Superconducting Detector Magnets

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1. Concept: $E = mc^2$

How to discover new (elementary) particles?

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

We need $E$, an energy production device (accelerator-collider), and an experiment to look at the shower of particles produced (detector).
**Concept: Colliders, circular vs. linear**

**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.

Collision energy

\[ E_{\text{TeV}} \approx 0.6 B_T R_{\text{km}} \]

9 T & 4.6 km $\rightarrow$ 14 TeV
Example: Large Hadron circular Collider

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

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

No Higgs without Superconductivity!

- 1232 dipoles magnets for bending
- 386 quadrupole magnets for focusing
- ~7000 Correction magnets
- Insertion and Final Focusing magnets
- ATLAS and CMS detector magnets
- Nb/Cu cavities for acceleration
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** $\Rightarrow$ positively charged particle
- **right turn** $\Rightarrow$ negatively charged particle
- **curvature** $\Rightarrow$ 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 “$4\pi$“ detector and its magnetic field?

**Radial thickness**

is the summation of:

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

**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

$$ F = q \left( E + \mathbf{v} \times \mathbf{B} \right) \quad (E \cong 0) $$

In the transverse direction, radius $R$, sagitta $s$:

$$ s = \frac{L}{8R} = \frac{qBL^2}{8p_t} $$

and momentum resolution

$$ \frac{\Delta p_t}{p_t} = \frac{p_t}{0.3BL^2} $$

- 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 $\rightarrow$ 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
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

$T_c : 11 \text{ K}$

$B_{c2} : 13 \text{ T}$

Very well developed

$\sim 1 \text{ €} / \text{ kA m}$
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, $\Delta(0)$ 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

\[ \phi_o = \frac{h}{2e} = 2 \times 10^{-15} \text{ Weber} \]

\[ B_{c2} = 3.1 \times 10^3 \gamma \rho_n T_c \]

$h = \text{Planck's constant, } e = \text{electronic charge}$

Critical temperature & upper critical field are linked

where $\rho_n$ is the normal state resistivity

$T_c$ and $B_{c2}$ are intrinsic material properties!

! Best superconductors are best resistors!
Critical current density

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

Spacing between flux lines:

\[ d = \left\{ \frac{2 \phi_0}{\sqrt{3} B} \right\}^{\frac{1}{2}} = 22nm \text{ at } 5T \]

A uniform distribution of flux lines gives no net current, so \( J_c = 0 \), but a gradient produces a net current density:

\[ \nabla x B = \mu_0 J = J_c \]

- 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

Flux lines lattice at 5 T, same scale.
Superconductors for magnets

- 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
- B2211 may do better than Y123 when anisotropy is considered
- B2212 or Y123 for DC magnets of 17 - 40 T provided cost comes down drastically
- ReBCO, Y123 in a magnet, not in // field!
- Minimum practical current density
Example: Superconductors in ATLAS Detector

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

- 1.25 mm diameter NbTi/Cu strand, 2900 A/mm² 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 mm²
- 56 km made
- Production by 2 suppliers

**For the End Cap Toroids**, size 41 x 12 mm²,

- 26 km made

**For the Central Solenoid**, size 30 x 4.3 mm²

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

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

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

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

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

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

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 further reduced from \( T_c \) to \( T_{cs} \), the current sharing temperature.

\[
T_{cs}(B,I) = T_b + (T_c(B) - T_b) \left( 1 - I/I_c \right) \quad \text{for} \quad T_{cs}(5 \, \text{T}, \frac{1}{2}I_c \, \text{A}) = 5.7 \, \text{K only!}
\]

- So we lost a lot of margin from 9.2 K \( \rightarrow \) 7.2 K \( \rightarrow \) 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, \( d_{\text{fil}} \)

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 \( \Delta T_1 \) will cause a \(-\Delta J_c\), so flux motion, leading to \( E \), this leading to heat and so again a \( \Delta T_2 \).
- When \( \Delta T_2 > \Delta T_1 \), the process will accelerate and the flux profile collapses.
- Based on simple slab model, the adiabatic stability criterion is found:

\[
d_{\text{fil}} \cdot J_c < \left\{ 3\, c \,(T_c - T_o) / \mu_o \right\}^{1/2}
\]

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

- For NbTi, \( c = 5600 \, \text{J/m}^3; \) \( T_c(5 \, \text{T}) = 7.2 \, \text{K}, \) \( T_o = 4.2 \, \text{K} \)
  and \( J_c = 3000 \, \text{A/mm}^2 \), we find \( d_{\text{fil}} < 70 \, \mu\text{m} \).
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 $\Delta T$
- Field profile has to change, field penetrates deeper, causing heat, taken up by enthalpy up to a certain limit
- Assuming $\eta = \text{sc/total ratio and current density } \eta J$
- 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 $J_c$ 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$_3$Sn 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.

LHC type Nb$_3$Sn Rutherford cable
• 33 stands single stage twisted.
• 13 kA at 11 T.

ATLAS Detector Magnet cable
• Al stabilized 40 strands Rutherford cable.
• 65 kA at 5 T.
Temperature jumps, low heat capacity

Why is release of heat so critical at 4 K?

- Heat capacity is strongly T-dependent
- Copper-NbTi composite:
  \[ C_p(T) = \eta((6.8/\eta + 43.8)T^3 + (97.4 + 69.8 B)T) \]
  \[ \mu J/mm^3K, \text{ at } 5 \text{ T and } 40\% \text{ NbTi in a Cu matrix:} \]
  - 2.5 \( \mu J/mm^3K \) at 4.2 K and
  - 0.5 \( \mu J/mm^3K \) at 1.9 K!
  - 2.5 \( \mu J/mm \) corresponds to a movement in a 1 mm wire at 5 T, 500 A of 1 \( \mu m \) only!

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

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

Minimum Propagation Zone (1-d case)

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

\[ J = \frac{I}{A} \]

Heat produced is equal to heat removed:

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

\[ L = \left\{ 2 \lambda (T_c - T_{bath}) / \rho J^2 \right\}^{1/2} = \text{MPZ} \]

Propagation occurs when \( L > \text{MPZ} \) and recovery when \( L < \text{MPZ} \)!
Minimum Propagation Zone, MPZ

Examples of MPZ in a various wires

- In a bare NbTi wire or filament:
  take 5 T; 3000 A/mm$^2$; $\rho = 6 \times 10^{-7} \Omega m$; $\lambda = 0.1$ W/mK; $T_c = 7$ K
  and we find MPZ of 0.3 $\mu$m only, pure NbTi can not be used!

- NbTi with CuNi matrix would give MPZ of 3 $\mu$m and 0.1 $\mu$J !

- Such wire is extremely sensitive to any heat pulse

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

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

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

✓ for a typical LHC cable we get about 15 mm

✓ and in the ATLAS conductor (600 mm$^2$ pure Al and 20 kA) we get about 500 mm !
Why magnets need High Current & Cables

Magnetic field and stored energy

\[ B \propto N \cdot I \quad \text{and} \quad E \propto B^2 \cdot \text{Volume} \]

Inductance: \[ L \propto N^2 \]

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

\[ \rightarrow \text{Thus low } N, \text{ high current } I! \]

Also \( I_{\text{safe}} \propto \frac{J \cdot E}{V_d} \), kV-range for \( V_d \).

with usual current densities this leads to 10-100 kA.

\[ \rightarrow \text{Given common strand currents of 100 to 500 A, we need for large scale magnets multi-strand cables with 20-1000 strands!} \]

No escape!
Scaling: $I_{\text{safe}} \propto J \times B^2 \times \text{Volume}$

- **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?

- No!

Cabled: may be, but to be developed

65000 A@5T Al-NbTi/Cu?

- Yes!

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

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

✓ Very flexible in choosing cable size, current rating, strength and helium cooling directly on the superconductor → maximum stability
The energy stored in a magnet is
\[ W_L = \frac{1}{2} LI^2 \, [J] = \frac{1}{2} \int BH \, dV, \]
the energy density being \( \frac{1}{2} BH \) or \( B^2/2\mu_0 \).

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

- \( W_L/m = \int_{T_0}^{T_m} C_p(T) \, dT = H(T_m) - H(T_0=4.2) \approx H(T_m) \) 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 $\rho J^2$ is taken up by the conductor enthalpy:

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

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

- $F$ 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 2-9 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

\[ \int_0^t J^2(t) \, dt = \int_0^T \frac{c(T)}{\rho(T)} \, dT = \text{constant} = F(T_m) \]

Simple solutions exist for constant or exponential decaying currents:

**Constant current:**

\[ J^2 t_m = F(T_m) \quad \Rightarrow \quad t_m < F/J^2 \]

**Exponential decay:**

\[ J^2 \tau/2 = F(T_m) \quad \Rightarrow \quad \tau < 2F/J^2 \]

**Examples**

- NbTi/Cu and CuNi matrix conductors with \( J = 500 \text{ A/mm}^2 \)
- \( F(300) \propto 1/\rho \)
- \( F(300) \) for Cu is \( \sim 1.4 \times 10^{17} \) and \( \sim 1.4 \times 10^{16} \) for CuNi (or pure NbTi)
- Maximum \( \tau \) in NbTi/Cu before reaching 300 K is a 0.1-1 second
- **Maximum \( \tau \) in pure NbTi or NbTi/CuNi is \( \sim \text{ms} \), 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 10 cm 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!

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 straightforward 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 toroids $3 \times 8 = 24$ coils are connected in series.
- The 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 $\approx 100$ 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.
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: \( J = \frac{NI}{L(b-a)} \)

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

\( B_o = \mu_0 nI \) for \( \beta \to \infty \)

\( \alpha = \frac{R}{r} \)
\( \beta = \frac{L}{2r} \)

N turns
I current
\( n = \frac{N}{L} \)

- With real CMS magnet sizes:
  
  \( r = 3200 \text{ mm}; R = 3418 \text{ mm} \)
  \( L = 12500 \text{ mm} \)
  \( N = 2180; I = 19500 \text{ A} \)

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

- 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:**
  - $B_0 = 4.17$ T
  (98% of infinite).

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

- **Real iron with gaps for detectors:**
  - $B_0 = 4.0$ T in center
  - $4.6$ T in conductor.

**Stored energy:**
- **FEM calculation yields:**
  \[
  \frac{1}{2\mu_0} \int B^2(r, z) dV = 2.6 \text{ GJ}
  \]
- **Simple approximation:**
  \[
  \frac{1}{2\mu_0} B^2 V = 2.46 \text{ GJ}, \quad V = \text{bore volume}
  \]
Design steps: Magnetic forces

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

\[ \mathbf{F} = \int (\mathbf{J} \times \mathbf{B}) \, dV \]

- 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:
\( F_a = +1.66 \text{ GN,} \)
\( F_r = -140 \text{ MN (14 kt)} \)

The “Ball” Pressure \( \approx \frac{F_r}{\text{surface}} = 6.6 \text{ MPa} \)
- Magnetic pressure \( = \frac{B^2}{2\mu_0} = 6.4 \text{ MPa} \) 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:

$$ \sigma_{\text{hoop}} = \frac{a P_r}{t} $$

To be respected design rule:

$$ \sigma_{\text{hoop,max}} = \frac{2}{3} \rho_{\text{yield}} $$

Structural coil thickness:

$$ t = \frac{3 r P_r}{2 \rho_{\text{yield}}} = 320 \text{ mm}, $$

using 100 MPa annealed Al5083, or

$$ t = 190 \text{ mm}, $$

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:

$$E = \frac{L_c I^2}{2} = \frac{1}{2\mu_0} \int B^2 \, dV \approx \frac{1}{2\mu_0} B_0^2 \, V, \text{ and } \quad L_c = \mu_0 N^2 \pi r^2 2 / L$$

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

In the windings section of

$\approx 320 \text{ mm} \times 12500 \text{ mm}$ 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/4.5 K including 5% cabling degradation is 3000 A/mm².
- We need margin so we run at 1/3 of the critical current, at 1000 A/mm².
- 19500 A and 1000 A/mm², \( \rightarrow \) need 19.5 A/mm² sc per turn=cable
- Self-field stability \( \rightarrow \) wire diameter <1.28 mm
- A minimum Cu/sc ratio is 1:1/1 \( \rightarrow \) Asc= 0.61 mm²
- 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 mm² \( \rightarrow \) we need \( \geq \)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:

<table>
<thead>
<tr>
<th>Strand Constituents</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>High homogeneity Nb-Ti</td>
<td>Nb 47±1 Wt % Ti</td>
</tr>
<tr>
<td>High Purity Copper</td>
<td>RRR &gt; 300</td>
</tr>
<tr>
<td>Niobium Barrier</td>
<td>Reactor Grade I</td>
</tr>
</tbody>
</table>

**Strand Design Parameters**

- Strand Diameter
- 
- $(Cu+\text{Barrier})/\text{Nb-Ti}$ ratio
- Filament diameter (mm)
- Number of Filaments
- Strand Unit length (m)
- Twist Pitch
- Strand Minimum Critical Current $I_c$ (A)
  - Criteria: 5 T, 4.2 K, 10 µV/m
  - $n$-value 5T
  - Final copper RRR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand Diameter</td>
<td>$1.280 \pm 0.005 \text{ mm}$</td>
</tr>
<tr>
<td>$(Cu+\text{Barrier})/\text{Nb-Ti}$ ratio</td>
<td>$1.1 \pm 0.1$</td>
</tr>
<tr>
<td>Filament diameter (mm)</td>
<td>$&lt;40$</td>
</tr>
<tr>
<td>Number of Filaments</td>
<td>552</td>
</tr>
<tr>
<td>Strand Unit length (m)</td>
<td>2750</td>
</tr>
<tr>
<td>Twist Pitch</td>
<td>$45 \pm 5 \text{ mm \ (RHS}}$</td>
</tr>
<tr>
<td>Strand Minimum Critical Current $I_c$ (A)</td>
<td>1925</td>
</tr>
<tr>
<td>Criteria: 5 T, 4.2 K, 10 µV/m</td>
<td></td>
</tr>
<tr>
<td>$n$-value 5T</td>
<td>$&gt;40$</td>
</tr>
<tr>
<td>Final copper RRR</td>
<td>$&gt;100$</td>
</tr>
</tbody>
</table>

**Rutherford cable**

- Cabling direction
- Nominal current
- Critical current at 5T, 4.2K
- Critical temperature at 4.6T
- Current sharing temperature at 4.6T and 19.5 kA
- Strand number
- Dimensions
- Cable transposition pitch
- Cable compacting ratio

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal current</td>
<td>19500 A</td>
</tr>
<tr>
<td>Critical current at 5T, 4.2K</td>
<td>$\geq 56000 \text{ A}$</td>
</tr>
<tr>
<td>Critical temperature at 4.6T</td>
<td>7.35 K</td>
</tr>
<tr>
<td>Current sharing temperature at 4.6T and 19.5 kA</td>
<td>$\geq 6.33 \text{ K}$</td>
</tr>
<tr>
<td>Strand number</td>
<td>32</td>
</tr>
<tr>
<td>Dimensions</td>
<td>20.68x2.34 mm$^2$</td>
</tr>
<tr>
<td>Cable transposition pitch</td>
<td>185 mm</td>
</tr>
<tr>
<td>Cable compacting ratio</td>
<td>87%</td>
</tr>
</tbody>
</table>
**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!
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......
Cavern length = 55 m  
width = 32 m  
height = 35 m.

ATLAS on surface and underground

- Underground cavern at -90 m.
- 2 shafts give access to a 50,000 m$^3$ cavern for the detector.
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 m³ 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
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
- 8 vacuum vessels
- 16 double pancakes
- 8 coil casings
- Cold mass integration
- 8 cold masses
- Instrumented
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

$H \rightarrow ZZ^(*) \rightarrow 4l\ (4e, 4\mu, 2e2\mu)$

4μ candidate with $m_{4\mu} = 124.6$ GeV
July 4, 2012

CERN press conference
It takes time…… Mr Higgs

“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

Collision energy = 0.6 x B x R

B: 1.8 x from NbTi to Nb$_3$Sn
B: 2.4 x from NbTi to HTS
R: 4-5 x more magnets

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

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

FCC study: \textit{ee, eh, hh} variants: study in progress since mid-February 2014.

**Design drivers for detector magnets**

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

Same tracking resolution?

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

$BL^2/\sigma$ has to be increased by factor 7!

- For same resolution $\sigma$, 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 $\lambda$ to 12 $\lambda$** (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.
Baseline Detector 4T/10m-20m + 2 side Solenoids

FCC-hh general purpose reference detector

100TeV pp collisions, $L_{\text{peak}} = 3 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, $L_{\text{int}} = 3/30 \text{ ab}^{-1}$

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 $\eta=6$
Unshielded Solenoid and 2 Forward Solenoids

Solenoid + Forward Solenoids

• Forward Solenoids enhance tracking for high-\(\eta\) 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 2019!

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field in center [T]</td>
<td>4</td>
</tr>
<tr>
<td>Free bore diameter [m]</td>
<td>10</td>
</tr>
<tr>
<td>Stored energy [GJ]</td>
<td>13.8</td>
</tr>
<tr>
<td>Cold mass main solenoid [kt]</td>
<td>1.05</td>
</tr>
<tr>
<td>Cold mass forward solenoid [t]</td>
<td>48</td>
</tr>
<tr>
<td>Vacuum vessel mass Main Solenoid [t]</td>
<td>875</td>
</tr>
<tr>
<td>Vac. vessel mass Forward Solenoid [t]</td>
<td>32</td>
</tr>
</tbody>
</table>
This concludes the course........