Study of a 5 Tesla large aperture coil for the CLIC detector

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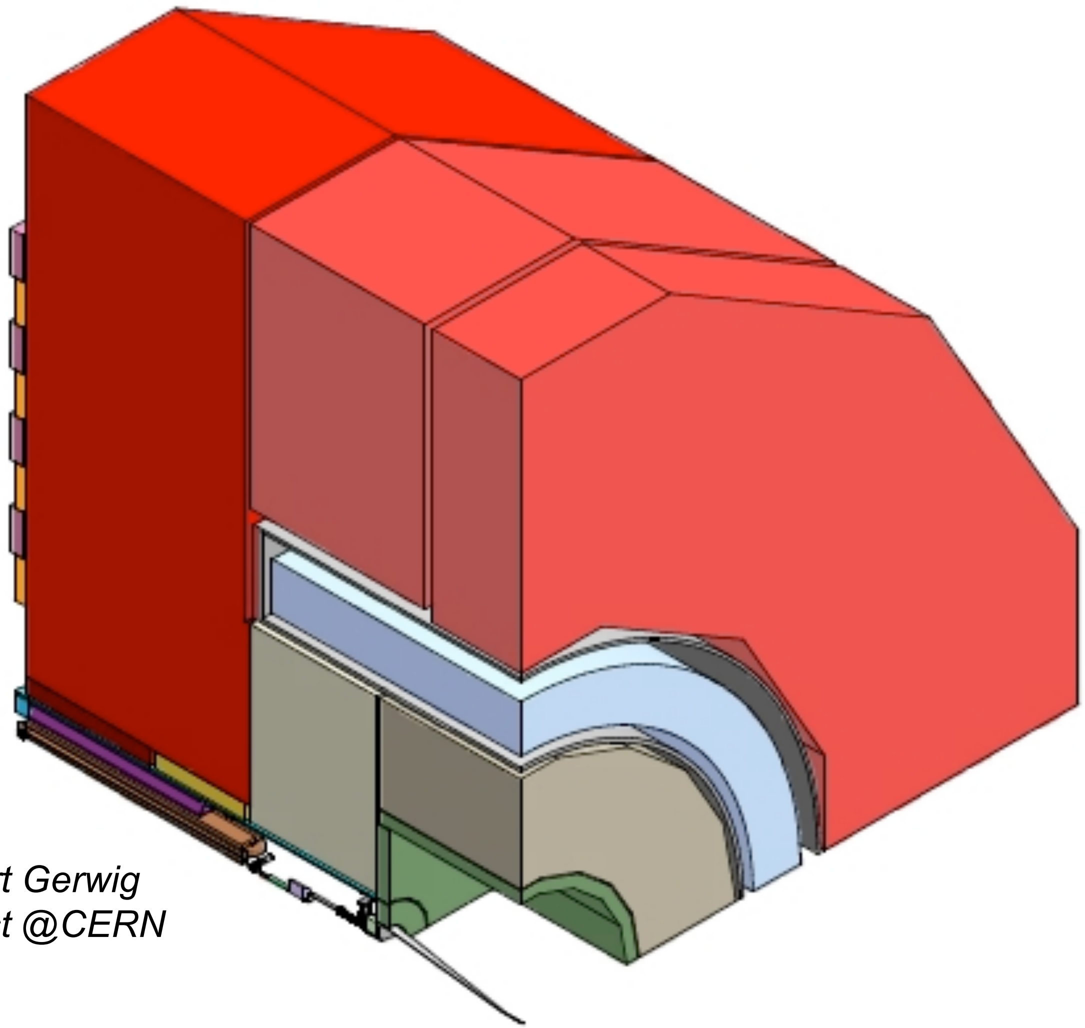
Main parameters:

Solenoidal field with external return iron yoke, field at IP is **5T**.

Superconducting coil, 6.2m long, Ø5.8m.

Vacuum tank aperture: Ø5.5m.



Courtesy : Hubert Gerwig & Nicolas Siegrist @CERN

SC coil main parameters:

Ampere-turns = **34 MA.turn**

Stored magnetic energy = **2.3 GJ**

The parameters are close to large existing coil such as the CMS magnet [1].

Design basics:

Multi-layered coil,

External mandrel for quench back protection scheme,

Indirectly cooled with LHe circuitry on external cylinder in thermosyphon mode,

Mechanically reinforced superconductor,

Insulation with fiberglass epoxy using vacuum impregnation.

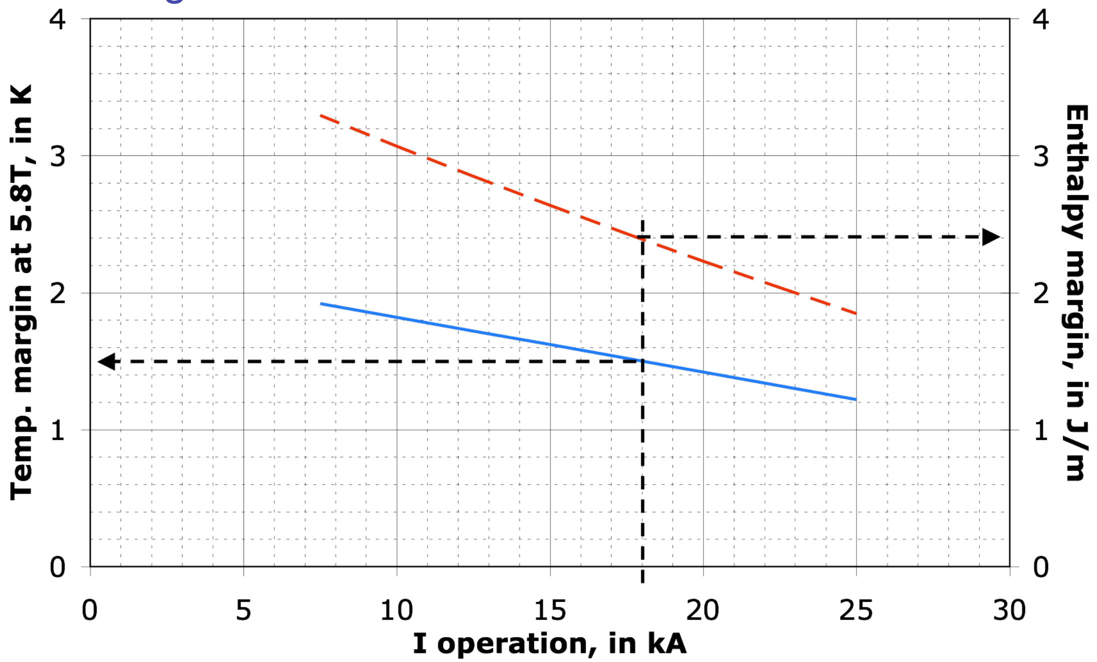
Cross section of CMS coil (slice of winding prototype)

Superconductor main parameters:

Maximum B-field on conductor is 5.8T,

Use of a NbTi cable with aluminum stabilizer is feasible :

- Rutherford cable with 40 SC strands (CMS strand data used [2]),
- Temperature margin is 1.5K with T_{coil}= 4.5K, corresponding to an enthalpy margin of 2.4J/m.



Reducing the current, the margin can be **increased**,

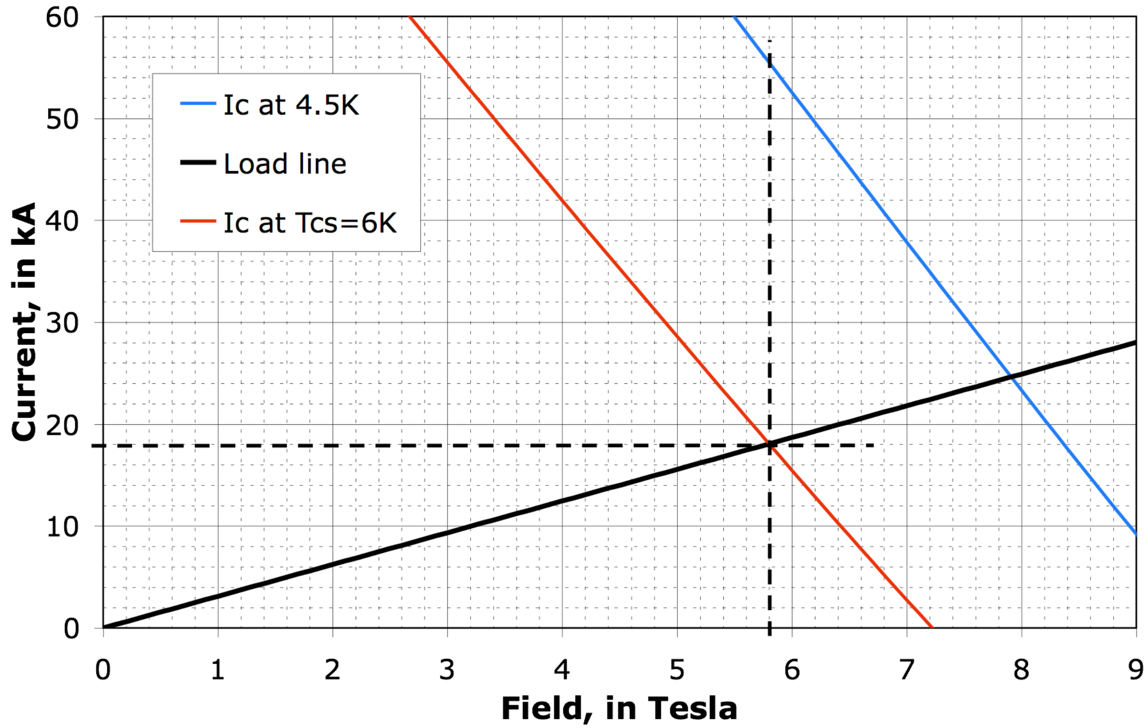
But the total **quantity of turns** also increases.

Superconductor main parameters:

⇒ Operating current : **18kA**

⇒ Operating temperature: **T_{max} = 4.5K.**

⇒ Electrical current ratio $I_{operation}/I_{critical}$ is **32%.**



Superconductor reinforcement :

To take the large magnetic forces acting on the conductor (magnetic pressure is 100bars!), **two options** are considered to **strengthen the conductor** based on the technologies already used on existing coils :

CMS-type:

non structural pure Al stabilizer welded to Al alloy structural reinforcement,

RRR of pure Al stabilizer is about 2000.

[3] A. Hervé et al.

Atlas Central Solenoid-type:

structural aluminum stabilizer *(Al-0.1wt%Ni)* with cold working,

RRR of structural stabilizer is 590.

[4] A. Yamamoto et al.

Superconducting coil dimensioning :

A relationship giving the magnetic energy per unit mass is [5] :

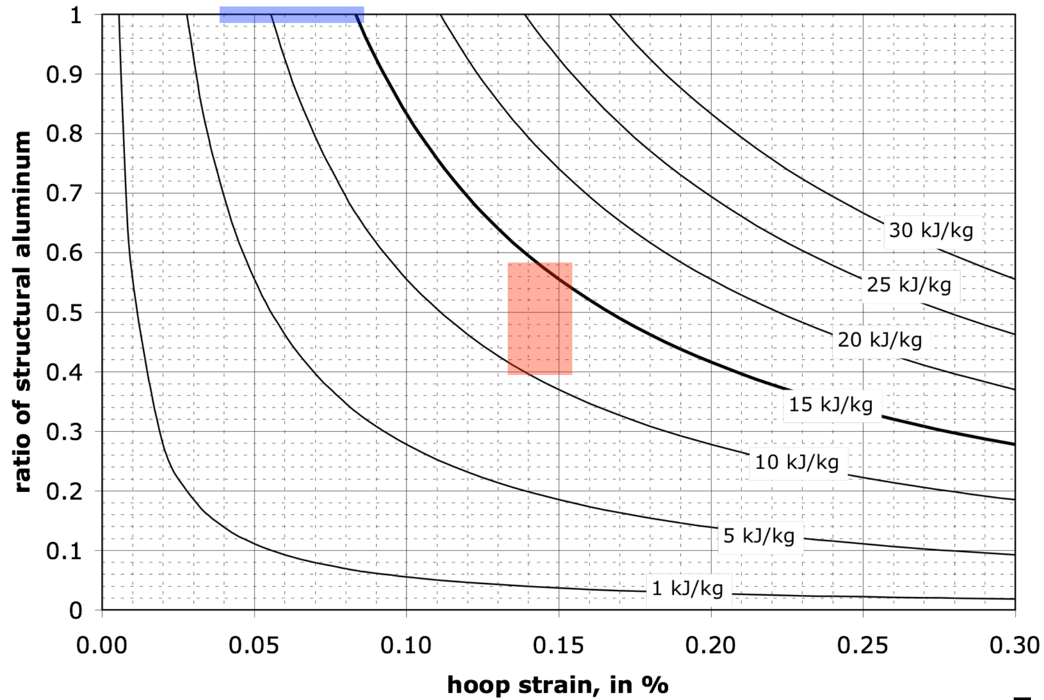
$$\frac{E}{M} = \alpha \ \frac{Y}{2\rho} \ \varepsilon$$

with: α: ratio of structural aluminum,
Y: Young's modulus,
ρ: specific mass,
ε: hoop strain.

⇒ **graph giving α vs ε :**

Targeted work areas:

- *Structural stabilizer Al-0.1wt%Ni*
- *AW6082 + Pure Aluminum*

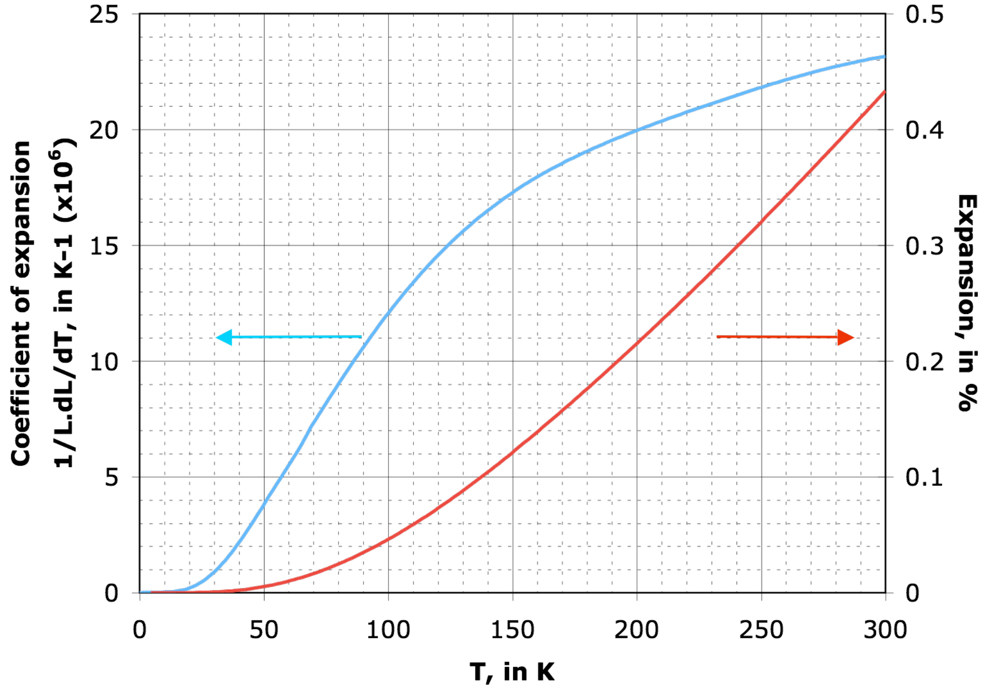


Superconducting coil dimensioning :

Using **E/M=14kJ/kg**:

Cold mass at 4.5K is **165 tons**.

Average **temperature=95K** if all magnetic energy is released in the coil. Stresses due to differential thermal expansion are limited.



Superconductor mechanics :

With an external cylinder of 50mm thickness, the estimated stresses are:

	AA + pure Al	Structural Al Stabilizer
Ratio of reinforcement	0.5	1
Hoop strain	**0.15%**	**0.08%**
Average hoop stress (tensile)	116 MPa	61 MPa
Average axial stress (compressive)	44 MPa	22 MPa
Von Mises stress on the alloy	**143 MPa**	**74 MPa**
0.2% yield strength at 4.2K of the alloy	**428 MPa (*)**	**110 MPa (**)**

(*) for CMS with AW-6082-T6 [6],

(**) for ATLAS CS with Al-0.1wt%Ni [7].

Safety factors shall be applied to the computed stresses : there is some margin in both cases.

Superconductor size :

With 18kA, there are **1890 turns**.

Minimizing the quantity of layers, with a realistic aspect ratio

Height/Width ≤ 7 (*obtained with smaller conductors*),

A number of **5 layers** is the target.

Then the conductor cross section dimensions are:

Height=97.4mm ; Width=15.6mm

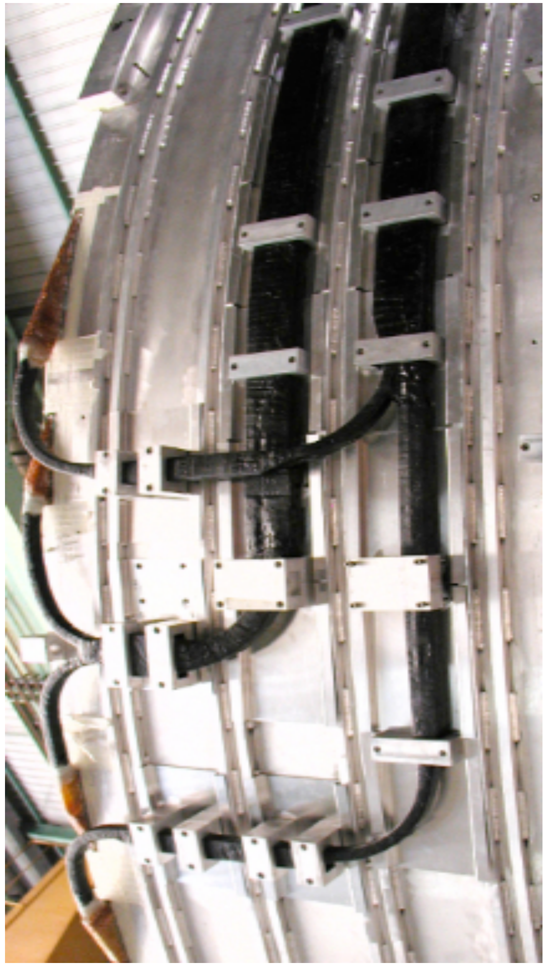
Coil total thickness = 550mm

Total conductor length: about **40km**. Length per layer: **8 km**
⇒ coil must be split in several modules:

3 modules is a fair choice.

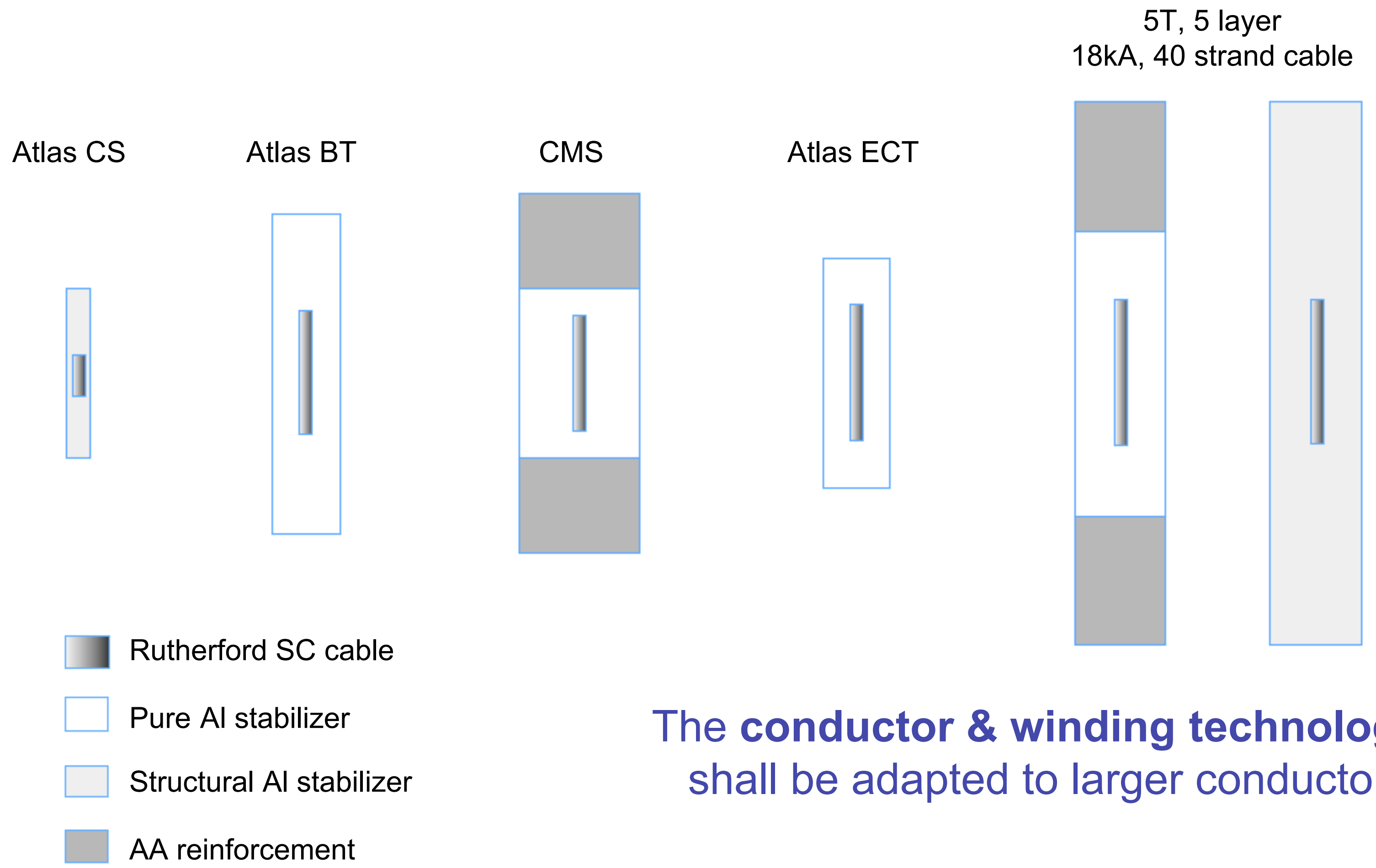
Electrical joints (module to module and layer to layer) according to the CMS design:

low field region on the outer radius of the external cylinder, close to cooling circuits, welded, stabilized.



CMS coil
layer to layer joints

Superconductor cross section overview :



The **conductor & winding technologies** shall be adapted to larger conductors.

Temperature gradient in the coil :

Either in steady state or during field ramping, the radial temperature gradient stays **below 0.1K**.

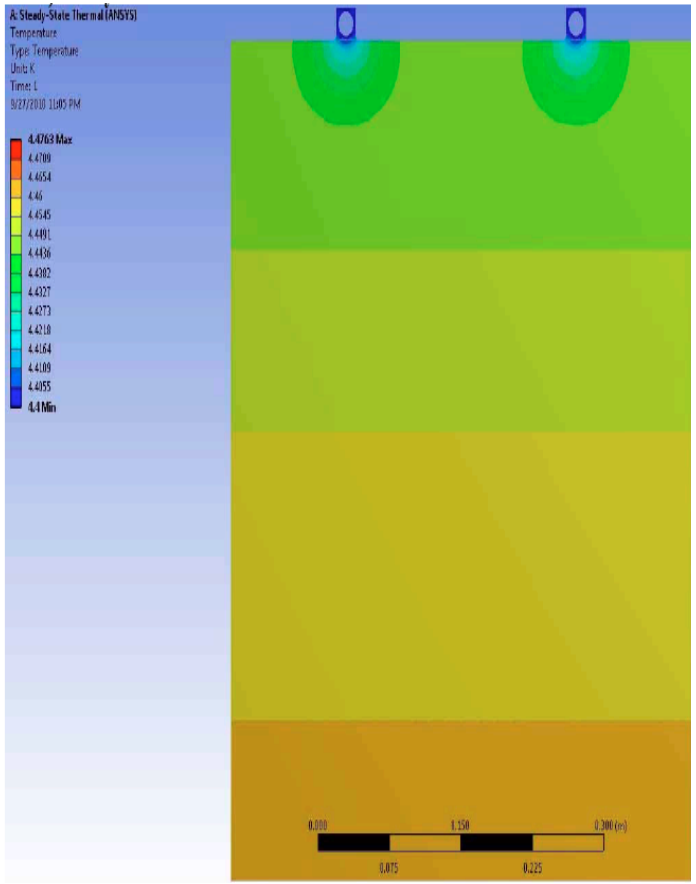
With a LHe coolant at **4.4K** (1.2 bars), the maximum temperature on the inner layer stays **below 4.5K** for each conductor option:

Steady state: T < 4.42K

Ramp 1.5A/s: T < 4.49K

The **temperature margin** of 1.5K is realistic with the 5 layer layout.

4.4K



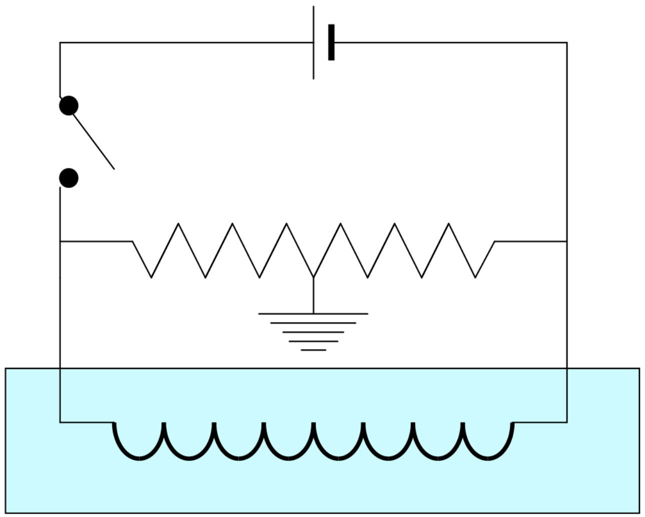
Courtesy Abhishek Sharma

Coil protection:

Based on the extraction of the energy into an external dump resistor.

The quench back effect limits the temperature gradient in the coil and the associated thermal stresses.

Voltage to ground is controlled and limited: +/- 300V to ground typically.



Inductance is 14 H

Coil protection:

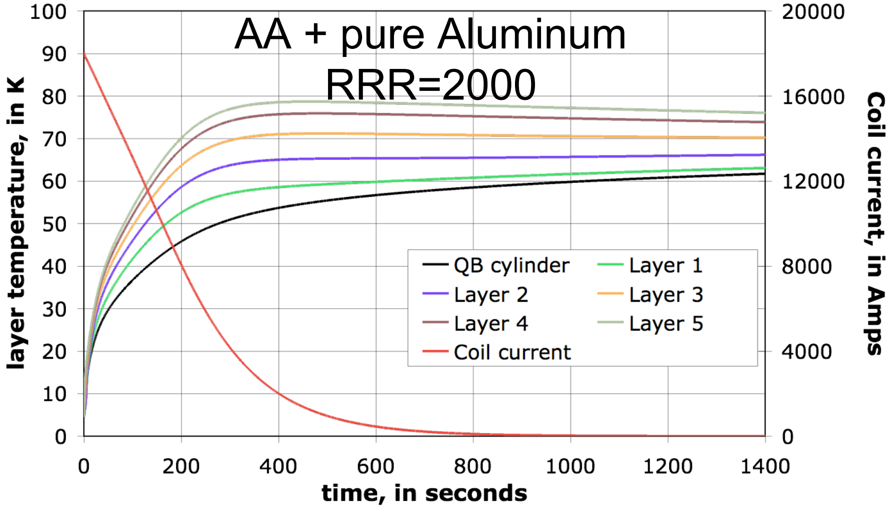
Temperature T_{max} of the adiabatic **hot spot** during the quench back protection is given by:

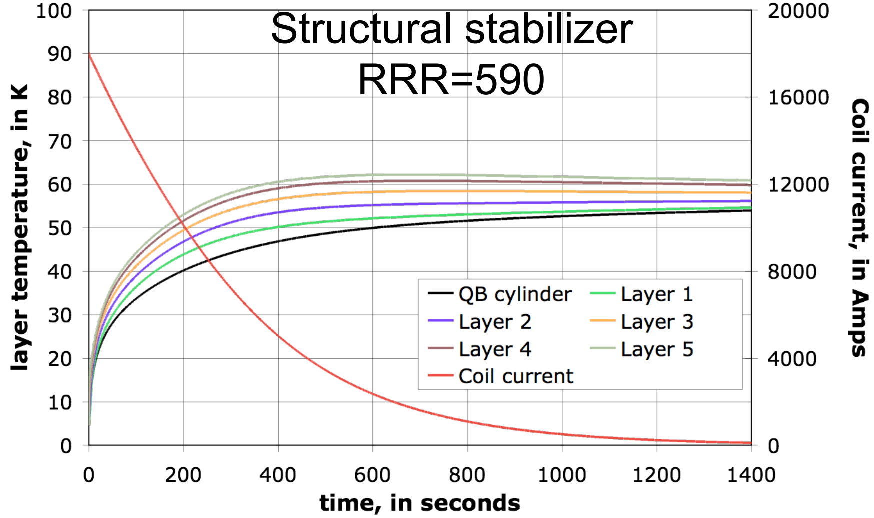
$$F(T_{\max}, RRR, B) = \int_{T_{ini}}^{T_{\max}} \frac{C_v(T)}{\rho(T, RRR, B)}\, dT = \frac{S_{stabilizer}}{S_{total}} \int_{o}^{+\infty} J^2\, dt$$

As the conductor with the structural stabilizer has a higher conducting cross section then the result is more favorable despite a lower RRR:

5 layers, 18kA-40 strand Fast dump on 0.033 ohm	**AA + pure Aluminum** *(RRR=2000)*	**Structural Al Stabilizer** *(RRR=590)*
T hot spot…………..…. (K)	83	66

Coil protection: fast discharge on external dump resistor with quench back





Fast Dump on R=0.033 ohm	**AA + pure Al** *(RRR=2000)*	**Struct. stabilizer** (*RRR=590*)
T max	79 K	62 K
T average	69 K	57 K
Discharge time constant ($I=I_0/e$)	231 s	323 s
% energy in dump resistor	59 %	78 %
Max. ΔT between adjacent layers	7 K	5 K

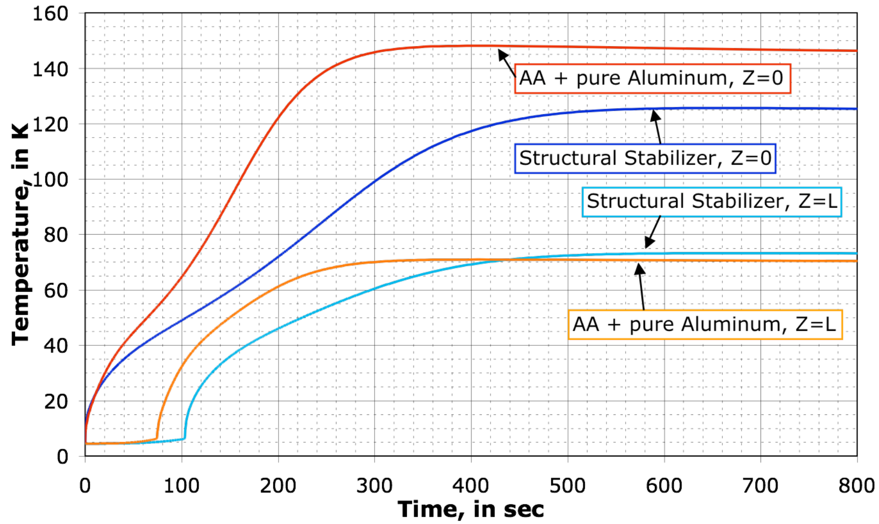
Coil protection fault :

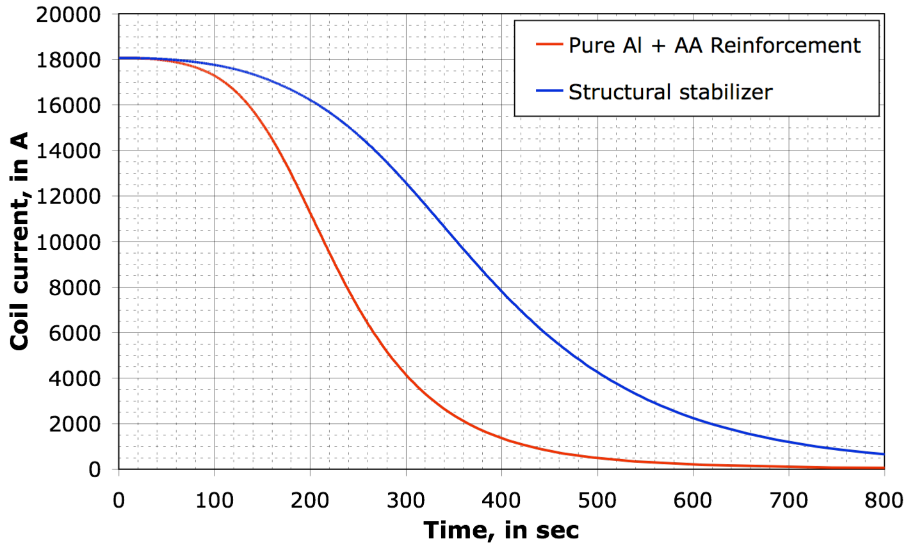
Ultimate fault case with quench propagation and no discharge on the external dump resistor: *all the energy is released in the cold mass.*

Model: quench propagating parallel to the coil axis from one coil end at Z=0 to the other at Z=L.

A quench back takes place which helps to limit the temperature gradient.

	AA + pure Aluminum *(RRR=2000)*	**Structural Al Stabilizer** *(RRR=590)*
ΔTmax	77K	53K
T-range at end of discharge	71K to 148K	73K to 126K





Consideration on coil design:

Mostly relies on the **capacity to manufacture a large conductor**, with strong mechanical properties, still **compatible with the coil winding** and the thermal treatment for impregnation (**coil curing cycle**).

A large conductor allows to **limit the quantity of layers**, which limits the radial temperature gradient.

The **CMS conductor design** can be applied, by welding the reinforcement to the pure aluminum stabilizer, and having the pure aluminum working at 0.15% strain (as in CMS).

The **structural stabilizer configuration** looks very promising, with favorable results for quench protection. Still the mechanical properties and aluminum Residual Resistivity Ratio of such a conductor shall be **uniform** enough on the cross section, and **high** enough at the end of the coil manufacturing processes.

Conductor R&D program:

To better estimate the feasibility to manufacture a large conductor with a structural stabilizer, **a dedicated R&D program is projected** thanks to the possibility to use the material left from the LHC detector conductor manufacturing:

•Build a 100m prototype length of large cross section,

•With some Al-Ni billettes provided by KEK from production balance of ATLAS CS,

•With CMS (or ATLAS) Rutherford cable (remaining lengths),

•Co-extrude with the available facilities and toolings:

the big co-extrusion press in Nexans (used for CMS and ATLAS BT - ECT), Cortaillod CH, can be available for this program,

All tooling used in Nexans for LHC detector conductors are also available: punch and dies, etc., which allows some saving on the cost of the program.

•Later cold work the coextruded conductor,

•Then it will be possible to **estimate the mechanical properties and RRR** at the end of the coil manufacturing, in particular after a realistic curing cycle.

Conclusion:

A 5T superconducting coil with a 6m diameter and 6m long can be designed with **NbTi aluminum stabilized superconductors**.

Such a coil, for a CLIC detector as proposed, would have **several features very close and similar to the CMS magnet**.

The main **challenge** is with the manufacturing of a **large superconductor**.

Two designs are available: the CMS conductor type and the ATLAS Central Solenoid conductor type.

A structural stabilizer, such as it was done with the ATLAS CS, appears **very promising**, and a **dedicated R&D program** has been started **in the frame of the Linear Collider Detector studies at CERN.**

References:

[1] F. Kircher, et al., “ CMS Coil Design and Assembly”, IEEE Trans. Appl. Superconductivity, Vol. 12, No. 1, Mar. 2002, p.395–398.

[2] P. Fabbricatore et al., “Electrical Characterization of S/C Conductor for the CMS Solenoid”, IEEE Trans. Appl. Superconductivity, Vol. 15, No. 2, Jun. 2005, p.1275–1278.

[3] Alain Hervé, “The CMS Detector Magnet”, IEEE Trans. Appl. Superconductivity, Vol . 10, No. 1, Mar. 2000, p.389-394.

[4] A. Yamamoto et al., “The ATLAS Central Solenoid”, Nuclear Instruments and Methods in Physics Research A, 584 (2008), p.53-74.

[5] A. Hervé et al., “Experience Gained from the Construction, Test and Operation of the Large 4-T CMS coil”, IEEE Trans. Appl. Superconductivity, Vol. 18, No. 2, Jun. 2008, p.346-351.

[6] S. Sequeira, S. Sgobba et al., “Aluminum Alloy Production for the Reinforcement of the CMS Conductor”, IEEE Trans. Appl. Superconductivity, Vol . 12, No. 1, Mar. 2002, p.424-427.

[7] K. Wada, A. Yamamoto, et al., “Development of High-Strength and High-RRR Aluminum-Stabilized Superconductor for the ATLAS Thin Solenoid”, IEEE Trans. Appl. Superconductivity, Vol . 10, No. 1, Mar. 2000, p.373-376.