Design principles of thin high field superconducting solenoids

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Outline

1) Introductory remarks
2) Magnetic Field
3) Magnetic Forces. Stress and Strain
4) Load Line and Margins
5) Stability
6) Quench and Protection
7) From Design to Construction

PARAMETERES COMING FROM CMS EXPERIMENT NEEDS

A solenoid field configuration has been chosen, with parameters following the detector requests : central field 4 T, free bore diameter 6 m, length 12.5 m.

The space allowed for the superconducting solenoid is limited to a region of DR=826 mm

General Requirement for Detector Magnets 1

A detector magnet must fulfill several requirements , coming from the physical goals of the experiments

1) The magnetic field amplitude is closely related to the energy of colliding beams and to the resolution in momentum measurement of emerging particles. The required magnetic field is in the range 1 T to 4 T , leading to the need of employing superconducting coils.

$$\frac{\Delta p}{p} \propto \frac{p}{qBL^2}$$

2) The choice of superconducting winding for the field generation is enhanced by the generally low space reserved to the magnetic system .

3) If electromagnetic or hadron calorimeters are put outside the coil, the materials used for the coil and its thickness should be optimized in order to minimize the radiation length

General Requirement for Detector Magnets 2

4) The magnet is fully integrated in the complete detector. Several detector sub-systems are generally supported by the magnet structure. This implies a strong dependence of the magnet mechanical system (usually a cryostat) on the other components of the detector.

5) It is strictly required that the magnet has a large safety margin when working at the normal operation. In fact a failure of a magnet component, such as an electrical joint or a pipe for LHe circulation etc., can lead to dismount a big part of the detector

What High Energy Physicists want

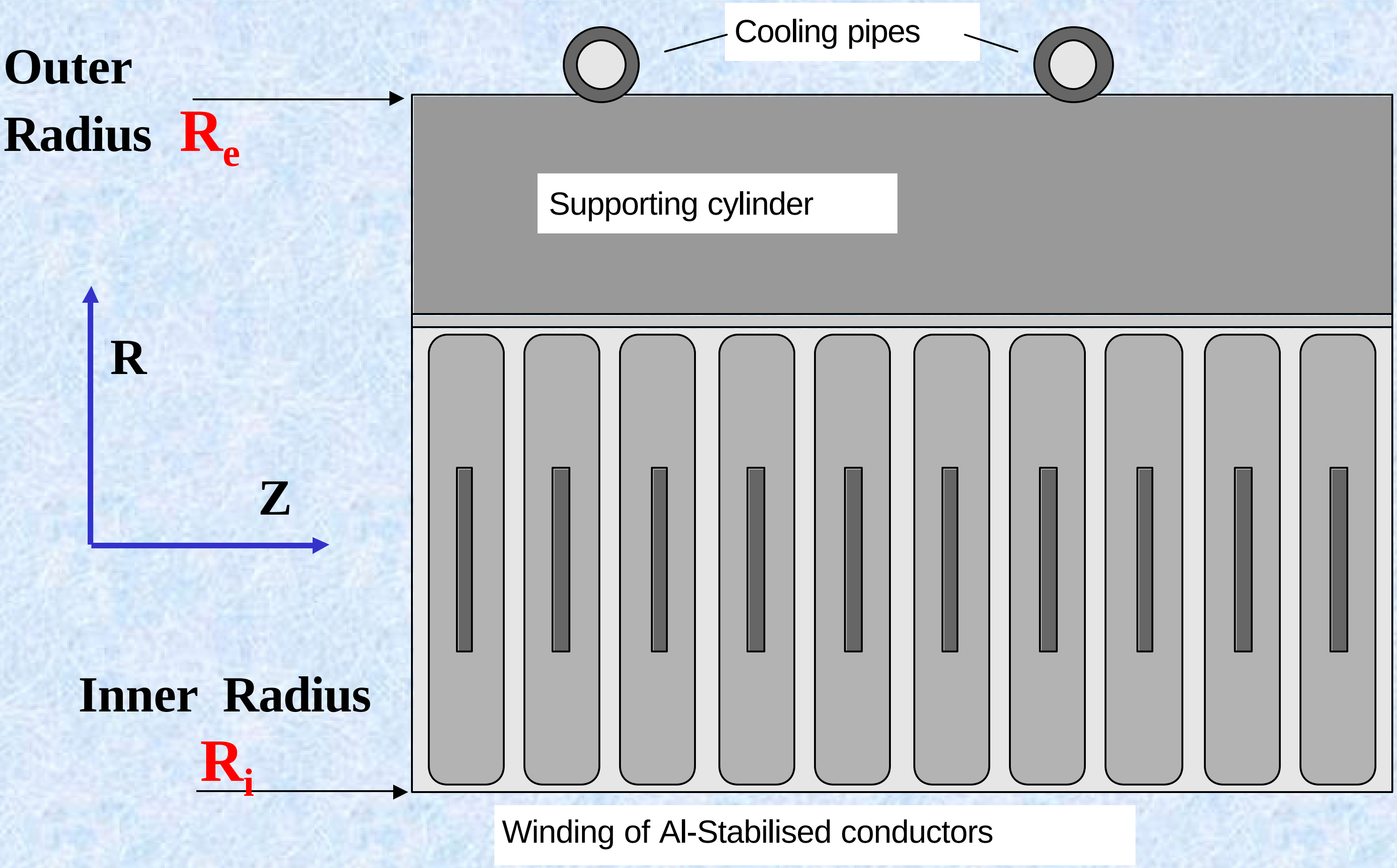
From the above points it is clear that a typical detector magnet should give a high field while occupying a space as smaller as possible. Furthermore it must be enough robust to support the central part of the detector and shall operate in a reliable way.

The thin high field solenoids

We have had several examples of detector magnets since the Sixties, but only in the Seventies a new succesful class of thin detector magnets was developed, i.e. The thin high field solenoids.

The first magnet of this class can be considered **CELLO** , built at Saclay for Petra Collider at DESY. CELLO was wound with an aluminium stabilized conductor. The cooling was indirect, in the sense that the cooling pipes were connected to the supporting structure, made by aluminium alloy.

Typical Cross section of a thin solenoid (cold mass)



Cooling pipes

Outer Radius R_e

Supporting cylinder

R

Z

Inner Radius R_i

Winding of Al-Stabilised conductors

$$DR = R_e - R_i$$

$$DR << R_i$$

Which are the basic motivations for this lay-out?

Let us start with the real lecture ……

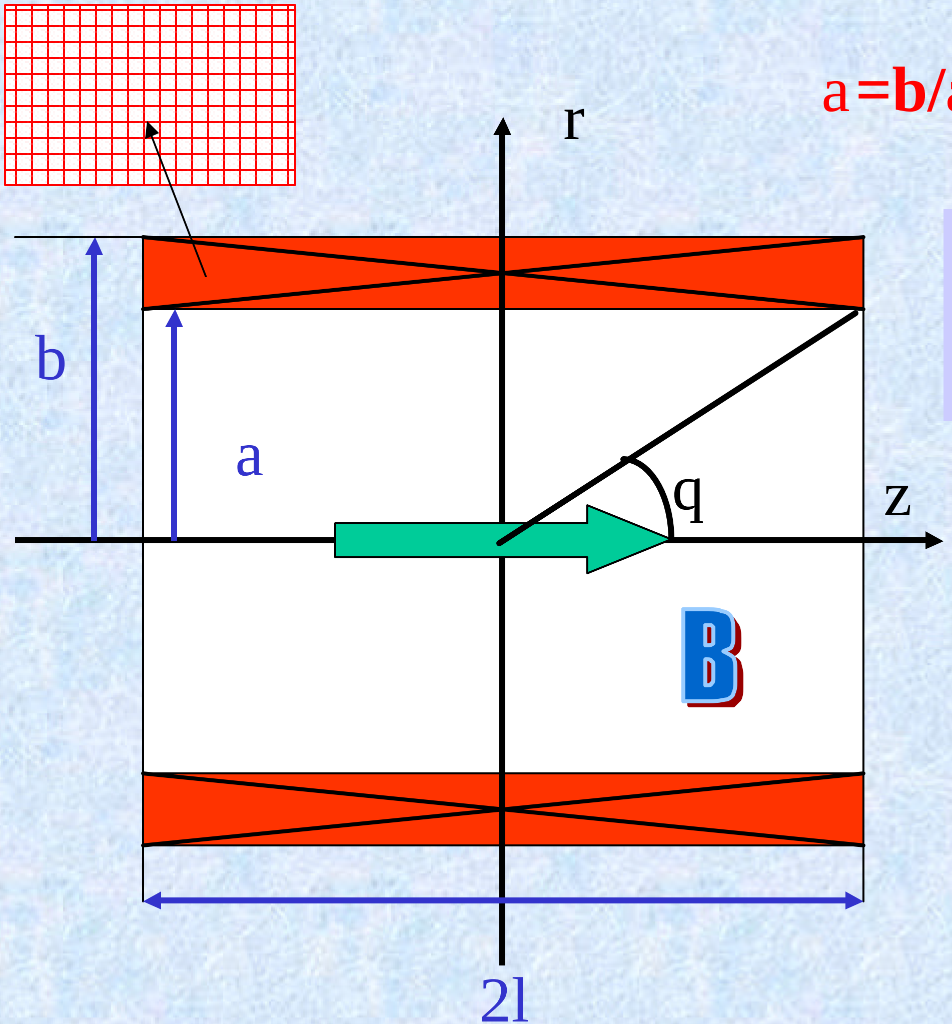
As a general guideline of this talk, I will try to show that, though complex design tools are required for performing the design of a high field superconducting thin solenoid (Finite Element Analyses), the basic design choices can be understood on the basis of simple analytical formulae.

References

1) M.Wilson Superconducting Magnets Oxford Sciences Pub.

2) A.Yamamoto IEEE Trans. On Applied Sup. Vol 14 N2 p.478

Magnetic Field generated by Solenoids



a=b/a; b=l/a; N turns; I current

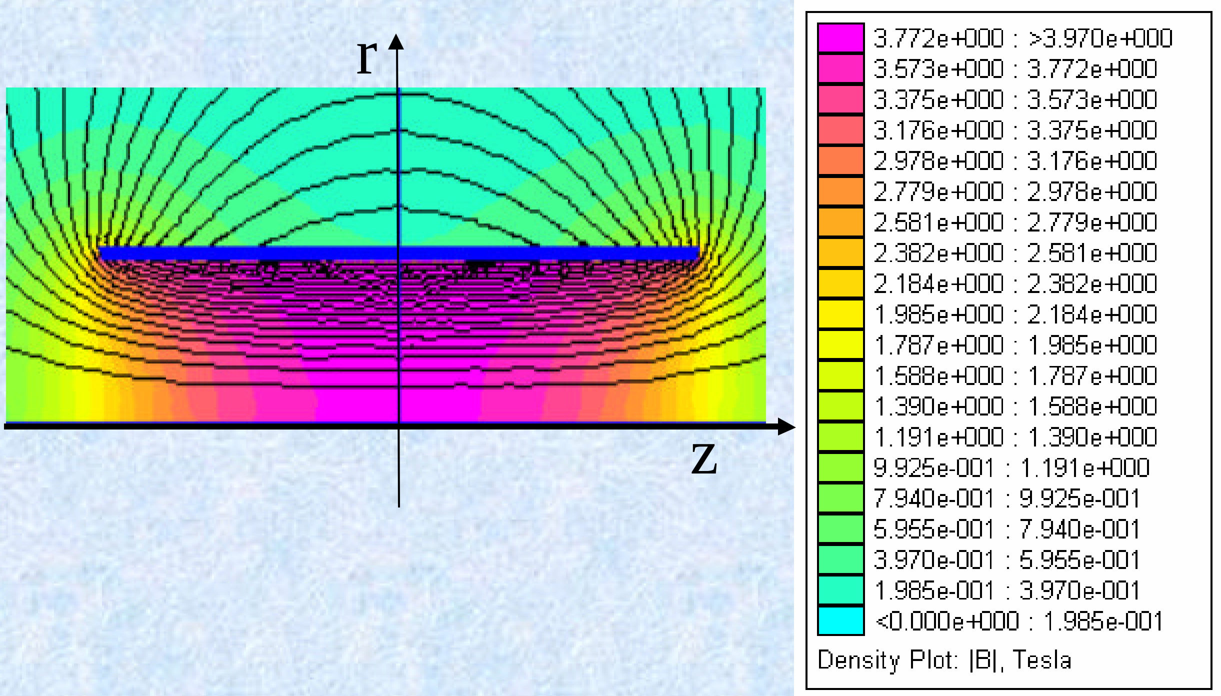
The over all current density is defined as: **J=NI/(2l (b-a))**

$$B_o = J\, a\, m_o b \,\ln\left\{ \frac{a + \left(a^2 + b^2\right)^{\frac{1}{2}}}{1 + \left(1 + b^2\right)^{\frac{1}{2}}} \right\}$$

For β→ ∞

$$B_o = m_o a J (a - 1) = m_o \frac{NI}{(b-a)2l}(b-a) = m_o n I$$

CMS Winding: no Magnetic Yoke



Inner Radius a =3.200 m

Outer Radius b= 3.418 m

Length 2l= 12.500 m

α=1.068; β= 1.953

I=19500; N= 2180

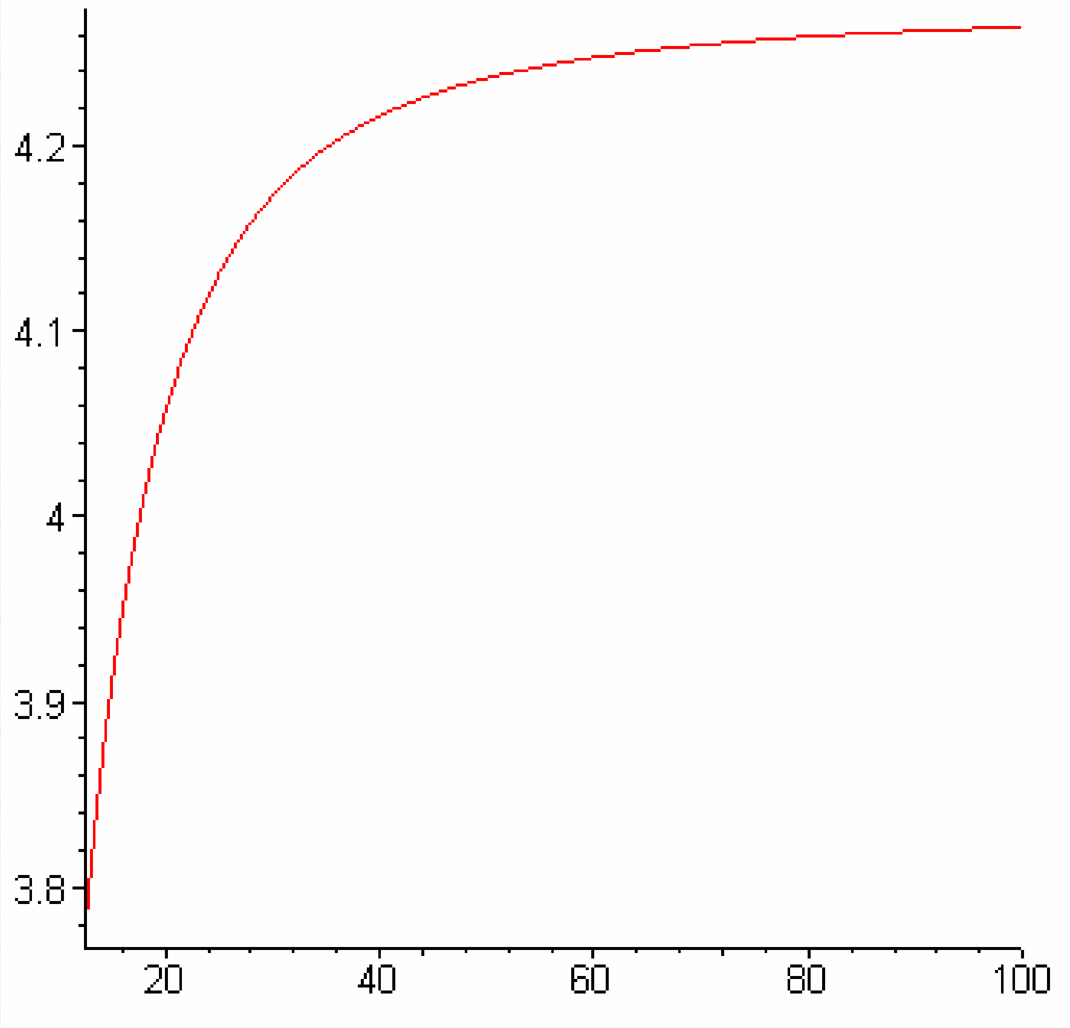
$J_{\text{overall}} = 1.56\ 10^7\ \text{A/m}^2$

$$B_o = \text{J a } m_o b \ \ln\left\{\frac{a + \left(a^2 + b^2\right)^{\frac{1}{2}}}{1 + \left(1 + b^2\right)^{\frac{1}{2}}}\right\} \quad \mathbf{= 3.77\ T}$$

$$B_o = m_o n I \quad \mathbf{= 4.27\ T}$$

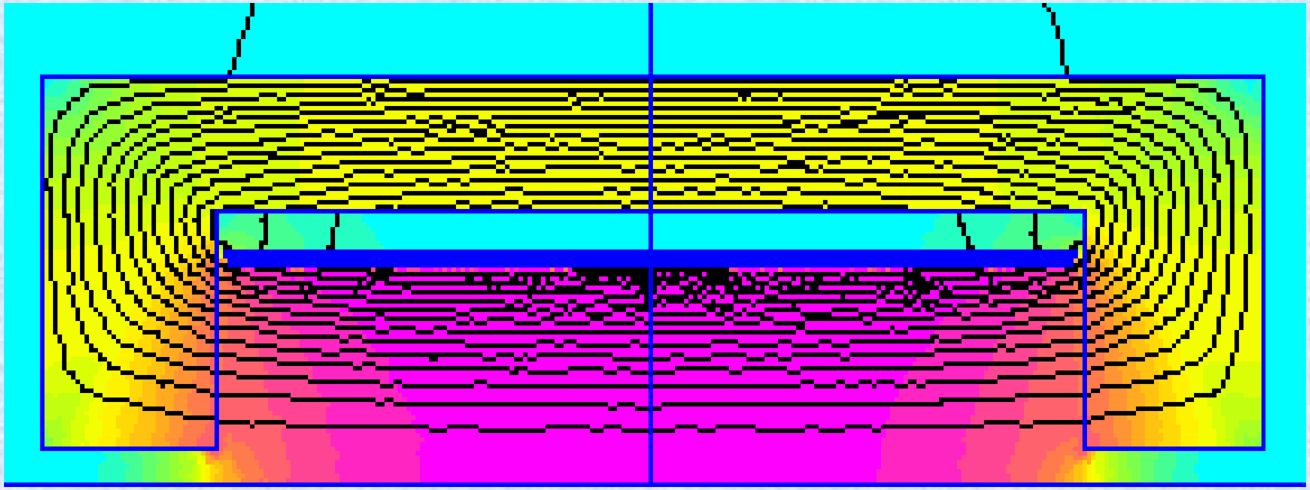
Magnetic Field

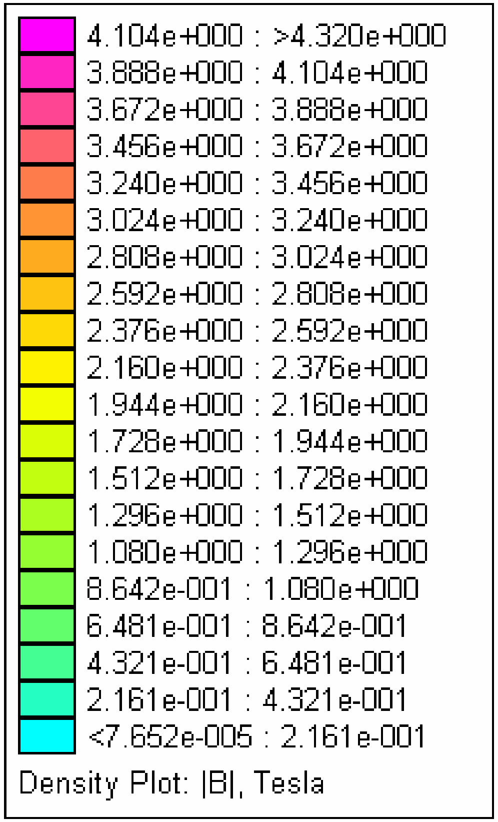
(T)



CMS coil length (m)

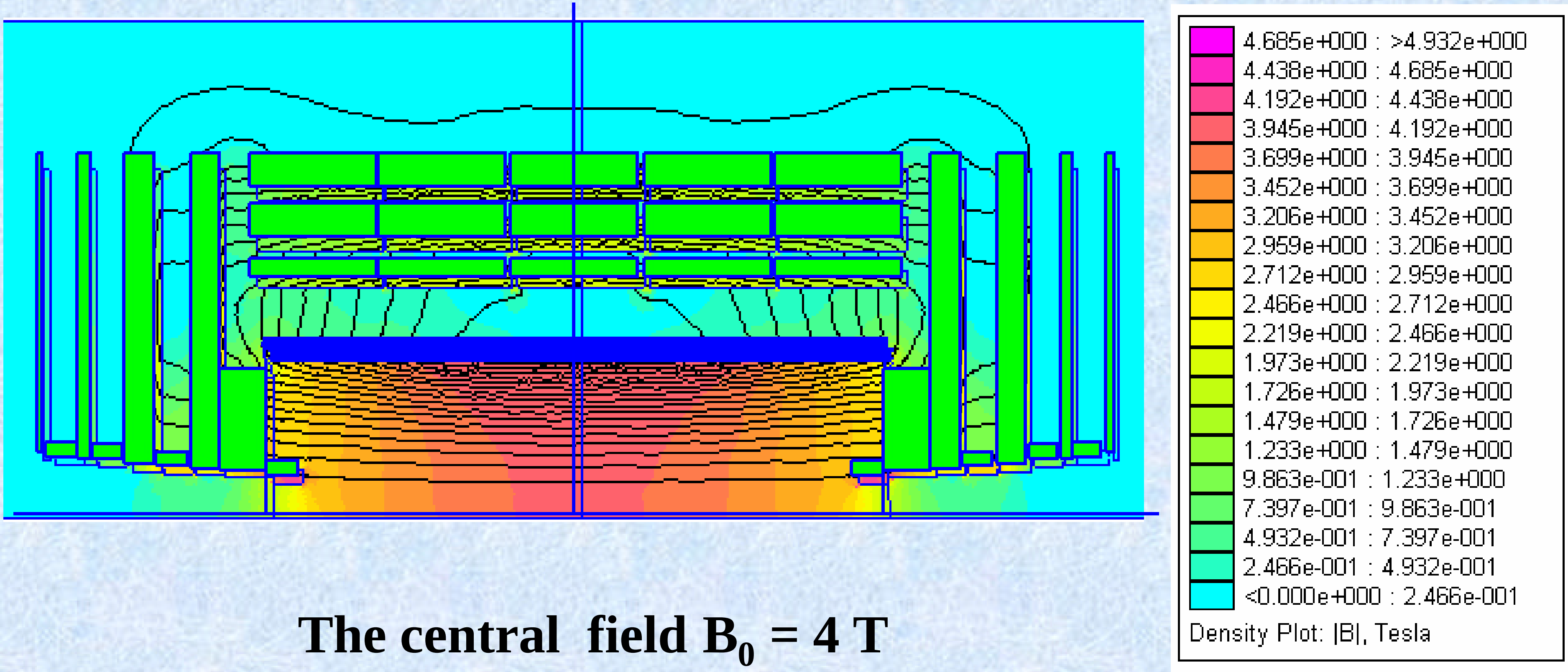
Let’s add a simple magnetic yoke acting as flux return





In this case the central field is B_0=4.17 T, i.e. closer to infinite long coil. The iron acts as a magnetic mirror prolonging the axial length of the coil

Passing to the real CMS magnetic configuration (2D)

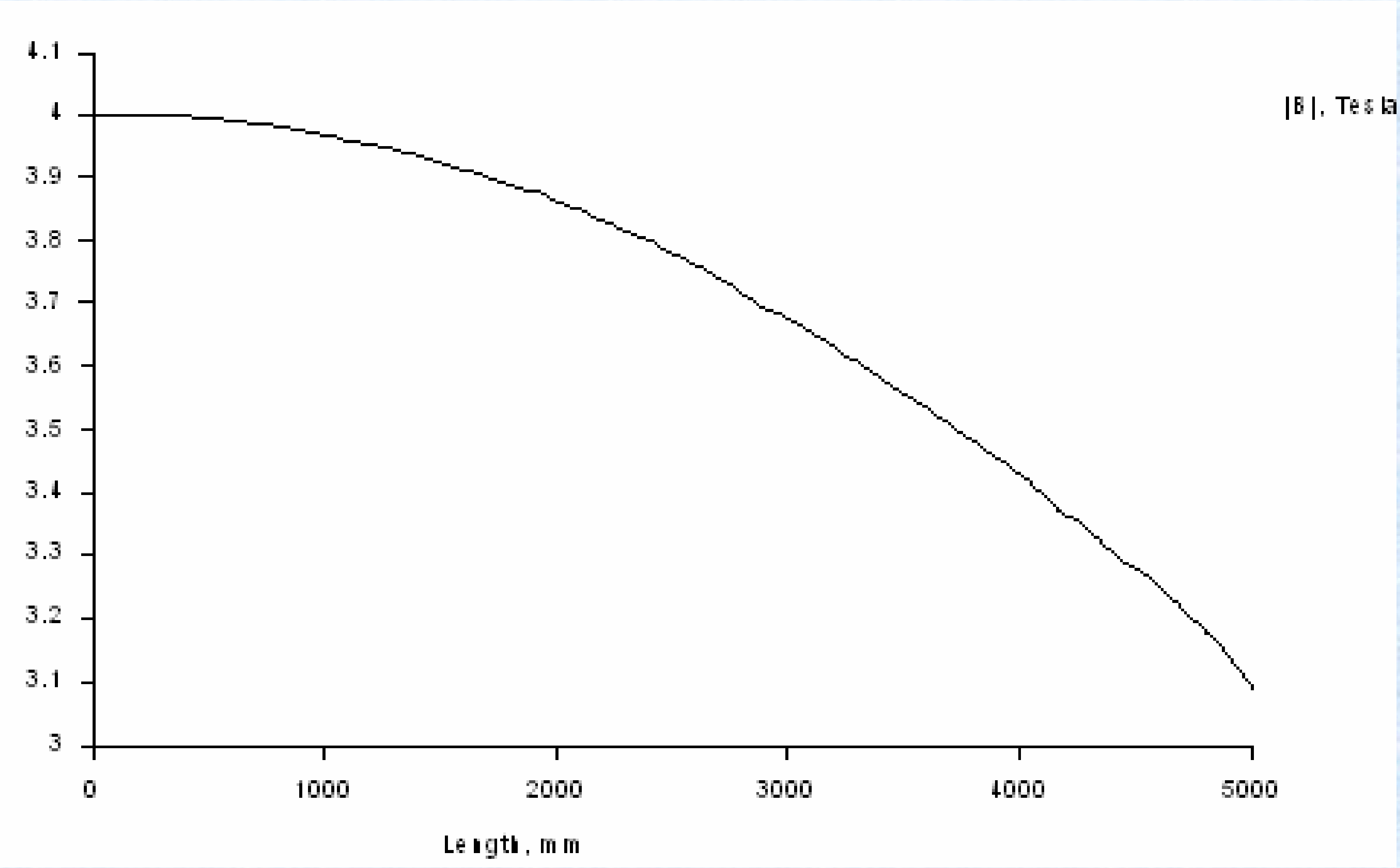


The central field B_0 = 4 T

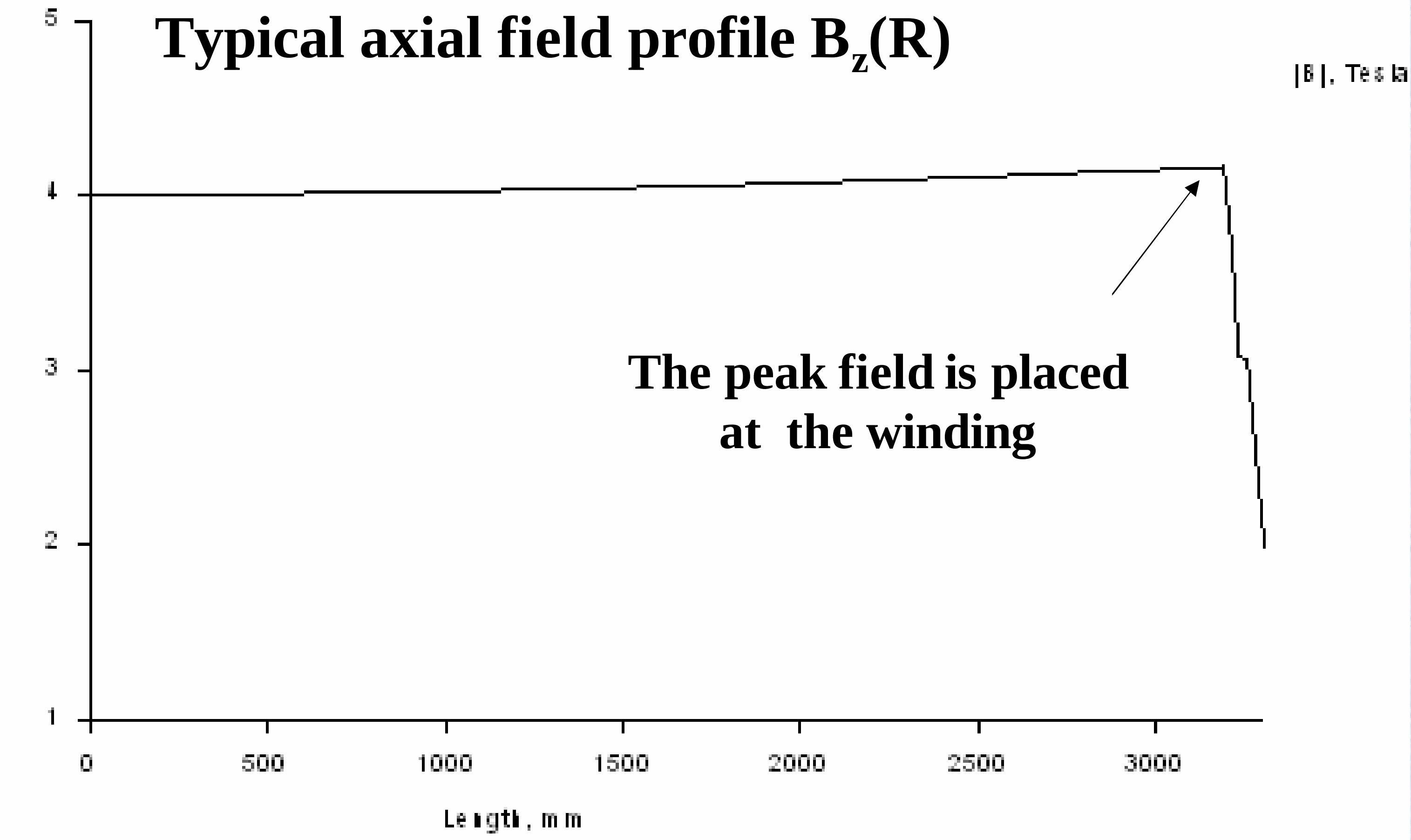
The peak field in the iron as high as 4.9 T

The peak field in the conductor B_p=4.6 T

Typical axial field profile $B_z(z)$



Typical axial field profile $B_z(R)$



The peak field is placed at the winding

The peak field in CMS winding is 4.6 T

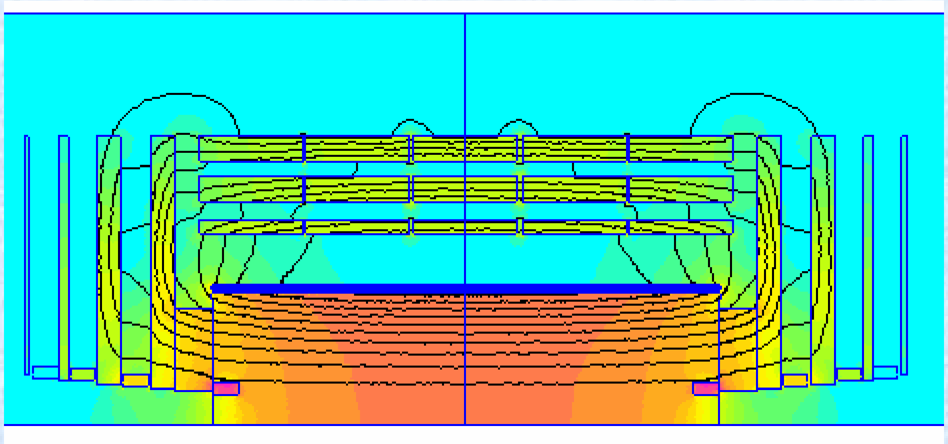
STORED MAGNETIC ENERGY

From FE analysis

$$E = \frac{1}{2m_0}\int_V B^2(r,z)dV = 2.6\ 10^9\ \text{Joule}$$

From simple formula

$$E = \frac{1}{2m_0}B_o^2 V_{coil} = \frac{1}{2m_0} * 4^2 * 402 = 2.56 10^9\ \text{Joule}$$



How large is 2.6 GJ energy?

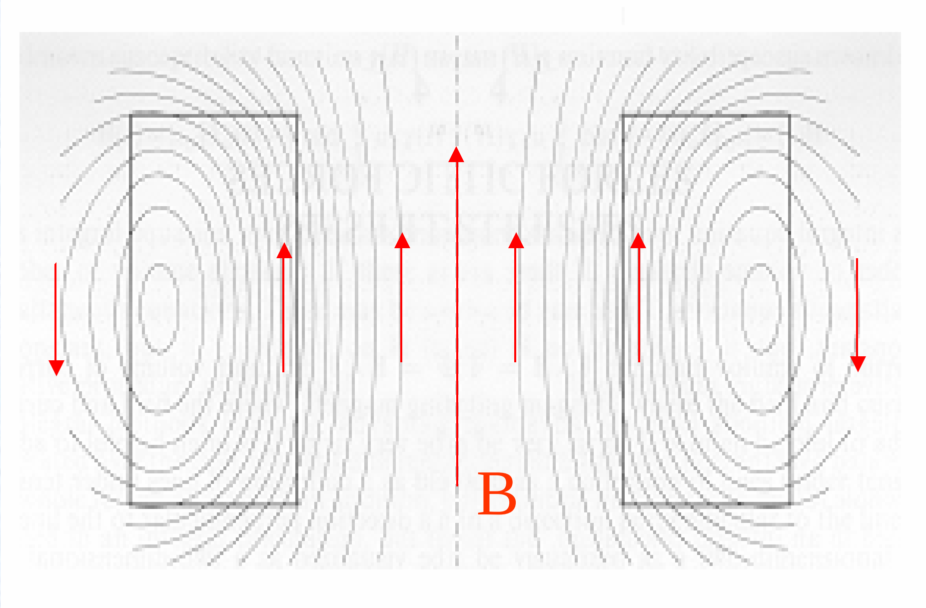
CMS coil can provide energy to our house for ˜ 1 month or we could melt 18 ton of gold.

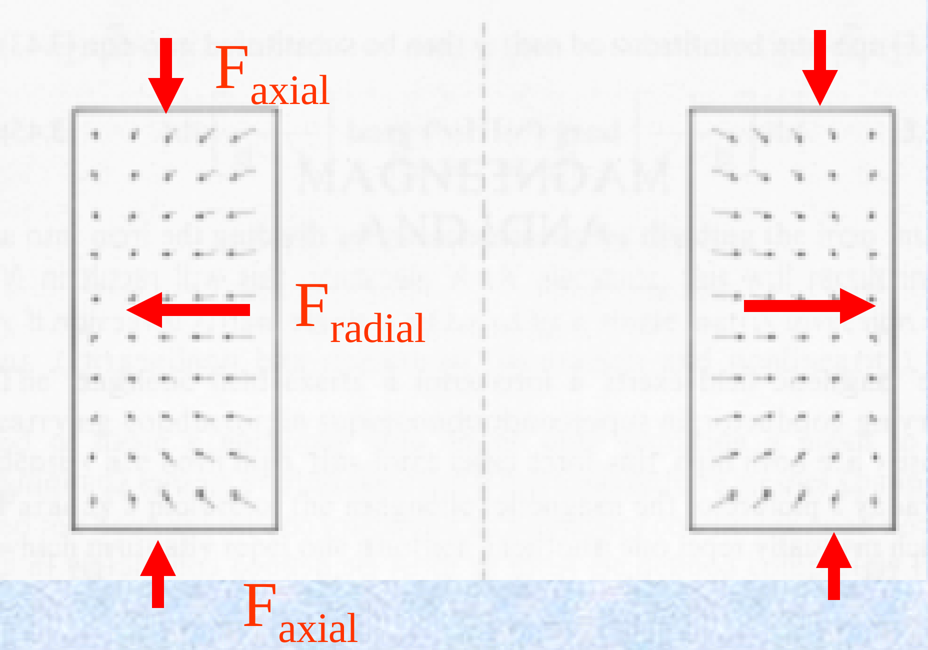
MAGNETIC FORCES

$$\vec{F} = \int_{Volume} \vec{J} \times \vec{B}\, dv$$

The radial field component causes axial forces

The axial field causes radial forces





The solenoids have to hold a compressive axial force and a opening radial force. With respect the radial force, thin solenois look like pressure vessels

For CMS coil

The total radial force $F_{radial} = 1.66\ 10^{9}$ N

Axial compression is as high as $F_{axial} = -1.4\ 10^{8}$ N (14000 ton)

The radial force causes a radial pressure:

$$P = \frac{F_{radial}}{Surface} = \frac{1.66\ 10^{9}}{2\pi\ \ 3.2\ \ 12.5} = 6.6\ 10^{6}\ \mathrm{Pa}$$

From a simple analytical approach…

$$\vec{F} = \nabla E \qquad F_r = \frac{d}{dr}\frac{B_0^2}{2\mu_0}V_{coil} = \boxed{\frac{B_0^2}{2\mu_0}}S$$

Magnetic pressure

$$\frac{B_0^2}{2\mu_0} = \frac{4^2}{2\mu_0} = 6.4\ 10^{6}\ \mathrm{Pa} \approx 64\,\mathrm{atm}$$

Hoop stress

Considering a thin solenoid as a vessel subjected to an inner pressure P_r, we can write the hoop stress

$$s_{hoop} = \frac{R\ \ P_r(B)}{t}$$

Where *t* is the coil thickness

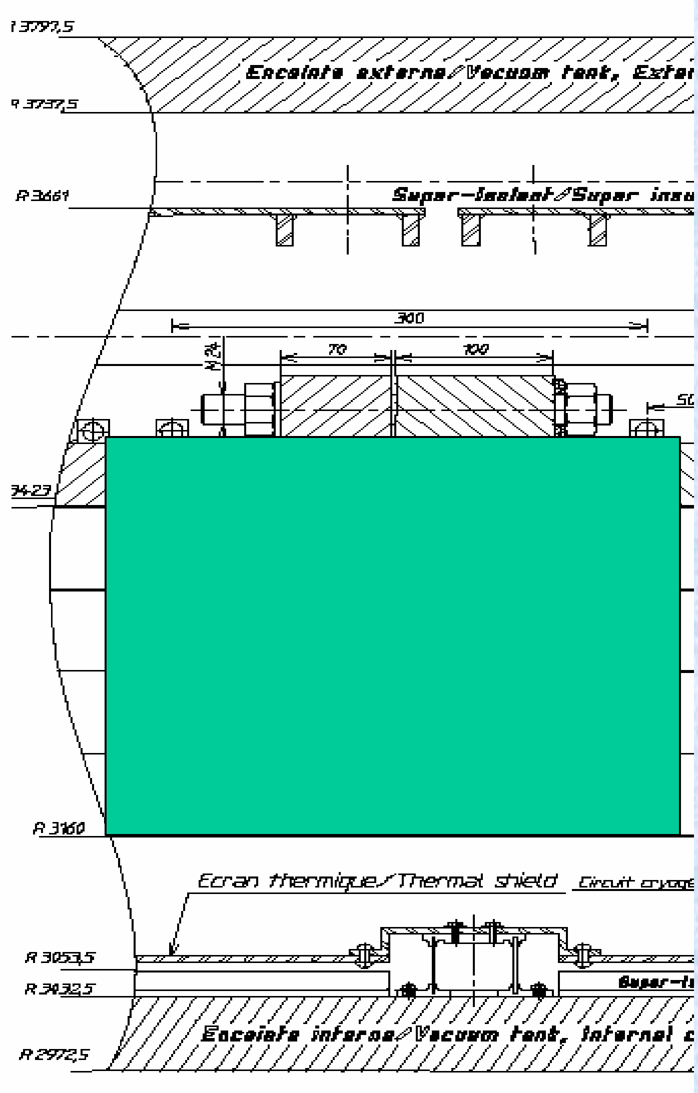
Choice of material → s $_{yield}$ → s $_{max}$ =2/3 s $_{yield}$ →Coil thickness

Here we mean the STRUCTURAL MATERIAL. In the past detector solenoids, the designers have involved Aluminium alloy 5083, which in the annealed state has an Yield stress of 100 MPa. Using this number, s max =66 MPa

$$t = \frac{3.2\text{m} ´ \ 6.7\ \ 10^6\ \text{Pa}}{66\ \ 10^6\ \text{Pa}} = 0.32\,\text{m}$$

Considering the radial space still required for the component carrying the current, too thick coil!!

Let’s construct (on the paper) the CMS coil



The radial space allowance for the coil is DR= 826 mm

Some space is required for vacuum vessel, thermal shield, suspension system.

The available cold mass thickness is 313 mm.

In the region 0.313 m × 12.5 m =3.91 m^2, we have to put 42.5 MA turns (to get 4 T field).

We have to fill the region with the SC component, the protecting and stabilising component and the structural one.

Inductance L and Current I_0

$$E = \frac{1}{2} L I_0^2 \qquad \mathrm{L} = \frac{2}{\mathrm{I}_o^2}\frac{\mathrm{B}_o^2}{2\mu_o}\pi R^2 l = \frac{\mu_o N^2 \pi R^2}{l}$$

We will see later that for reasons related to the quench protection I_o shall assume a value around 20000 A. This lead to an inductance L~14 H.

The resulting number of turns is then:

$$\mathrm{N} \approx \sqrt{\frac{\mathrm{Ll}}{\mu_o \pi \mathrm{R}^2}} = \sqrt{\frac{14 \;\; 12.5}{\mu_o \pi \; 3.2^2}} = 2080 \quad \text{or} \quad \mathrm{N} \approx \frac{\text{Ampere-turns}}{\mathrm{I}_0} = \frac{42.5 \;\; 10^6}{20000} = 2125$$

Further optimization will lead to fix the current at 19500 A resulting in N=2180 turns

With 2180 turns, the cross section for each turn is 3.91 m^2/2180= 1795 mm^2

Each turn is composed of 4 different components:

1. **The superconductor.**
2. **The matrix made of a material with good electrical conductivity, for stability and protection. For reasons related to the stability, the matrix is made of pure Aluminium 99.996**
3. **Mechanical reinforcement. Not present in past detector magnets, being the support structure external to the winding, usually an external mandrel, which has several functions. Let us assume to include in our design a 50 mm thick mandrel (further to the reinforcement included in the conductor)**
4. **The insulation**

The space available for 2180 turns is a rect. cross section 0.263 × 12.5 m^2

Finalising conductor definition: Dimensions

N layers × Conductor height (radial) = 0.263 m

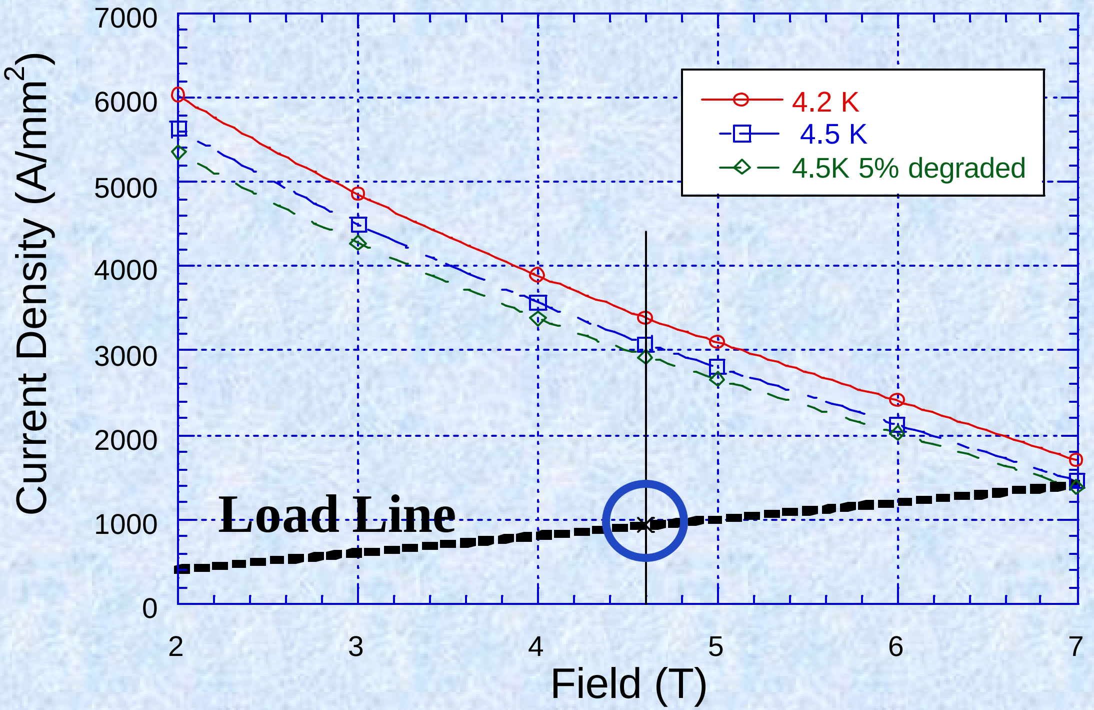
N turn per layer × Conductor thickness (axial) = 12.5 m

N layers × N turns per layer = 2180

Number of layers	Number of turn per layer	Conductor height (mm)	Conductor thickness (mm)
1	2180	263.00	5.73
2	1090	131.50	11.47
3	727	87.67	17.20
4	545	65.75	22.94
5	436	52.60	28.67
6	363	43.83	34.40
7	311	37.57	40.14
8	273	32.88	45.87
9	242	29.22	51.61
10	218	26.30	57.34

Finalising conductor definition: Superconductor

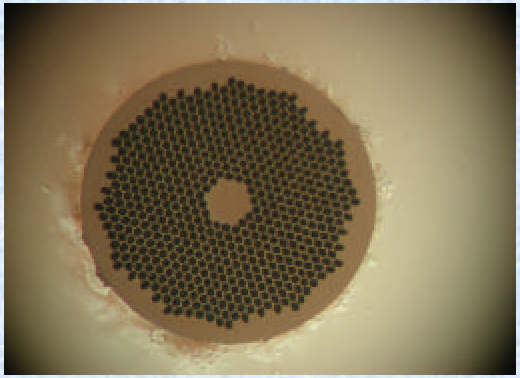
The classical material for application is NbTi, which is superconductor under 9.3 K (at 0 magnetic field). The current capability depends on field and temperature



The peak field at the coil is 4.6 T. If we want to operate at 1/3 of the critical current, the current density shall be ~ 1000 A/mm^2.

For a current of 19500 A the required cross section is ~ 19.5 mm^2

The basic element of a composite S/C conductor: the strand



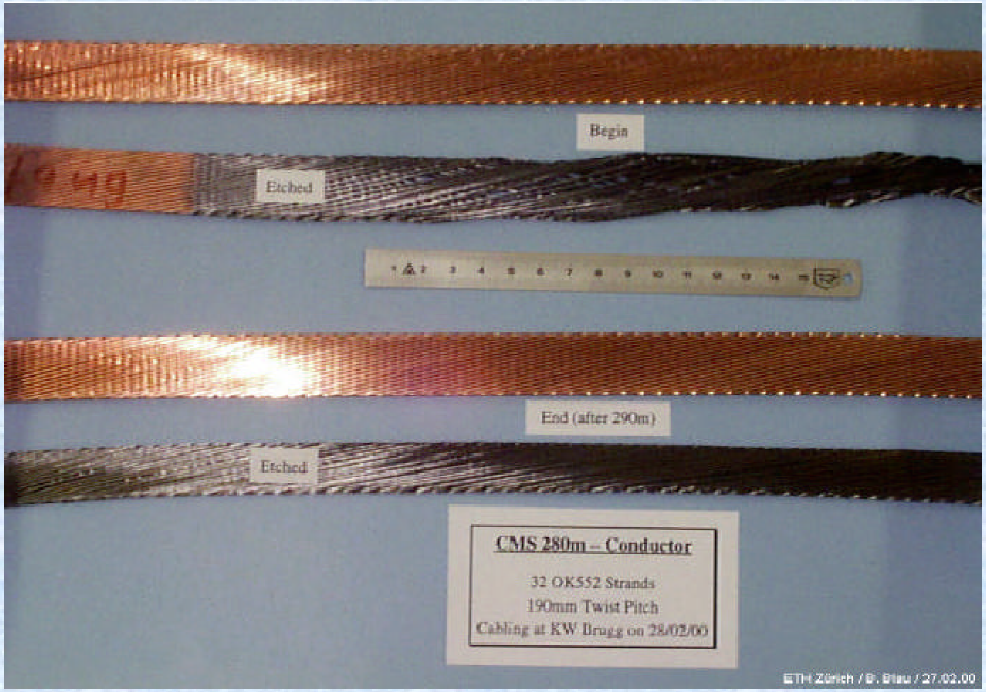
Strand cross section 1.286 mm^2

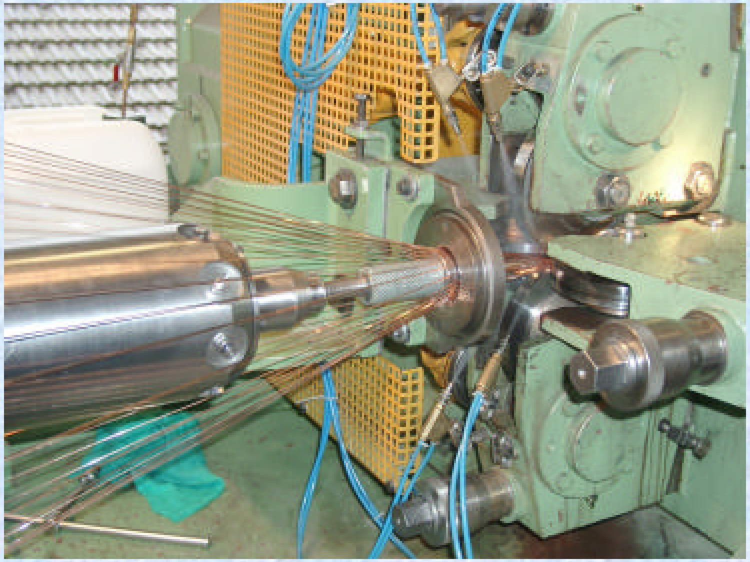
S/C cross section 0.613 mm^2

We need 32 strands

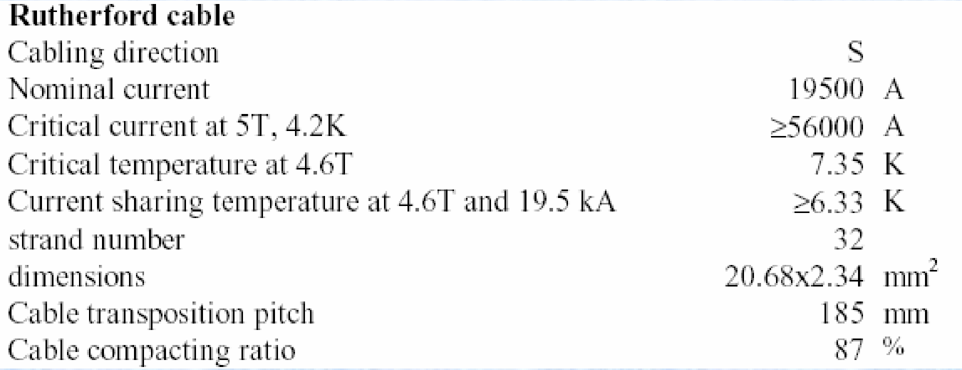
Strand Constituents	**Material**
High homogeneity Nb-Ti	Nb 47±1 Wt % Ti
High Purity Copper	RRR > 300
Niobium Barrier	Reactor Grade I
Strand Design Parameters	**Parameters**
Strand Diameter	1.280 ± 0.005 mm
(Cu+Barrier)/Nb-Ti ratio	1.1 ± 0.1
Filament diameter (mm)	< 40
Number of Filaments	• 552
Strand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

The following step: the superconducting cable



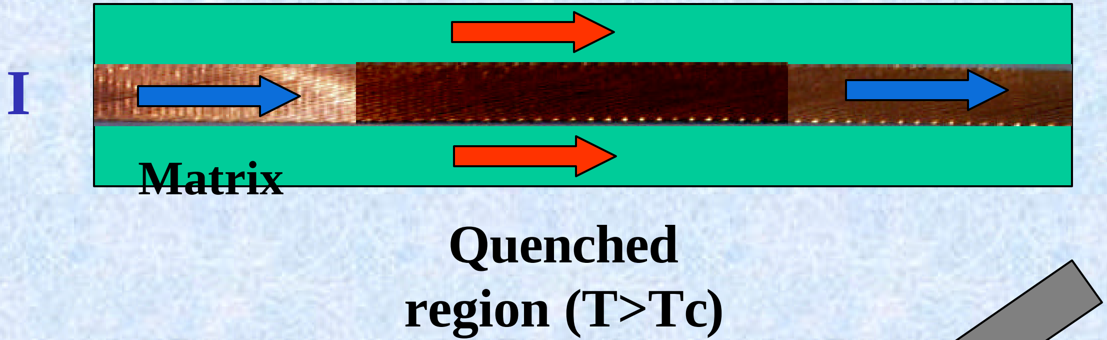


Cabling operation (at Brugg)



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	%

The S/C cable needs stabilization and protection, involving the use of a high electrical conductivity material



Stability

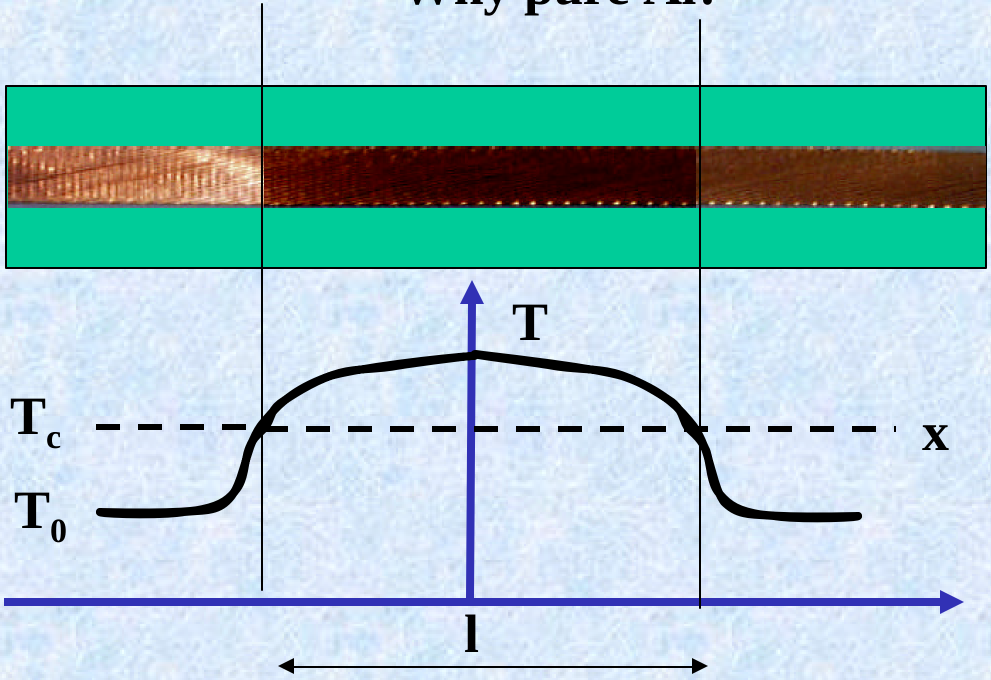
In case of a localized transition S/C→Normal, the stabilizing material provides an alternative path to the current. Under some conditions the quenched zone may recover.

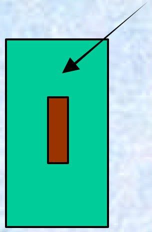
Protection

In case of normal zone propagation, the power dissipation can be kept as low as possible by controlling the cross section of the stabilising matrix.

Matrix of
high purity Al 99.996
($\rho < 2.4\ 10^{-11}\ \Omega m$)

Why pure Al?





Matrix Cross Section A

Condition for equilibrium

$$2kA(T_c - T_0)/l = J_c^2 \rho A l$$

⇓

Minimum Propagating Zone $$l = \sqrt{\frac{2k(T_c - T_0)}{J_c^2 \rho}}$$

$$\rho k = L_0 T$$ ⇒ $$l = \frac{\sqrt{2L_0 T_0 (T_c - T_0)}}{J_c \rho}$$ ⇒ $$\mathrm{MPZ} \propto \frac{A}{\rho}$$

Among practical metals with low electrical resistivity we can consider pure Copper or Aluminium. Making the comparison on the basis of the same weight :

$$\textbf{for Cu}: \frac{A}{r_{Cu}} \;;\quad \textbf{for Al}: \frac{A}{r_{Al}}\,\frac{d_{Cu}}{d_{Al}}$$

$$RRR = \frac{r(T = 300k)}{r(T = T_c)}$$

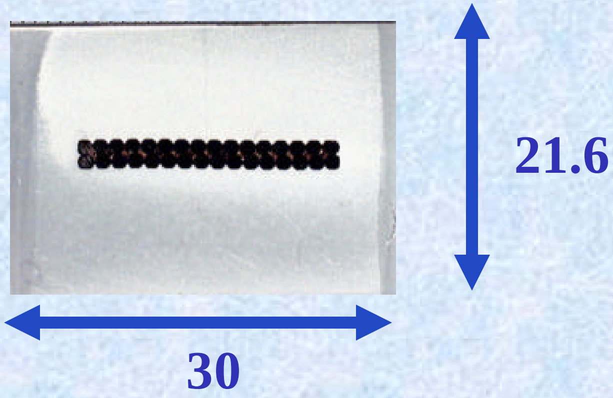
Cu RRR100 and Al RRR1000

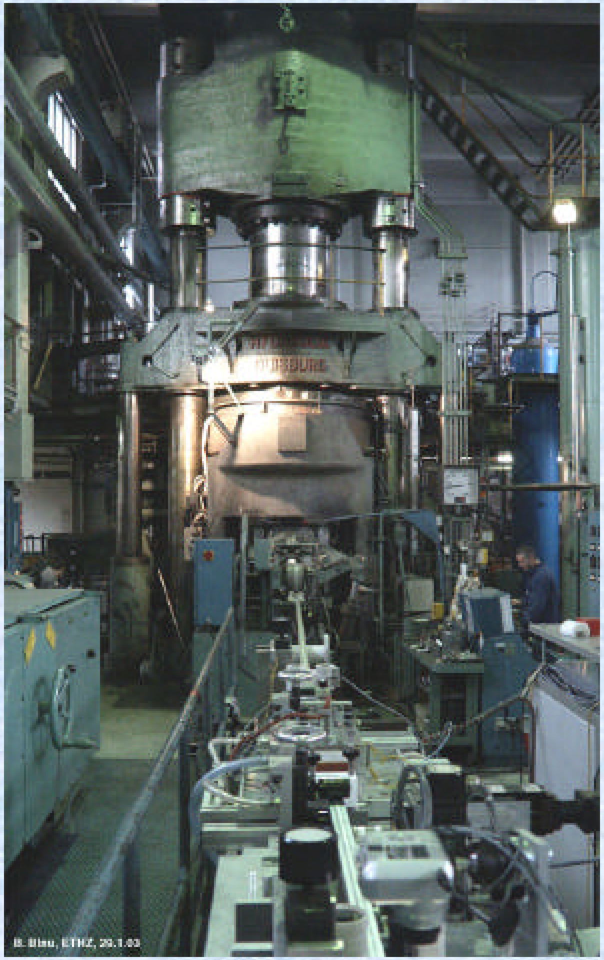
$$\text{at } T = 4.2\,k \quad \frac{r_{Al}}{r_{Cu}} = 0.15$$

MPZ Al ~ 20 MPZ Cu →

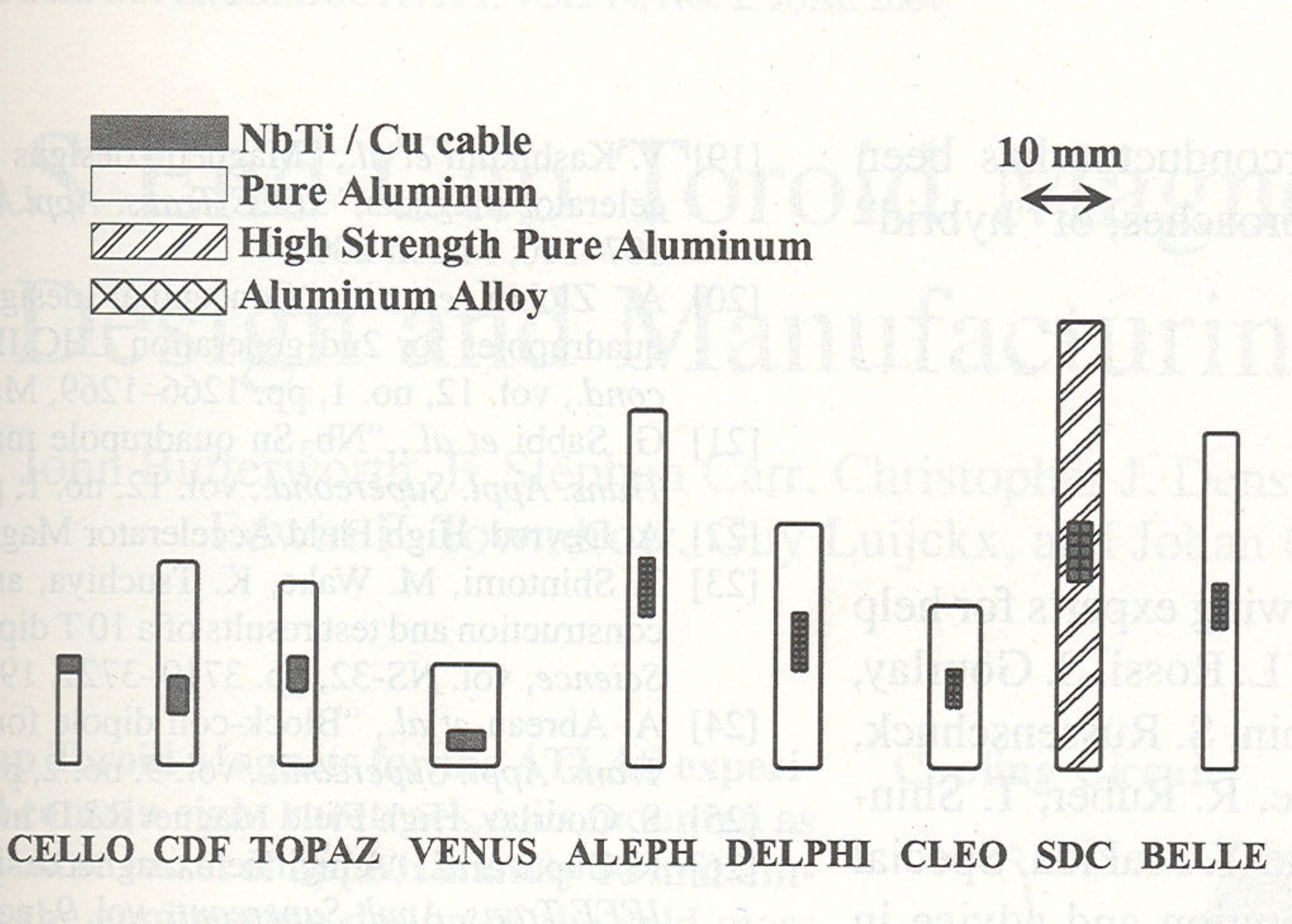
Pure Al is highly preferable … but it is mechanically very soft.

The stabilising/protecting pure Al is coupled to cable by a co-extrusion process



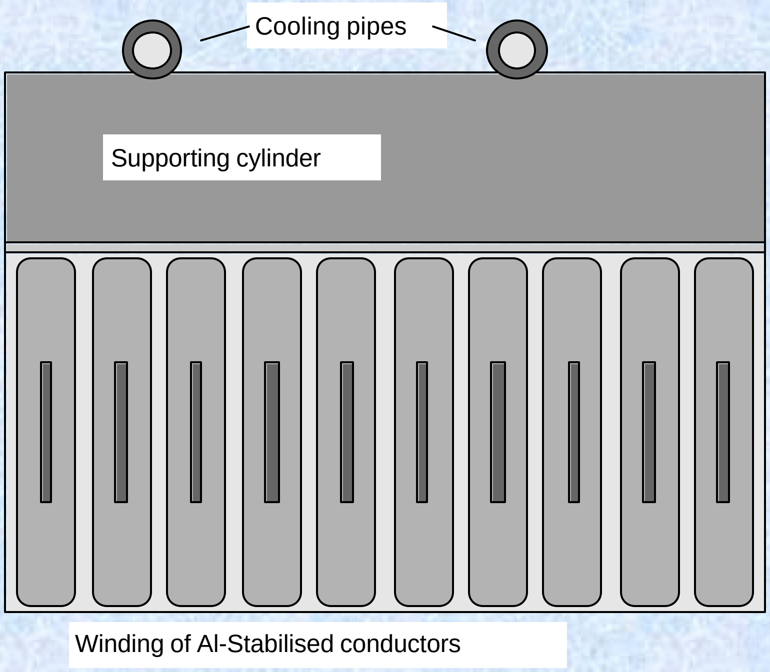


Aluminium Stabilised Conductors for Detector Magnets (before LHC)



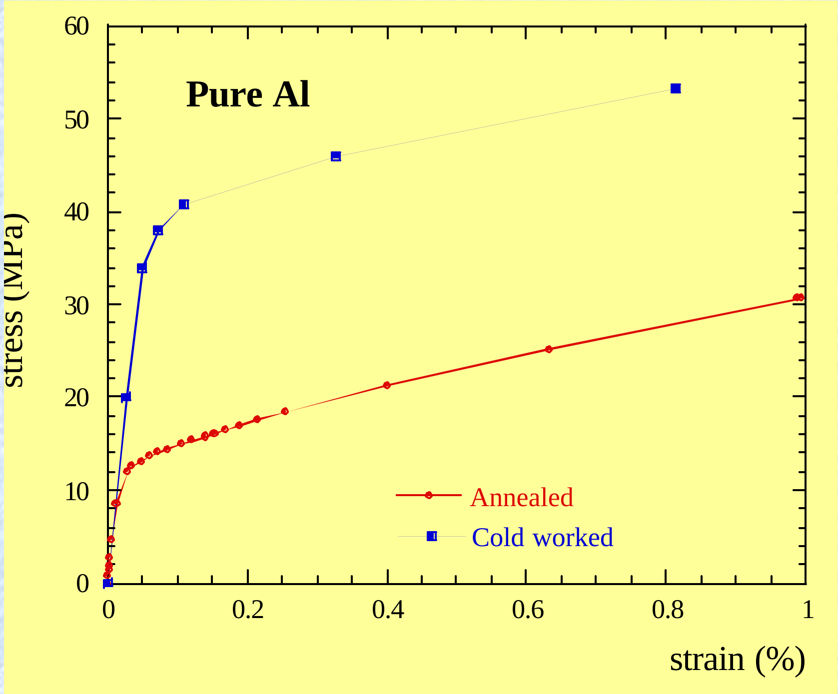
A.Yamamoto MT-18 Conference

Now we can understand better this layout

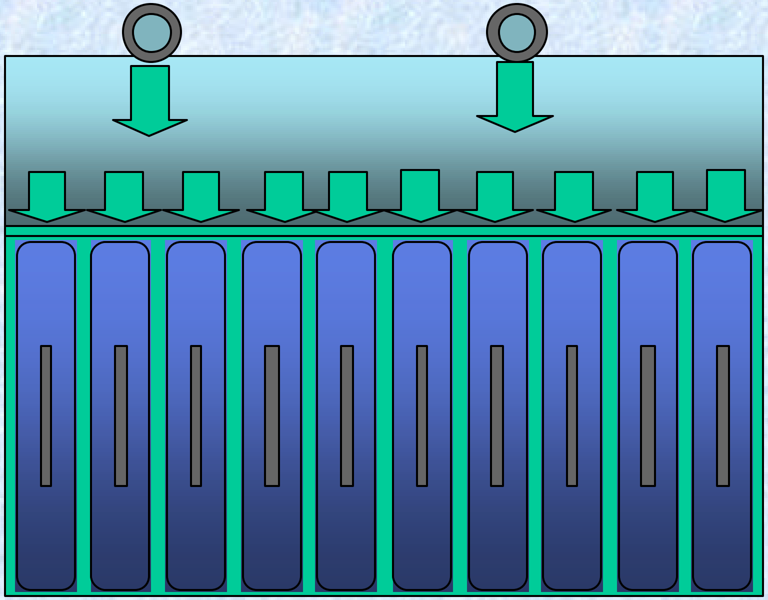


Question is: Which is the role of supporting cylinder?

The main role is mechanical: it has to provide the hoop strength. Pure Al of the winding has limited capability



Al-5083 alloy has a yield strength as high as 100 MPa in annealed state. It can be hardened and get up to 220 MPa



Other important function of the supporting cylinder is to guarantee a homogeneous cooling of the winding. The cooling is provided by LHe circulating in the pipes connected to the cylinder.

We can have heat dissipations in the winding causing temperature gradients (Electrical joints inside the winding, Radiation losses at the inner radius, Eddy currents in winding and mandrel during coil charge and dis-charge, plastic deformation)

The max tolerated DT is in the order of few tenth of K. We must guarantee an optimum cooling condition controlling the insulation thickness. This is the reason because …

… we do not use layout of this kind!!

The winding of the conductor on the lower inertia would be more simple, but we will have too much insulation between cooling pipes and inner layers.

(Apart of complications coming from the need of more electrical layer-to-layer joints)

Design principles of thin high field superconducting solenoids

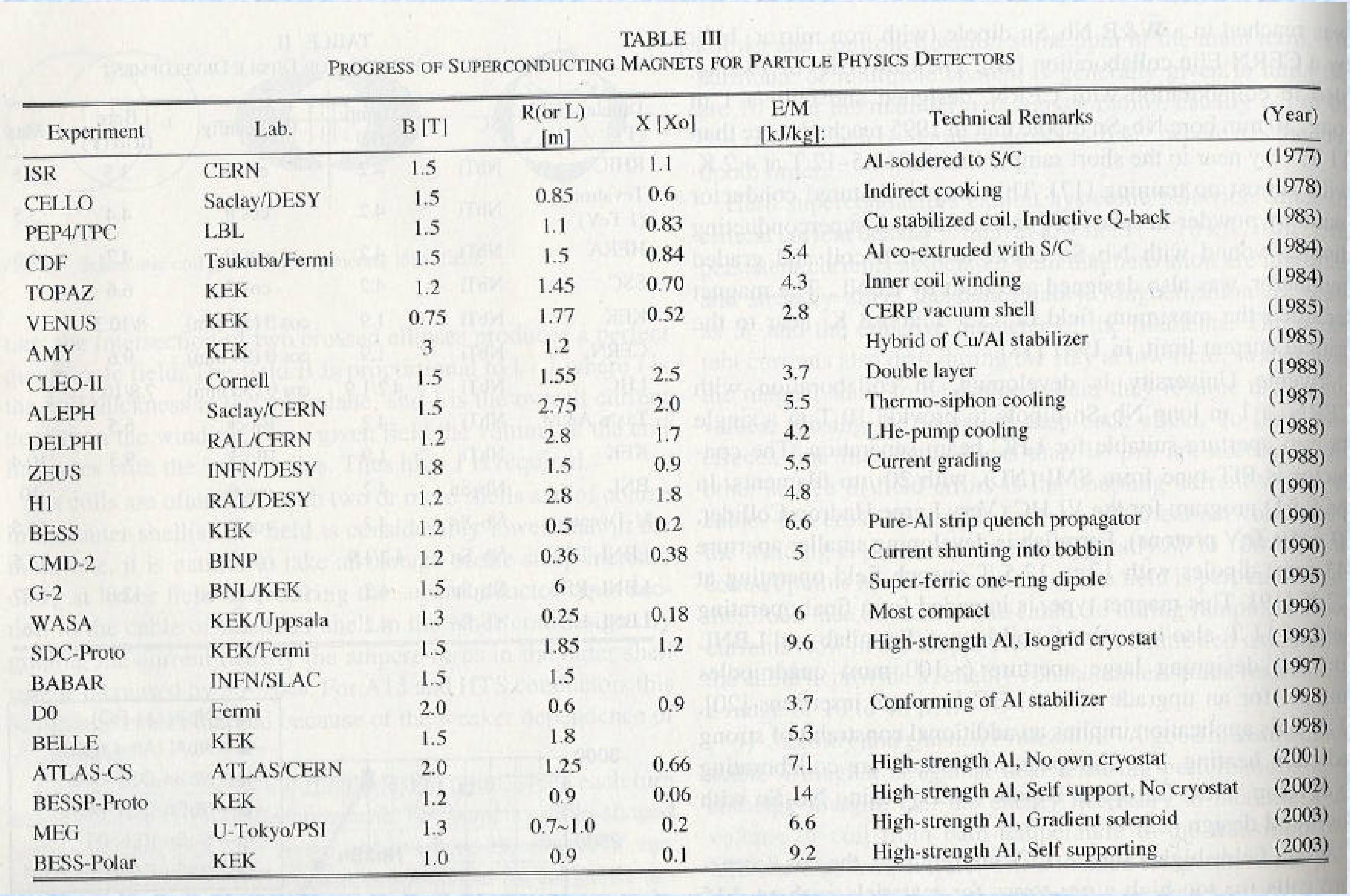


TABLE III
PROGRESS OF SUPERCONDUCTING MAGNETS FOR PARTICLE PHYSICS DETECTORS

Experiment	Lab.	B [T]	R(or L) [m]	X [Xo]	E/M [kJ/kg]	Technical Remarks	(Year)
ISR	CERN	1.5		1.1		Al-soldered to S/C	(1977)
CELLO	Saclay/DESY	1.5	0.85	0.6		Indirect cooking	(1978)
PEP4/TPC	LBL	1.5	1.1	0.83		Cu stabilized coil, Inductive Q-back	(1983)
CDF	Tsukuba/Fermi	1.5	1.5	0.84	5.4	Al co-extruded with S/C	(1984)
TOPAZ	KEK	1.2	1.45	0.70	4.3	Inner coil winding	(1984)
VENUS	KEK	0.75	1.77	0.52	2.8	CERP vacuum shell	(1985)
AMY	KEK	3	1.2			Hybrid of Cu/Al stabilizer	(1985)
CLEO-II	Cornell	1.5	1.55	2.5	3.7	Double layer	(1988)
ALEPH	Saclay/CERN	1.5	2.75	2.0	5.5	Thermo-siphon cooling	(1987)
DELPHI	RAL/CERN	1.2	2.8	1.7	4.2	LHe-pump cooling	(1988)
ZEUS	INFN/DESY	1.8	1.5	0.9	5.5	Current grading	(1988)
H1	RAL/DESY	1.2	2.8	1.8	4.8		(1990)
BESS	KEK	1.2	0.5	0.2	6.6	Pure-Al strip quench propagator	(1990)
CMD-2	BINP	1.2	0.36	0.38	5	Current shunting into bobbin	(1990)
G-2	BNL/KEK	1.5	6			Super-ferric one-ring dipole	(1995)
WASA	KEK/Uppsala	1.3	0.25	0.18	6	Most compact	(1996)
SDC-Proto	KEK/Fermi	1.5	1.85	1.2	9.6	High-strength Al, Isogrid cryostat	(1993)
BABAR	INFN/SLAC	1.5	1.5				(1997)
D0	Fermi	2.0	0.6	0.9	3.7	Conforming of Al stabilizer	(1998)
BELLE	KEK	1.5	1.8		5.3		(1998)
ATLAS-CS	ATLAS/CERN	2.0	1.25	0.66	7.1	High-strength Al, No own cryostat	(2001)
BESSP-Proto	KEK	1.2	0.9	0.06	14	High-strength Al, Self support, No cryostat	(2002)
MEG	U-Tokyo/PSI	1.3	0.7~1.0	0.2	6.6	High-strength Al, Gradient solenoid	(2003)
BESS-Polar	KEK	1.0	0.9	0.1	9.2	High-strength Al, Self supporting	(2003)

On the basis of discussed concepts let us go on with CMS coil design...

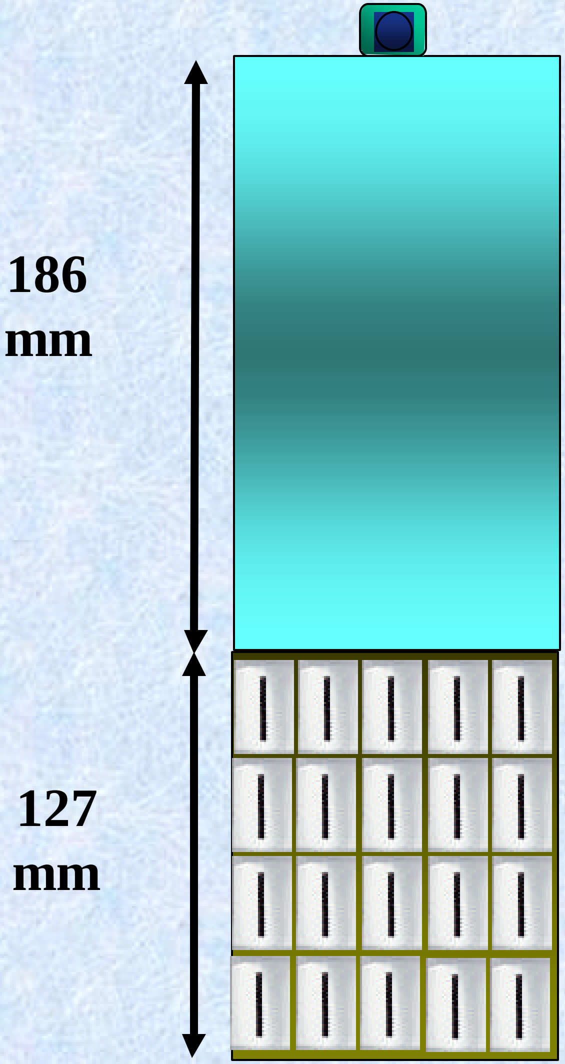
CMS coil shall have 4 layers of pure Al stabilised conductors 21.6 mm × 30.0 mm

Considering the insulation and considering the radial allowed space (313 mm) we have a layout of the kind→ where there is a thick supporting cylinder 186 mm thick

$$\sigma_{hoop} = \frac{RP_r}{t} = \frac{3.2\,m \times 6.7\,10^{7}\,MPa}{0.186\,m} = 115\,MPa$$

We need an Al-alloy with an yield strength $\sigma_{0.2}$ >115 ×3/2=170 MPa

(The choice was for Al5083-H321)



Following the guidelines of the thin solenoids design we have defined a CMS coil layout with two main components: 1) the Al stabilised conductor having the electrical function and 2) the supporting cylinder (mandrel) having the mechanical function.

Are we happy? No! Because the magnetic forces are generated in the soft conductors, but they must be hold by the mandrel. Due the required Ampere-turns we have 4 layers; the conductors of the inner layers are too far from the mandrel.

Typical problem: CMS coil shall hold an axial compressive force of 1400 MN. The force is applied to the winding causing an axial stress of 55 MPa deforming plastically the winding, unless the force is transferred to the mandrel, but we will have shear stress both in the soft aluminium and at the interface winding-mandrel

Only winding supports axial force

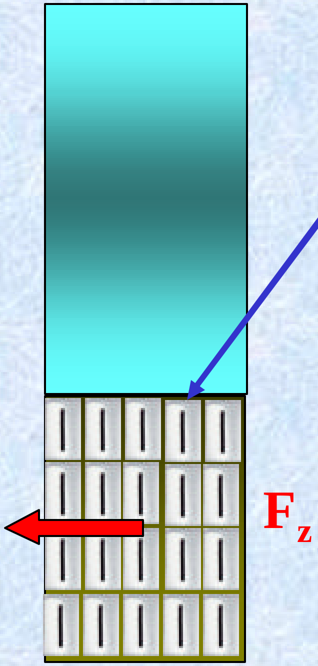
$$\sigma_z = \frac{F_z}{2\pi R t} = \frac{1400\,\mathrm{MN}}{2\pi\, 3.2\,\mathrm{m} \times 0.127\,\mathrm{m}} = 55\,\mathrm{MPa}$$

Not possible

Winding + Mandrels support axial force

$$\sigma_z = \frac{F_z}{2\pi R t} = \frac{1400\,\mathrm{MN}}{2\pi\, 3.2\,\mathrm{m} \times 0.313\,\mathrm{m}} = 22\,\mathrm{MPa}$$

Ok ..



... But shear stress at the bonding Mandrel-Winding

$$\sigma_{shear}(z) = \frac{F_z(z)}{\Delta z} = \frac{4 B_r I}{\Delta z} = \frac{4 \times 2 \times 19500}{0.0226} = 7\mathrm{MPa}$$

It would be better to hold the force, just where it is generated, i.e. in the conductor ⟹ **Reinforced Conductor**

Reinforced Conductor

In order to better distribute the stresses in the whole winding, avoiding large shear stresses in the insulation and in the interfaces, in CMS coil the reinforcement has been directly included in the conductor.

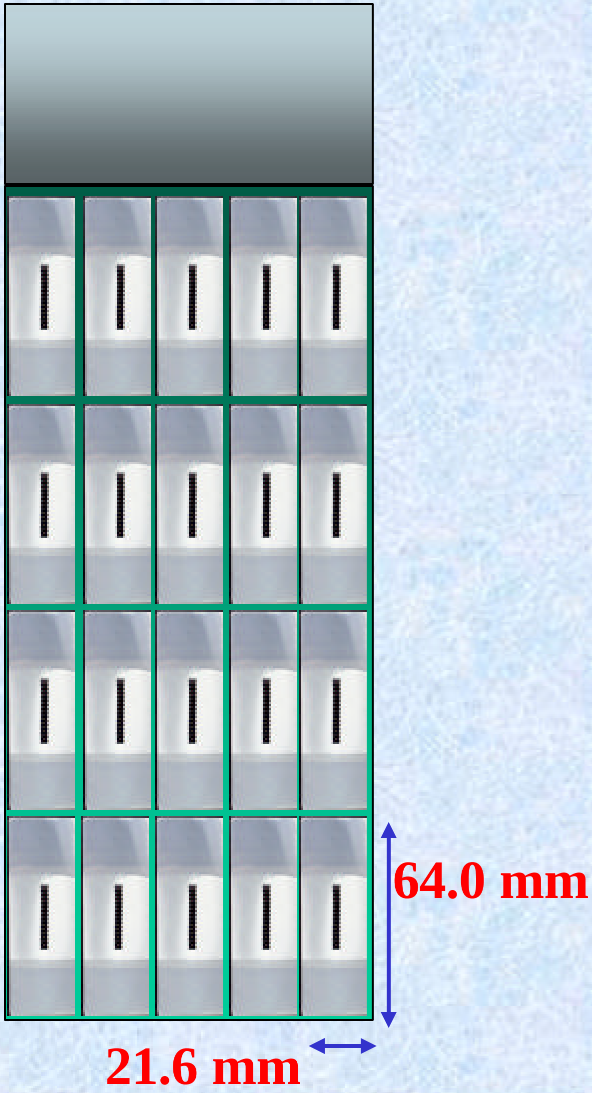
A much thinner supporting mandrel has been kept for the other functions related to this component:

1) Homogenize coil cooling

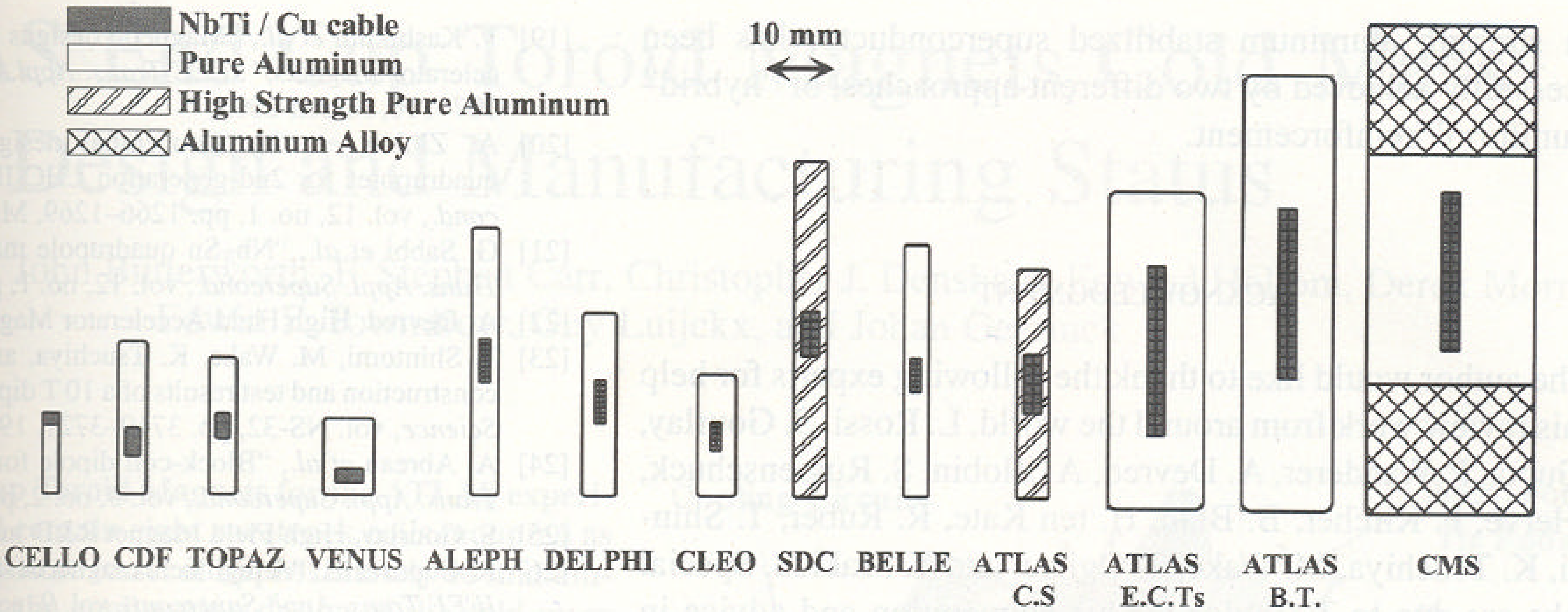
2) Protection (Quench back)

3) Support for winding operations

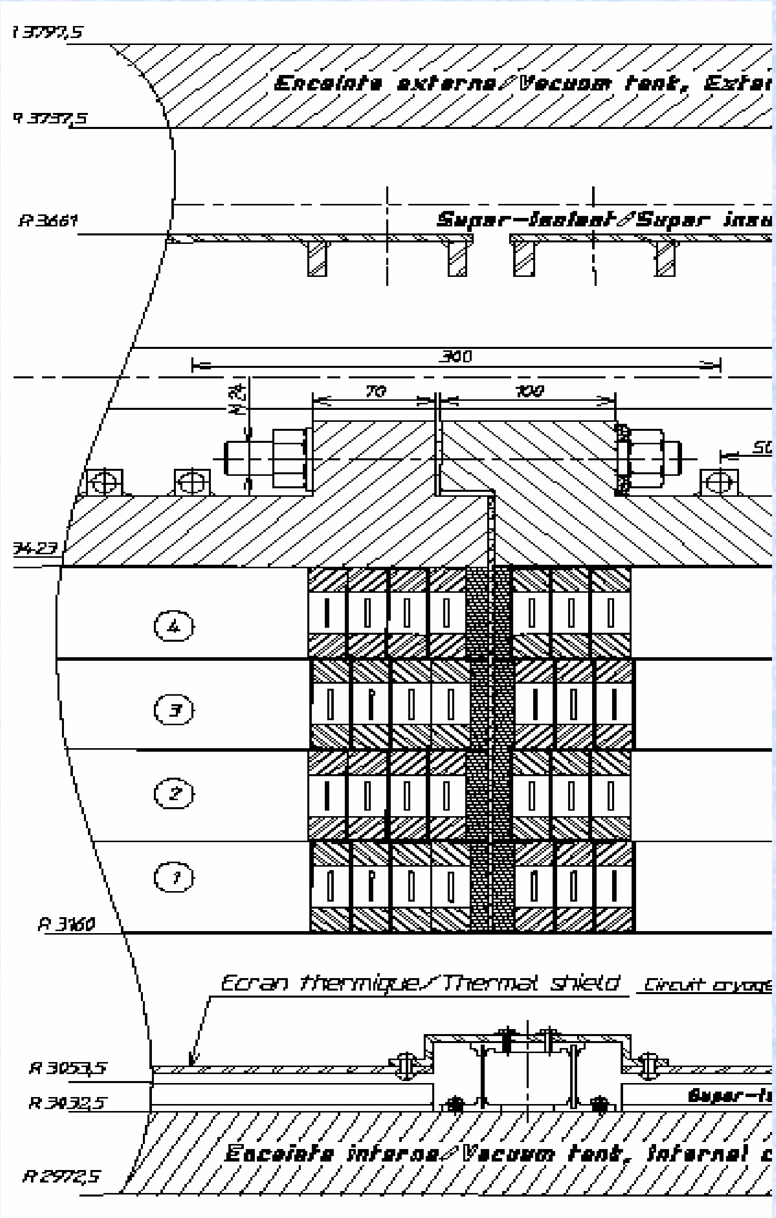
4) Interface of the coil with supporting system

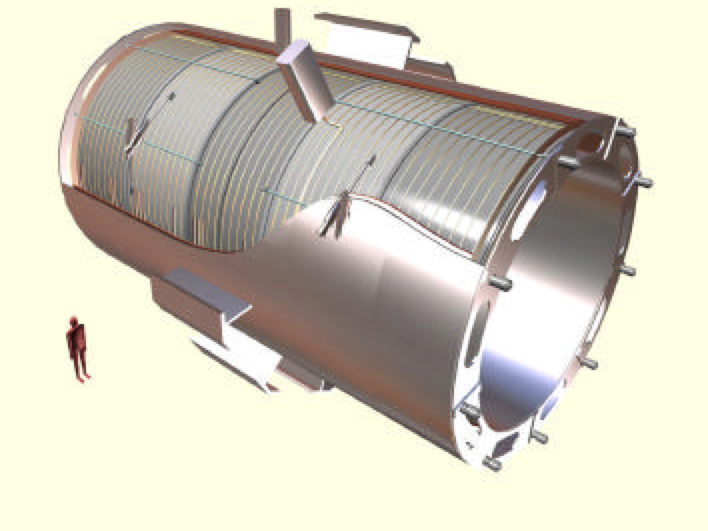


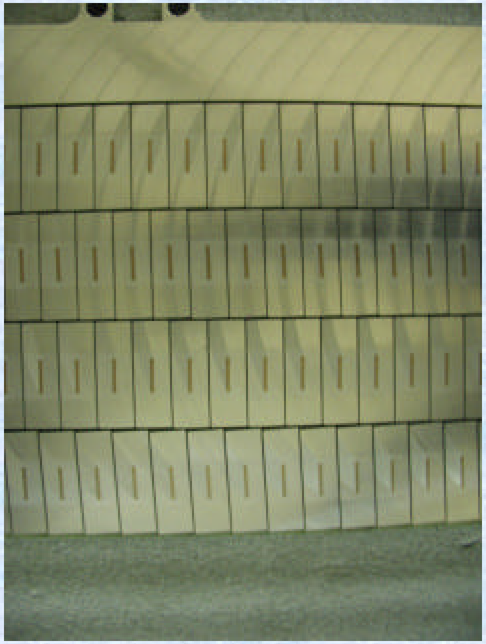
Design principles of thin high field superconducting solenoids

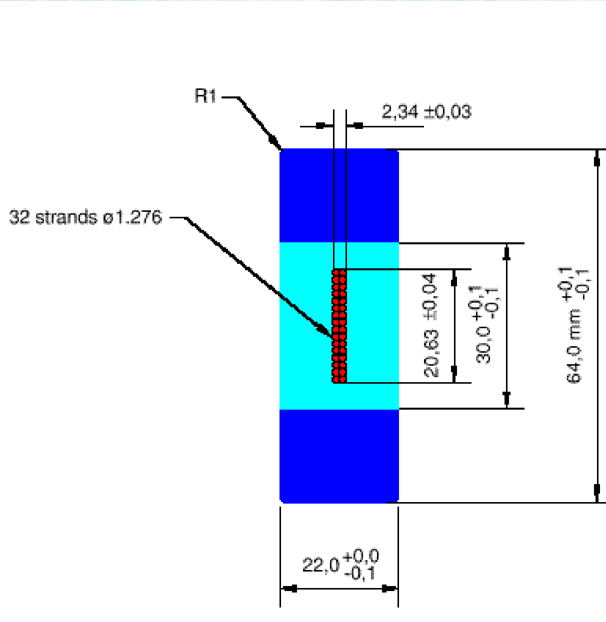


Design principles of thin high field superconducting solenoids









Comparison among high field thin solenoids

As proposed by A. Yamamoto, an interesting comparison can be done on the basis of the ratio E/M (Stored Energy [kJoule])/ Cold Mass [kg]).

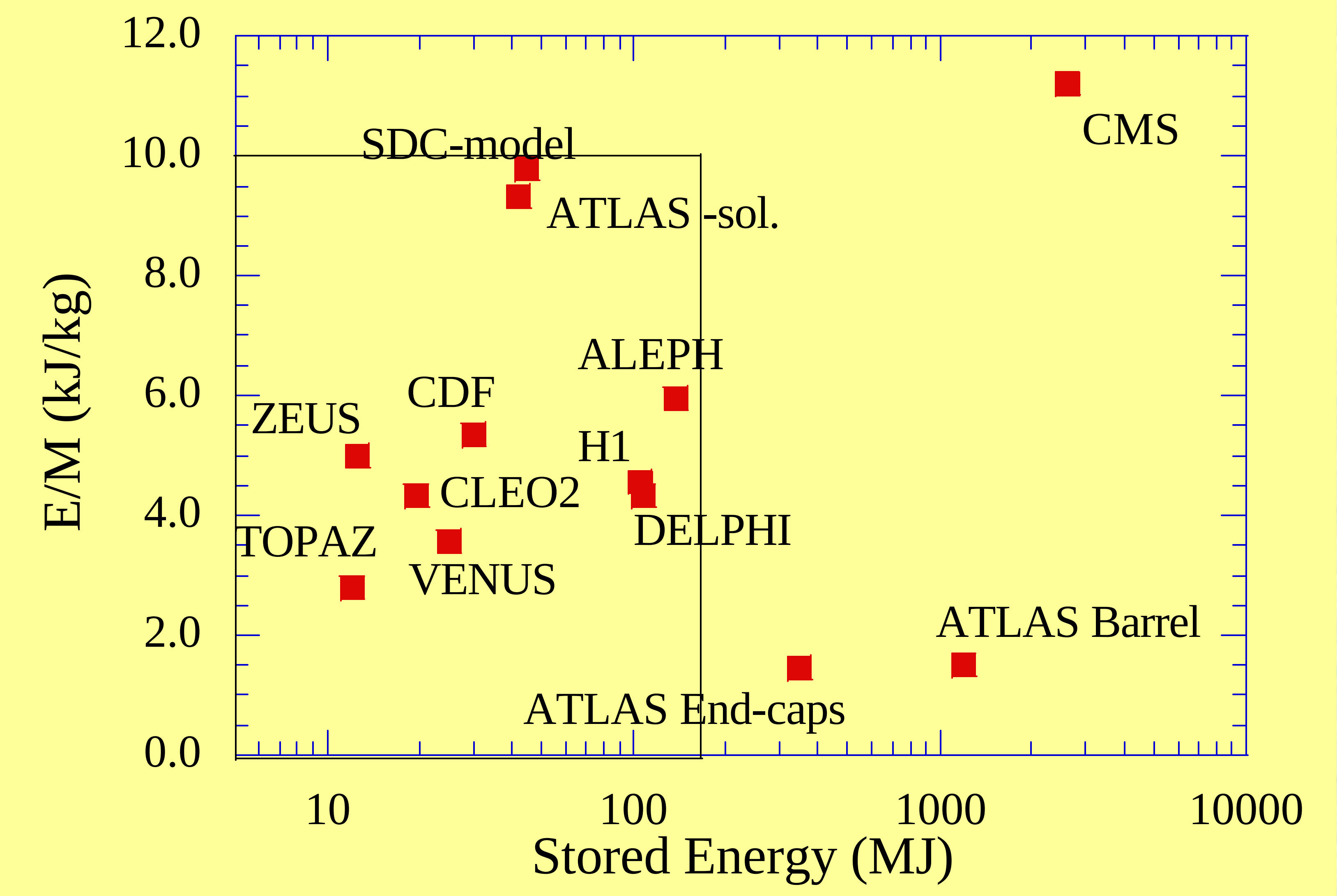
$$\frac{E}{M} = \frac{B_0^2}{2\mu_0}\pi R^2 l \frac{1}{2\pi R\, l\, t\, \delta} = \frac{B_0^2}{2\mu_0}\frac{R}{2t\delta} = \frac{\sigma}{2\delta} = \frac{Y\varepsilon}{2\delta}$$

Where ε is the strain , Y the elastic modulus and δ the density

When comparing Al stabilised solenoids the ratio E/M give a direct idea how much the coil is mechanically strained

A further meaning of E/M ratio is directly related to the maximum temperature in the coil if all stored energy is dissipated as heat

$$\frac{E}{M} = \int_{T_{in}}^{T_{fin}} C\,dT = H_{Al}(T_{fin}) - H_{Al}(T_{in})$$


E/M (kJ/kg)
Stored Energy (MJ)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
10
100
1000
10000
CMS
SDC-model
ATLAS -sol.
ALEPH
CDF
ZEUS
H1
CLEO2
DELPHI
TOPAZ
VENUS
ATLAS Barrel
ATLAS End-caps

Design principles of thin high field superconducting solenoids

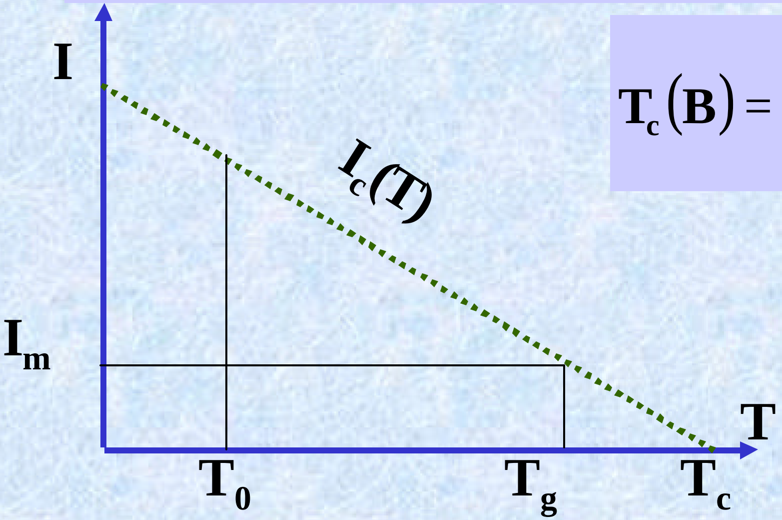
	ALEPH	DELPHI	CMS
Central Field (T)	**1.5**	**1.2**	**4.0**
Inner Bore (m)	**4.96**	**5.2**	**6.3**
Length (m)	**7**	**7.4**	**12.5**
Stored Energy (MJ)	**137**	**108**	**2690**
Current (A)	**5000**	**5000**	**19500**
Cold mass weight (t)	**23**	**24**	**225**
Radial pressure (MPa)	**0.9**	**0.6**	**6.4**
Axial compressive force (MN)	**40**	**-**	**148**
Mechanical Strain %	**0.05**	**-**	**0.15**

Stability

Enthalpy Margin: It is allowed to have heat releases inside the winding (localized or distributed). It is only required that the coil maximum temperature does not exceed the current sharing temperature:

$$T_g = T_c(B) - \left[T_c(B) - T_0\right]\frac{I_m}{I_{c0}(B)}$$

where Tc is the critical temperature at the operating field, I_m is the magnet current and I_{c0} is the critical current .



$$T_c(B) = T_{c0}\left(1 - \frac{B}{B_{c20}}\right)^{0.59} = 9.3\left(1 - \frac{4.6}{13.9}\right)^{0.59} = 7.34\,\mathrm{K}$$

$$\frac{I_m}{I_{c0}(B = 4.6\mathrm{T})} = \frac{1}{3} \qquad T_0 = 4.5\mathrm{K}$$

$$T_g(B = 4.6\,\mathrm{T}) = 6.40\,\mathrm{K}$$

We can calculate the maximum energy for unit volume $E_{u.v.}$ (enthalpy margin) which cause a temperature rise from 4.5 K (the magnet operating temperature) to 6.4 K (the current sharing temperature at B=4.6 T).

$$E_{u.v.} = \int_{4.5}^{6.4} C_p(T)\,\delta\,dT$$

where C_p is the specific heat in J kg^{-1} K^{-1} and δ the density.

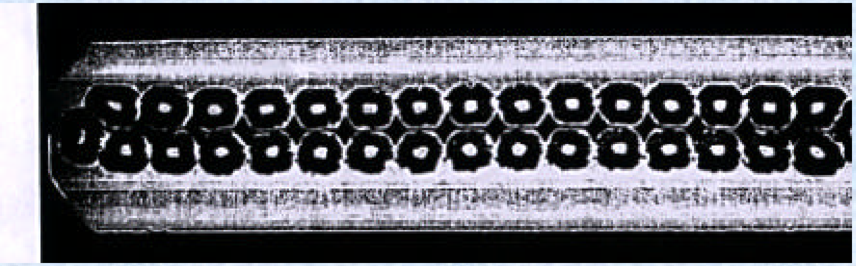
By averaging the thermal properties among the four components of the winding (Aluminium, Copper, NbTi and fiberglass epoxy) we found $E_{u.v.}$ = 2000 J/m^3. It can be written as energy per unit conductor length $E_{u.l.}$ = 2.92 J/m

Enthalphy margin protects the coil

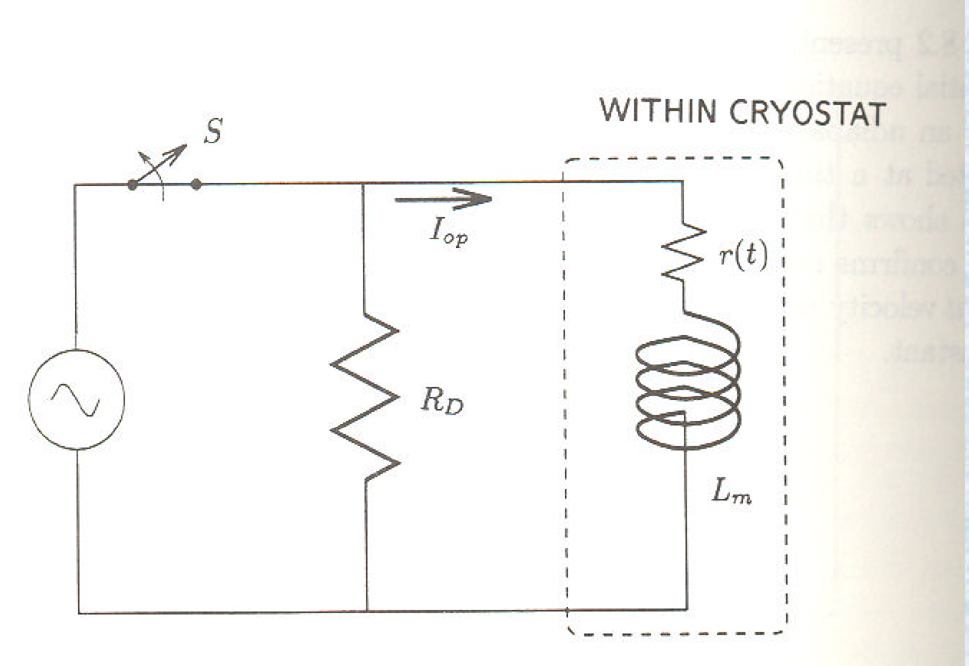
In a Rutherford cable inside pure aluminium, we can observe the existence of voids. The worst situation happens when, under the action of the axial force, half of the Rutherford moves against the other half. Considering an average gap between the two halves s= 0.013 mm (10% of the strand thickness), the energy dissipation for unit length **W = (B I s)** is

$$W= 4.3 \times 10000 \times 1.3\ 10^{-5} = 0.56\ J/m$$

Here the average field in first layer B=4.3 T has been considered. This energy is well inside the enthalpy margin.



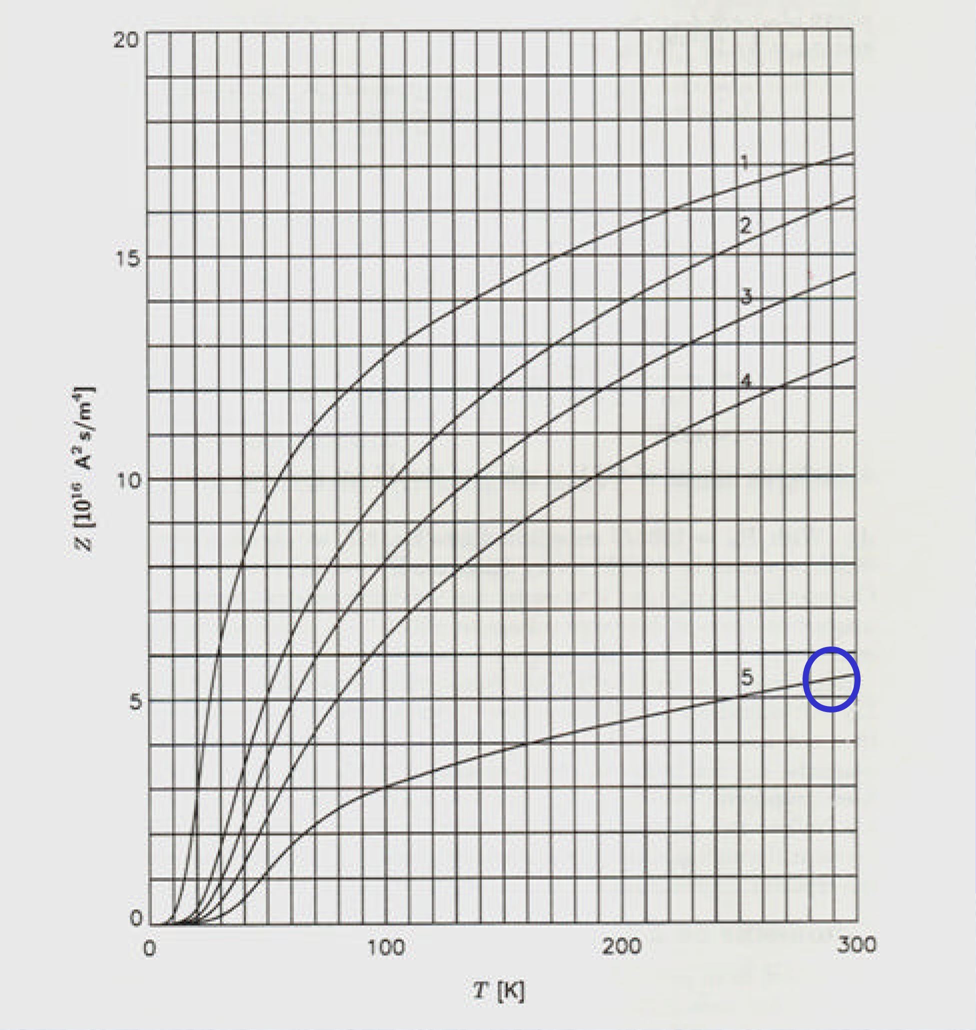
Quench and Protection



In case of Quench a resistance r(t) grows inside the coil. As a Quench Detecting System reveals the normal zone, the power supply is disconnected and the current decays in a close LR circuit.

$$\text{Hot spot}: \; r(t) << R_D \quad \Rightarrow \int_{T_i}^{T_f} \frac{C_p(T)}{\rho_m(T)} dT = Z(T_i, T_f) = \frac{1}{A_m A_t} \frac{I_{op}^2 L_m}{2R_D}$$

A_m = Matrix Cross section A_t = Total Cross section



Z(4.2, Tf): 1) Silver 99.99%; 2 Copper RRR200; 3) Copper RRR100; 4) CopperRRR 50; 5) Aluminium 99.99%

$$Z(T_i, T_f) = \frac{J_{ov}^2}{a}\frac{E}{VI_0} \quad \text{with } a = \frac{A_m}{A_t}$$

Max allowed voltage $V = 1000$ V

$$J_{ov} = \frac{NI_0}{DR\ l} = \frac{42.5\ \text{MAturns}}{3.287\ m^2} = 1.3\,10^7\ \frac{A}{m^2}$$

$$aI_0 = 7300\ A$$

With a =1, no space for structural material;

a ~ 0.33÷0.4 → I_0 18000 ÷22000 A

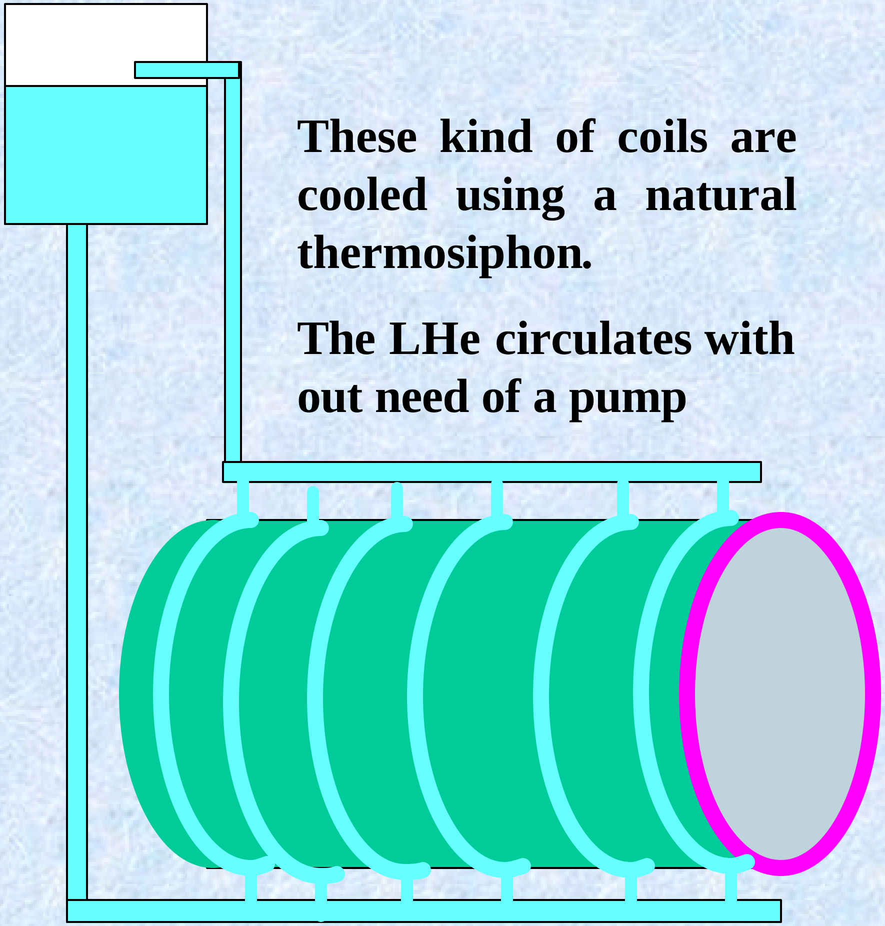
$$J_{ov\,matrix} = \frac{I_0}{A_m} = \frac{20000\ A}{648\ mm^2} \approx 30\ \frac{A}{mm^2}$$

From Design to Construction

For constructing a *thin* solenoid for HEP….

1) Construct the external mandrel

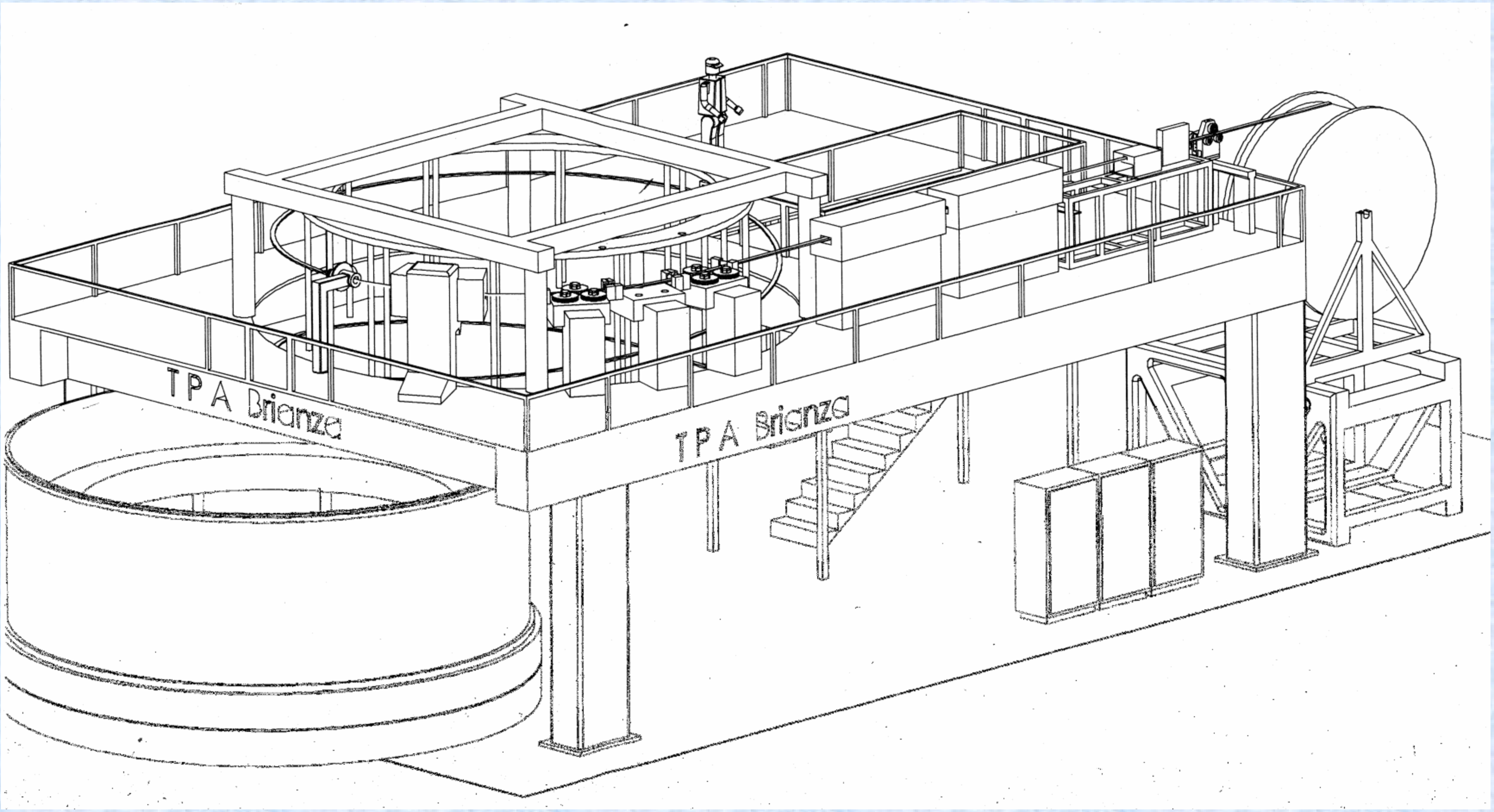
Integrate the cooling circuits to the mandrel



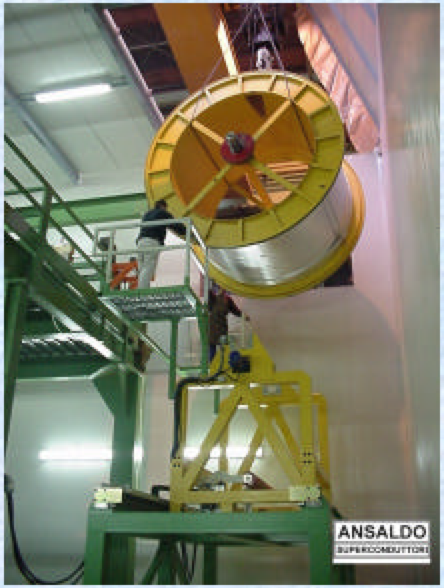
These kind of coils are cooled using a natural thermosiphon.

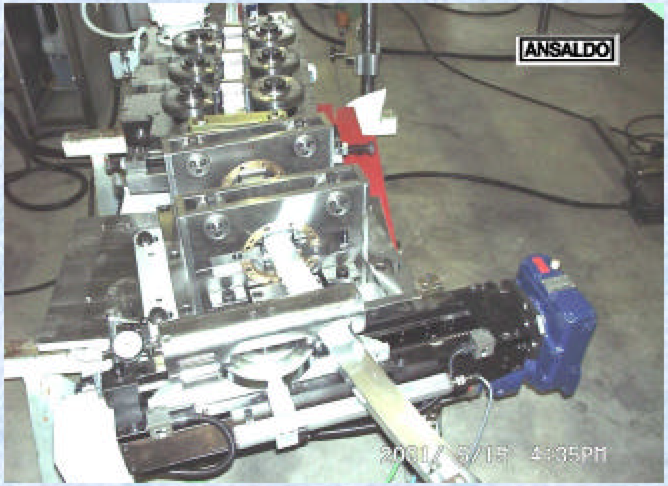
The LHe circulates with out need of a pump

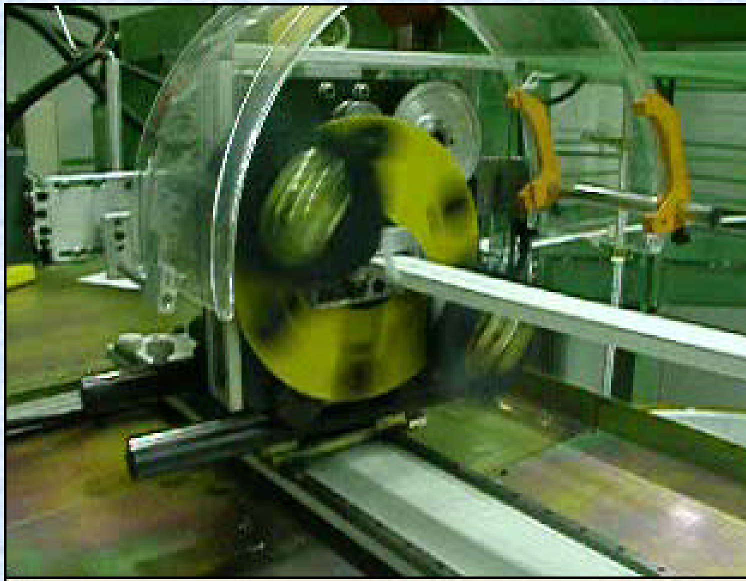
Set-up a suitable winding line… for inner winding technology



Let’s go with winding operation

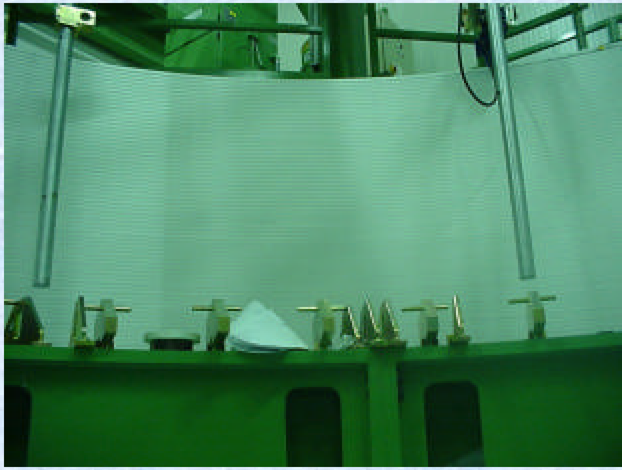






wrapping

bending



Prepare coil for vacuum impregnation with epoxy resin

Put the coil in a large autoclave

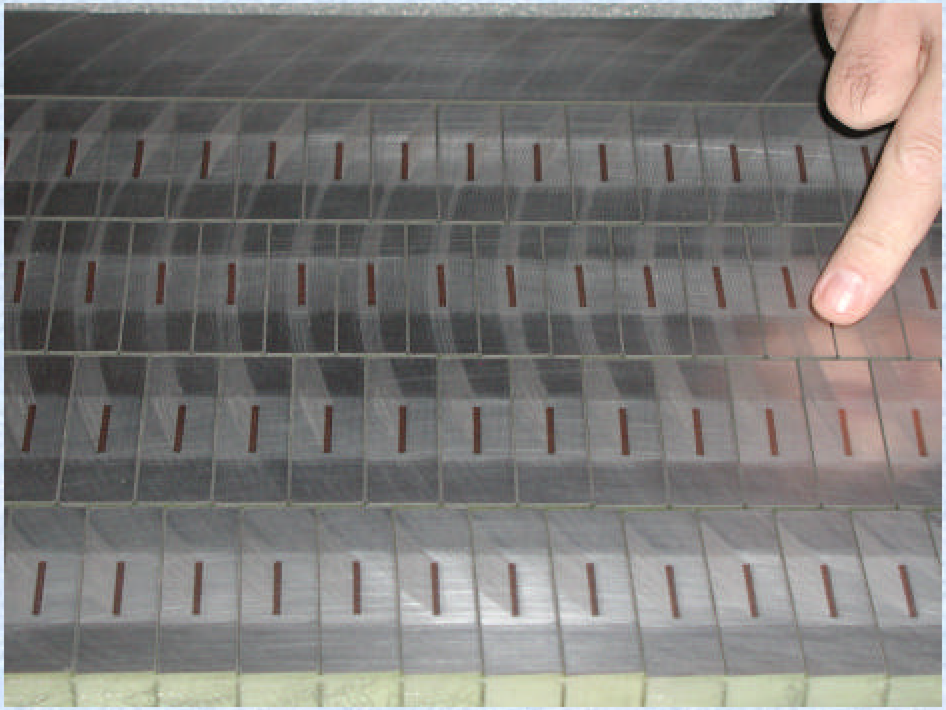
Vacuum impregnation with epoxy resin is one of the most critical aspect of the coil construction. A premture resin polimerization may led to damage irreversibly the coil

Each CM module required 1000 l of resin

Remove impregnation mold, Clean the coil and Perform electrical exits

If the coil is a prototype, then section it to look inside

Check of quality of the winding in terms of axial and radial compactation. Adhesion.



Transport it to the final location. Some times this aspect is not trivial!!


Feb. 2005

The CMS solenoid is presently at this stage of the assembly.

It shall be integrated in the vacuum chamber after mounting the thermal shields.