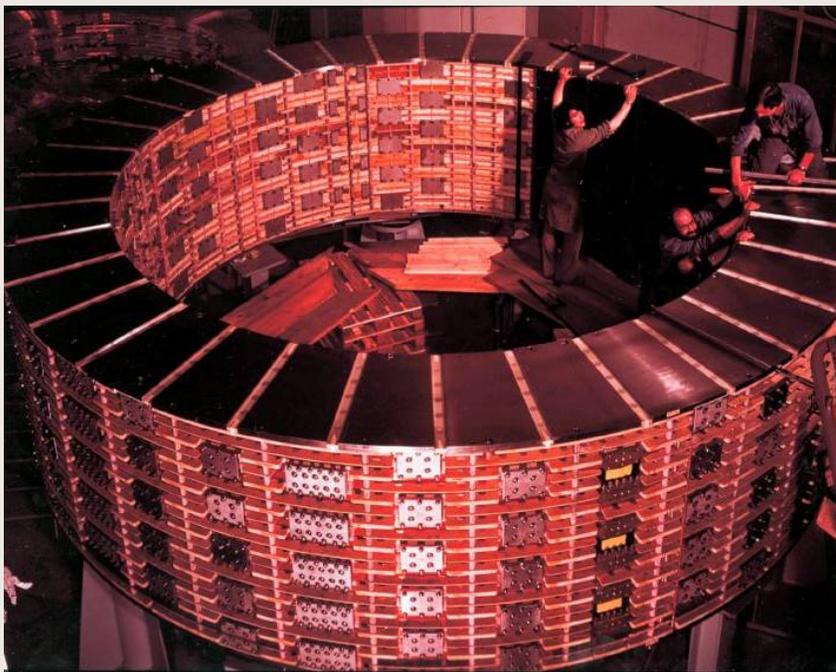


# The Large Superconducting Solenoids for Detectors in High Energy Physics Experiments: 40 years of developments



From BEBC to

CMS



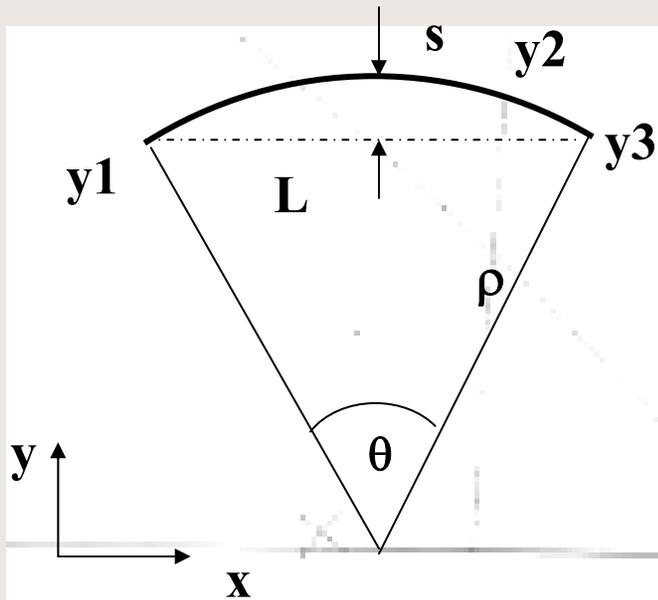
## Aknowledgements

Thanks to

**H.Desportes** and **F. Wittegenstein** for providing photos of the pioner magnets developed in the sixties and seventeens.

**A. Herve** for the fruitfull discussions (some slides shown here were extracted from his presentation to MT20 in Philadelphia)

**E.Baynham** and **A.Yamamoto**. Some slides has been extracted from presentations they did in past conferences



$$p_{\perp} = qB\rho$$

$$p_T \text{ (GeV/c)} = 0.3B\rho \text{ (T}\cdot\text{m)}$$

$$s = \rho(1 - \cos \theta/2) \approx \rho \frac{\theta^2}{8} \approx \frac{0.3}{8} \frac{L^2 B}{p_T}$$

$$\frac{\sigma(p_T)}{p_T} \Big|^{meas.} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}} \sigma(x)}{s} = \frac{\sigma(x) \cdot 8 p_T}{0.3 \cdot B L^2} \cdot \sqrt{\frac{3}{2}}$$

Limited space allowed for the coil



Superconducting  
magnets with large  
dimensions

BRIT. J. APPL. PHYS., 1962, VOL. 13

## International Conference on High Magnetic Fields, Massachusetts Institute of Technology, November 1961

### 4. High critical field superconductors

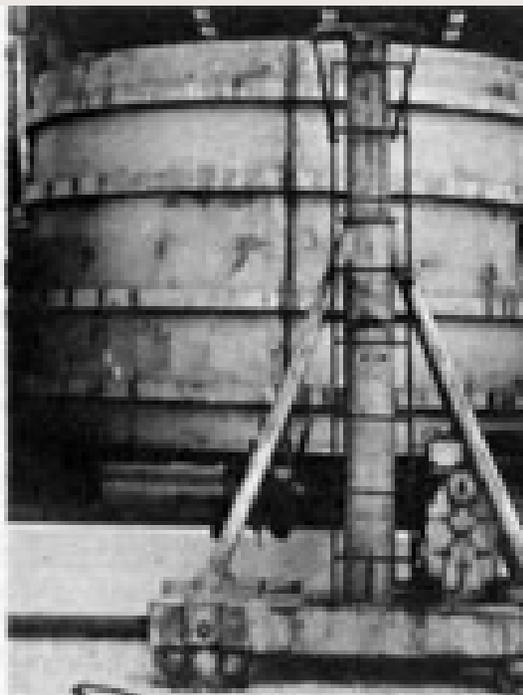
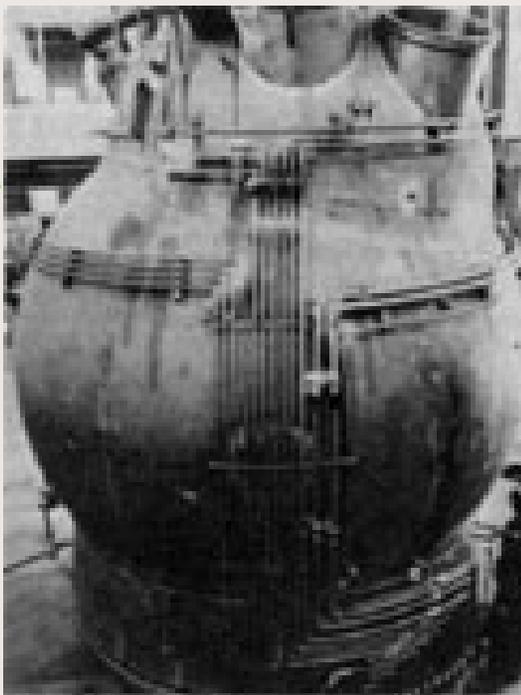
There is a very useful review of the situation with high critical field superconductors by Kunzler (1961) which appeared just before this conference. We assume a knowledge of the contents of that paper as a 'platform' for this section. Several laboratories reported the use of niobium-zirconium alloys and niobium tin in working solenoids. A coil with an inside diameter of 0.25 in. fabricated from Nb<sub>3</sub>Sn 'wire' which had yielded fields of about 69 kG at about 1.5° K was reported by Bell Telephone Laboratories. At M.I.T. experiments with similar wire had produced fields of about 28 kG. Westinghouse Research Laboratories described a coil using Nb-Zr, inner diameter 0.15 in., which had generated 56 kG, and Atomic International, Canoga Park, California, a similar coil of inner diameter 0.5 in. in which a field of 59 kG had been generated. In both of these coils the alloy contained 25% Zr. (Since the conference at least two American firms are now offering to build solenoids capable of 50 kG with an inner diameter of 2 in. using Nb-Zr wire.)

The first practical sc wires in NbZr, NbTi and Nb<sub>3</sub>Sn appeared 50 years later the discovery of superconductivity by K.Onnes.

The first (small) magnets soon after

**First very large magnets for Particle Physics (surprisingly) developed few years later, with conductor technology far to be mature**

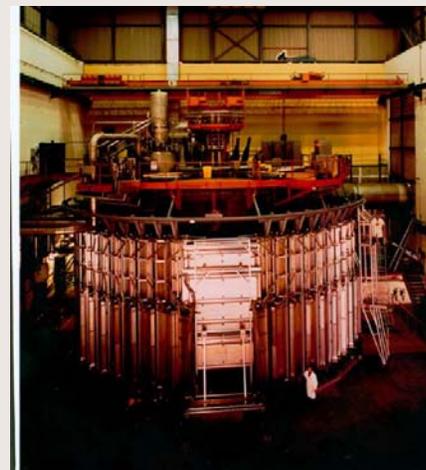
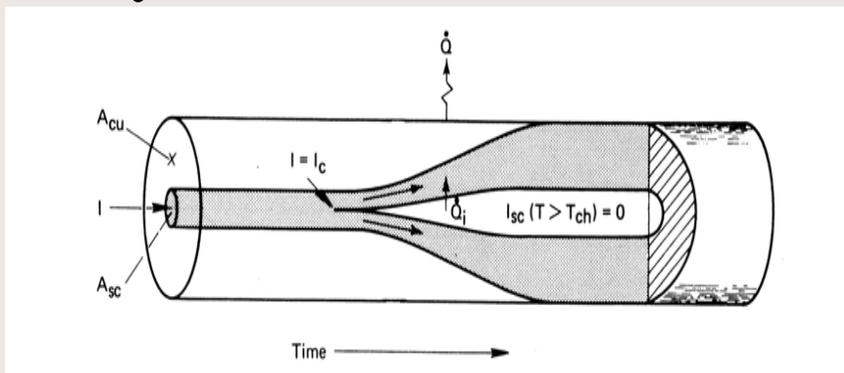
One pioneer was the split coil solenoid for the 12-ft bubble chamber at Argonne in the ZGS accelerator (1968).



Magnetic field **1.8T**  
in **4.5m** diameter  
and **3m** height.

Stored Energy  
**80MJ**. Conductor in  
NbTi (**40 km**).

## 12-ft and successors were *pool boiling* based on the Stekly criterion



$$\dot{G} = \rho_{Cu} I_c^2 / A_{Cu}$$

$$\dot{Q} = Ph(T_c - T_b)$$

$$\alpha = \frac{\dot{G}}{\dot{Q}} = \frac{\rho_{Cu} I_c^2}{(PA)_{Cu} h(T_c - T_b)}$$

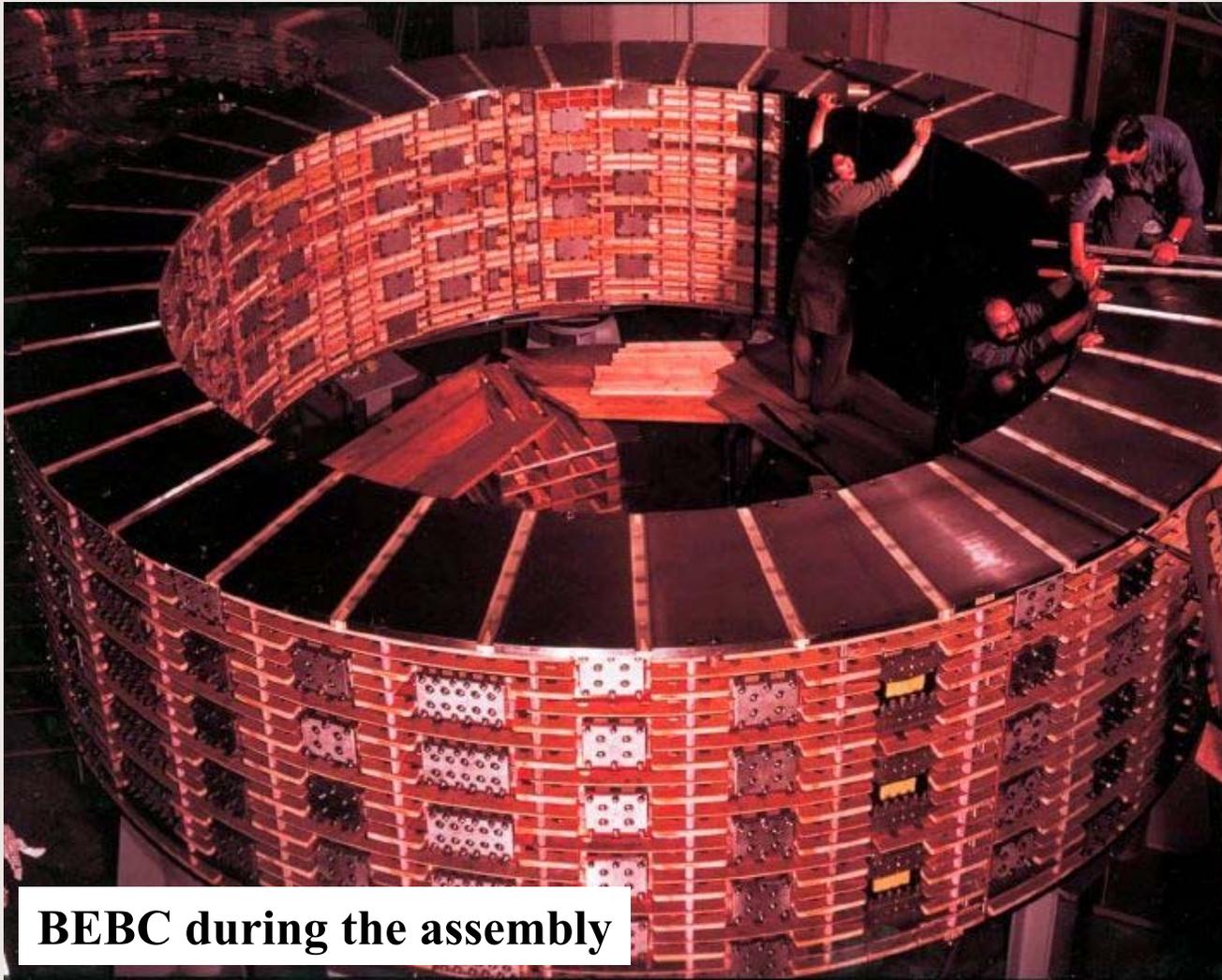
Characteristics of large Bubble Chamber Magnets

	7-Ft BC B.N.L.	12-Ft BC A.N.L.	15-Ft BC FERMILAB	BEBE C.E.R.N.
B.C. diameter (m)	2.13	3.65	3.8	3.7
LH <sup>2</sup> volume (m <sup>3</sup> )	12	26	33	35
Beam access gap(m)	0.2(cold)	0.17	0.56	0.4
Winding I.D. (m)	2.4	4.8	4.26	4.72
Winding O.D. (m)	2.75	5.28	5.23	5.98
Coil separation(m)	0.29	0.54	0.99	1.05
Coil length (m)	0.84	1.13	0.97	1.5
Central field (T)	3.	1.8	3	3.45
Peak field (T)	4.	2.	5.1	5.
Rated current (A)	6 000	2 000	5 000	5 700
Amp x turns (A)	8.4 10 <sup>6</sup>	5x10 <sup>6</sup>	14.3 10 <sup>6</sup>	20x10 <sup>6</sup>
Average Jc (A/cm <sup>2</sup> )	2 500	775	1 885	1 050
Stored energy (MJ)	72	80	400	800
Cold weight (t)	24	90	100	330
Test time	1970	1968	1972	1972

**BEBC during the winding**



x21.10.7c

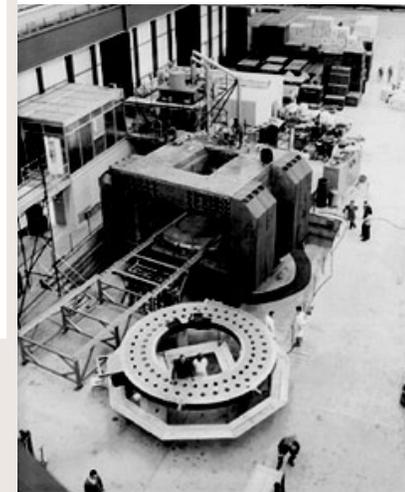
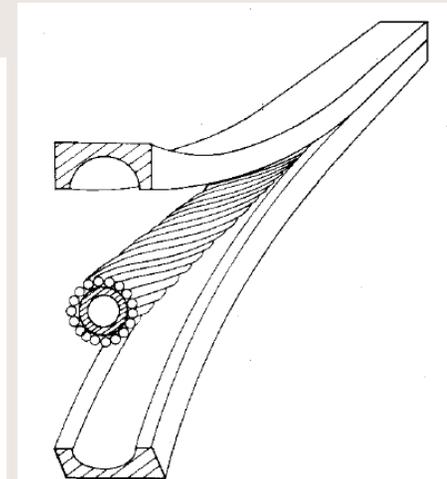


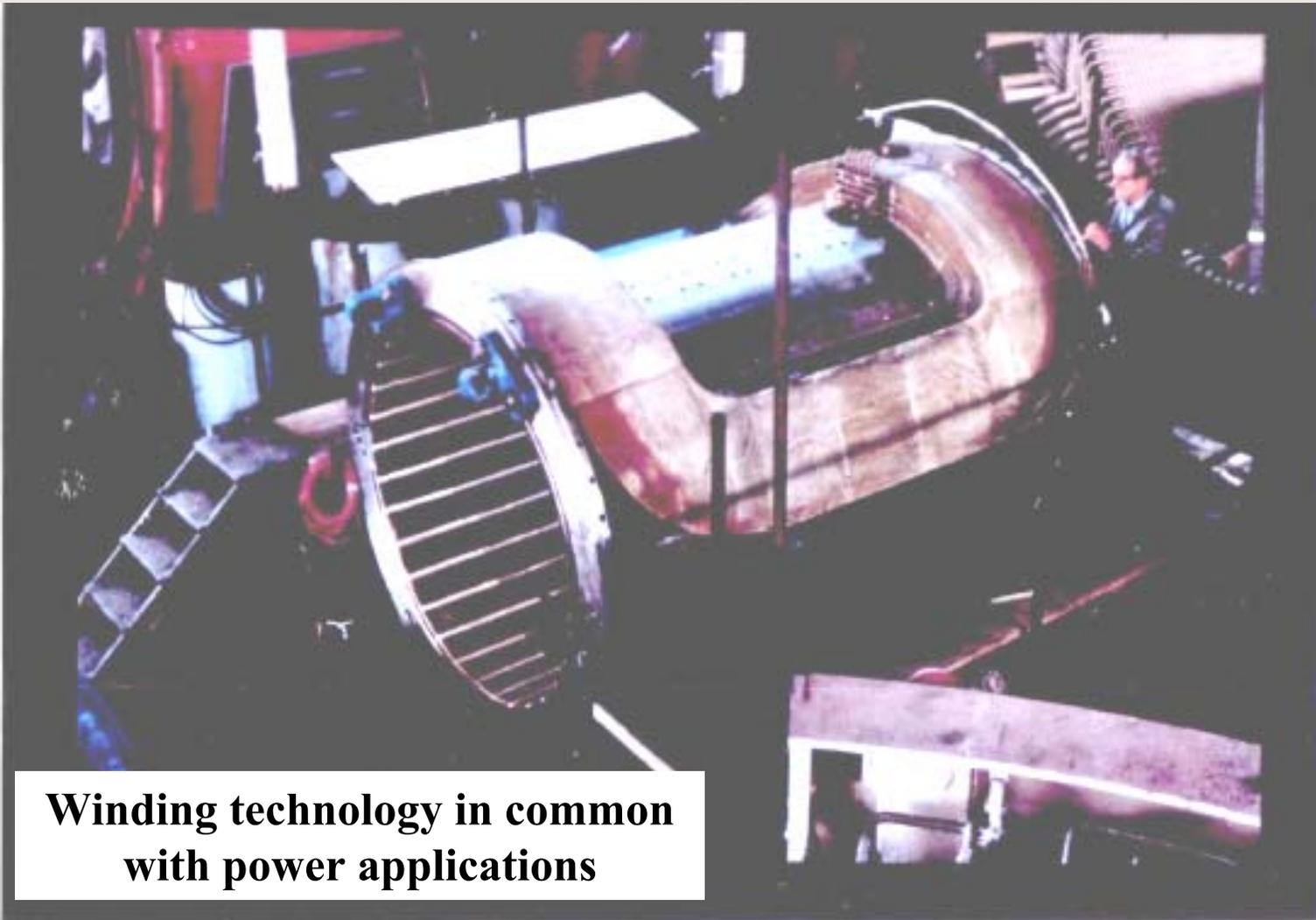
**BEBC during the assembly**

## Forced flow magnets

Large split-coil iron-core S.C. magnets

		OMEGA C.E.R.N.	VERTEX MAG C.E.R.N.	CYCLOTRON FERMILAB.
Pole diameter	(m)	3	2	4.3
Free gap between poles	(m)	2	2	1.3
Free gap between coils	(m)	1.5	1.	1.5
Iron weight	(t)	1 300	300	2 000
Coil winding I.D.	(m)	3.58	2.27	5.2
Coil winding O.D.	(m)	4.9	3.27	5.5
Coil height	(m)	0.24	0.29	0.12
Rated current	(A)	5 000	5 000	1 000
Amp x turns	(A)	$4 \times 10^6$	$2.5 \times 10^6$	$2 \times 10^6$
Average Jc	(A/cm <sup>2</sup> )	1 260	1 200	6 000
Central field	(T)	1.8	1.5	1.5
Stored energy	(MJ)	50	20	32.5
Axial force on each coil	(t)	2 000		530
Heat loss at 4.5 K		300 W		13.1/hr





**Winding technology in common  
with power applications**



The development of colliding beams demanded for solenoidal magnets (axi-symmetric field) transparent to radiation (calorimeters placed outside). At the same time it was realized that a LHe bath cooling system was useless for dc magnets, provided that a good stability is guaranteed and the disturbances of mechanical nature limited. → **The indirectly cooled thin high field solenoids.**

## CELLO – Indirect cooling – Pure Al-stabilised conductor

### Basic ideas

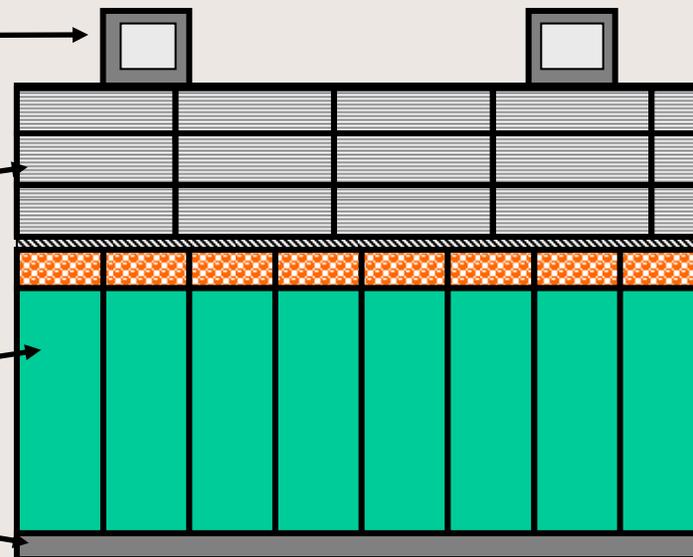
Monolithic wire  
 soft soldered to Al-  
 pure stabiliser

Indirect cooling

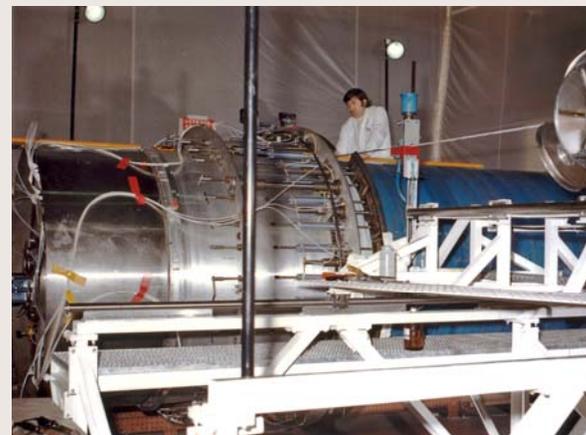
External support

Al-stabilised  
 conductor

Mandrel



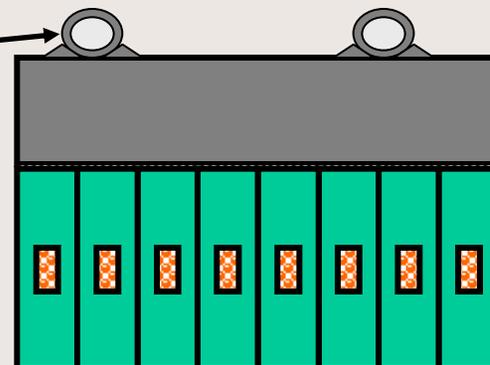
Parameters		
Field	1.5	T
Coil Radius	0.85	m
Length	3.6	m
Stored Energy	5.1	MJ
Cold mass	1	tonnes



## CDF – First co-extrude conductor – Al-alloy support- Shrink-fit operation

Parameters		
Field	1.5	T
Coil Radius	01.5	m
Length	4.8	m
Sored Energy	30	MJ

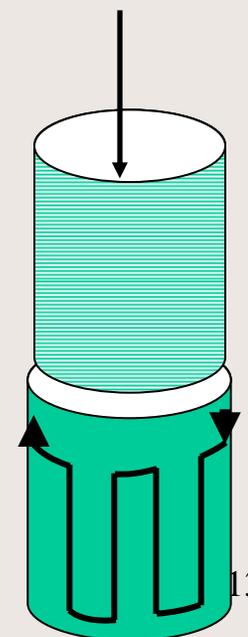
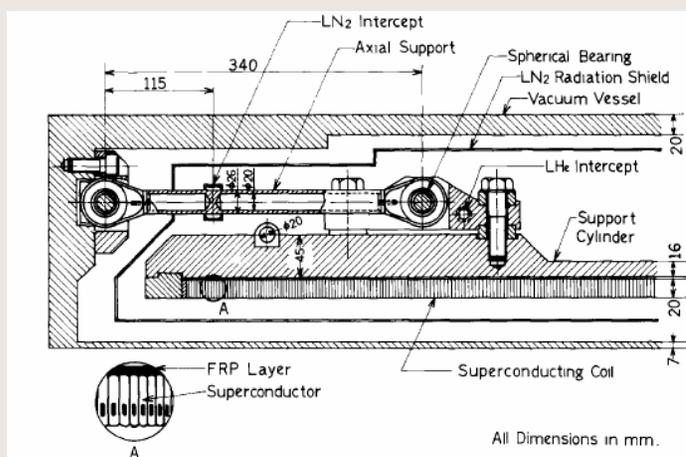
Cooling pipes directly welded on cylinder



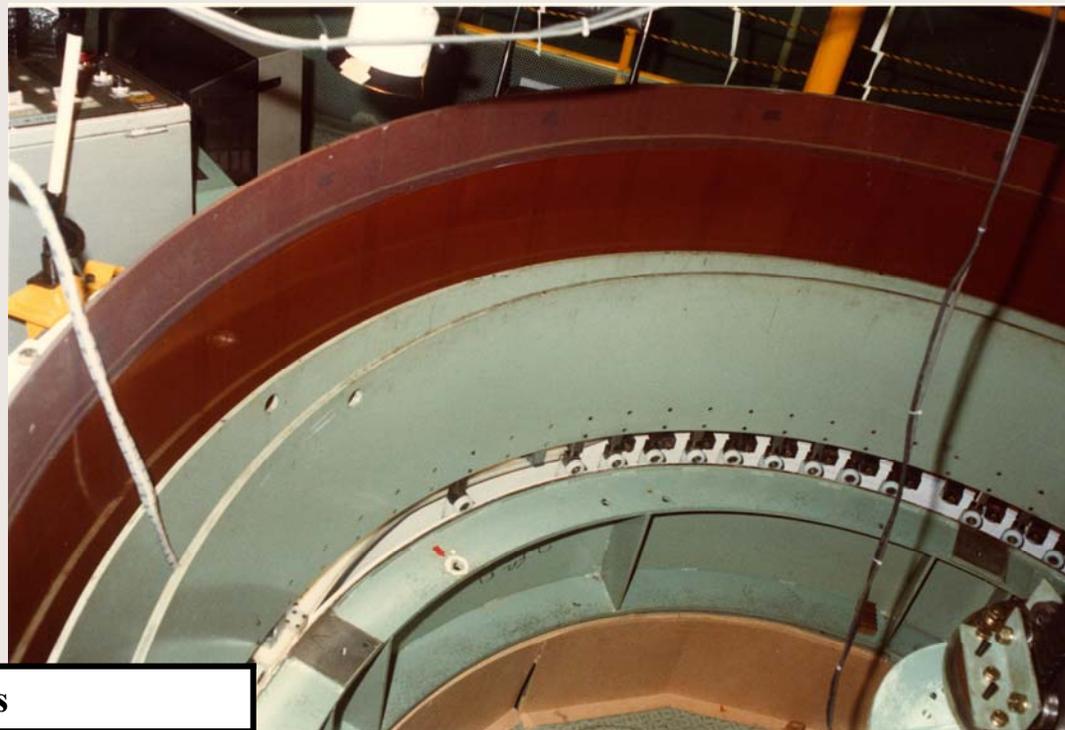
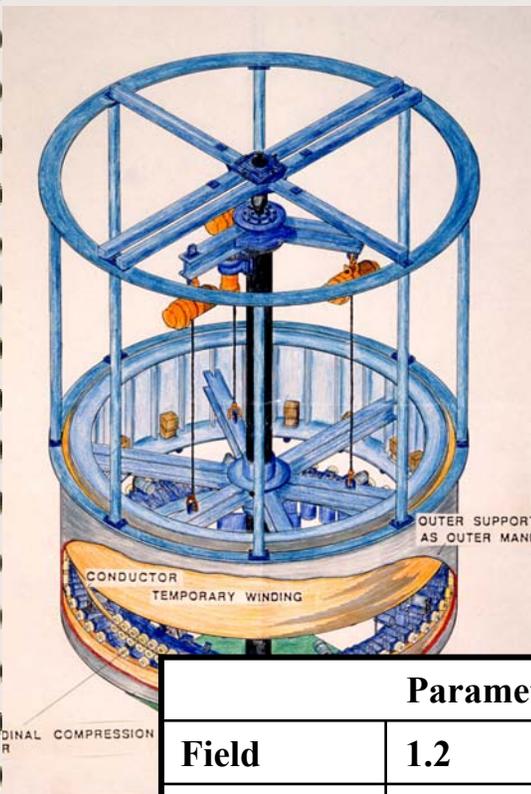
After the winding the coil is shrink-fitted inside the outer cylindrical support



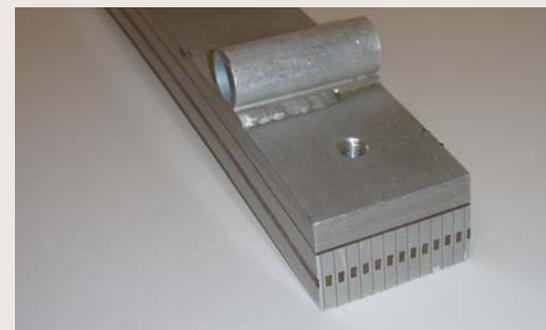
Superconducting solenoid coil was being made at Hitachi company.



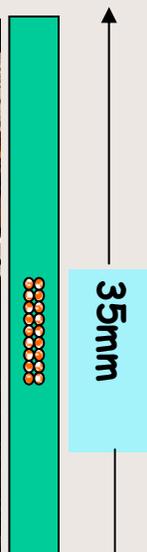
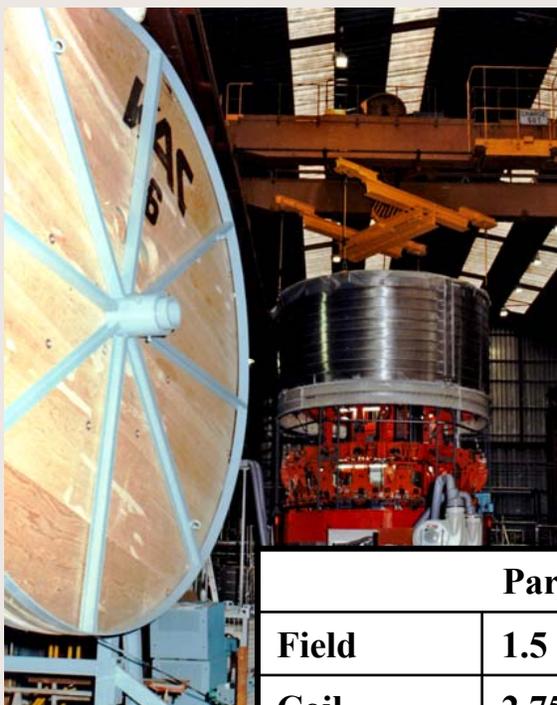
## TOPAZ - For the first time the inner winding operation



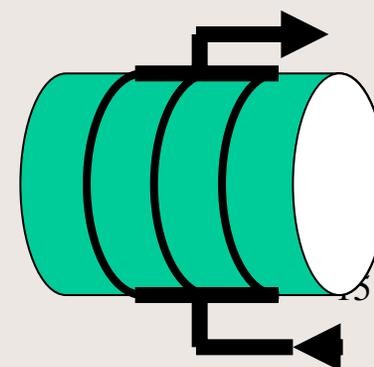
Parameters		
Field	1.2	T
Coil Radius	1.45	m
Length	5.1	m
Stored Energy	19	MJ



## ALEPH – Rutherford cable- Resin impregnation under vacuum – Thermo-siphon

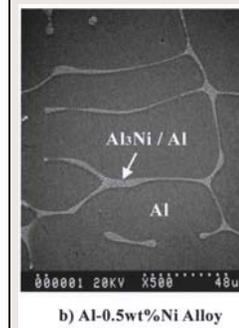
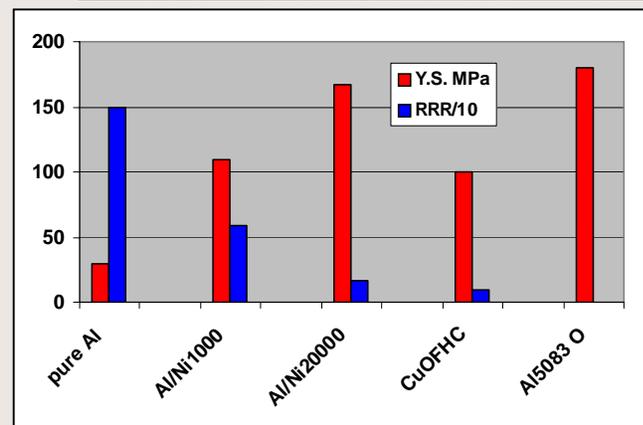
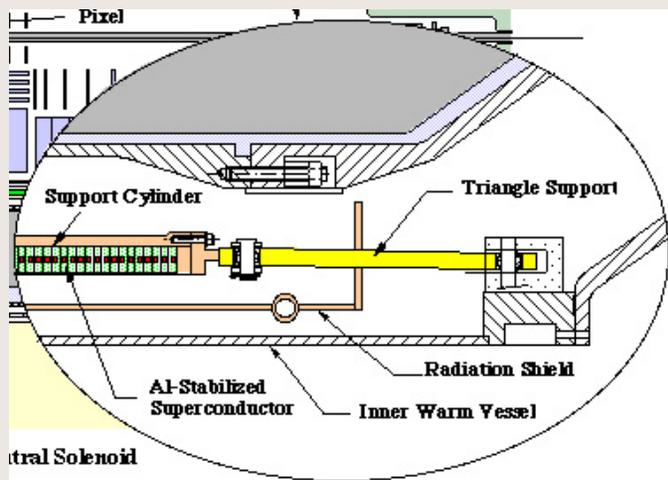


Parameters		
Field	1.5	T
Coil Radius	2.75	m
Length	6.4	m
Stored Energy	130	MJ



## ATLAS CS – Hi strength Al/Ni alloy

Parameters		
Field	2	T
Coil Radius	1.25	m
Length	3.66	m
Stored Energy	30	MJ

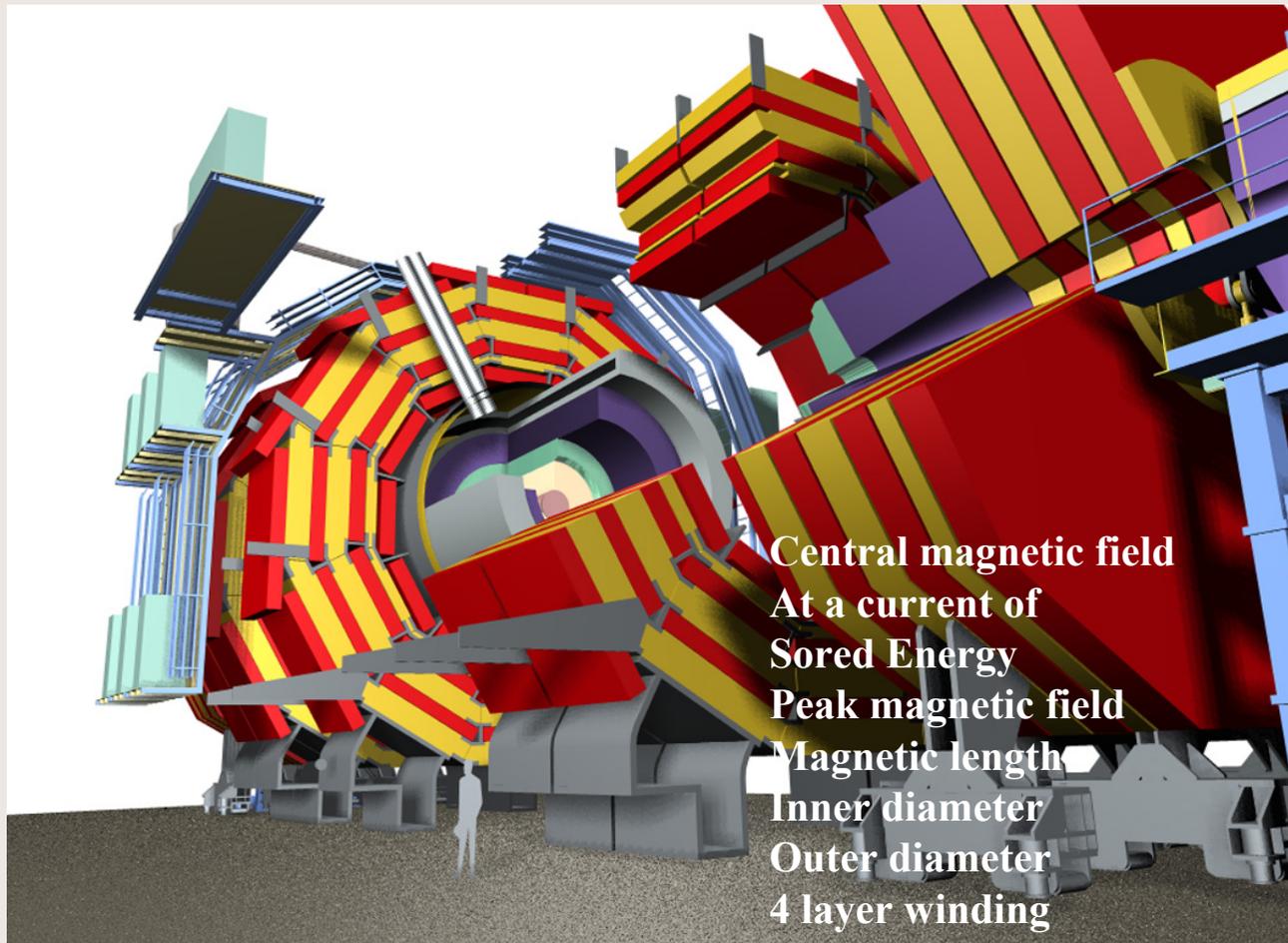


## Development of Detector Solenoid/Ring-Dipole Magnets

Experiment --Lab.	B [T]	R (or L) [m]	X [Xo]	E/M [kJ/kg]:	Technical Remark	(Year)
ISR CERN	1.5	1.1			Al-soldered to S/C	(1977)
CELLO Saclay/DESY	1.5	0.85	0.6		Indirect cooling	(1978)
*PEP4 LBL	1.5	1.1	0.83		Cu stab, in. Q-back	(1983)
CDF Tsukuba/Fermi	1.5	1.5	0.84	5.4	Al co-extrusion	(1984)
TOPAZ KEK	1.2	1.45	0.70	4.3	Inner coil winding,	(1984)
VENUS KEK	0.75	1.75	0.52	2.8	CFRP vacuum shell,	(1985)
AMY KEK	3	1.2			Hybrid of Cu/Al stab.	(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	(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	Thin-Al, Pure-Al strip	(1990)
*CMD-2 BINP	1.2	0.36	0.38	5	Current shunting	(1990)
G-2 BNL/KEK	1.5	6			One-ring dipole	(1995)
WASA KEK/Uppsala	1.3	0.25	0.18	6	Thinnest	(1996)
SDC-prt KEK/Fermi	1.5 (2)	1.85	1.2	9.6	High-st. Al, Isogrid	(1993)
CLOE INFN						(1997)
BABAR INFN/SLAC	1.5	1.5				(1997)
D0 Fermi*	2.0	0.6	0.9	3.7	Conforming of Al	(1998)
BELLE KEK*	1.5	1.8		5.3		(1998)

(Red is presently operated)

## 1994- CMS TECHNICAL PROPOSAL : The magnet is beyond the up to date technology



4 T  
20000 A  
2520 MJ  
4.6T  
12.5 m  
6.32 m  
6.95 m



CMS is an International Collaboration made of more than 2000 Scientists from 39 Countries and 150 Institutes.

The Magnet is a 100 MUS\$ Common Project of the Collaboration the main participating Institutes to the Magnet Project have been

- CEA / Saclay : Engineering and integration
- ETHZ / Zürich : Conductor
- INFN / Genova : Winding
- Fermilab : Strand procurement and Field Mapping
- University of Wisconsin : End Cap Yoke construction
- CERN : Barrel Yoke, External Cryogenics, Conductor, Control, Project Management and Coordination

## A basic parameter for comparing different magnets

The ratio  $E/M$  Stored Energy [kJoule]/ Cold Mass [kg]

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

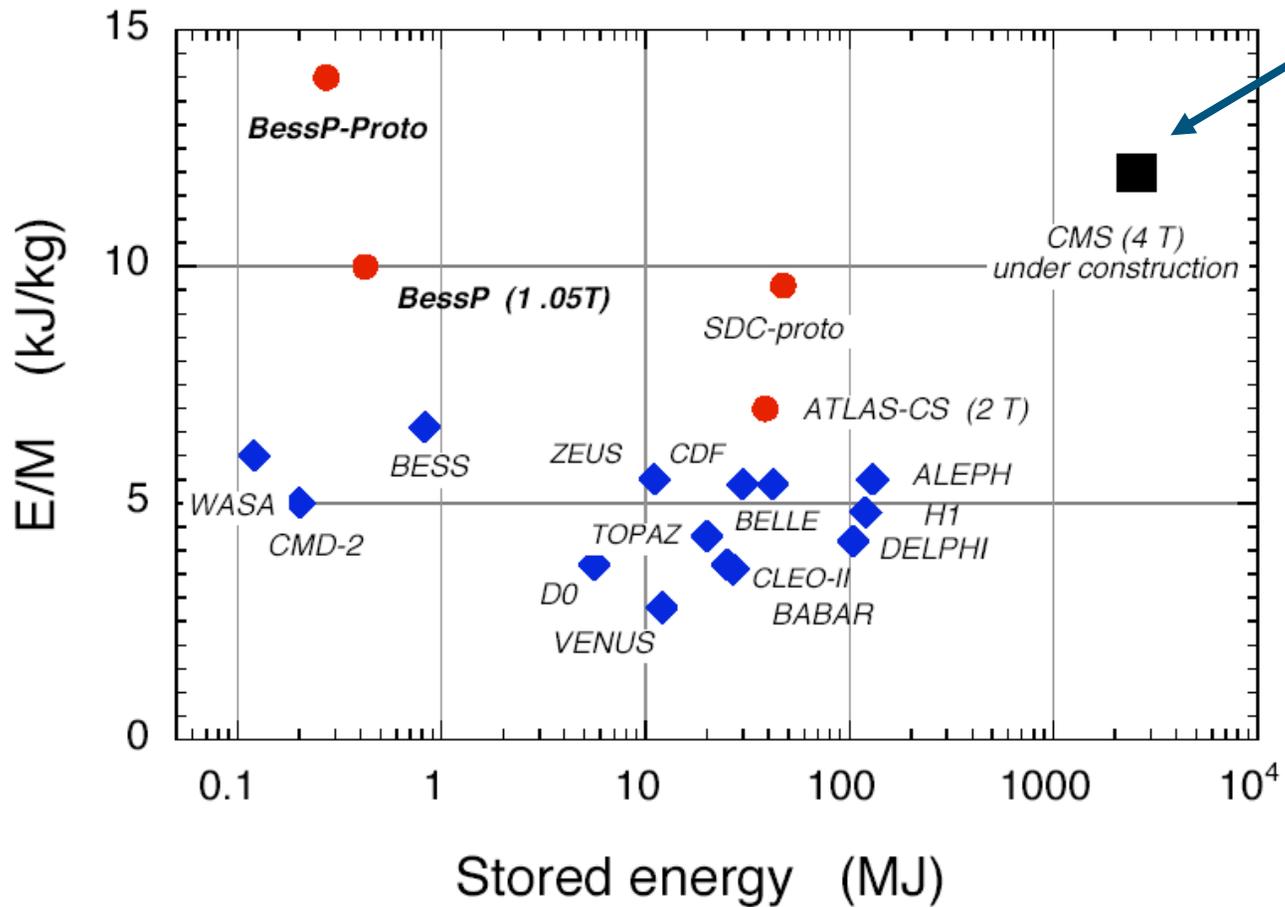
Where  $\varepsilon$  is the strain ,  $Y$  the elastic modulus,  $\delta$  the density,  
 $\alpha$  is the fraction of the mechanical resistant material

The ratio  $E/M$  gives a direct information of the mechanical deformation. For CMS  $\varepsilon=0.15\%$

$E/M$  gives also an information of the max temperature in the coil after a quench.

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

E/M ratio vs E for several solenoids



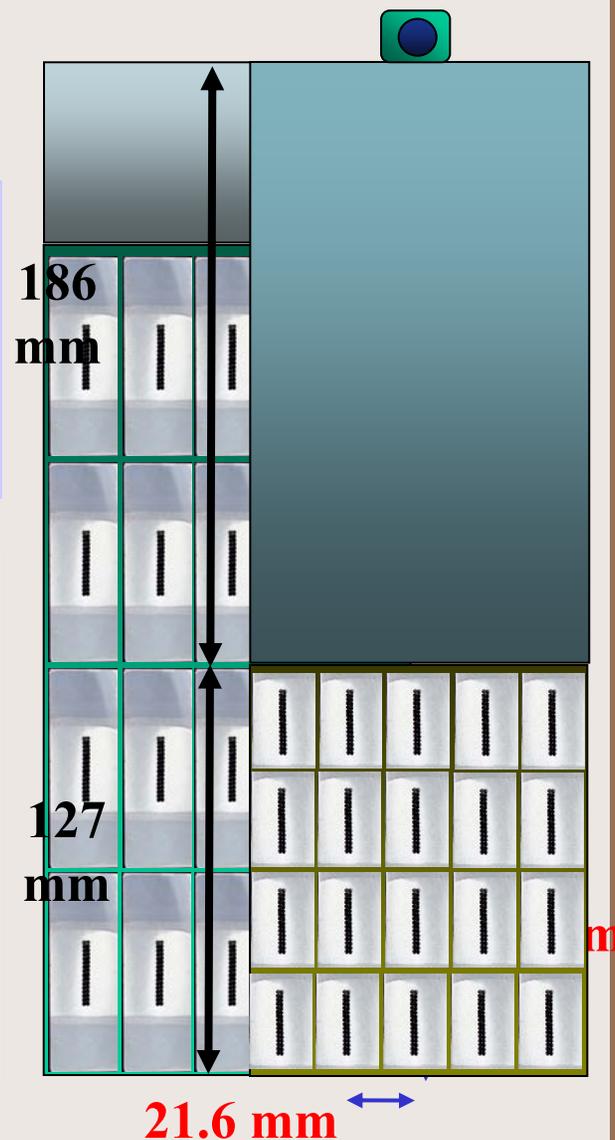
This 'anomalous' positioning meant that innovative solutions were needed to face this challenge

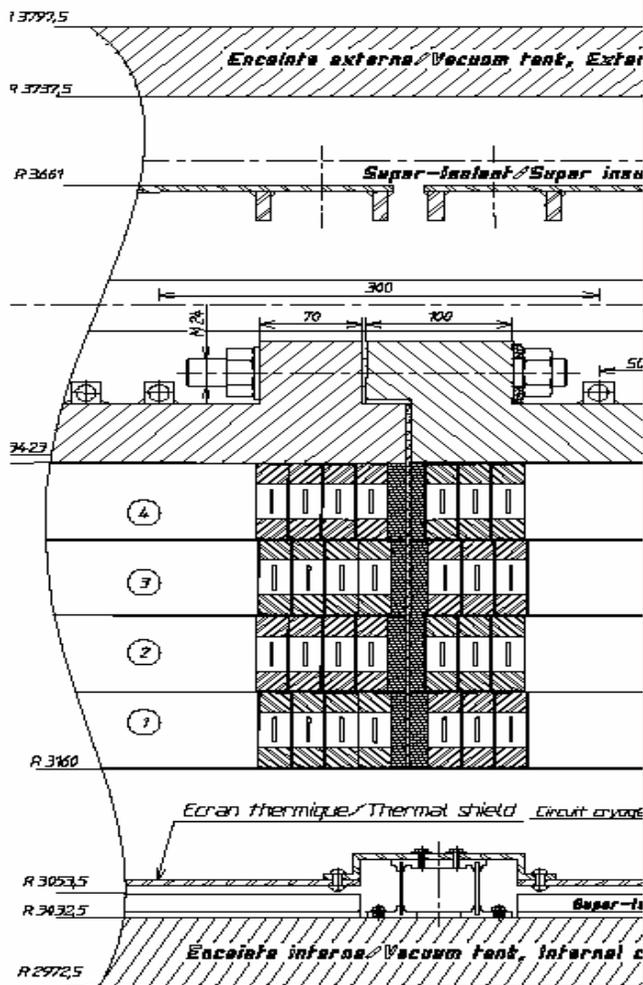
## Reinforced Conductor

The basic idea in CMS design was to include the mechanical reinforcement in the conductor. This choice allow to minimize the shear stresses in the winding

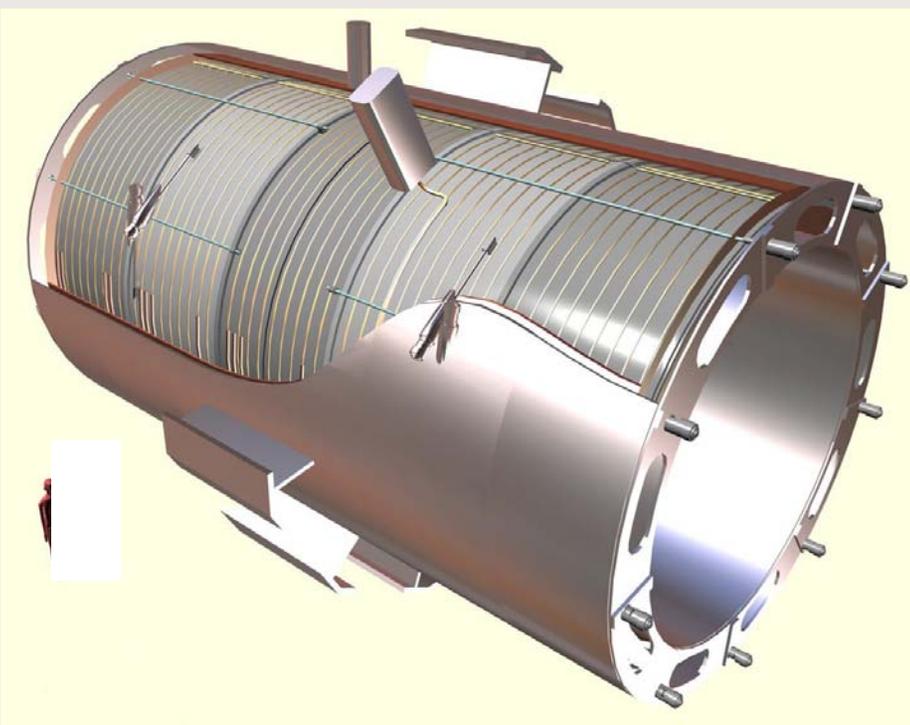
A (thin ) mandrel is still present for:

- 1) Homogenizing the temperature of the coil during cool-down
- 2) Protection- Quench back
- 3) Supporting the winding during construction
- 4) Anchoring the supporting system of the cold mass in the vacuum chamber

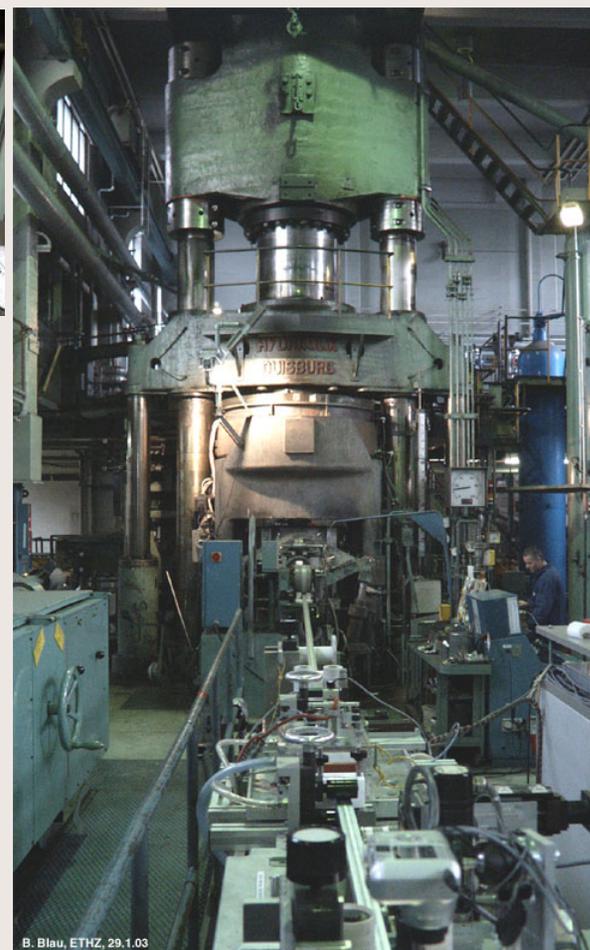
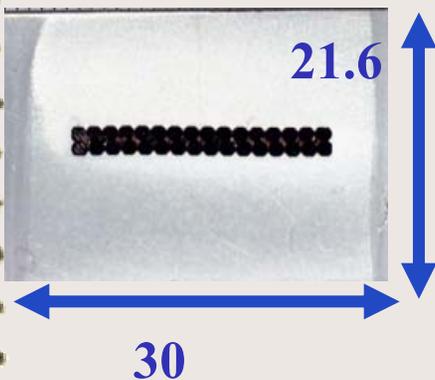




At the completion of the technical design, the CMS was conceived as a 5 module coil, requiring **R&D developments at industrial level of conductor and winding technologies**

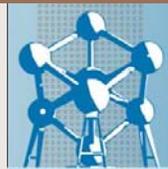


## Co-extrusion of 2.5 km length with continuous process



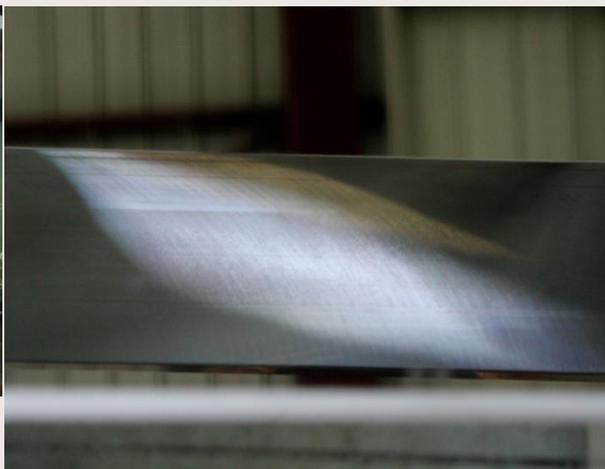
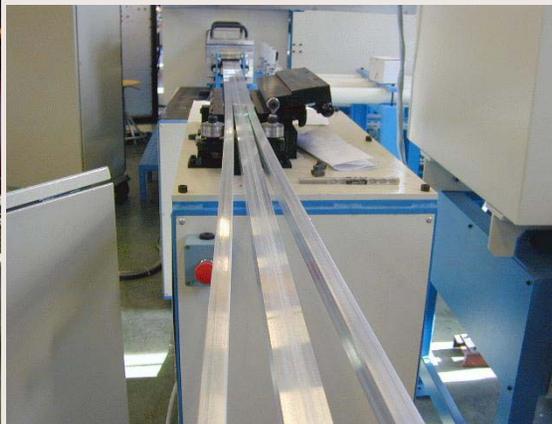


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EUCAS 19 September 2007 P.Fabbricatore INFN-Ge

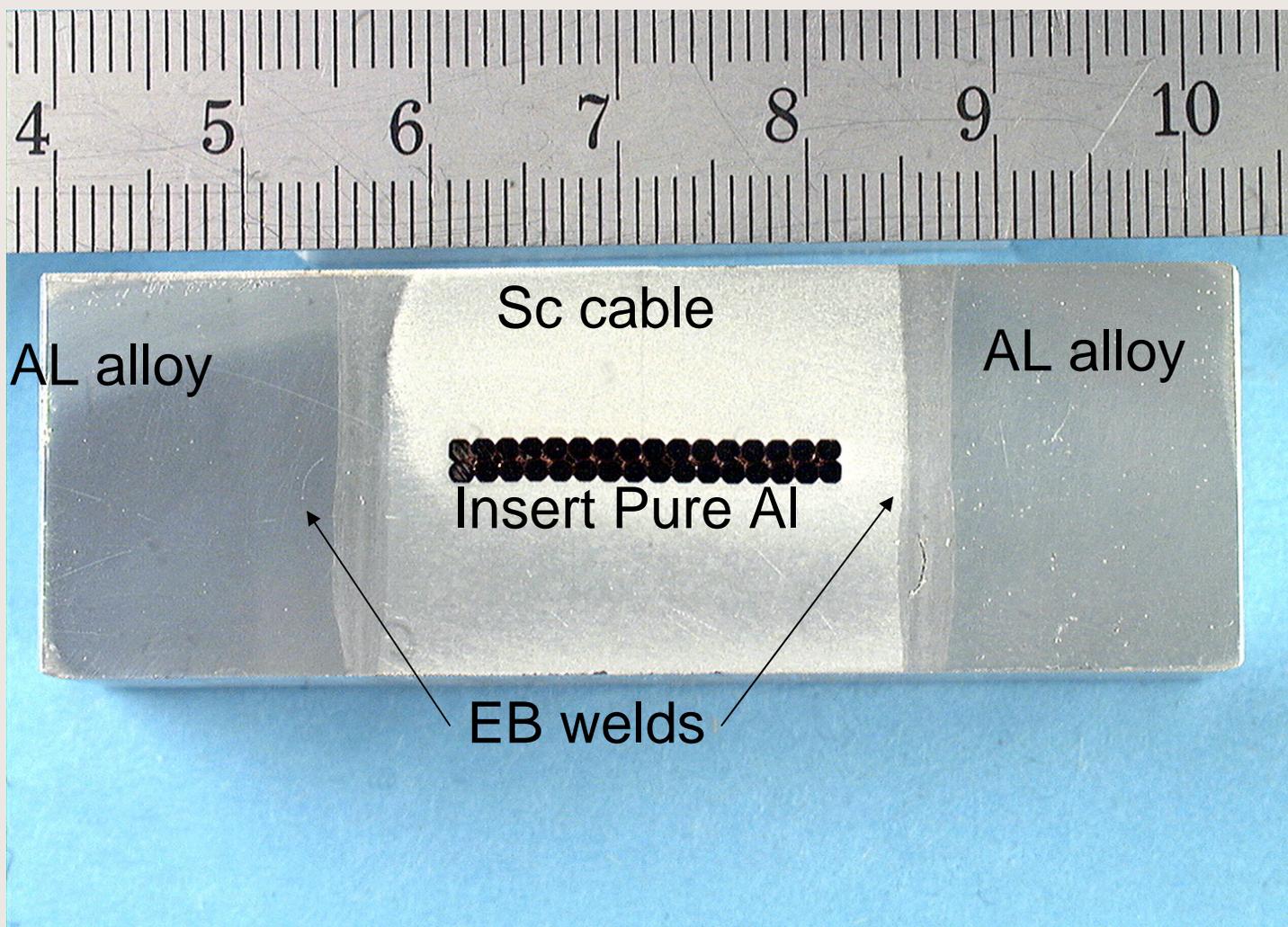


EUCAS'07

## Continuous EB-welding of each 2.5 km length



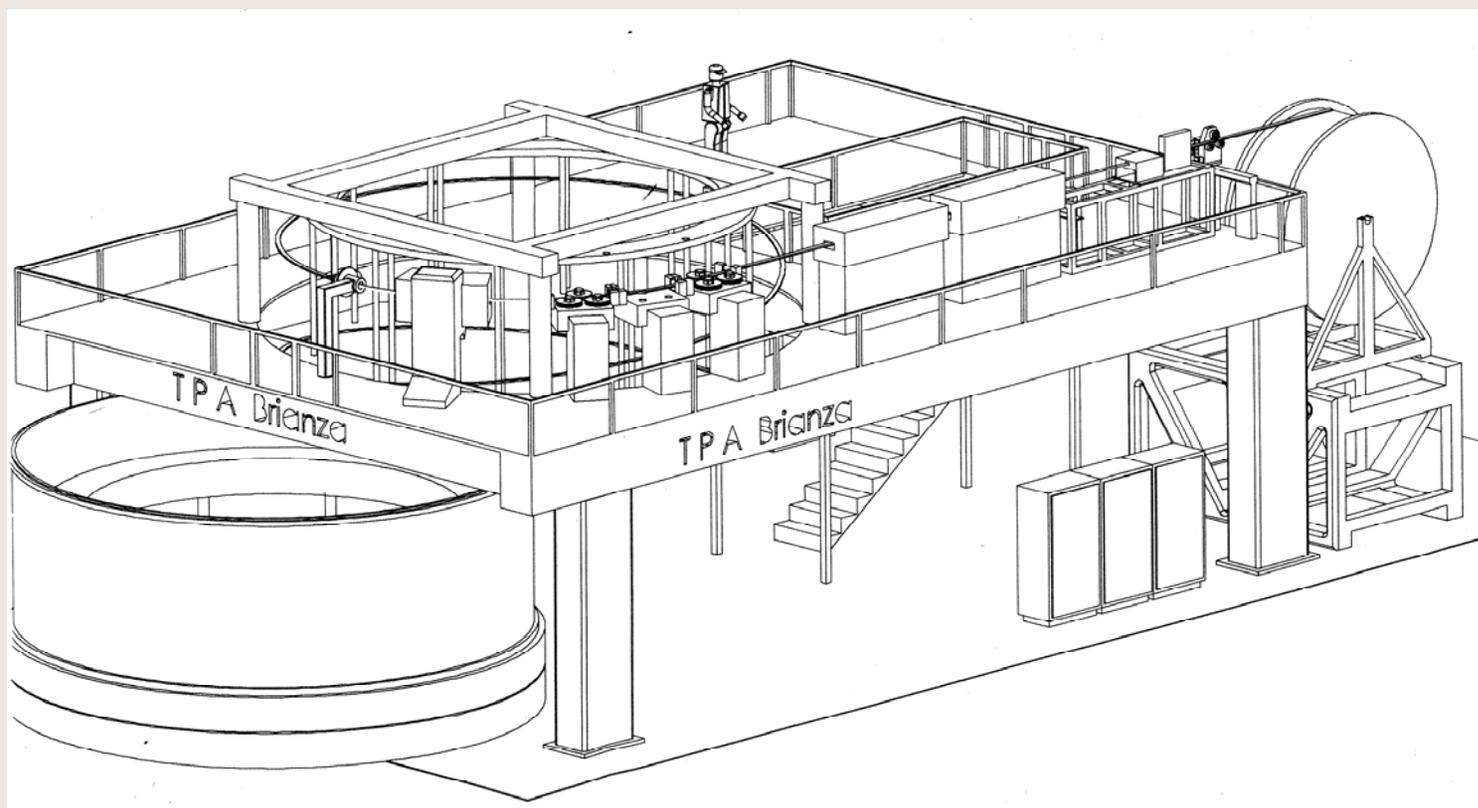
## Final conductor



## Developments of the winding techniques for a reinforced conductor



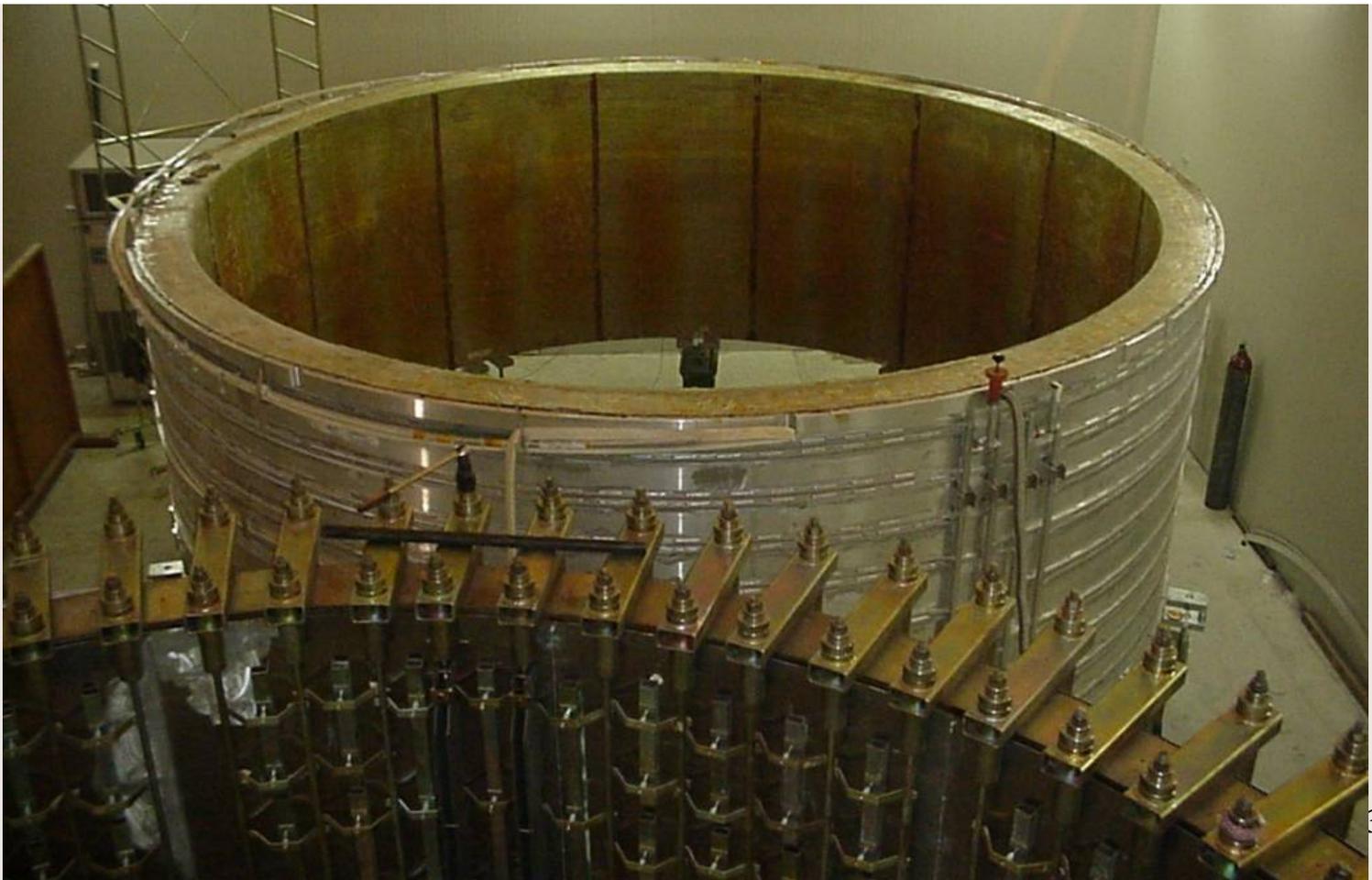
## The fully automated winding line developed for the winding of each module



## **Resin impregnation under vacuum involving 1000 l of epoxy**



After impregnation the inner surface presented excess of resin needing to be removed

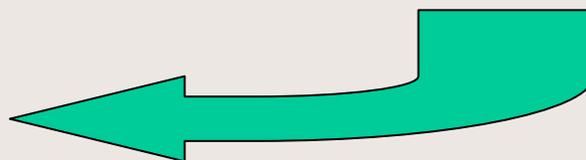
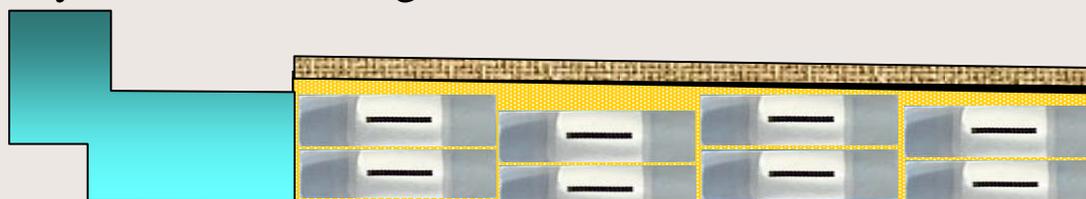


## **Machining of the inner wall of a 50 ton superconducting module**

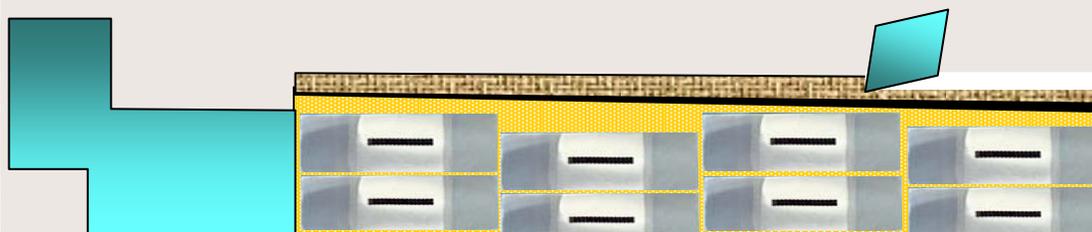


## Module to module coupling

After the impregnation the top surface of a module is not enough flat to couple mechanically with another module. This problem was solved by gluing a 5 mm G11 plates onto this not very flat surface using STYCAST resin



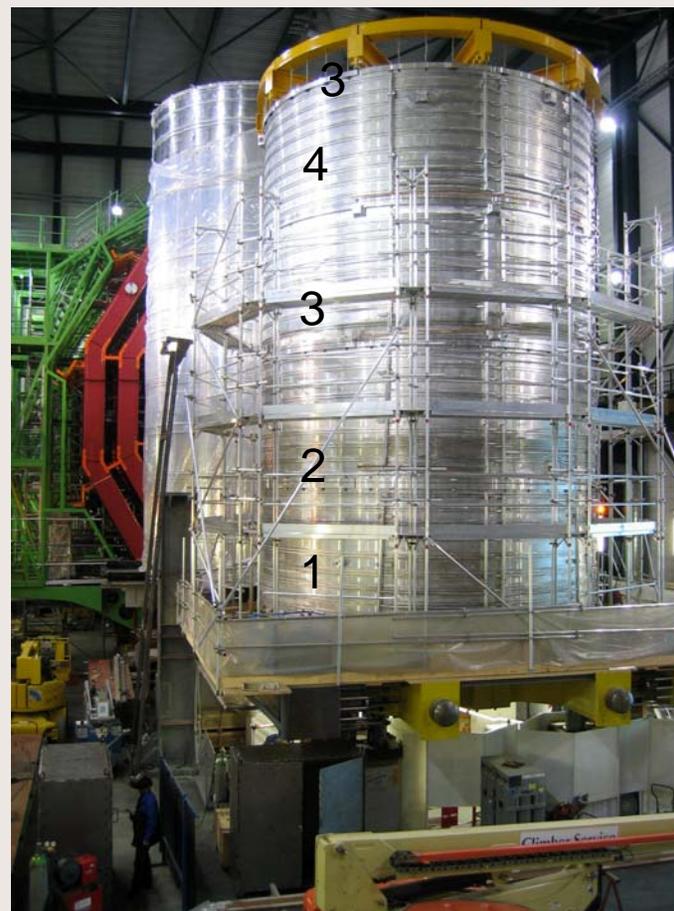
Each 50 t module is then positioned on a large vertical lathe for machining the top surface



The coil has been assembled with vertical axis



This allows a very precise coupling  
But how to insert the 220-t coil  
inside the vacuum vessel with  
horizontal axis?





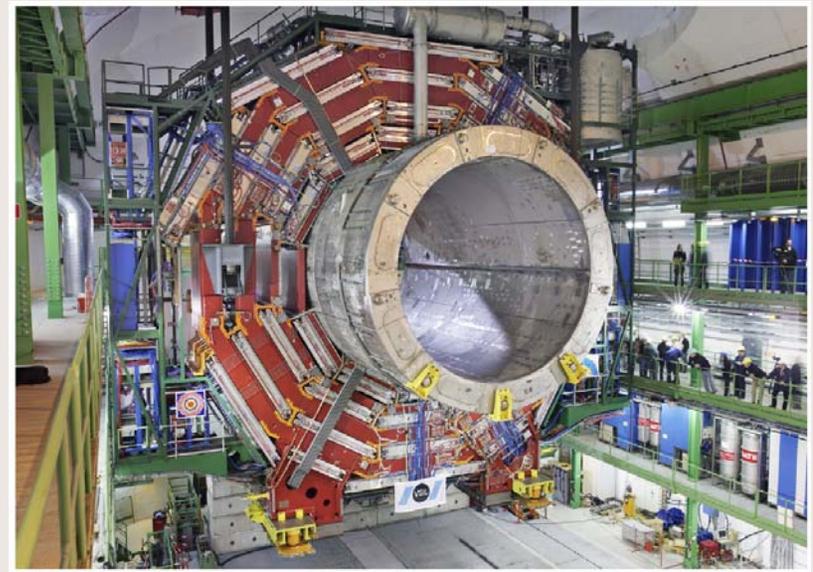
August 2005: Coil swivelling





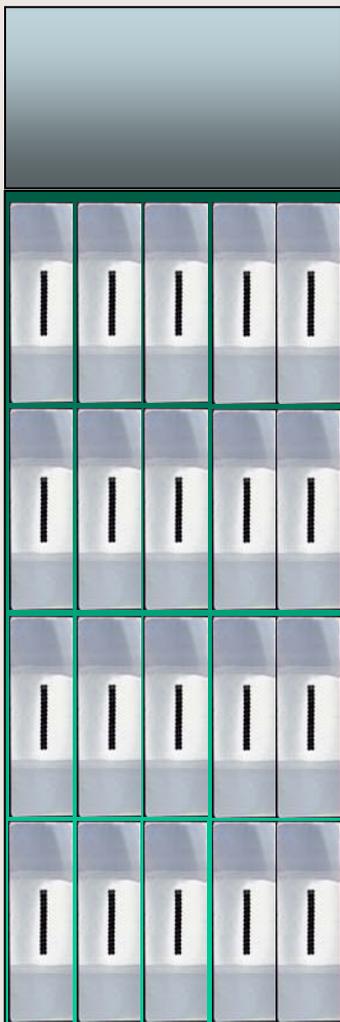
January 2006: End of the CMS Magnet Manufacturing

**The CMS magnet has been successfully tested in the second half of 2006 and placed in the cavern for final assembly of the detector.**



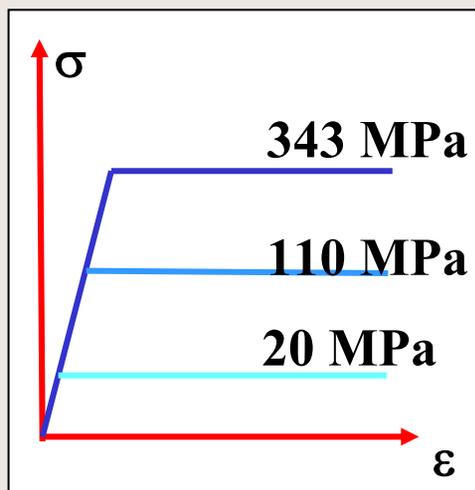
YB0 landing in the CMS experiment hall

## What about the future? (Physicist are starting to think now to ILC)



The CMS magnet is now a reference for future Detector Magnets. May we need larger and/or higher field solenoid? We have to face two problems: mechanics and stability margin.

The first step towards high field could be the replacement of the pure Al with the high strength Ni diluite alloy (like ATLAS CS)



$$\frac{\sigma}{\sigma_{CMS}} = \frac{Y \varepsilon_{CMS} \Delta R_{Al alloy} + \sigma_{Al Ni} \Delta R_{Al Ni}}{Y_{all} \varepsilon_{CMS} \Delta R_{Al alloy} + \sigma_{Al pure} \Delta R_{Al pure}}$$

$$\Delta R_{Al alloy} \approx \Delta R_{Al stab}$$

$$\frac{\sigma}{\sigma_{CMS}} = \frac{115 + 110}{115 + 20} = 1.7 \rightarrow \frac{B}{B_{CMS}} = 1.3$$

$$\rightarrow B = 5.2 \text{ T} \rightarrow BR^2 = 47$$

$$T_c(B) = T_{c0} \left(1 - \frac{B}{B_{c20}}\right)^{0.59}$$



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## Temperature Margin

$$T_c(B) = T_{c0} \left(1 - \frac{B}{B_{c20}}\right)^{0.59} \quad \text{For NbTi } T_{c0} = 9.25 \text{ K } B_{c20} = 13.9 \text{ T.}$$

At  $B = 4.6 \text{ T}$  (Peak field in CMS)  $T_c = 7.35 \text{ K}$

The interesting parameter is the current sharing temperature

$$T_g = T_c - (T_c - T_0) \frac{I_0}{I_c(T_0, B)}$$

$I_{op} = 19140 \text{ A}$ ,  $I_c(T=4.5\text{K}, B=4.6 \text{ T}) = 55600 \text{ A} \rightarrow T_g = 6.35 \text{ K}$ .

The temperature margin in CMS is consequently  $\Delta T = 6.35 - 4.5 = 1.85 \text{ K}$

At  $5.2 \text{ T}$  central field the margin is lower:  $1.4 \text{ K}$  (still acceptable considering that CMS worked up to a temperature of  $5.4 \text{ K}$ ). I personally believe that a margin of  $1 \text{ K}$  is enough. That means a central field of  $6 \text{ T}$  (at  $I/I_c = 0.33$ )

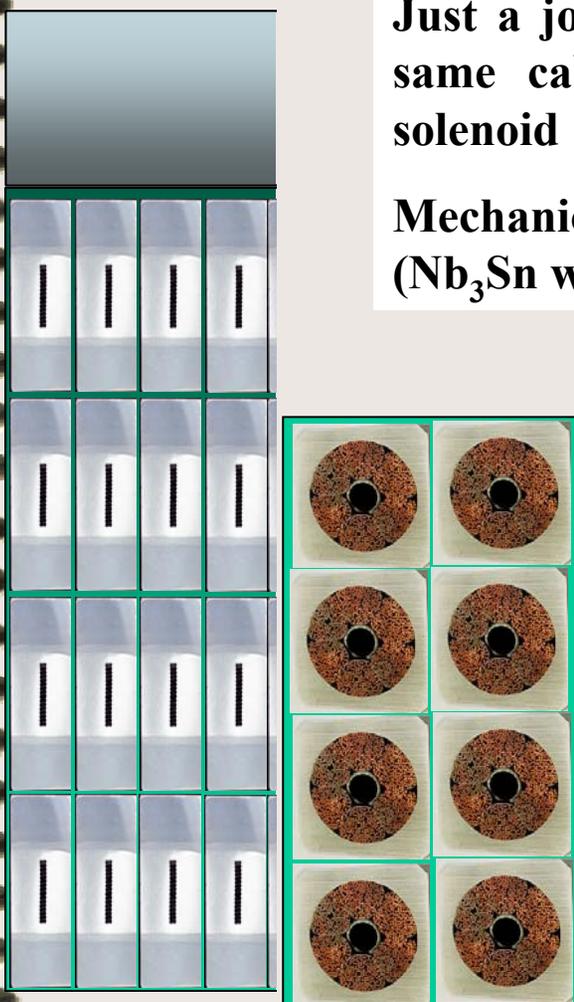
## OTHER OPTION?

**Just a joke! Here it is shown the CMS section using the same cable in conduit foreseen for the ITER central solenoid**

**Mechanically this coil could generate a field as high as 9 T (Nb<sub>3</sub>Sn would be needed in this case).**

**Of course many complications from constructive point of view (at least 130 electrical joints required with insulators for allowing an electrical series and 130 hydraulic parallel circuits)**

**In fact the four detectors under study for ILC (SiD, GLD, SDC and 4° option) are based on superconducting coils conceptually similar to CMS)**





## **CONCLUSIONS**

- **The recently tested CMS magnet is the present ending line of 40 years of developments at the edge of the up-to-date technology.**
- **CMS is a milestone because important magnet characteristics were moved up of one order of magnitude**
- **Long R&D activities (at laboratory and industrial level) for both conductor and winding technologies we required.**
- **With these dimensions the technology could be extrapolated for obtaining up to 5 T magnet (Conductor R&D is needed)**
- **For far future (may be not for ILC) other options could be considered based on the next achievements coming from fusion (ITER project)**