MAGNETIC FIELD GEOMETRIES

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SUMMARY

- Introduction

  1 - The various field geometries

  2 - Past of the detector magnets

    . the precursors of the 70's

    . the maturity period in the 80's

    . the SSC abortive projects

    . the first toroid (CEBAF)

  3 - The present situation for LHC

  4 - The limitations for the future

    Conclusions

INTRODUCTION

- Magnets were, are, and will be used in most of the detectors for colliders

- Various magnetic field configurations have been used, producing dipolar, solenoidal or toroidal field

- The size of the detector increases with the size of the collider, and so for the magnet, which is more often a superconducting one

- LHC detector magnets are a big step from LEP detector magnets

- Can the present technical limitations can be pushed further ?

1 - The various field geometries

Why to use a magnetic field in a detector ?

- For a particule of charge q in a constant magnetic field B over a length L :

. Momentum $p = mv = q \rho B$ (ρ = bending radius)

. Deflection over L $\Phi = L / \rho$

. Sagitta $s \sim q BL^2 / 8 p$

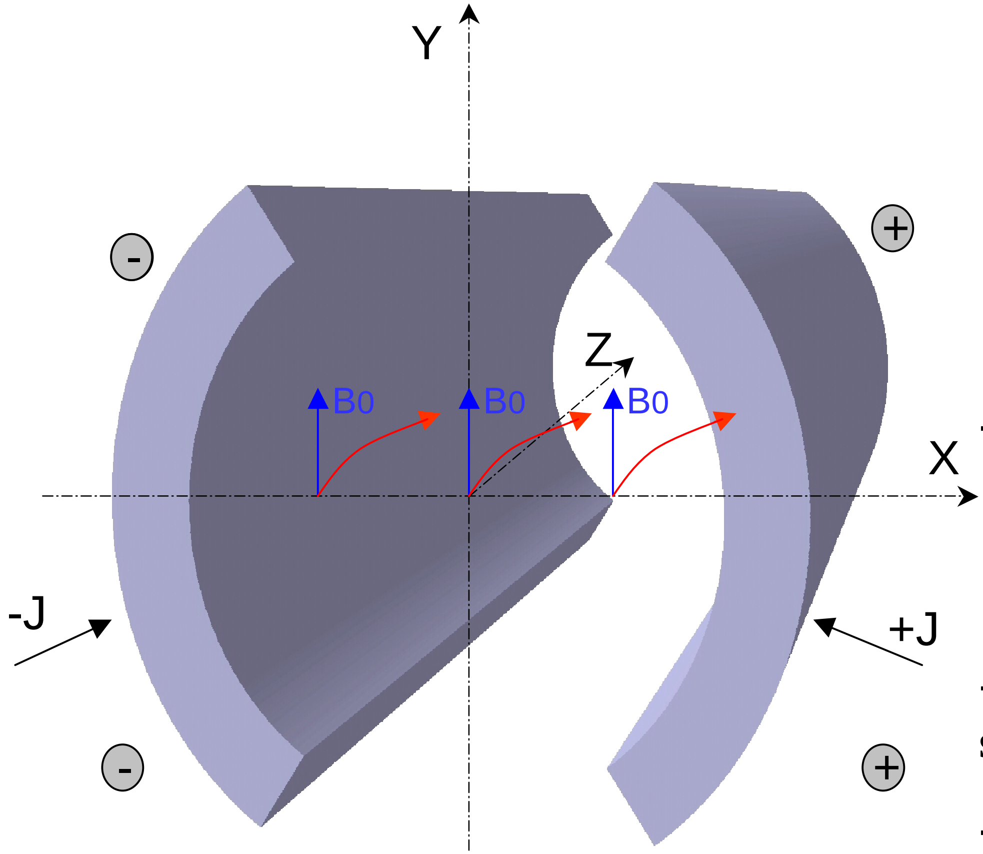
- Three main magnetic configurations can be used :

. Dipoles

. Solenoids (thick or thin)

. Toroids

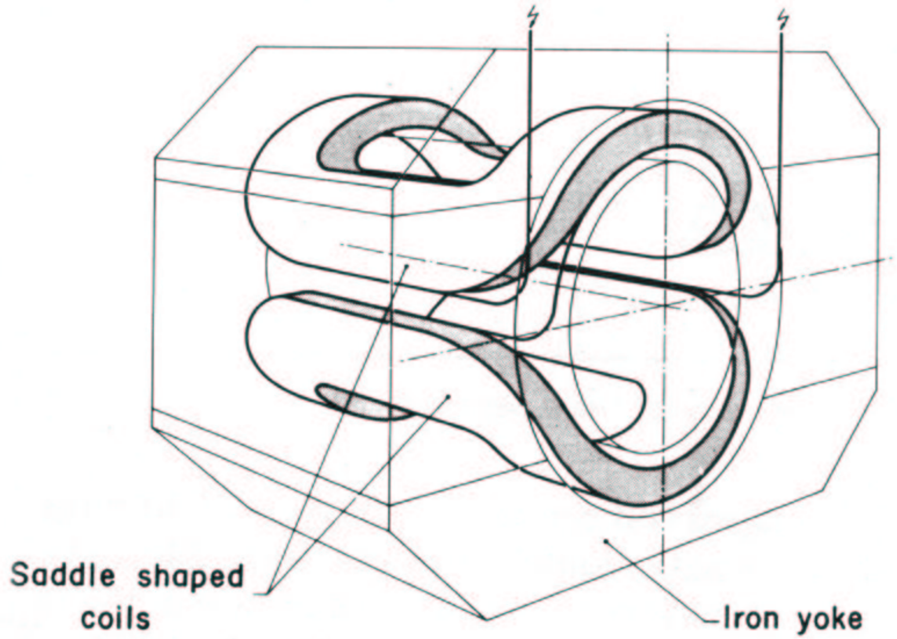
DIPOLE FIELDS

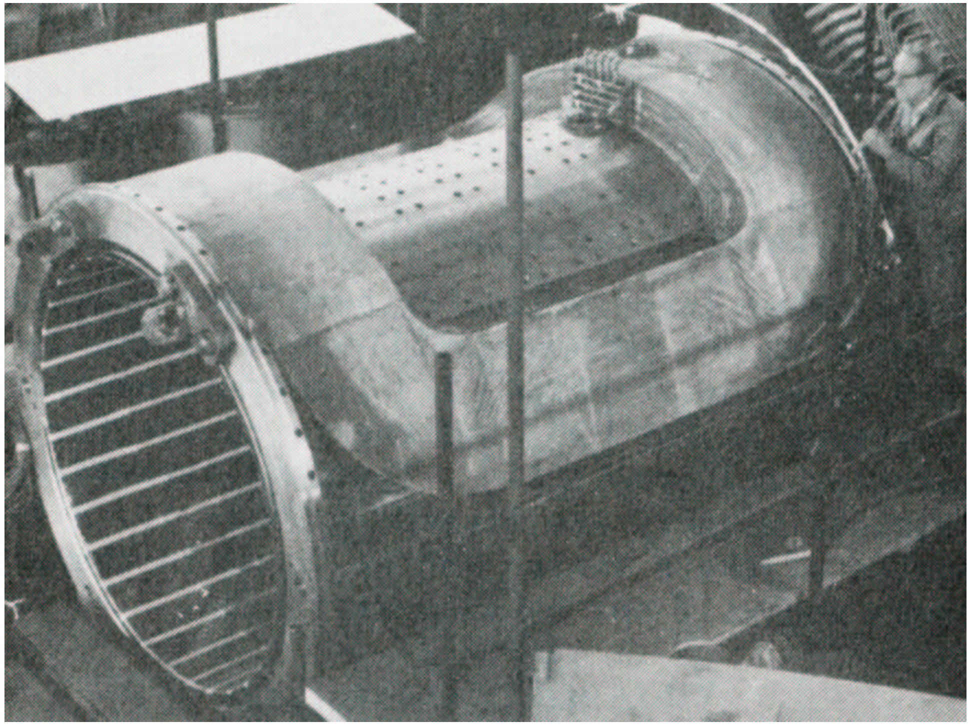


Bx = 0
By = B_0

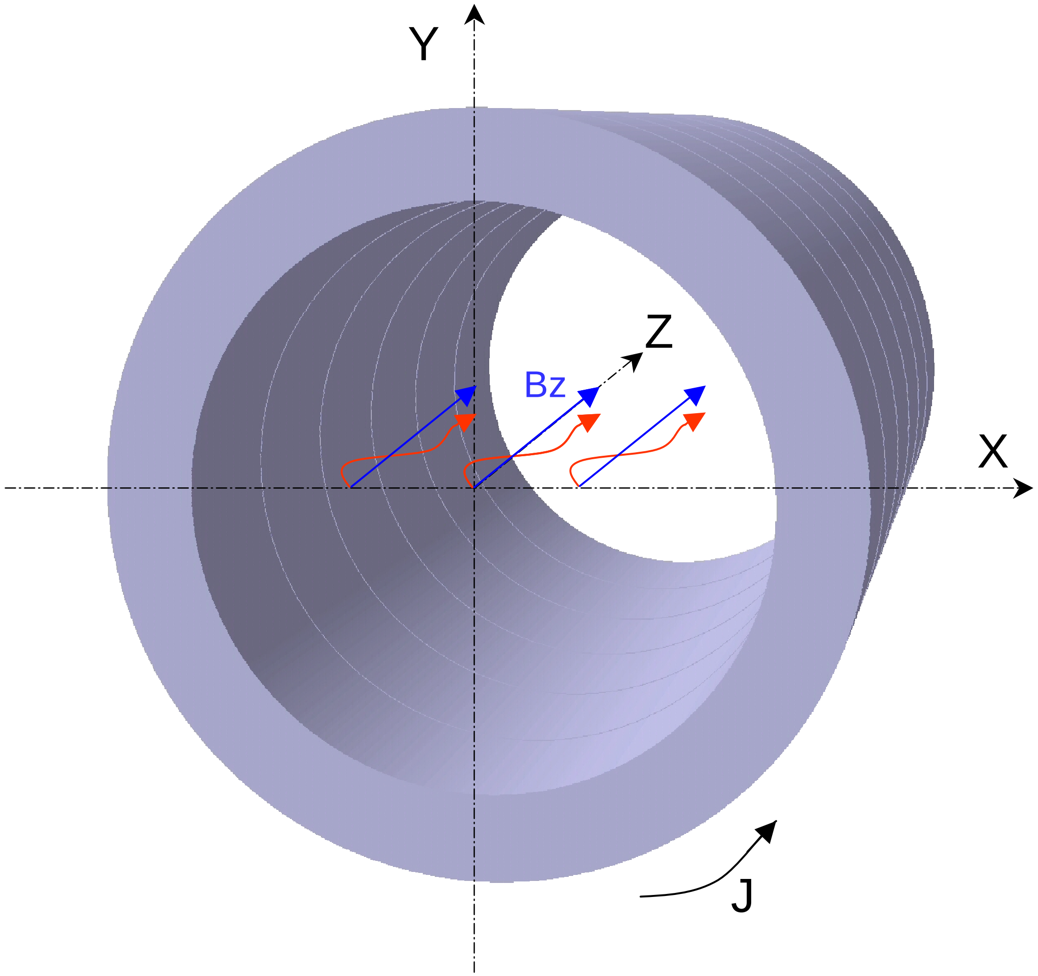
- **Uniform field perpendicular to the beam axis**
  - **. Large split-coil iron-core magnets**
  - **. Saddle-shape magnets**
- **Maximum efficiency for particules emitted at small angles**
- **Large interaction forces between coil and iron**

SADDLE SHAPED COILS





SOLENOID FIELD



$Bx = 0$
$By = 0$
$Bz = B_0$

- Constant axial field ⇒ helical motion of the particules

- Very good momentum resolution at large angle

- The most widely used structure (compact, efficient)

- Thin solenoid concept

TOROIDS

- Main advantages

  . no field along the axis

  . magnetic field always transversal to the particule momentum

  . no (or low) fringing field outside the toroid

  . an open mechanical structure

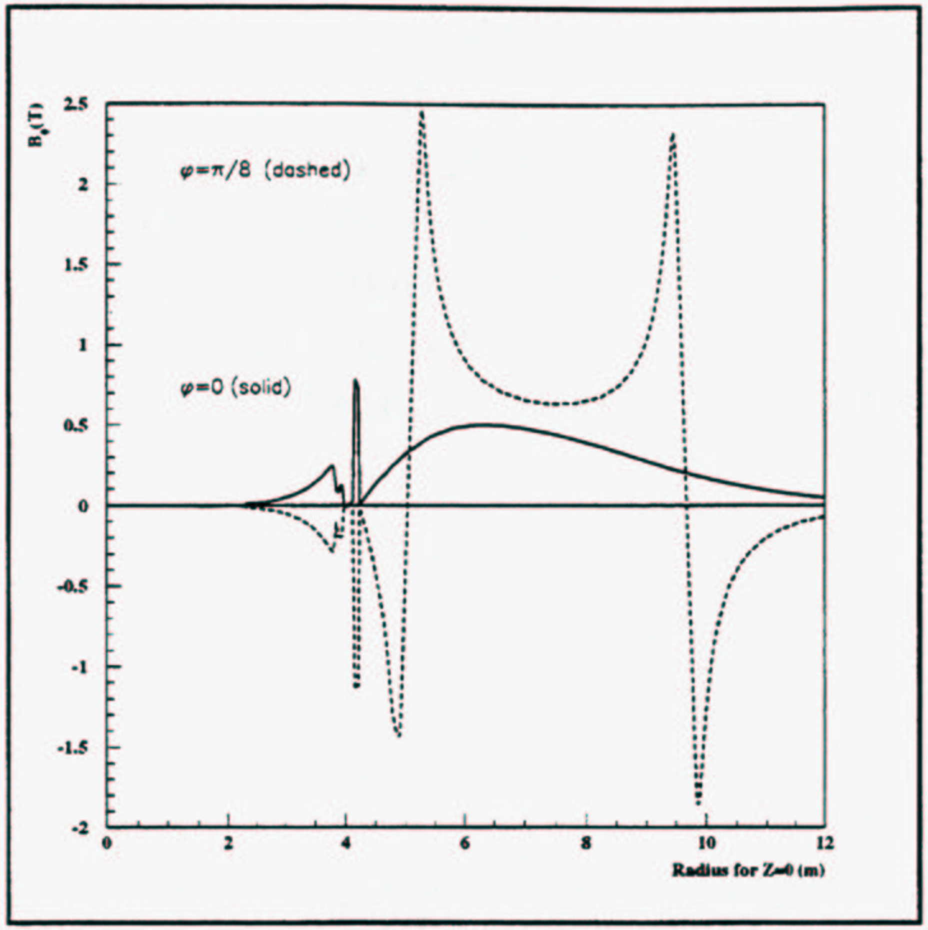
  . the best momentum resolution at low angle

- But

  . very inhomogeneous magnetic field

  . maximum field on the coil much higher than the useful field

TOROIDAL FIELD



From ATLAS Barrel Toroid TDR

ADVANTAGES/INCONVENIENTS OF EACH CONFIGURATION

- The three magnetic configurations will be used on LHC
  - . ALICE : conventional Al solenoid (L3) + conv. Al dipole
  - . ATLAS : thin SC solenoid + SC barrel toroid + SC end cap toroids
  - . CMS : SC thick solenoid
  - . LHC-b : conventional Al dipole

- There is clearly not a best solution
- All configurations have advantages and inconvenients
- Main design goals of the detector and performances of the other sub-detectors must be taken into account when choosing the magnet configuration

COMPARISON OF SPECTOMETER CONCEPTS

(from CEBAF Hall B CDR)

	Solenoid	Dipole	Toroid
θ-range	+	+	++
Φ-range	+++	- -	-
Momentum range	++	++	++
Momentum resolution			
small θ, high p	--	++	++
large θ, low p	++	++	++
Particle identification	+	++	++
Maximum luminosity	++	-	++
Polarized target operation	- -	-	++
Open structure for neutron ToF	- -	+	++
Simple trajectory reconstruction	++	-	-

2 - Past of the detector magnets

. the precursors of the 70's

THE PRECURSORS OF THE 70'S

	Omega	Pluto	Cello	TPC
Designer (operation)	CERN (1970)	DESY (1972)	Saclay (1979)	LBL (1980)
Type	Split SC coil + iron core	SC thick solen.	SC thin solen.	SC thin solen.
Field (T)	1.8	2.0	1.5	1.5
Warm diam. (m)	1.5 (gap between coils)	1.4	1.5	2.0
Length (m)	3 (pole diameter)	1.15	3.5	3.4
Stored energy (MJ)	50	4	7	11
Rad. Thickness (Xo)	-	4	0.5	0.4
	Hollow conductor	1st SC solen. for colliders	Indirect cooling	Inductive compling

OMEGA MAGNET

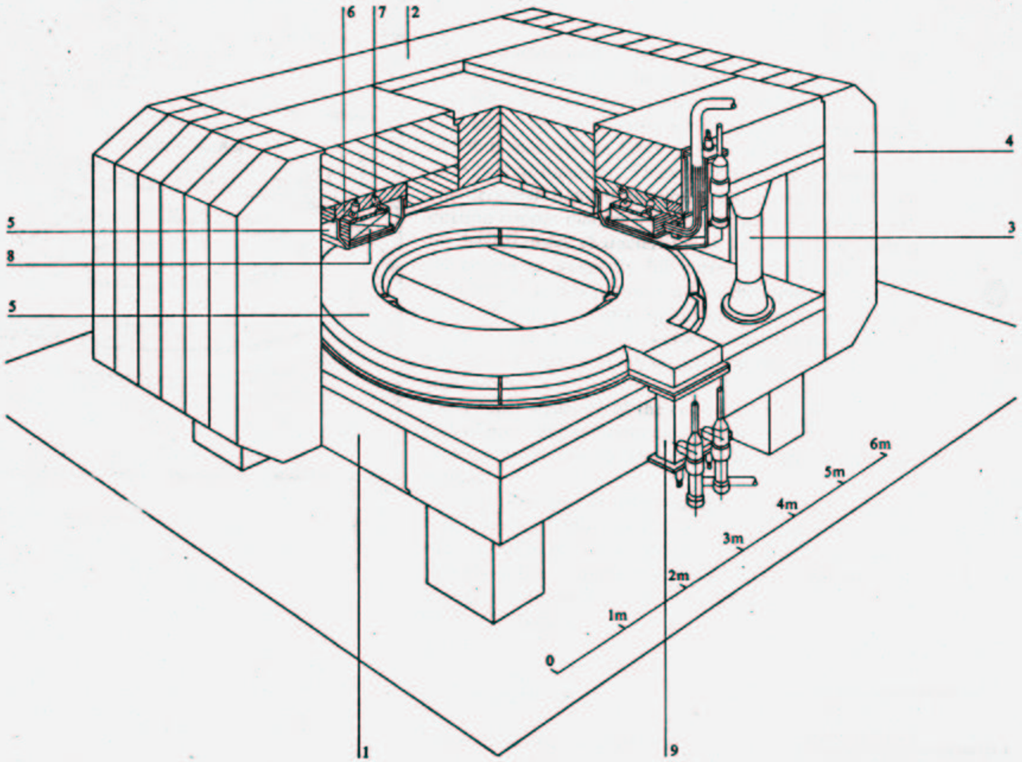
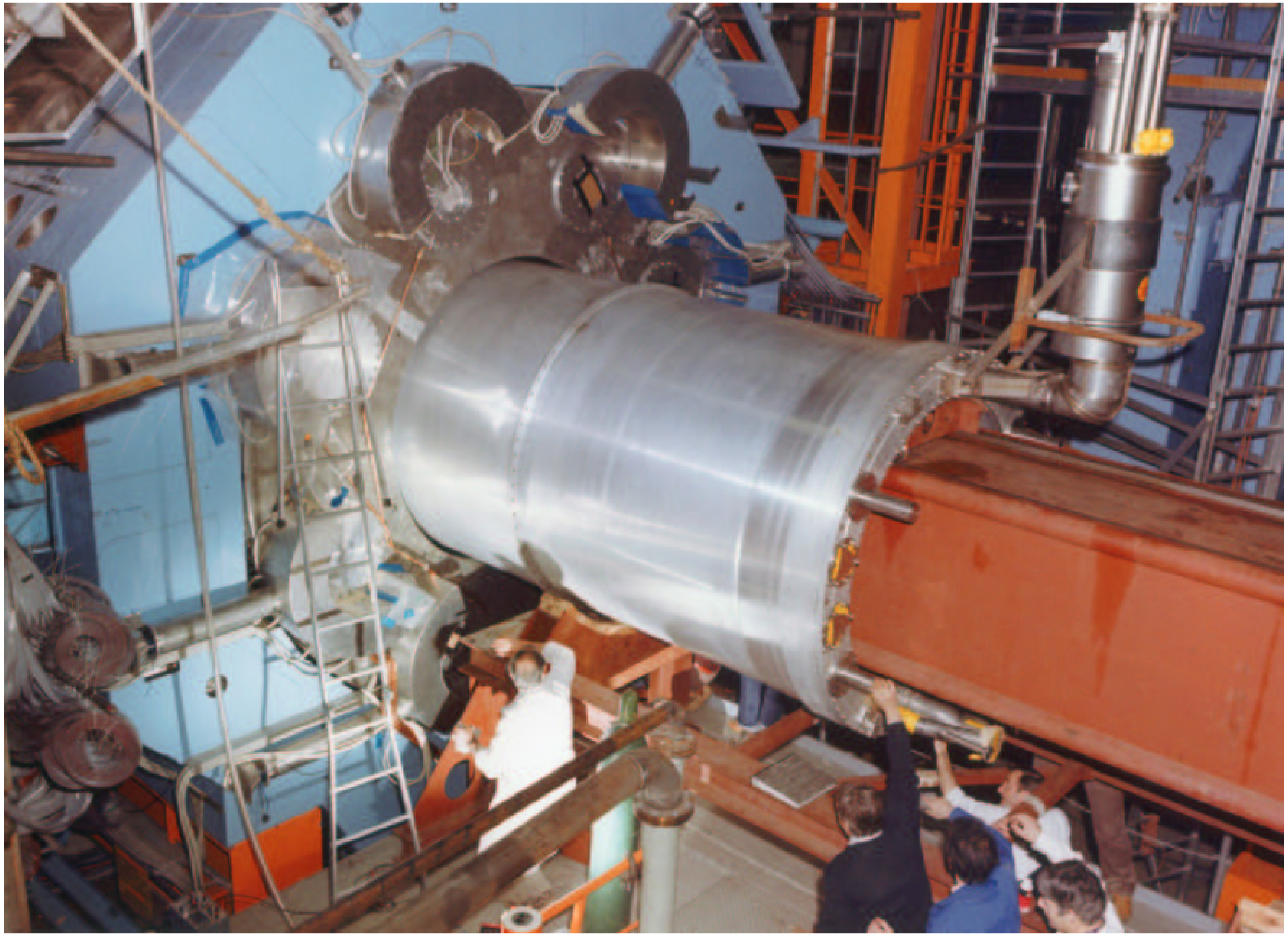


Fig. 1 - Cut-away view of the 'Omega' magnet

1 = Lower yoke
2 = Upper yoke
3 = Support column
4 = Return yoke sections (for separate removal)
5 = Vacuum tank (antimagnetic steel)
6 = Yoke ring
7 = Coil support elements
8 = Superconducting energizing coil
9 = Current leads and coolant leads

CELLO MAGNET



CONCEPT OF THIN SOLENOIDS

For minimizing the amount of matter in the coil and its cryostat :

. subtitution for low mass materials (Al instead of Cu and S.S)

. increase of Jc in the superconductor (no more adiabatic stability)

. indirect cooling by external pipes

. intrinsic protection (Al shunts, quench back tube) for quasi-uniform distribution of the strored energy in case of quench

2 - Past of the detector magnets

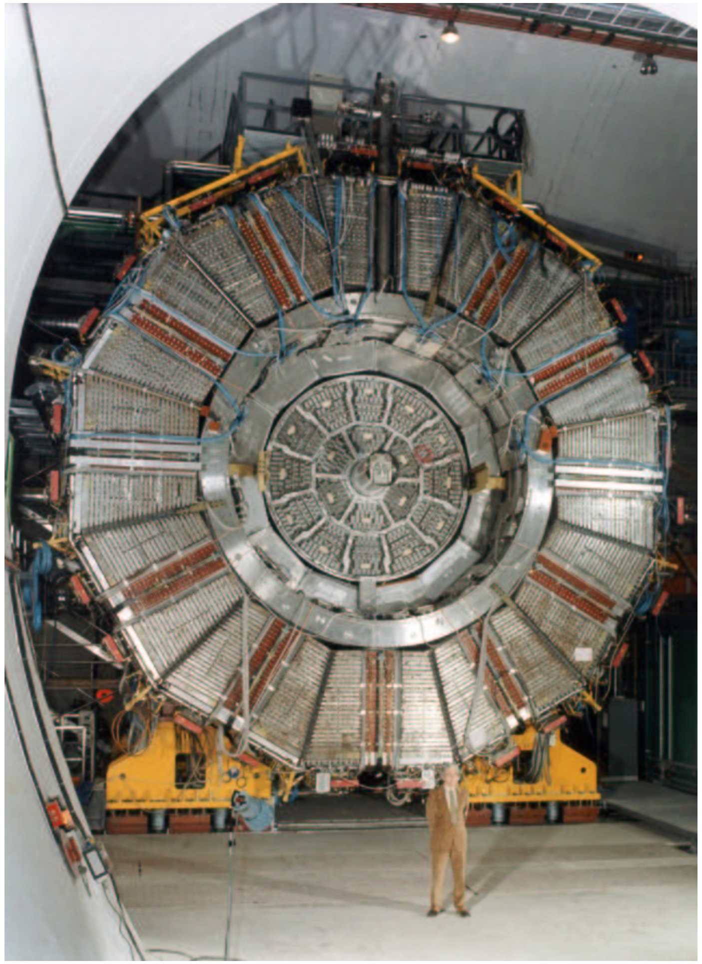
. the maturity period in the 80’s (Tristan, LEP, Teslatron)

THE MATURITY PERIOD OF THE 80'S

	TOPAZ	ALEPH	L3
Designer (operation)	KEK (1984)	Saclay (1987)	CERN (1987)
Type	SC thin solenoid	SC thin solenoid	Conv. Dip. (Al cond.)
Field (T)	1.2	1.5	0.5
Warm diam. (m)	2.7	5	11.9
Length (m)	5	6.35	11.9
Stored energy (MJ)	20	137	150
Radiation thickness (Xo)	0.7	2.0	-
	First inner winding	The largest SC magnet (with DELPHI)	The whole detector is inside the magnet On site assembly.

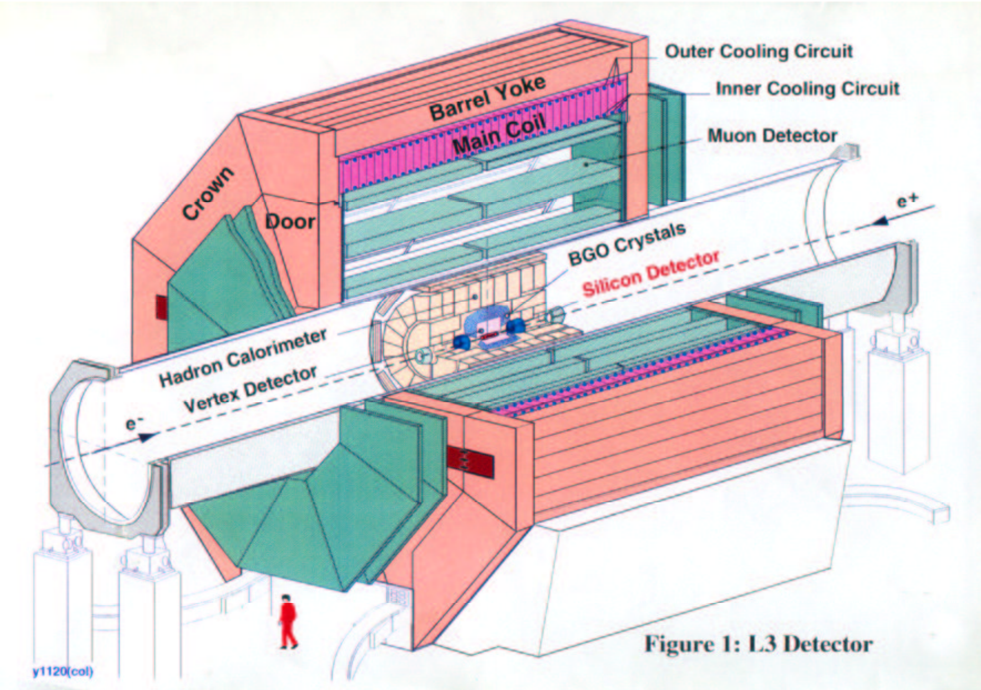
ALEPH SOLENOID

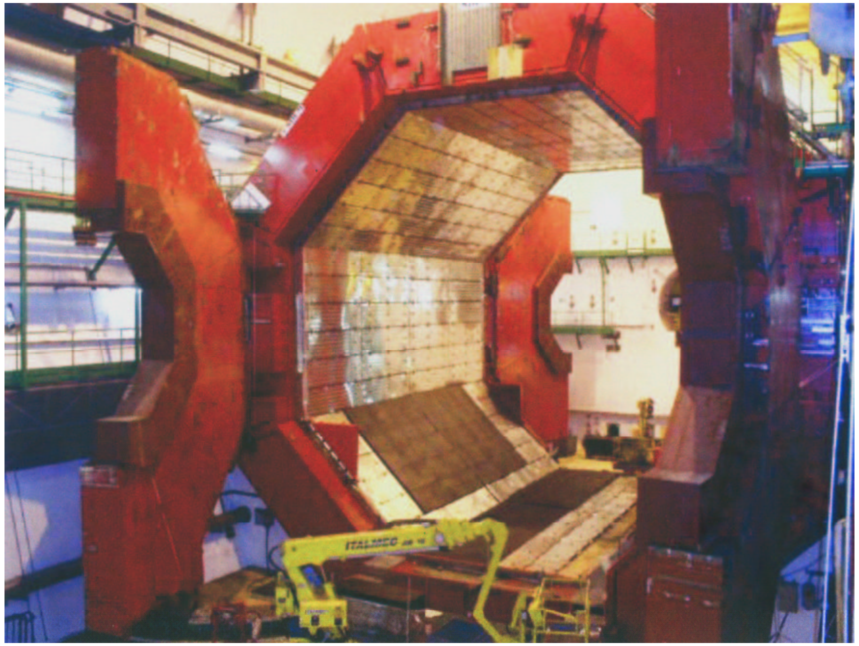
The coil alone (Saclay)



The coil inside the detector (CERN)

L3 MAGNET





L3 detector

Construction phase

THE MATURITY PERIOD OF THE 80'S

This is the « golden age » for the developments of thin solenoids (KEK/Tristan, CERN/LHC, FNAL/Tevatron)

Main progress in the technology

. internal winding technique

. large aluminium stabilized conductor

. extensive use of Al for the cryostat

For conventional magnets, the L3 concept is to include the whole detector inside the magnet. Its huge dimensions required special methods of construction, in particular on-site assembly.

2 - Past of the detector magnets

. the SSC abortive projects

- Although the SSC detector magnets were only built on paper, the solutions which were foreseen are interested enough to be recalled

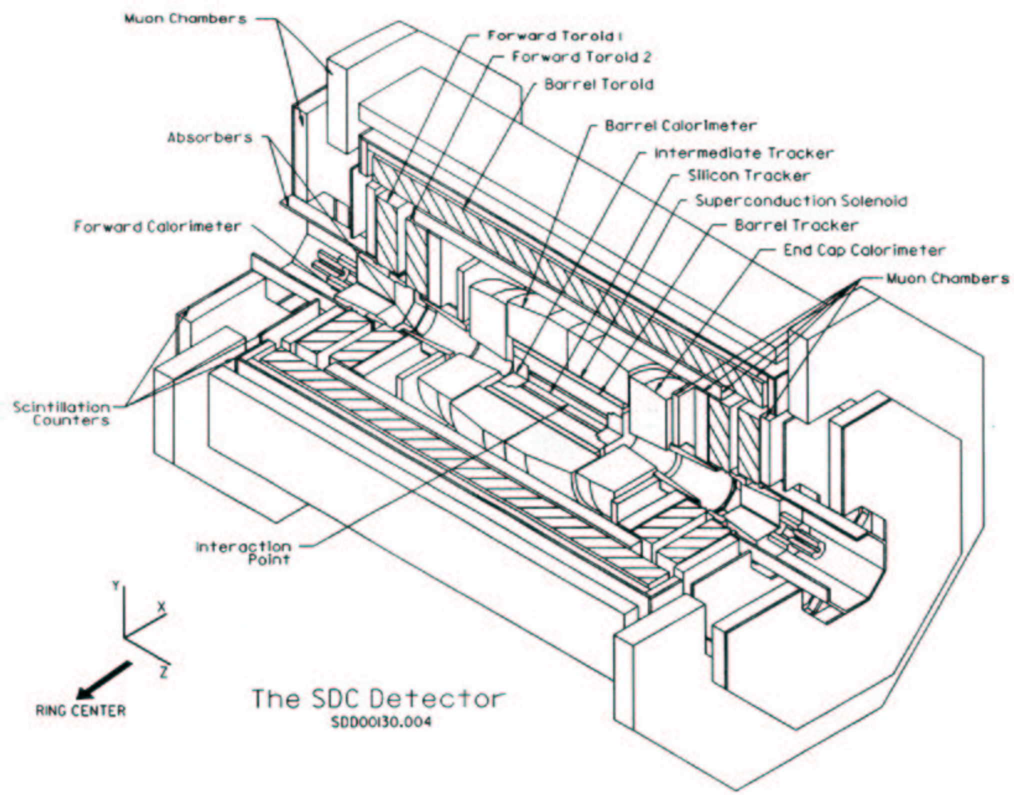
- Two detectors were proposed for the SSC 20 x 20 TeV pp collider

. SDC : thin central SC solenoid + outer conventional toroid

. GEM : huge SC solenoid, covering the whole detector

- A challenging proposal was also made for a 6 T compact (∅ 2 m x L 2.5 m) and thin (1.8 radiation length) solenoid

THE SDC DETECTOR



SC solenoid

Field 2T

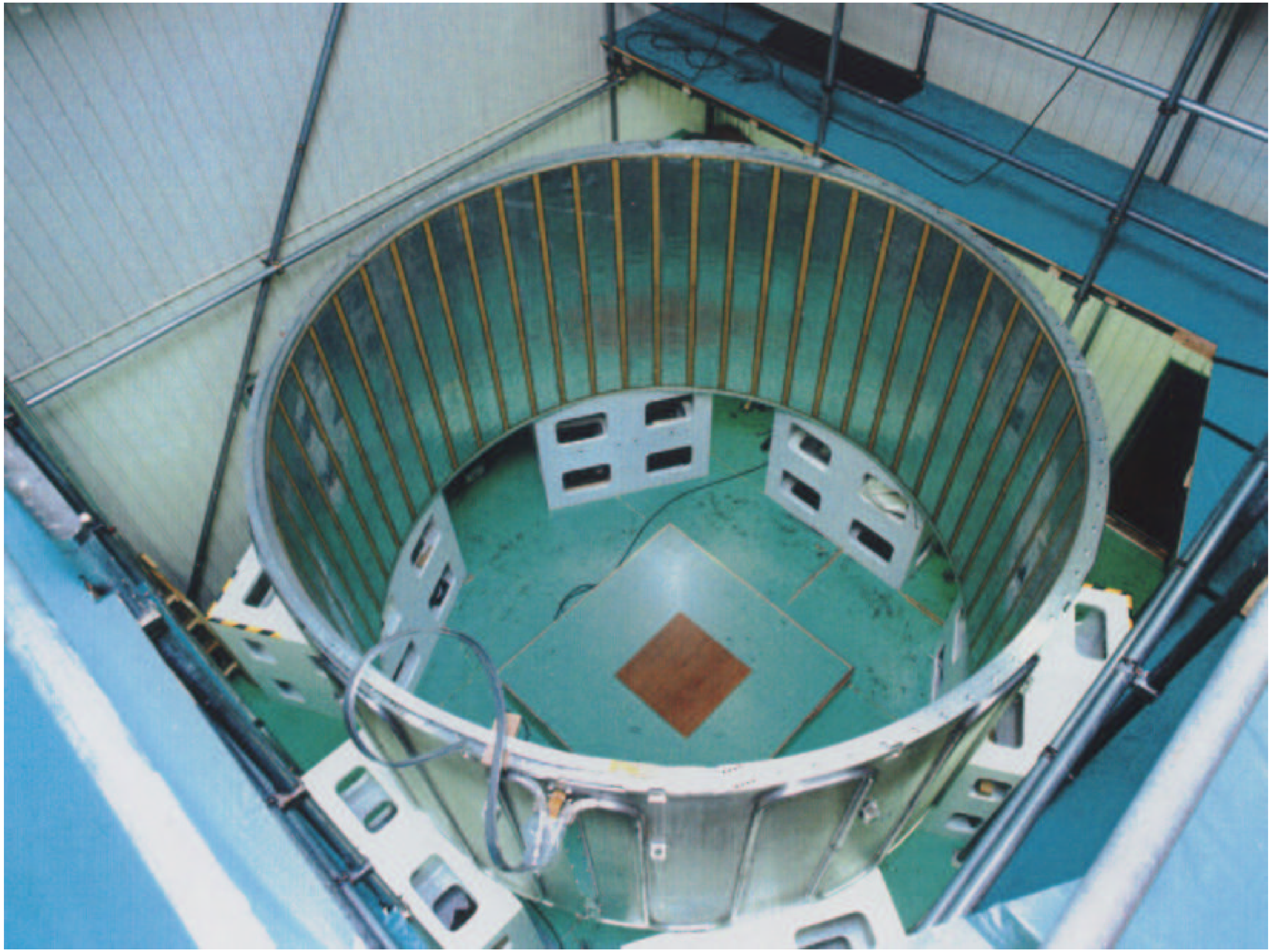
∅ warm 3.4 m

Length 8.8 m

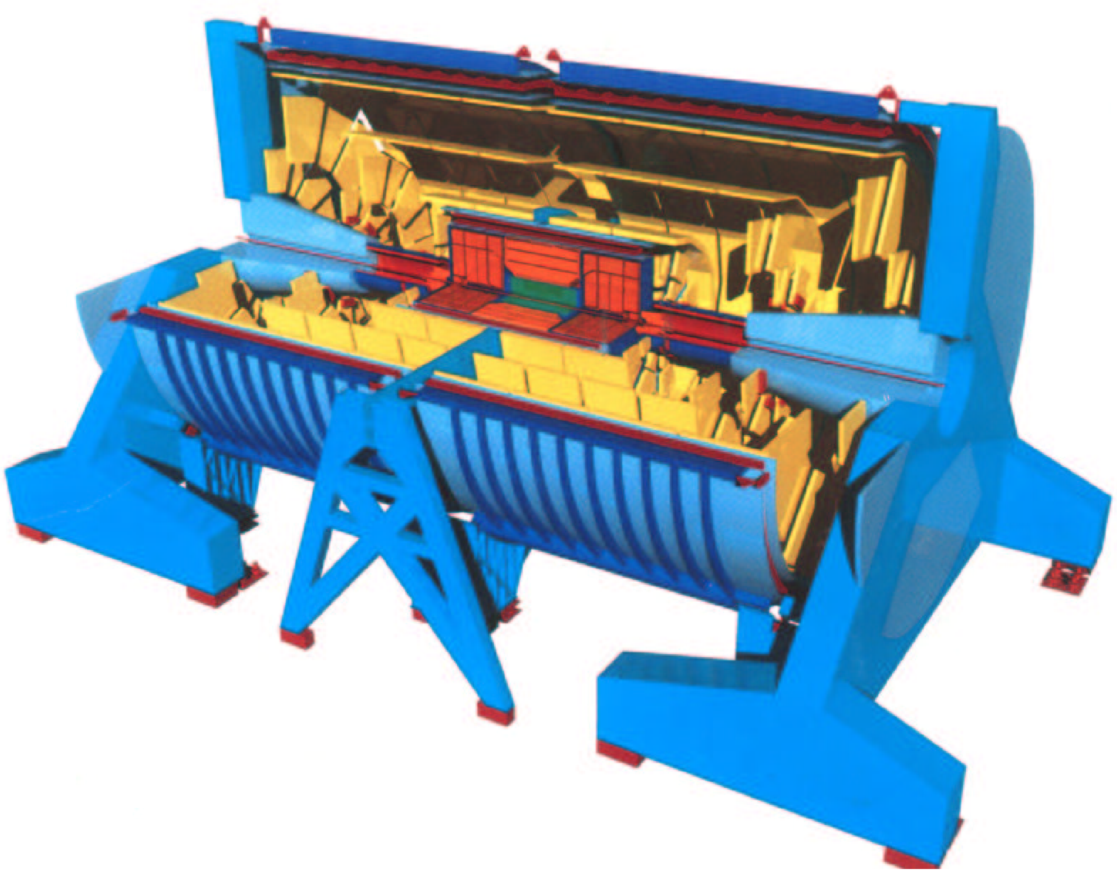
Stored energy 146 MJ

radiation thickness 1.2 Xo

THE SDC PROTOTYPE COIL



THE GEM DETECTOR



SC solenoid

Field 0.8 T

Warm ∅ 18 m

Length 31 m

Stored energy 3100 MJ

Cable in conduit

No yoke

On site fabrication

2 - Past of the detector magnets

. the first toroid (CEBAF)

CEBAF TOROID

It is worth mentioning the first use of a toroidal detector magnet at CEBAF/CLAS in 1995

. 6-coil toroid

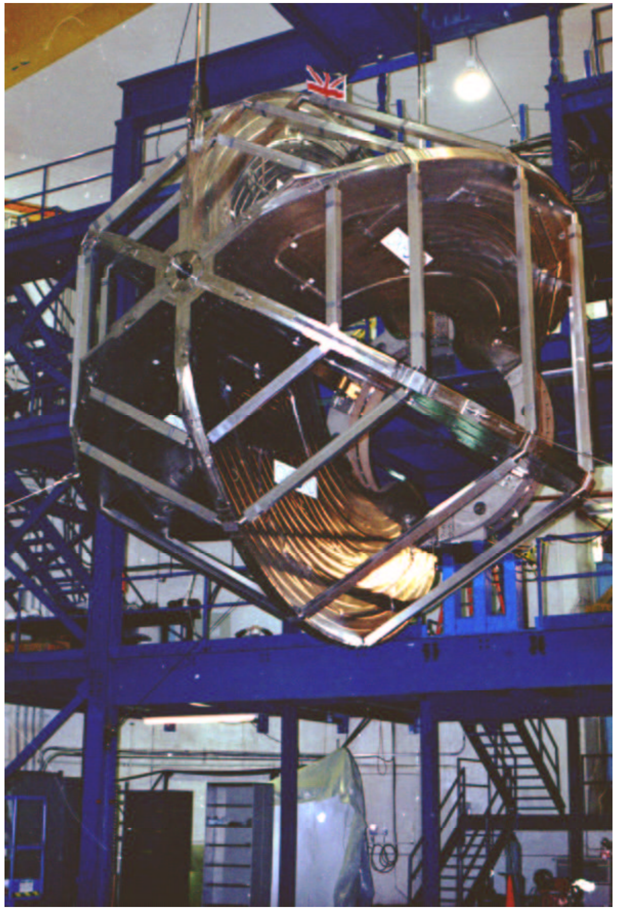
. Dimension of each coil

~ 4.7 x 2.7 m

. Maximum useful field 2.0 T

. Peak field at conductor 3.5 T

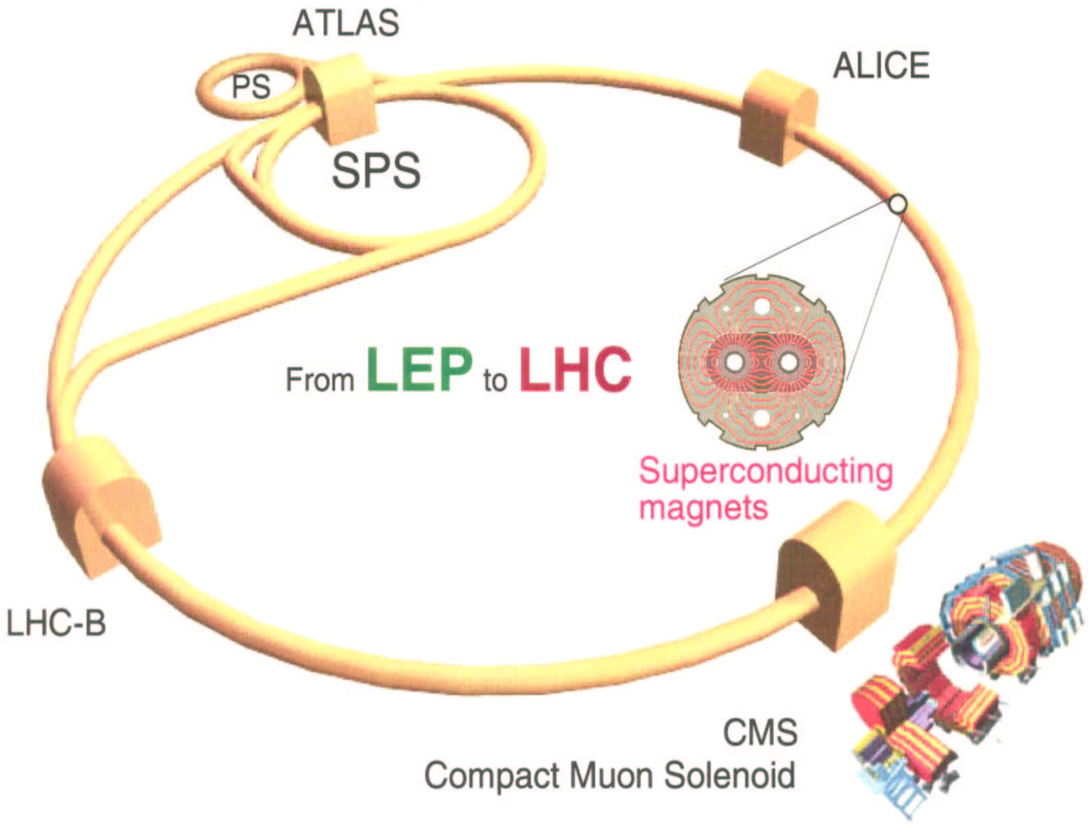
. Stored energy 18 MJ



Courtesy A. Daël

3 - The present situation for LHC

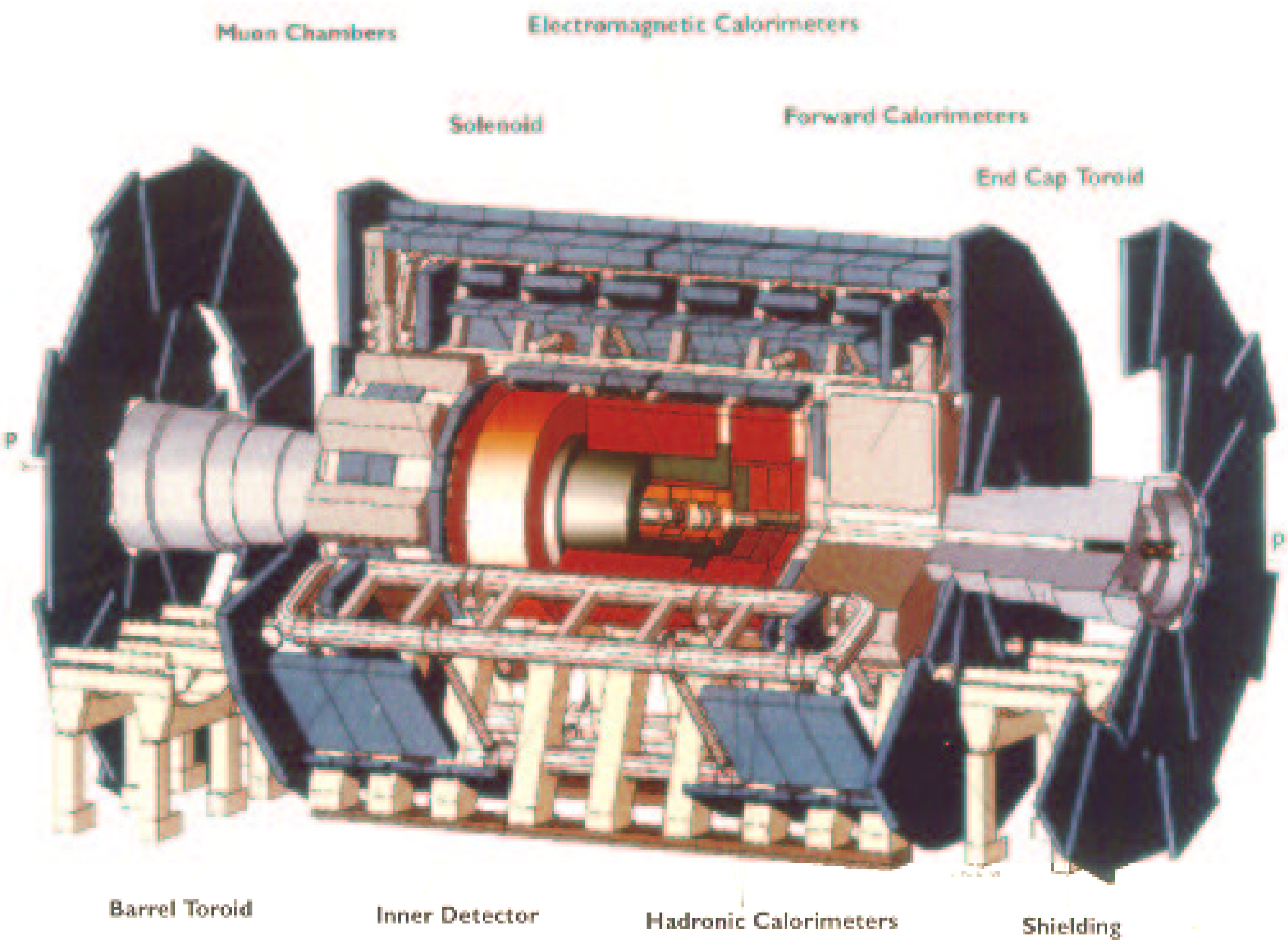
The Large Hadron Collider (LHC)



SC DETECTOR MAGNETS FOR LHC

- Several SC magnets with different structure
  - . ATLAS (thin solenoid + Barrel toroid + End-cap toroids)
  - . CMS (solenoid)
- Common points
  - . large international collaboration
  - . large involvement of the industrial firms
  - . size and requested performances never realized before
  - . similar technical choices (conductor, winding, cooling)
- And also some differences, mainly the strategy for assembly and tests
  - . ATLAS : partial tests in surface, assembly and final test in cavern
  - . CMS : assembly and test in surface before transfer to the cavern

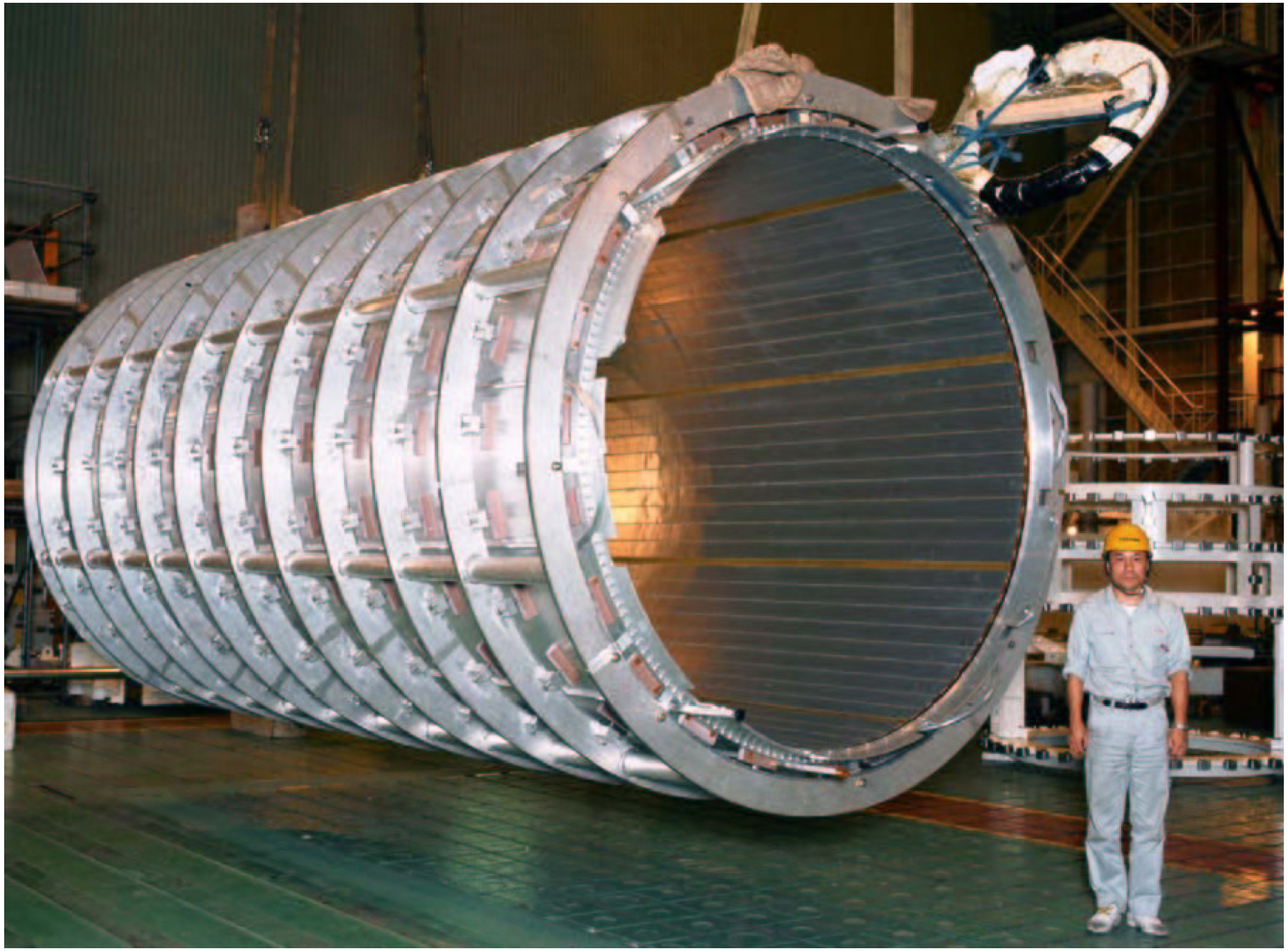
ATLAS DETECTOR



ATLAS MAGNET

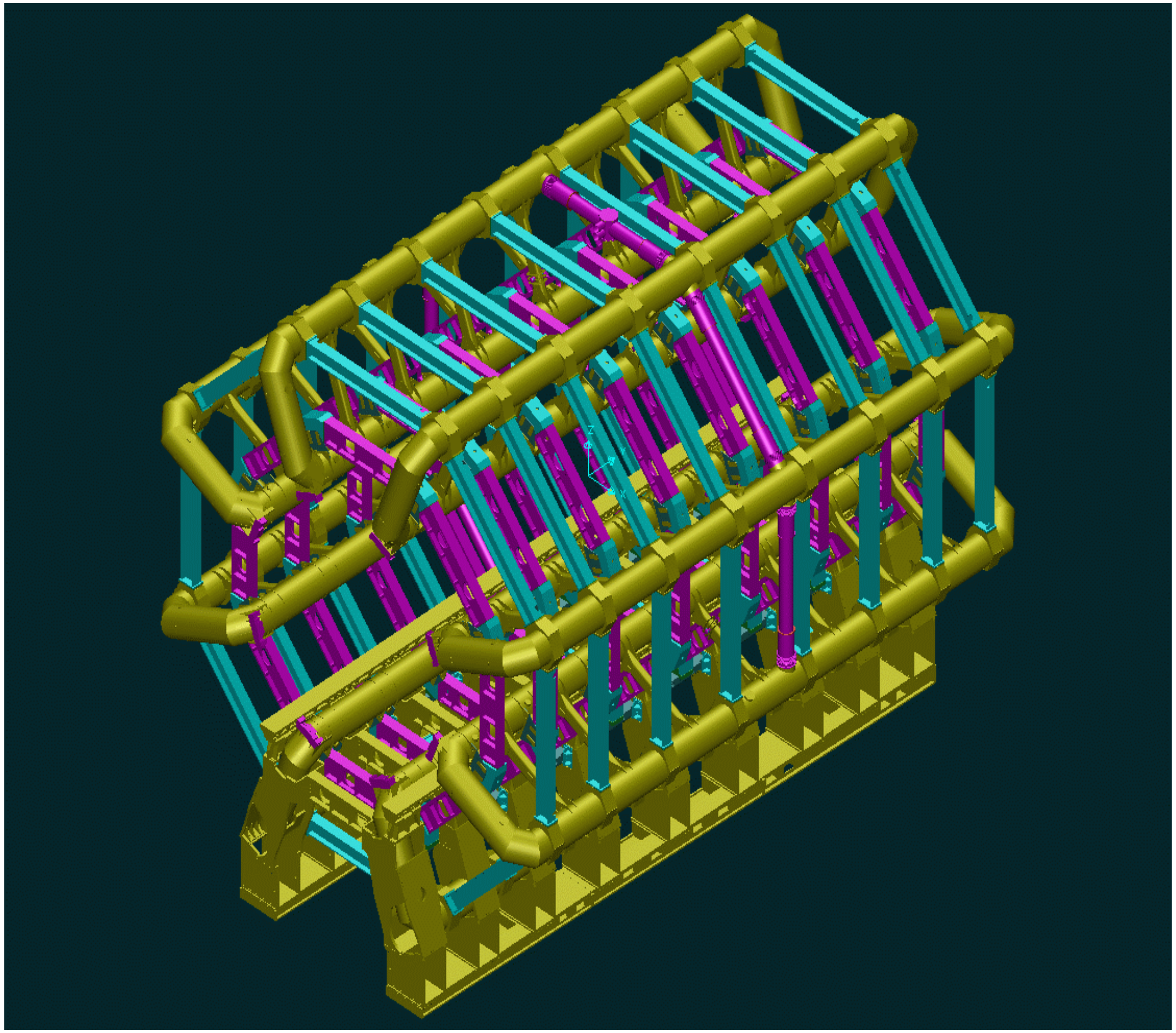
	CENTRAL SOLENOID	BARREL TOROID	END-CAP TOROID
Warm bore diam (m)	2.37	-	-
Inner diameter (m)	2.46	9.4	1.65
Outer diameter (m)	2.63	20.1	10.7
Axial length (m)	5.3	25.3	5
Number of coils	1	8	2 x 8
Total cold mass (t)	5.4	370	2 x 160
Rad. thickness (Xo)	0.66	-	-
Central field (T)	2	~ 1	~ 1
Peak field (T)	2.6	3.9	4.1
Current (kA)	0.76	20	20
Stored energy (GJ)	0.04	1.08	2 x 0.25

ATLAS SOLENOID

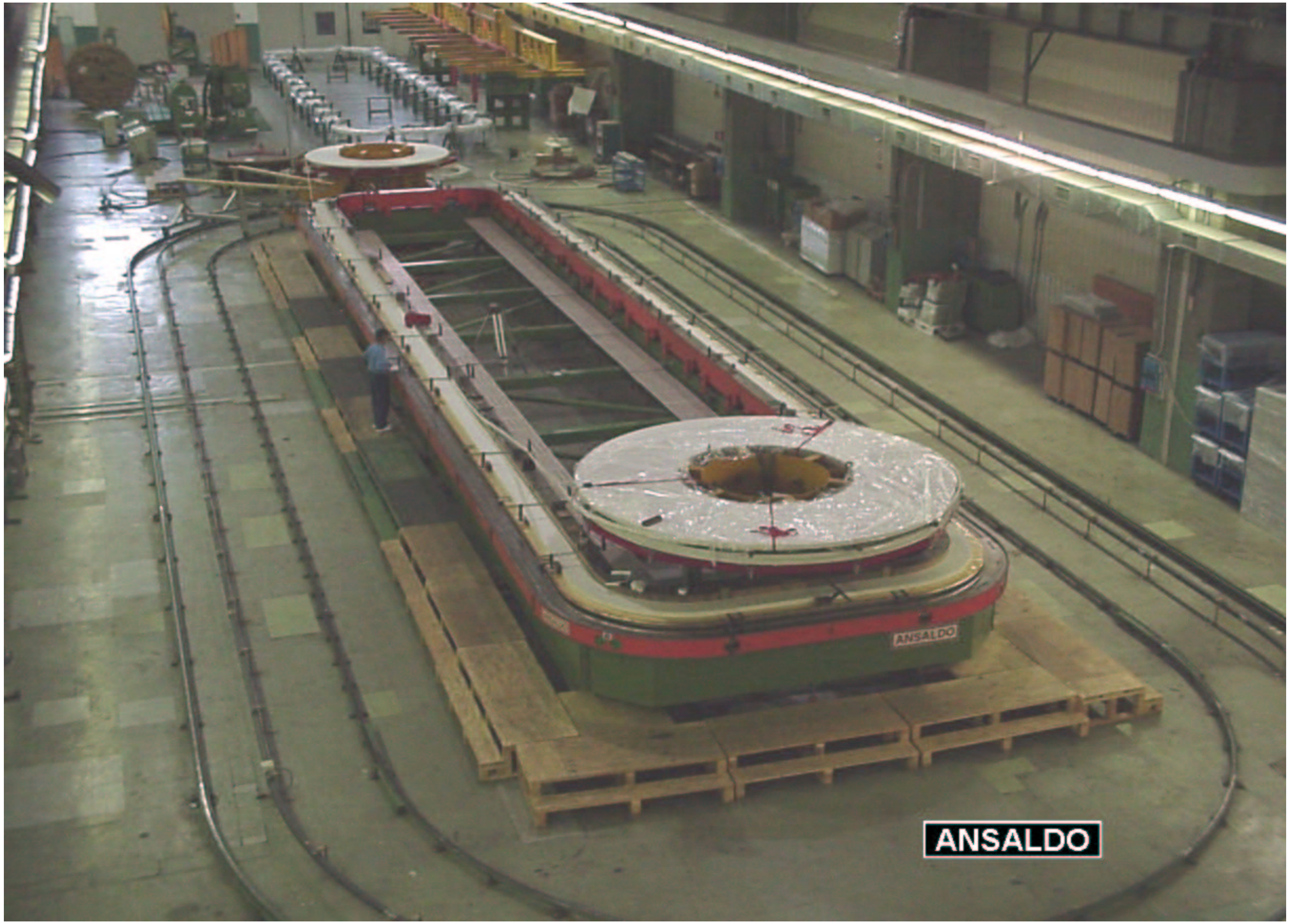


Courtesy A. Yamamoto

ATLAS BT TOROID



ATLAS BT WINDING



ATLAS BT DOUBLE PANCAKE

BT COIL ASSEMBLY AT CERN (1)

BT COIL ASSEMBLY AT CERN (2)

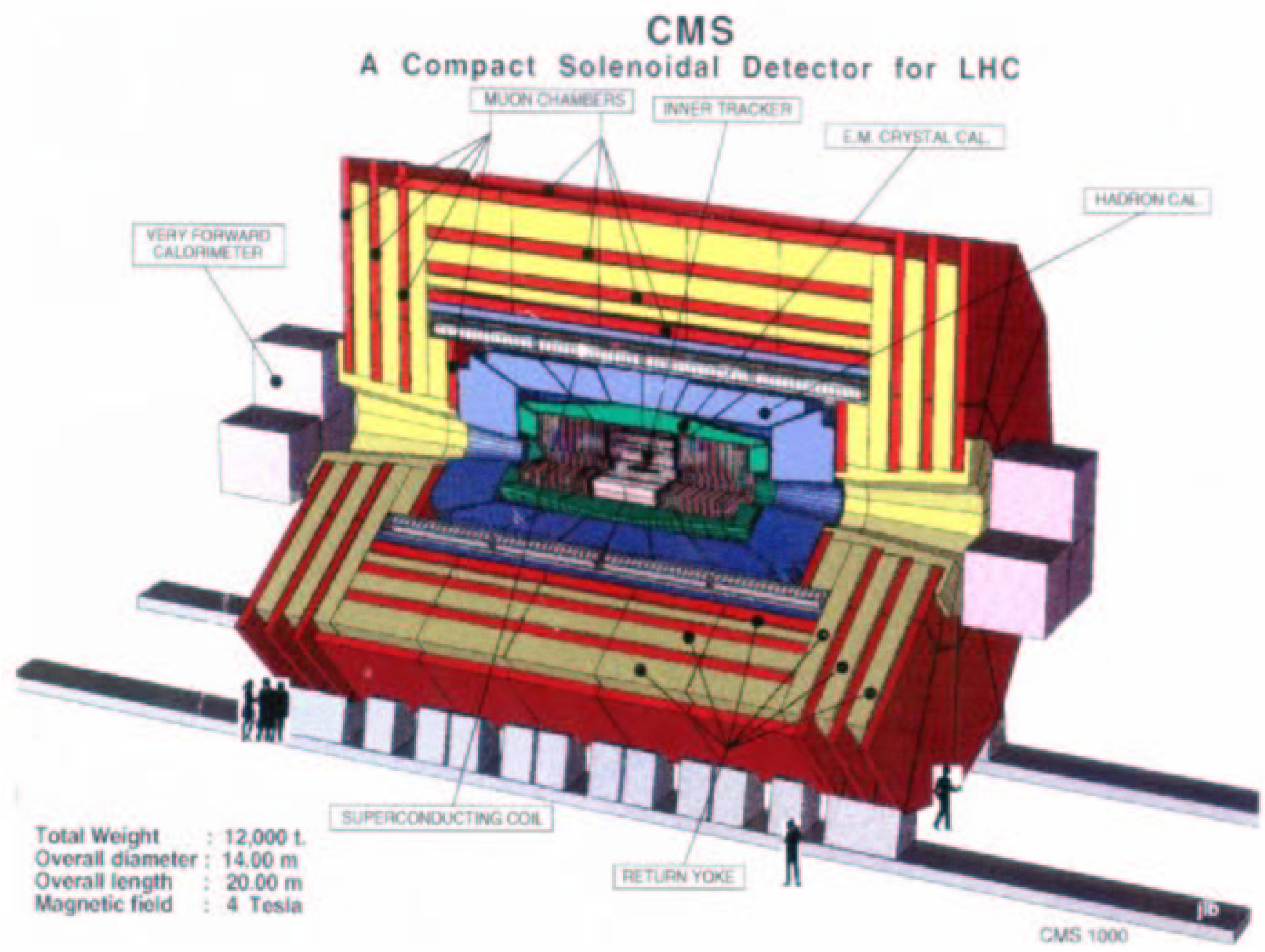
SURFACE TEST OF THE ATLAS BO COIL

Each ATLAS BT coil will be separatly tested in the surface hall

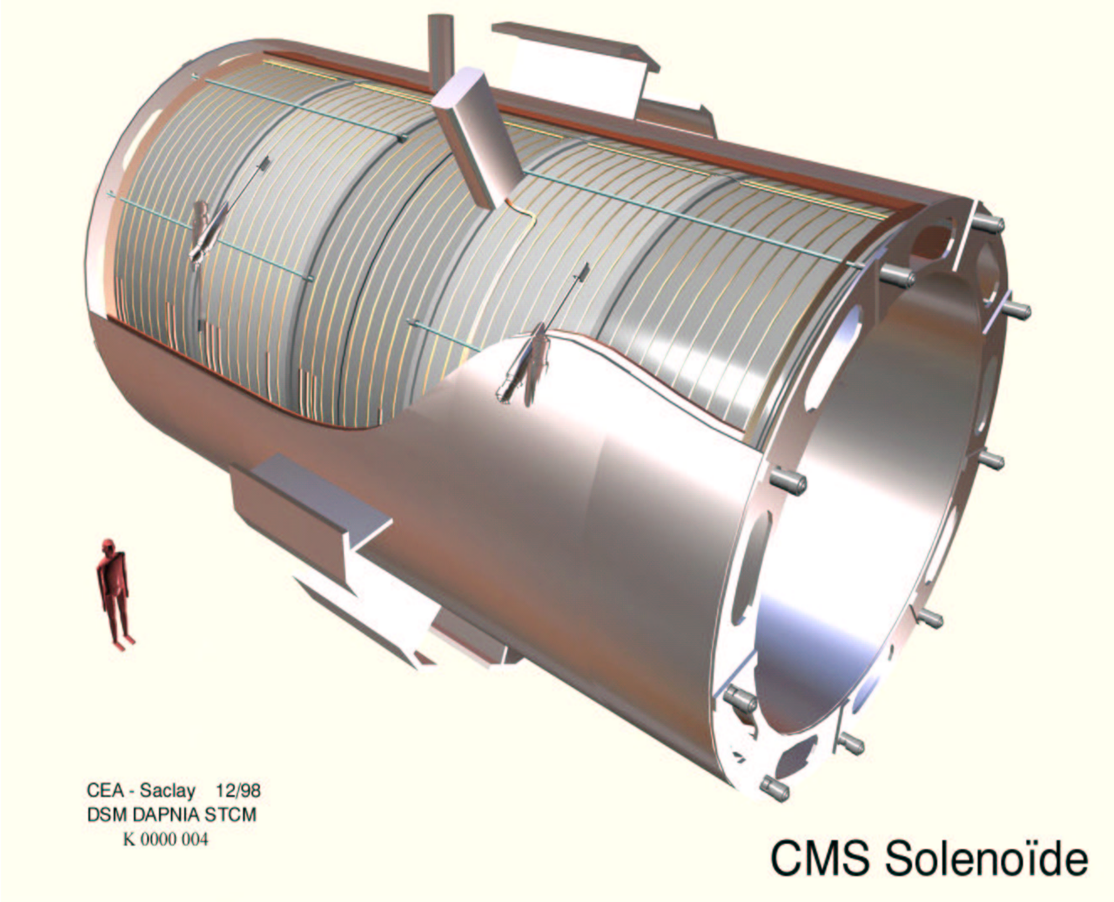
ATLAS CAVERN

The BT toroid assembly and the test of the BT + ECT coils together will be done in the cavern

CMS DETECTOR



CMS SOLENOID



Central field : 4 T

Nominal current : 20 kA

Stored energy : 2.7 GJ

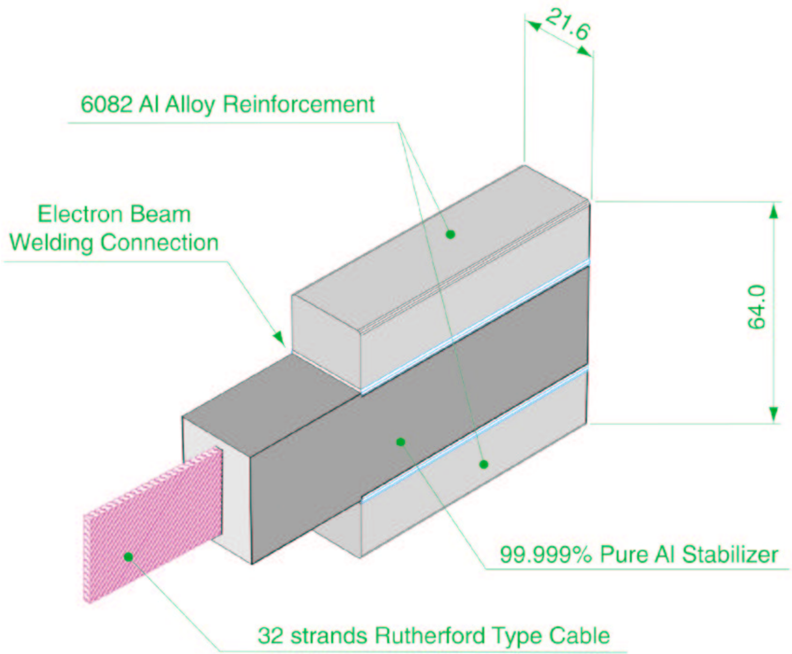
Cold mass

Length : 12.5 m

Internal diameter : 6 m

Weight : 220 t

CMS CONDUCTOR



Courtesy B. Blau

Rectangular shaped cable contains 32 superconducting (Niobium-Titanium) strands

Rutherford type cable embedded in high purity aluminium profile for thermal and electrical stabilization

Conductor is mechanically reinforced by two aluminium-alloy sections in order to counteract the magnetic force where it is created

Current carrying capability:
60 000 A @ 5 T, 4.2 K

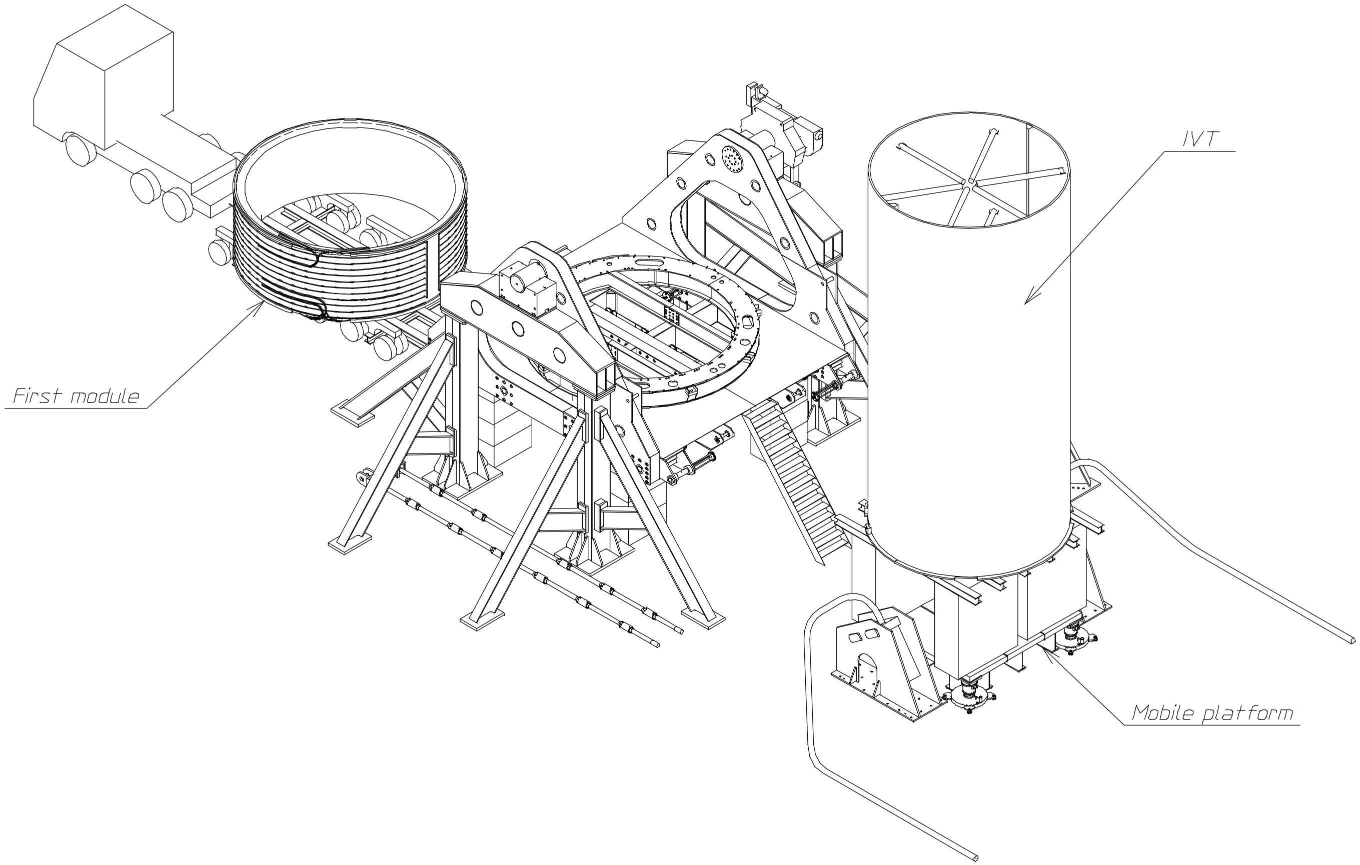
CMS WINDING

Courtesy P. Fabbricatore

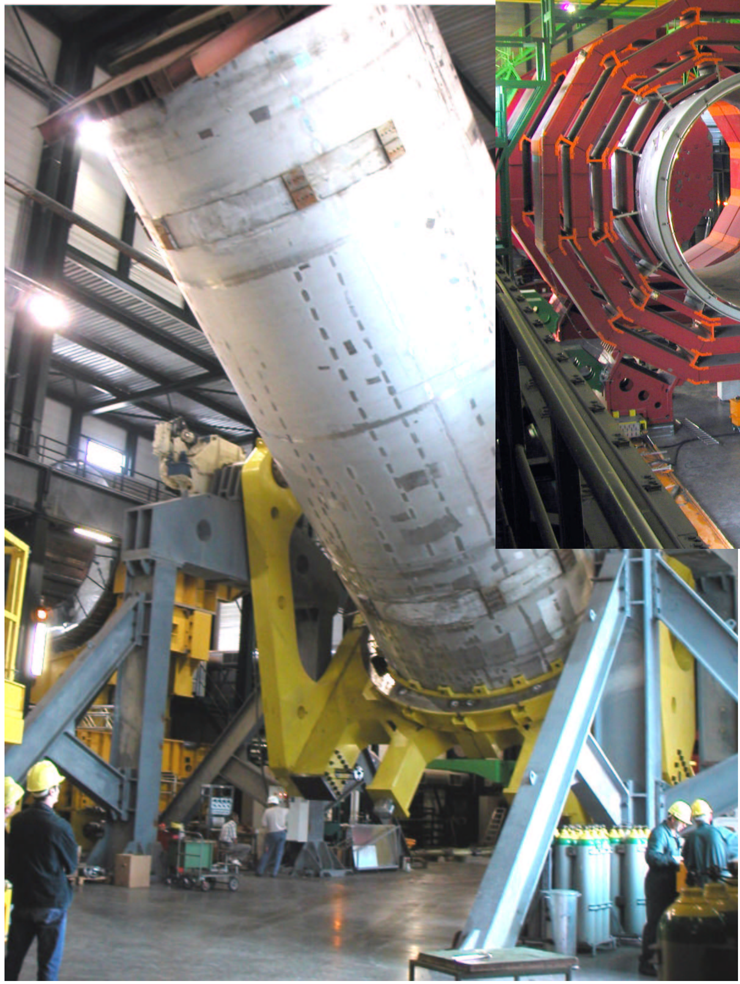
CMS CB-2 MODULE

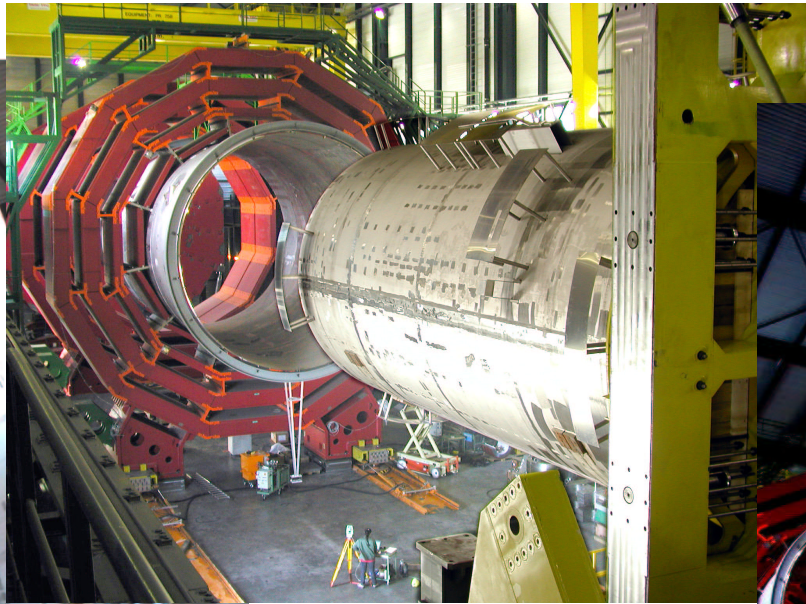
Courtesy P. Fabbricatore

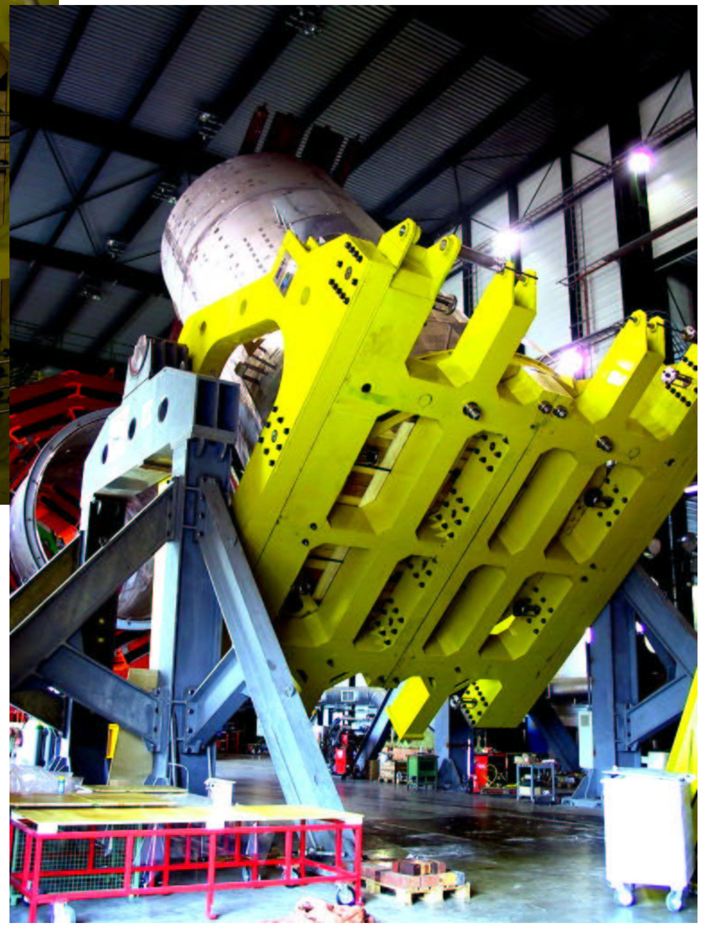
ASSEMBLY PRINCIPLE



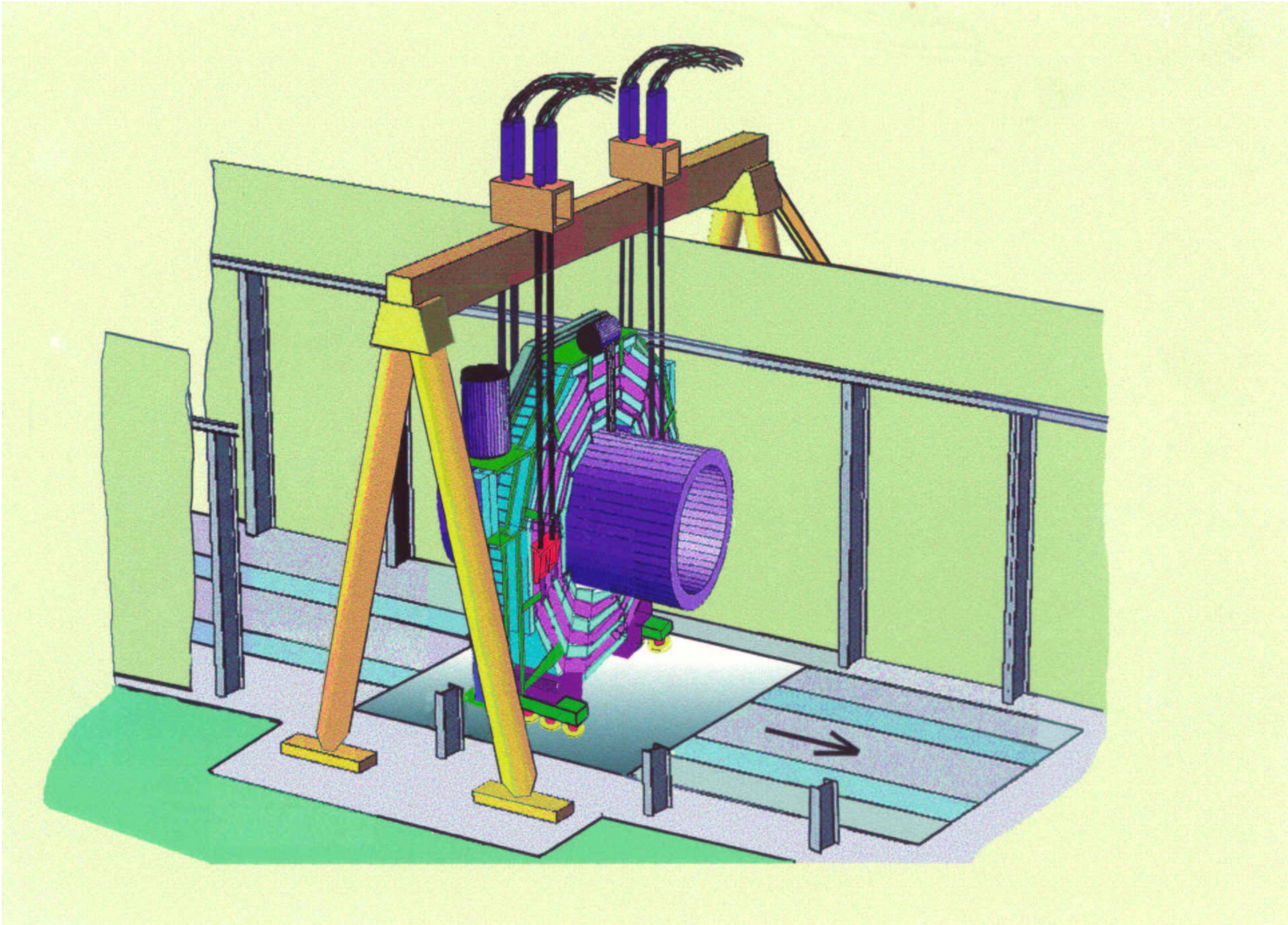
SWIVELING PLATFORM TESTS AT CERN







TRANSFERT TO CAVERN



After the surface test, the magnet will be dissembled and transfered to the cavern where will be re-assembled

4 - The limitations for the future

RELEVANT PARAMETERS (FOR SOLENOIDS)

- Basic parameters for the specification
  - . Field B, length L, radius R
  - . Eventually : field homogeneity, radiation thickness, interaction length
- Parameters relevant for the physics
  - . BL^2 (sagitta)
  - . BR^2 (momentum resolution)
- Parameters relevant for the magnet designer
  - . $B^2 R$ (mechanical forces)
  - . $B^2 R/\Delta R$ (protection in case of quench, ΔR : coil thickness)
- Parameter relevant for the ressource manager
  - . Cost : $C = \alpha (RL)^{0.8} + \beta (B^2 R^2 L)^{0.7}$

(from A. Hervé)

LIMITATIONS (1)

- B : intrinsic value : B_c ~ 10 T for NbTi

~ 20 T for Nb_3Sn

- R : . road transportation R_{max} ~ 3.5 m

. Other mean of transportation (airlift ?)

the limitation is now the manufacture and handling

- L : no limitation, as long as a modular system is acceptable

LIMITATIONS (2)

- **Mechanical forces**
  - **. Forces must be held by the conductor and/or the external support structure**
  - **. the electrical insulation must also withstand the stress (shear stress in particular)**

- **Protection in case of quench**
  - **. importance of the value of the stored energy per unit of cold mass (E/M ratio)**
  - **. necessity of fast quench propagation after a quench has started**

DEVELOPMENTS UNDER WAY

- Conductor reinforcement

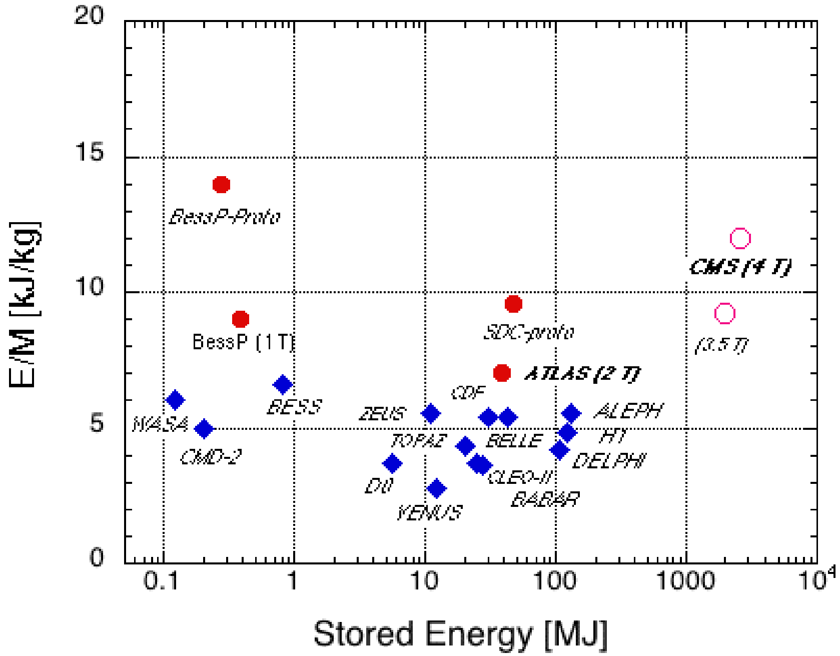
  . homogeneous reinforcement of Al conductor : micro alloying + cold work (A. Yamamoto)

  . hybrid configuration (CMS conductor)

- Quench protection

  . Increase operational E/M ratio by using passive (quench back tube, Al strips) and active (heaters) quench propagation systems

E/M RATIO OF SOLENOIDAL DETECTOR MAGNETS



Courtesy A. Yamamoto

MY PERSONAL FEELING

For detector solenoidal magnets, my personal feeling about the limits :

. limit of B^2 R ~ 60 T^2 m for the forces

. optimum of L/D between 1.5 and 2 (D coil diameter) for the dimensions

. limit of E/M ~ 15 kJ/kg for the protection (specially for thin solenoid)

CONCLUSIONS

- Big improvements, both in size and in performances, have been done since the Pluto magnet construction

- The progress of the realization of the two LHC large SC magnets shows that most of the challenges are now solved

- However, only the successful test of these magnets will justify the options which were choosen, as will as their correct realization

- For the future, some progress in term of performances will probably be made, but clearly not with the same magnetitude as during the last thirty years