Superconductivity and ancillary cryogenics at CERN: from bubble chambers to accelerators

Philippe Lebrun

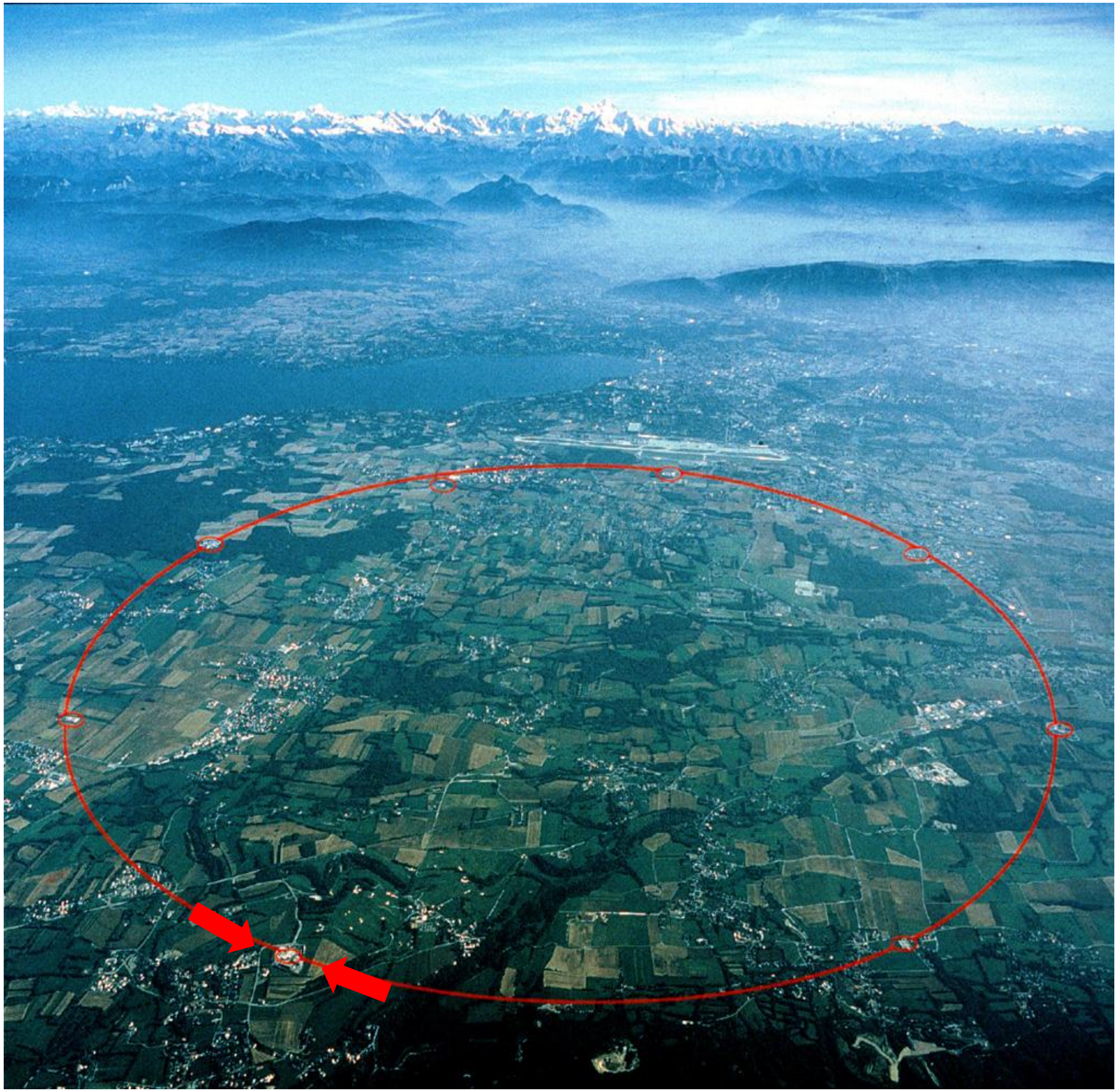
CERN, Geneva, Switzerland

The Roots of LHC Technology:

CERN Centennial Superconductivity Symposium

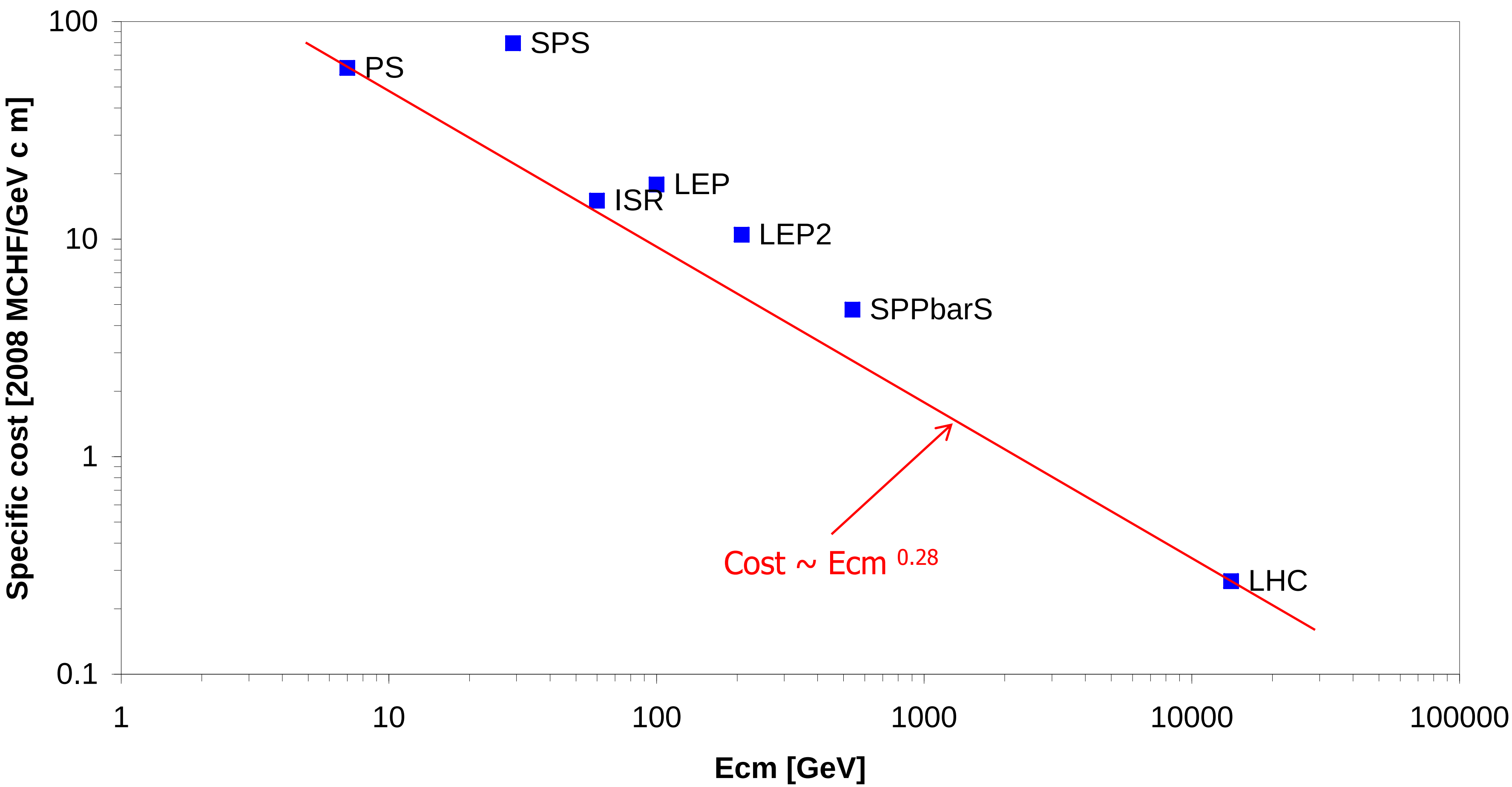
CERN, Geneva, 8 December 2011

The LHC, the largest superconducting machine in the world
26.7 km circumference, 9300 SC magnets, maximum field 8.3 T

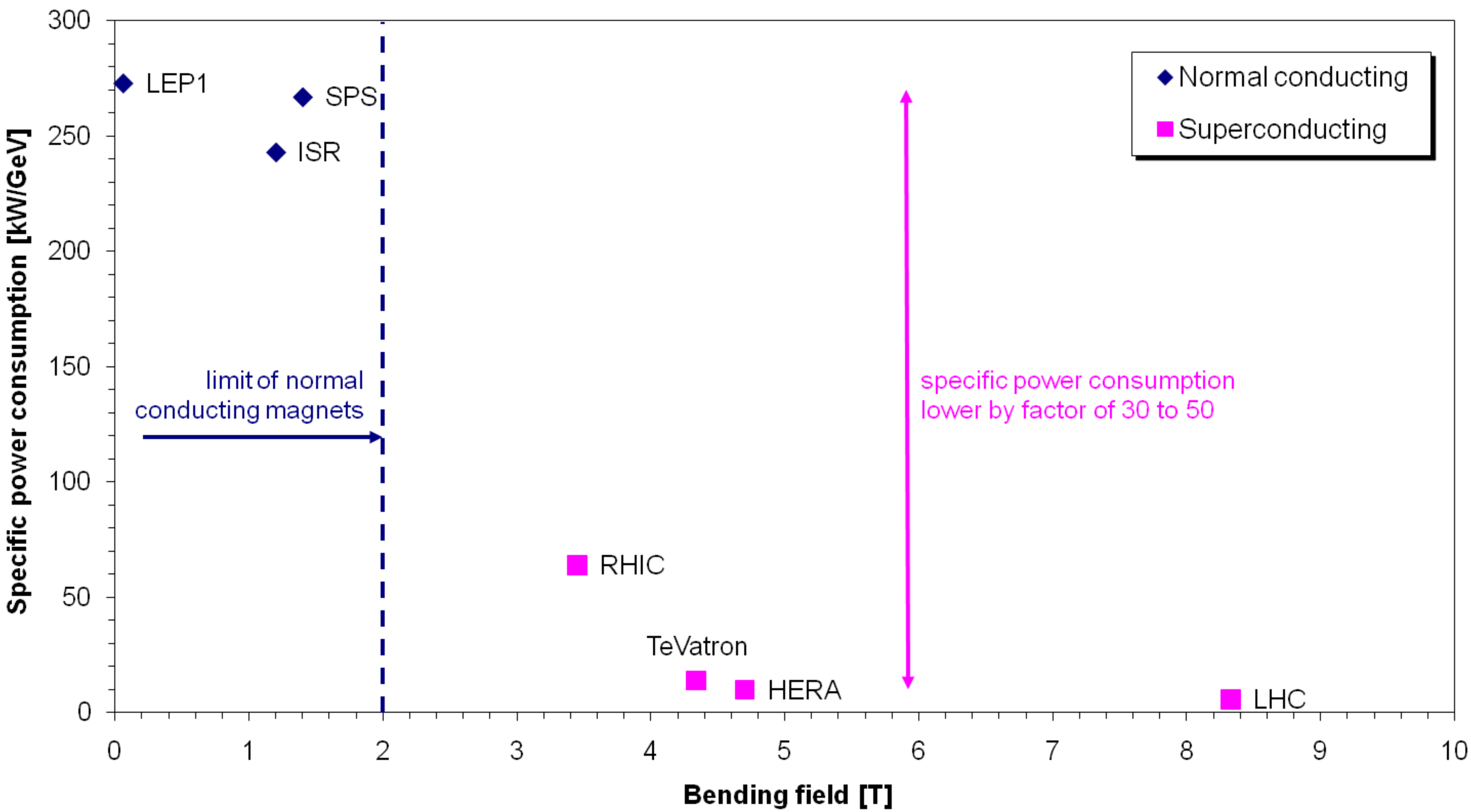


A sustained decrease in specific investment cost

Specific cost vs center-of-mass energy of CERN accelerators



Energy efficiency through advanced magnet technology
Specific power consumption of particle colliders



Physicists long-lasting interest for high magnetic fields
Journal de Physique, Février 1910

PRODUCTION DE CHAMPS MAGNÉTIQUES INTENSES AU MOYEN DE BOBINES SANS FER ;

Par M. Ch. FABRY.

Les procédés actuellement en usage pour produire des champs magnétiques n'ont pas permis de dépasser une cinquantaine de mille gauss, et encore de pareilles valeurs n'ont-elles été atteintes que dans des volumes très faibles, insuffisants pour certaines expériences. C'est ainsi que le phénomène de Zeeman n'a pas été étudié dans des champs dépassant 36 000.

M. Jean Perrin a appelé l'attention des physiciens ([2]) sur l'intérêt qu'il y aurait à obtenir des champs bien plus intenses, et sur la possibilité d'y arriver au moyen de bobines sans fer refroidies dans l'air liquide pour diminuer leur résistance. « Il est désirable, dit M. Perrin, de créer dès maintenant un mouvement d'opinion dans ce sens, et, si tôt que possible, à titre d'essai, de réaliser 100 000 gauss dans un espace notable. »

Onnes tries to use the newly discovered superconductors to build Perrin's 100'000 gauss magnet…

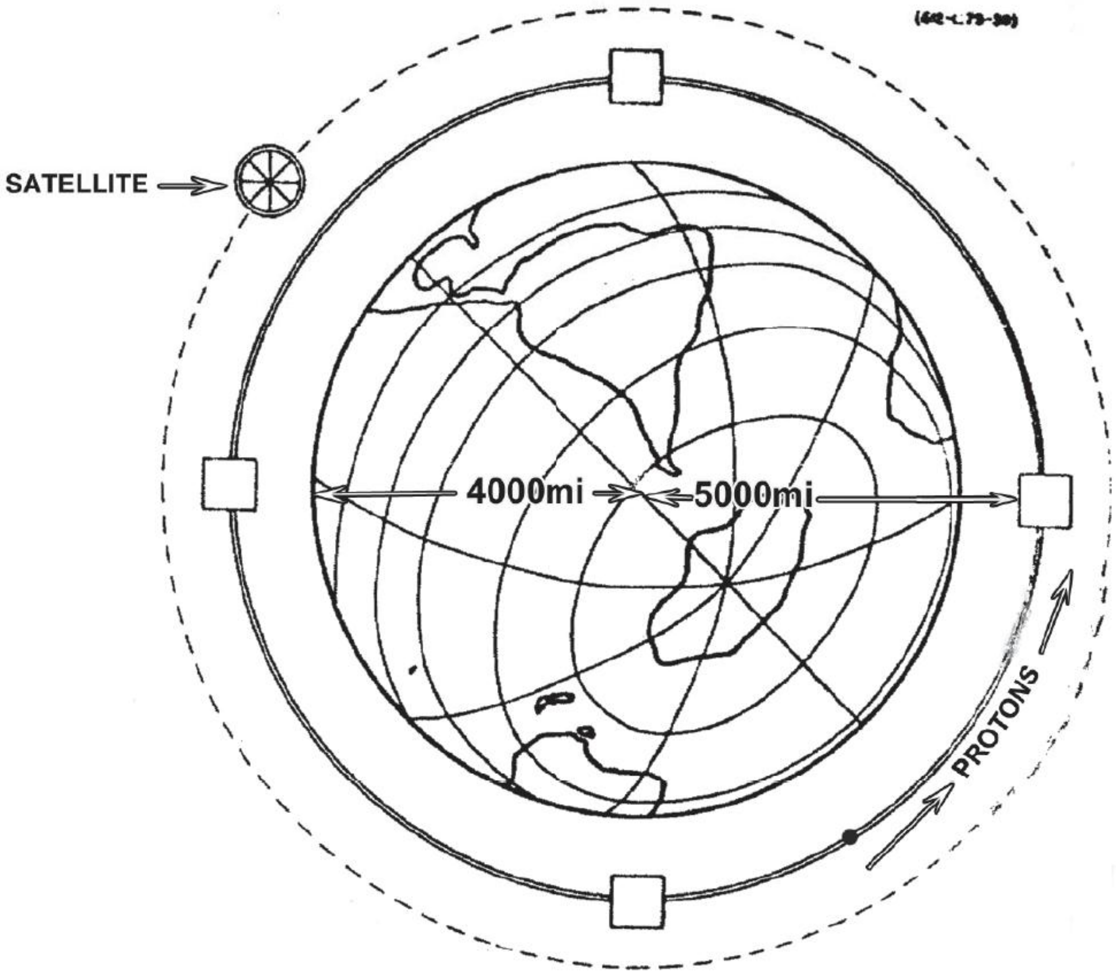
dendum 2.) There is also the question as to whether the absence of Joule heat makes feasible the production of strong magnetic fields using coils without iron,* for a current of very great density can be sent through very fine, closely wound wire spirals. Thus we were successful in sending a current of 0.8 amperes, i.e. of 56 amperes per square millimetre, through a coil, which contained 1,000 turns of a diameter of 1/70 square mm per square centimetre at right angles to the turns.

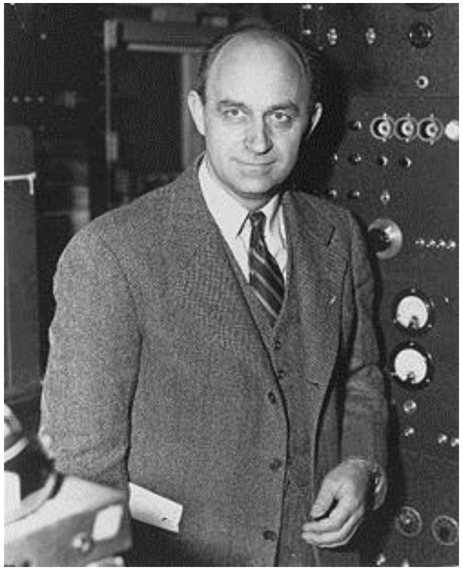
…but stumbles on the « critical field »!

after this lecture was given and produced surprising results. In fields below a threshold value (for lead at the boiling point of helium 600 Gauss), which was not reached during the experiment with the small coil mentioned in the text, there is no magnetic resistance at all. In fields above this threshold value a relatively large resistance arises at once, and grows considerably with the field. Thus in an unexpected way a difficulty in the production of intensive magnetic fields with coils without iron faced us. The discovery of the

H.K. Onnes, Nobel Lecture, 1913

Fermi's 1954 concept for the « Ultimate Accelerator » was not superconducting!

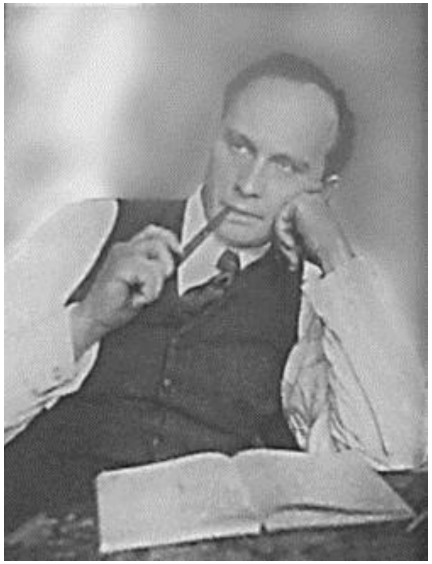




E_{beam} = 5000 TeV
B = 2 T
R = 8000 km ~ 5000 miles

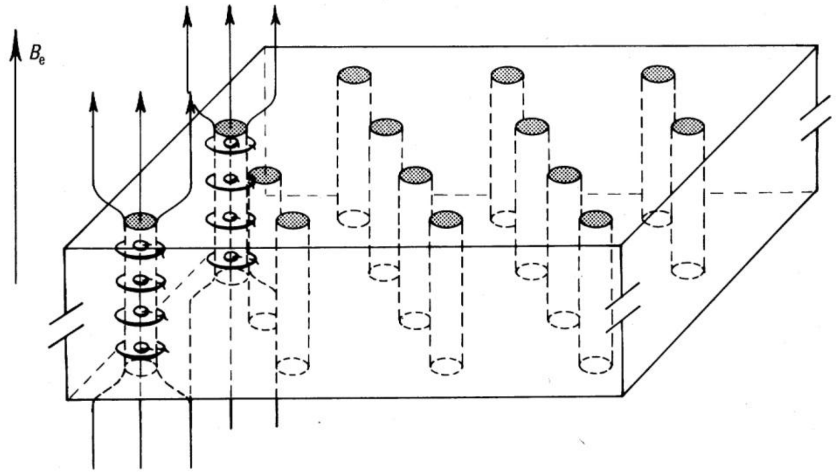
E. Fermi, APS Lecture, Columbia University, 29 January 1954

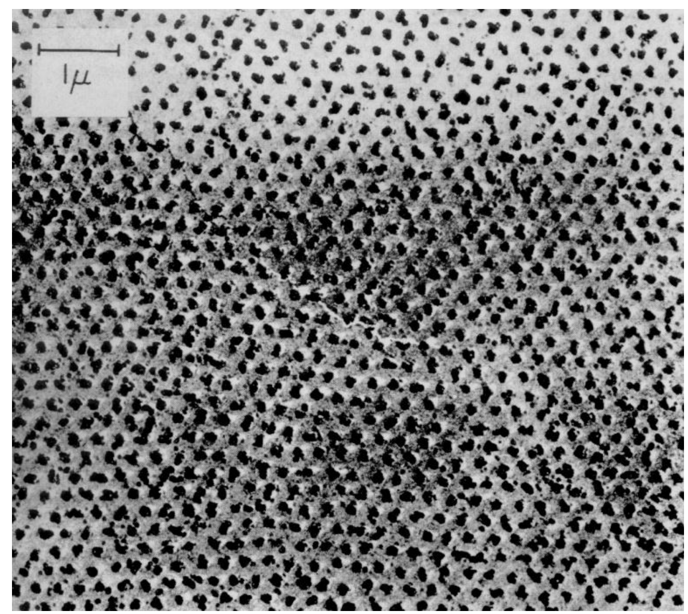
Although hinted since the 1930s, local penetration of magnetic field in type II superconductors was established only in 1954

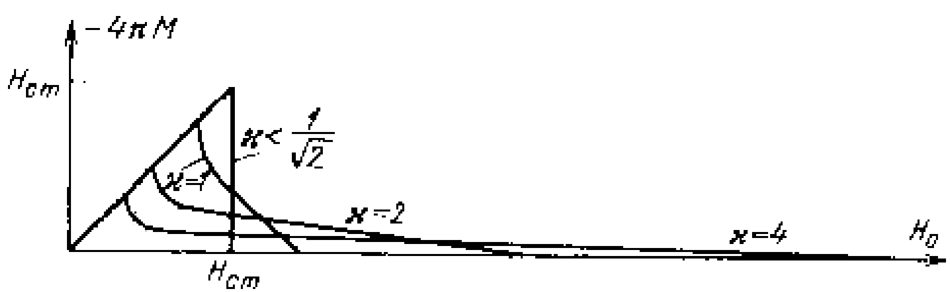


Lev Shubnikov

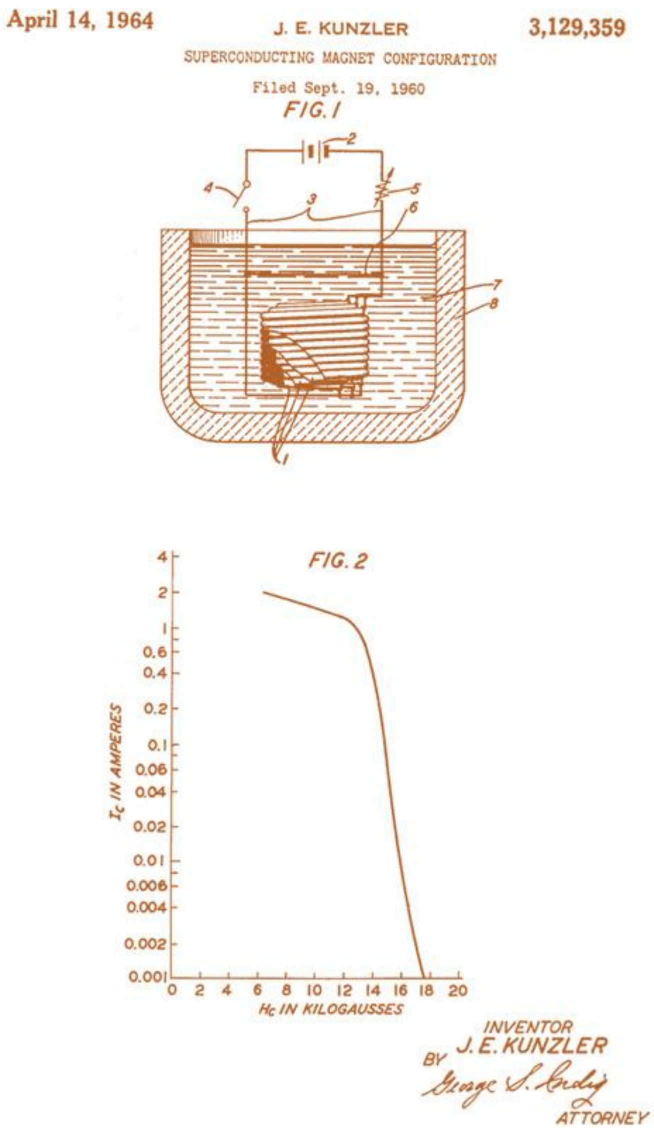
Alexei Abrikosov







Superconductivity becomes a technology
First patent for a « high-field » superconducting magnet (1960)



Patent filed in 1960 (registered in 1964) by J. Kunzler of Bell laboratories

The magnet, wound with molybdenum-rhenium alloy conductor, reached 1,5 T (15’000 gauss)

Discovery of the technological material Nb-Ti alloys (1961)

PHYSICAL REVIEW VOLUME 123, NUMBER 5 SEPTEMBER 1, 1961

Superconducting Solid Solution Alloys of the Transition Elements

J. K. Hulm and R. D. Blaugher
Westinghouse Research Laboratories, Pittsburgh, Pennsylvania

(Received April 19, 1961)

The solid solution alloys formed by the incomplete *d*-shell metals in groups 4, 5, 6, and 7 have been tested for superconductivity down to 1°K. For alloys formed between neighboring elements in a given *row* of the periodic table, two transit
proximately equal to 4.7 and 6.4, respe
upper maximum is absent. Similar max
rows of the periodic table, thus confirn
normal density-of-states function, $N(0)$
these peaks lying at about the same com
ent work. The relationship of T_c to $N($
data are also presented for alloys comp
In this case, the form of the relationshi

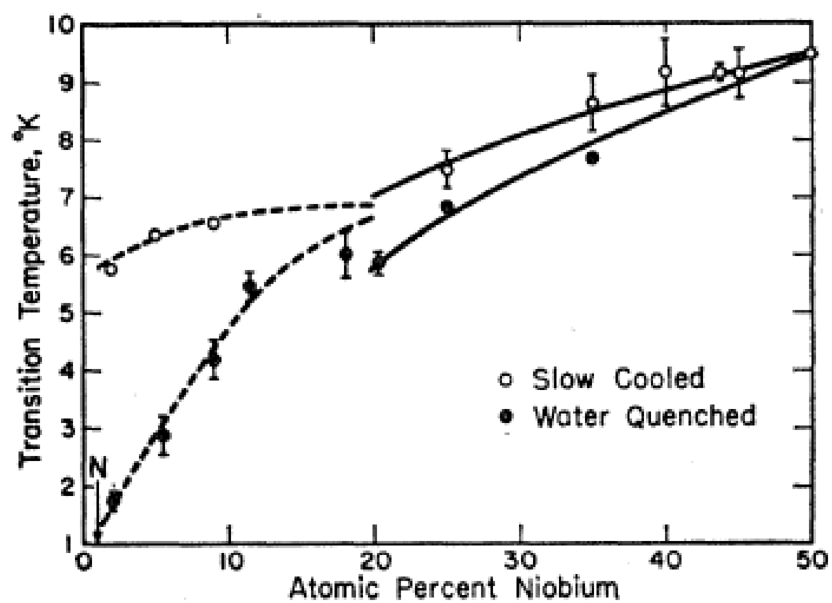


Fig. 6. Transition temperature versus composition for titanium-niobium alloys prepared by different types of heat treatment.

Origins of superconductivity at CERN: tests of Nb-Zr wire & magnet

P.G. Innocenti & G. Kuhn, NPA int. 62-1 & 62-10 (1962)

NPA/Int. 62-1
16th January, 1962.

PRELIMINARY TESTS ON SUPERCONDUCTIVITY

1. Introduction.

After the discovery that the intermetallic compound Nb_3Sn and some Nb-Zr alloys remain superconductive in high magnetic fields with appreciable current densities 1) 2) 3) 4) 5) 6), there has been a revival of studies on the practical applications of superconductivity in the construction of electro-magnets.

Recent papers 7) 8) 9) show some of the advantages of superconducting magnets compared with air-cored magnets of conventional design, with pulsed or dc excitation, and with cryogenic magnets.

The practical construction of superconducting magnets rests on the fact that current densities of the same order of magnitude of those obtained in short samples may also be obtained in wires of considerable lengths as used in winding coils : this is not yet the usual case.

Of the two materials of interest at present, Nb_3Sn and Nb-Zr, the latter seems to have more immediate application due to its more desirable mechanical properties, although its critical magnetic field is lower than that of Nb_3Sn.

We have therefore chosen Nb-Zr as the main subject of this preliminary investigation.

2. Description of samples and results.

2.1 The first aim of the series of experiments described in the present paper was the achievement of the superconductive state in Nb wire. In fact one can believe that superconducting was obtained in a Nb wire 0.127 mm diameter, 30 m long. The wire was wound on a perspex tube

./.

PS/3052

NPA/Int. 62-10
Meyrin, 13th September 1962

PRELIMINARY TESTS ON SUPERCONDUCTIVITY II

CONTENTS

PS/3445

Cooling by forced flow of liquid & supercritical helium

M. Morpurgo, NP Internal Report 67-15 (1967)

SUPERCONDUCTING COILS COOLED BY HELIUM FORCED CIRCULATION

M. Morpurgo

1. GENERAL

Superconducting coils are normally operated immersed in a liquid-helium bath. Alternatively, it seems possible to wind the coils with a hollow conductor and to cool it with a forced circulation of helium.

We think that this method of cooling will show the following advantages:

a) Each point of the conductor will be correctly cooled, and thus a good coil stability will be guaranteed.

b) The absence of flow channels and of empty spaces between conductors will allow an improved mechanical design and construction of the coil. For the same reason, a better electrical coil insulation will be possible.

c) The cryrostat construction will be simplified. In fact, the cryrostat will reduce to a vacuum tank and nitrogen shield.

d) The amount of helium contained in the hollow conductor will, in general, be smaller than the corresponding amount of helium required to fill the cryrostat of a conventional superconducting coil.

We think that these advantages will be particularly evident for coils of large dimensions. In the case of small coils, they will be counterbalanced by the difficulty of having (with forced cooling) at the same time a relatively small feeding current and a high over-all current density in the coil cross-section. Large values of feeding current will originate excessive power losses in the input leads.

With the purpose of studying experimentally the technical problems related to forced cooling of superconducting coils, we have constructed an apparatus to circulate the helium, and a small test coil.

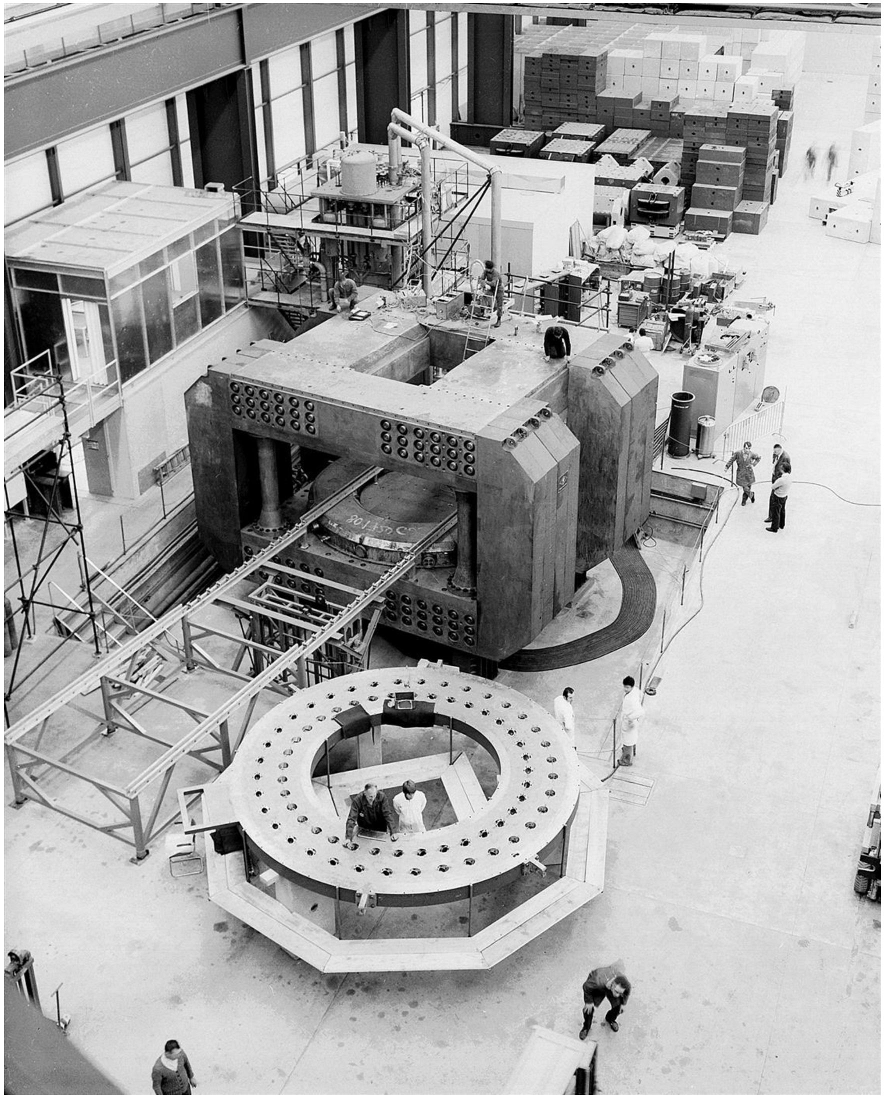
Details of this work are reported in the following chapters.

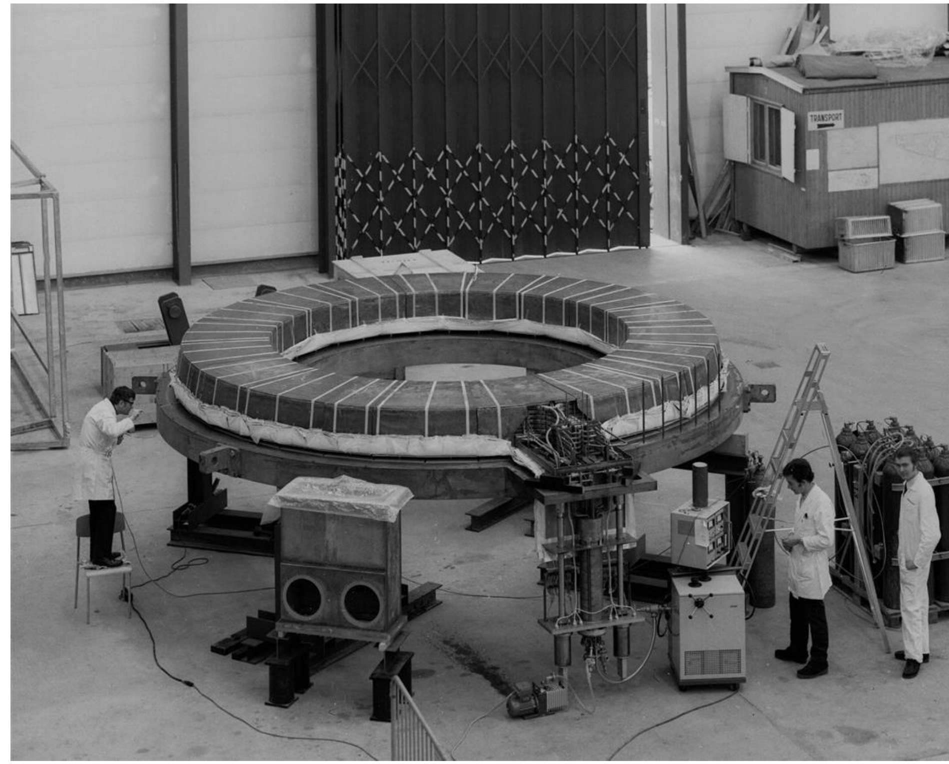
67/1256/5
SIS/sb

Three-piston circulator pump for LHe

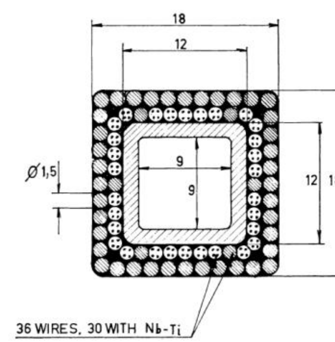
Omega, the first internally-cooled superconductor magnet

Proposed 1969, completed 1972



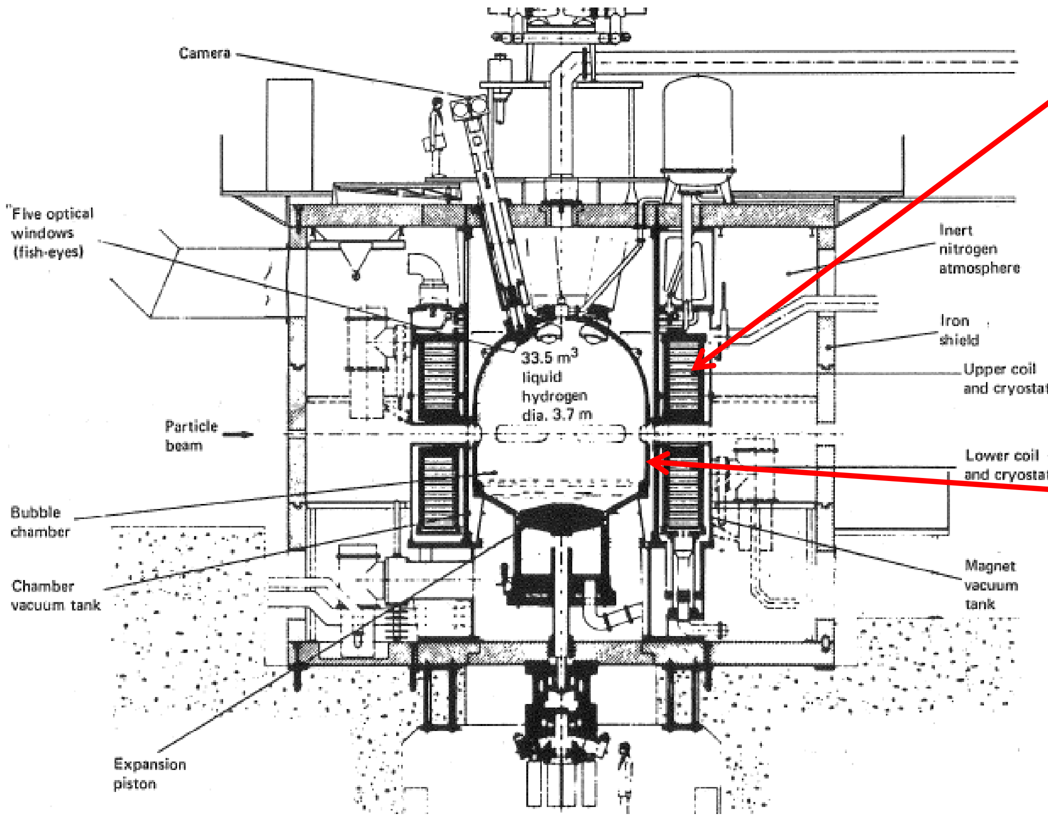


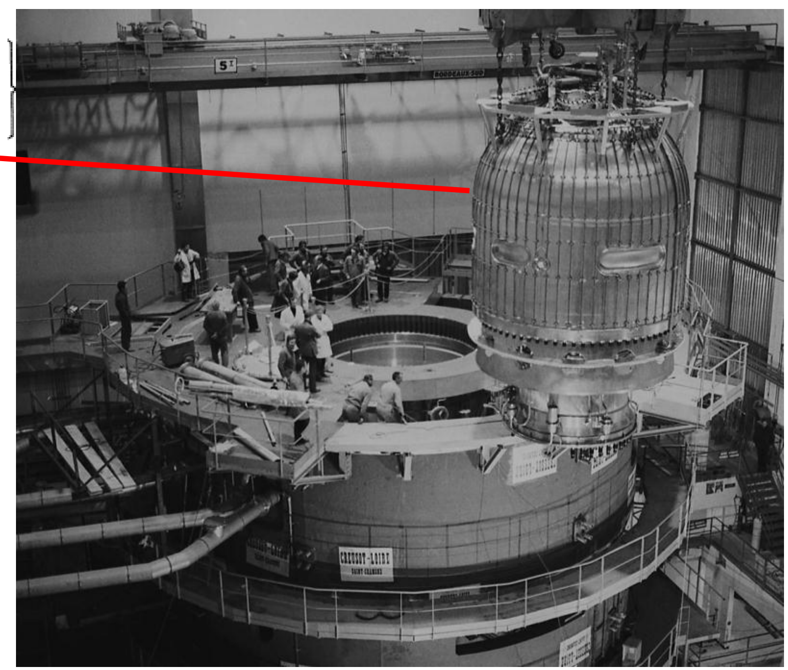
Field at the centre	18 kG
Coil inner diameter	3 m
Free distance between coils	1.5 m
Free distance between poles	2 m
Over-all weight	1400 tons
Nominal current	5000 A
Number of turns	408 turns/coil
Stored energy	50 MJ.



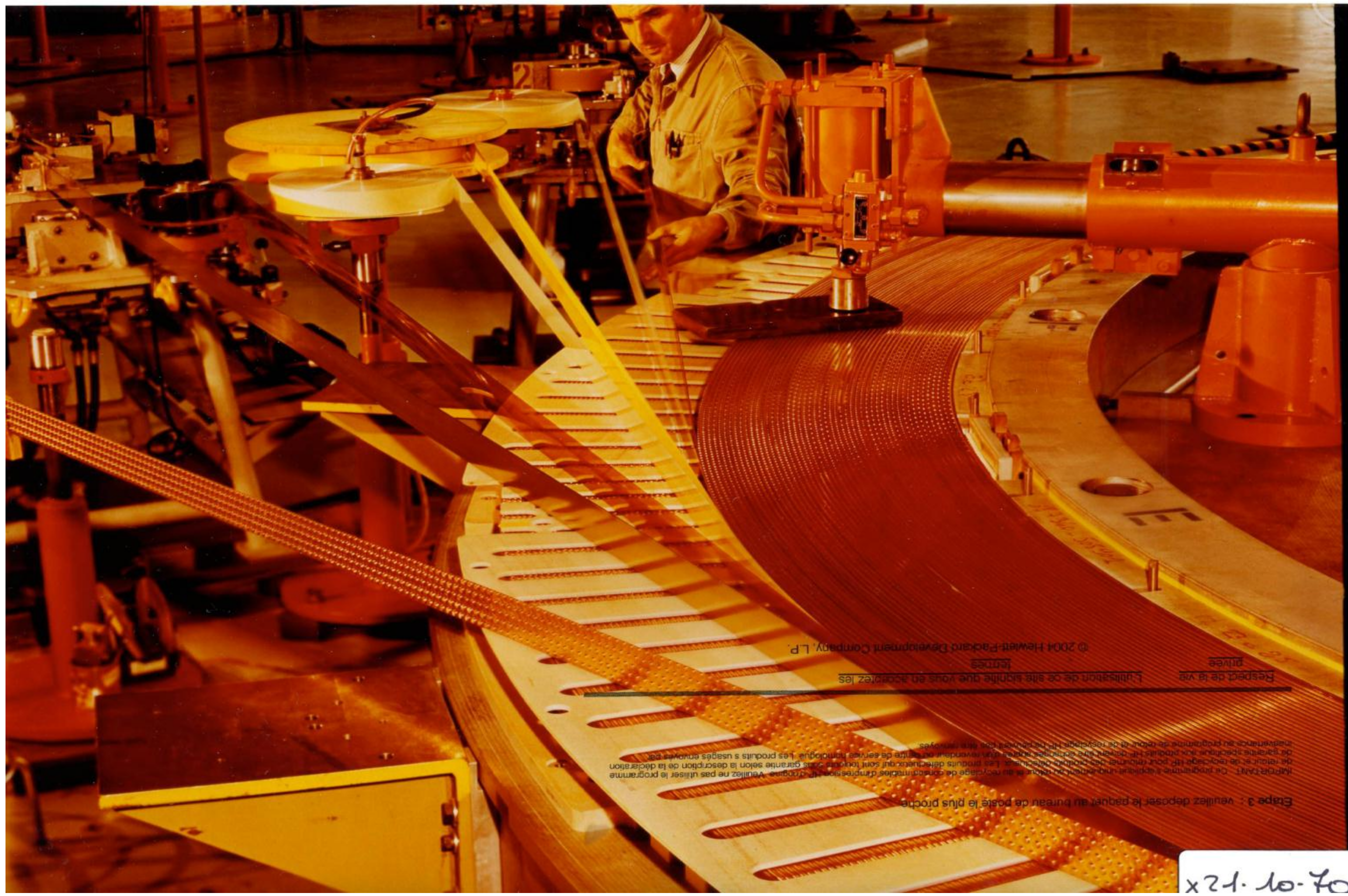
M. Morpurgo

BEBC magnet and chamber assembly (1971)





Winding of BEBC superconducting magnet (1970)

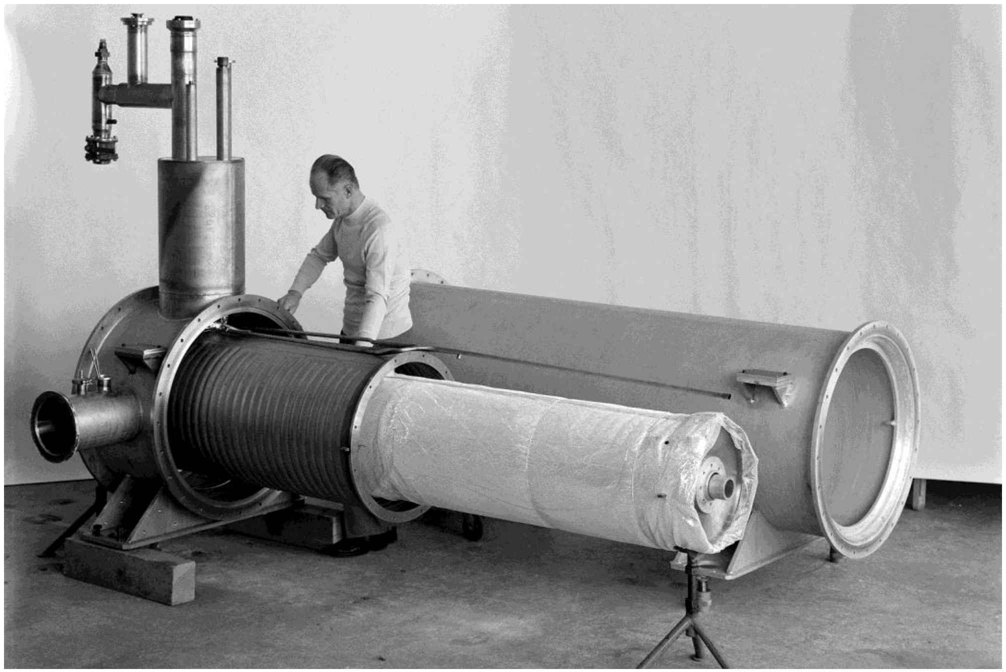


Central field 3.5 T
Nominal current 5.7 kA
Inner coil diameter 4.7 m
He bath cooled

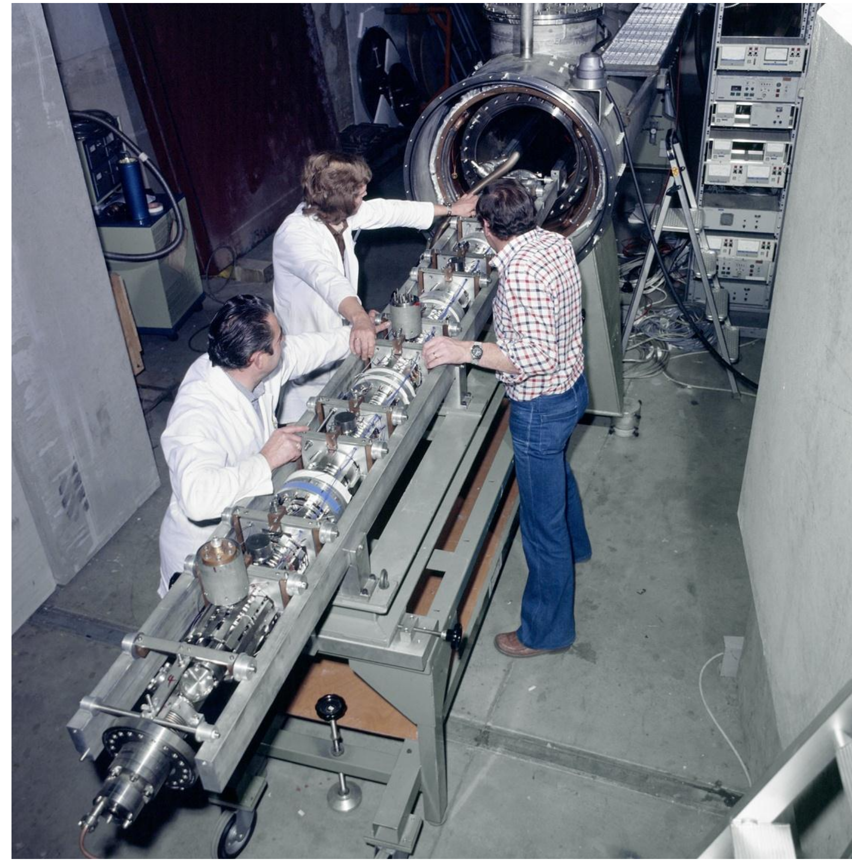
Conductor Nb-Ti/Cu 61 x 3 mm^2
Stored energy 800 MJ
Magnet & cryostat mass 350 t
Magnetic circuit mass 2000 t

F. Wittgenstein

Superconducting devices for West Area beam lines



One of three cos θ SC dipoles (1975-77)
Central field 4.75 T
Magnetic length 2.28 m
Nominal current 700 A
Cold bore aperture 74 mm

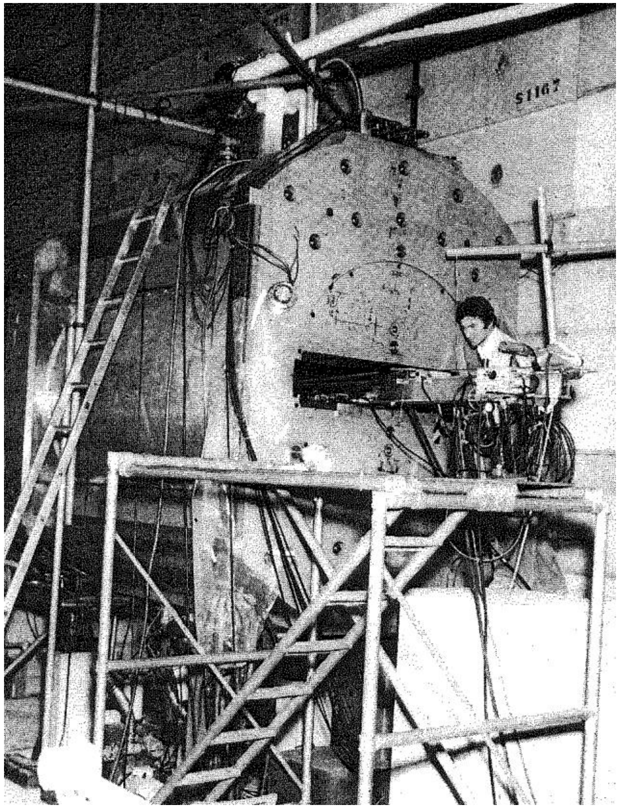


SC RF separator (1977) built by KfK Karlsruhe
2.87 GHz (S-band)
Deflecting field 1 MV/m
Operated in superfluid helium at 1.8 K

G. Kesseler

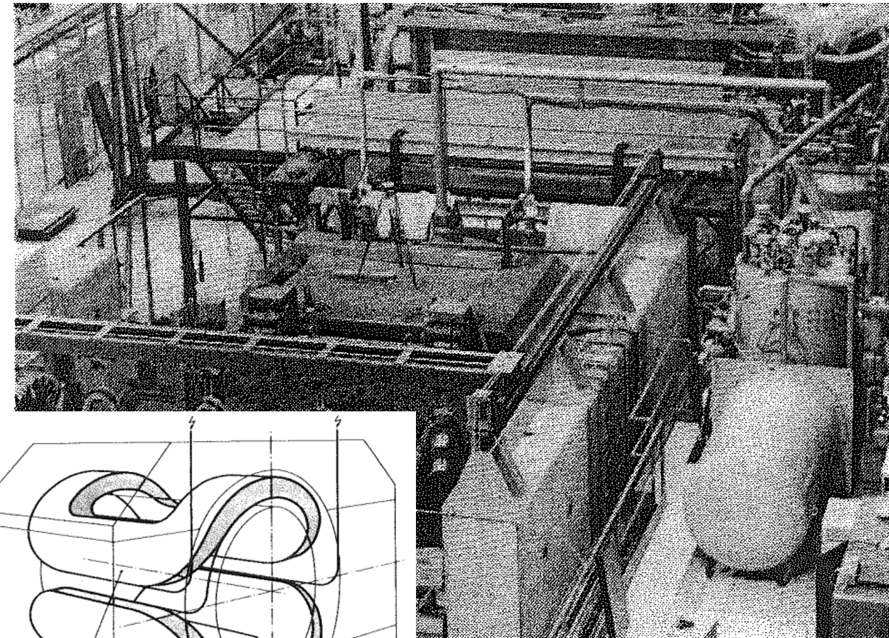
A. Citron (KfK) & H. Lengeler (CERN)

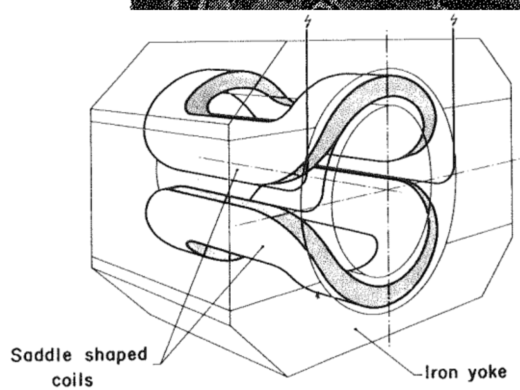
Detector magnets for ISR and North Area
M. Morpurgo (1977-1979)



ISR solenoid, He bath cooled

Field at the centre	= 1.5 T
Current	= 2200 A
Number of turns	= 1000
Useful (warm) bore	= 1.38 m
Gap between poles	= 1.8 m
Stored energy	≃ 3 MJ
Weight of the magnet cold part	≃ 1.7 tons
Total magnet weight	≃ 70 tons





Large dipole, forced-flow cooled

Central maximum field	1.9 T
Free warm bore	1.6 m
Over-all length	3.5 m
Weight of the cold part of the magnet	≅ 40 t
Over-all weight	230 t
Maximum current	6000 A
Stored energy	≅ 20 MJ

Superconducting magnets & the SPS saga (1964-1973)

1964 Design study of a 300 GeV proton synchrotron based on normal-conducting magnets

1967 The German Atomic Energy Advisory Committee asks for a redesign, using « modern techniques », e.g. superconducting magnets

1969 J. Adams, project director, drafts a technical strategy document for the machine: « superconducting magnets would not be feasible in the short term, and would better be exploited in the next generation of machines »

January 1970 Postponement of decision on siting by Germany

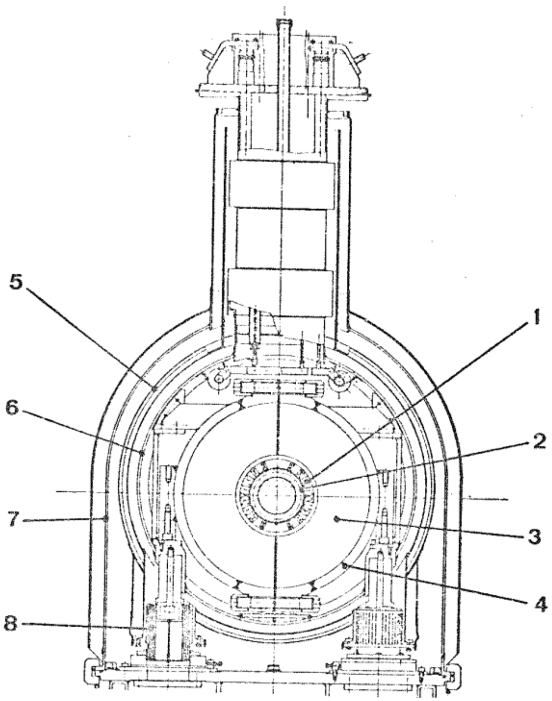
February 1970 New proposal by J. Adams to build the 300 GeV adjacent to CERN I (Meyrin), and to install at first only half of the magnets (« missing magnet scheme ») => GESSS collaboration

1973 Decision to build a 400 GeV machine with all normal-conducting magnets from the onset

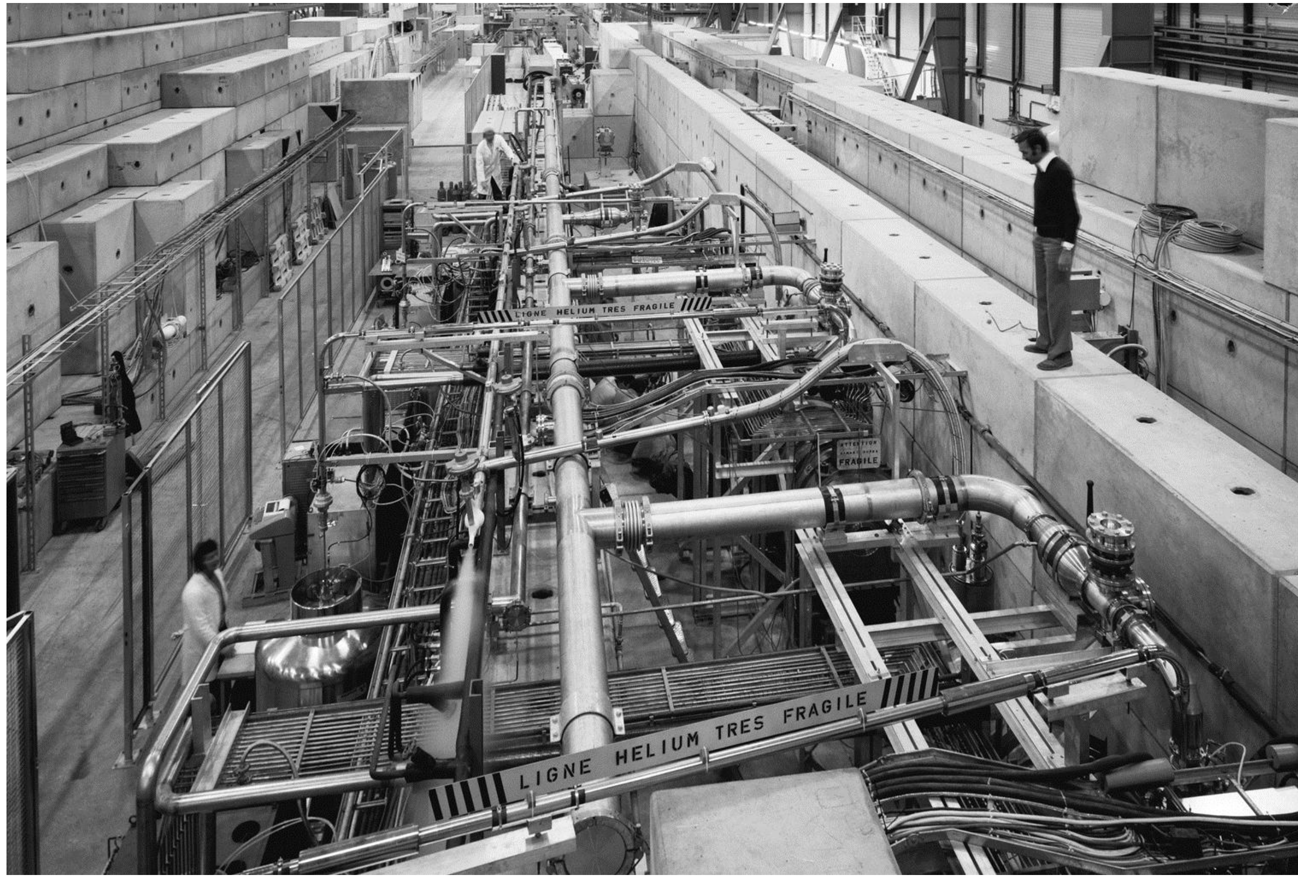
1976 First proton beams accelerated to 400 GeV

Beam line magnets for the North Area (1978)

Cross-section of CESAR dipole



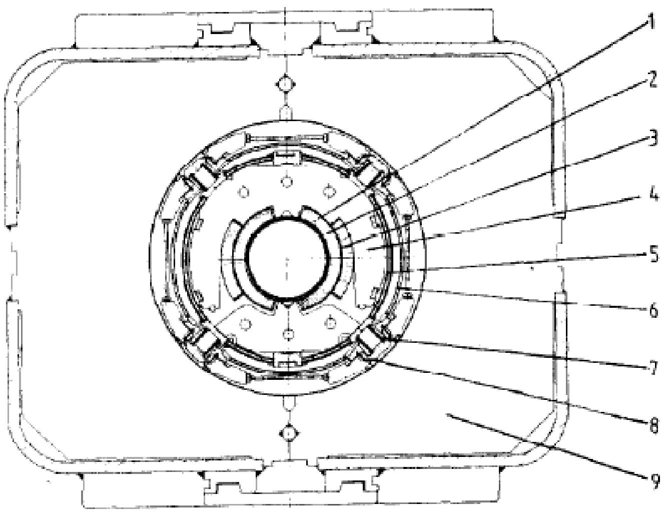
Warm bore aperture (circular)	100 mm
Inner diameter of the winding	150 mm
Outer diameter of the winding	197.6 mm
Central field	4.5 T
Magnetic length	2.04 m
Current density at 4.5 T	$2.5.10^8$ A/m2
Stored energy	520 kJ
Length of the cryostat	2.86 m
Width of the cryostat	0.96 m



Superconducting magnets (two MBS dipoles (CESAR) of 150 mm bore and 4.5 T, and one quadrupole (CASTOR) of 90 mm bore and 54 T/m) installed in hall EHN1

J. Pérot (CEA Saclay) & D. Leroy (CERN)

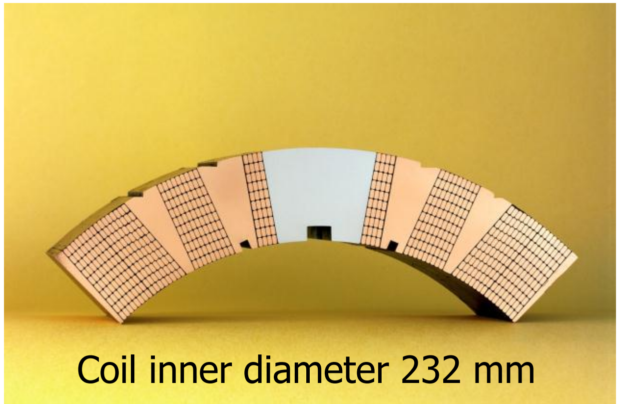
P0 prototype beam transport magnet for SPS (1982)



Cold bore diameter	66	mm
Inner diameter of the winding	72	mm
Outer diameter of the winding	113.2	mm
Outer diameter of the collared coils	167.0	mm
Inner diameter of the iron yoke	240.0	mm
Overall current density at Bo=4.2T	303	A/mm^2
Self-inductance	37.3	mH
Magnetic lenght	5.60	m
Load line B_0	0.0934T/A	
$\int B_0 dl$ at 4500 A	23	Tm
Weight of the cold part	1050	kgs

D. Leroy

Eight ISR « low-β » quadrupoles (1980)
Developed at CERN, produced by industry

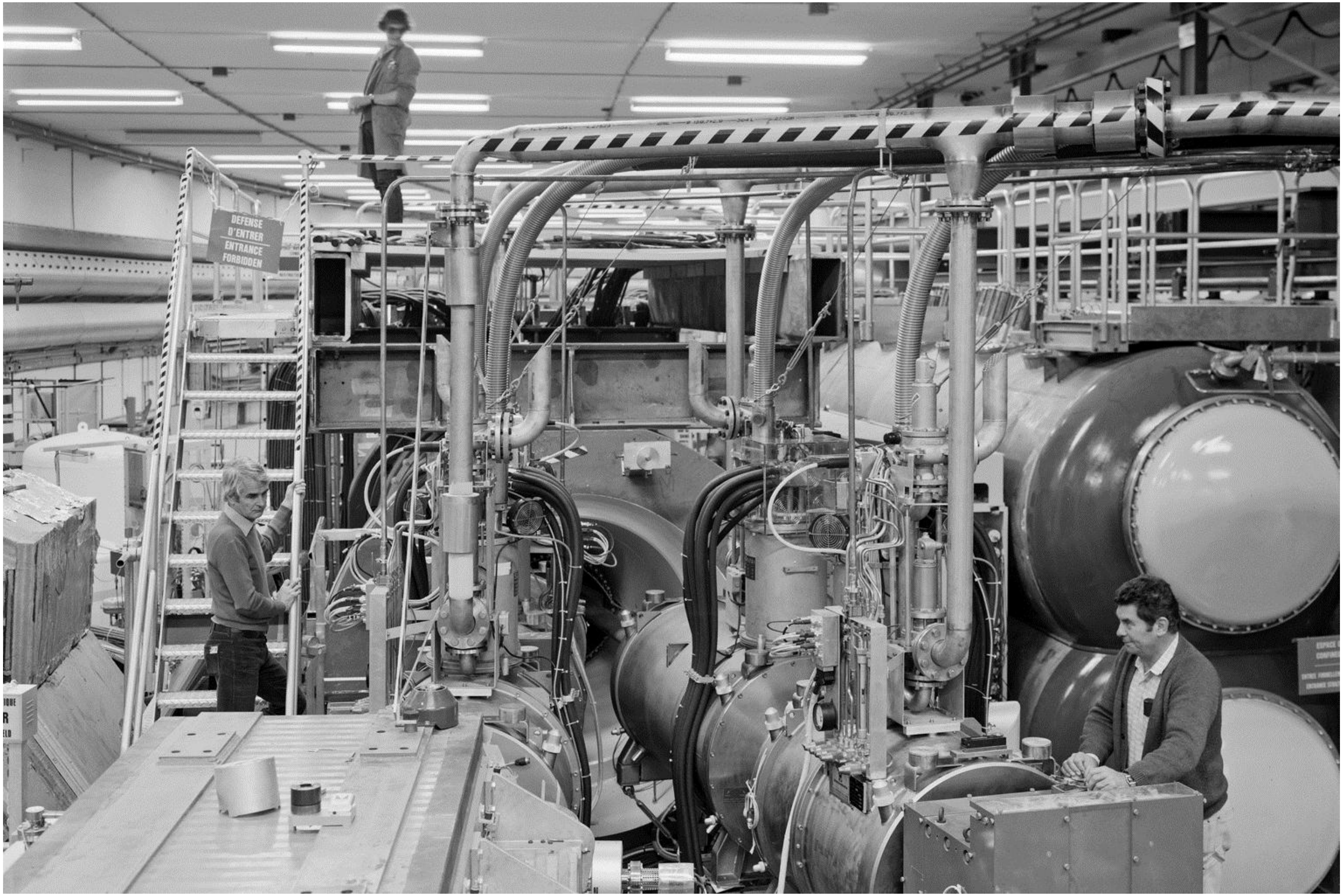


Coil inner diameter 232 mm

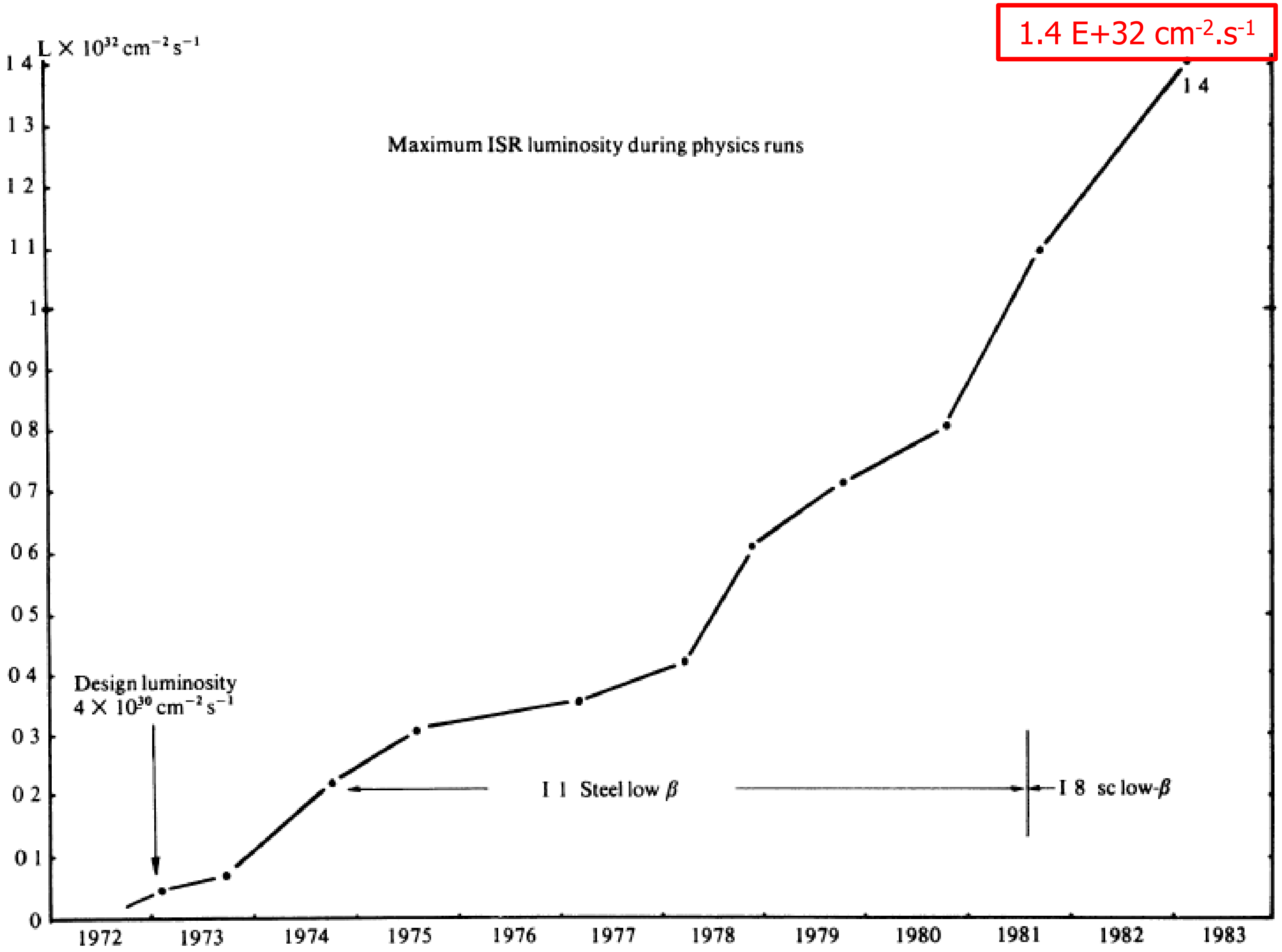
Name		SL1/SL2	SL3/SL4	SL5/SL6	SL7/SL8
Quadrupole magnetic length	[m]	0.65	1.15	1.15	0.65
Quadrupole gradient	[T m-1]	40.0	42.9	37.9	37.9
Sextupole magnetic length	[m]	0.74	1.24	1.24	0.74
Sextupole gradient derivative	[T m-2]	20.6	18.7	21.1	21.5

L. Resegotti, R. Perin *et al.*

The superconducting insertion at ISR
First superconducting magnet system routinely operated in an accelerator

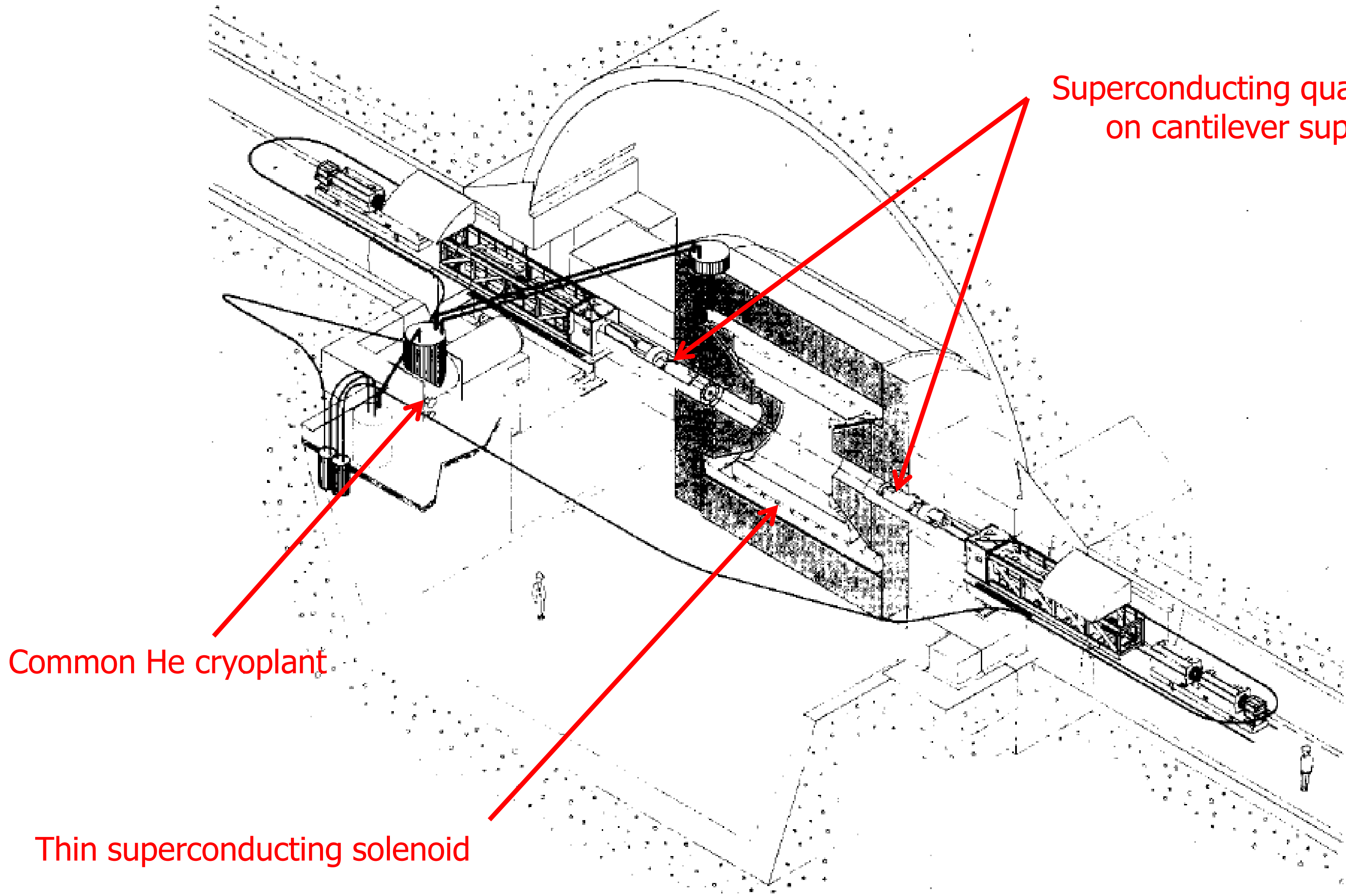


Maximum ISR luminosity during physics runs

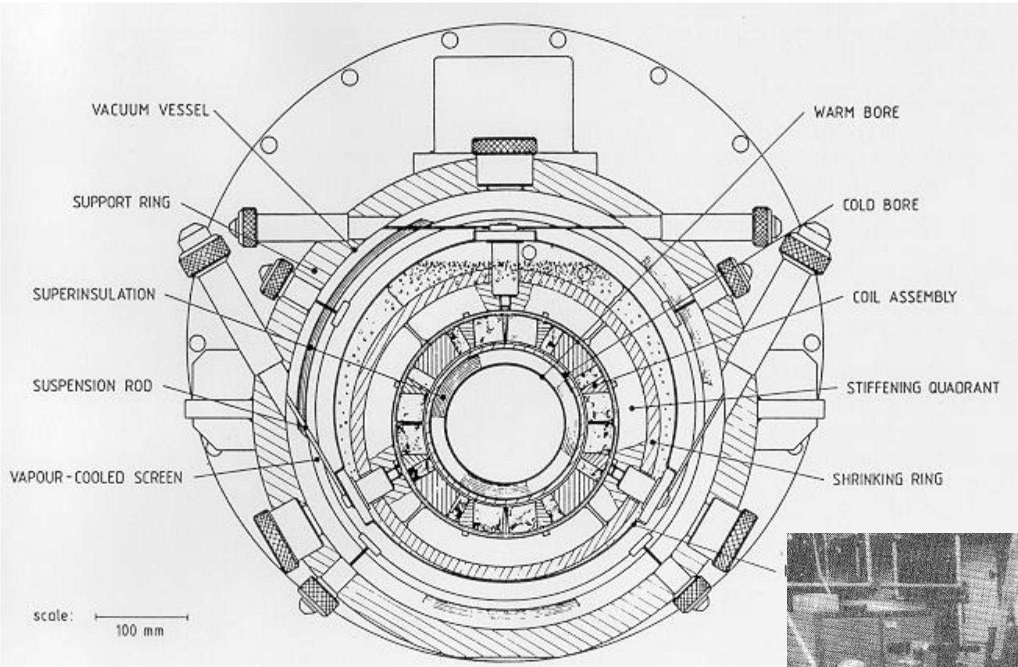


M. Jacob & K. Johnsen (1984)

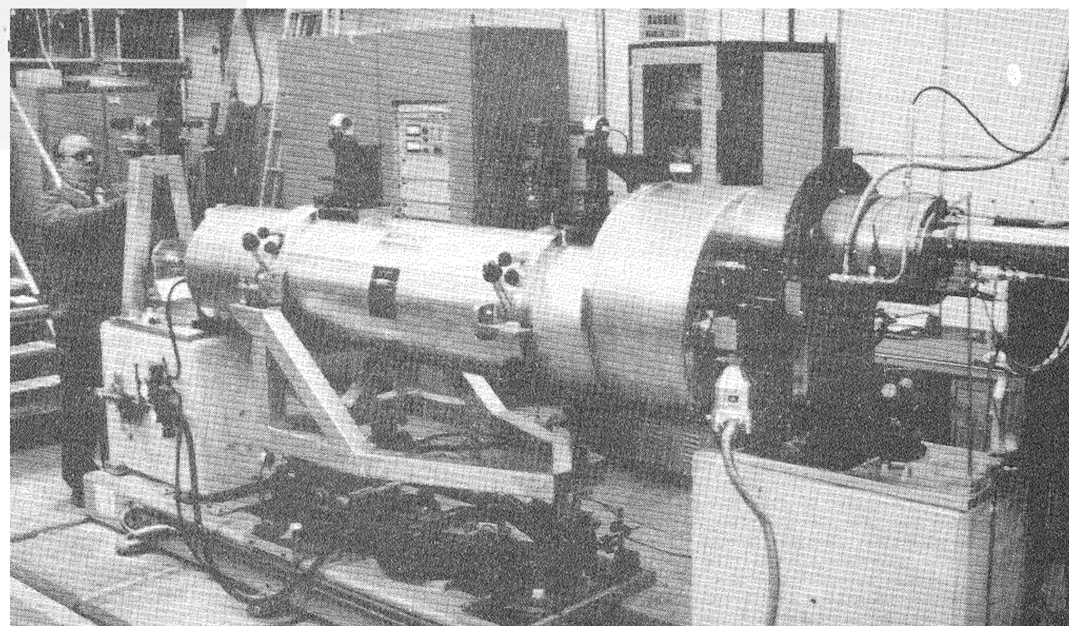
Layout of typical LEP experimental area (1989)
Magnets in « data-taking » positions



Two generations of 8 slim « low-β » quadrupoles for LEP
T. Taylor *et al.* (1988 and 1994)

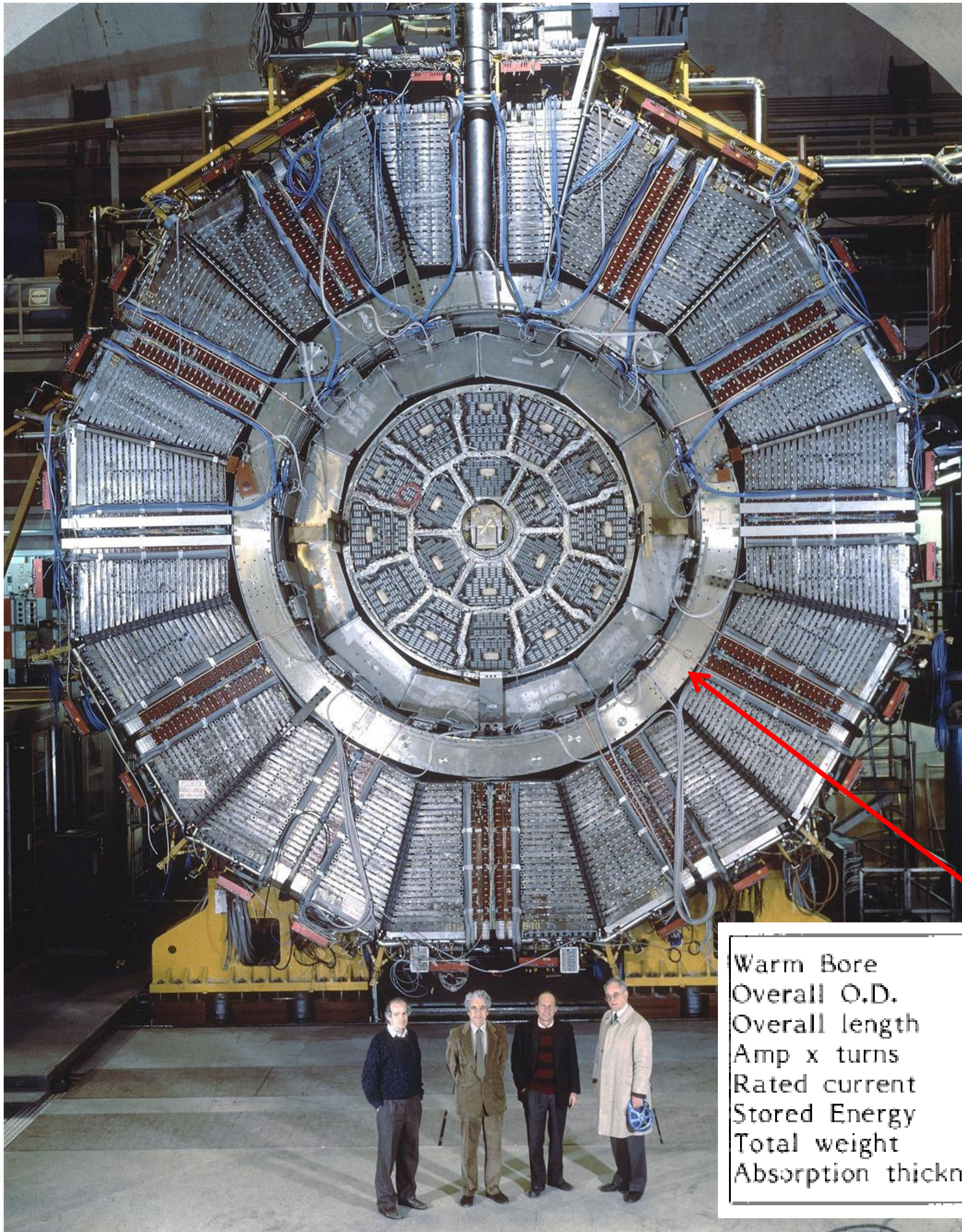


Nominal gradient (for 65 GeV beams)	36	$T\ m^{-1}$
Minimum operational gradient	10	$T\ m^{-1}$
Magnetic length	2	m
Good field aperture (diameter)	100	mm
Tolerance on integrated gradient (at limit of useful aperture)	0.2	%
Minimum clear aperture (background)	120	mm
Length of cryostat (along axis)	2.5	m
Maximum superimposed field	0.6	T
Maximum ramp rate	0.3	$T\ m^{-1}\ s^{-1}$
Nominal current	1625	A
Peak field in winding (at nominal current, with external field)	4	T
Stored energy (at nominal current)	310	kJ
Maximum test current	2000	A
Warm bore (inside diameter)	130	mm
Inner coil diameter	180	mm
Outer coil diameter	240	mm
Maximum tilt of magnet in service (transverse or longitudinal)	1.5	%



ALEPH solenoid

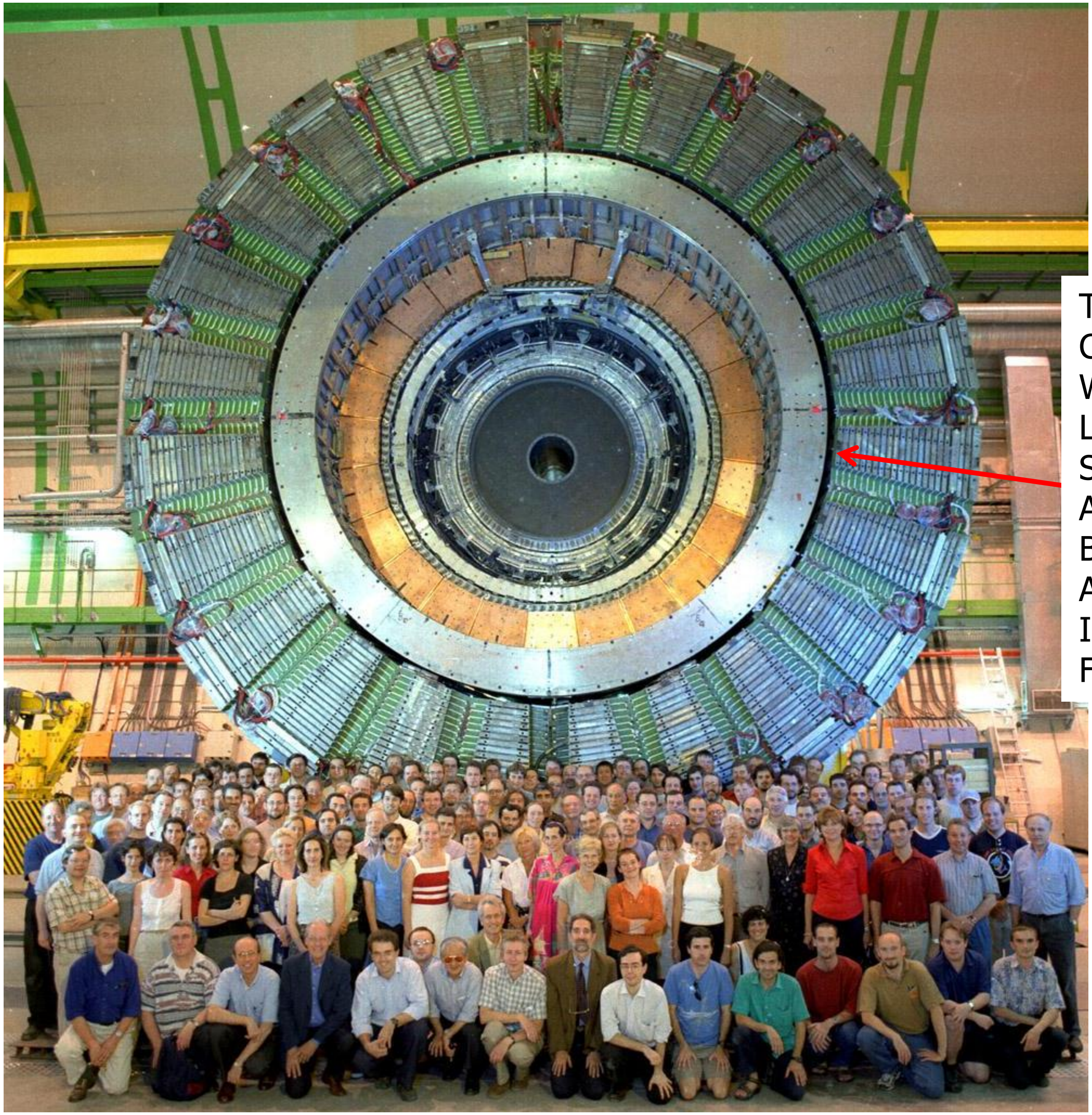
CEA Saclay (1988)



Thin superconducting solenoid
Central field 1.5 T
Al-stabilized Nb-Ti conductor
Bobbinless winding
Al external support cylinder
Indirect cooling
Two-phase He thermosyphon

Warm Bore	5 m
Overall O.D.	5.8 m
Overall length	7 m
Amp x turns	$9.5\ 10^6$
Rated current	5000 Amps
Stored Energy	136 MJ
Total weight	65 ton
Absorption thickness	0.5 λ_{abs}

DELPHI solenoid
RAL (1987)



- Thin superconducting solenoid
- Central field 1.2 T
- Warm bore 5.2 m
- Length 6.8 m
- Stored energy 110 MJ
- Al-stabilized Nb-Ti conductor
- Bobbinless winding
- Al external support cylinder
- Indirect cooling
- Forced flow of two-phase He

The DELPHI solenoid in the hairpins of Col de la Faucille
Winter 1987

CERN

Ref.: EF/PHB/HL/tj

Date: 11.12.1978

MEMORANDUM

To : Dr. J.B. Adams, Executive Director-General

From : Ph. Bernard, H. Lengeler (EF)

Subject : Tentative programme for studies of superconductivity in view of LEP-applications

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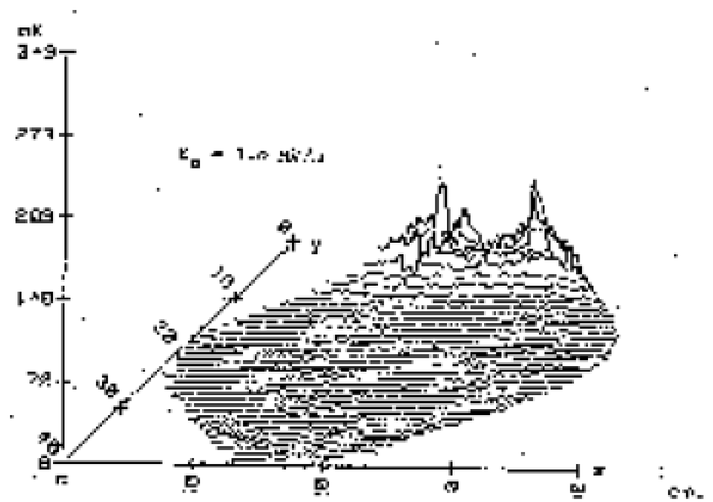
1. AIM

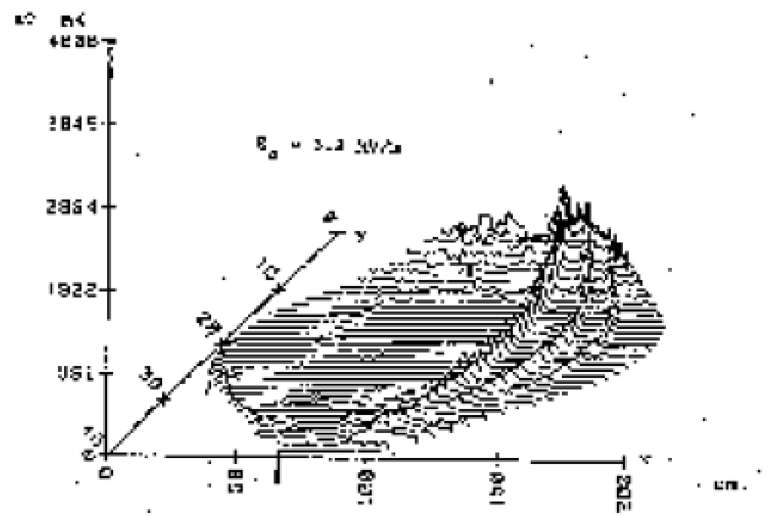
Recent studies of large e^+e^- storage rings have shown the interest of a superconducting (SC) acceleration system as regards to both power consumption and achievable maximum particle energy. Unfortunately the present status of r.f.-SC and the technical know-how accumulated hitherto in SC accelerator and r.f. separator projects appears to be an insufficient basis for a large scale application involving many hundred metres of SC accelerator structures. Therefore we consider that the first stage of a programme aiming at a large SC electron storage ring should be a feasibility study.

We propose that such a study should be under-taken at CERN and in close association with European research centres and universities already working in the field of r.f.-SC.

Diagnostics: temperature mapping system

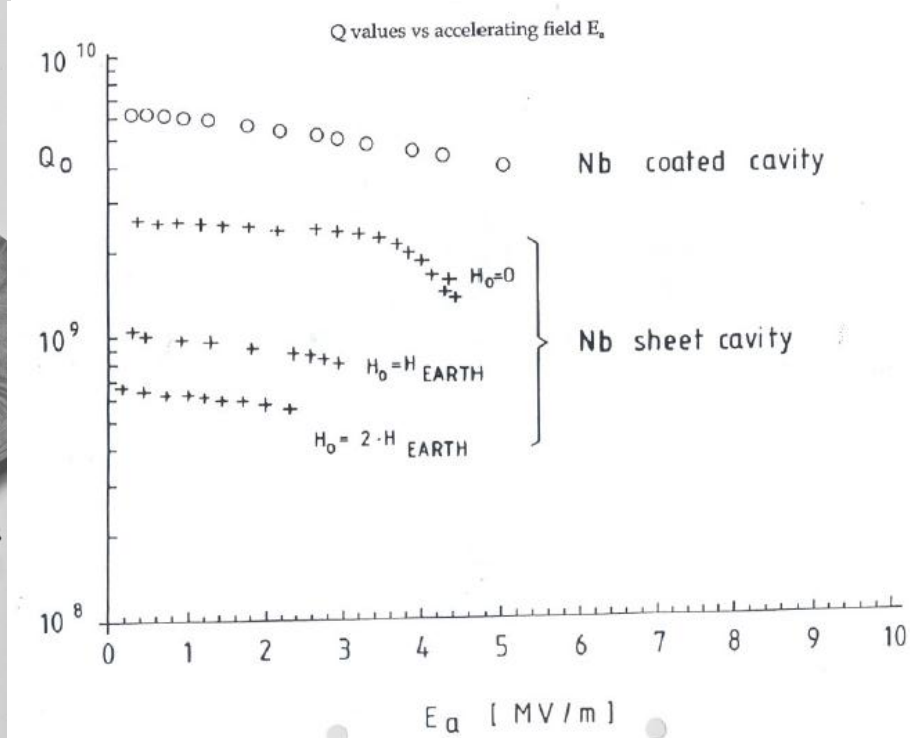
H. Lengeler



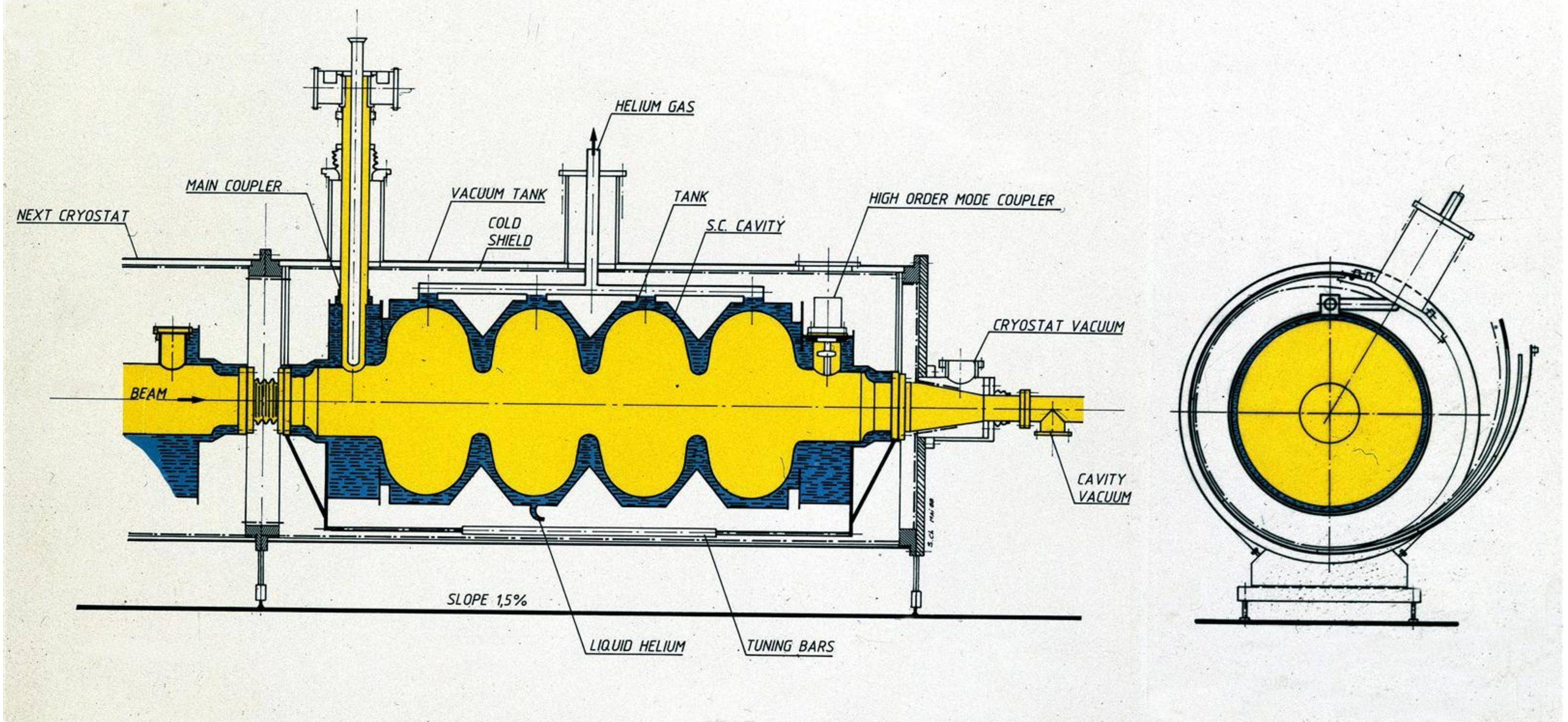


Development of Nb-on-Cu coated cavities for LEP

C. Benvenuti and his team, with
cut-away magnetron and coated cavity

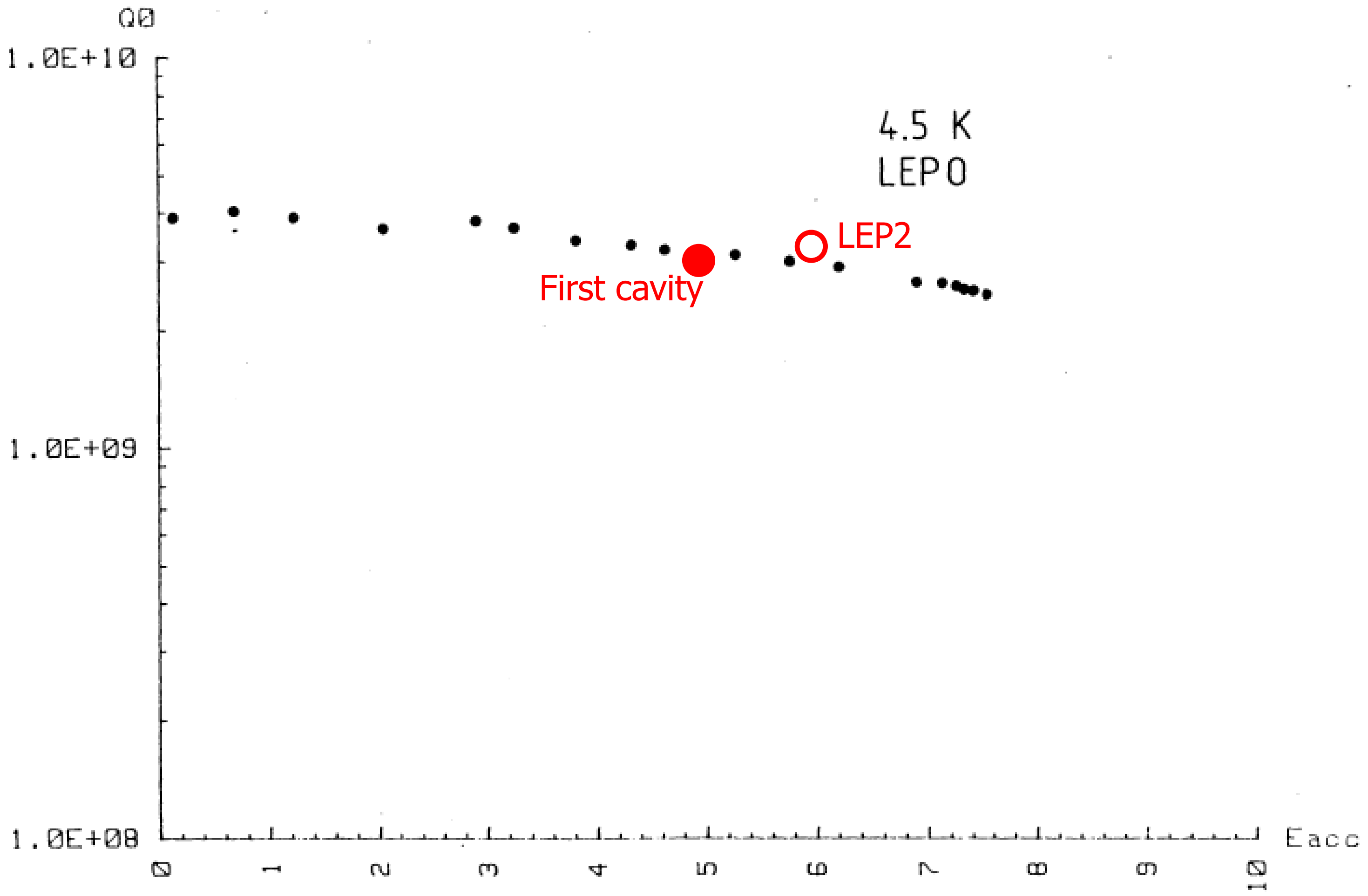


LEP 4-cell cavity in helium vessel and cryostat



SUPERCONDUCTING CAVITY WITH ITS CRYOSTAT

First 352 MHz four-cell cavity for LEP (1990)



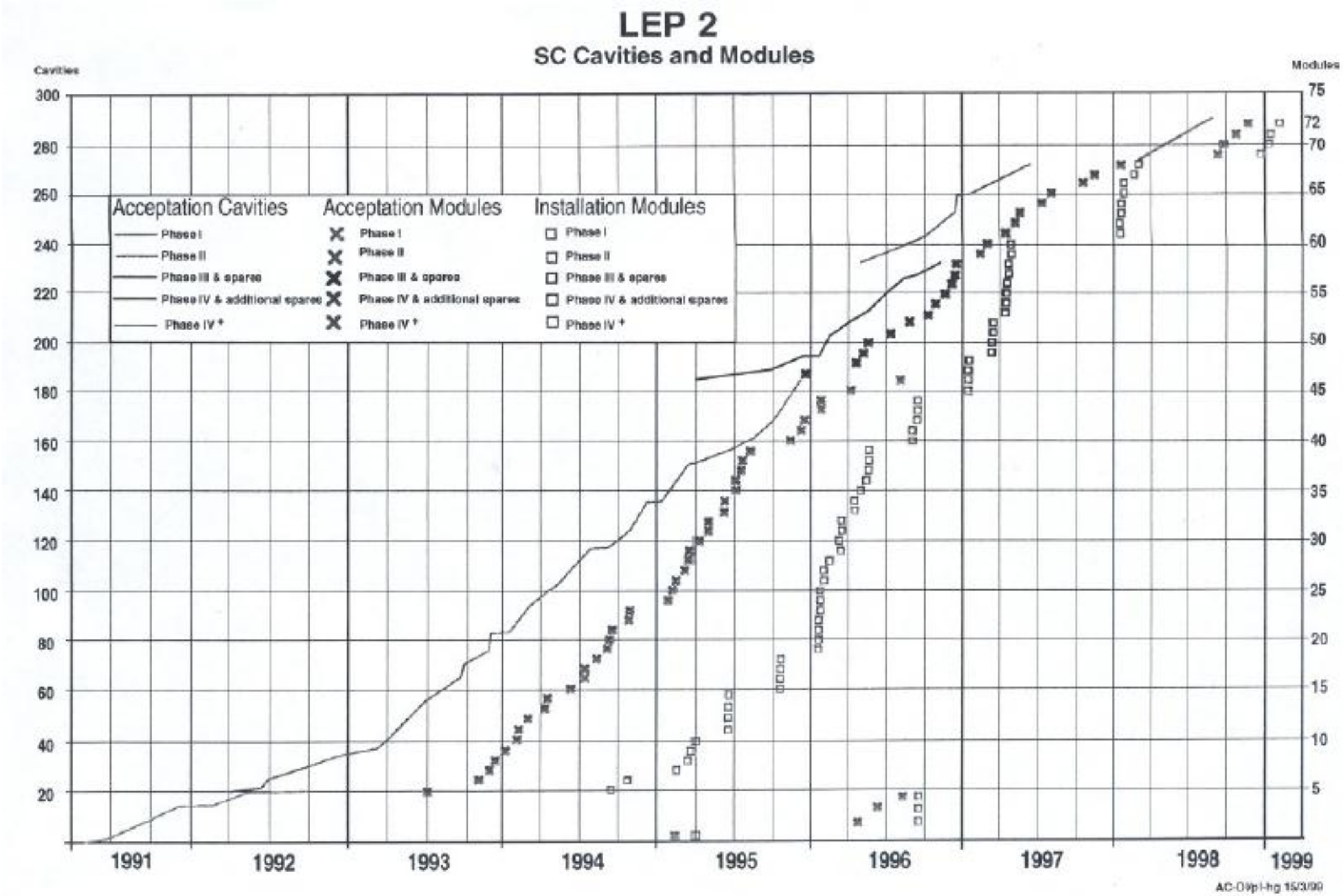
LEP2 RF cryomodules

Cryomodule assembly
in clean room

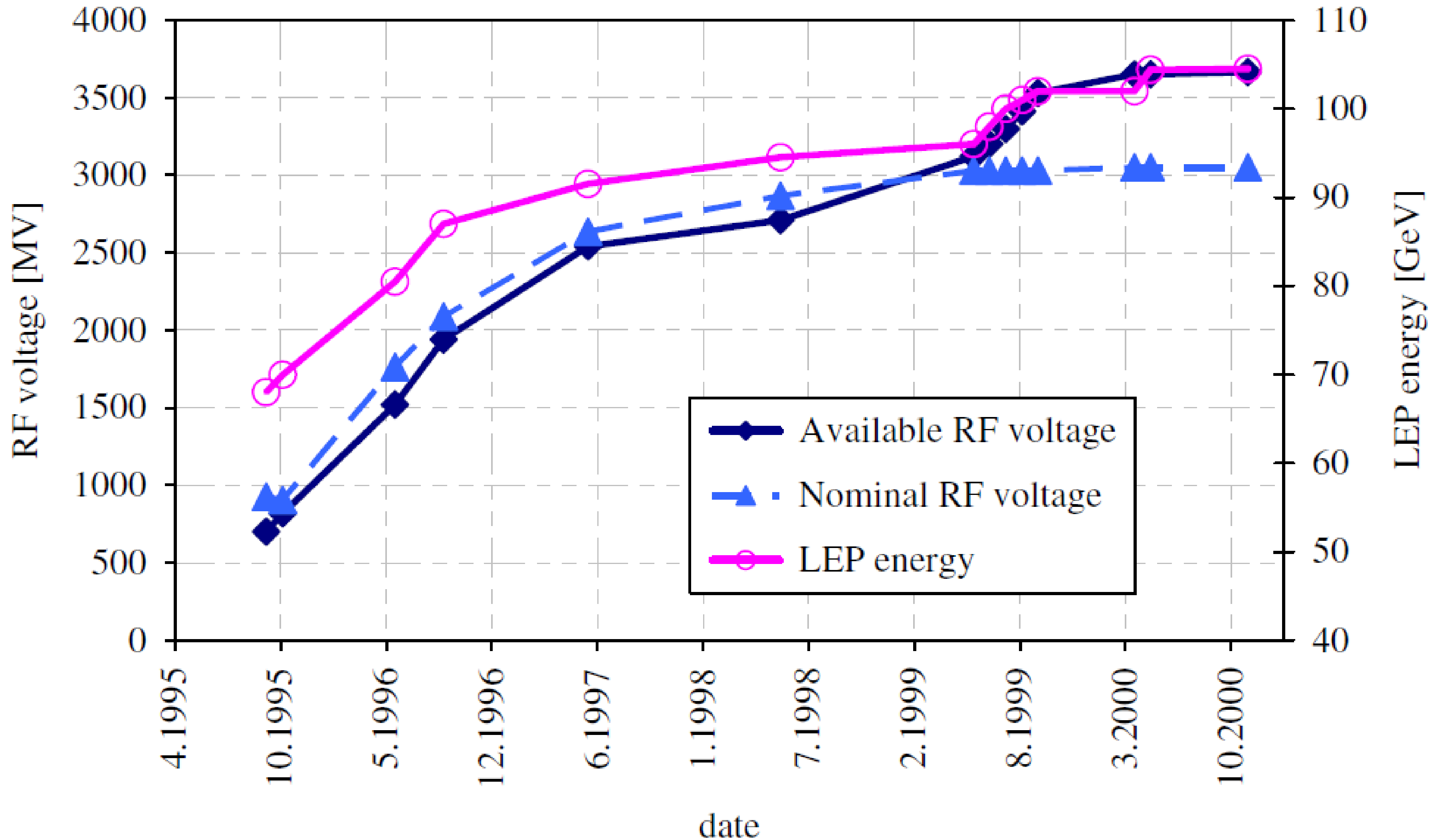
RF frequency	352.209 MHz
No. of cells/cavity	4
No. of cavities/module	4
No. of modules installed	72
Module length	11.28 m
Liquid helium/module	800 l
R/Q (circuit Ohm)	232 Ω
Active length (four cells)	1.70 m
Nominal gradient	6 MV/m
Q_o at 6 MV/m (4.5 K)	3.2×10^9
Q_{ext} Main coupler (nominal)	2.2×10^6
Dynamic cryogenic losses at 6 MV/m per cavity	< 70 W
Static cryogenic losses per complete module	< 90 W

Cryomodule
in LEP tunnel

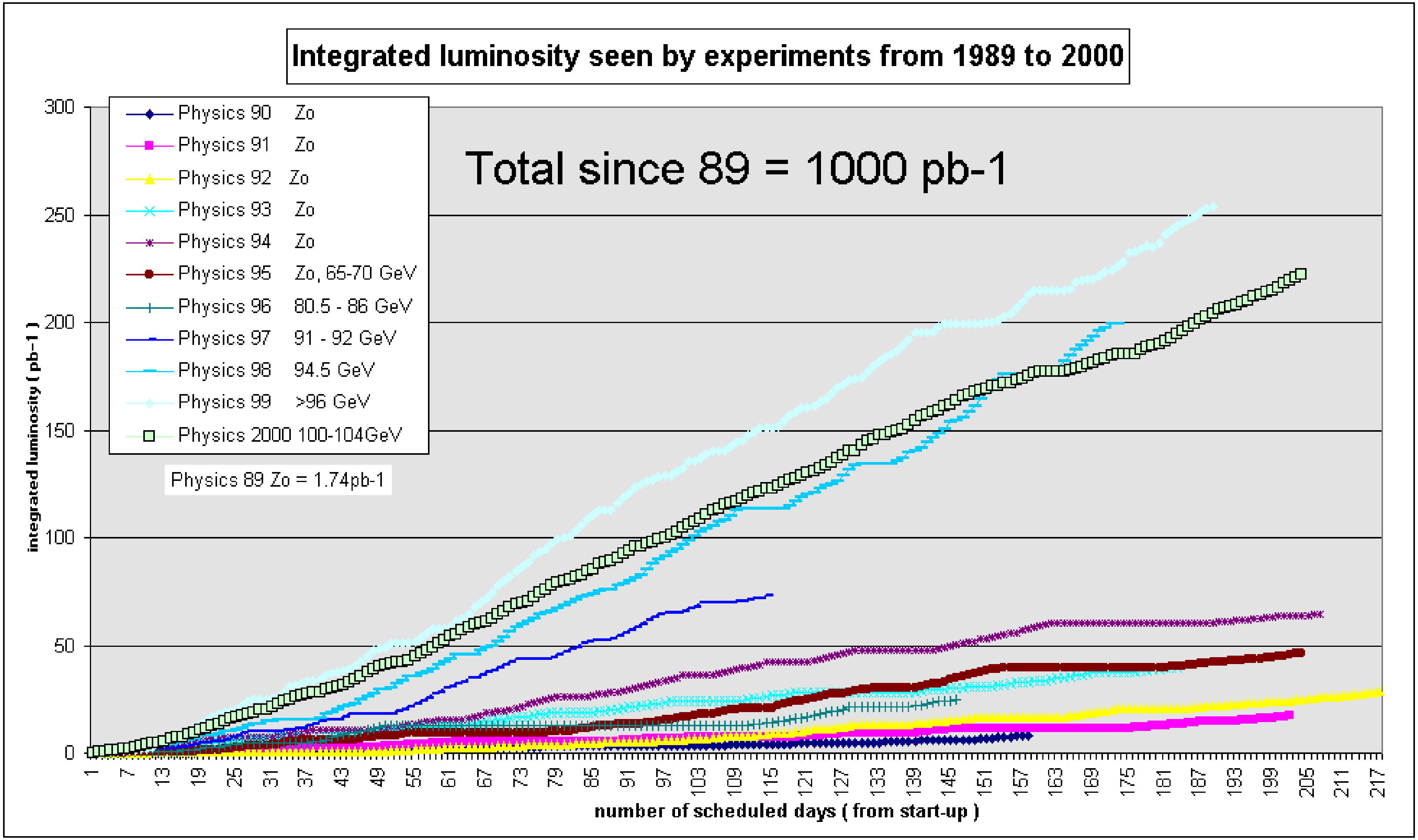
Development of the LEP2 program

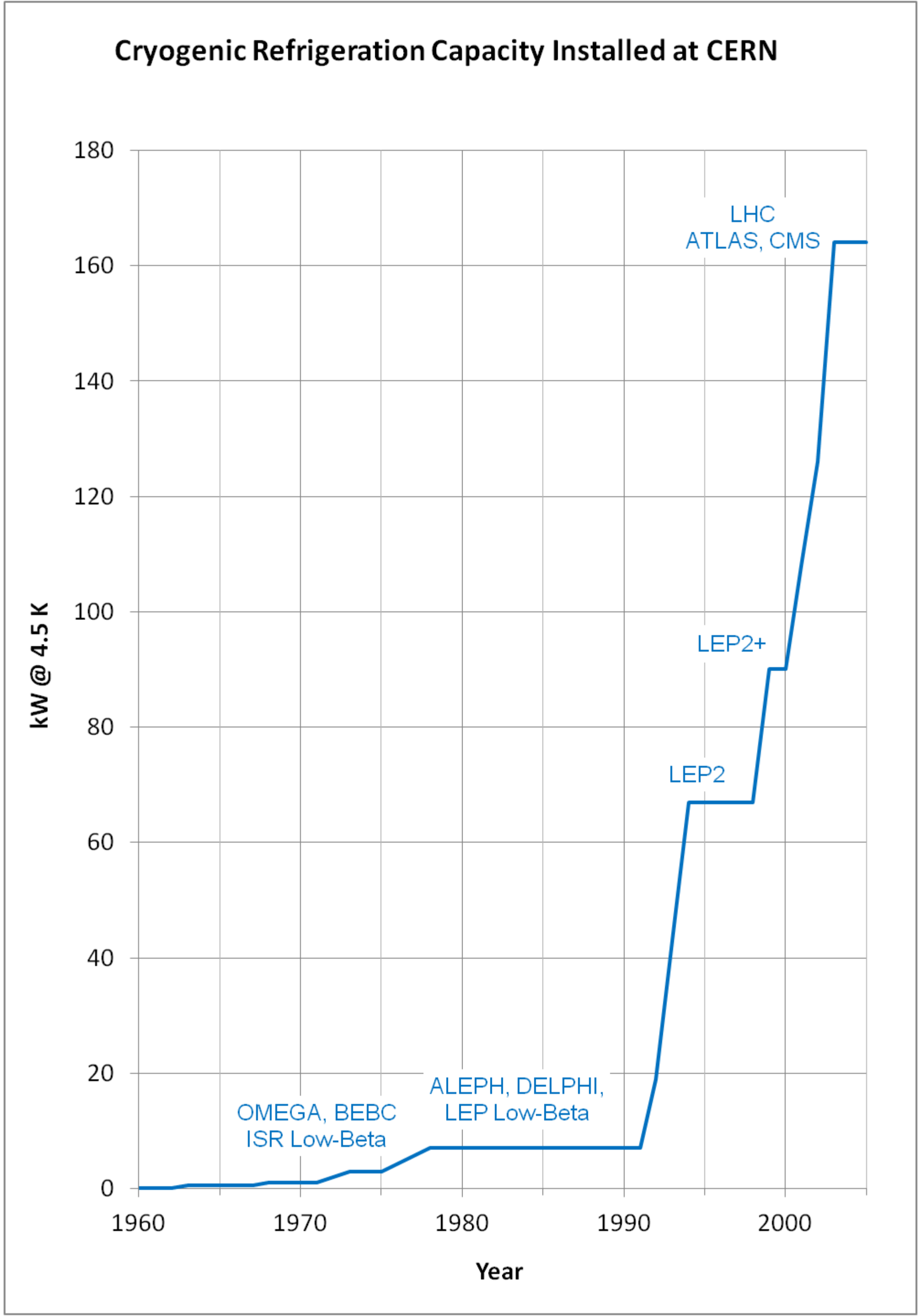


Total RF voltage & LEP energy



LEP performance 1989-2000





Development of He cryogenics reflects that of superconductivity

- Technology
- Installed capacity
- Efficiency
- Reliability

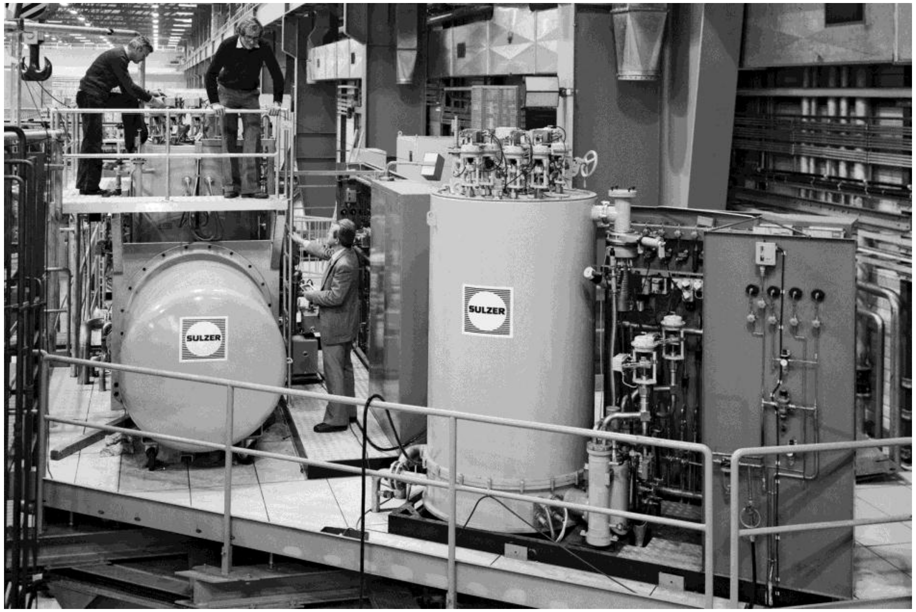
Technology
From dry piston to oil-injected screw compressors

Sulzer piston compressors in North Area (1977)

Oil-injected screw compressors at LEP2 (1996)

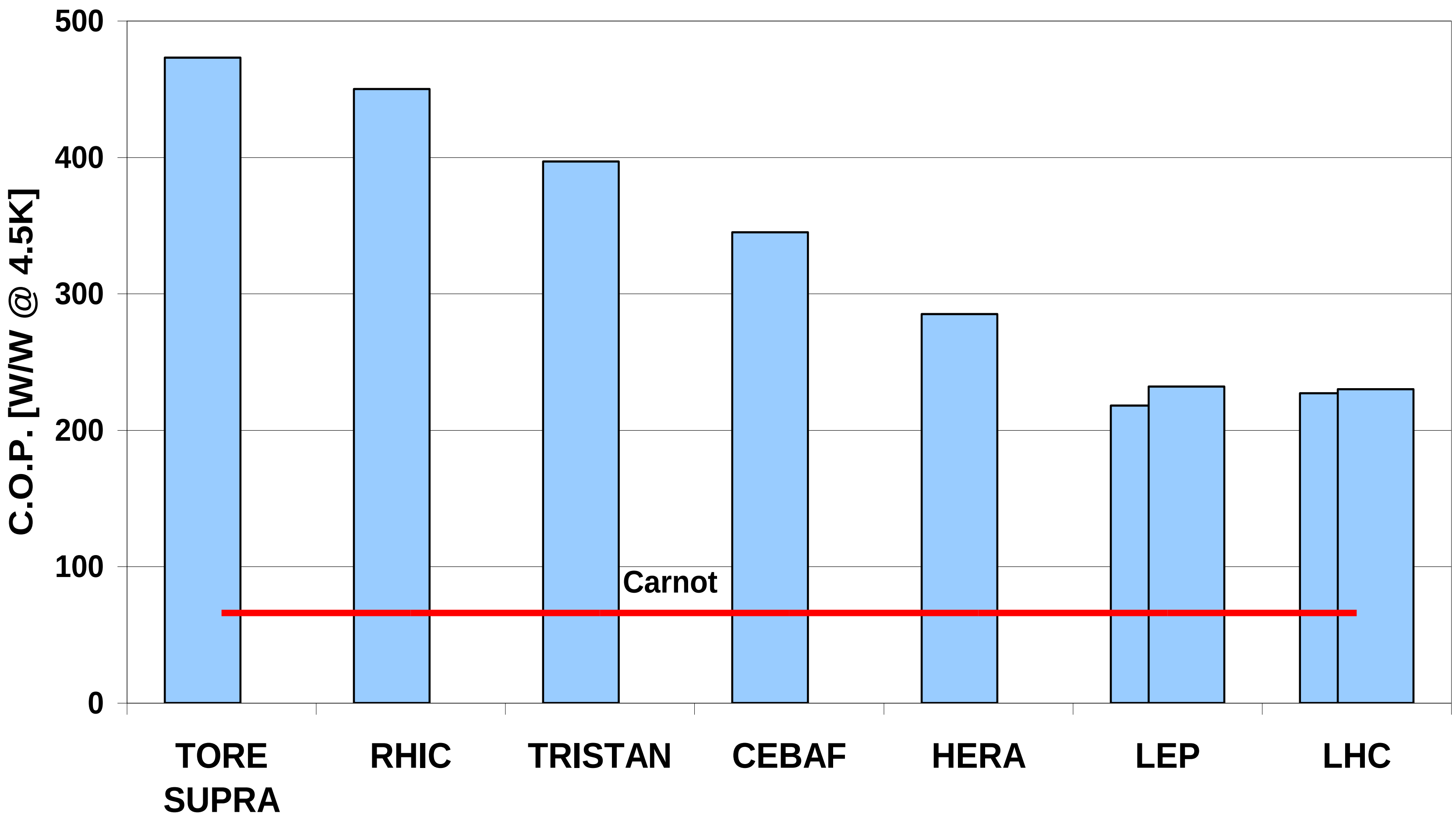
Unit capacity
From 400 W to 18 kW at 4.5 K

Coldboxes in North Area (1977)



Coldboxes at LEP/LHC (1996)

Efficiency
C.O.P. of large cryogenic helium refrigerators at 4.5 K



Concluding remarks

- CERN has recognized the potential of superconductivity for particle detectors and accelerators since the early years of its technological availability, and developed and implemented it in a number of ever bolder projects, which constitute achievements by themselves
- This approach proved an excellent training ground for preparing young applied physicists, engineers and technicians to face the challenges of the future « big one », the LHC

If we have seen a little further it is by standing on the shoulders of giants

Isaac Newton

Acknowledgements

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  - PierGiorgio Innocenti
  - Christine Sutton
  - François Wittgenstein
- I am grateful to CERN for having given me the opportunity to live and work through these exciting years and contribute to some of these projects