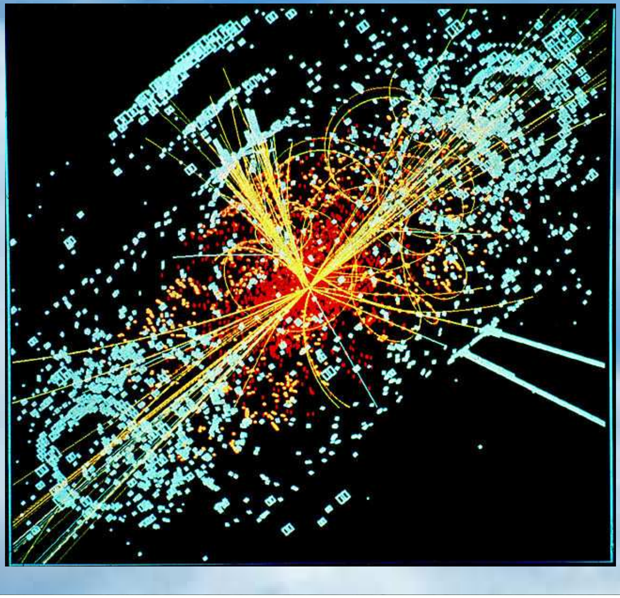
The superconducting magnets for particle detectors: a crossroads between …

Technology

Science

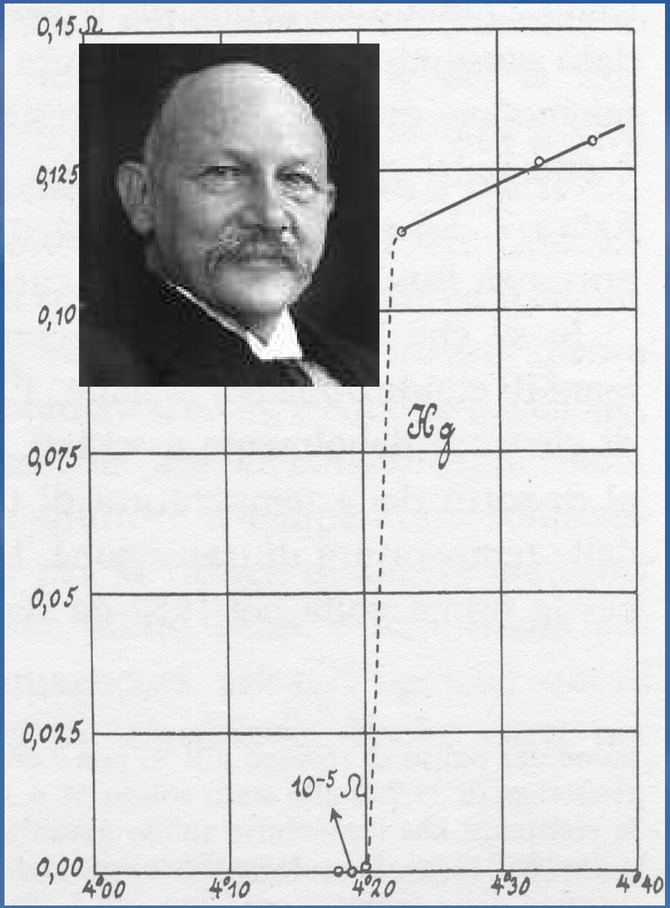


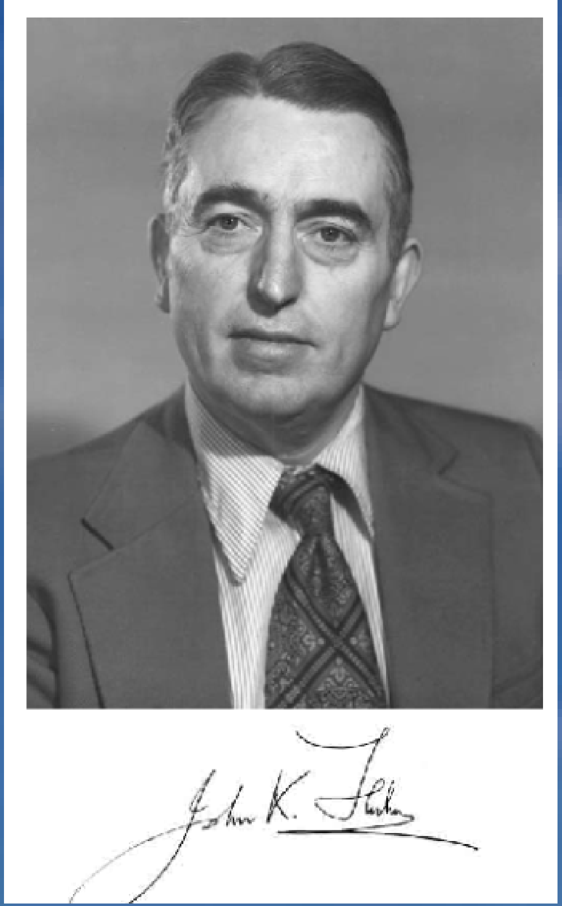
P.Fabbricatore
INFN Genova

Summary

1) Superconductivity and superconducting magnets
2) Detector requirements
3) An historical review of the technologies
4) Future

After the discovery of the superconductivity in 1911 by K. Onnes, the first practical sc wires in NbZr, NbTi and Nb_3Sn appeared 50 years later when J.K.Hulm, with co-workers at the Westinghouse Research Laboratories, developed the first commercial superconducting wires.



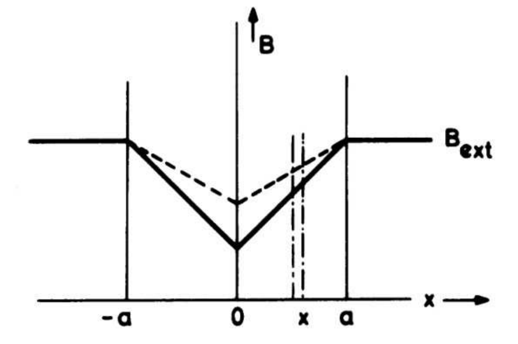


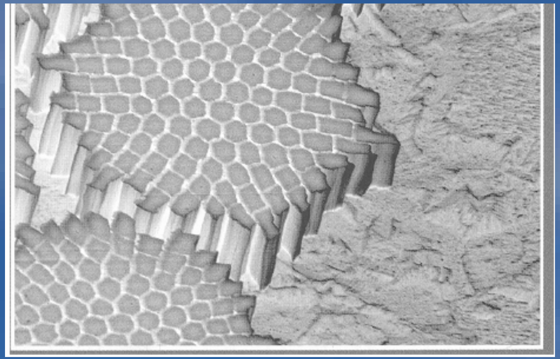
Steps toward the development of sc wires for applications

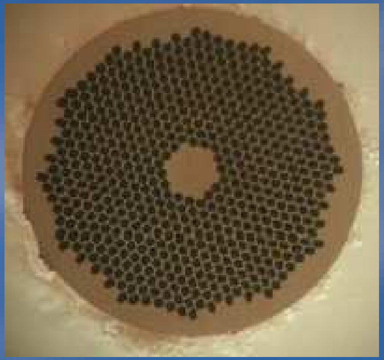
(Not yet completely done in 1961)

1- Development of practical material: **II type with pinning centers**

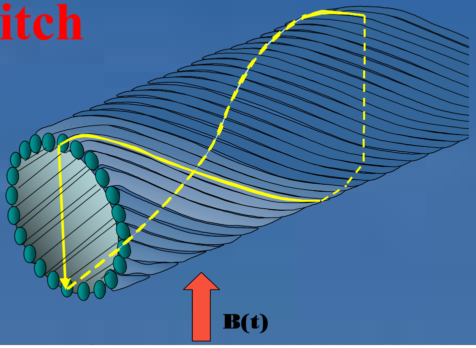
2- Flux jumps instabilities→ **Fine filaments**



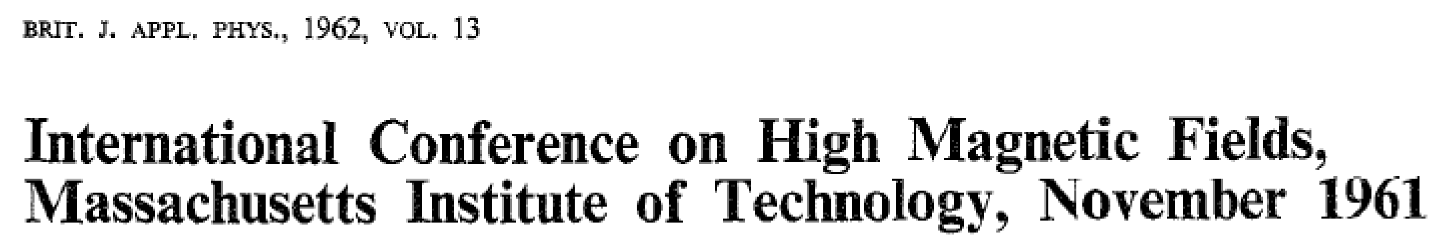




3- Coupling currents → **Twist pitch**

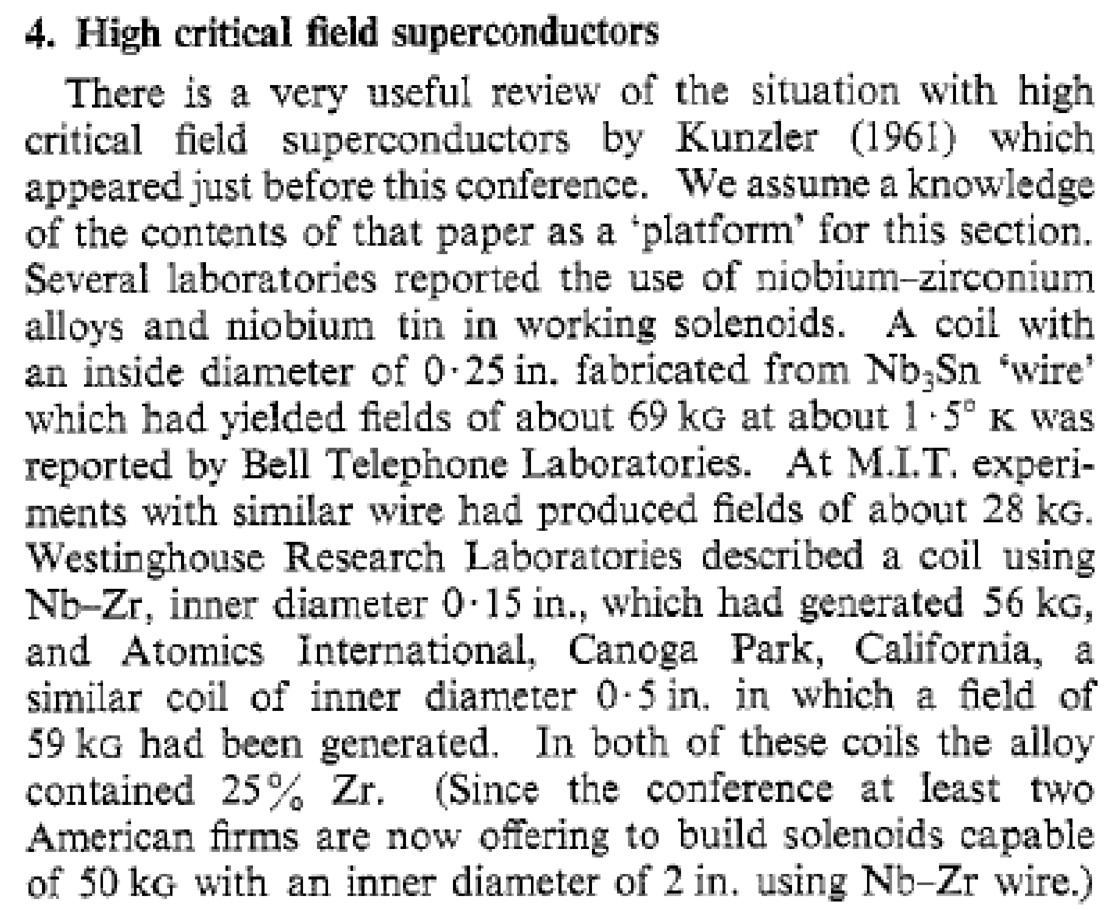


$$\tau = \frac{\mu_0}{2\rho_{et}}\left(\frac{l_p}{2\pi}\right)^2$$



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

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

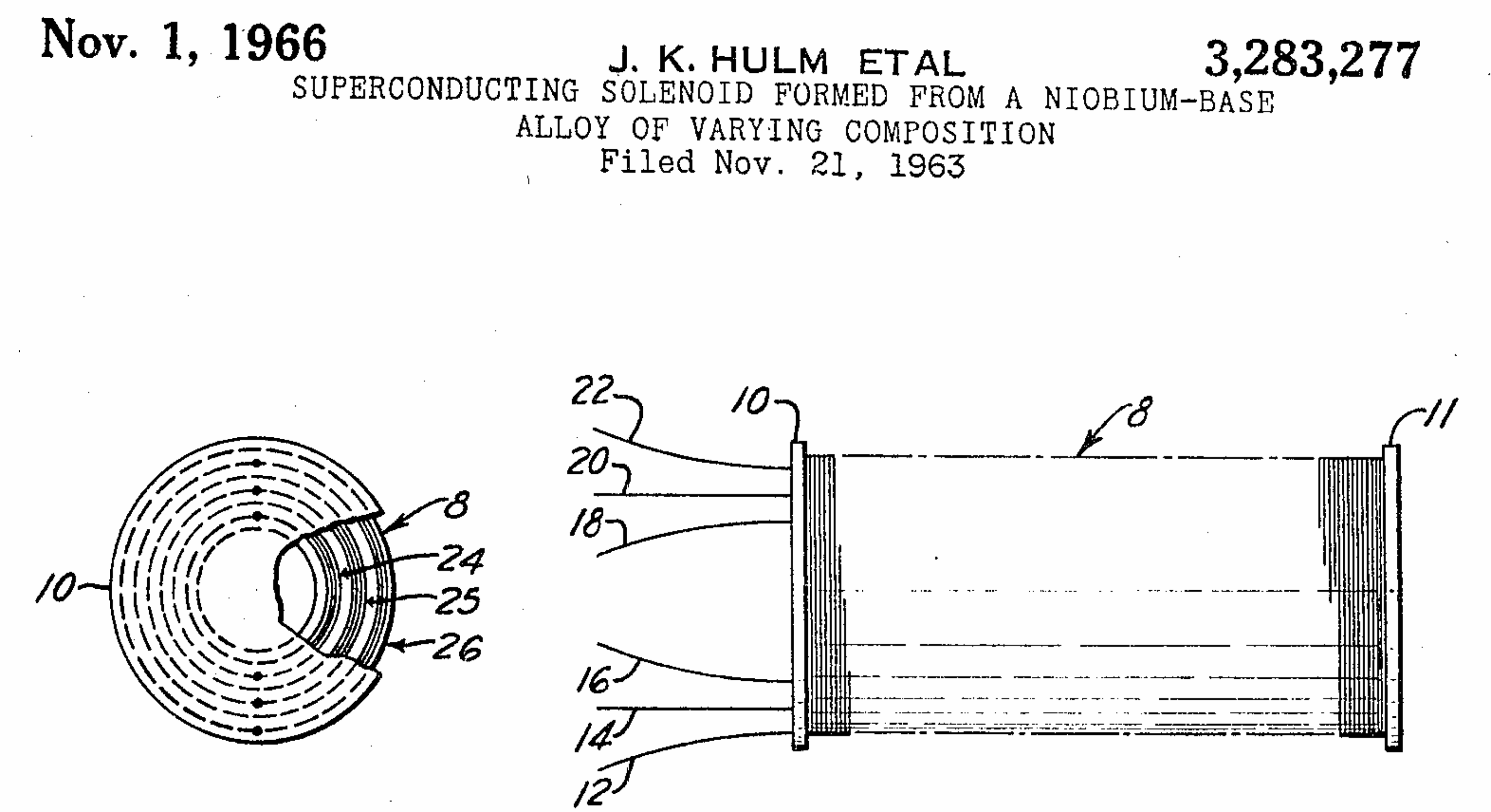


4. High critical field superconductors

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_3Sn ‘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 Atomics 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.)

As John Hulm recalled some years later :

“Those tiny, primitive magnets were, of course, terribly unstable and tended to damage themselves on normalization, for reasons that are now well understood. One had to have faith to believe that these erratic toys of the low temperature physicists would ever be of any consequence as large engineered devices”

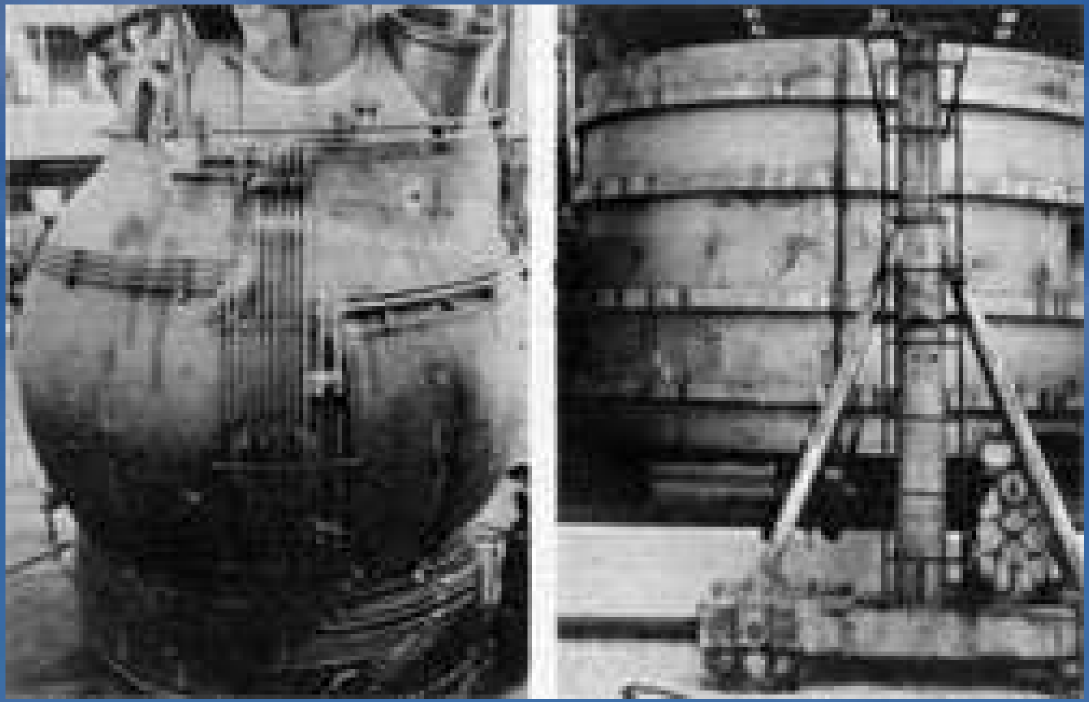


Nov. 1, 1966 J. K. HULM ETAL 3,283,277

SUPERCONDUCTING SOLENOID FORMED FROM A NIOBIUM-BASE
ALLOY OF VARYING COMPOSITION
Filed Nov. 21, 1963

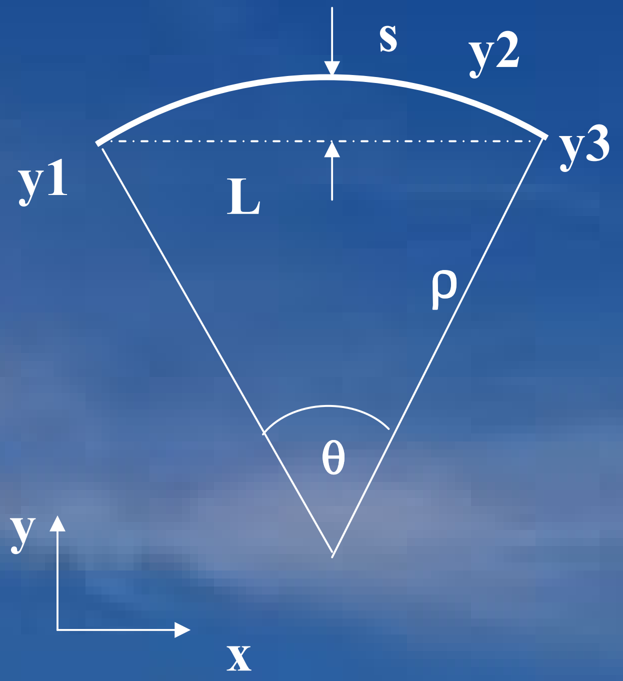
First very large magnets for Particle Physics (surprisingly) developed only few years later, with conductor technology far to be mature

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



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

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



$$p_\perp = qB\rho$$

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

$$\frac{L}{2\rho} = \sin\theta/2 \approx \theta/2 \quad \rightarrow \quad \theta \approx \frac{0.3L\cdot B}{p_T}$$

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

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\,\sigma(x)}{s} = \frac{\sigma(x)\cdot 8p_T}{0.3\cdot BL^2}\cdot\sqrt{\frac{3}{2}}$$

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)} \quad (N > 10)$$

Superconducting magnets with large dimensions

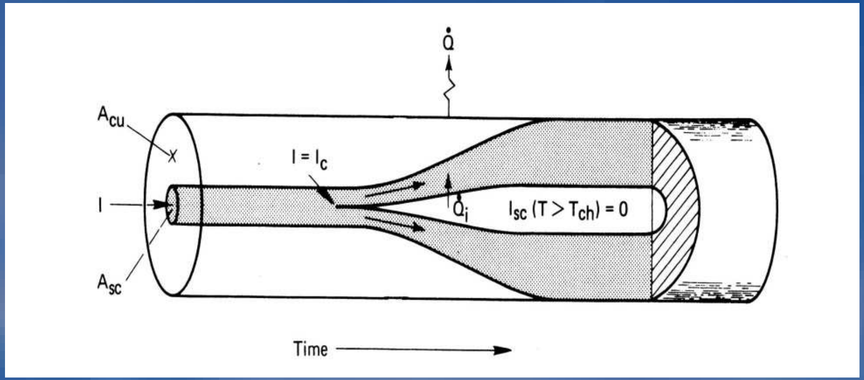
General Requirements for Detector Magnets

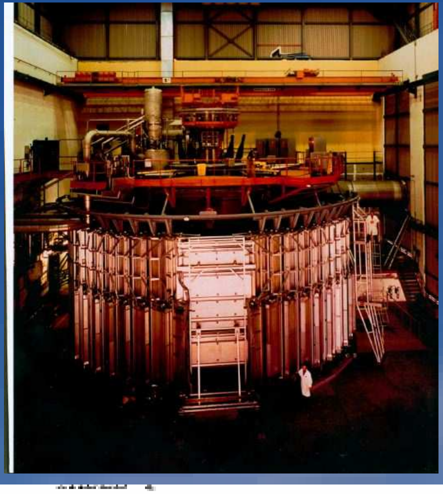
1) The magnetic field amplitude is closely related to the energy of colliding beams and to the resolution in momentum measurement of emerging particles. The required magnetic field is > 1 T in large volumes , leading to the need of employing superconducting coils.

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

3) 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

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

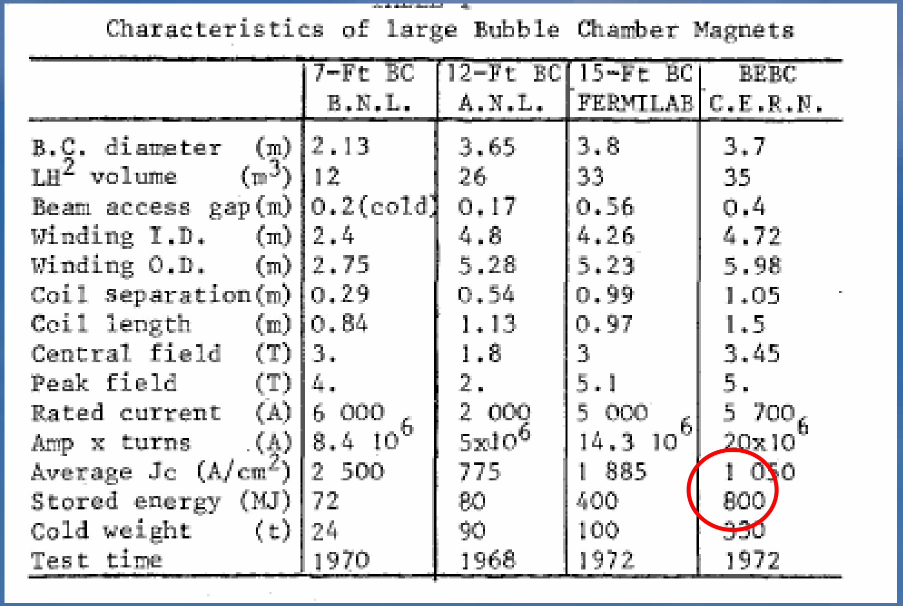




$$\dot{G} = \rho_{Cu} I_c^2 / A_{Cu}$$

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

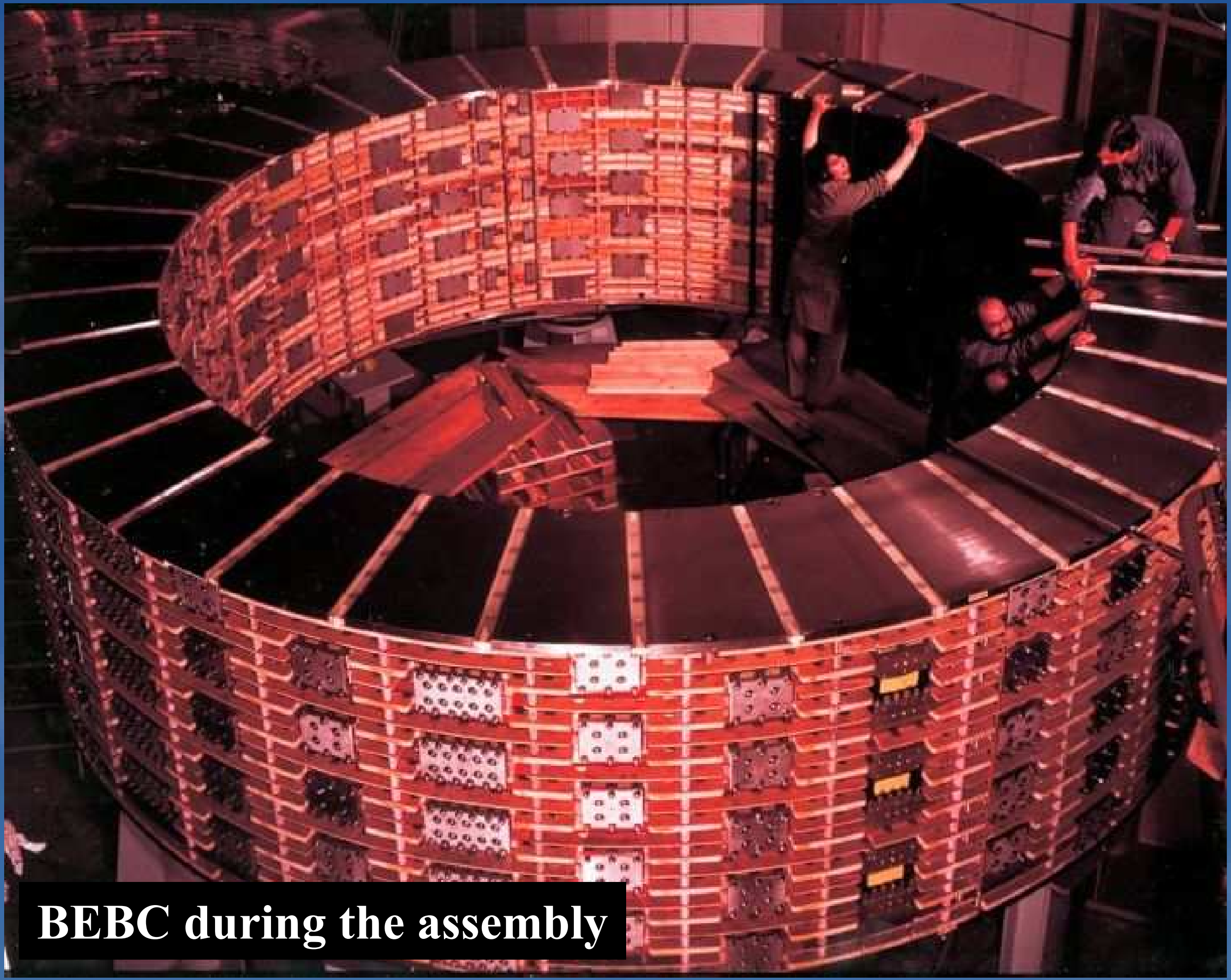
$$\alpha = \frac{\dot{G}}{\dot{Q}} = \frac{\rho_{Cu} I_c^2}{(PA)_{Cu} h(T_c - T_b)}$$



Characteristics of large Bubble Chamber Magnets

	7-Ft BC B.N.L.	12-Ft BC A.N.L.	15-Ft BC FERMILAB	BEBC C.E.R.N.
B.C. diameter (m)	2.13	3.65	3.8	3.7
LH^2 volume (m^3)	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)	$8.4\ 10^6$	$5x10^6$	$14.3\ 10^6$	$20x10^6$
Average Jc (A/cm^2)	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
(thank to F.Wittgenstein)



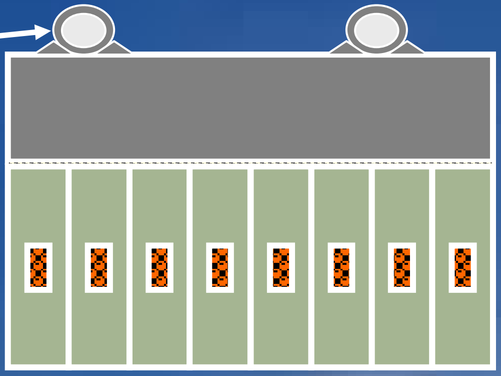
BEBC during the assembly

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 powerful cooling system was useless for dc magnets, provided that a good stability is guaranteed and the disturbances of mechanical nature limited. → The thin high field solenoids.

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

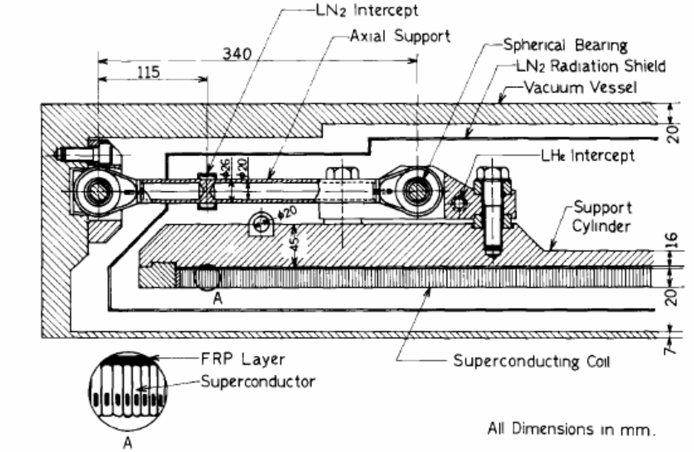
Parameters		
Field	1.5	T
Coil Radius	01.5	m
Length	4.8	m
Sored Energy	30	MJ

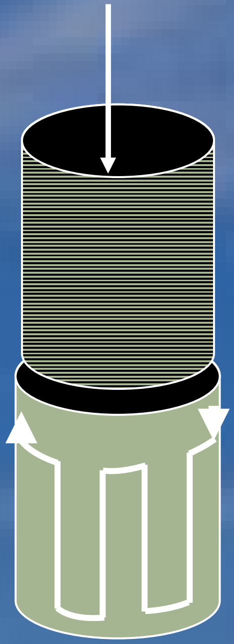
Cooling pipes directly welded on Al5083 cylinder



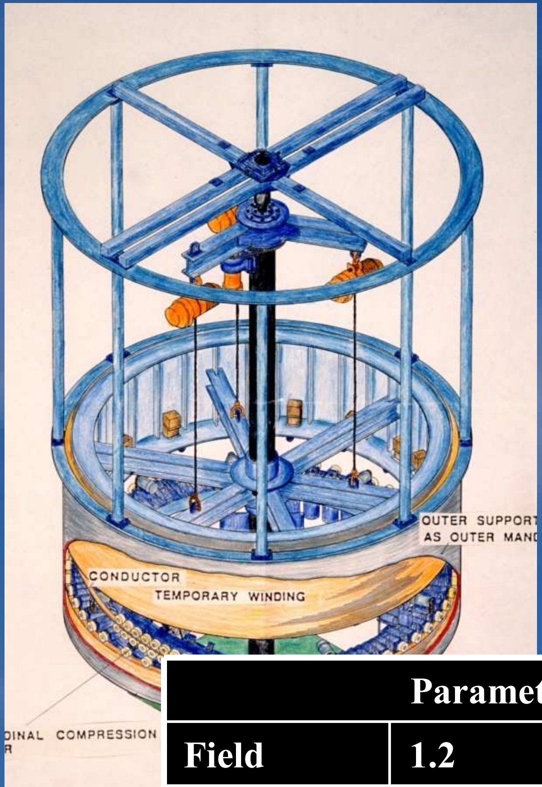
After the winding the coil is shrink-fitted inside the outer cylindrical support

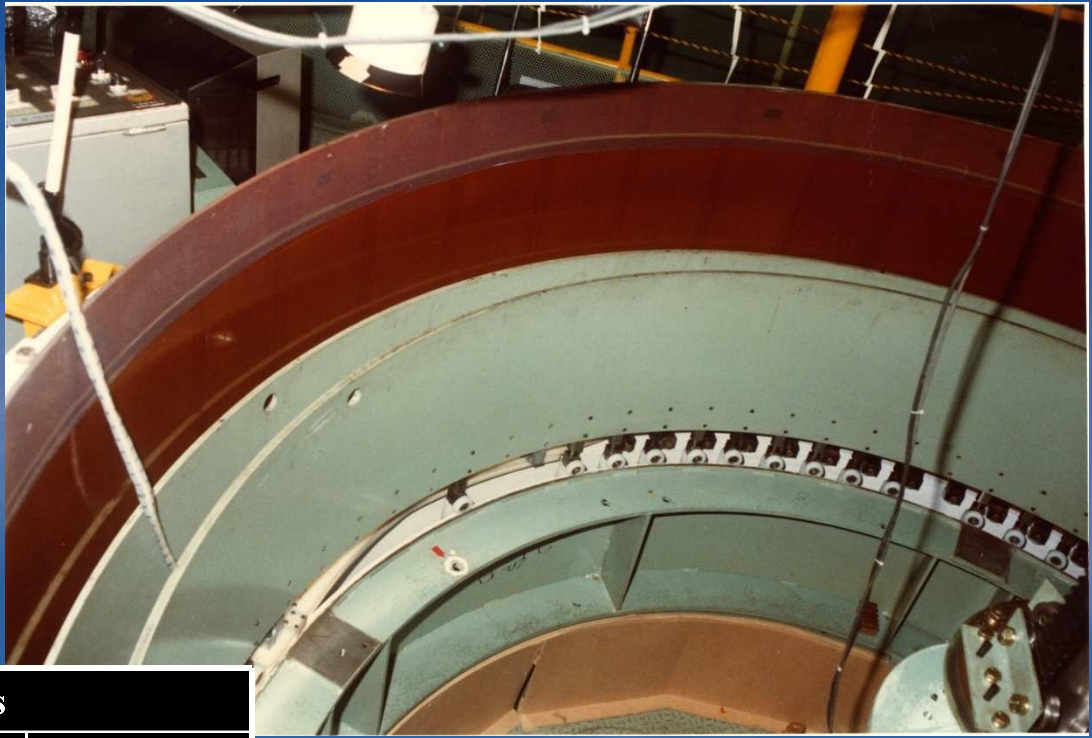
Superconducting solenoid coil was being made at Hitachi company.



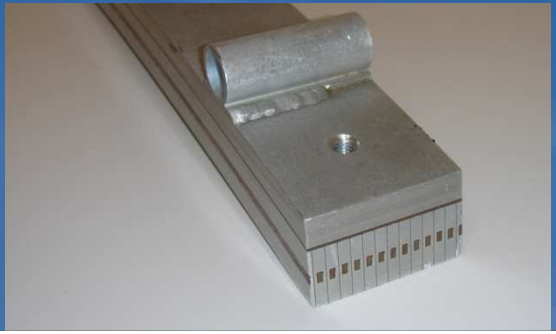


TOPAZ - For the first time the inner winding operation

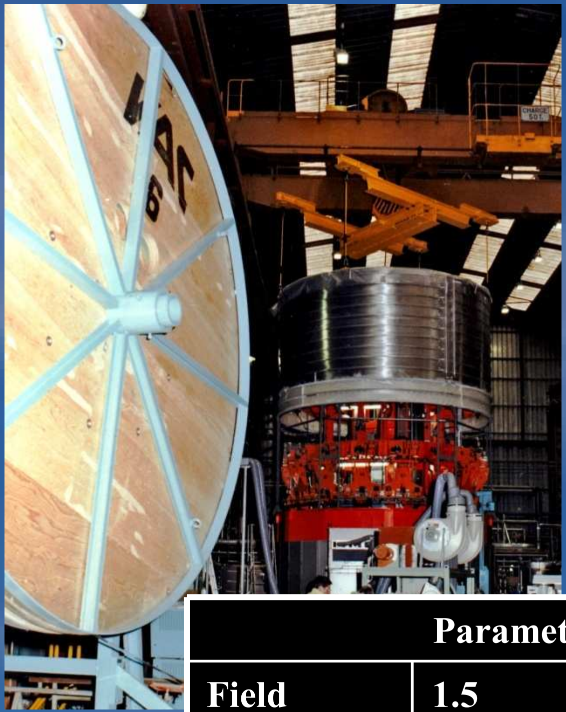


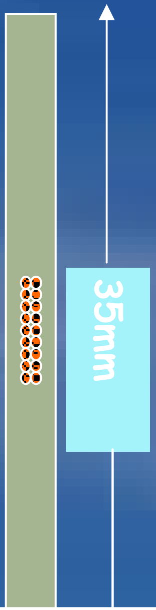


Parameters		
Field	1.2	T
Coil Radius	1.45	m
Length	5.1	m
Stored Energy	19	MJ

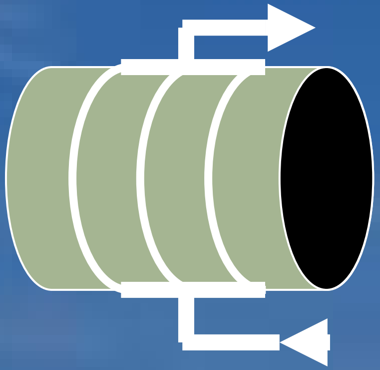


ALEPH – Rutherford cable- Resin impregnation under vacuum – Thermo-siphon



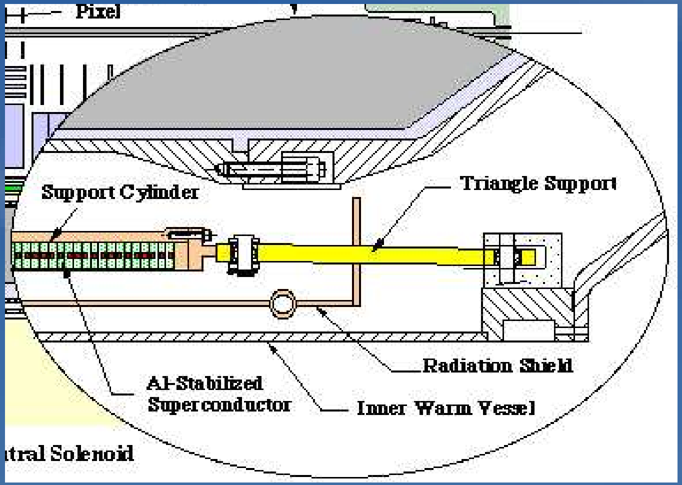


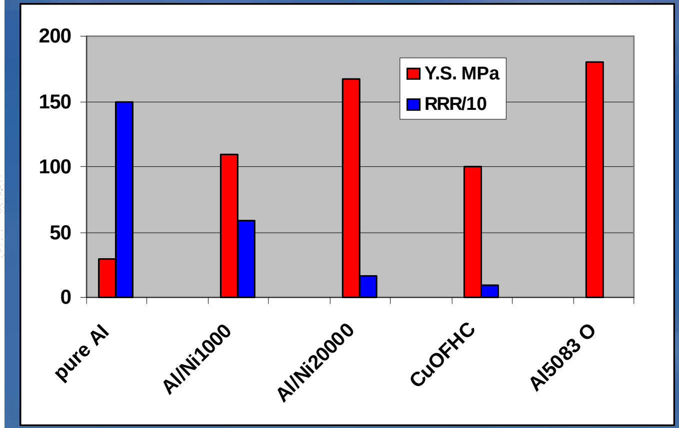
Parameters		
Field	1.5	T
Coil Radius	2.75	m
Length	6.4	m
Sored Energy	130	MJ

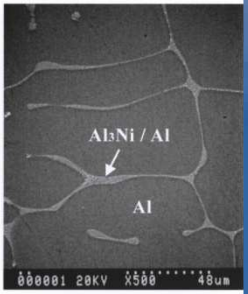


ATLAS CS – Hi strength Al diluted alloy

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

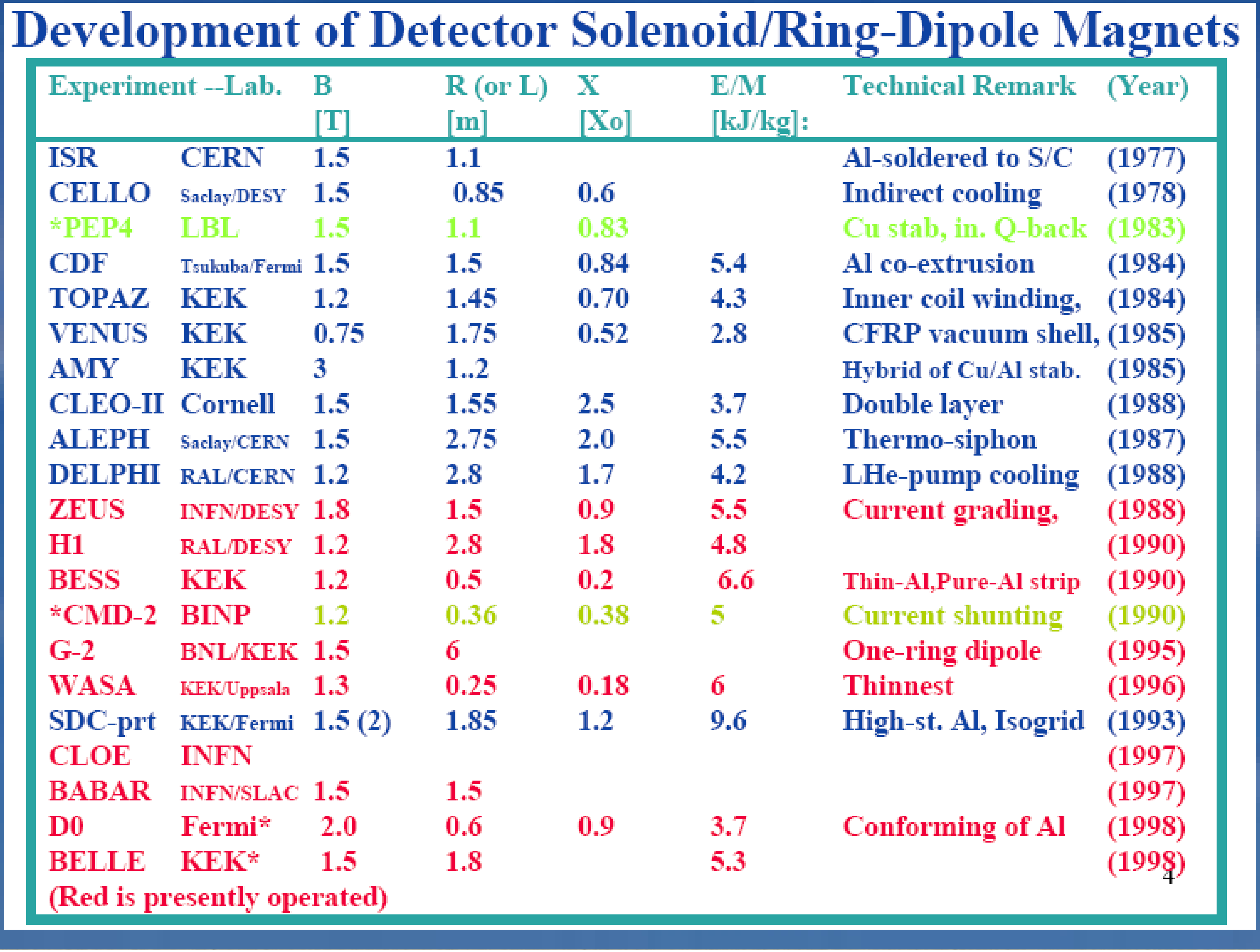






b) Al-0.5wt%Ni Alloy

Before LHC

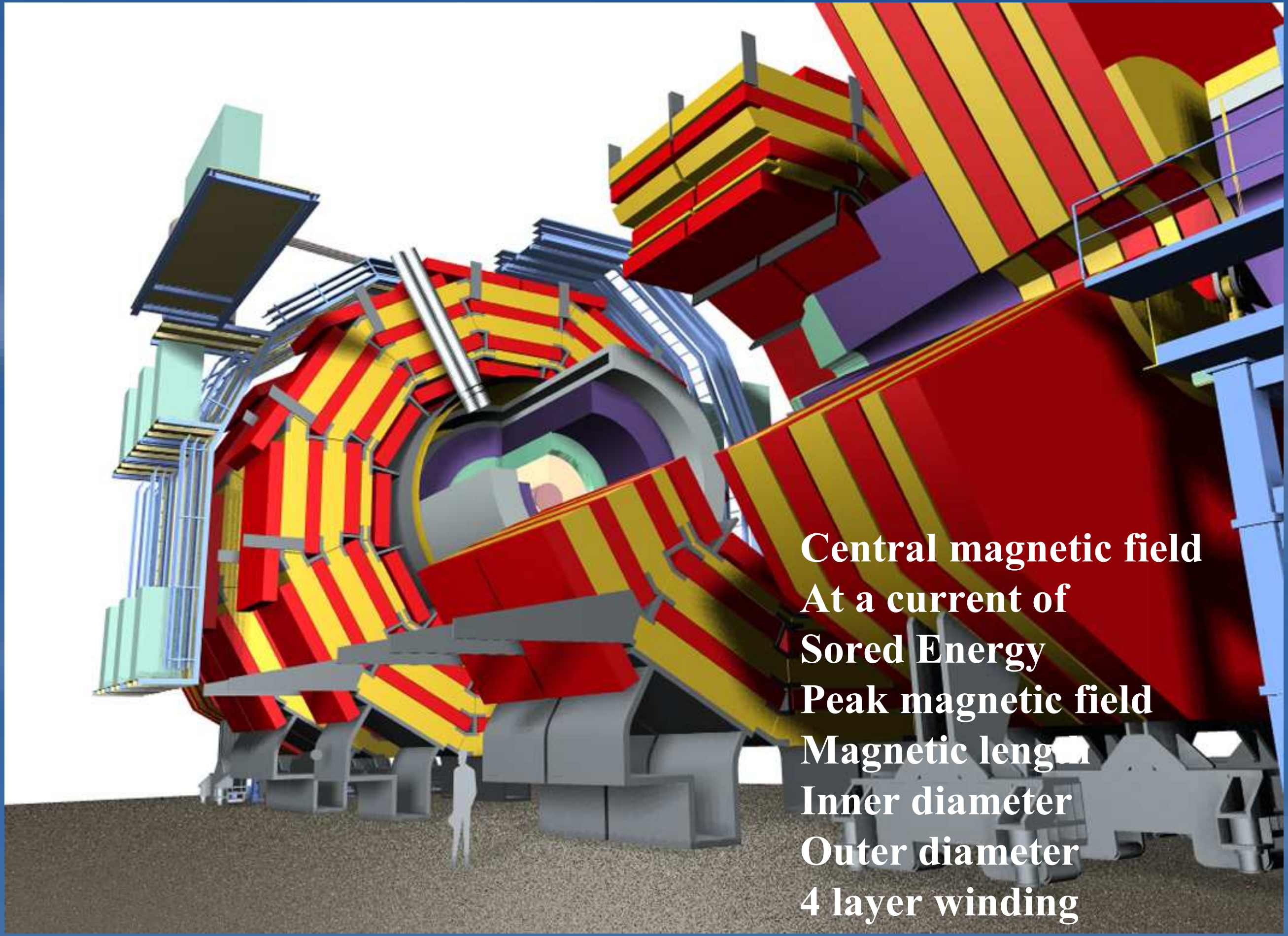


Development of Detector Solenoid/Ring-Dipole Magnets

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



Central magnetic field	4 T
At a current of	20000 A
Sored Energy	2520 MJ
Peak magnetic field	4.6T
Magnetic length	12.5 m
Inner diameter	6.32 m
Outer diameter	6.95 m
4 layer winding	

A basic parameter for comparing different magnets

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

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

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

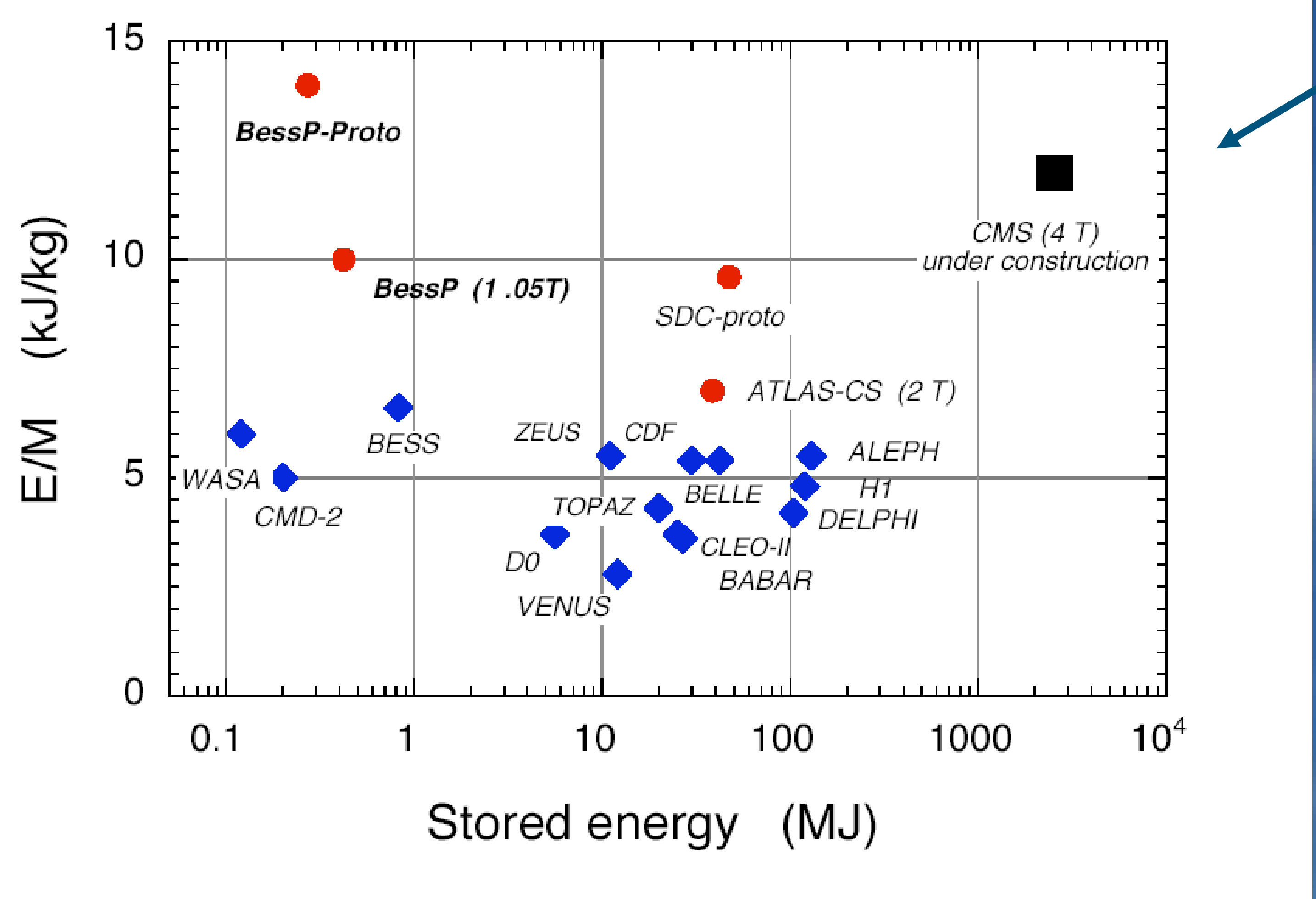
α is the fraction of the mechanical resistent material

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

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

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

E/M ratio vs E for several solenoids



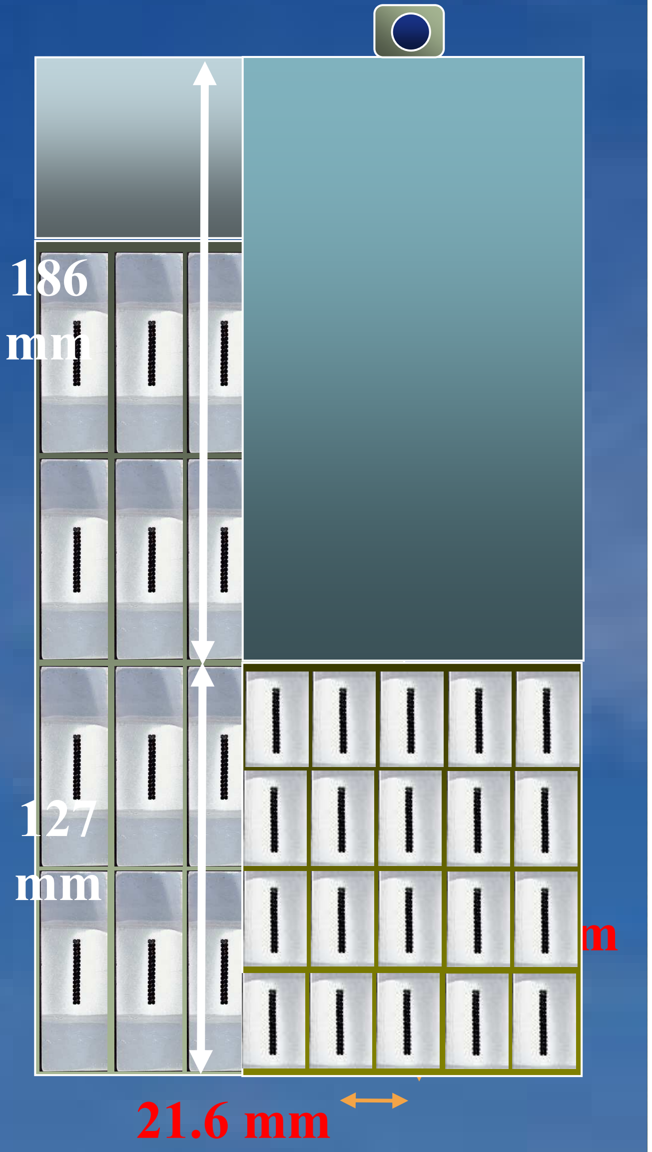
This 'anomalous' positioning meant that innovative solutions were needed to face this challenge

Reinforced Conductor

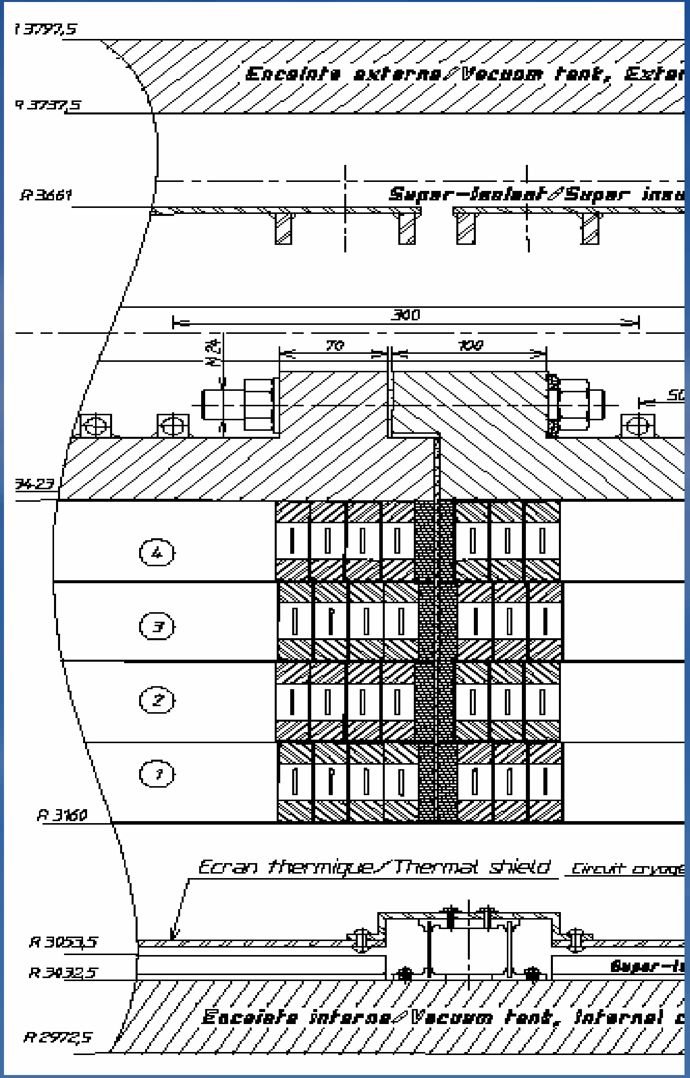
The basic idea in CMS design was to include the mechanical reinforcement in the conductor. This choice allow to minimize the shear stresses in the winding

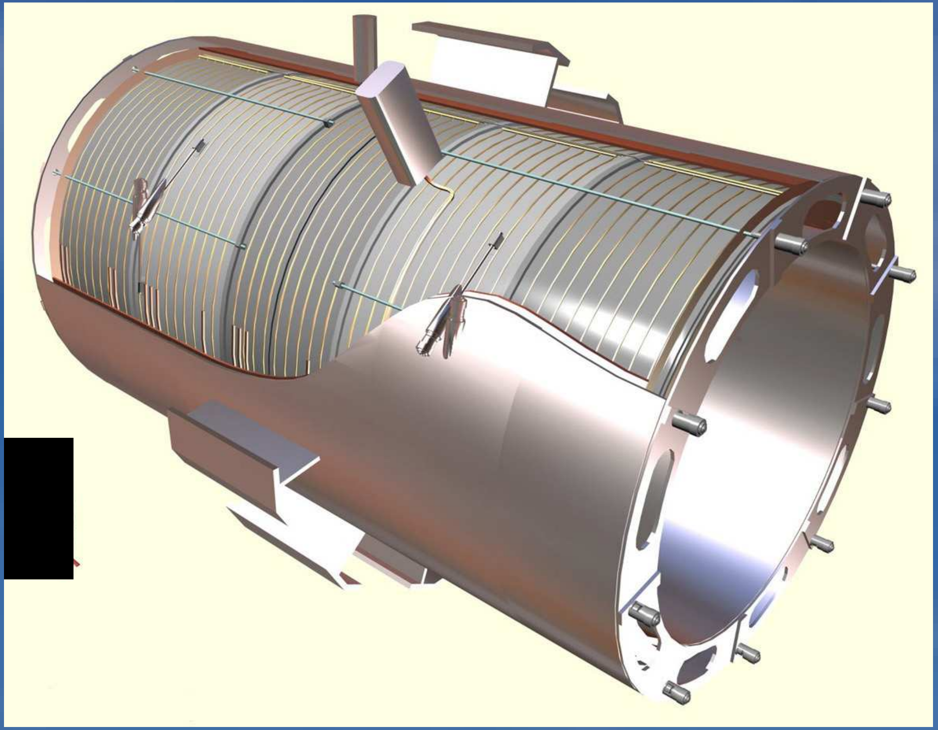
A (thin) mandrel is still present for:

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

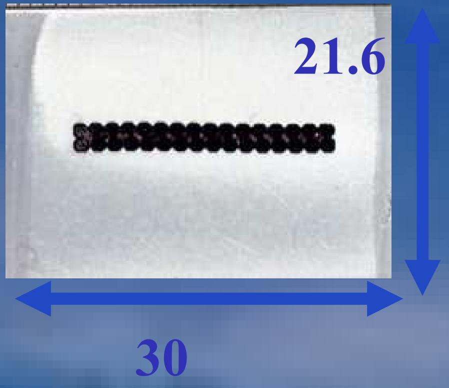


At the completion of the technical design, the CMS was conceived as a 5 module coil, requiring R&D developments at industrial level of conductor and winding technologies

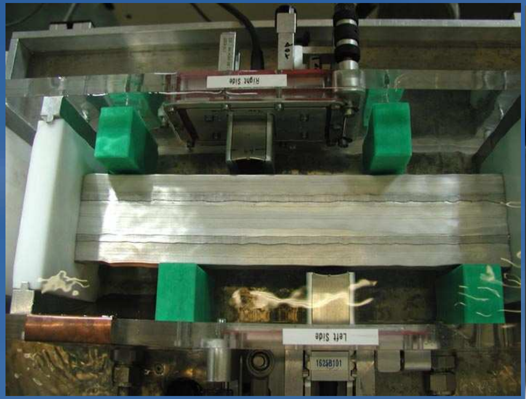


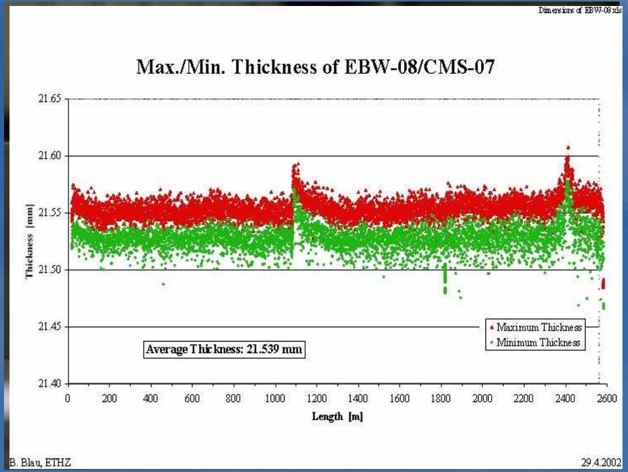


Co-extrusion of 2.5 km length with continuous process

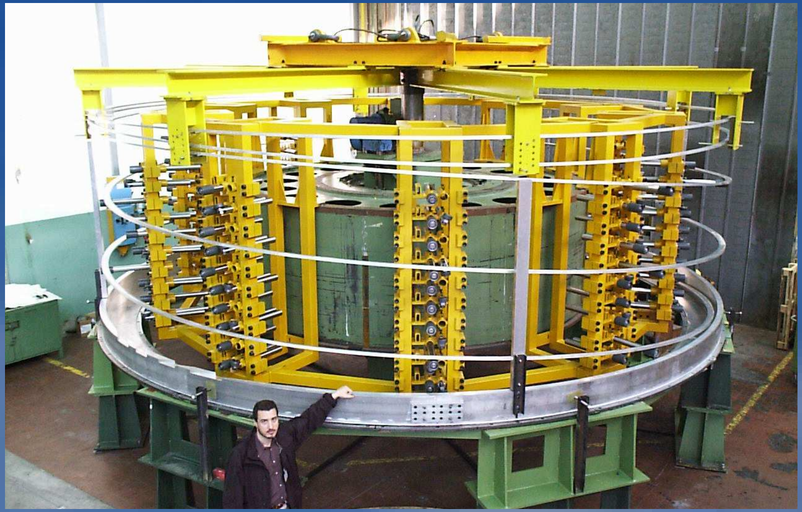


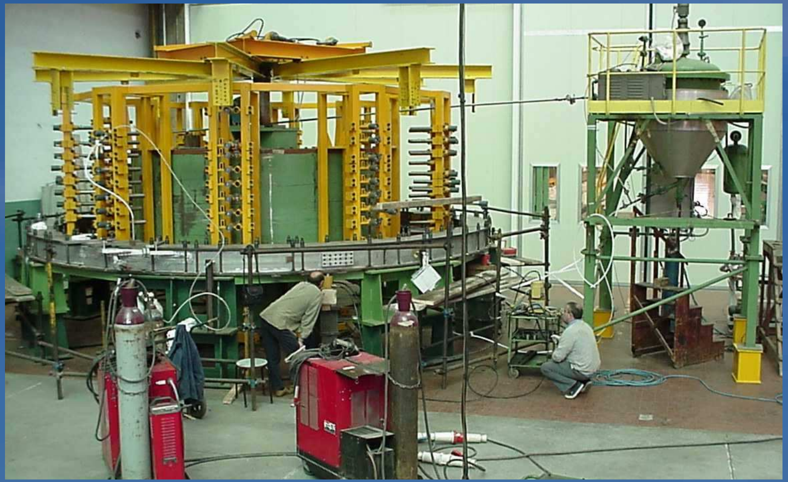
Continuous EB-welding of each 2.5 km length



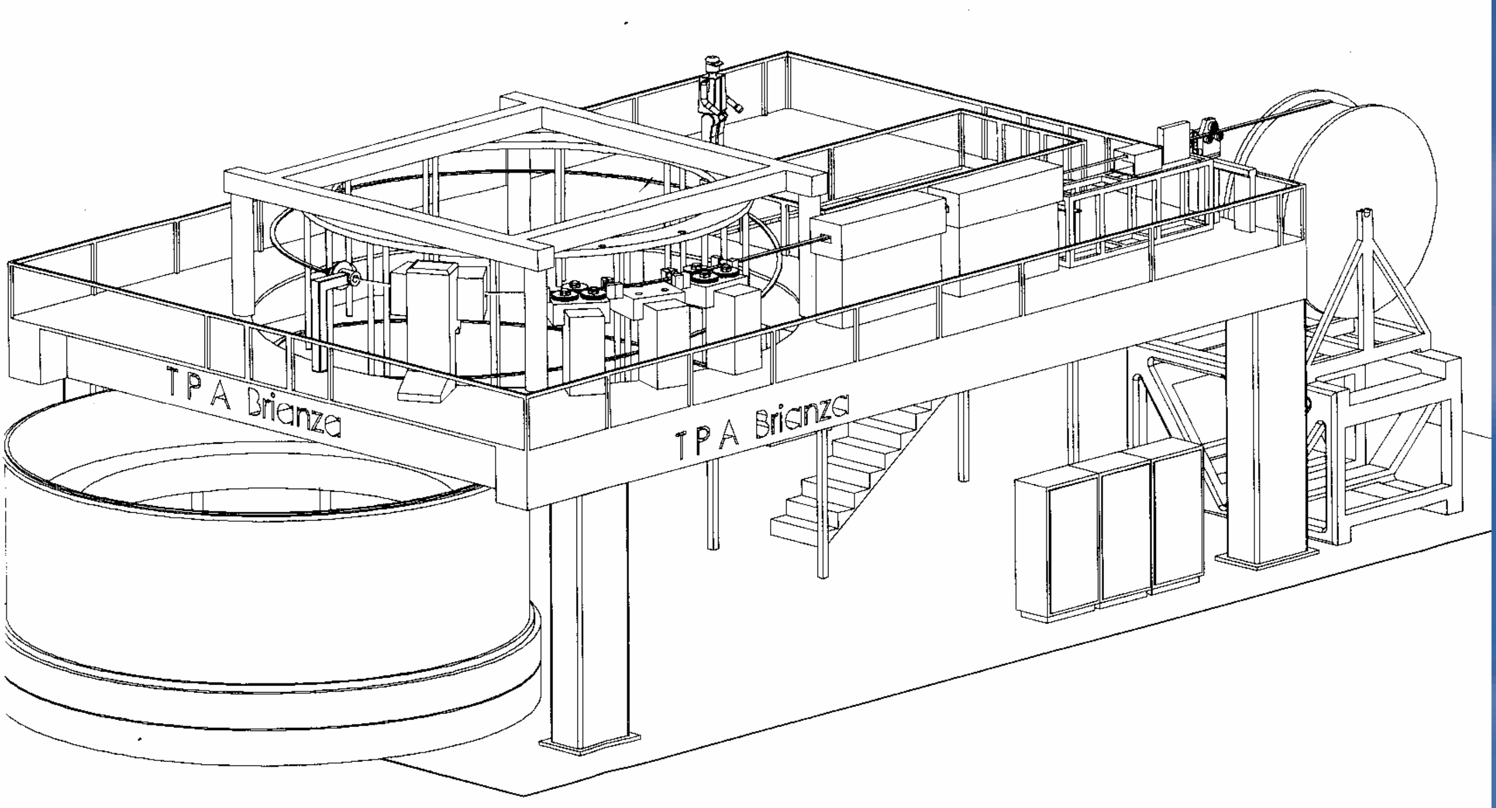


Developments of the winding techniques for a reinforced conductor





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

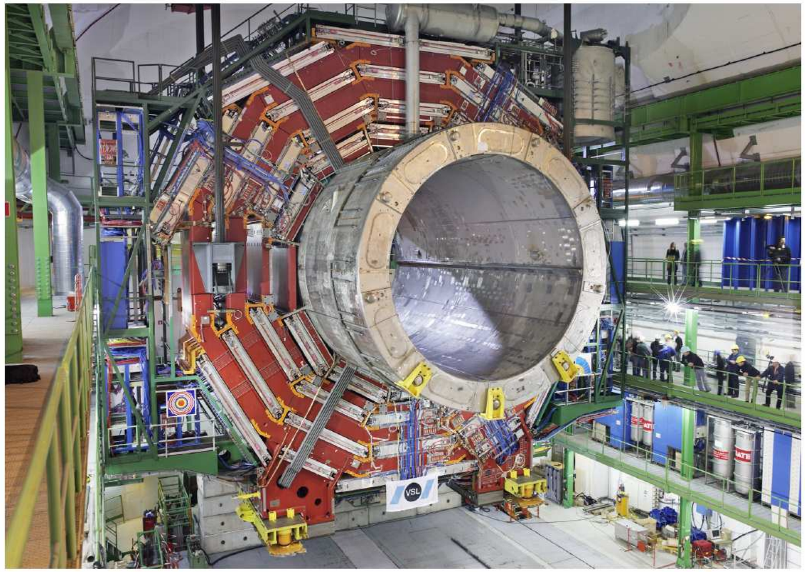


The coil was assembled with vertical axis

August 2005: Coil swivelling

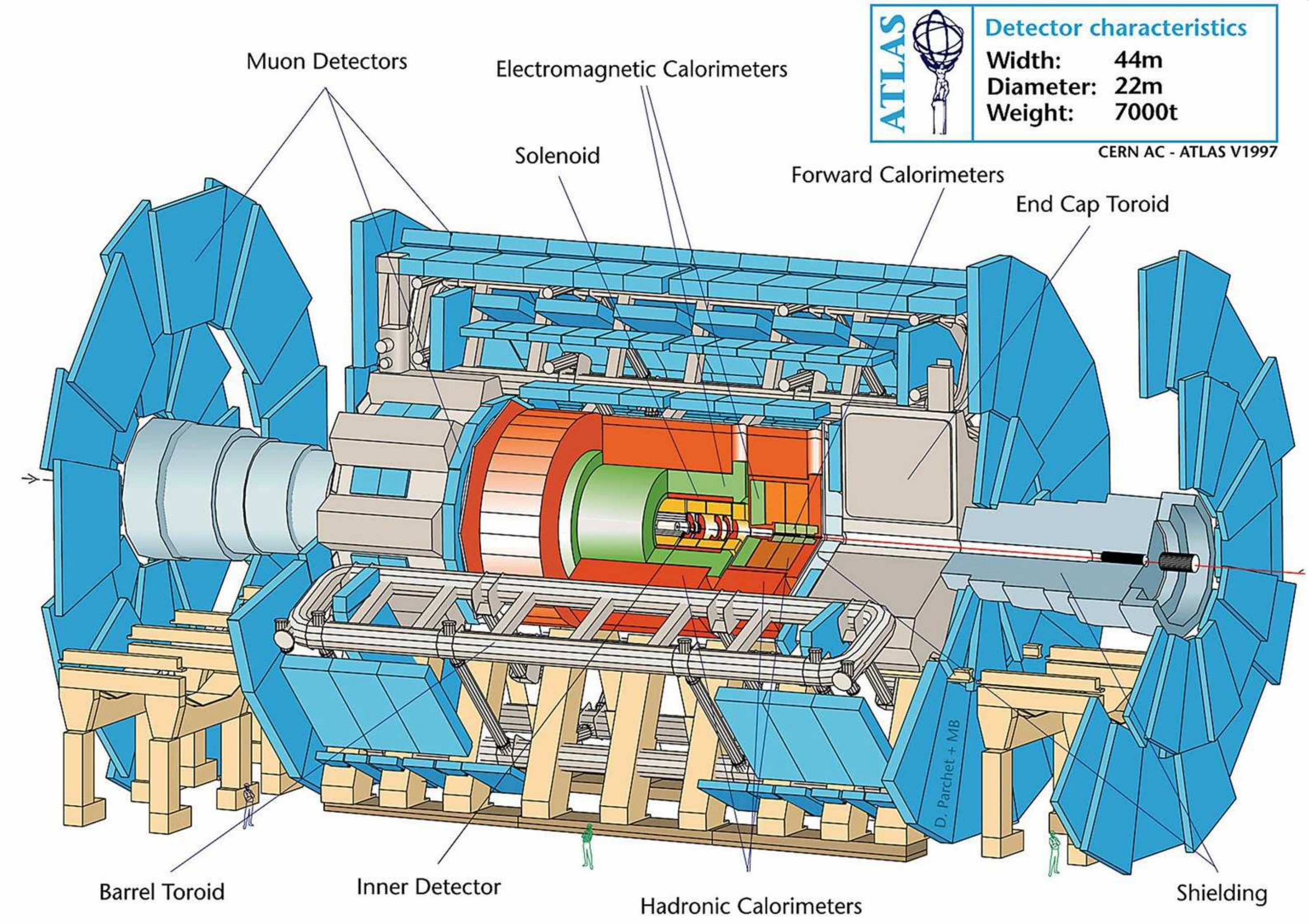
January 2006: End of the CMS Magnet Manufacturing

The CMS magnet was succesfully tested in the second half of 2006 and operated till now contributing to the dicovery of Higgs boson

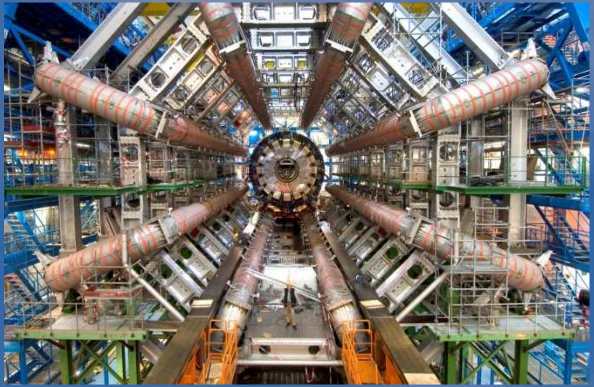


YB0 landing in the CMS experiment hall

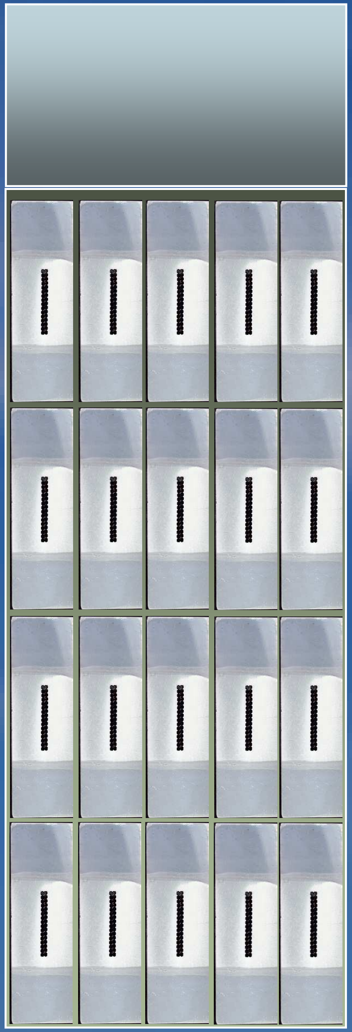
ATLAS: the big brother of CMS



A gigantic story

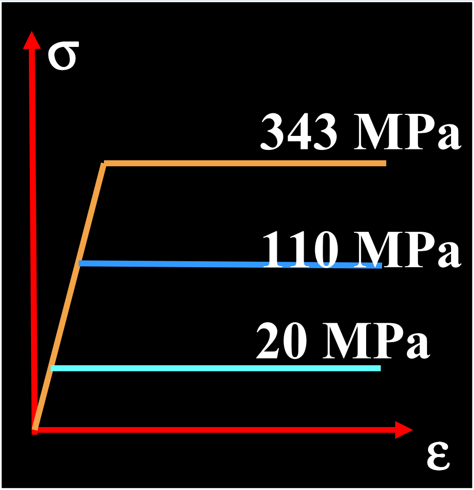


What about the future? (Linear Collider ?)



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)



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

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

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

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

Temperature Margin

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

For NbTi T_{c0} = 9.25 K B_{c20} = 13.9 T.

At B = 4.6 T (Peak field in CMS) T_c = 7.35 K

The interesting parameter is the current sharing temperature

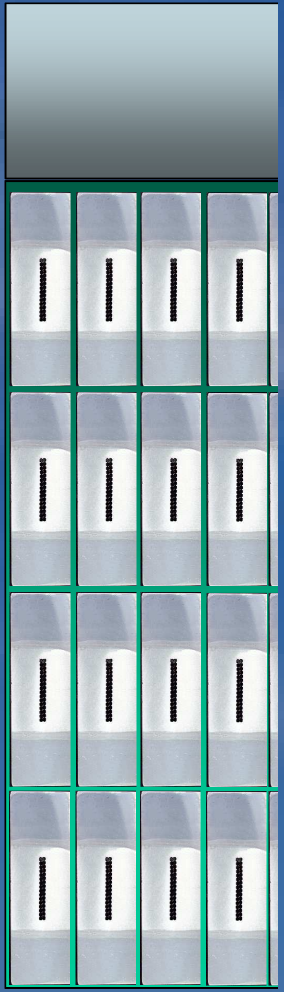
$$T_g = T_c - (T_c - T_0)\frac{I_0}{I_c(T_0, B)}$$

Iop =19140 A, Ic(T=4.5K ,B= 4.6 T) = 55600 A →Tg = 6.35 K.

The temperature margin in CMS is consequently ΔT=6.35-4.5=1.85 K

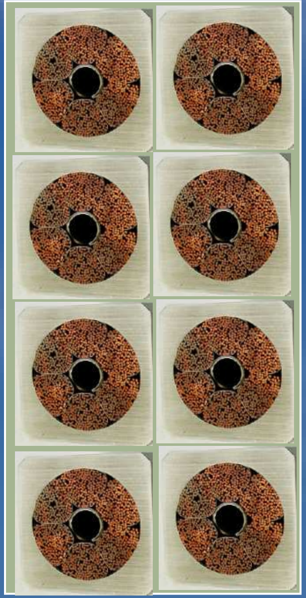
At 5.2 T central field the margin is lower: 1.4 K (still acceptable considering that CMS worked up to a temperature of 5.4 K). I personally believe that a margin of 1 K is enough. That means a central field of 6 T (at I/Ic=0.33)

OTHER OPTION?



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

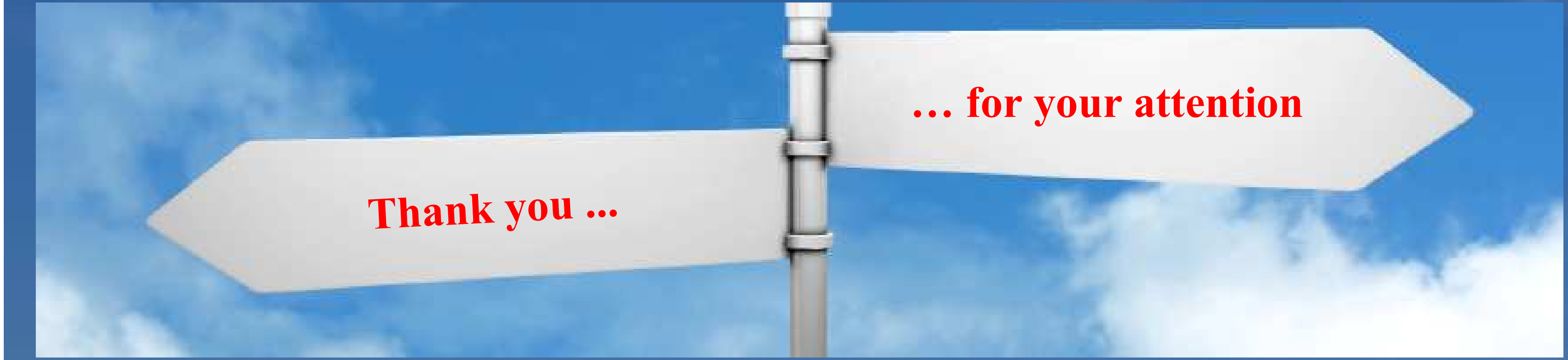
Mechanically this coil could generate a field as high as 9 T (Nb_3Sn would be needed in this case).



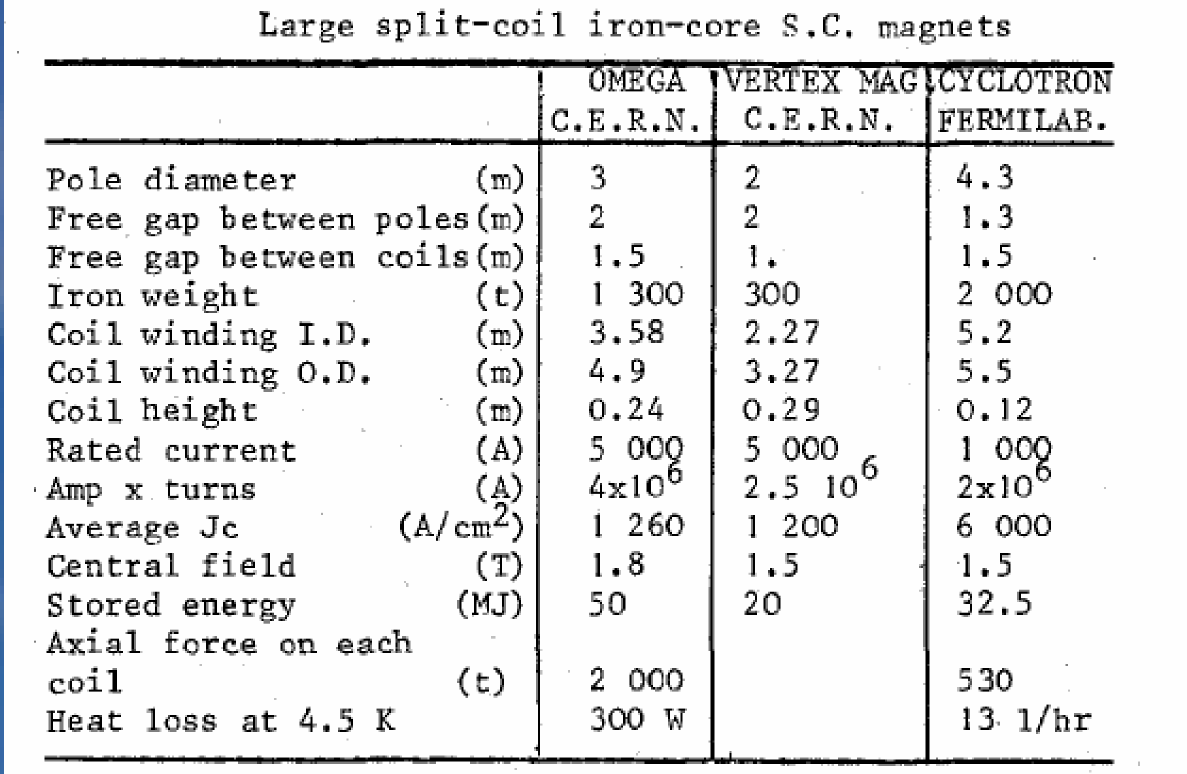
Of course many complications from constructive point of view (at least 130 electrical joints required with insulators for allowing an electrical series and 130 hydraulic parallel circuits)

CONCLUSIONS

- The detector magnets are evolving since 50 years, requiring any time developments at the edge of the up-to-date technology.
- As the accelerated particle energy increased, the requirement in momentum resolution demanded for new technologies involving superconducting cables. Now and … in future.
- In the sixties the detector magnet had an important role in pushing the superconducting technology

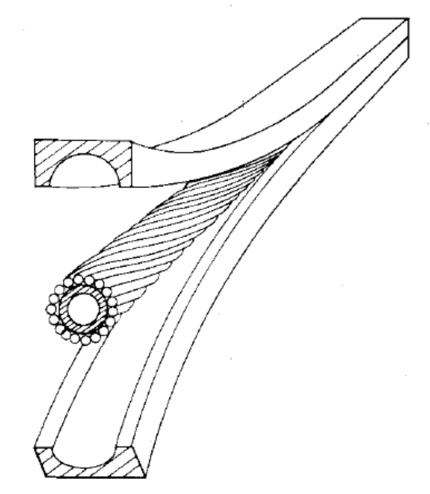


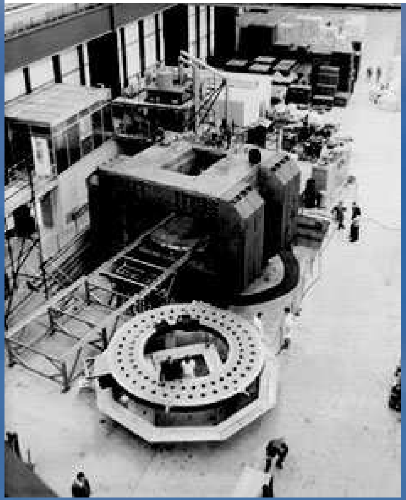
Forced flow magnets

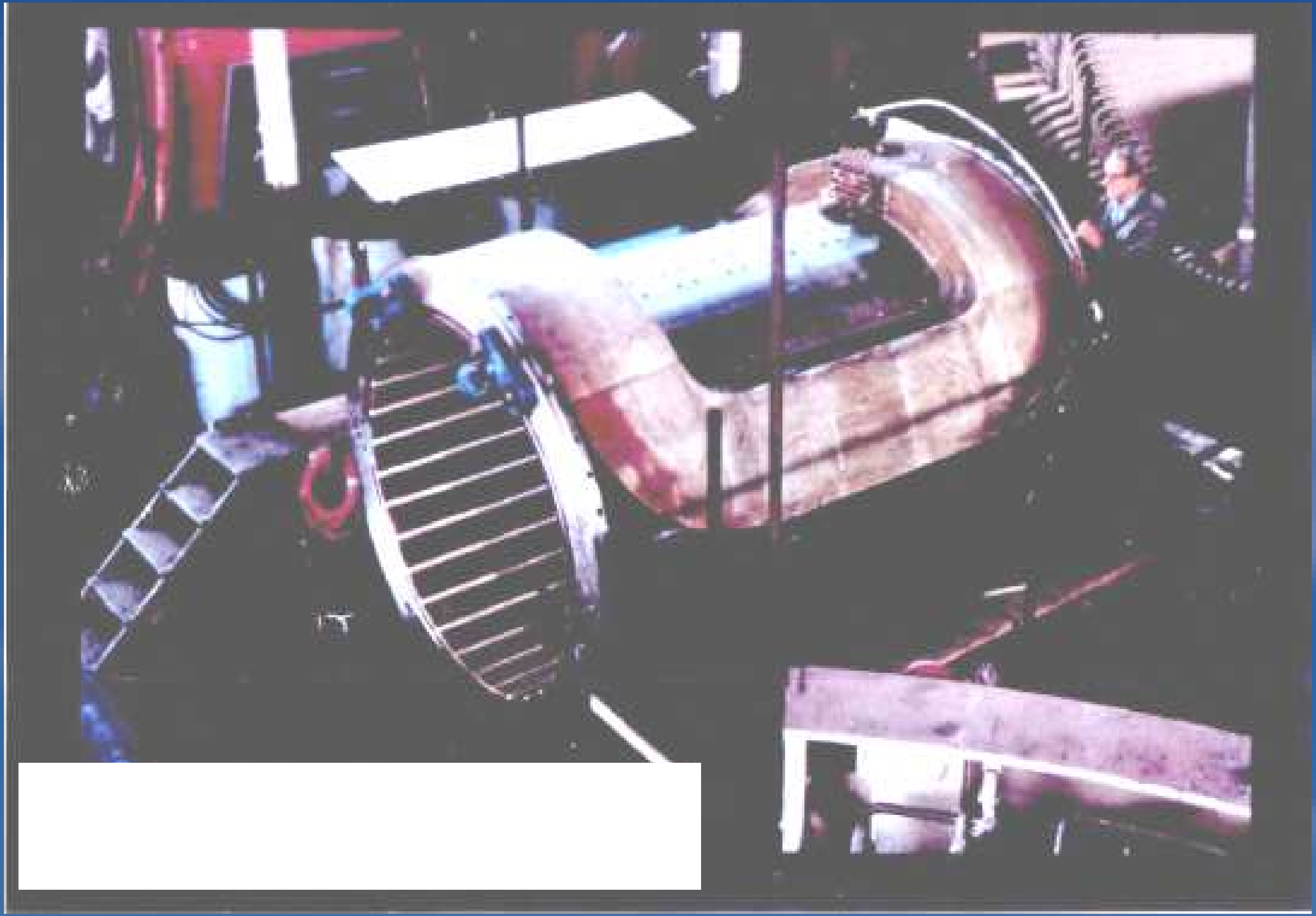


Large split-coil iron-core S.C. magnets

	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)	$4x10^6$	$2.5\ 10^6$	$2x10^6$
Average Jc (A/cm^2)	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

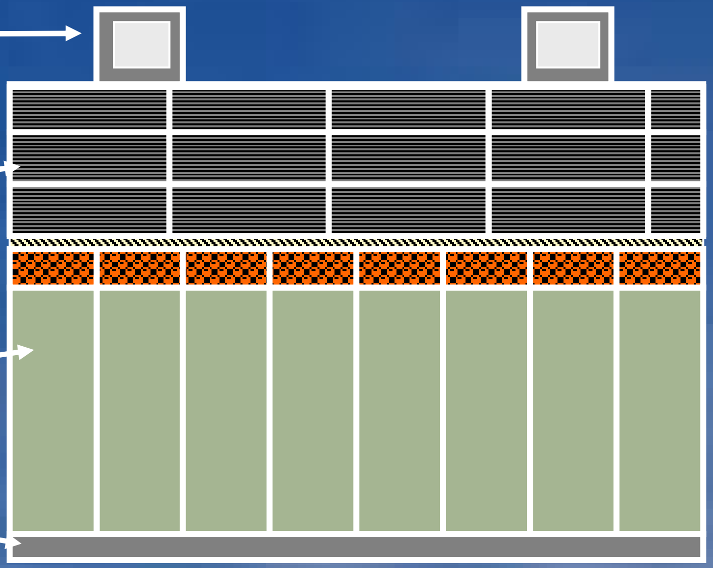






CELLO built at Saclay for Petra Collider at DESY. – Indirect cooling – Pure Al-stabilised conductor

Basic ideas



Indirect coooling

External support

Al-stabilised conductor

Mandrel

Monolithic wire soft soldered to Al-pure stabiliser

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