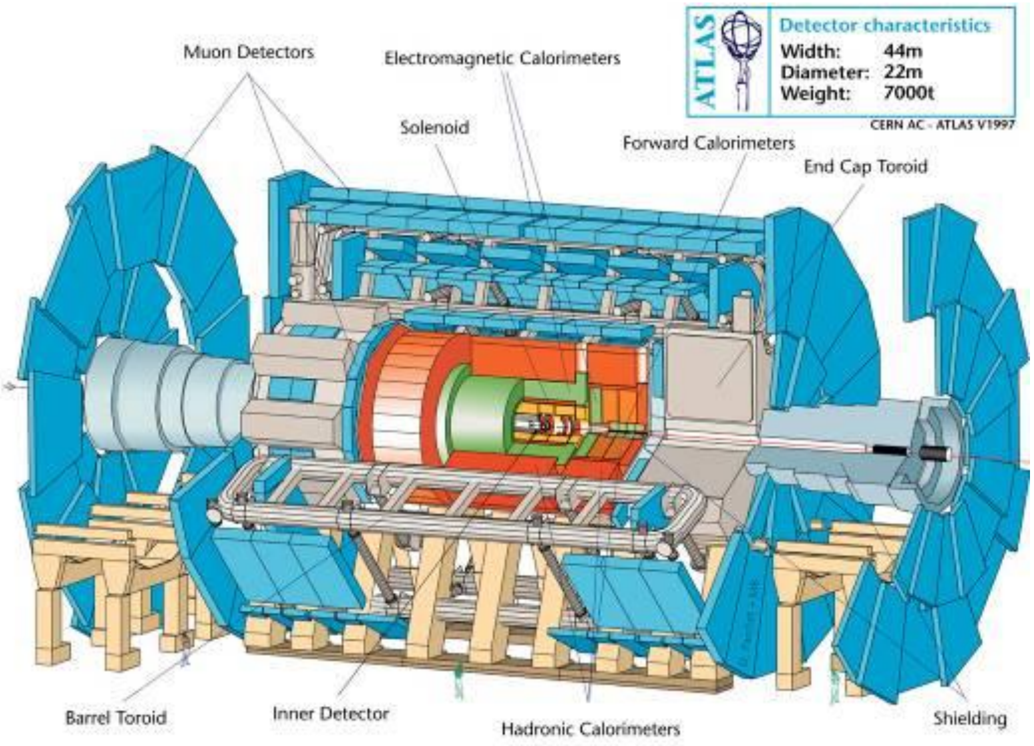
90 km superconductor

20.5 kA at 4.1 T

1.6 GJ stored energy

4.7 K conduction cooled

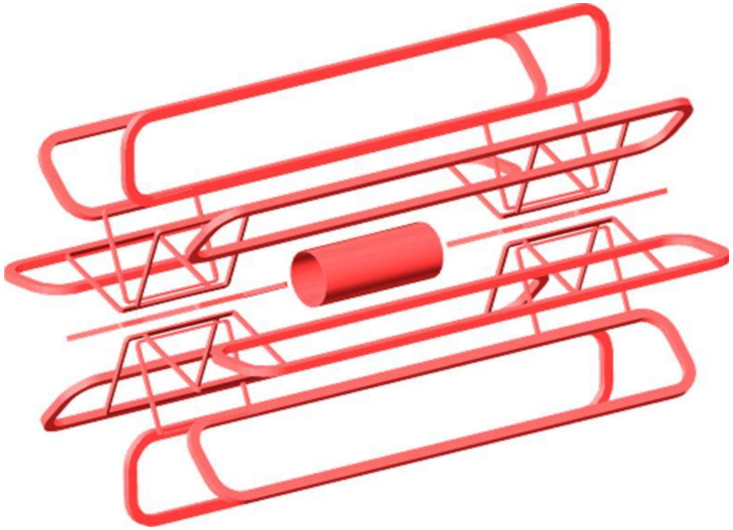
9 yrs of construction 98-07

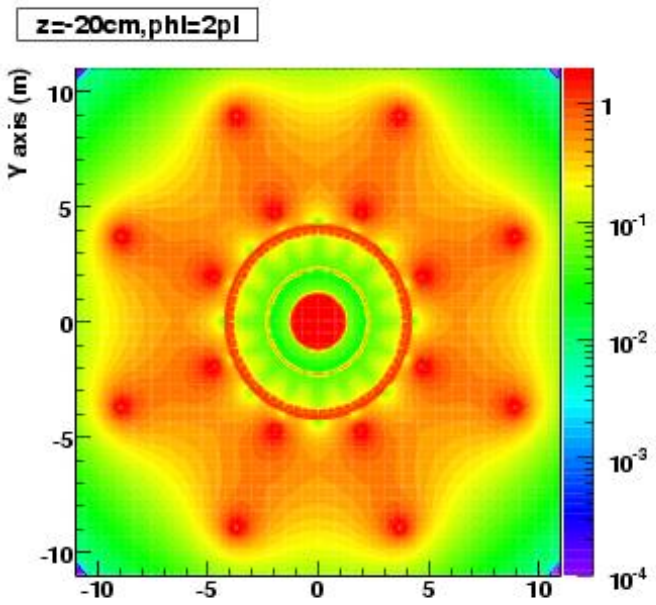


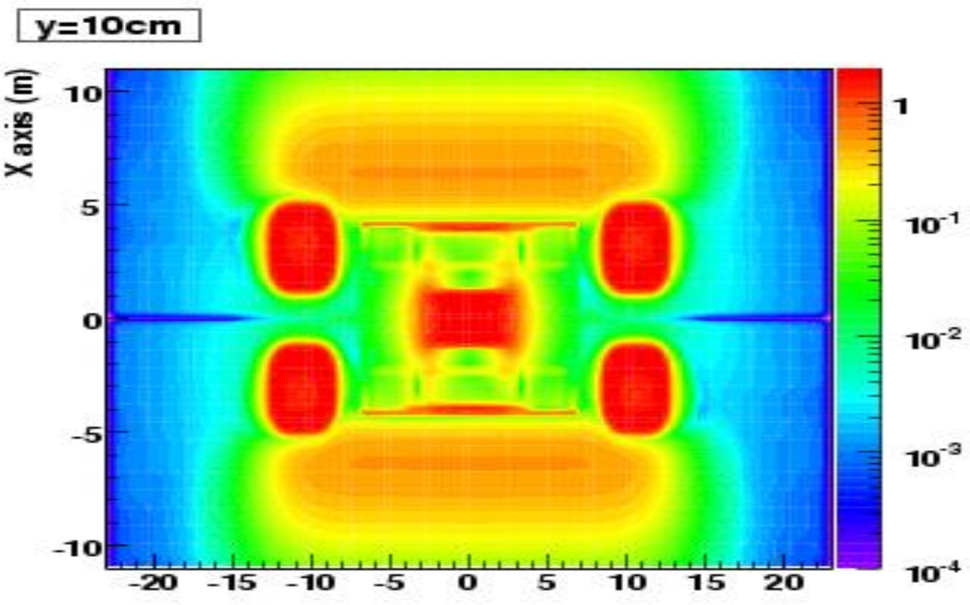
So far the largest trio of toroids ever built

Magnetic field configuration

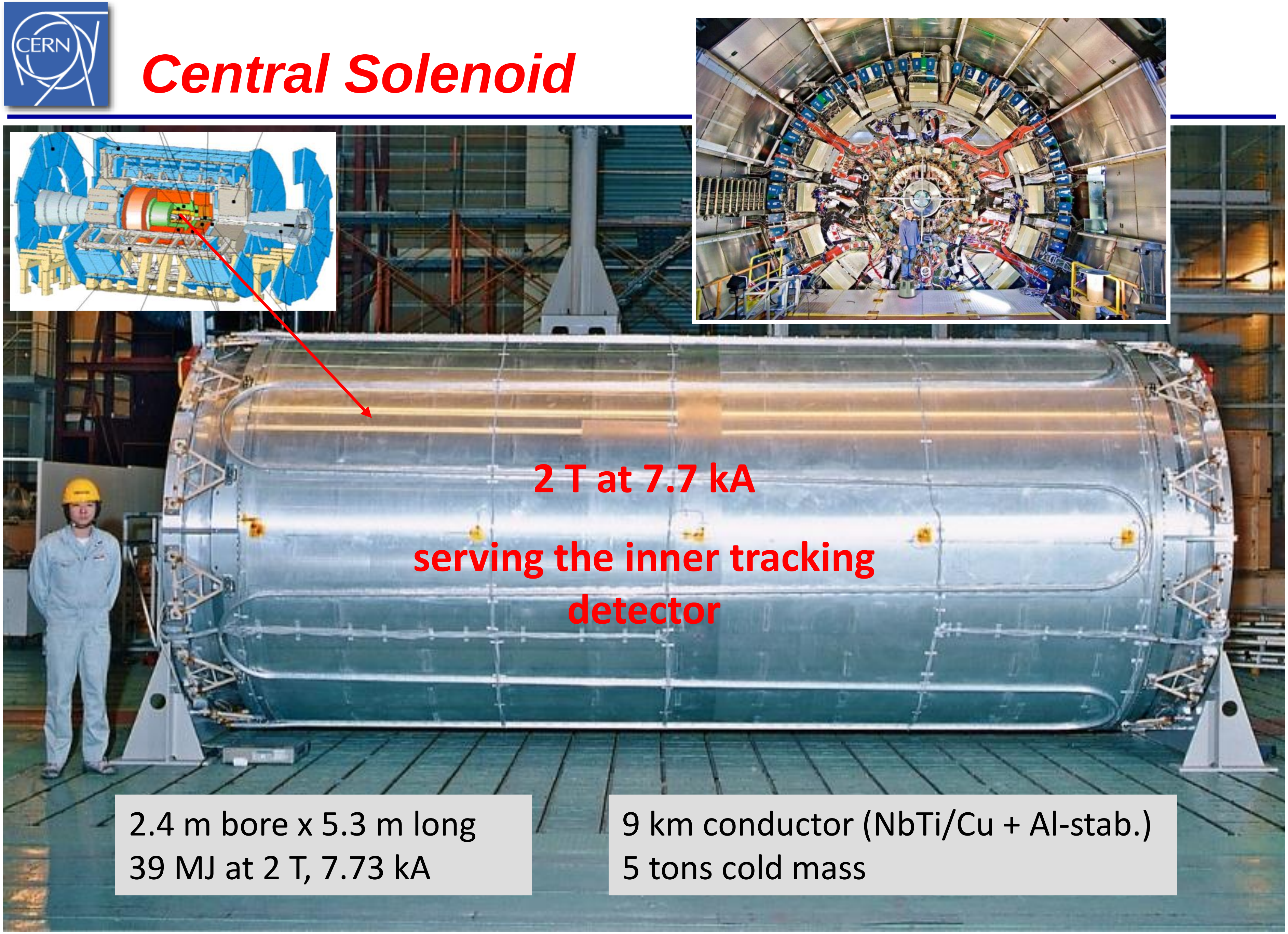
- 2 T in Solenoid closed via return yoke
  2.6 T peak in windings
- ~ 0.8 T average in Barrel Toroid torus
  3.9 T peak in windings
- ~ 1.3 T average in End Cap Toroid
  4.1 T peak in windings







Central Solenoid



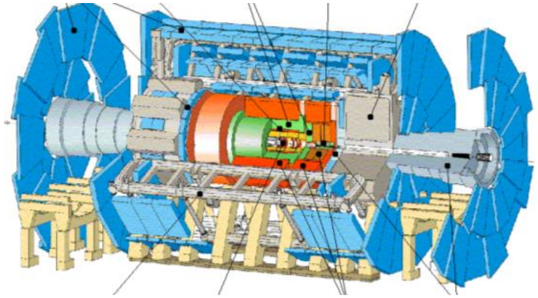
2 T at 7.7 kA

serving the inner tracking detector

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

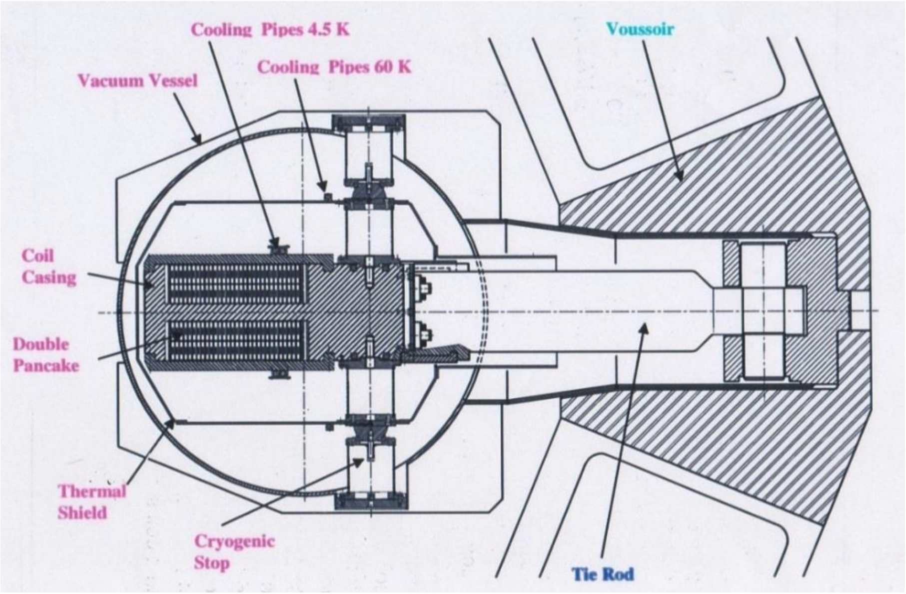
9 km conductor (NbTi/Cu + Al-stab.)
5 tons cold mass

ATLAS Barrel Toroid Integration



Construction of a single coil,
8 of these constitute the toroid

- Two racetrack double pancakes
- 2 x 60 turns, pre-stressed and glued in an Al 5083 casing
- Forced flow indirect cooling via redundant circuits of Al 1050 alloy tubes glued on the casing
- Al alloy thermal shield panels
- Superinsulation
- 8 Ti Tie rods
- 16 fre lateral supports
- Instrumentation
- SS vacuum vessel
- Al-alloy warm structure



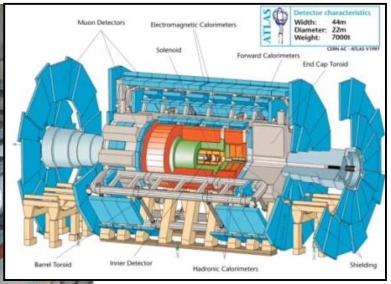
ATLAS: manufacturing the parts


56 km superconductor

16 double pancakes

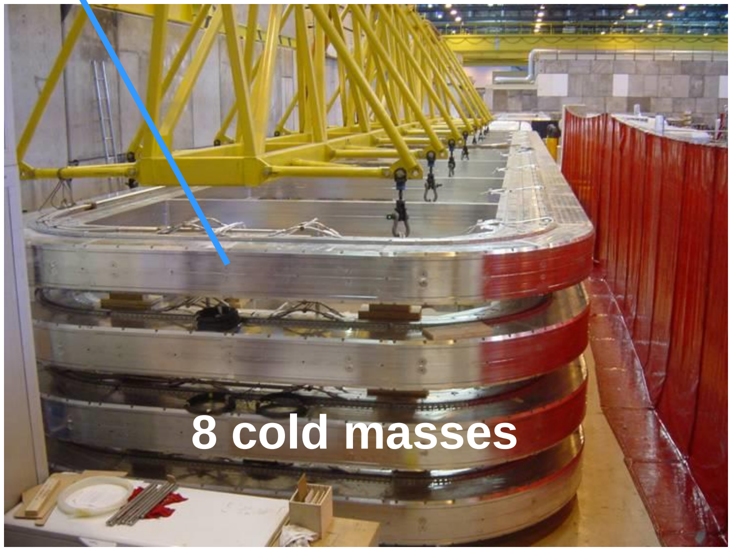

8 coil casings


8 vacuum vessels




instrumented

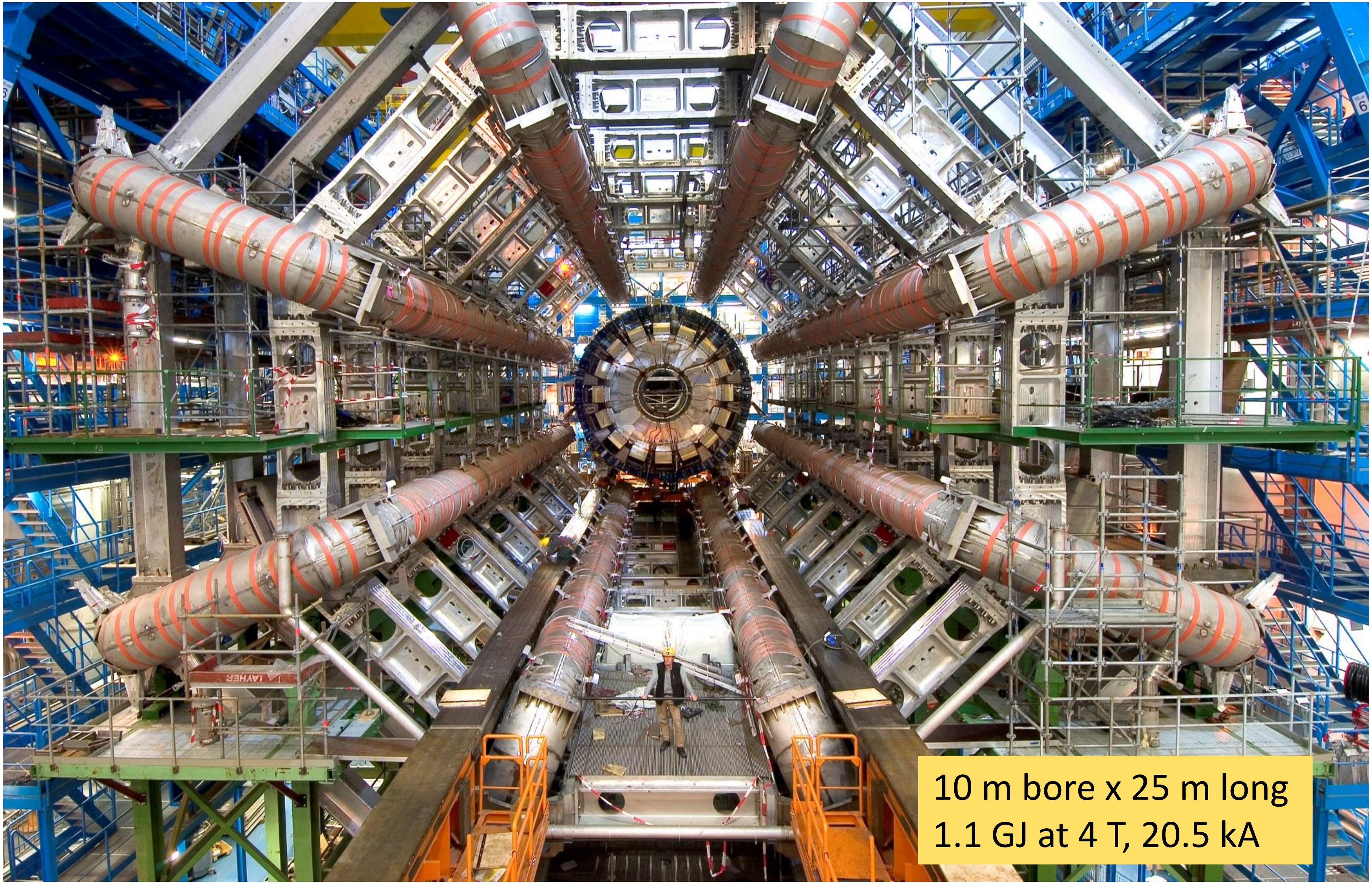

cold mass
integration


8 cold masses

ATLAS: Start of Barrel Toroid assembly

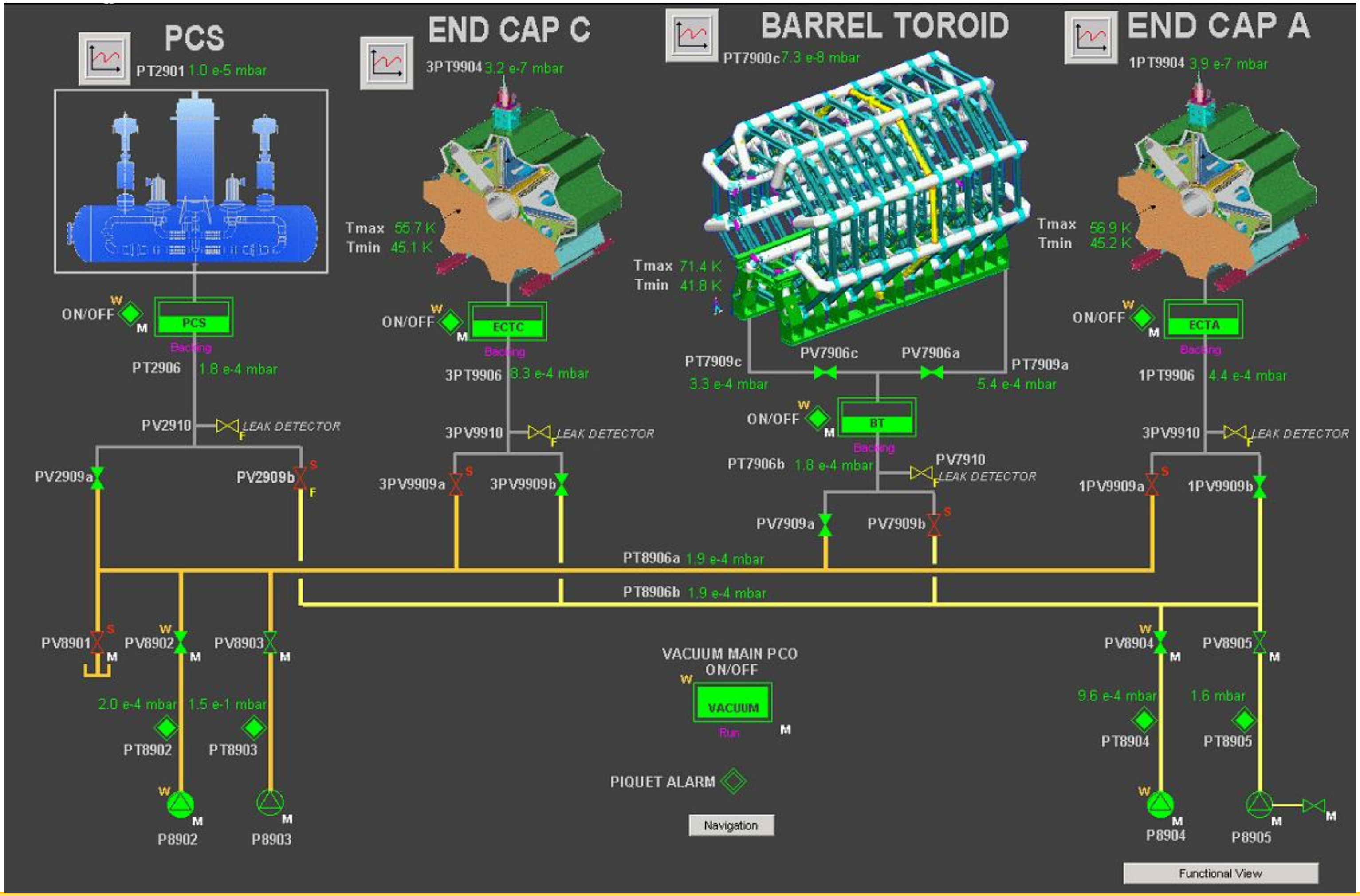
- Transport, decent, reception
- Complex but safe manipulations
- Lowering using 2 lifting frames
- Hydraulic winch with load capacity 190 t

ATLAS: Barrel Toroid in cavern (Nov 05)



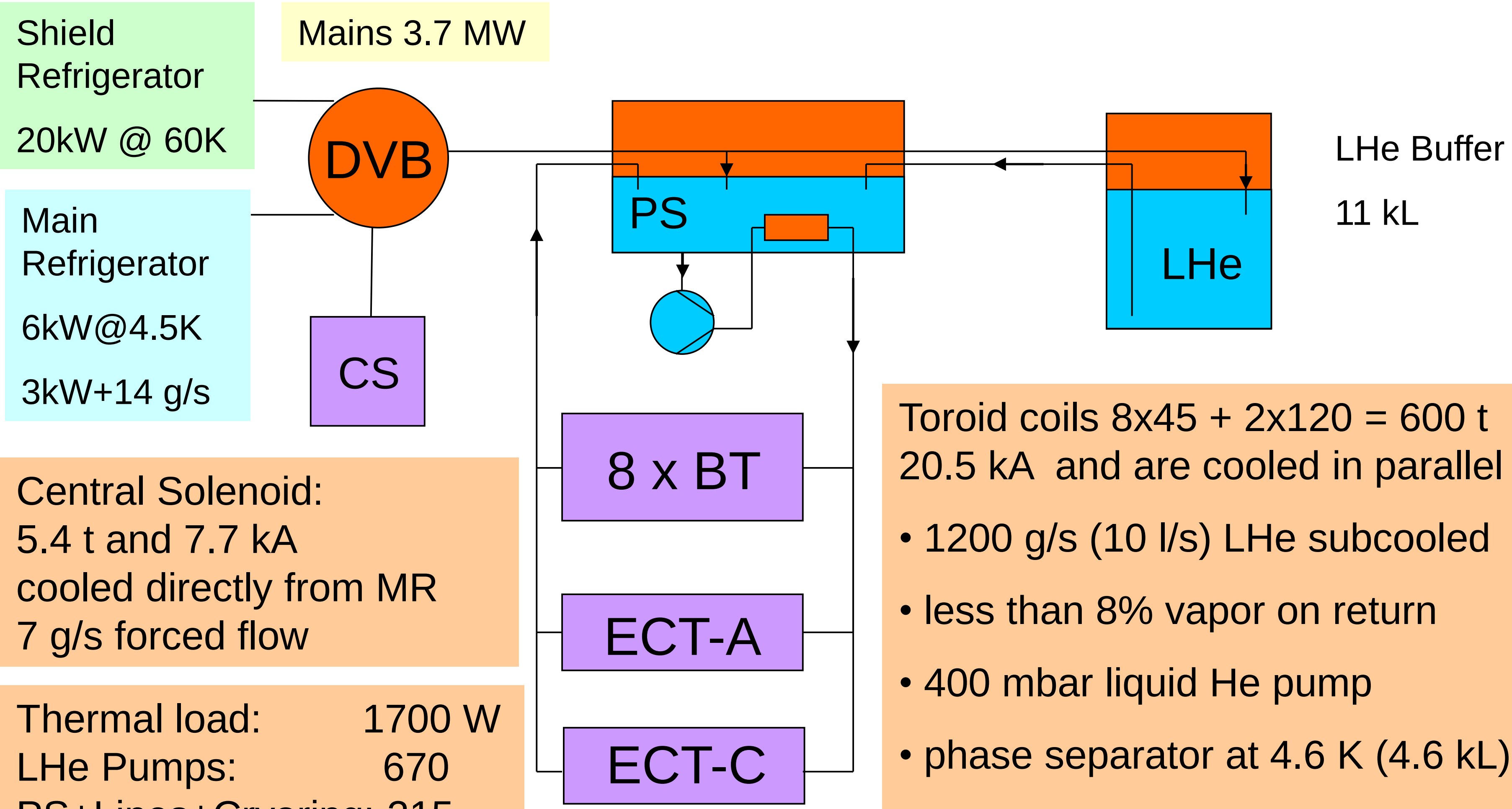
10 m bore x 25 m long
1.1 GJ at 4 T, 20.5 kA

Magnet system services: isolation vacuum



- 4 backing pumps, 21 diffusion pumps, stops when no water cooling and power
- must run 24/7, on UPS & diesel, redundant water cooling circuits

Magnet services: helium cryogenics



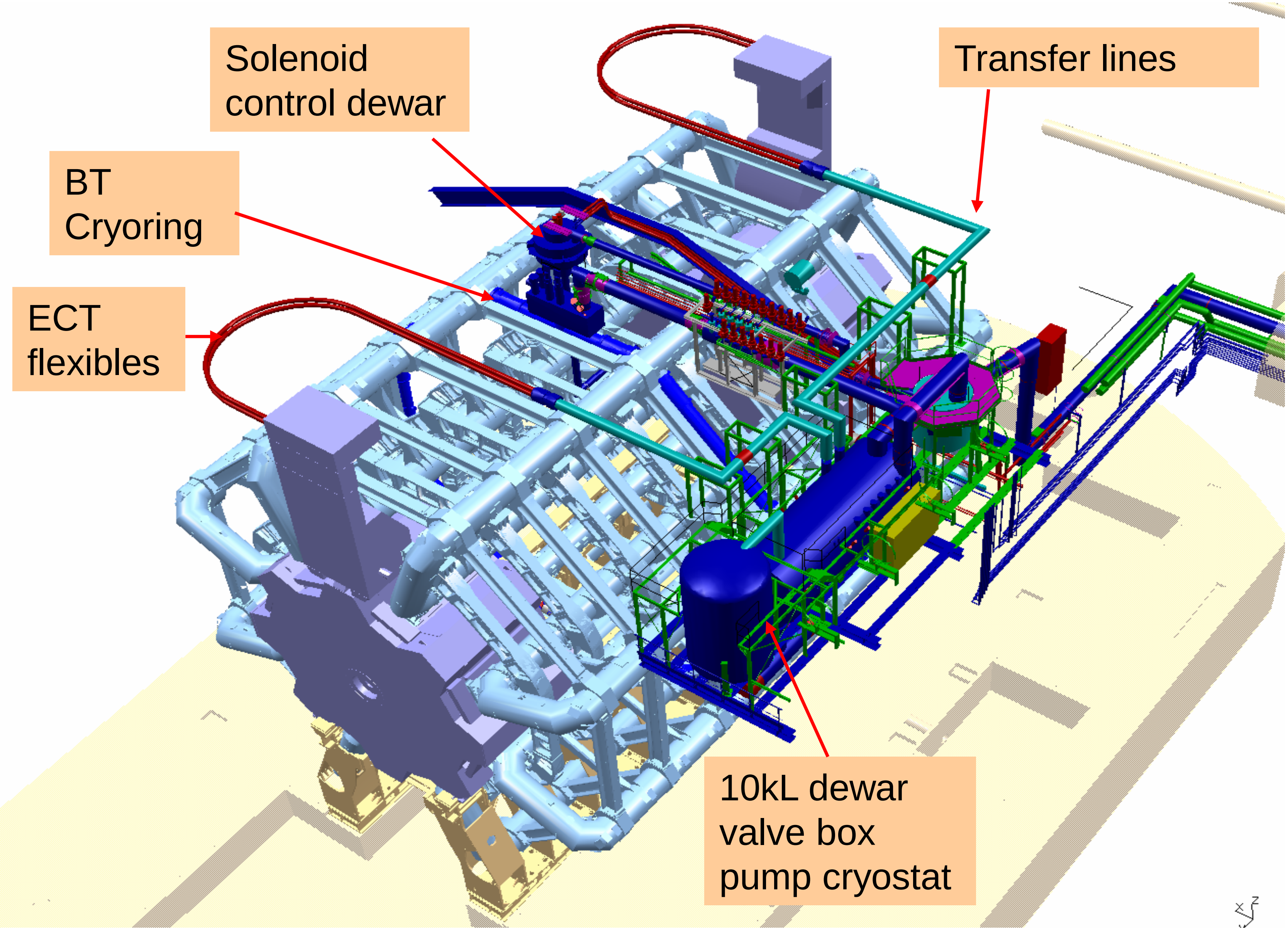
Central Solenoid:
5.4 t and 7.7 kA
cooled directly from MR
7 g/s forced flow

Thermal load:	1700 W
LHe Pumps:	670
PS+Lines+Cryoring:	215
Barrel Toroid:	510
End Cap Toroids:	290
Solenoid:	17

Toroid coils 8x45 + 2x120 = 600 t
20.5 kA and are cooled in parallel

- 1200 g/s (10 l/s) LHe subcooled
- less than 8% vapor on return
- 400 mbar liquid He pump
- phase separator at 4.6 K (4.6 kL)
- 11 kL He to avoid fast dump and allow slow dump in 2 hrs
- 12 g/s of LHe for 8 current leads

ATLAS: He proximity cryogenics



Solenoid control dewar

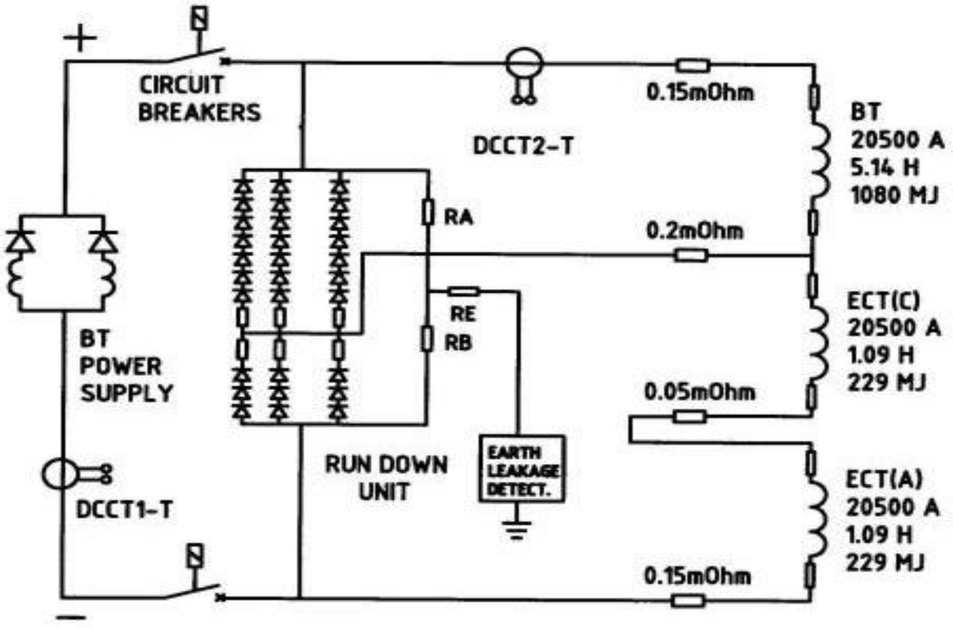
Transfer lines

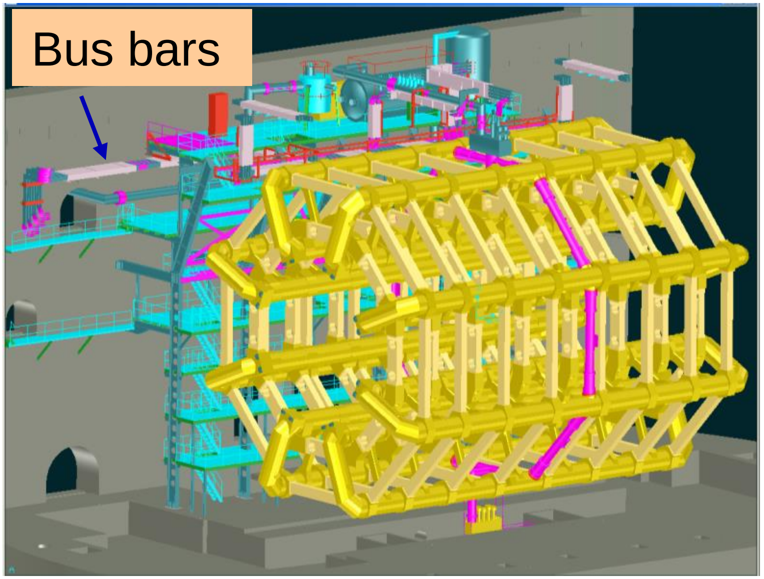
BT Cryoring

ECT flexibles

10kL dewar
valve box
pump cryostat

Magnet services: current, 20.4 kA – 18 V



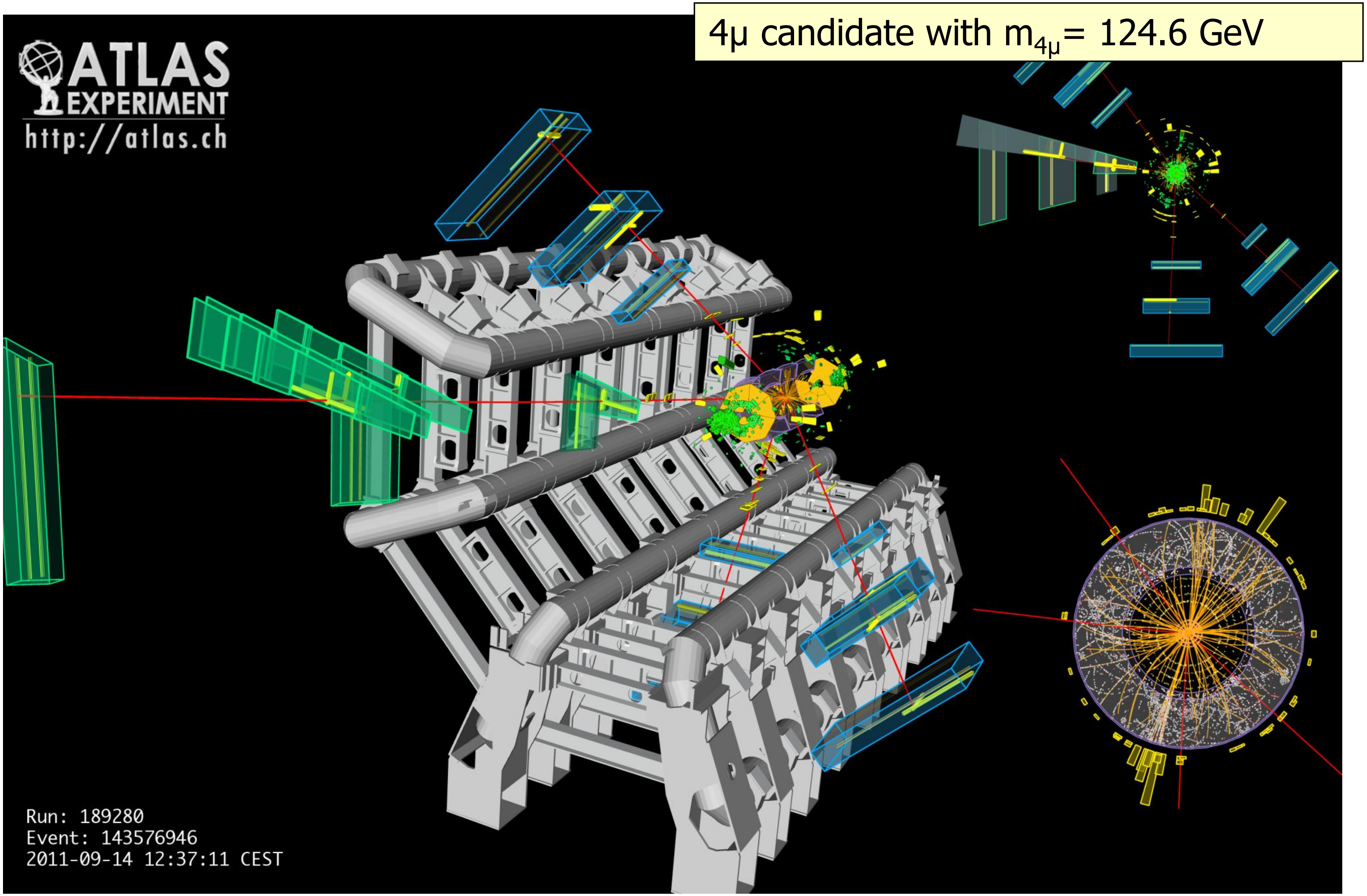

Bus bars

Toroids in series:
- dump in parallel
- power convertor
- 2 switches
- dump resistors
- diode units
- 240 m Al bus bars

Higgs events

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

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



July 4, 2012
CERN press conference

International Herald Tribune

THE GLOBAL EDITION OF THE NEW YORK TIMES

Discovery upends world of physics

CERN reports finding particle that could solve mysteries large and small

The New York Times

NEW YORK, THURSDAY, JULY 5, 2012

Physicists Find Elusive Particle Seen as Key to Universe

Oil Backed Up, Iranians Put It On Idled Ships

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The Economist

A giant leap for science

Finding the Higgs boson

Volkskrant.nl

NIEUWS POLITIEK OPINIE BUITENLAND SPORT TECH & MEDIA

BINNENLAND CULTUUR ECONOMIE REIZEN WETENSCHAP & GEZONDHEID OPMERKELIJK

Higgs-deeltje 'zeer waarschijnlijk gevonden'

Door: Redactie/AP – 04/07/12, 09:21

'I think we have it'

© ANP. De presentatie van testresultaten in de zoektocht naar het Higgs-deeltje, vandaag.

UPDATE Een team wetenschappers bij de deeltjesversneller van de Europese onderzoeksorganisatie CERN in Genève hebben sterke bewijzen gevonden voor een deeltje dat verdacht veel lijkt op het Higgs-boson of Higgs-deeltje. Dat maakte CERN bekend tijdens een persconferentie in Genève.

VERWANT NIEUWS

Higgs: nooit verwa 04/07/12

'Maatschappij heef 04/07/12

Deeltjesfysici wach 04/07/12

'God-deeltje mogel 03/07/12

CERN ziet 'voetspo Higgs-deeltje - 02/0

MEER OVER

Le Monde

ce : la matière dévoilée

IMPÔTS CE QUI VA CHANGER

ALGÉRIE L'INDÉPENDANCE

'God particle' discovery has scientists giddy. Page A2

The Gazette

EL PAIS

EL PERIÓDICO GLOBAL EN ESPAÑOL

la partícula clave para ensión del universo

В ТЕАТРЫ БУДУТ ПУСКАТЬ ПО МОБИЛЬНЫМ ТЕЛЕФОНАМ

МК

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ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ

«КРЕМЛЕВСКИЕ» САМОЛЕТЫ ПРИШЛОСЬ МЕНЯТЬ НА ПЕРЕПРАВЕ

МЕТРО СПУСТЯТ НА ВОДУ

AD ALGEMEEN DAGBLAD

EINDELIJK GELIJK NA 48 JAAR

Frankfurter Allgemeine

ZEITUNG FÜR DEUTSCHLAND

Masse macht's

CHINA DAILY

THURSDAY, July 5, 2012

IMPORTANT MATTER Scientists claim to have discovered 'God particle'

THE TIMES OF INDIA

Big bang moment: Scientists may have found 'God particle'

THE HINDU

Elusive particle found, looks like Higgs boson

CORRIERE DELLA SERA

La particella che può svelare i segreti dell'universo

Nomine Rai bloccate Scontro Fini-Schifani

gazeta WYBORCZA.PL

Cząstkę Higgsa fizycy najpierw wymyślili, potem szukali 40 lat

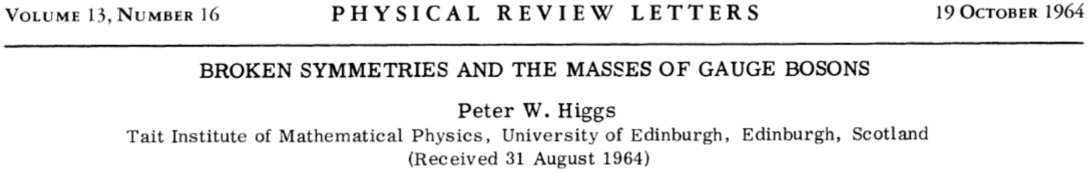
BOSKA MASA

আনন্দবাজার পত্রিকা

বিজ্ঞানের 'ঈশ্বর' দর্শন

'পেয়েছি, যা খুঁজছিলাম'

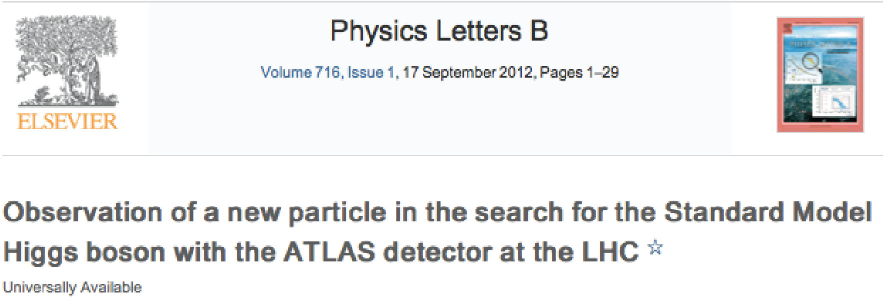
It takes time……. Mr Higgs



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)



ELSEVIER

Physics Letters B
Volume 716, Issue 1, 17 September 2012, Pages 1–29

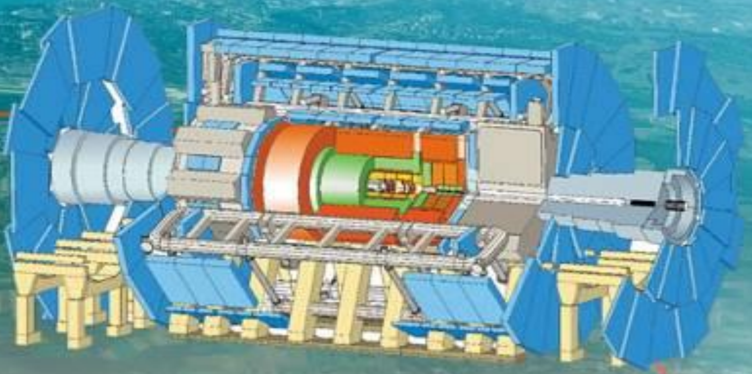
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

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

Luxury very performing option

Downscaled accepted baseline Detector

Options for increasing colliding energy

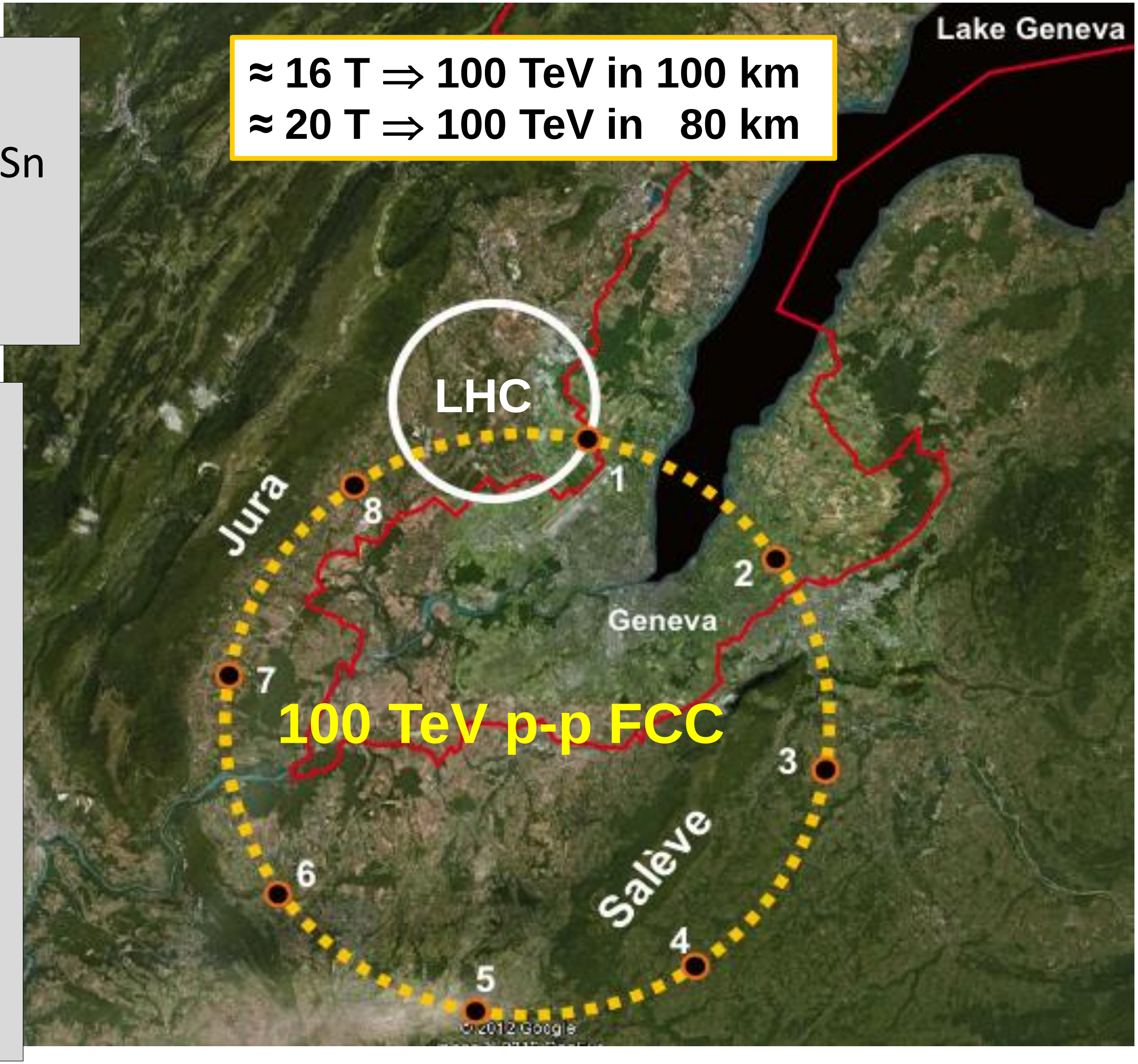
Energy = 0.3 x B x R

B: 1.8 x from NbTi to Nb_3Sn

B: 2.4 x from NbTi to HTS

R: 4-5 x more magnets

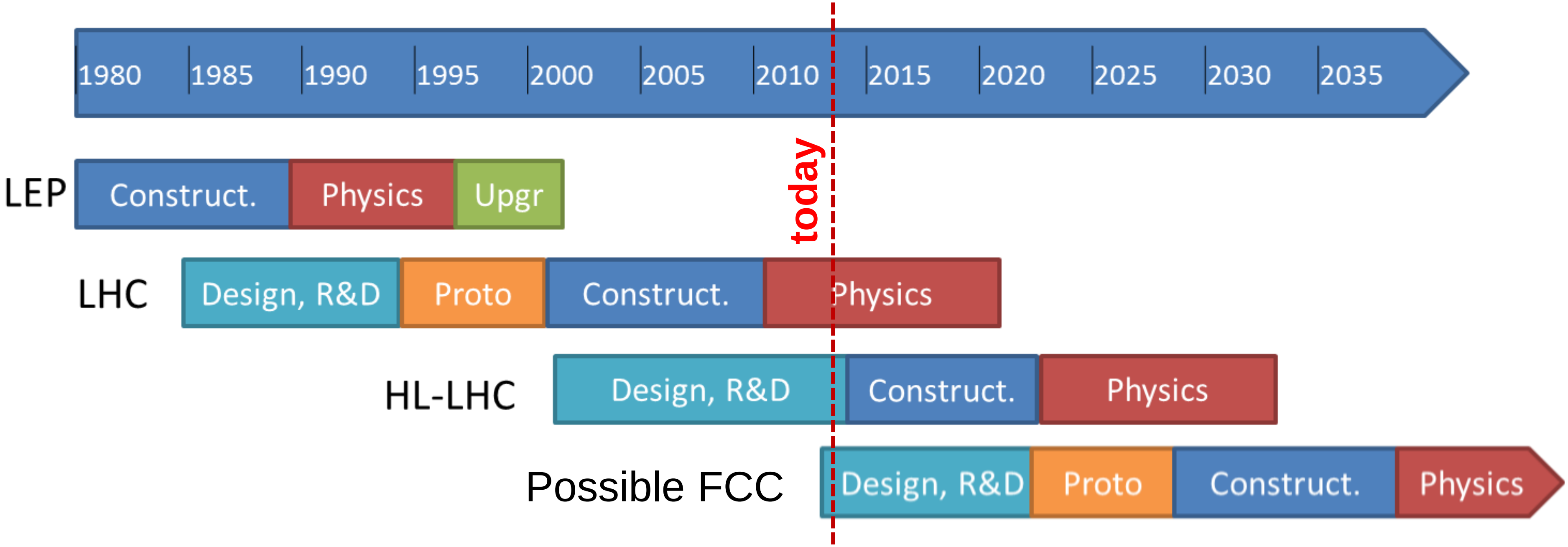
- New 80-100 km tunnel in Geneva area
- pp-collider (VHE-LHC) defining the size
- Options for adding an e+e collider (TLEP) p-e collider (VLHeC)
- CERN-hosted study with international collaboration


≈ 16 T ⇒ 100 TeV in 100 km

≈ 20 T ⇒ 100 TeV in 80 km

It easily takes 30 years time……. start now

> *“CERN should undertake design studies for accelerator projects in a global context, with emphasis on **proton-proton** and electron- positron **high-energy frontier machines.”***



1980 1985 1990 1995 2000 2005 2010 2015 2020 2025 2030 2035

today

LEP: Construct. | Physics | Upgr

LHC: Design, R&D | Proto | Construct. | Physics

HL-LHC: Design, R&D | Construct. | Physics

Possible FCC: Design, R&D | Proto | Construct. | Physics

FCC Study : p-p towards 100 TeV. Study in progress sine mid-February 2014.

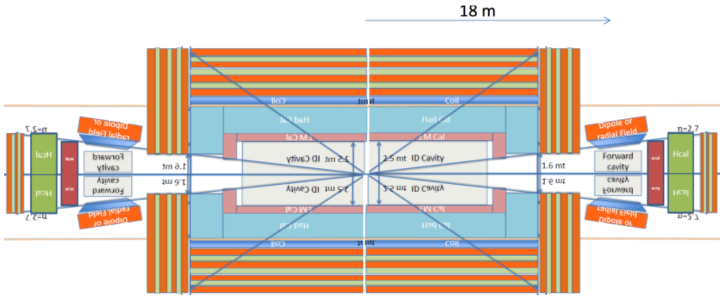
Leading to Conceptual Design Report by ed of 2018

Design drivers for detector magnets

Bending power: 100 TeV, a 7 x higher collision energy than 14 TeV of present LHC

Same tracking resolution ?

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$



BL^2/σ has to be increased by factor 7 !

- For same resolution **σ, for a** single solenoid, increase field to 6 T in 12 m bore!

Also need low-angle coverage in forward direction

- add a dipole or iron toroid for on-beam bending featuring some 10 Tm!

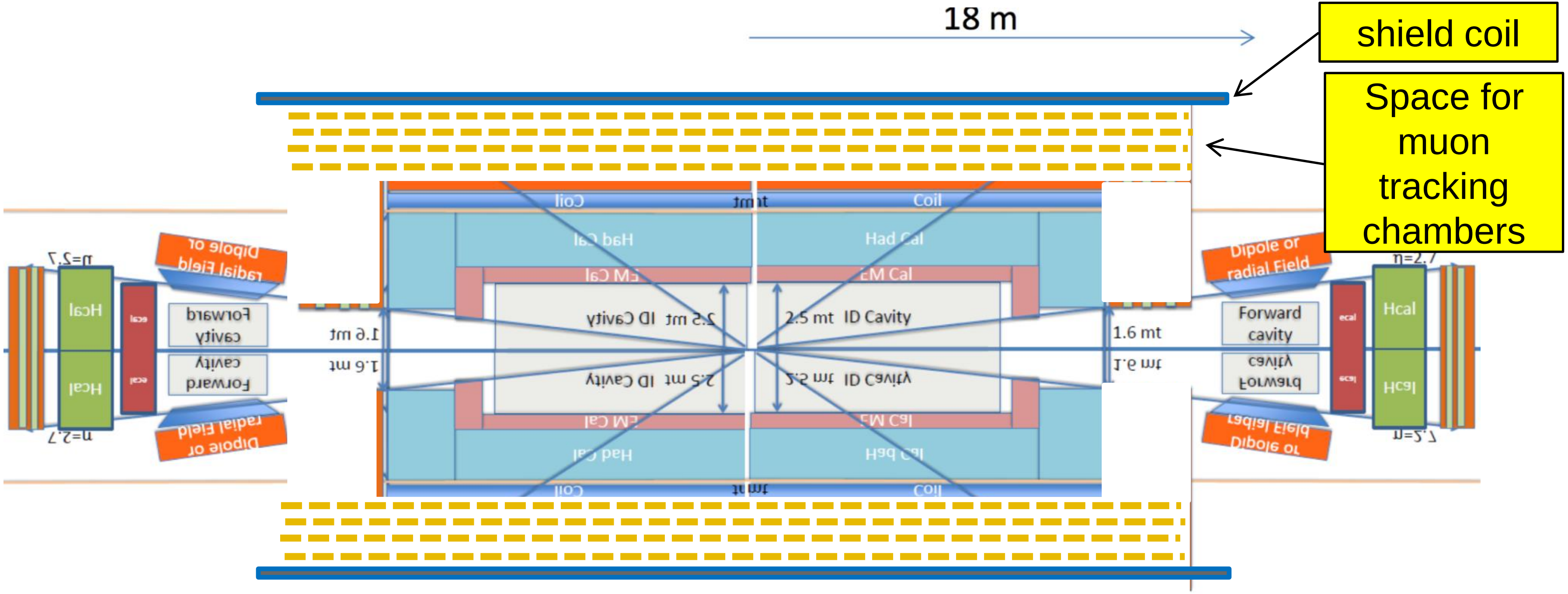
HCAL depth increase from 10 λ to 12 λ (iron) radial thickness some 3.0 m!

- Free bore of solenoid or toroid increases to 6 m and length accordingly.

ECAL to cover low angles, move out, from 5 to 15 m, system gets longer.

- **Higher magnetic field, larger bore, longer system.**

Option: Twin Solenoid + Dipoles



shield coil

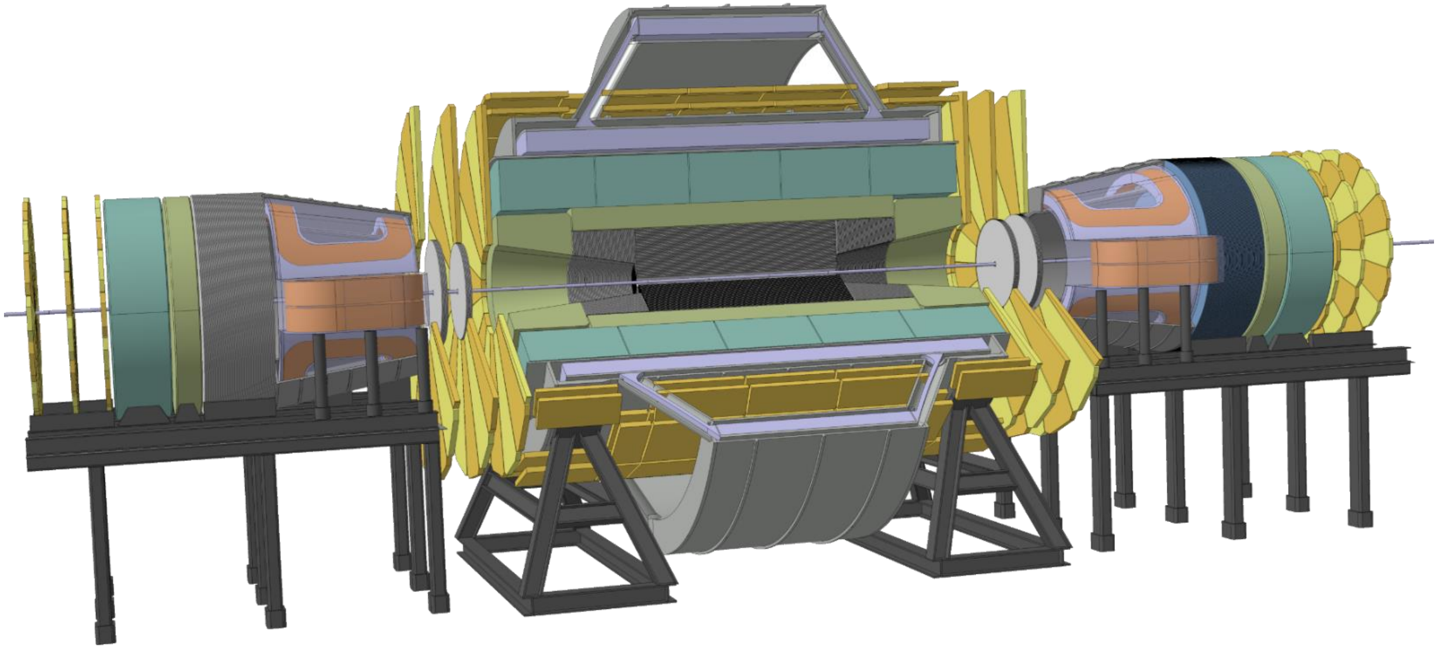
Space for muon tracking chambers

Twin Solenoid: a 6 T, 12 m dia x 23 m long main solenoid + an active shielding coil

Important advantages:

- ✓ **Nice Muon tracking space:** area with 2 - 3 T for tracking in 4-5 layers.
- ✓ **Light:** 2 coils + structures, ≈ 5 kt, only ≈ 4% of the option with yoke!
- ✓ **Much smaller:** system outer diameter is significantly less than with iron.

Design: 6T/12m Twin Solenoid & Dipoles



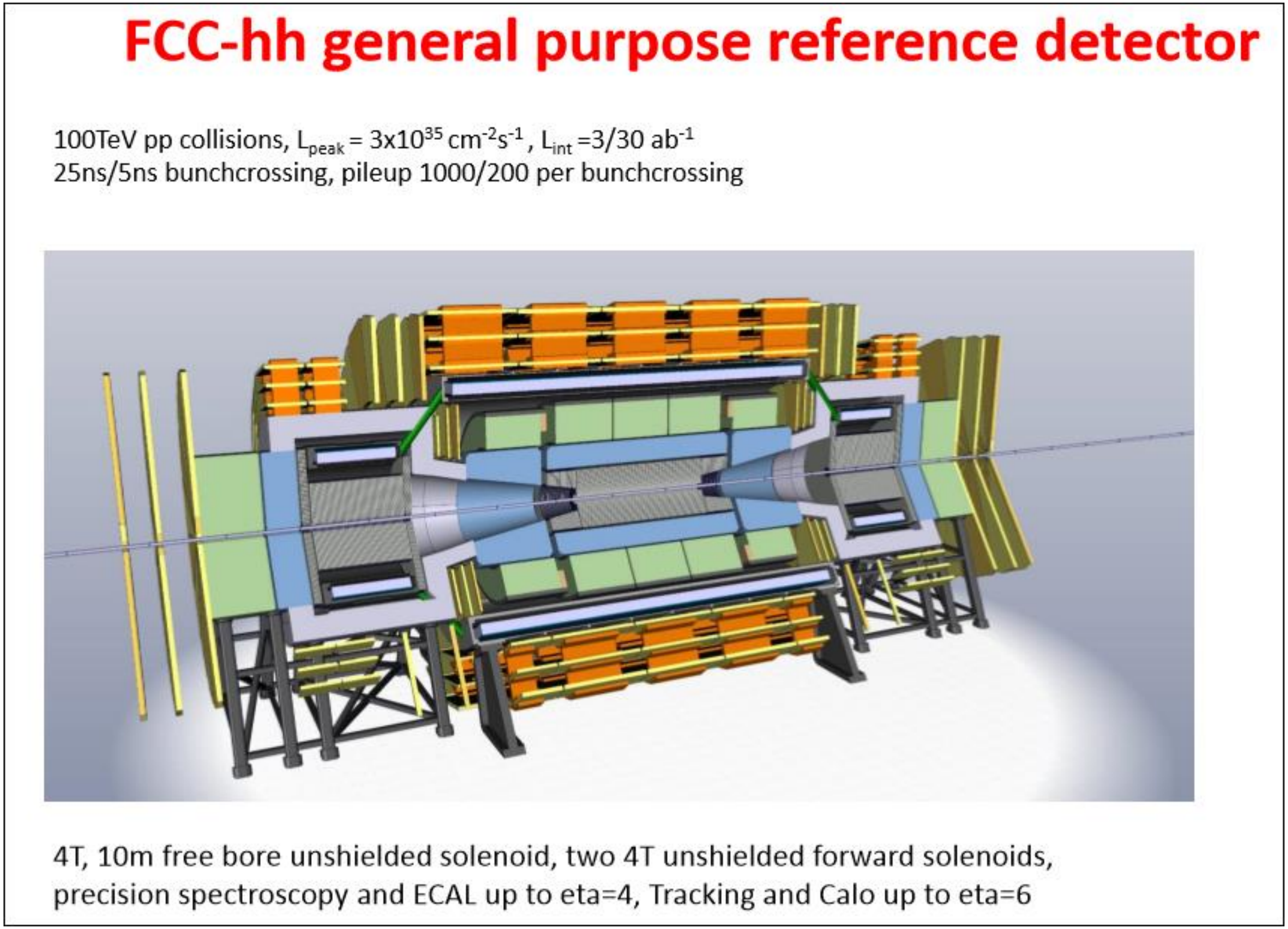
Best performing "ultimate system" assuming same inner detector granularity of 25 micron

6T/12m actively shielded Twin Solenoid and forward dipoles

But, very expensive because of size and stored energy.

	Twin Solenoid	Dipoles
Stored energy	53 GJ	2x1.5 GJ
Total mass	7 kt	0.5 kt
Peak field	6.5 T	6.0 T
Current	80 kA	20 kA
Conductor	102 km	2 x 37 km
Bore x Length	12 m x 20 m	6 m x 6 m

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



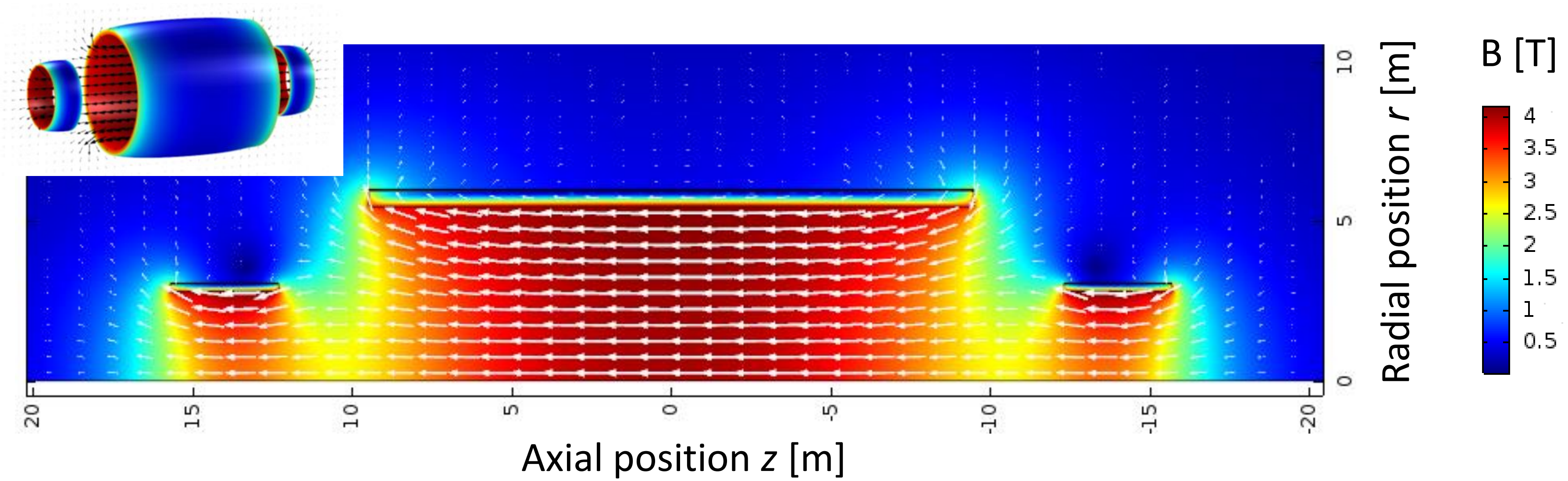
FCC-hh general purpose reference detector

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

- ✓ Downscaling in field and bore by assuming a finer ID granularity, from 25 down to 10 micron, then 4T in 10m bore, cheaper & “affordable”

Unshielded Solenoid and 2 Forward Solenoids



Solenoid + Forward Solenoids

- Forward Solenoids enhance tracking for high-η particles
- Main solenoid: 4 T over 10 m free bore
- Forward solenoid: Free bore allowing particles at $\eta \geq 2.5$ to pass through
- **This is the approved baseline for the CDR in 2018!**

Property	Value
Magnetic field in center [T]	4
Free bore diameter [m]	10
Stored energy [GJ]	13.8
Cold mass main solenoid [kt]	1.05
Cold mass forward solenoid [t]	48
Vacuum vessel mass Main Solenoid [t]	875
Vacuum vessel mass Forward Solenoid [t]	32

This concludes the course……..