Superconducting Magnets Part II

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CAS - February 2018

Overview

- Why superconductors ? A motivation
- Superconducting magnet design
  - Magnetic field and field quality
  - Margins and stability
  - Forces and mechanics
  - Quench protection

Part I

- A brief history of superconducting HEP magnets
- The making of a superconducting LHC magnet
- Towards higher fields
  - High field LTS magnets
  - Outlook of HTS magnets
- Other superconducting magnet systems

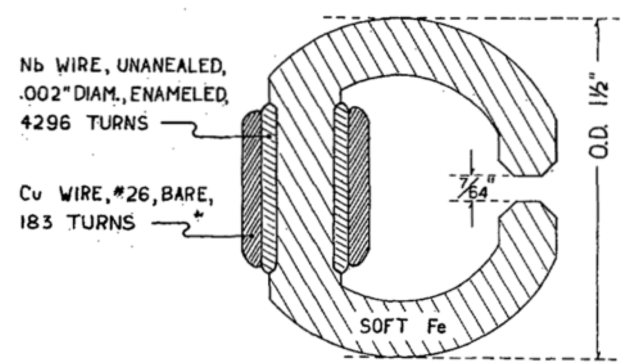
Part II

Overview

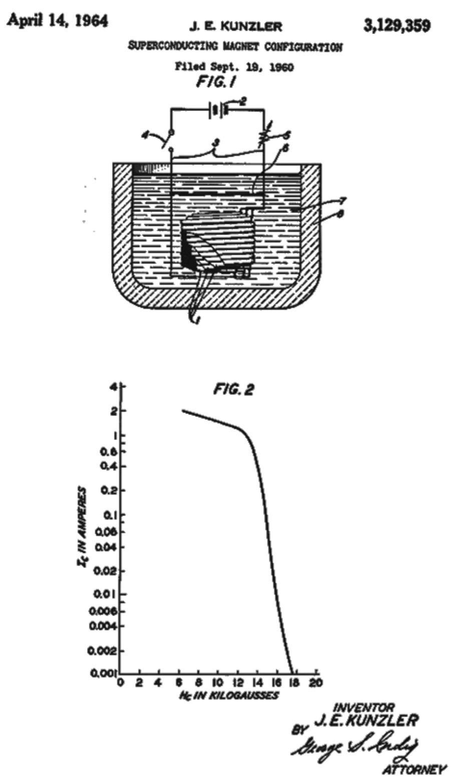
- A brief history of superconducting HEP magnets
- The making of a superconducting LHC magnet
- Towards higher fields
  - High field LTS magnets
  - Outlook of HTS magnets
- Other superconducting magnet systems

Magnet engineering is born !

- **G. Yntema, 1954: Nb wire on an iron-core, produced 0.71 T** (*"I saw no reason why a magnet could not be made with superconducting windings, so I gave it a try"*)



*G.*B. Yntema, IEEE Trans. Mag., 23(2), 390-395, 1987

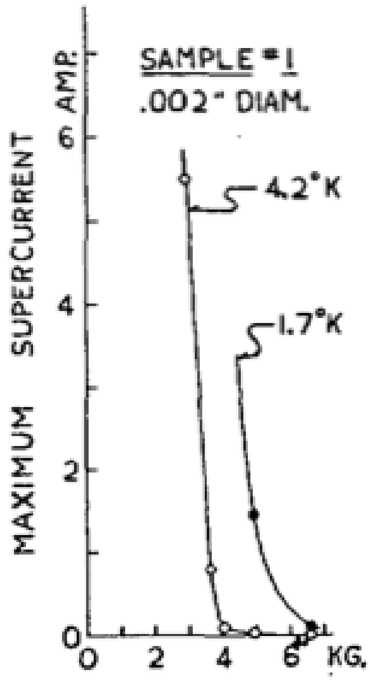


- J. Hulm, 1955: Nb-wire air-core solenoid, produced 0.6 T
- S. Autler, 1960: Nb wire on an iron-core, produced 1.4 T for a solid state MASER
- **J.E. Kunzler, September 19, 1960: first patent for a Superconducting Magnet Configuration (Patent 3,129,359, April 14th, 1964)**

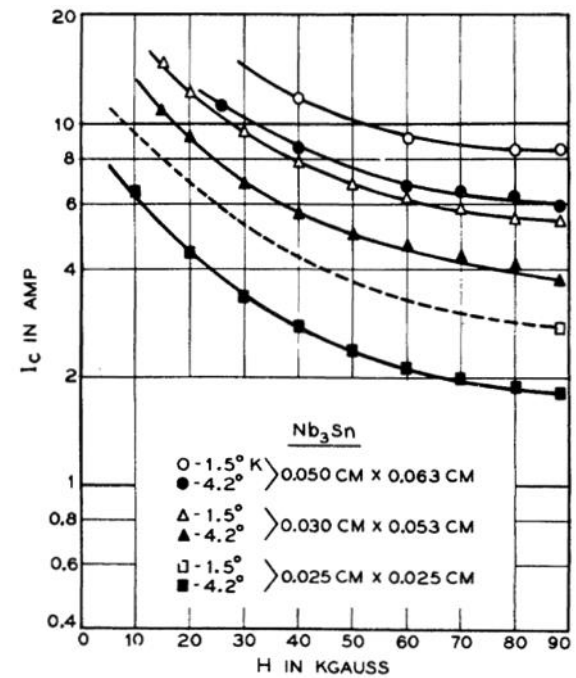
Jc ! Jc ! Jc !

Al “Mac” McInturff

- Cold worked Nb wires (Yntema, 1954): 1000 A/mm² at 0.5 T and 1.7 K
- Mo_3Re wires (Kunzler, 1959): 500 A/mm² at 1.5 T and 1.5 K
- Nb_3Sn wires (Kunzler, 1961): up to 1000 A/mm² at 9 T and 1.5 K
- NbTi wires (Berlincourt, 1962): from 440 A/mm² at 3T and 4.2 K to 100 A/mm² at 10 T and 4.2 K



G.B. Yntema, IEEE Trans. Mag., 23(2), 390-395, 1987



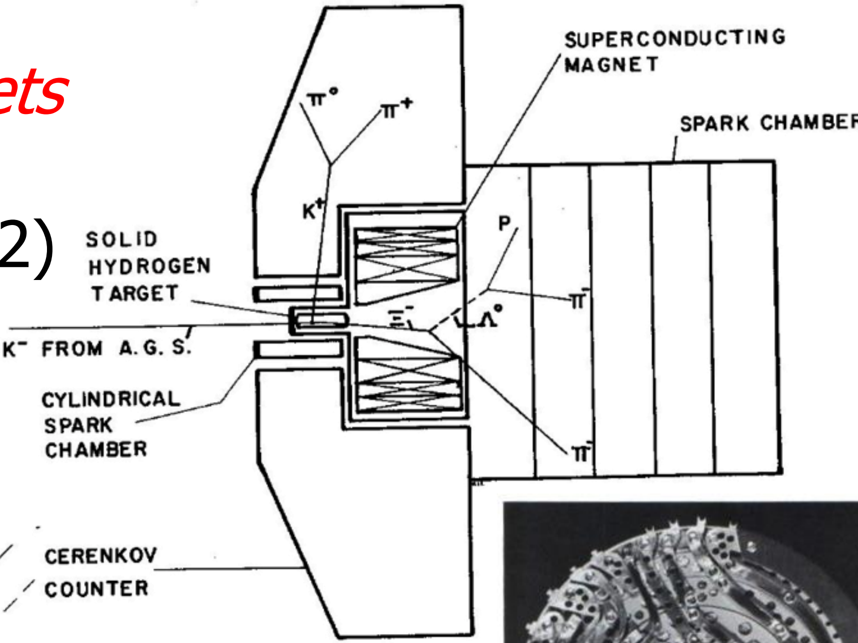
J. Kunzler, IEEE Trans. Mag., 23(2), 396-402, 1987

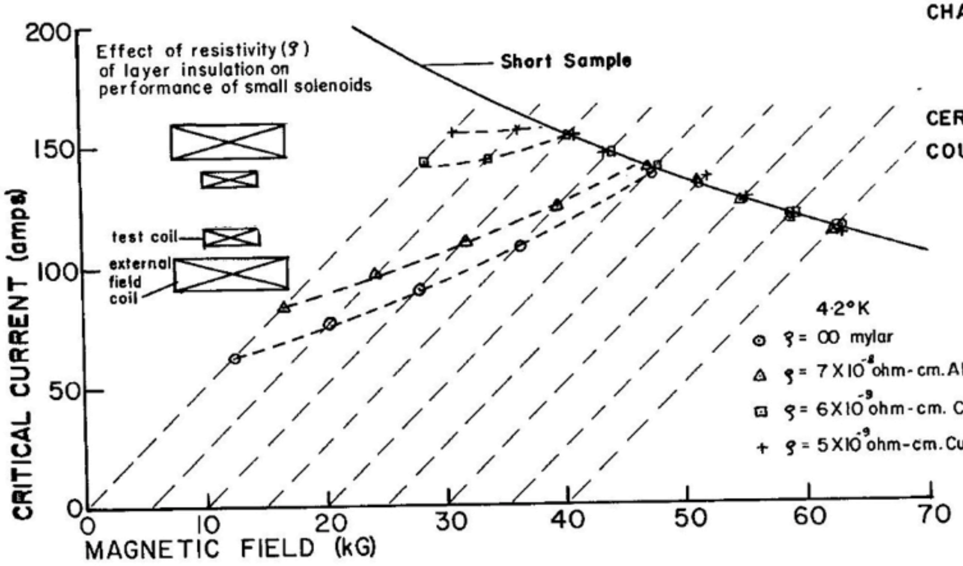
Setting the scene

- International Conference on High Magnetic Fields, hosted by MIT, Boston, 1961:
  - J.E. Kunzler (Bell Labs) Nb_3Sn magnet achieves 68 kGauss, barely surpassing the 60 kGauss reported by J. Hulm (Westinghouse) and T. Berlincourt (Atomics International) in NbZr solenoids
- The *scotch bet* (Tanenbaum vs. Kunzler):
  - a bottle of scotch for every 3 kG above 25 kG
  - **The first 10 T solenoid was built by Kunzler's group 2 crates of scotch later**

Dealing with flux-jumps

- *"Those tiny, primitive magnets were, of course, terribly unstable"* (J. Hulm, ASC 1982)





W.B. Sampson, Proc. Int. Symp. Mag. Tech., SLAC, 530-535, 1965

The 1968 *Woodstock* of superconducting accelerators

BNL 50155 (C-55)

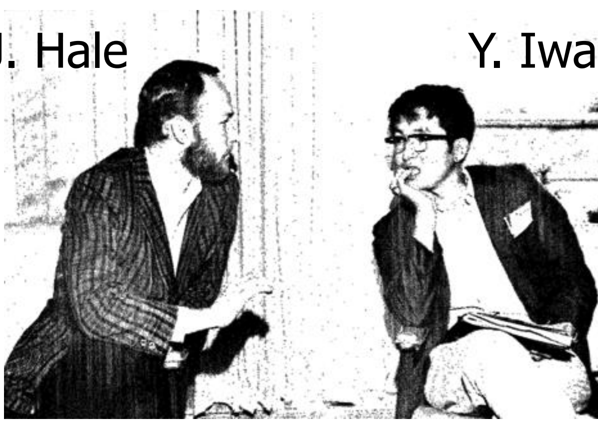
M. Morpurgo B. Montgomery

PROCEEDINGS OF THE 1968 SUMMER STUDY
ON SUPERCONDUCTING DEVICES AND ACCELERATORS
Part I (pp. 1-376)

BROOKHAVEN NATIONAL LABORATORY
June 10 – July 19, 1968

W. Sampson P. Smith

J. Hale Y. Iwasa



ASSOCIATED UNIVERSITIES INC
BROOKHAVEN NATIONAL LABORATORY

- A six weeks summer study organized and hosted by BNL in 1968
- The ***crème de la crème*** addresses material and engineering issues of superconducting accelerators

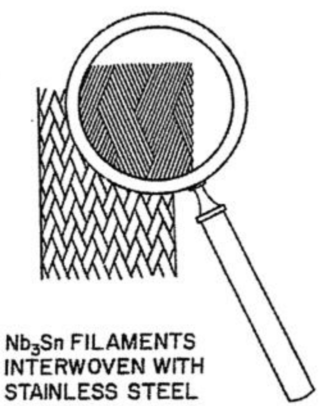
First ideas are discussed

- Issues addressed at the 1968 Summer Study
  - Stability and stabilization strategies
  - Flux-jump instability, filamentary superconductors
  - AC loss, coupling and the need of twisting
  - **Potential for the use in superconducting synchrotrons**

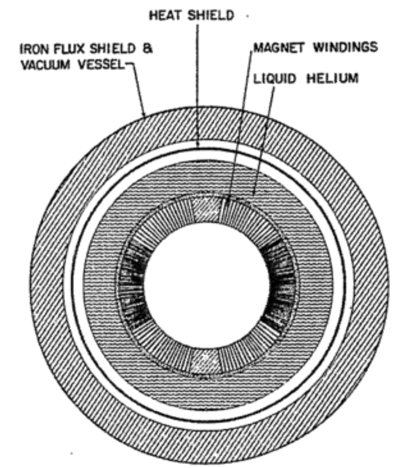
A 2000 GEV SUPERCONDUCTING SYNCHROTRON*

W.B. Sampson
Brookhaven National Laboratory
Upton, New York

Energy	2000 GeV
Injection energy	30 GeV (AGS)
Radius	1.5 km
Aperture	30 cm^2
Peak field	60 kG

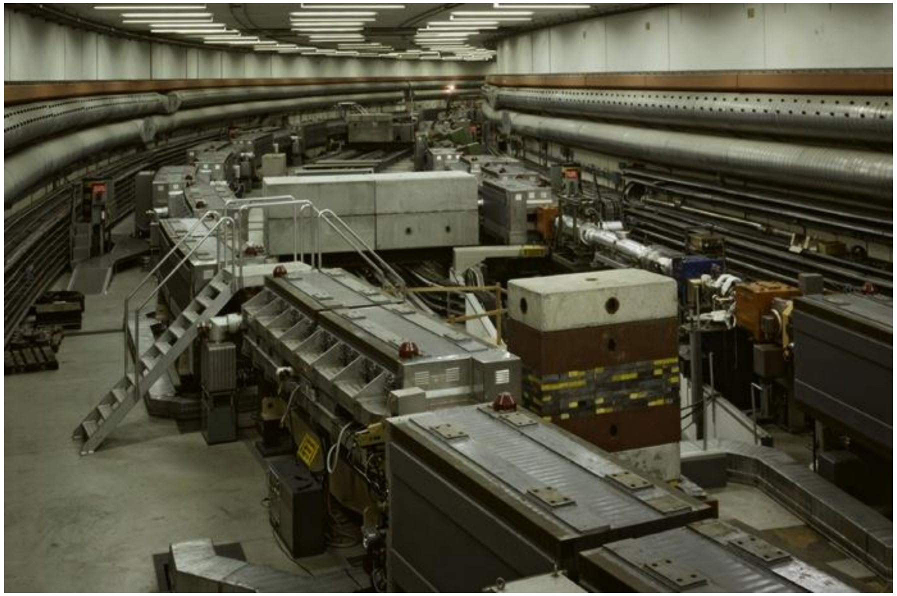


Nb_3Sn FILAMENTS INTERWOVEN WITH STAINLESS STEEL

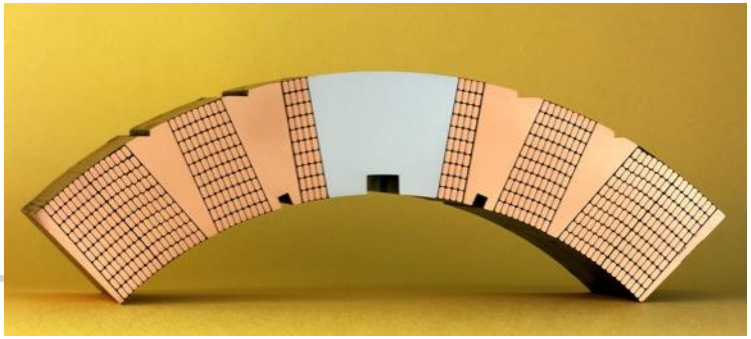


The ISR's

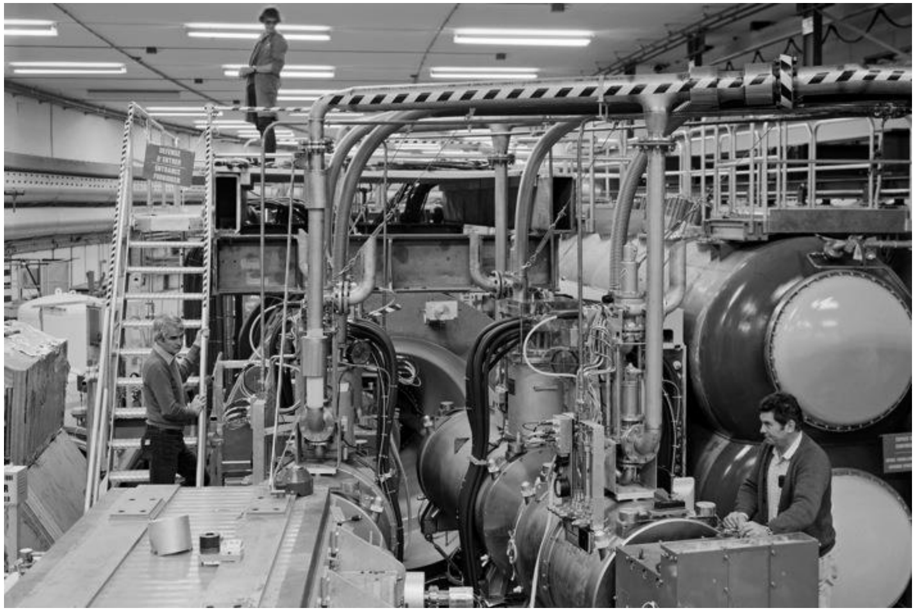
- The Intersecting Storage Rings (ISR) was the world first hadron collider
- It ran from 1971 to 1984 with maximum center-of-mass energy of 31+31GeV
- Held the record luminosity (1.4 x 10^{32} 1/cm^2 s) for hadron colliders till 2004
- **Hosted the first accelerator SC quadrupole magnets**



ISR low-β quads

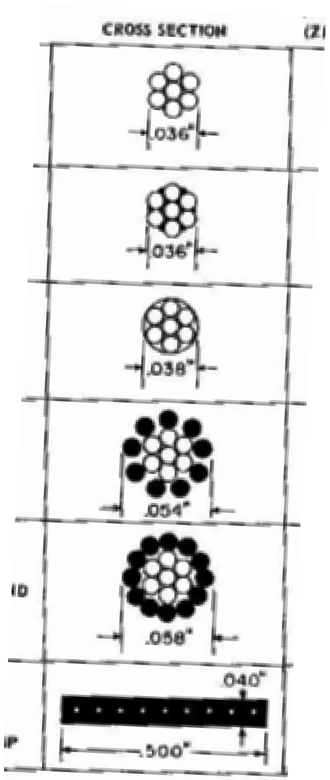


- **1973** – Study launched on low-beta (high-luminosity) insertions using superconducting quadrupole magnets
- **1976** – First prototype of a superconducting quadrupole tested

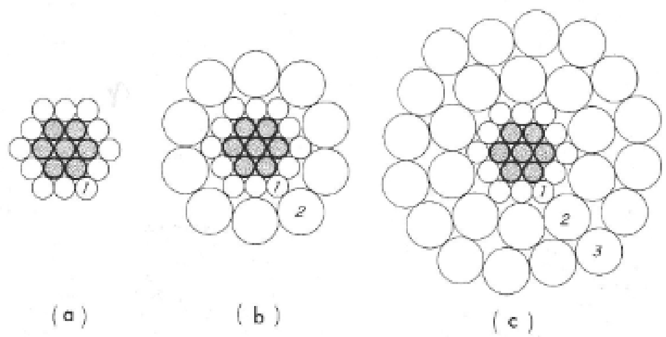


- **1985** – Manufacture of 8 quadrupoles (4 of L=1.15 m, 4 of L=0.65 m) begins at Alsthom. They are installed at intersection I8 of the ISR, enhancing luminosity by a factor 7

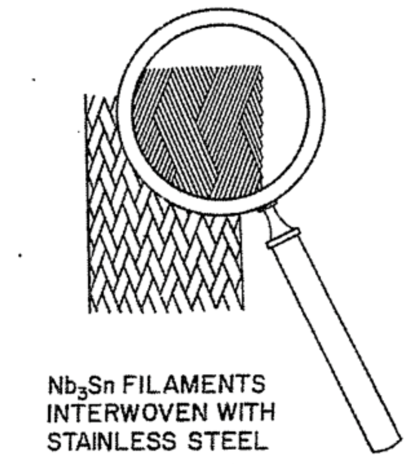
From strands to cables



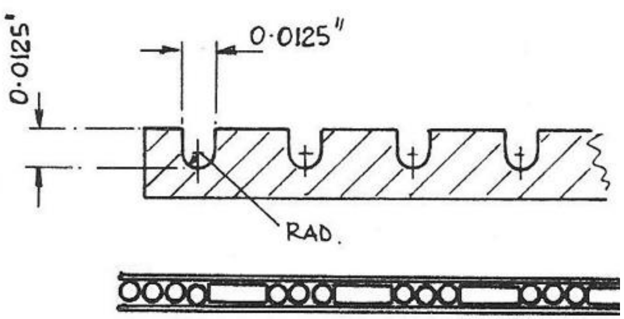
Z.J.J. Stekly, Proc. Int. Symp. Mag. Tech., SLAC, 550-559, 1965



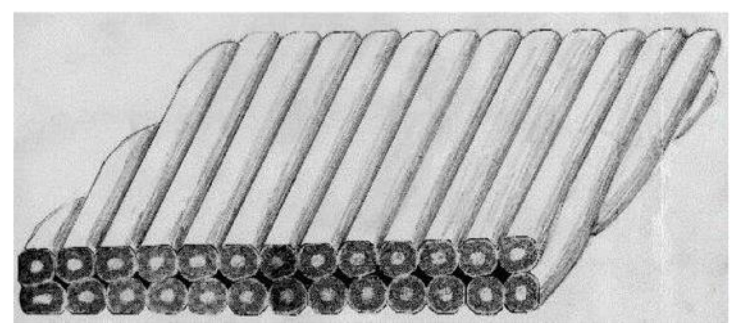
C. Laverick, Proc. Int. Symp. Mag. Tech., SLAC, 560-567, 1965



W.B. Sampson, Proc. 1968 Summer Study, BNL, 998-1001, BNL 50155 (C-55), 1968



R.B. Hopes, G.R. Fallon, Proc. Int. Conf. Mag. Tech., Oxford, 524-528, 1967



G. E. Gallagher-Daggitt, *Superconductor Cables for Pulsed Dipole Magnets*, Rutherford Laboratory Memorandum No.RHEL/M/A25, 1973.

Race of two

Science

AAAS

14 Apr 1978

RESEARCH NEWS

Two Superconducting Accelerators: Physics Spurs Technology

Exotic new products derived from research on superconductivity have been predicted to revolutionize things ranging from railroads to power lines, but it is now virtually certain that the first major activity superconductivity will revolutionize will be that of accelerator building.

ties of the wire used in the electromagnets that keep the particles orbiting in a circle. As the energy of the particles increases, the field of the magnets must increase appropriately to keep the particles in the proper track. The power dissipated in the magnet coils due to resistive losses is considerable, especially

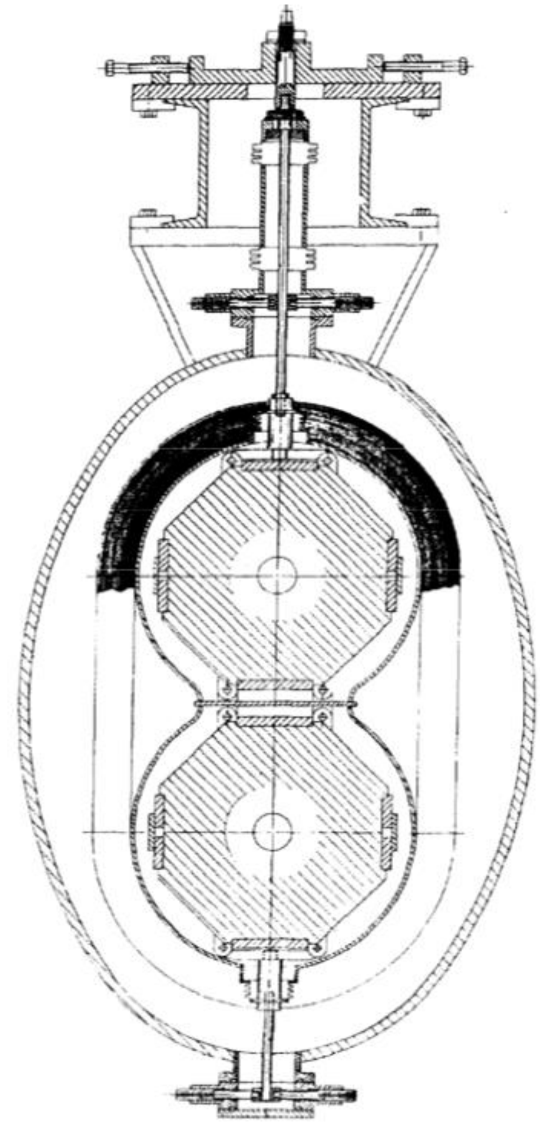
pulsed magnets that could be "ramped" upward over a period of seconds or tens of seconds as required for a synchrotron. Such operation creates stresses and heating losses that are not present in constant-field magnets.

Special multifilamentary wires that reduce the heating losses in pulsed mag-

Isabelle

- **1963** – Summer Study at BNL considers storage rings for a colliding beam accelerator
- **1970** – Idea revived by J.Blewett
- **1972** – Fitch Committee recommends that BNL develops the concept for an *Intersecting Storage Accelerator + BELLE* (ISABELLE)
- **1973** – Design study at Brookhaven completed for a 200+200 GeV proton collider
- **1978** – Groundbreaking

Cross section of the cryostated magnets

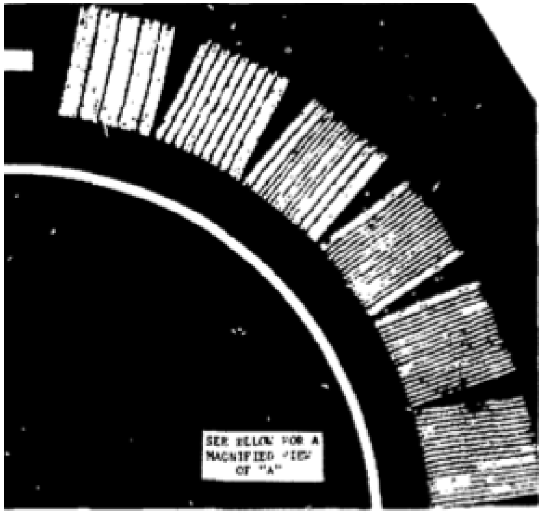


F.E. Mills, Isabelle Design Study, Proc. PAC 1973, 1036-1038, 1973

Isabelle

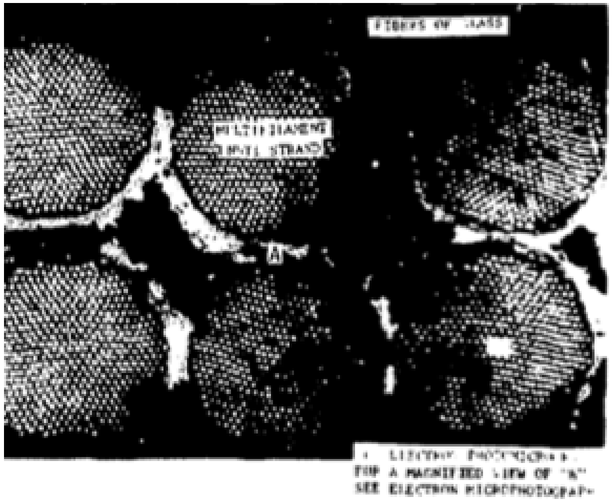
B. Palmer

- **1979** – Successful test of model magnet, reaching 5 T
- Energy raised from 200 to 400 Gev, requiring nominal dipole field from 4 to 5 T (single layer, large braided cable)
- Construction started before completion of the supporting magnet R&D



PHOTOGRAPH OF CROSS SECTION OF QUADRANT OF THE ISABELLE DIPOLE WINDING

"*Isabelle*" braid



PHOTOMICROGRAPH OF BRAIDED CONDUCTOR

A.D. McInturff, , Superconducting Magnets at Brookhaven National Laboratory, World Electrotechnical Congress, Moscow, USSR, 6/21-25/77

From Isabelle, to CBA, into oblivion

The New York Times

TROUBLES CONTINUE FOR L.I. ACCELERATOR

By WALTER SULLIVAN (The New York Times); National Desk
June 7, 1981, Sunday
Late City Final Edition, Section 1, Page 30, Column 1, 961 words

June 7th, 1981

[DISPLAYING ABSTRACT]

Budget cuts and development difficulties have so hampered construction of a machine designed to produce the world's most powerful subatomic collisions that a high-level review panel is considering radical changes in the project. Almost $80 mil
built at the Broo
three years ago
the machine's m
of protons, the r
two miles long.
electron-volts, t

BIG ACCELERATOR ON LONG ISLAND GETS A 'NO' VOTE

By WILLIAM J. BROAD (The New York Times); National Desk
July 14, 1983, Thursday
Late City Final Edition, Section B, Page 6, Column 6, 379 words

July 14th, 1983

[DISPLAYING ABSTRACT]

A panel of top physicists who advise the Federal Government recommended yesterday that an incomplete atom smasher at the Brookhaven National Laboratory on Long Island be scrapped. The move, upholding an earlier decision of a
subcommittee, almos
recently renamed the
machine already runs
the country, the finis

- Technical difficulties in magnet performance experienced in 1981
- Machined renamed to Colliding Beams Accelerator
- Production cost increases, timeline slips
- Questions on competitiveness vs. new 20 TeV concept (SSC)

Project cancelled by DOE in 1983, after spending > 200 M$, large part of which in civil engineering (tunnel)

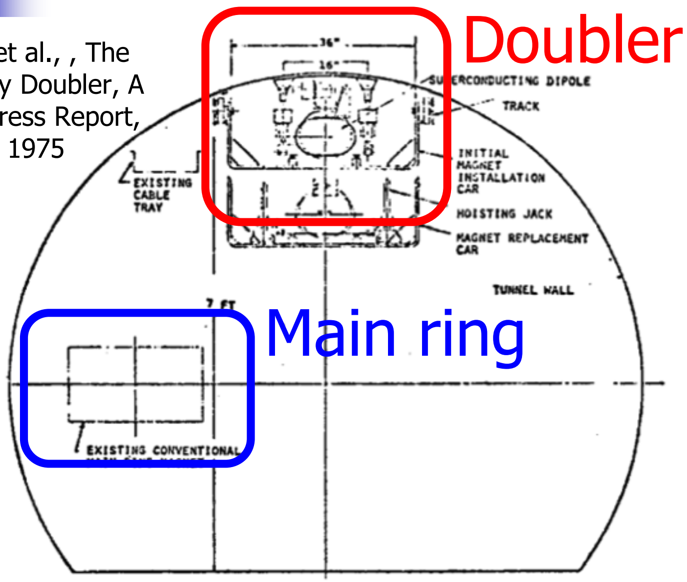
The energy *doubler* and *saver* at NAL

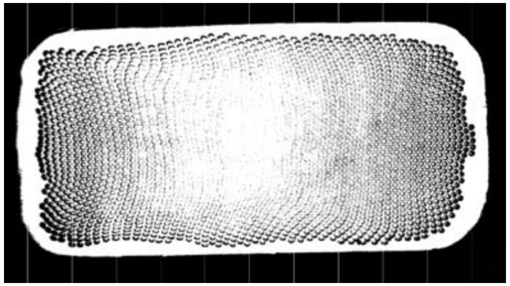
- Robert R. Wilson, March 9th, 1971, in Washington, D.C.:

"It appears now that such a possibility [500 GeV] may become feasible in the concept of what I like to call an 'energy doubler.' It is a small-bore superconducting magnet that can be mounted 'pickaback' on the present main ring magnet. If successful, it should be of modest cost and should enable us to achieve higher energies -- as much as 1,000 BeV. Just as important, though, is that operation above the 200 BeV level would cost much less using the superconducting magnet than it would using our present copper and iron magnets… I would hope, too, that … the Committee will challenge me to build as extensive experimental facilities and attain as high an energy as is possible without exceeding the Congressional authorization of $250,000,000."

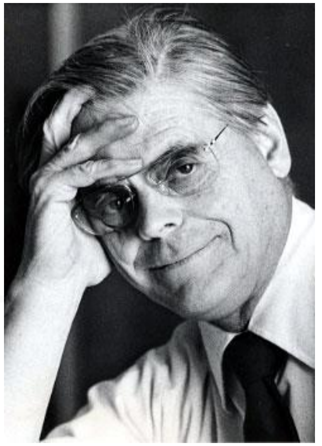
Concepts for the doubler

W.B. Fowler, et al., , The Fermilab Energy Doubler, A Two-Year Progress Report, TM-558, 1975

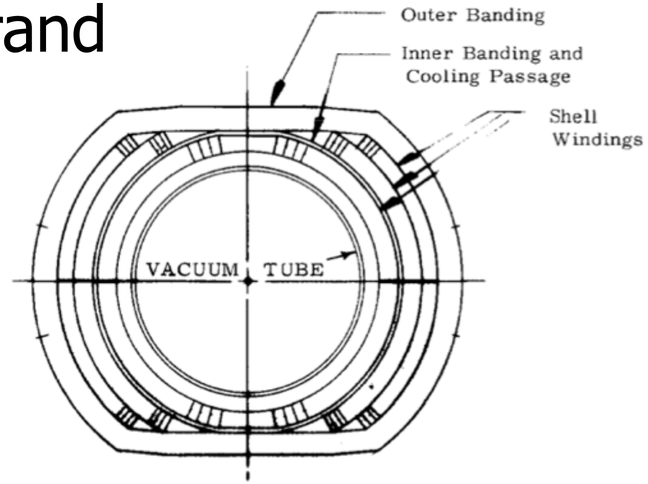


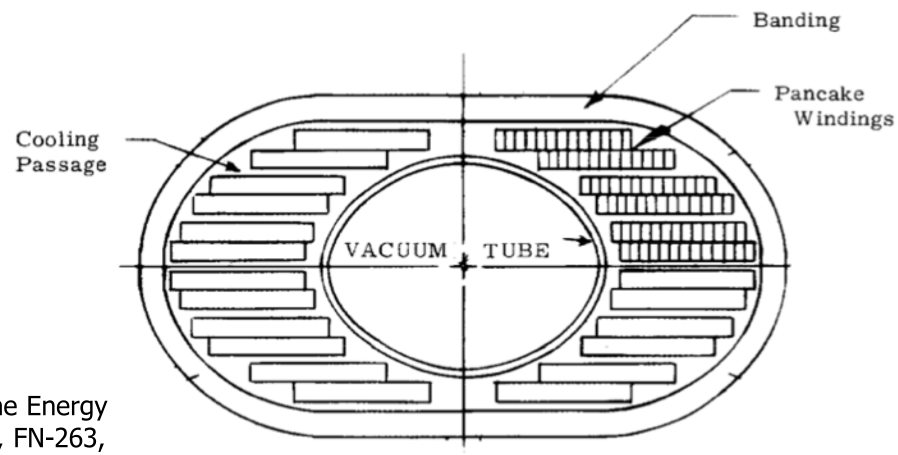


Superconducting strand



R. Wilson





Dipole magnet concepts

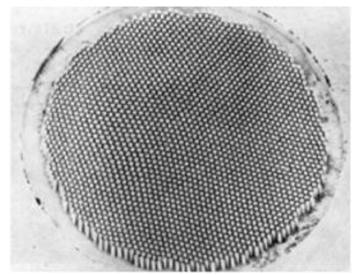
R.R. Wilson, et al., , The Energy Doubler Design Srtudy, FN-263, 1974

From the Doubler/Saver, to the Tevatron

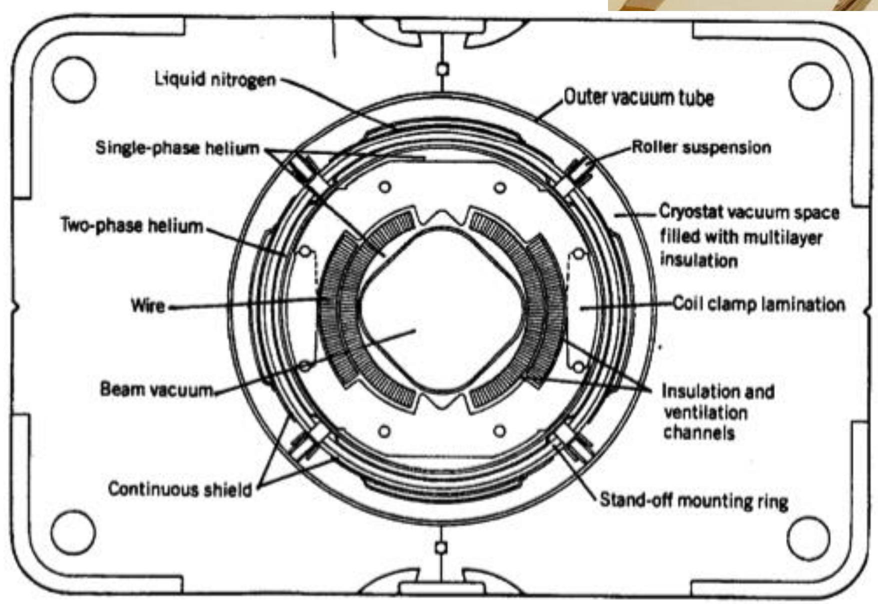
We started out by straightforwardly applying logic and Maxwell's Laws. This attempt only demonstrated the hubris of experimental physicists; there were too many unknown and uncontrollable variables. Our next approach, largely Edisonian, was to build dozens and dozens of supermagnets, each only about one foot long but full scale in cross section. We built on our successes, tried to avoid repeating our failures, and accumulated experience; gradually the magnets improved until by now they are of quite adequate quality for an accelerator or a storage ring. Two rules summarize our experience: Permit little or no motion of the superconductor, and let the helium coolant bathe the superconductor as directly as possible. To this we might add that the superconductor should be as filamented as is practical.

R.R. Wilson, The Tevatron, TM-763, 1978

Nb-Ti/Cu strand

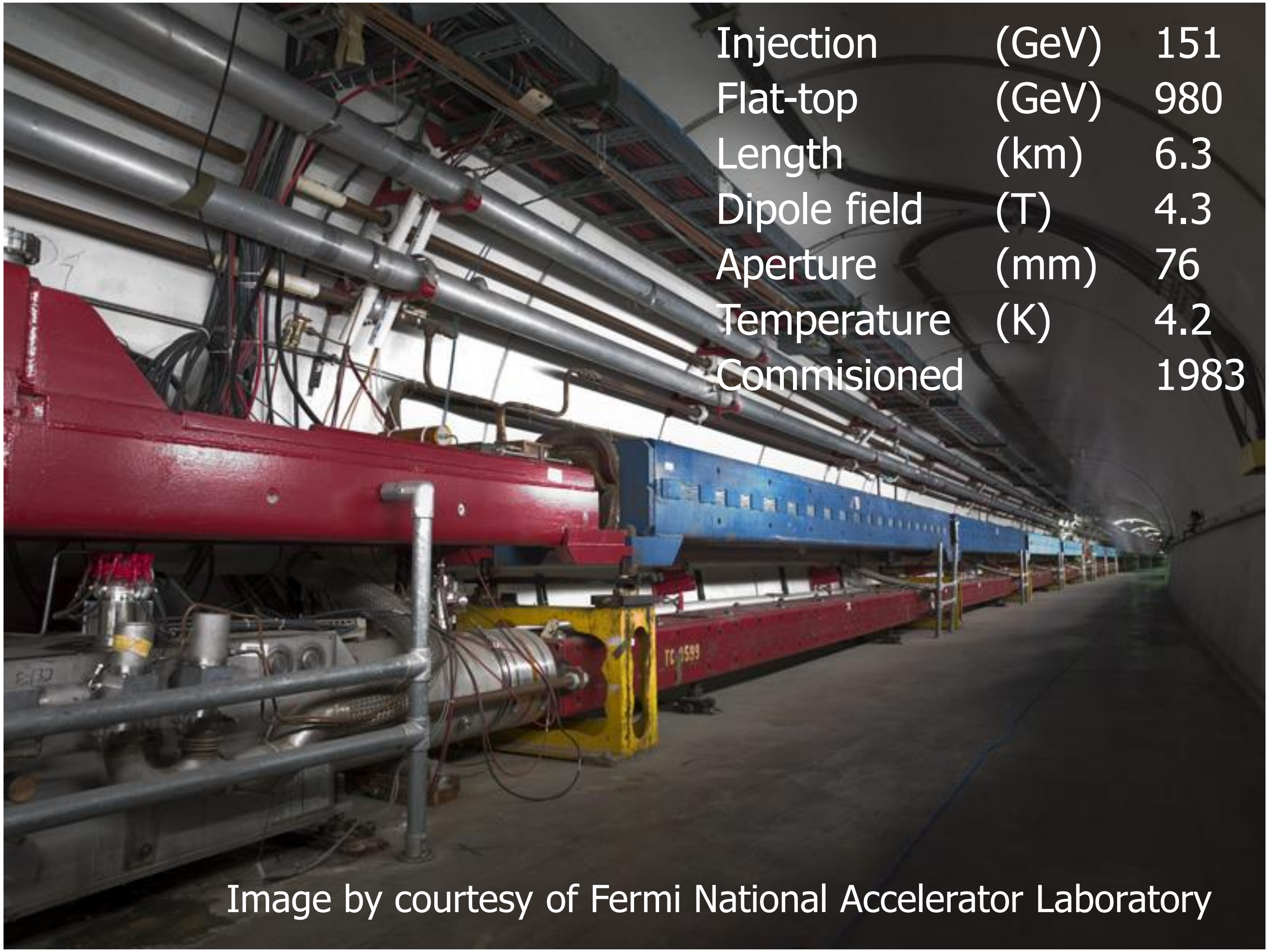


Rutherford cable



Dipole cross section

The Tevatron !

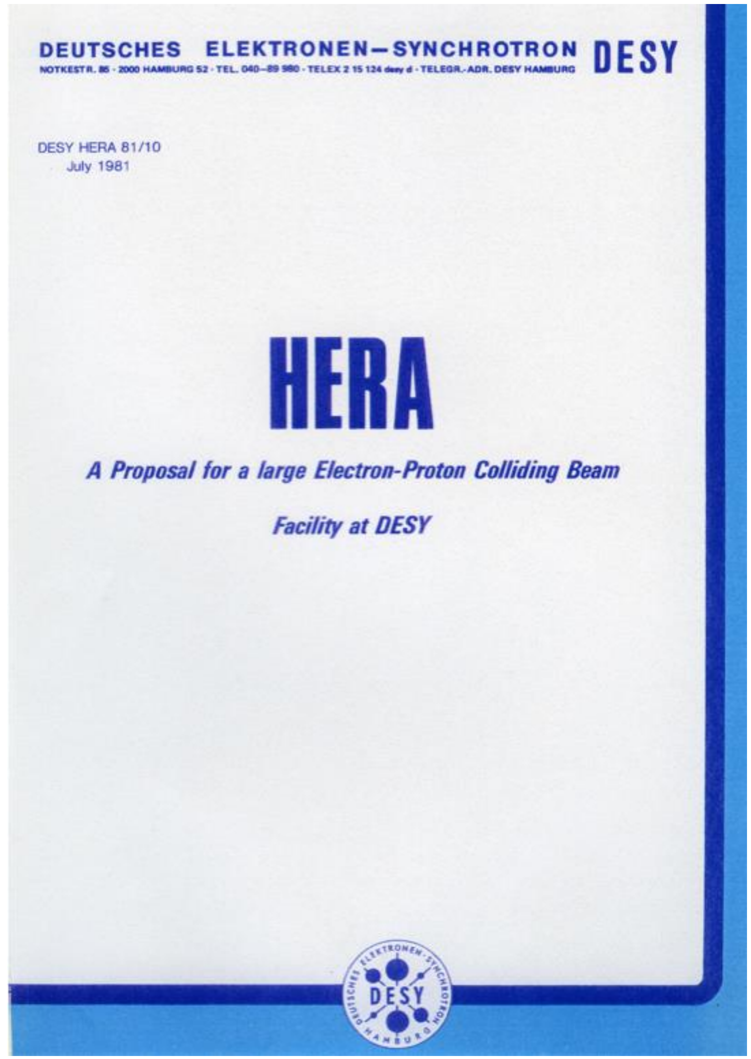


Injection	(GeV)	151
Flat-top	(GeV)	980
Length	(km)	6.3
Dipole field	(T)	4.3
Aperture	(mm)	76
Temperature	(K)	4.2
Commisioned		1983

Image by courtesy of Fermi National Accelerator Laboratory

Hadron Elektron Ring Anlage

- **1972** – H. Gerke, H. Wiedemann, B. H. Wiik, G. Wolf: "DORIS as ep-collider".
- **1977** – Ch. Llewellyin-Smith, B. H. Wiik: "Physics with large electron-proton colliding rings".
- **1980** – ECFA report: "Study on the proton-electron storage ring project HERA", U. Amaldi: "The green book".

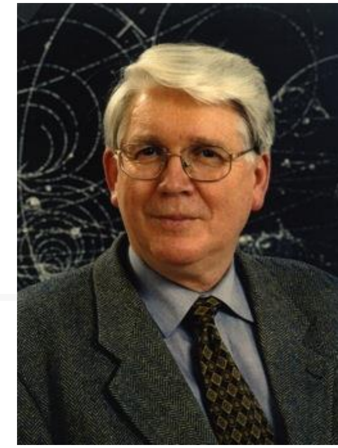


DEUTSCHES ELEKTRONEN—SYNCHROTRON DESY
NOTKESTR. 85 · 2000 HAMBURG 52 · TEL. 040–89 980 · TELEX 2 15 124 desy d · TELEGR.-ADR. DESY HAMBURG

DESY HERA 81/10
July 1981

HERA

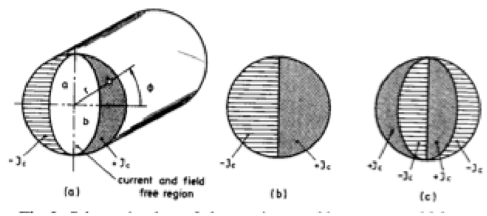
A Proposal for a large Electron-Proton Colliding Beam Facility at DESY



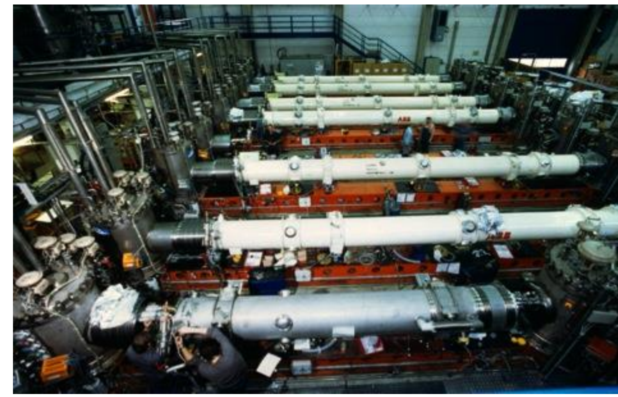
B.H. Wiik

July 1981

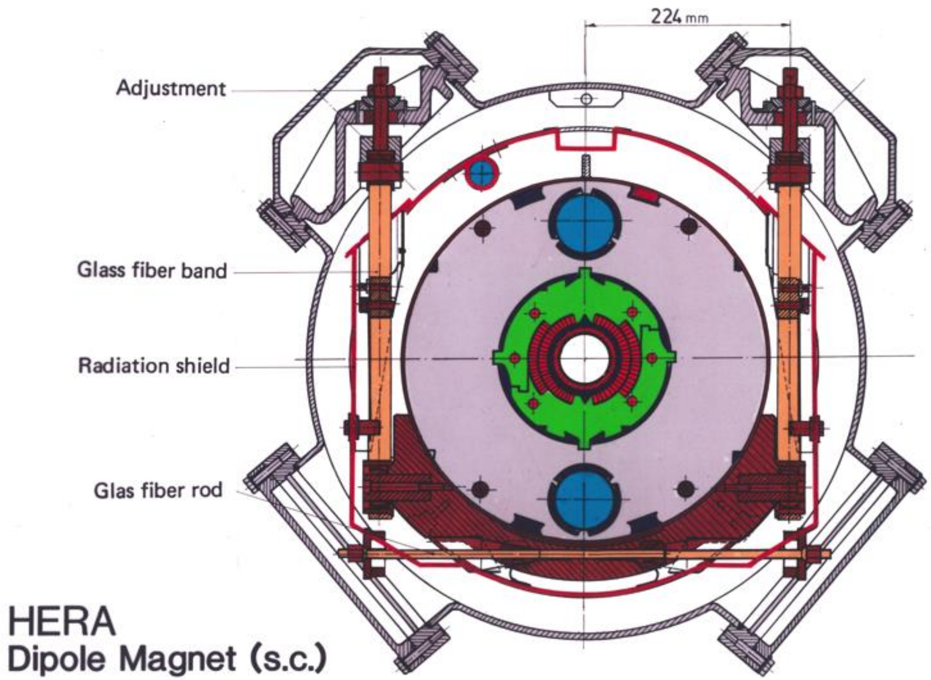
Accelerator technology at HERA



H. Brueck, et al., Z. Phys. C - Particles and Fields 44, 385 392 (1989)



SC magnet testing



Reference magnets

International collaborations and celebrations

International Collaboration in the Construction of the HERA Collider

The electron-proton collider HERA, 1984 - 1990 built at DESY, the German High Energy Physics Laboratory in Hamburg, is the result of an international collaboration with contributions from laboratories and research centres from six countries. These contributions came in the form of components for the HERA storage rings and injection systems, developed and constructed by the participating institutes in collaboration with their local industry. Additionally skilled staff from five countries were sent to DESY for one to three years to join in the HERA construction.

The contributions in detail are:

Canada

TRIUMF Laboratory, Vancouver
Design and construction of the 80 metre beam transport system to take the 50 MeV negative hydrogen ions from the linear accelerator "LINAC III" to the proton synchrotron "DESY III".

Chalk River Nuclear Laboratory AECL, Chalk River
Design, construction and test of the 52 Mega-Hertz radiofrequency systems for the proton acceleration in PETRA II and the take over of the proton bunches injected into HERA.

France

CEN Laboratory, Saclay
In collaboration with DESY, design of the superconducting quadrupole magnets for the proton storage ring, development of the production tools and prototype construction, technical responsibility for the whole series production of 246 quadrupoles in two production lines, and as a French contribution the supply of 126 quadrupoles manufactured by French industry.

Israel

Weizmann Institute of Science, Rehovot
Design, construction and test of the transition sections of the main current leads which connect the 4.5 K coil and the room temperature current leads for the superconducting magnets of the proton storage ring.

Italy

Istituto Nazionale di Fisica Nucleare INFN, Roma
Delivery of 232 superconducting 10 metre long bending magnets, manufactured completely by Italian industry - this amounts to half of the total number of superconducting dipoles needed for the proton storage ring.

Netherlands

National Institute for High Energy Physics NIKHEF, Amsterdam
Development of superconducting correction elements in co-operation with DESY and Dutch industry, delivery of about 450 correction quadrupole and sextupole coils and 250 correction dipoles manufactured by Dutch industry.

United States

Brookhaven National Laboratory BNL, Upton
Quality control (short sample tests) of single wires and of the total quantity of all superconducting cable for the dipole and quadrupole magnet coils, and correction elements.

PR China, CSFR, former GDR, Poland, United Kingdom

Physcists, engineers and technicians from five countries were sent to DESY to collaborate in the HERA construction, most of them on a rotating basis (their stay in Hamburg was normally between one and three years). About 50 people from P.R. China, 3 from Czechoslovakia, 3 from Germany GDR, 40 from Poland, and 3 from United Kingdom worked at DESY at the same time. They were engaged in nearly all the proton aspects of the project, for example: H^- injection system (source, r.f. quadrupole, and linear accelerator), vacuum system for the proton ring, test of the superconducting magnets, proton beam absorption system, design of the proton r.f. system, beam orbit calculation, and in the development of superconducting r.f. cavities for the electron ring.

HERA !

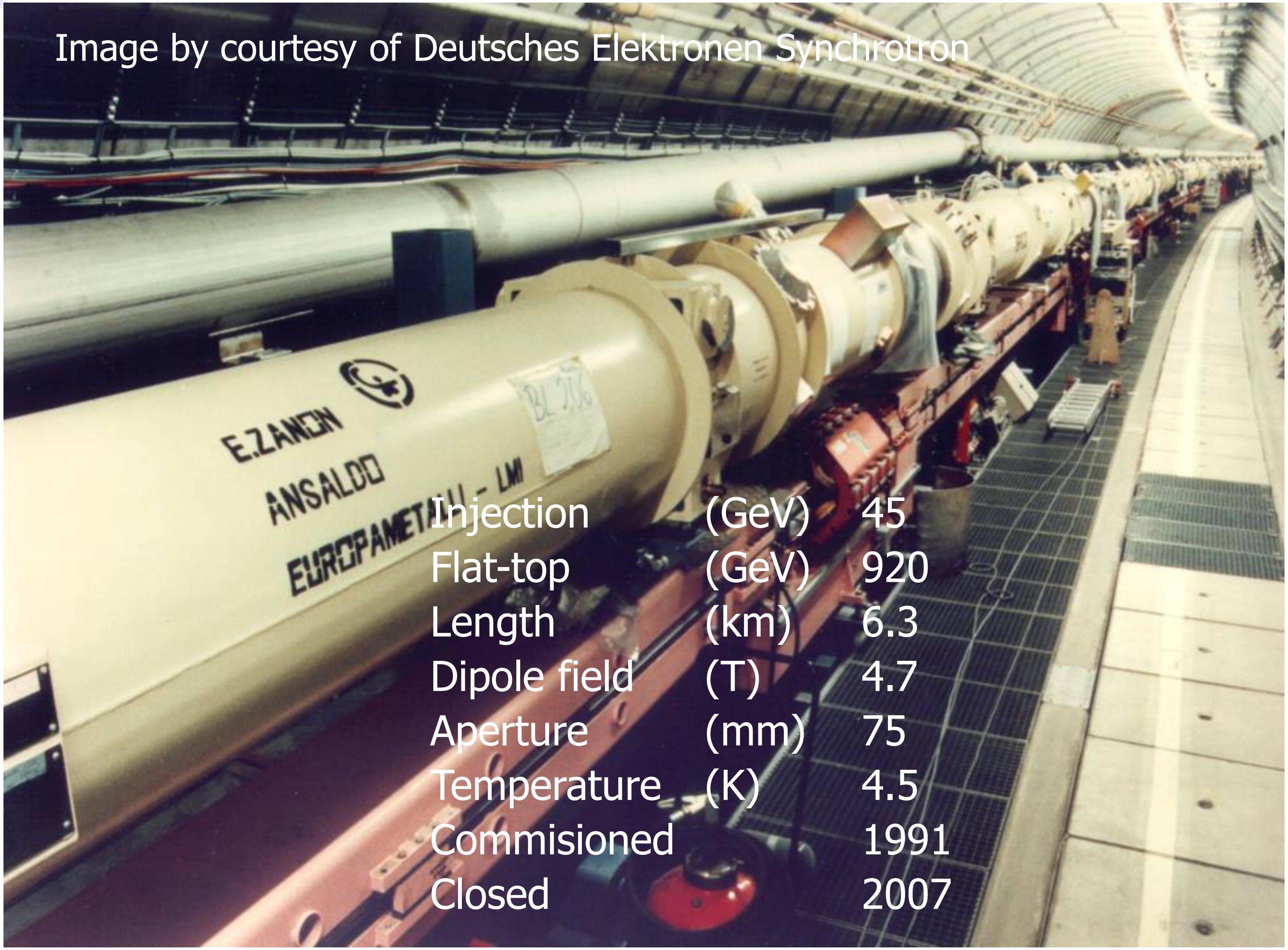


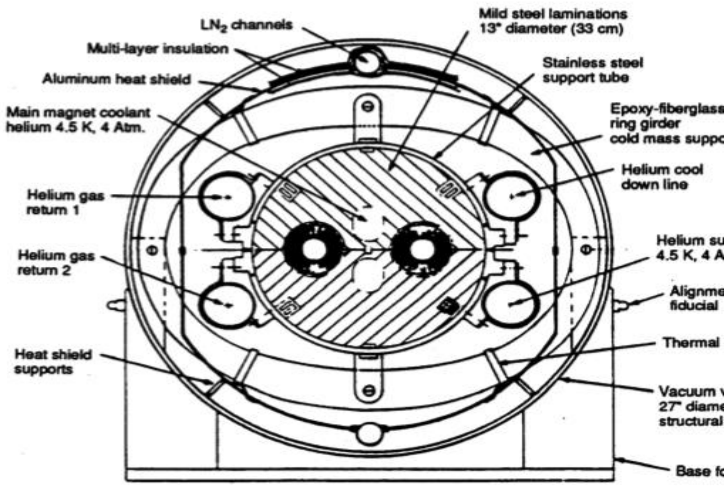
Image by courtesy of Deutsches Elektronen Synchrotron

Injection	(GeV)	45
Flat-top	(GeV)	920
Length	(km)	6.3
Dipole field	(T)	4.7
Aperture	(mm)	75
Temperature	(K)	4.5
Commisioned		1991
Closed		2007

The *sine-qua-non* accelerator

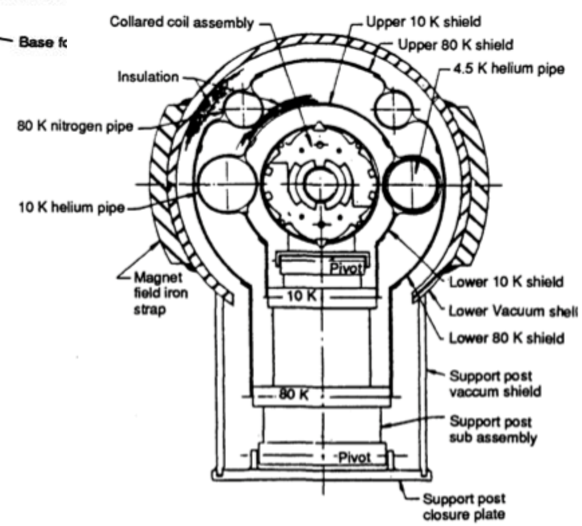
- **July 1983** – HEPAP recommendation of "…exploiting our superconducting magnet technology with an energy goal of 10 to 20 TeV per beam…"
- **1984** – National Reference Designs Study (RDS) for a 20 TeV proton machine, hosted by LBNL, DOE recommends proceeding with R&D
- **1984** – Central Design Group (CDG) formed at LBNL
- **1987** – Site selection process
- **1989** – Superconducting Super Collider (SSC) Laboratory established in Texas
- **1991** – Major construction start. Seventeen shafts sunk and 23.5 km (14.6 mi) of tunnel by late 1993

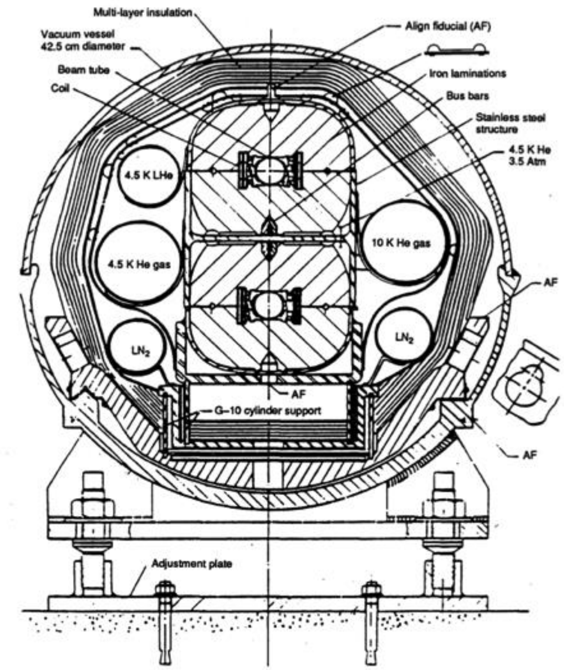
SSC magnet options



6.5 T, *high field*, two-in-one option, (by BNL and LBNL) resurrected from the *waning days* of ISABELLE/CBA

5T *medium field* option (by FNAL), based on the Tevatron cos-θ coils





3T superferric *low field* option (by TAC)

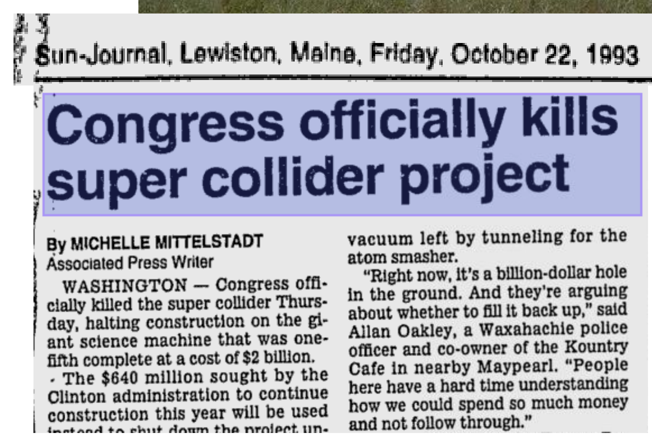
From SSC to Desertron to obli

Main shaft

Construction site

SSC buildings

- **1987** – Heated debate on cost. Estimate of 4.4 B$ strongly supported by the Texas representative at Congress
- **1993** – Cost projection reaches 12 B$, similar to the ISS. Strong criticism triggered an audit from DOE
- **October 1993** – Congress cancels the project, after 2 B$ were spent in the program



Sun-Journal, Lewiston, Maine, Friday, October 22, 1993

Congress officially kills super collider project

By MICHELLE MITTELSTADT
Associated Press Writer

WASHINGTON — Congress officially killed the super collider Thursday, halting construction on the giant science machine that was one-fifth complete at a cost of $2 billion.

The $640 million sought by the Clinton administration to continue construction this year will be used

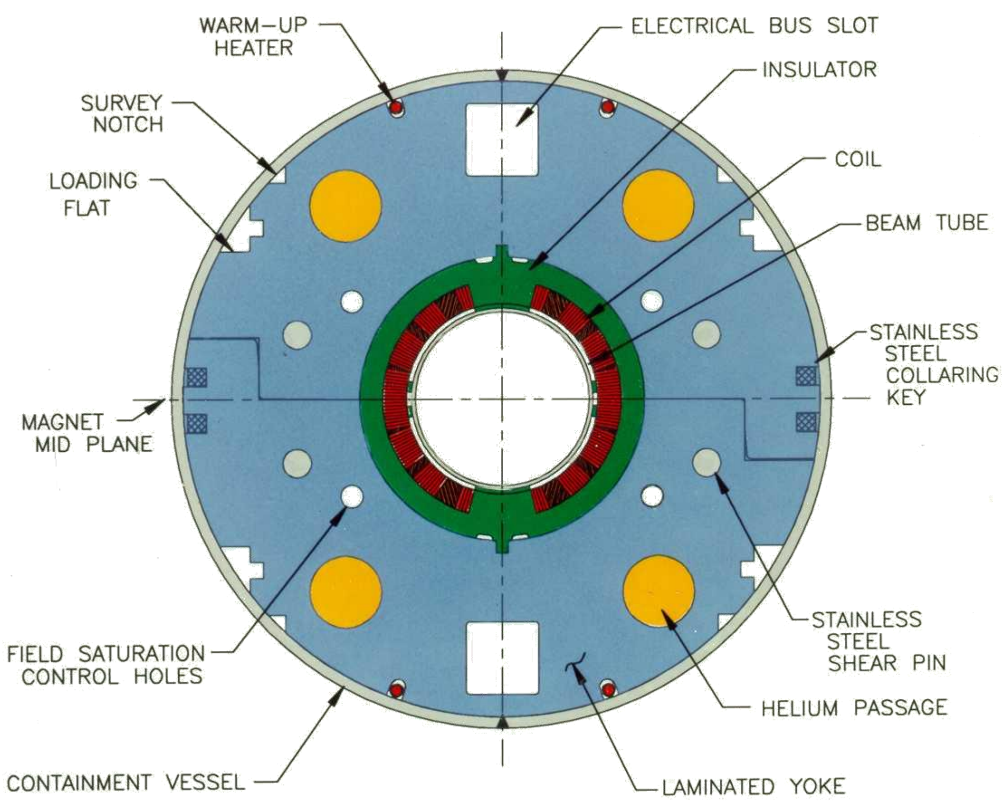
vacuum left by tunneling for the atom smasher.

"Right now, it's a billion-dollar hole in the ground. And they're arguing about whether to fill it back up," said Allan Oakley, a Waxahachie police officer and co-owner of the Kountry Cafe in nearby Maypearl. "People here have a hard time understanding how we could spend so much money and not follow through."

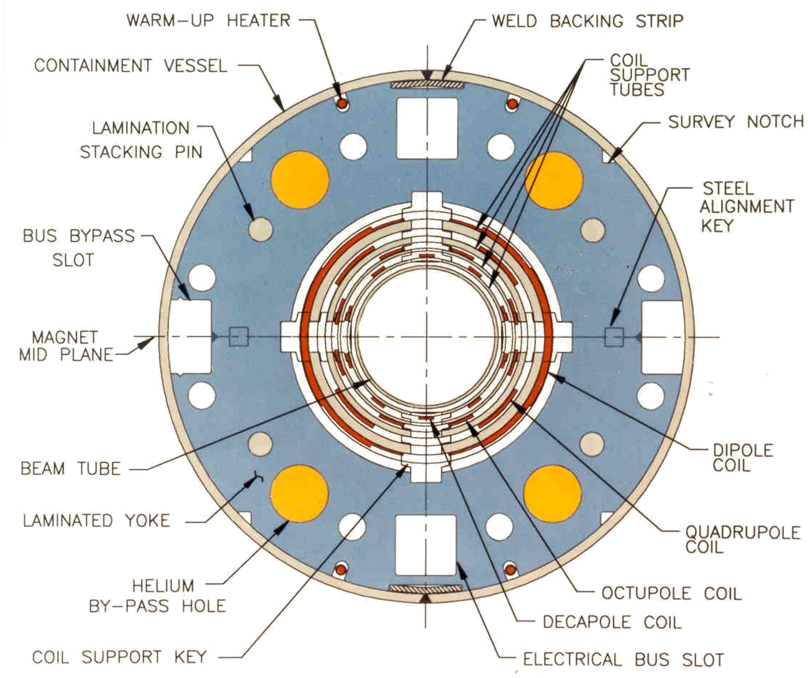
A phoenix from the ashes

- **1983** – At the meeting of the U.S. Nuclear Science Advisory Committee (NSAC) in Aurora(NY) a physics quorum pledged for a heavy ion collider in the CBA tunnel
- **1984** – First proposal submitted
- **1991** – Funding released to start construction of the Relativistic Heavy Ion Collider (RHIC)

Magnet technology at RHIC



Arc dipole



Nested correctors

RHIC !

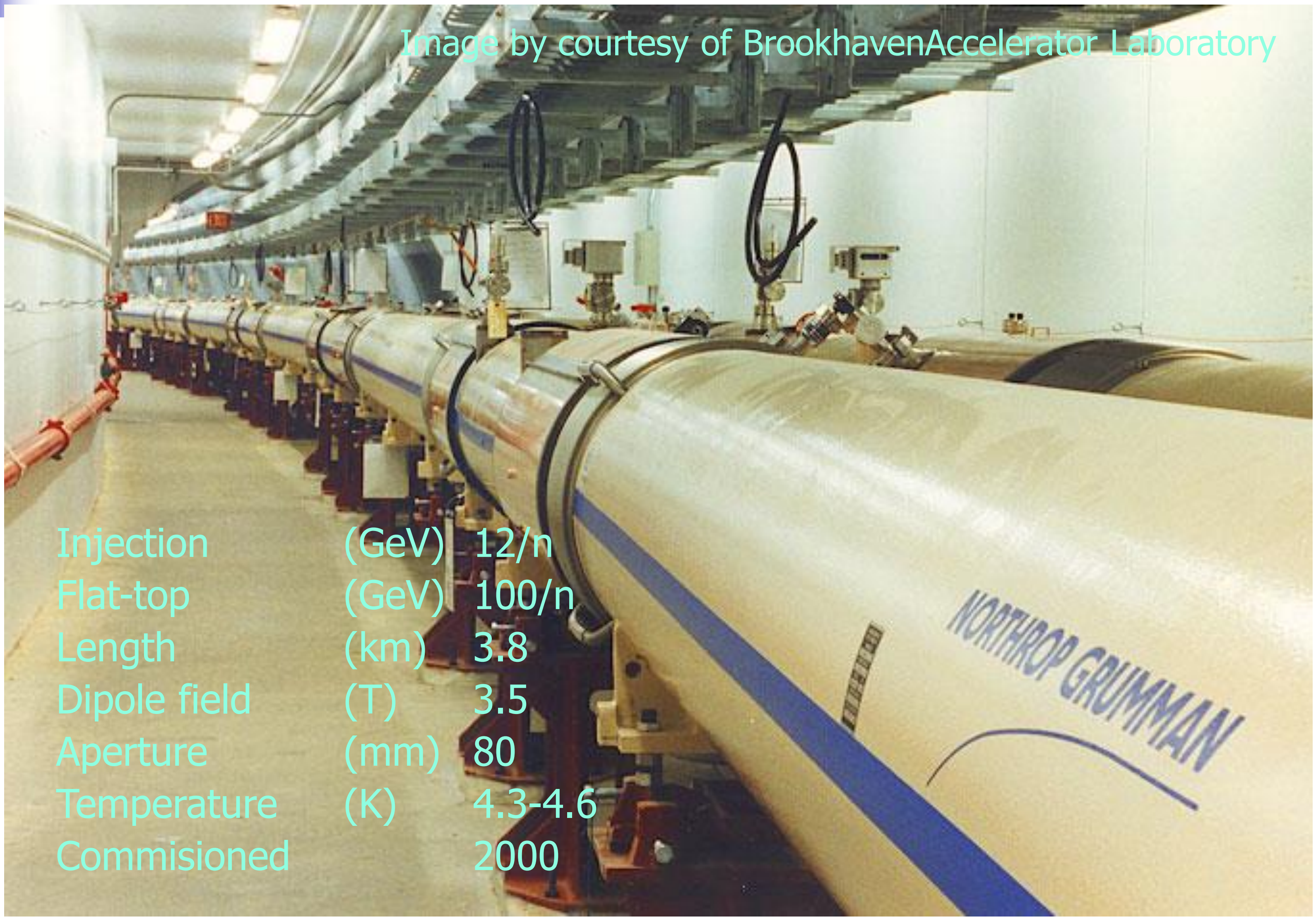


Image by courtesy of BrookhavenAccelerator Laboratory

Injection	(GeV)	12/n
Flat-top	(GeV)	100/n
Length	(km)	3.8
Dipole field	(T)	3.5
Aperture	(mm)	80
Temperature	(K)	4.3-4.6
Commisioned		2000

Labouring for Half a Century (LHC)

- **1984** – Concept and preliminary studies
- **1988** – Model magnets demonstrate feasibility
- **1990** – R&D program launched
- **1994** – Project approved by the CERN council
- **1996-1999** – Transfer of technology to industry
- **1998** – Start civil engineering
- **1998 – 2001** – Main contracts signed
- **2003** – Start tunnel installation
- **2005-2007** – Magnet installation
- **2007** – First sector test
- **2008-2030** – Physics

Personal Note: joined CERN 1995

LHC Origins
ECFA – Lausanne 1984

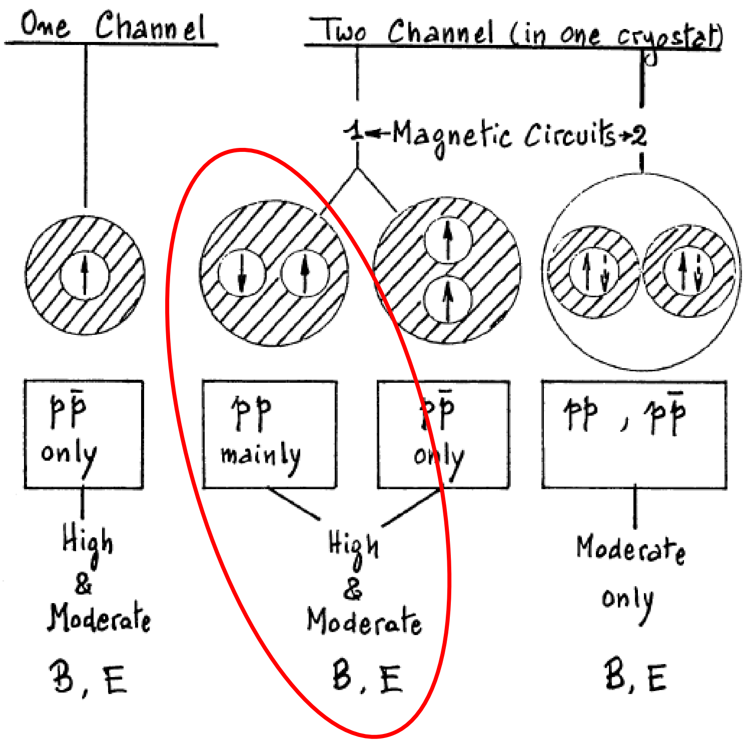
CERN COURIER

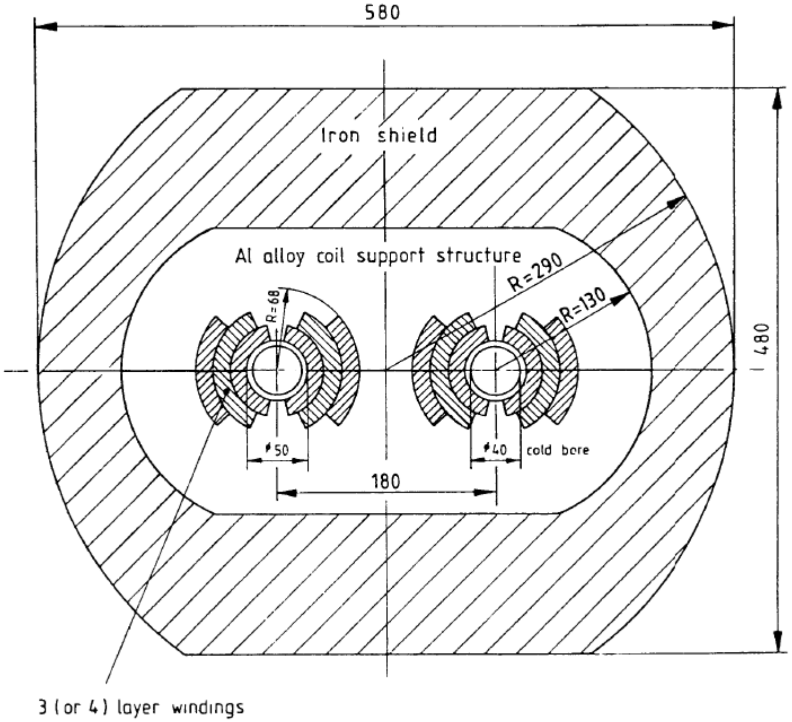
Sep 19, 2008

Early days: Lausanne LHC workshop (archive)

In March 1984 a major workshop provided a chance to look to the next step beyond the construction and exploitation of LEP.

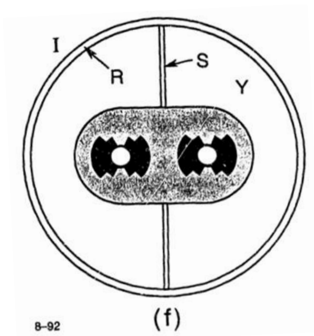
G. Brianti



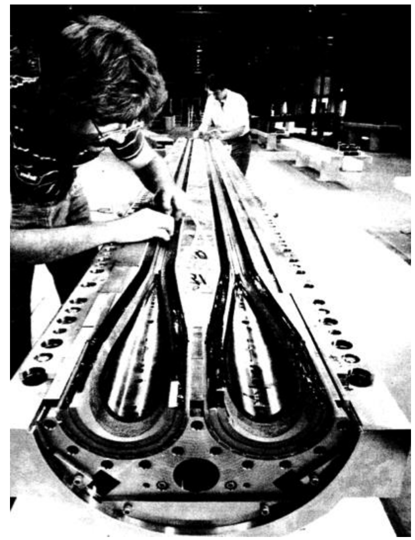


Synopsis of hadron collider options for the LEP tu

Earlier traces of the *two-in-one* concept

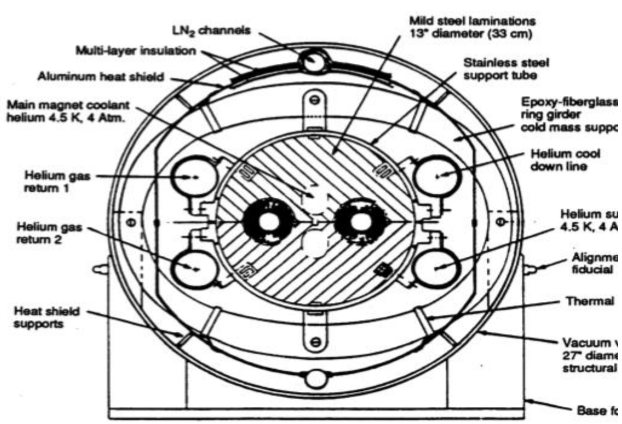


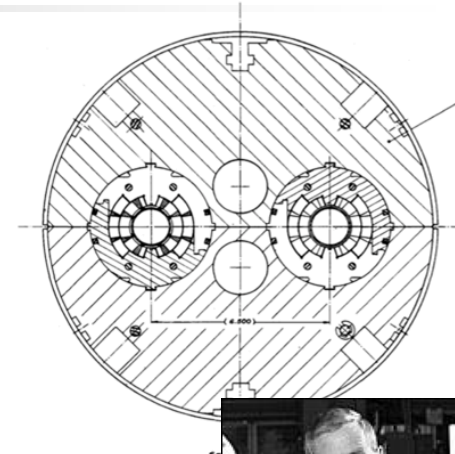
John P. Blewett, 1971



Assembly work at BNL

SSC high field





Per F. Dahl, The SSC Dipole: Its Conceptual Origin and Early Design History, SSCL-320, 1990

Robert B. Palmer, Superconducting Accelerator Magnets: A Review of their Design and Training, ICHEP 92, SLAC-PUB-5899, 1992

SSC vs. LHC

- G. Brianti had various reasons for *headaches* in the race of the two projects:
  - The existing LEP tunnel imposed a given radius and cross sectional space to the new accelerator – Field !
  - The missing factor in energy (8.5+8.5 TeV for LHC vs. 20+20 TeV for SSC) needed to be compensated by a higher luminosity (design value of 10^{34} 1/cm^2 s for LHC vs. 10^{33} 1/cm^2 s for SSC) – Aperture and quality !
- R&D focus was the key !
  - **High field**: aim at 8 to 10 T bore field
  - **Two-in-one**: to gain space in the crammed tunnel space for the widest possible magnet bore

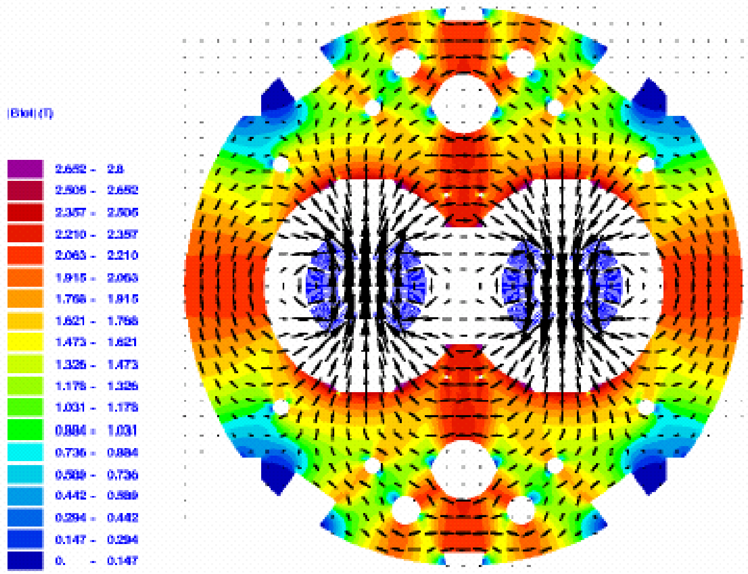
LHC twin-apertu

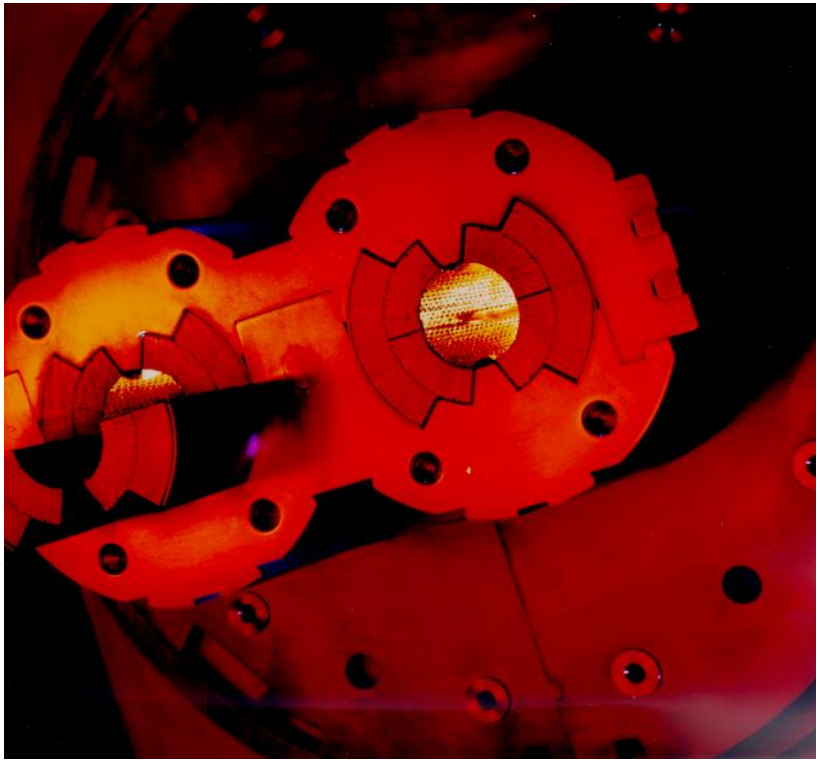
Concept perfected (design), demonstrated (models and prototypes) and realized on a **large industrial scale**


R. Perin

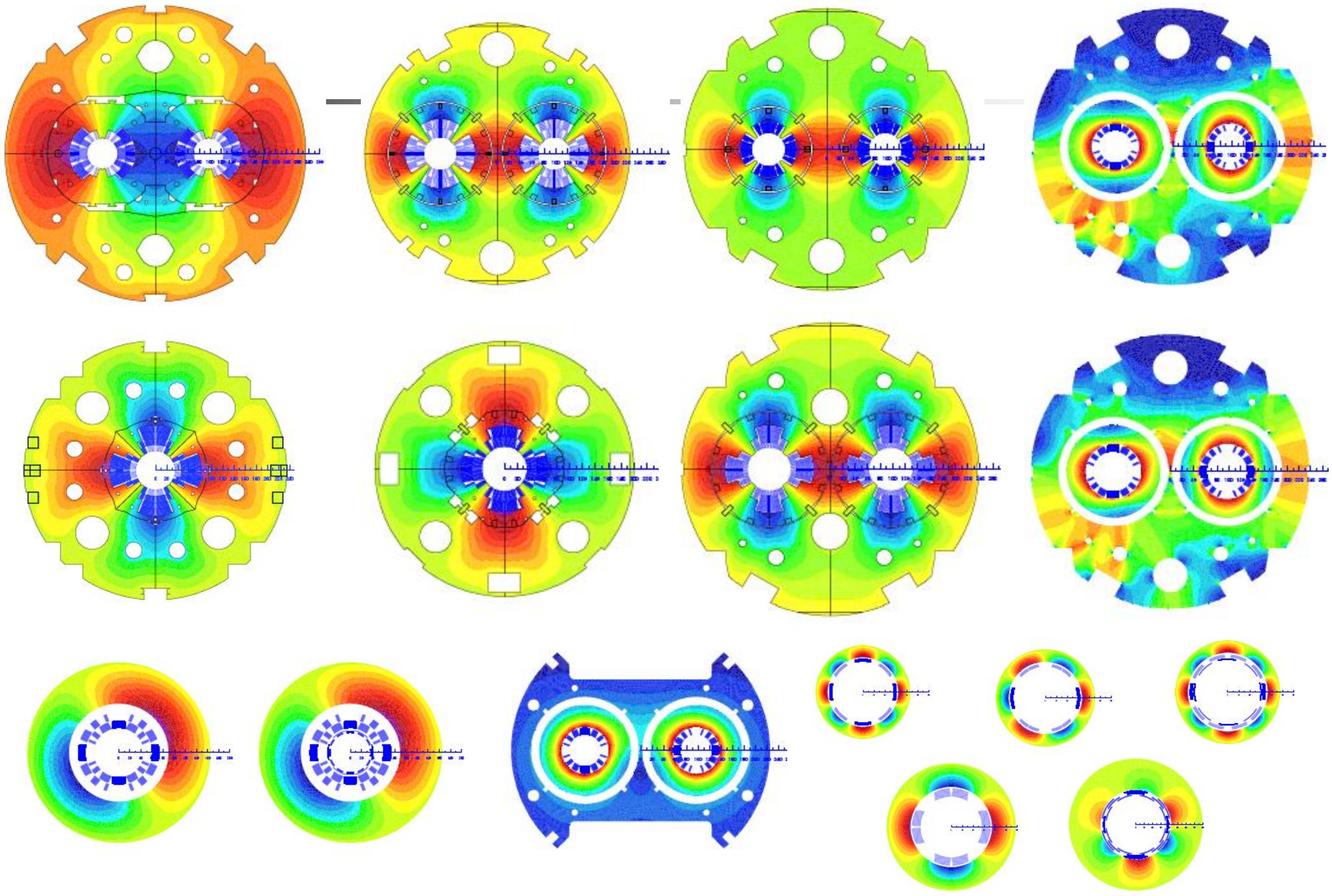

C. Wyss


L. Rossi



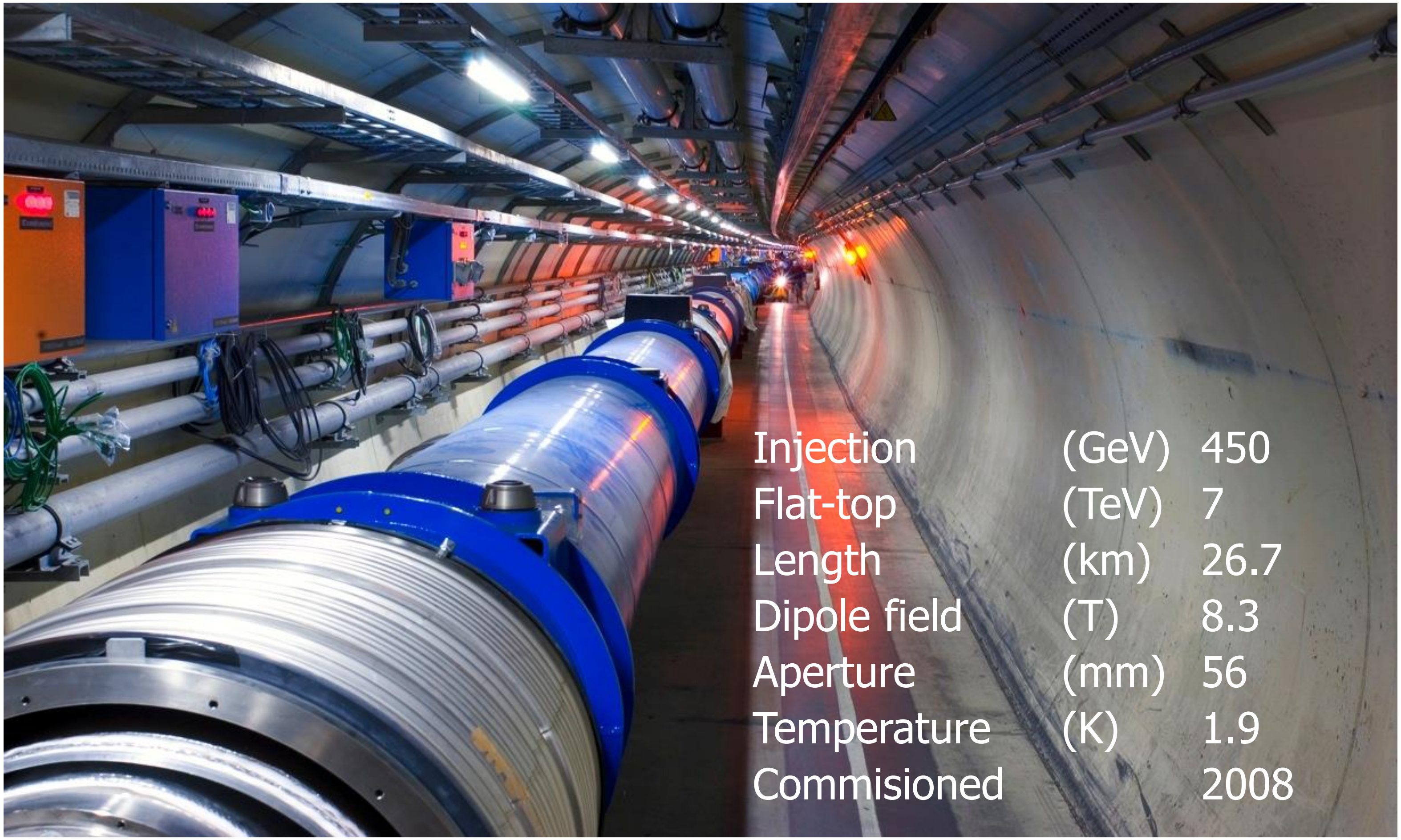


The LHC superconducting magnet zoo



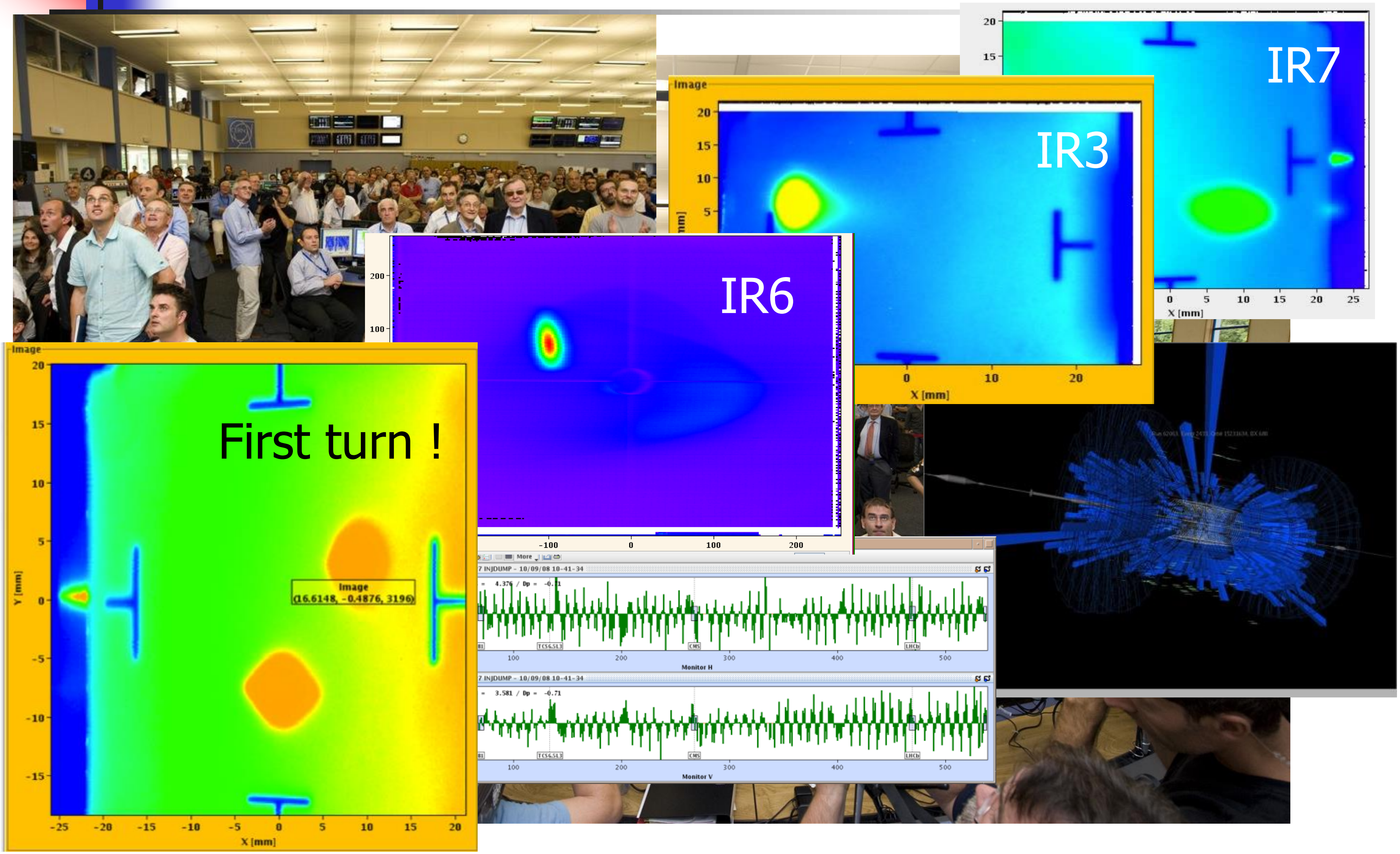
By courtesy of S. Russenschuck (CERN)

LHC !



Injection	(GeV)	450
Flat-top	(TeV)	7
Length	(km)	26.7
Dipole field	(T)	8.3
Aperture	(mm)	56
Temperature	(K)	1.9
Commisioned		2008

September 10th, 2008…

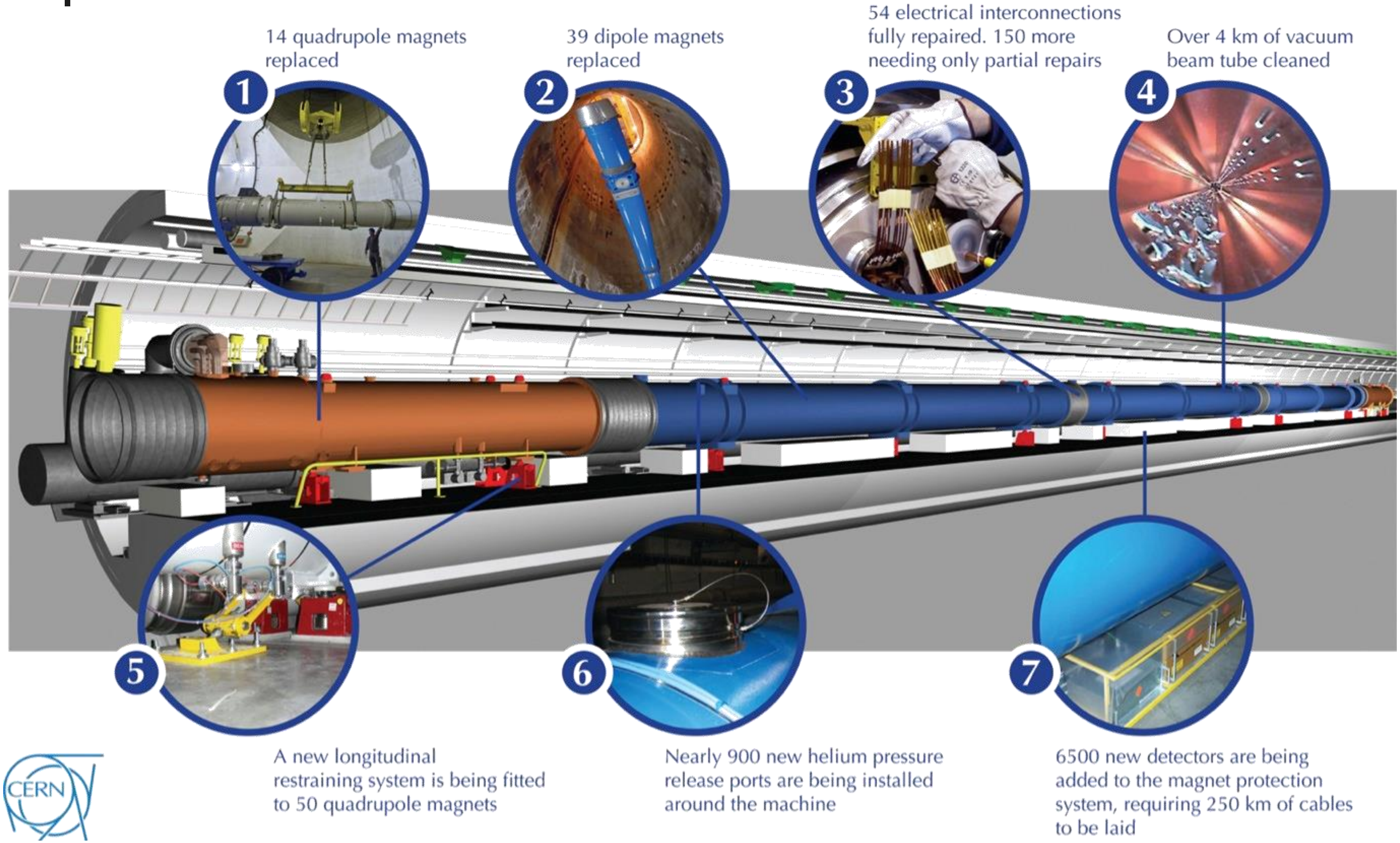


…September 19th, 2008…

Unprotected quench of defective joint

Magnet displacement

…back to work in 2009…



CERN

…November 30th, 2009…

Overview

- A brief history of superconducting HEP magnets
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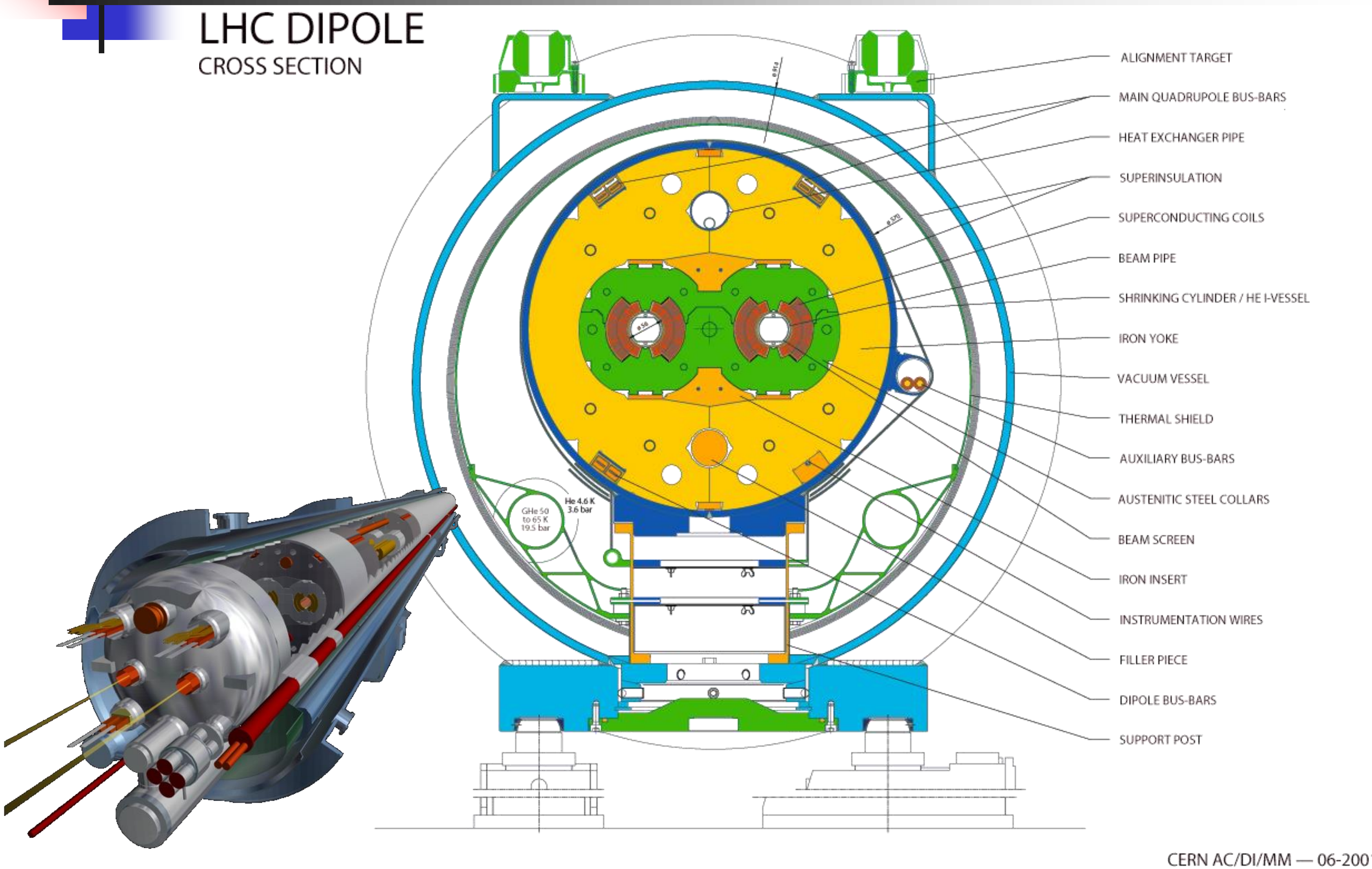
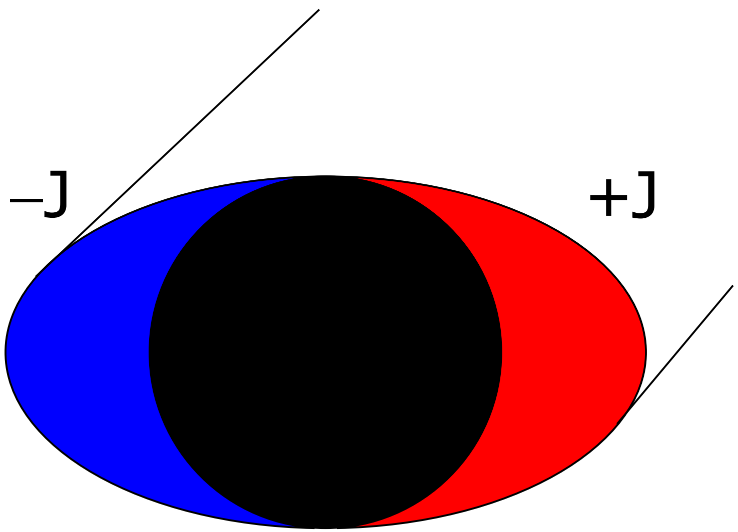
- Other superconducting magnet systems

LHC dipole

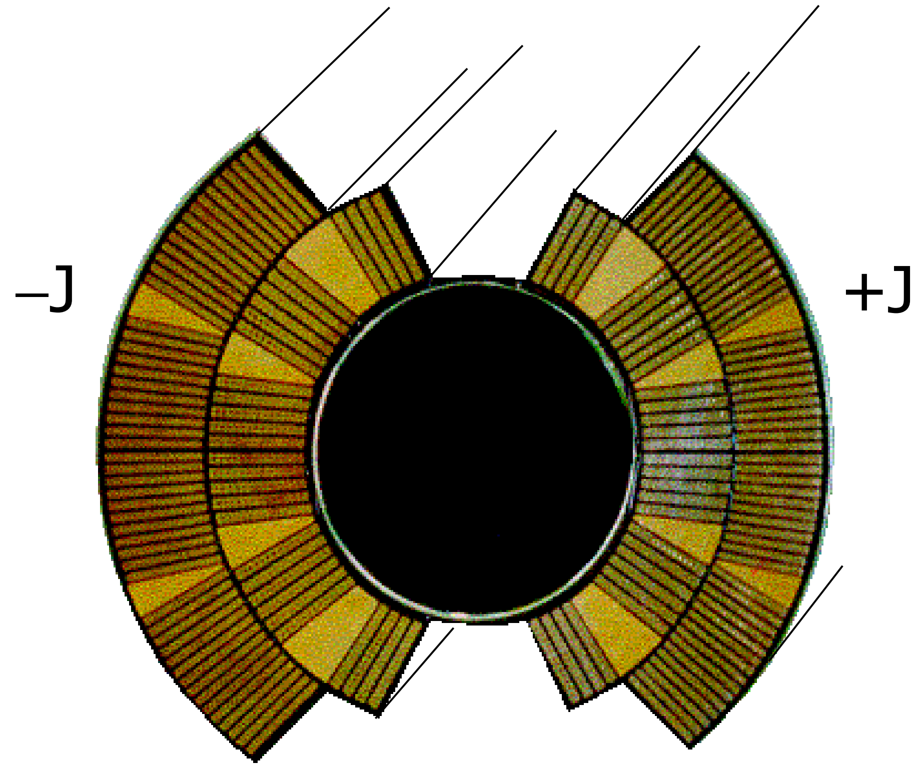
$B_{nominal}$	8.3	(T)
current	11850	(A)
stored energy	≈ 10	(MJ)
cold mass	≈ 35	(tonnes)



Superconducting dipole magnet coil



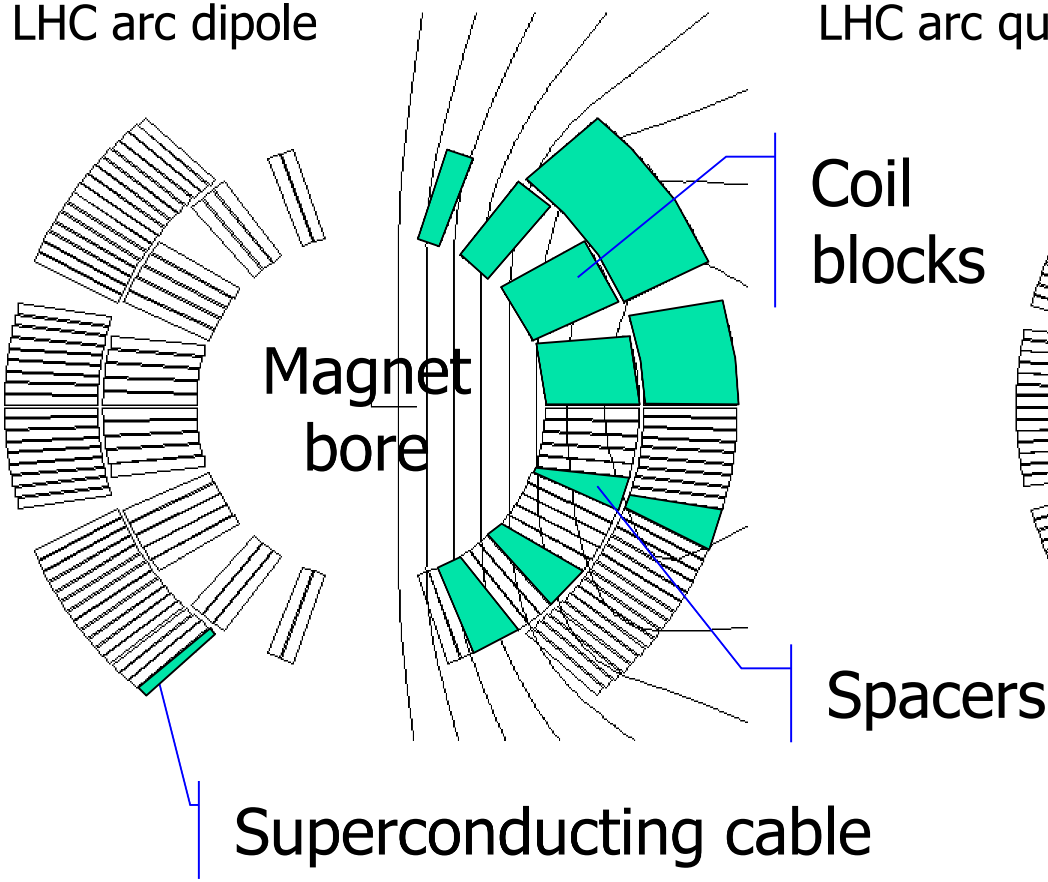
Ideal current distribution that generates a perfect dipole



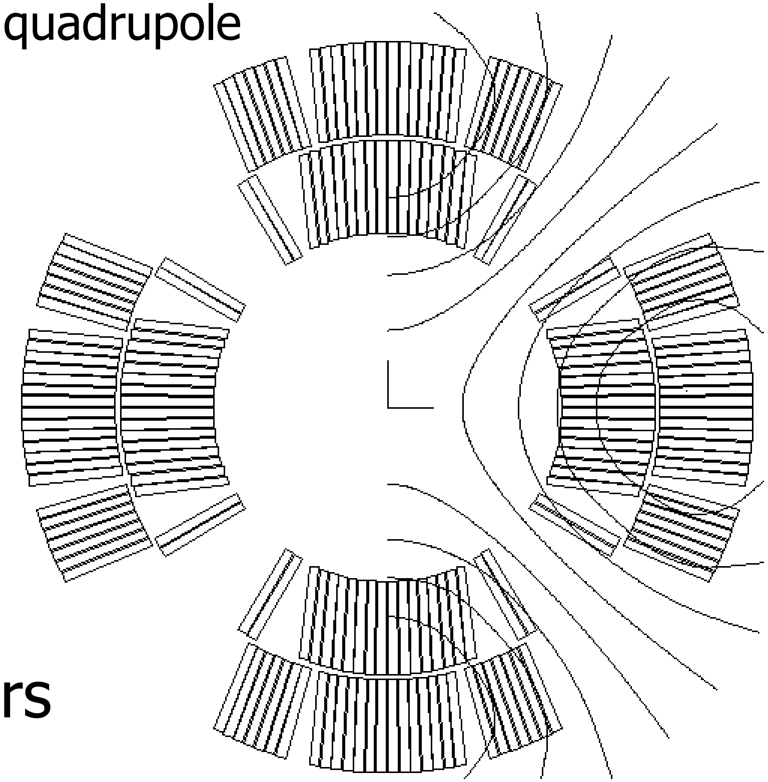
Practical approximation of the ideal distribution using Rutherford cables

Technical coil windings

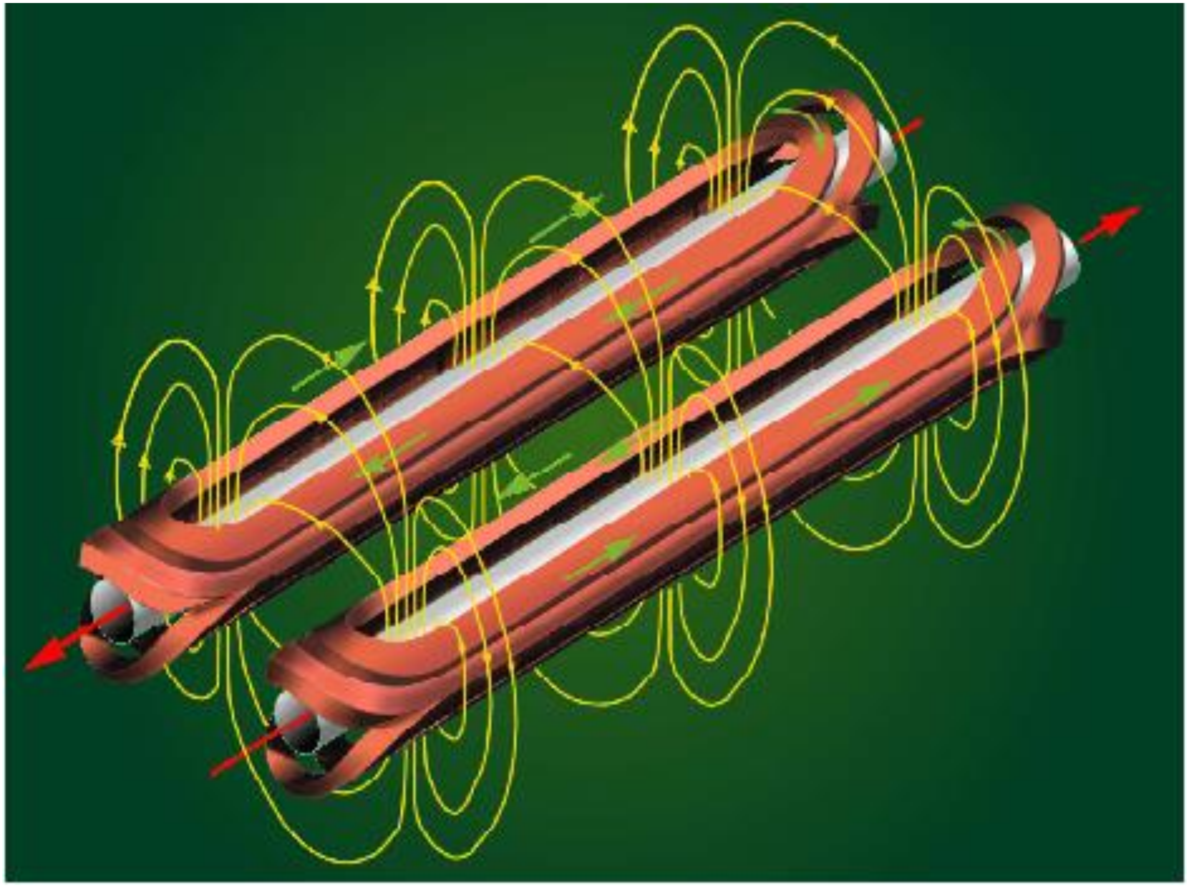
LHC arc dipole



LHC arc quadrupole

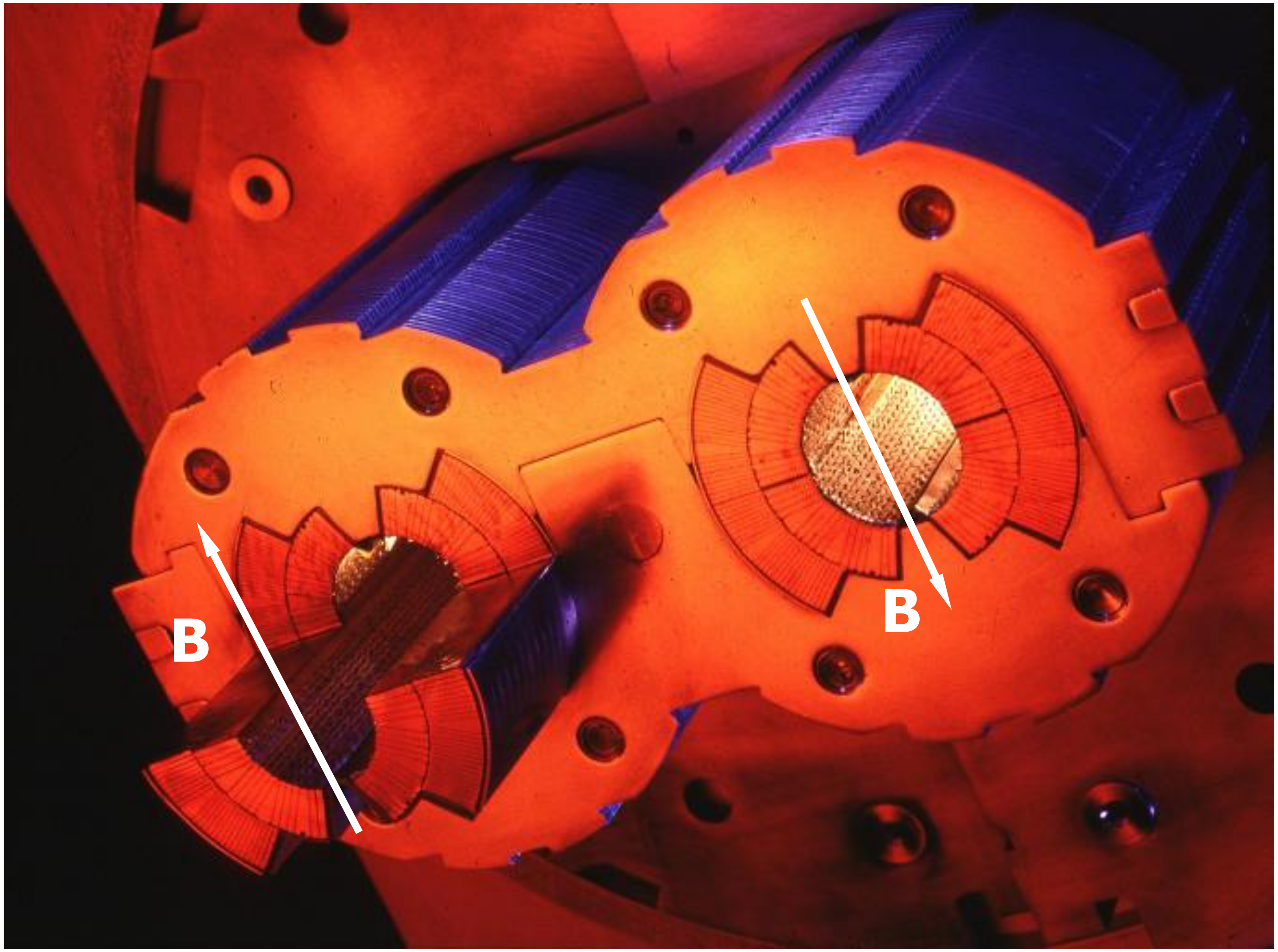


Twin coil principle

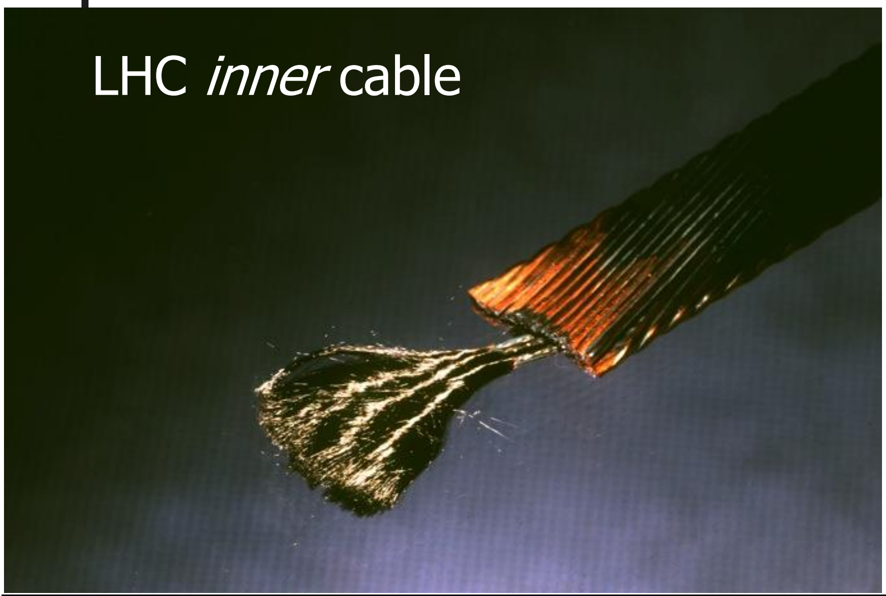


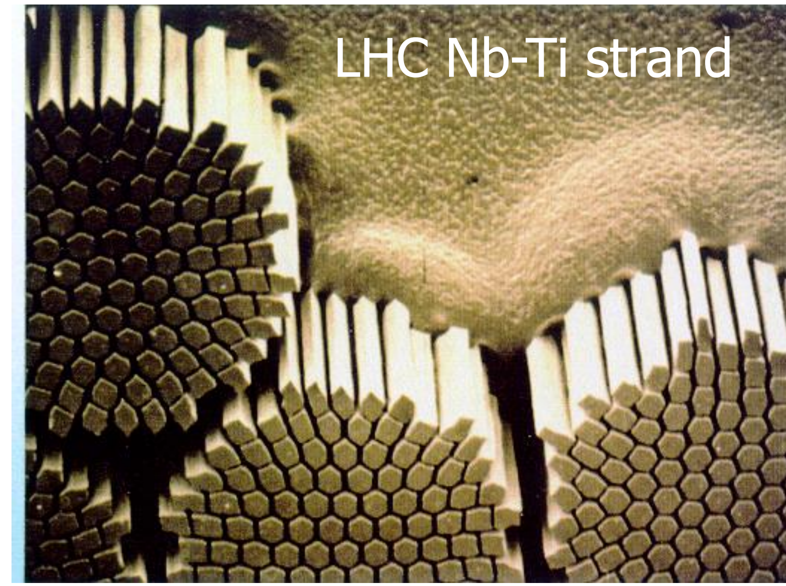
Combine two magnets in one
Save volume, material, cost

LHC dipole coils



Fine cables

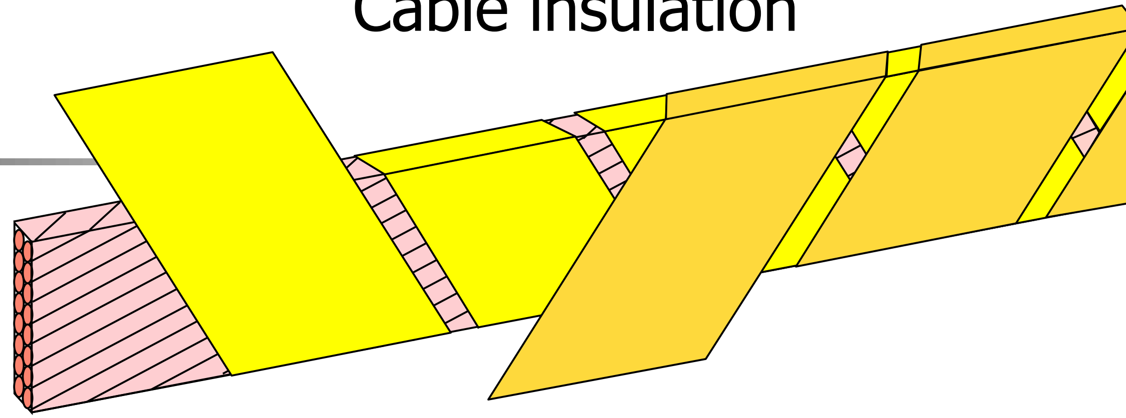




7500 km of superconducting cables with tightly controlled properties (state-of-the-art production)

Coil winding

Cable insulation

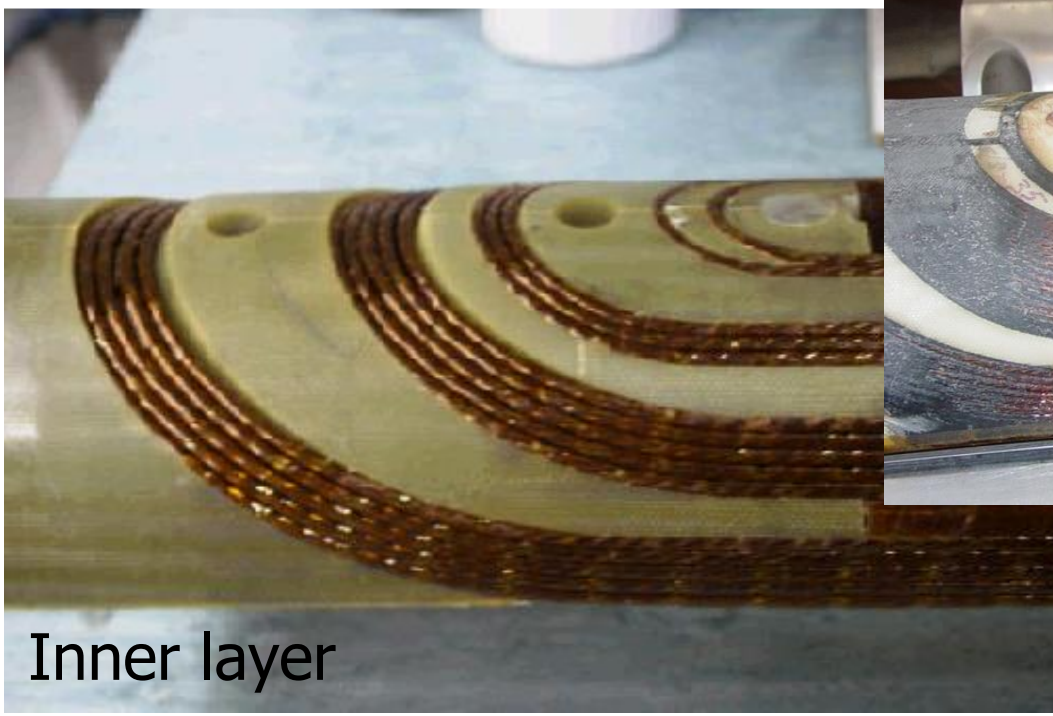


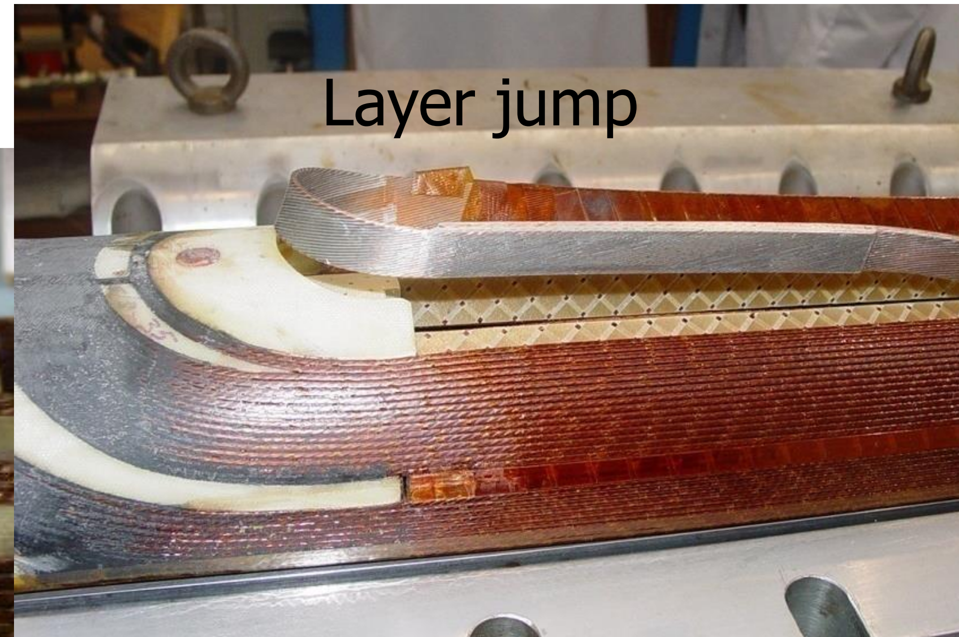
10 μm precision !

Coil winding machine

Stored coils

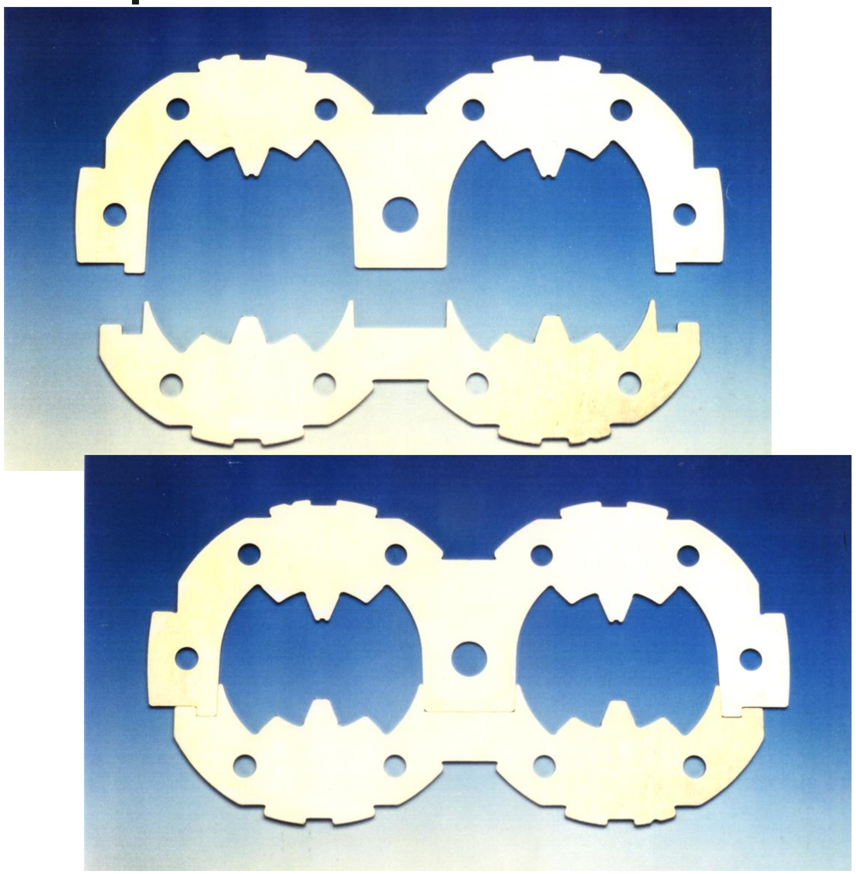
Ends

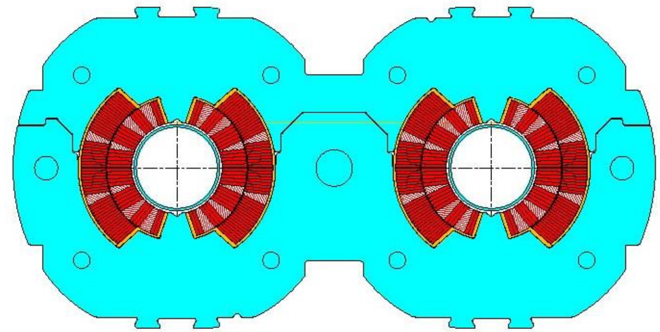




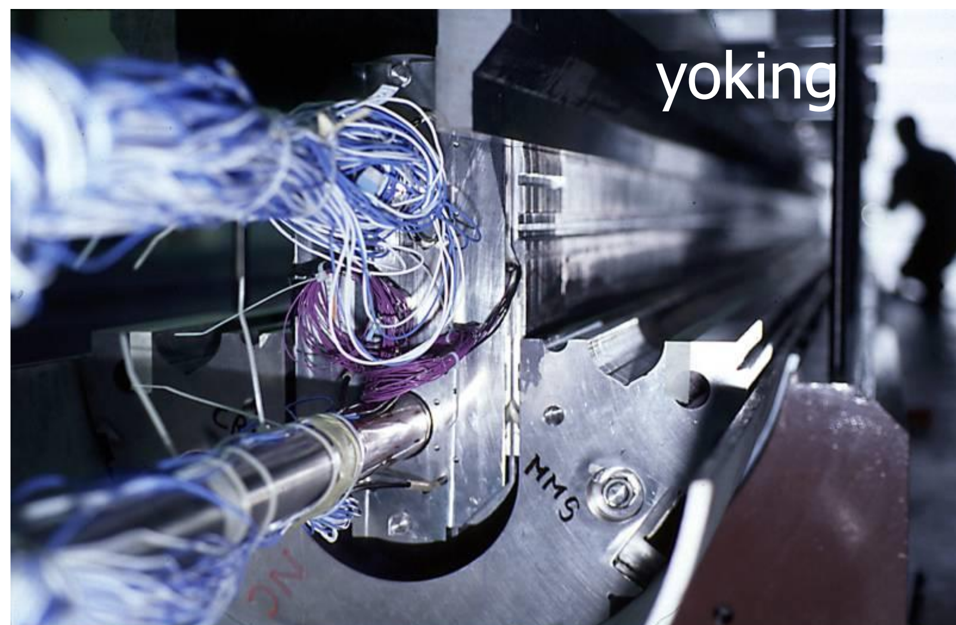
Ends, transitions, and any deviation from the regular structure are the most delicate part of the magnet

Collaring and yoking





collaring

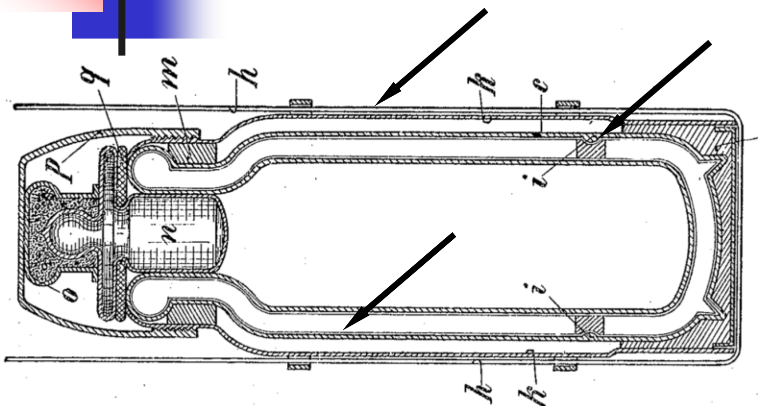


Magnet assembly

Alstom
Noell
Ansaldo

Cold mass

Cryostat



Thermal screens

Low conduction foot

Cryo-magnets and tests

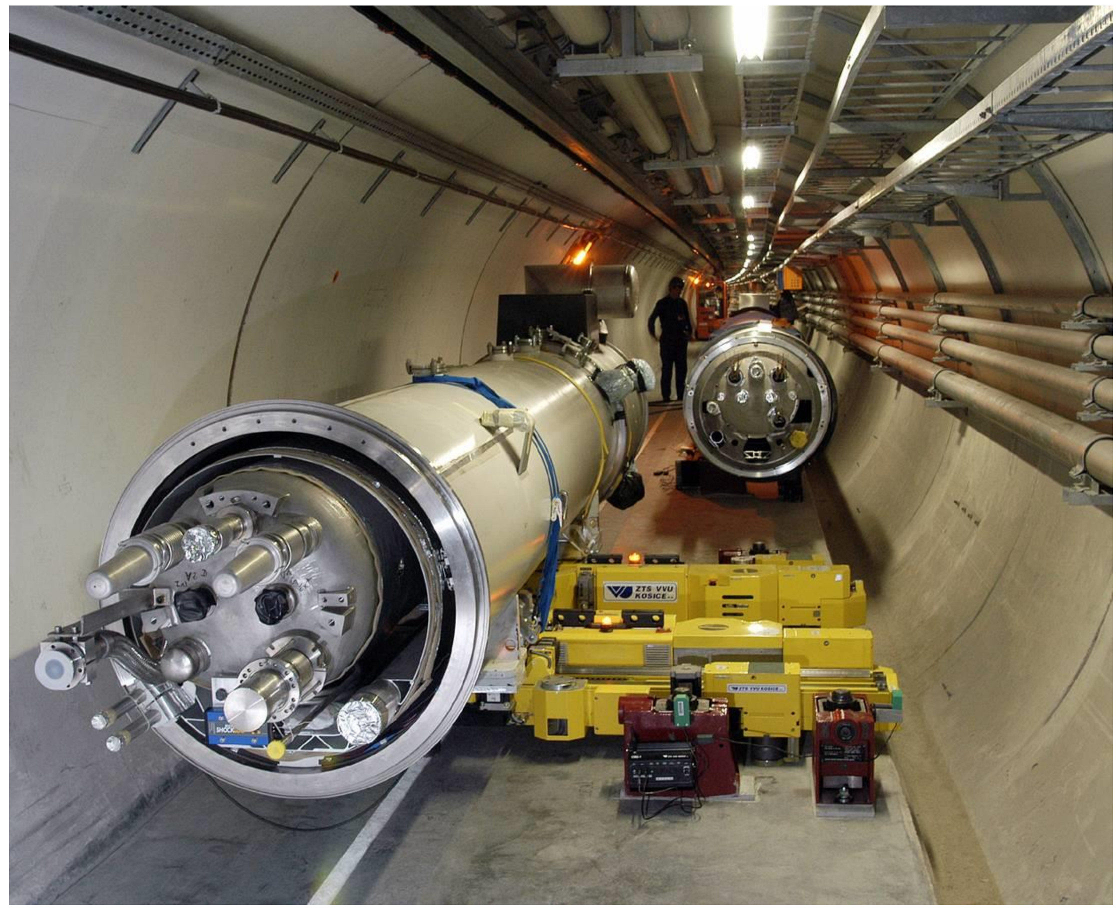
Magnet reception, cryostating, preparation for cold test and “stripping” for installation

Magnet powering tests and magnetic measurements

Magnet installation

Descent in the tunnel

Magnet transport and installation



Interconnection

65’000 electrical joints

Induction-heated soldering

Ultrasonic welding

Very low resistance

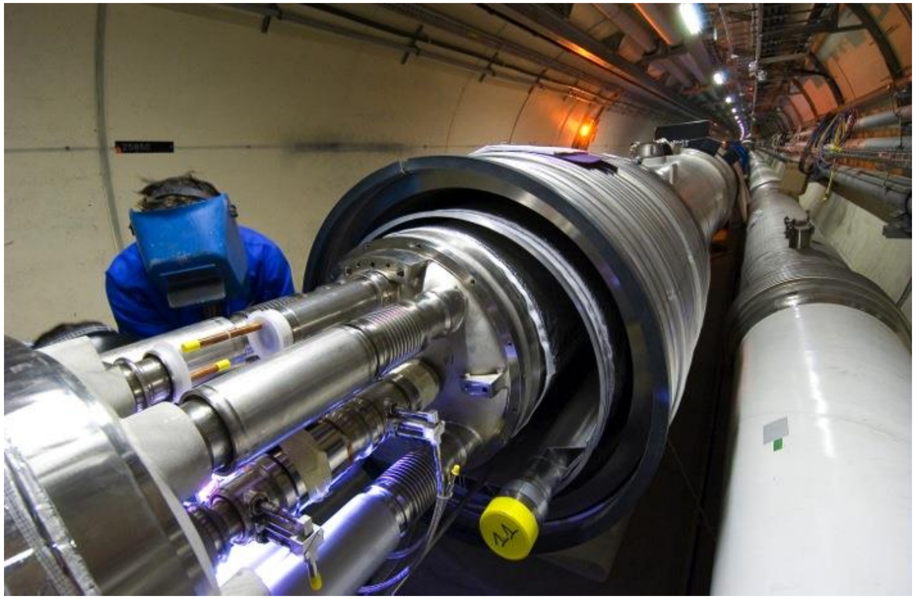
HV electrical insulation

40’000 cryogenic junctions

Orbital TIG welding

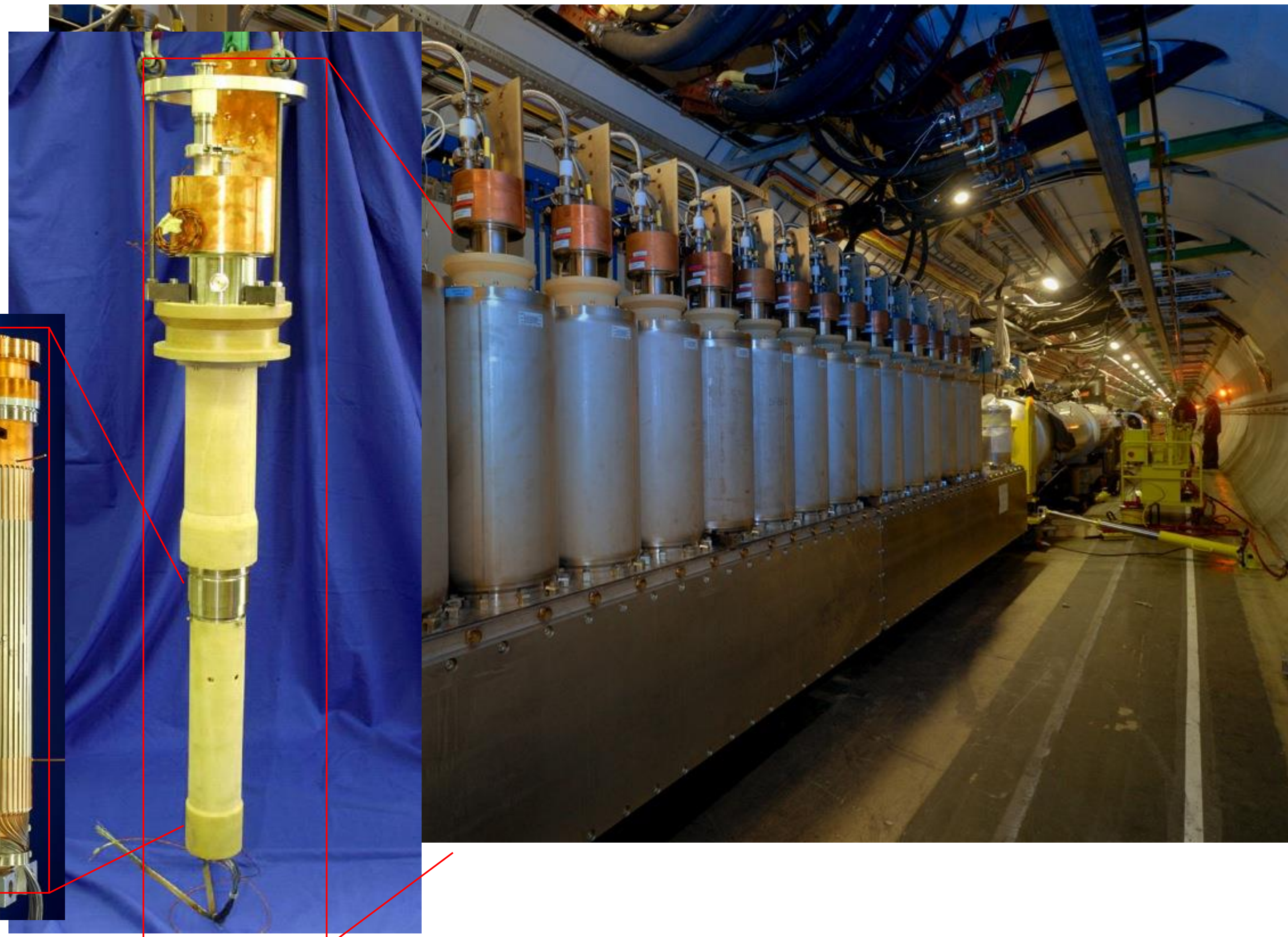
Weld quality

Helium leaktightness



Large scale use of HTS

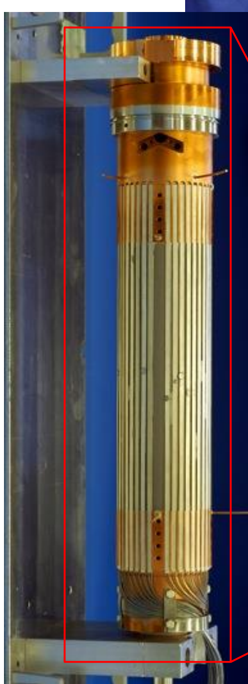
Warm end
(300K)



50 K

BSCCO
2223

4.2 K



Finally, in the tunnel !

Overview

- A brief history of superconducting HEP magnets
- The making of a superconducting LHC magnet
- Towards higher fields
  - High field LTS magnets
  - Outlook of HTS magnets
- Other superconducting magnet systems

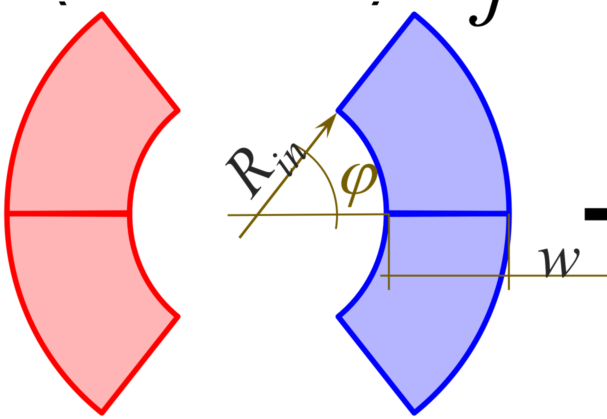
Dipole field generated by a current distribution with constant current density J over a sector of inner radius R_{in}, outer radius R_{out}, coil width $w = R_{out} - R_{in}$ and opening angle φ

$$B = \frac{2\mu_0}{\pi} J w \sin(\varphi)$$

First challenge : Jc

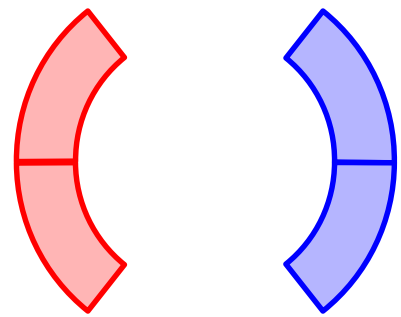
$$A_{coil} = 2\varphi\left(w^2 + 2R_{in}w\right) \propto \frac{1}{J^n} \qquad n \approx 1 \ldots 2$$

In the range of typical magnet designs considered $n \approx 1.5$



$$w \propto \frac{1}{J}$$

$J \uparrow$

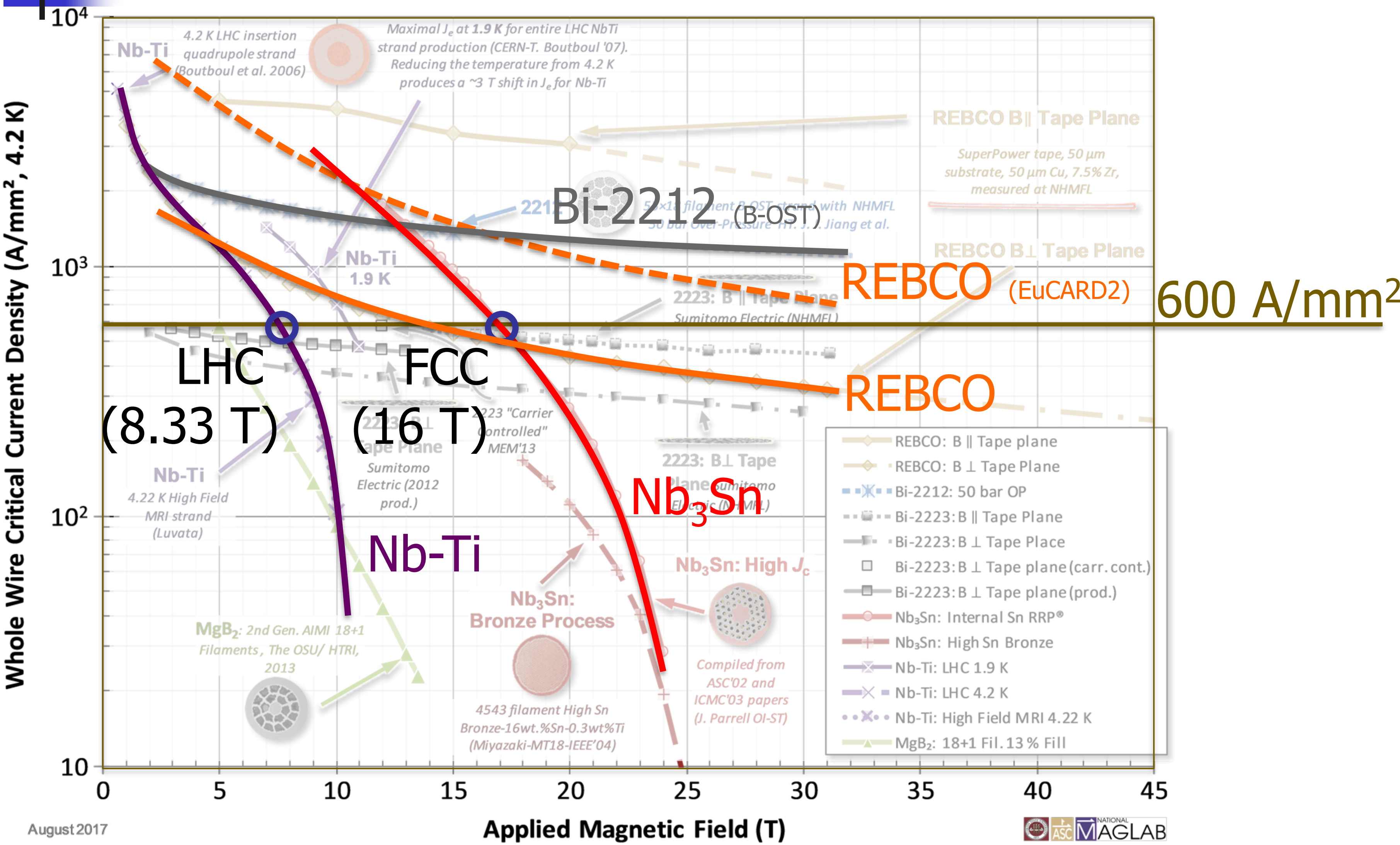


B	(T)	16
J	(A/mm²)	300
w	(mm)	76
A_{coil}	(mm²)	20,000

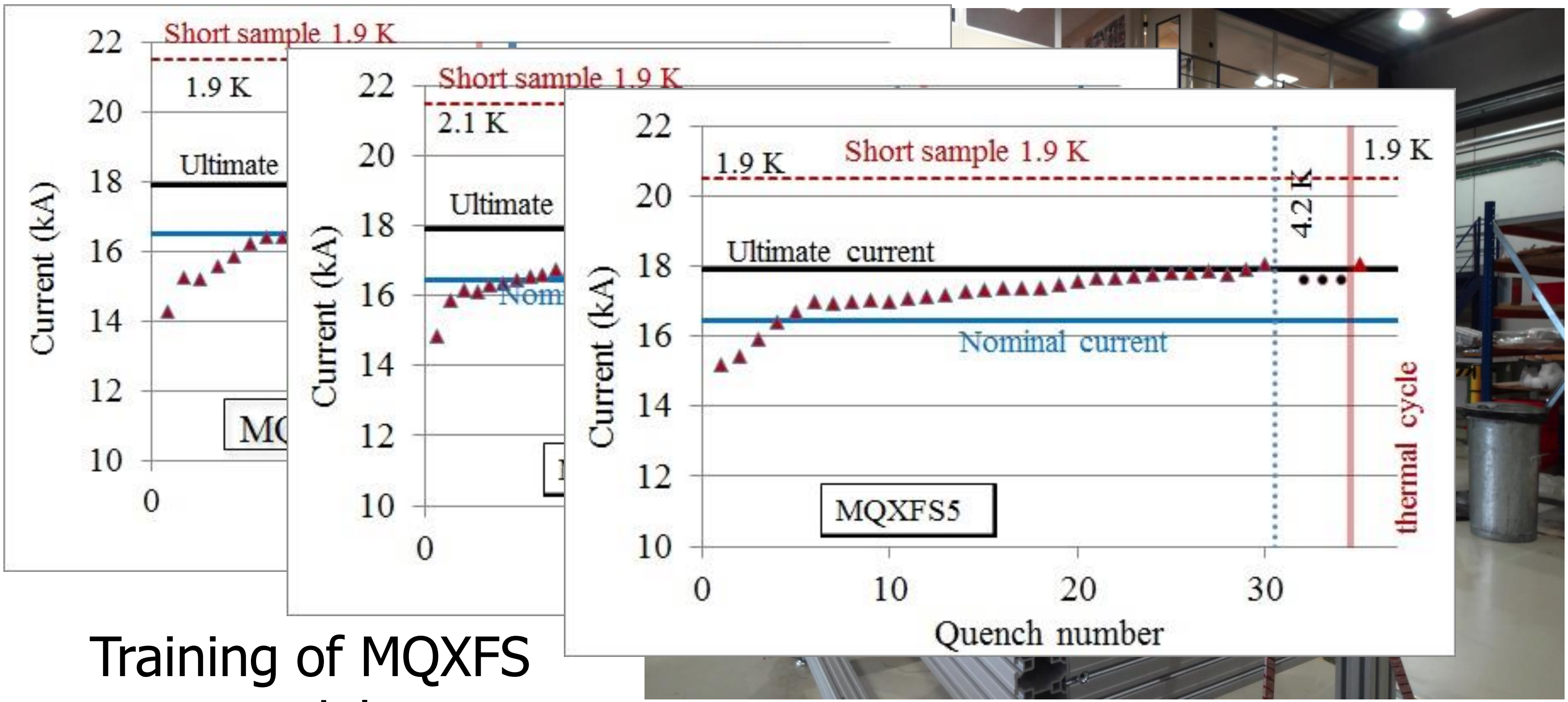
$$A_{coil} \propto M_{coil} \propto COST$$

16	
600	Factor 2
38	
7000	Factor 3

Challenge#1: Jc



Challenge#2: Abolish training !

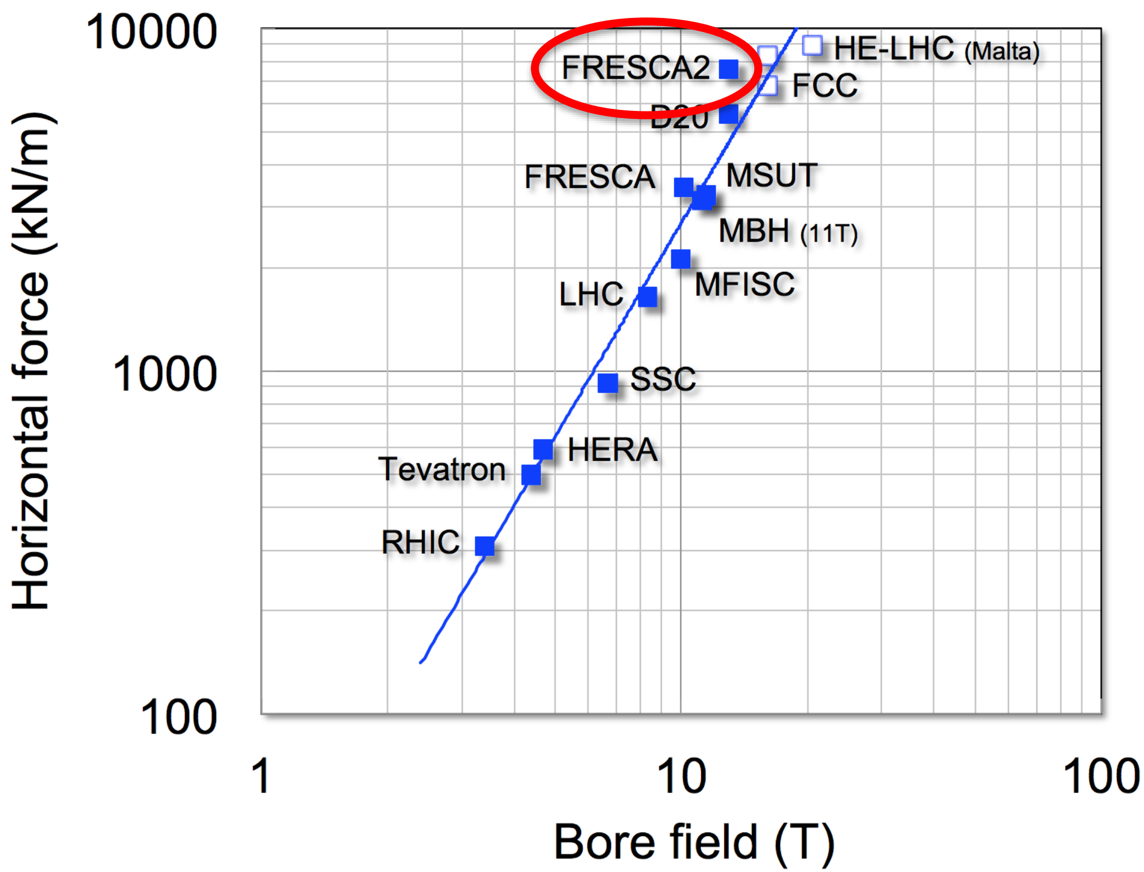


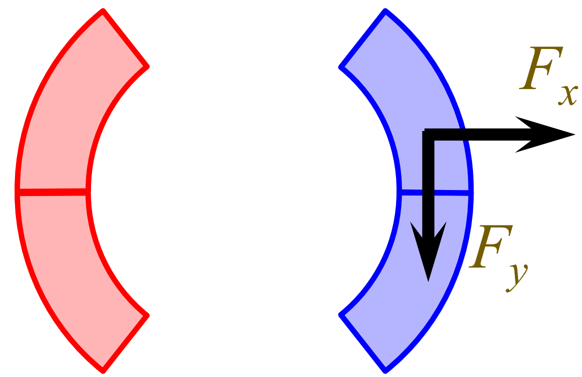
Training of MQXFS models

Lorentz forces in the plane of a thin coil of radius R_{in} generating a dipole field B (thin shell approximation), referred to a coil quarter

$$F_x = -F_y \approx \frac{4}{3}\frac{B^2}{2\mu_0}R_{in}$$

Mechanics at high fields

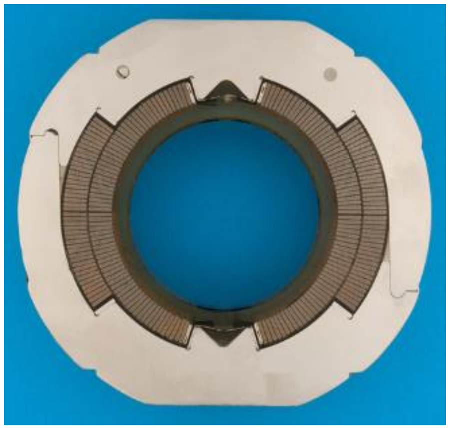




Progression of F_x:

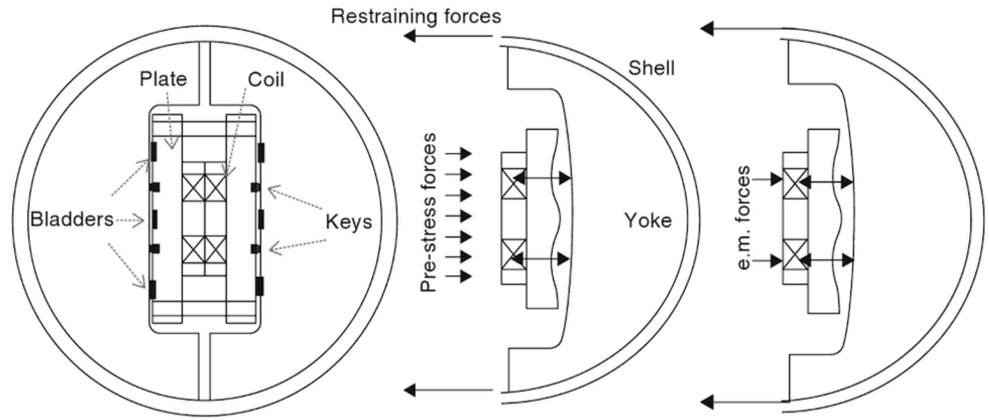
LHC MB(8.33T) ≈ 1.7 MN/m
LHC MBH(11T) ≈ 3.2 MN/m
FRESCA2(13T) ≈ 7.6 MN/m
FCC MB(16T) ≈ 8 MN/m
HE-LHC MB(20T) ≈ 10 MN/m

Old structures, new structures



mid 1970's, FNAL: Collared coils

A. Tollestrup, Proc. Int Conf. on the History of Original Ideas and Basic Discoveries in Particle Physics, Erice (1994).

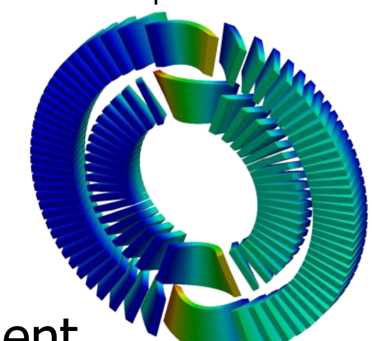


2002, LBNL: Bladder and keys

R.R. Hafalia, et al., IEEE TAS, 12(1) (2002), pp. 47-50.

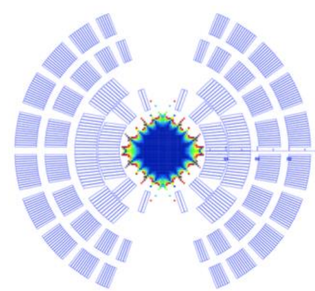
2014, LBNL: CCT

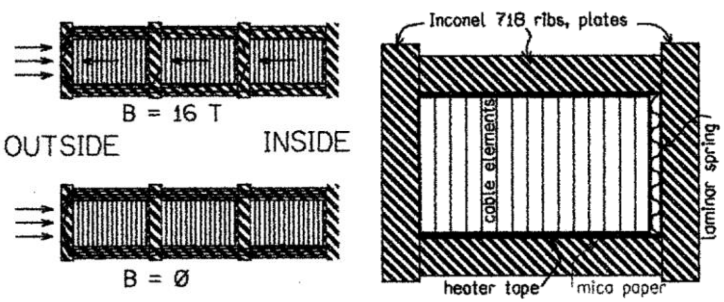
S. Caspi, et al., IEEE TAS (2014), p. 4001804.



2017, FNAL: SM cos(θ)

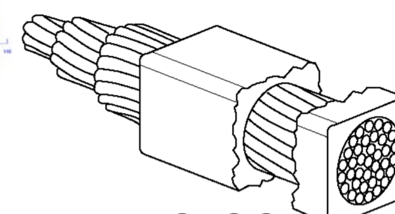
V. Kashikin, et al., Proc. IPAC, Copenhagen (2017), pp. 3597-3599.





1998, TAMU: Stress management

N. Diaczenko, et al., Proc. PAC, Vancouver (1997), pp.3443-3345.

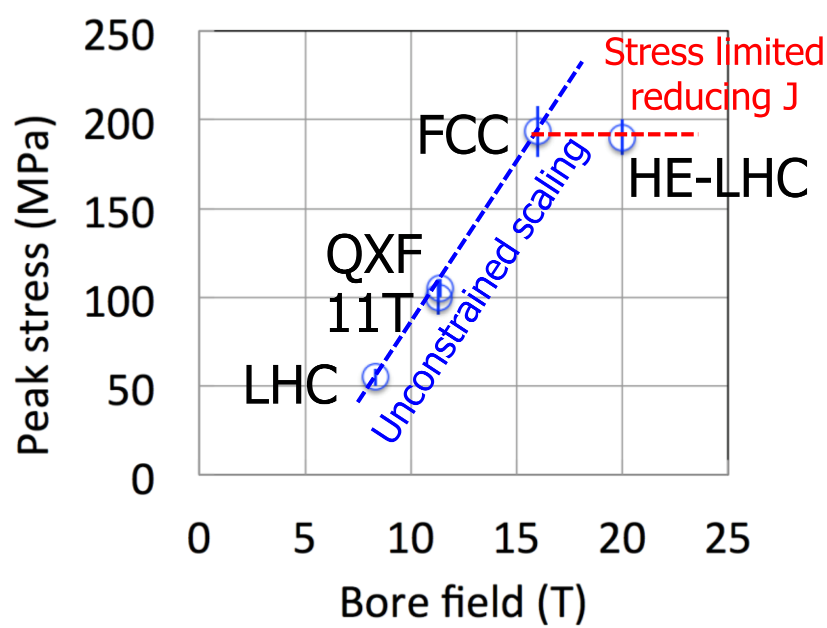


1975, MIT: CICC

M.O. Hoenig, et al., Proc. 5th Magn. Tech. Conf., Frascati(1975), p. 519.

Challenge#3: Structures and stress

$$\left.\begin{array}{l} F \mu B^2 \\ w \mu \dfrac{B}{J} \end{array}\right\} \longrightarrow s \gg \frac{F}{w} \mu JB$$



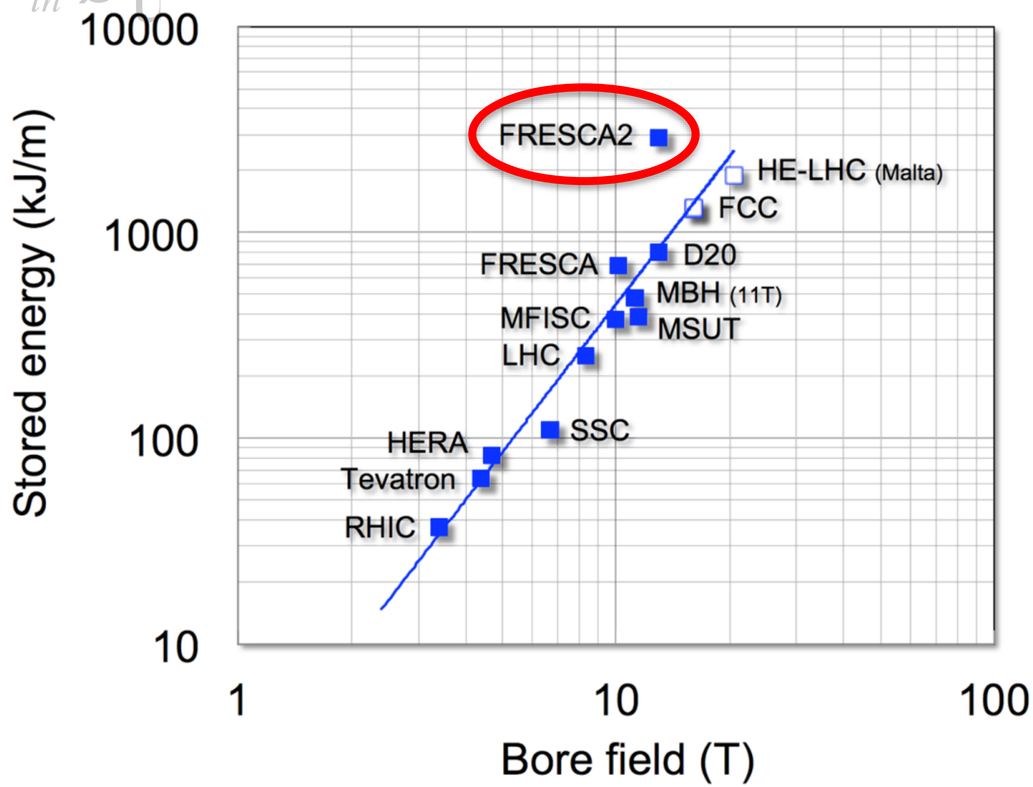
Protection at high fields

$$E/l = \frac{\pi B^2 R_{in}^2}{\mu_0}\left[1 + \frac{2}{3}\frac{w}{R_{in}} + \frac{1}{6}\left(\frac{w}{R_{in}}\right)^2\right]$$

Energy per unit length in a sector coil of inner radius R_{in}, outer radius R_{out}, coil width $w = R_{out}-R_{in}$ producing a dipole field B

$$V/l \approx \frac{2E/l}{\tau I_{op}}$$

Voltage per unit length for an external dump with time constant τ



A simple exercise:

$J_{Cu} \approx$ 1000…1250 (A/mm²)
$dT/dt \approx$ 1000…2000 (K/s)
$\tau_{(300\ K)} \approx$ 0.15…0.3 (s)

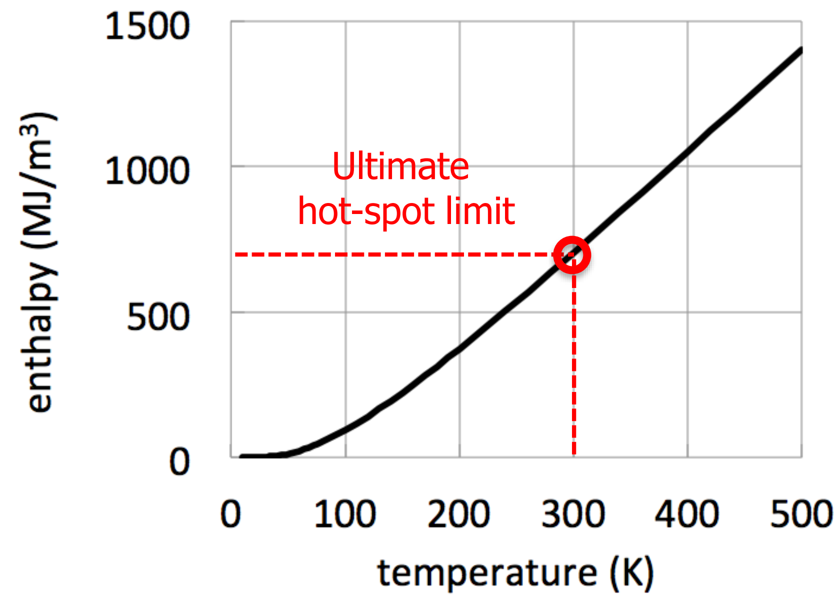
$I_{op} \approx$ 15 (kA)
$E/l \approx$ 1000 (kJ/m)
$V/l \approx$ 500…1000 (V/m)

It is not possible to protect accelerator magnet strings using an external dump

Challenge#4: Ultimate protection limit

$$\left.\begin{array}{l} E/l \propto B^2 \\ A_{coil} \propto \left(\frac{B}{J}\right)^n \end{array}\right\} \rightarrow e \approx \frac{E/l}{A_{coil}} \propto J^n B^{2-n}$$

In the range of typical magnet designs considered $n \approx 1.5$



Typical energy densities e:

LHC MB(8.33T) ≈ 50 MJ/m^3
LHC MBH(11T) ≈ 85 MJ/m^3
FRESCA2(13T) ≈ 100 MJ/m^3

FCC MB(16T) ≈ 200 MJ/m^3

Overview

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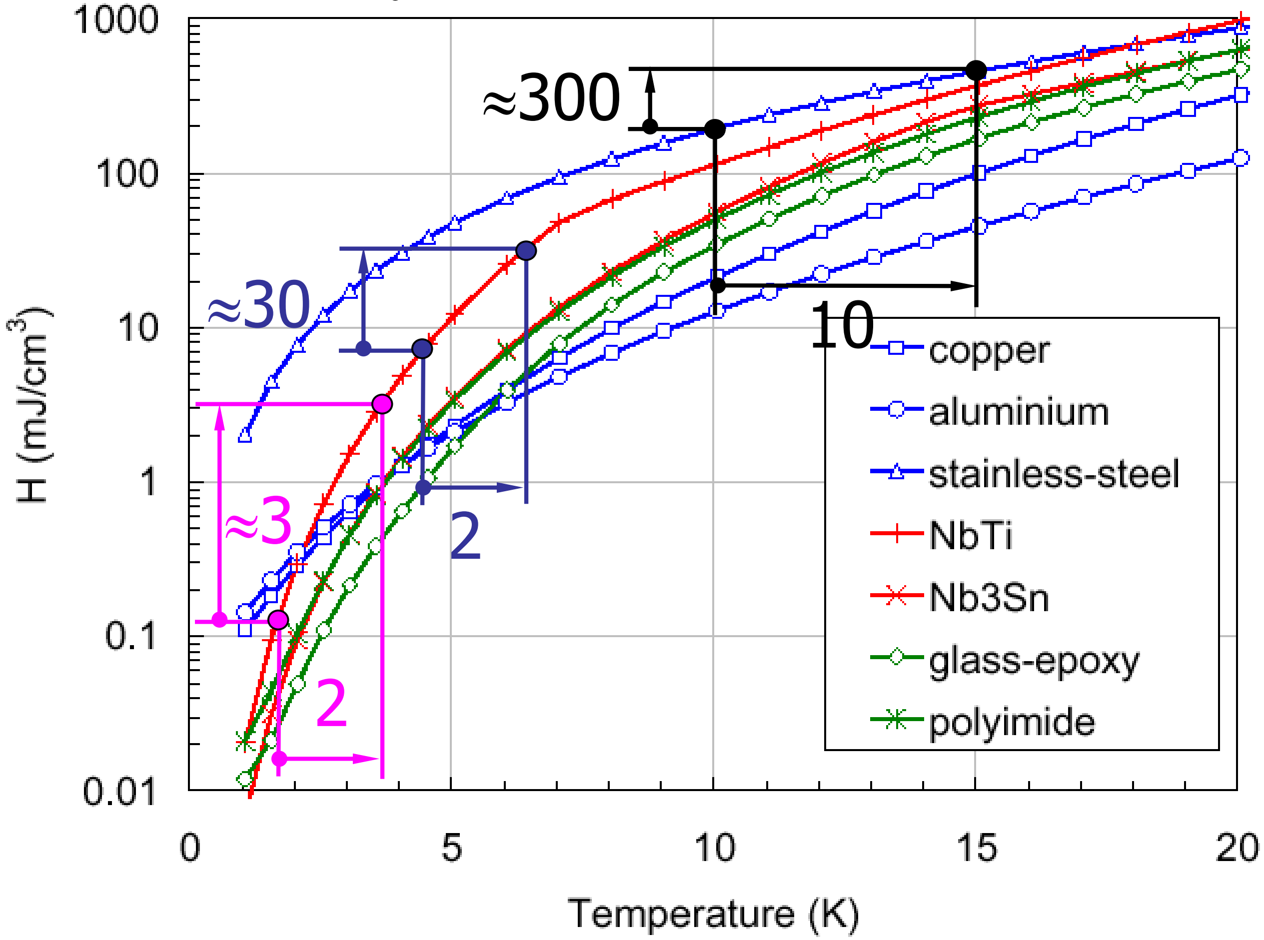
Stability (and no training) in HTS

$$H(T) = \int_0^T C(T')\,dT'$$



HTS challenges

- ✓ HTS materials have spectacular critical fields (100 T, and higher) and engineering current densities (1000 A/mm^2 at 4.2 K and 20 T, and higher)
- ✓ Stability is large enough (100…1000 mJ/cm^3) to withstand any foreseeable and unforeseeable internal and external perturbation
- We could build them right away ?

Challenge #1: Quench detection

- Quench propagation speed

$$v_{adiabatic} = \frac{J_{op}}{C}\sqrt{\frac{\eta_{st} k_{st}}{\left(T_J - T_{op}\right)}}$$

Example LTS:

$J_{op} \approx 100 \times 10^6$ (A/mm^2)
$C \approx \rho \times c_p = 10^4 \times 10^{-1}$ (J/m^3 K)
$\eta \approx 10^{-9}$ (Ω m)
$k \approx 100$ (W/m K)
$T_J - T_{op} \approx 2$ (K)

$v \approx 22$ m/s

Example HTS:

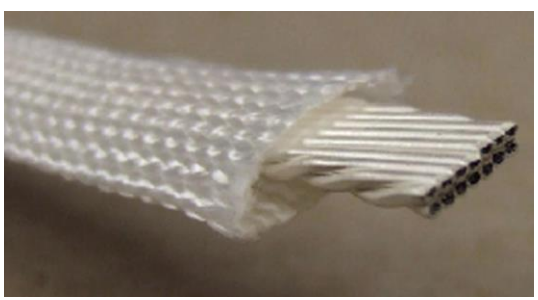
$J_{op} \approx 100 \times 10^6$ (A/mm^2)
$C \approx \rho \times c_p = 10^4 \times$ **10** (J/m^3 K)
$\eta \approx$ **10^{-9}** (Ω m)
$k \approx$ **10** (W/m K)
$T_J - T_{op} \approx$ **10** (K)

$v \approx 3$ cm/s

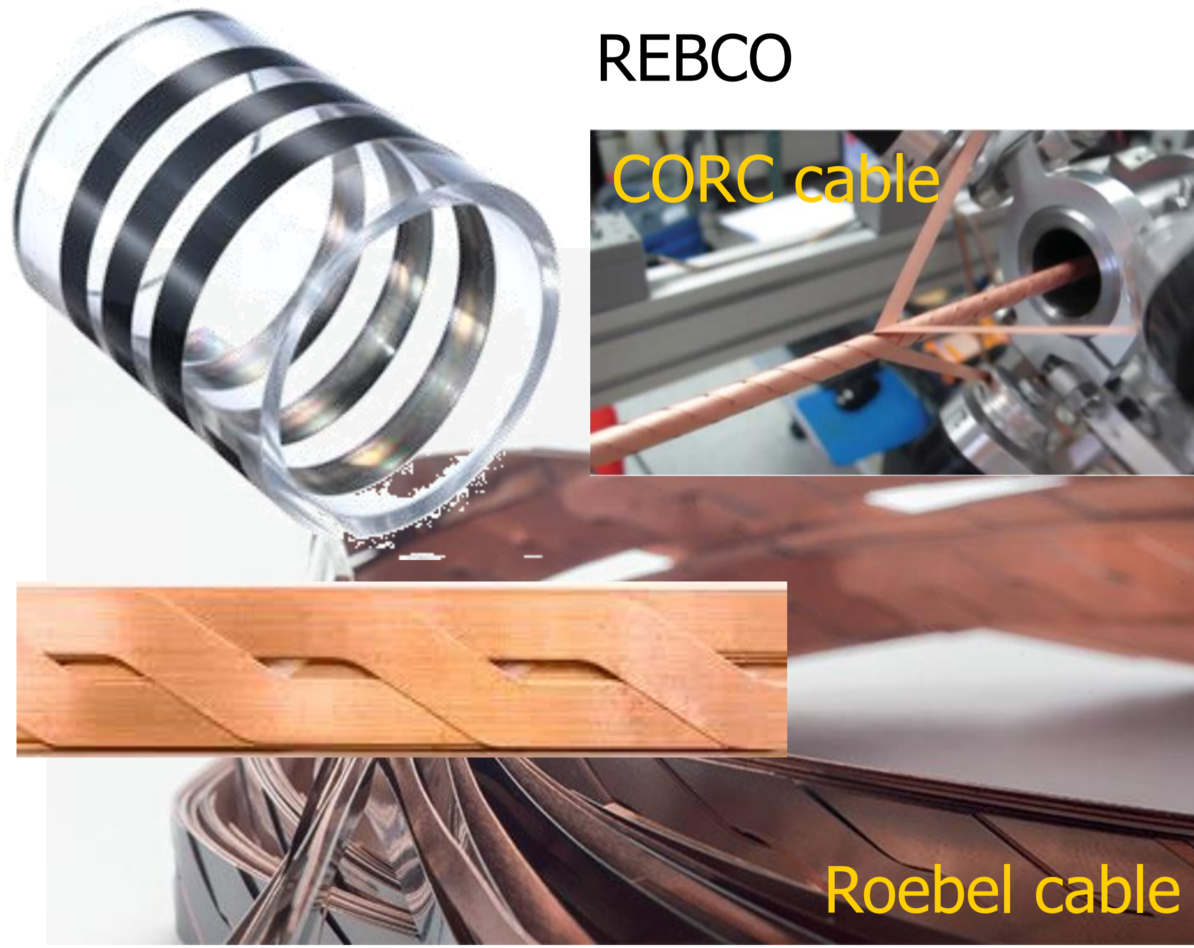
The detection of a quench is a major challenge in HTS magnets

Challenge #2: Wires and cables

BSCCO-2212



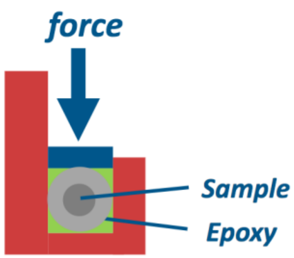
REBCO

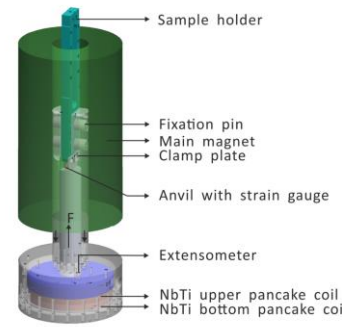


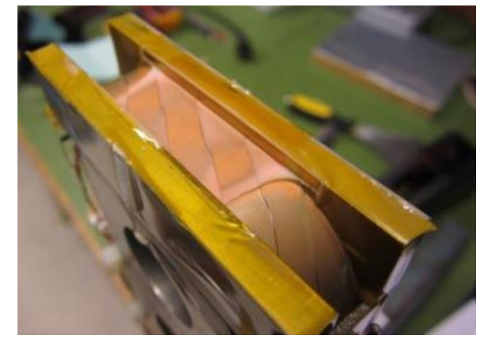
HT at 900 C, 50…100 bar

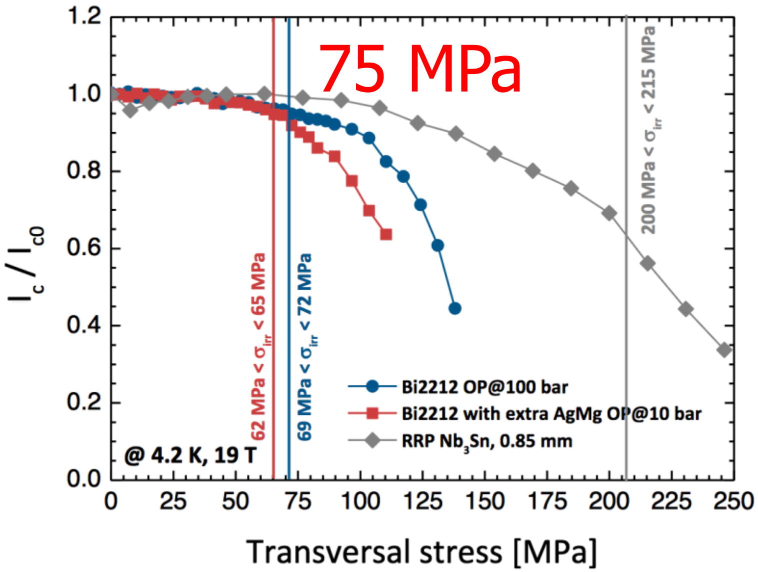
2…10 mm tapes, cannot be folded

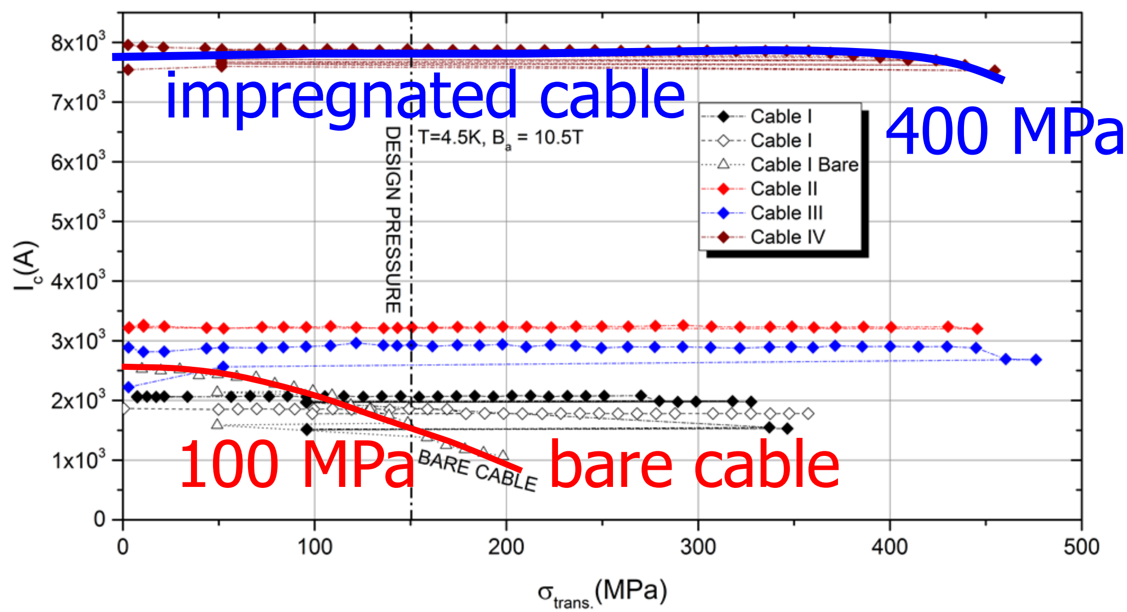
Challenge #3: Stress











BSCCO-2212 wire

REBCO Roebel cable

Challenge #4: Material *availability*

- Cost of material is usually compared on the basis of identical unit current carrying capacity:

C [EUR/kA m] = 10^3 c[EUR/kg] ρ[kg/m^3] / J_E[A/m^2]

- Nb-Ti: C ≈ 0.5 EUR/kA m (5T, 4.2K)
- Nb_3Sn: C ≈ 10 EUR/kA m (12T, 4.2K)
- REBCO: C ≈ 100…400 EUR/kA m (20T, 4.2K)
- BSCCO-2212: C ≈ 250 EUR/kA m (20T, 4.2K)

- Note: Cu has a C ≈ 20 EUR/kA m at RT

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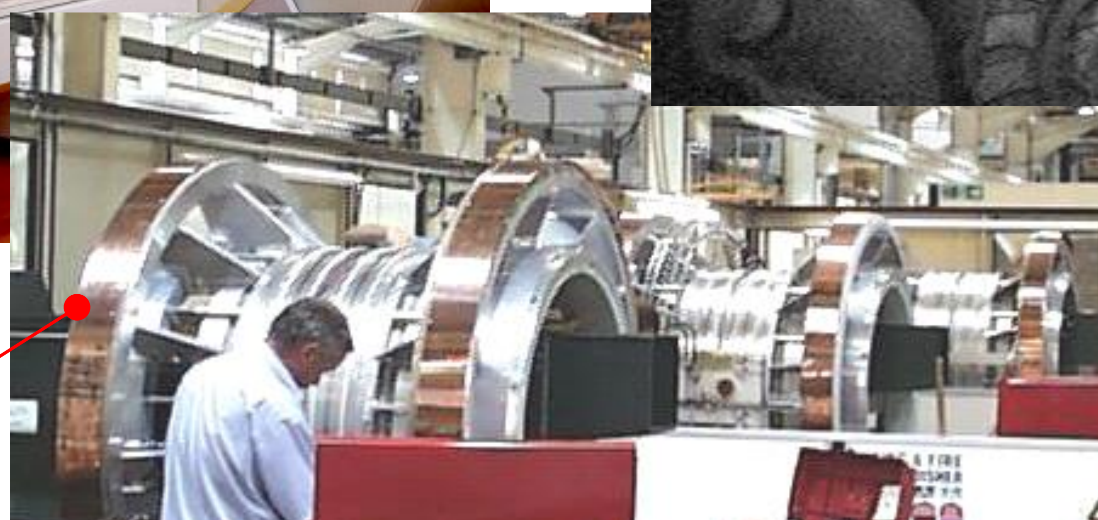
Magnetic Resonance Imaging (MRI)

photos courtesy of
SIEMENS



patient's view

engineer's view

surgeon's view

photo courtesy of
OXFORD
Magnet Technology

NMR spectroscopy

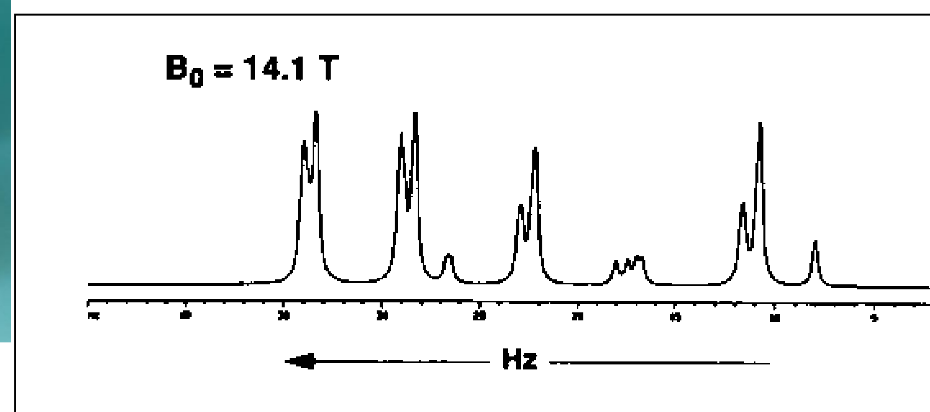


photo courtesy of
OXFORD
Magnet Technology

Motors & generators

Motor with HTS rotor

American Superconductor and Reliance

700 MW generator

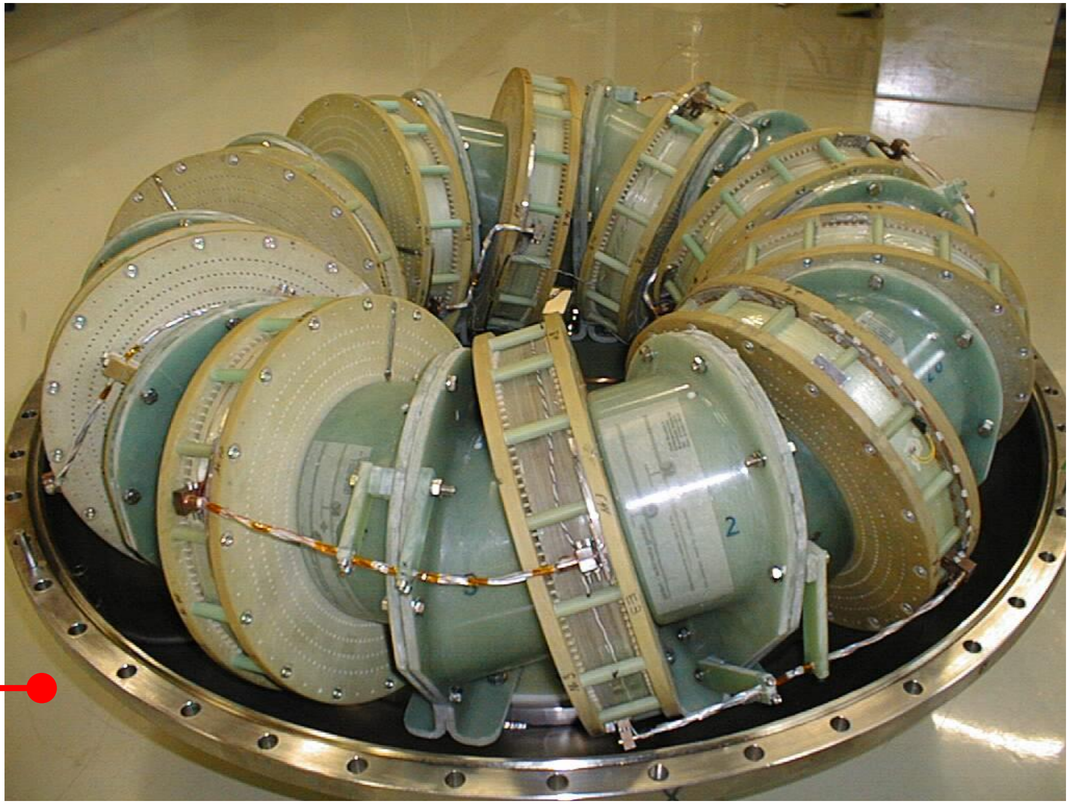
NbTi rotor

Hitachi, Toshiba, Mitsubishi

Transformers & energy storage

HTS Transformer
630 kVA,   18.7kV to 0.42 kV

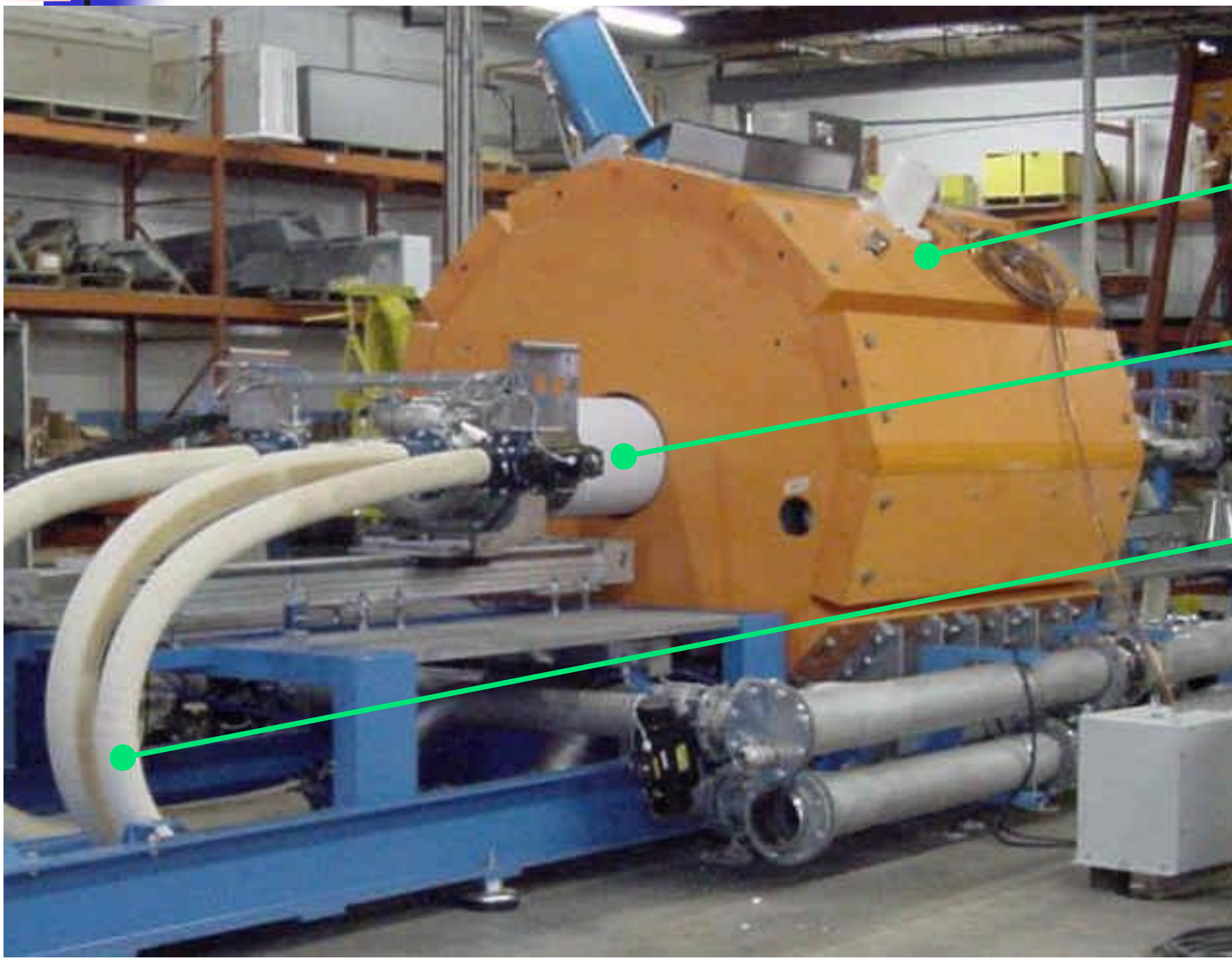
ABB



Toroidal magnet of 200 kJ / 160 kW energy store
(B = 4 T, dia. = 1.1 m)

KfZ Karlsruhe

Magnetic separation

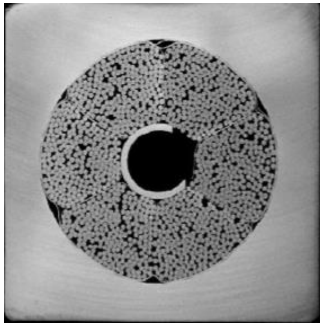


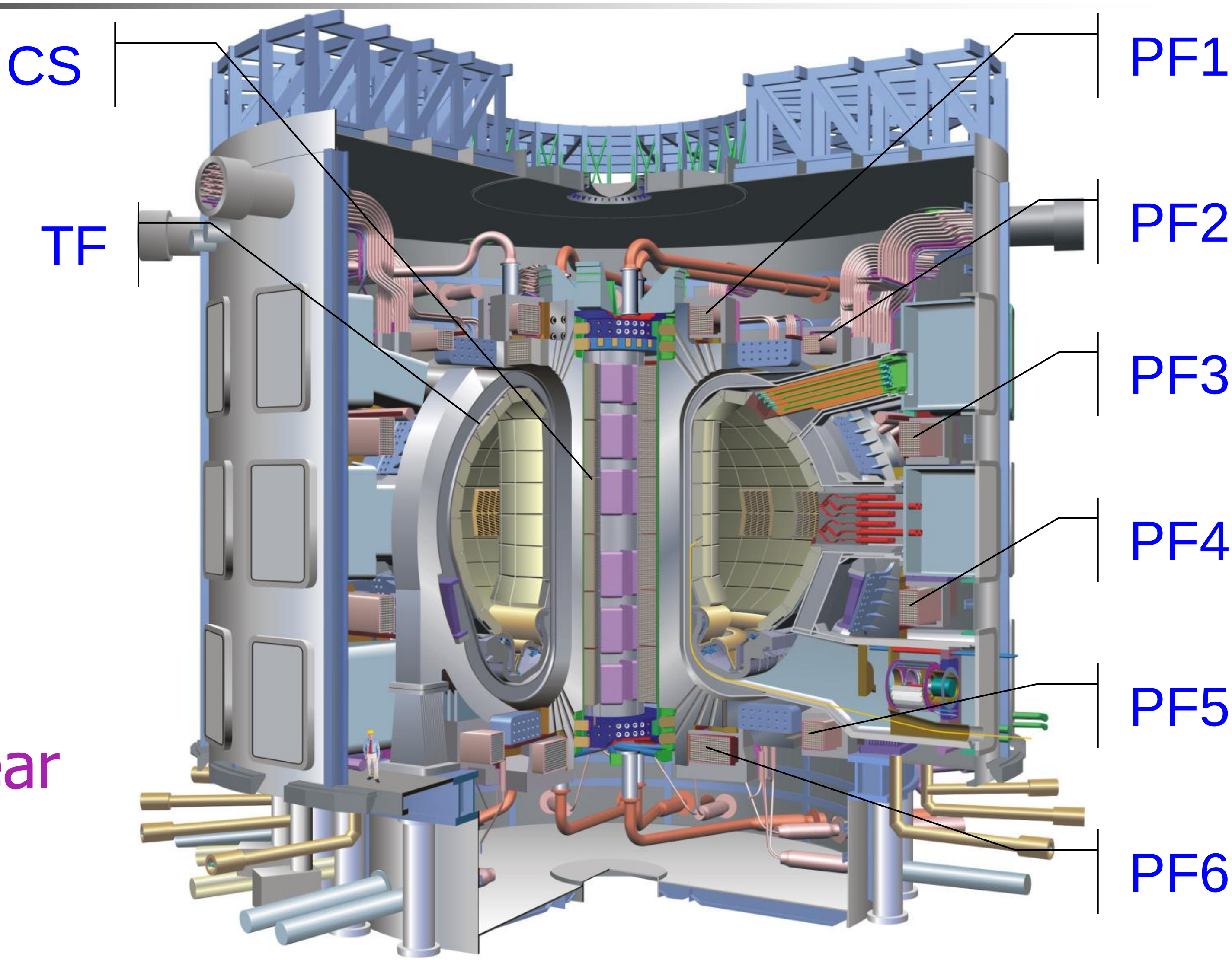
superconducting solenoid, enclosed within iron shield

stainless steel canister containing ferromagnetic mesh

pipes feeding the kaolin slurry for separation

Thermonuclear fusion

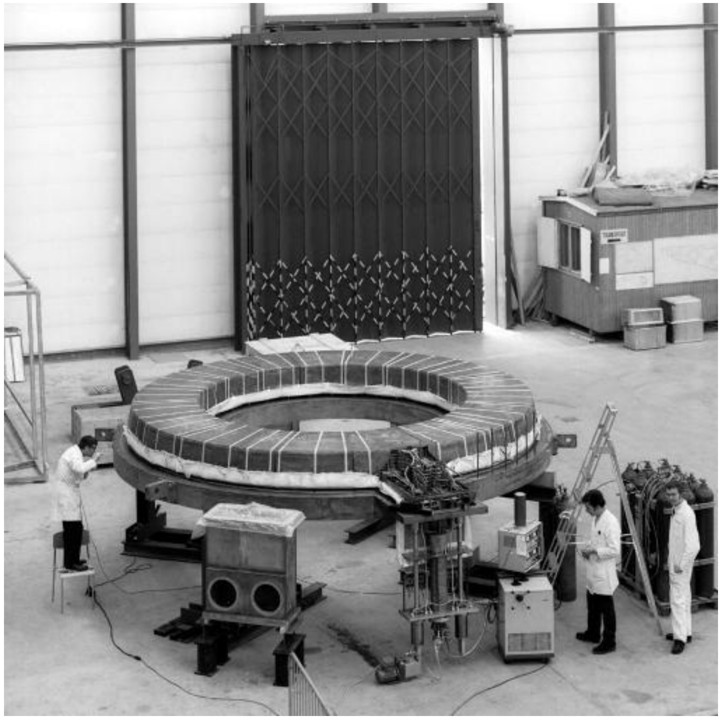




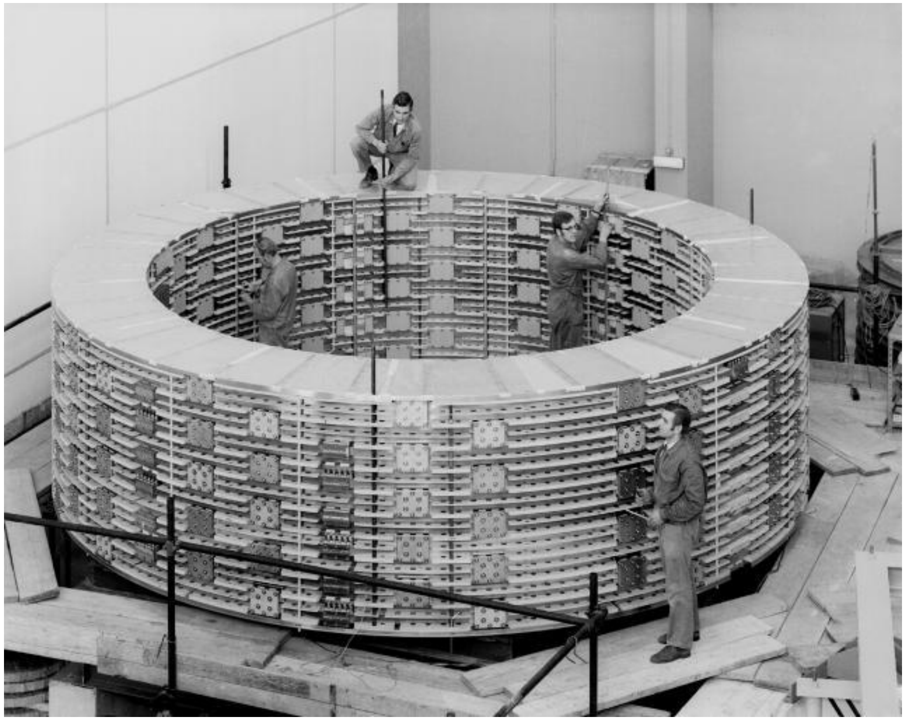
ITER

International Thermonuclear Experimental Reactor

HEP detectors of the past...

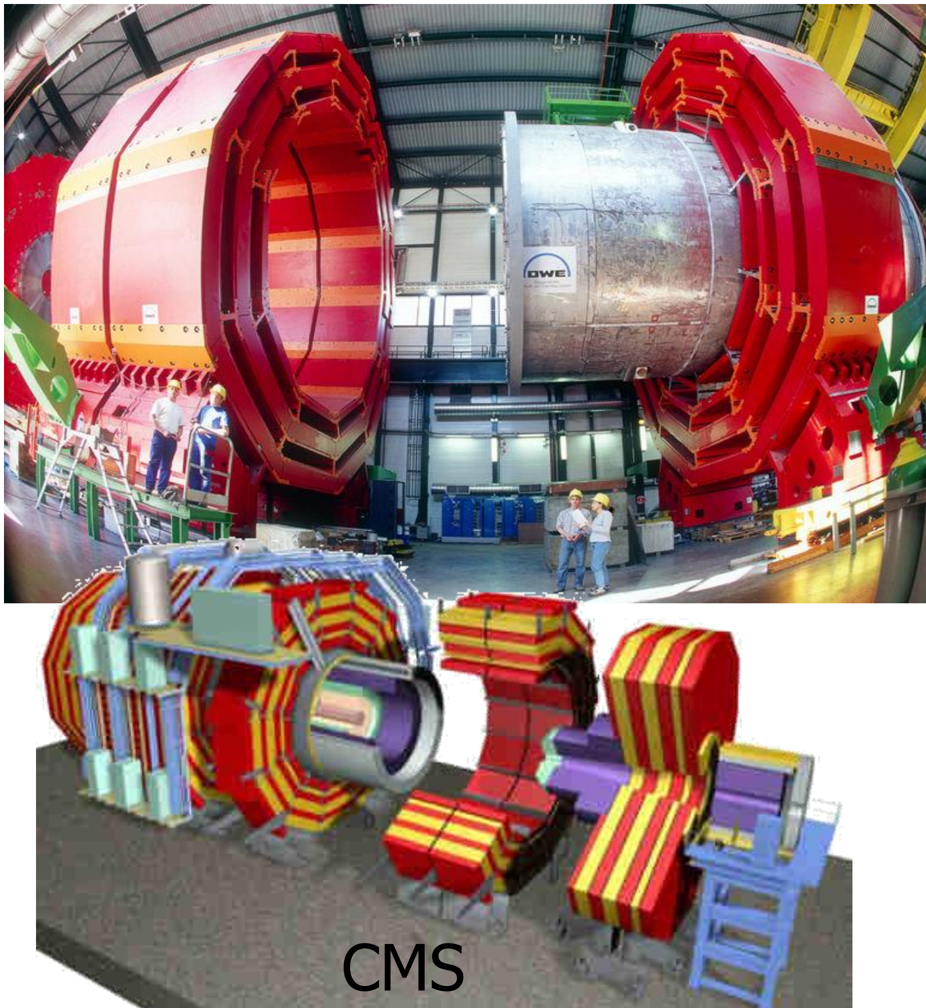


Omega

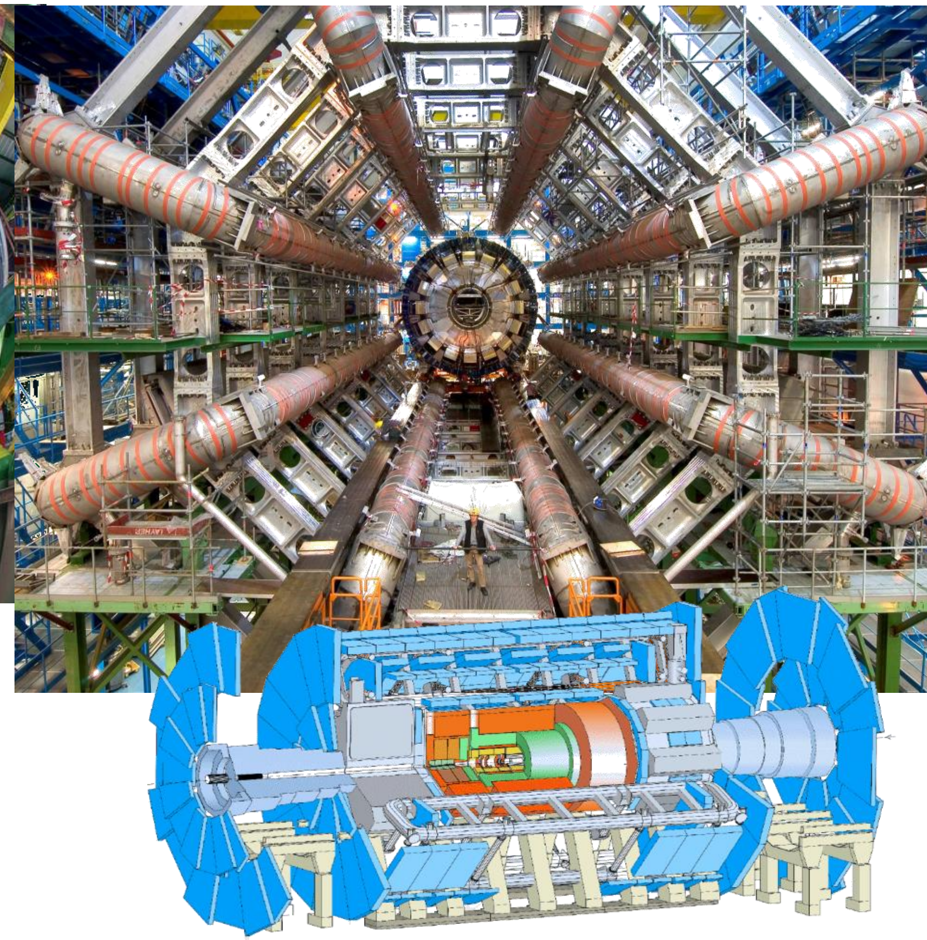


BEBC

… and HEP of the present (CMS and ATLAS)



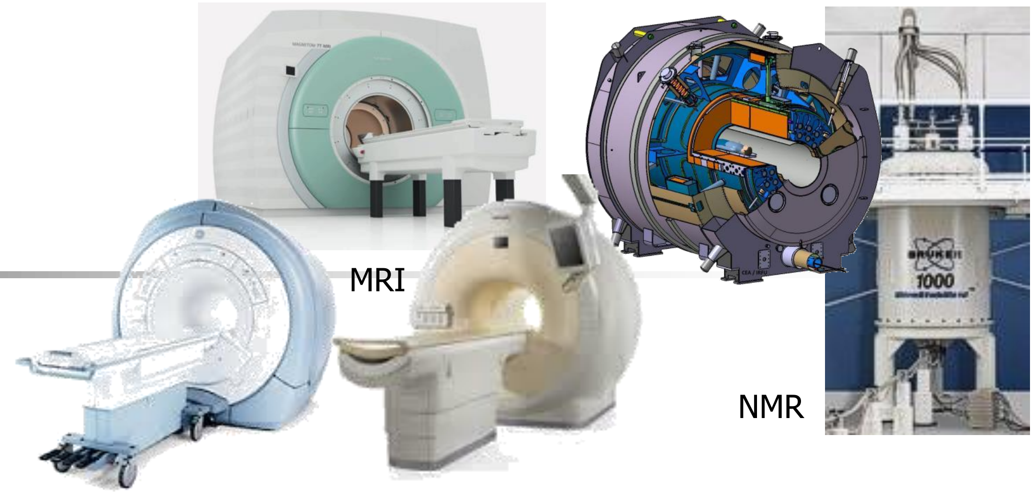
CMS

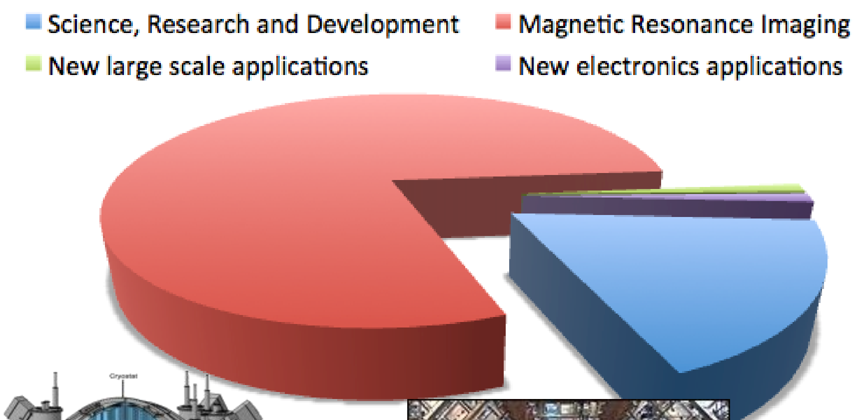


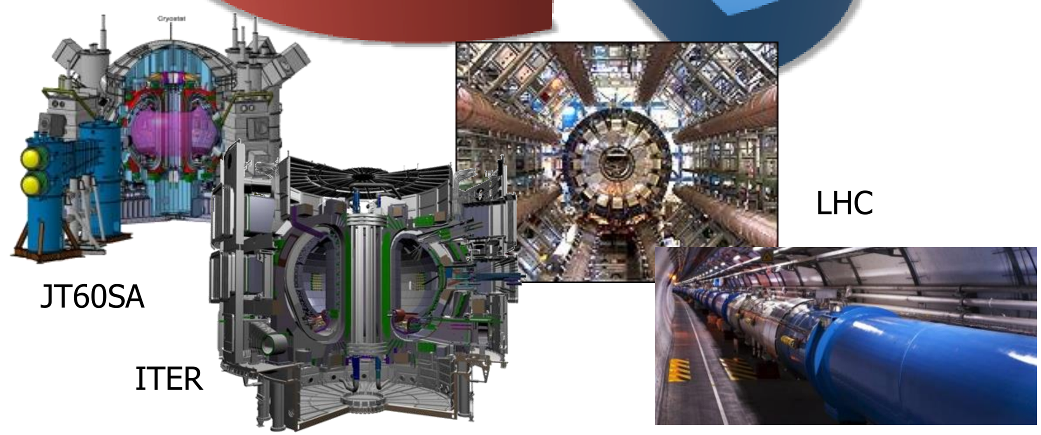
ATLAS

SC market

- At present, the vast majority of the use of superconductors is for magnet applications:
  - MRI: 5.5 BUSD/year[1]
  - NMR, science and research: approximately 1 BUSD/year[1]
- Large scale projects (HEP, Fusion) represent only a fraction of the total market:
  - Evaluated cost of LHC magnet system (material): 2 BUSD[2]
  - Quoted cost of ITER magnet system (material): 1.4 BUSD[3]



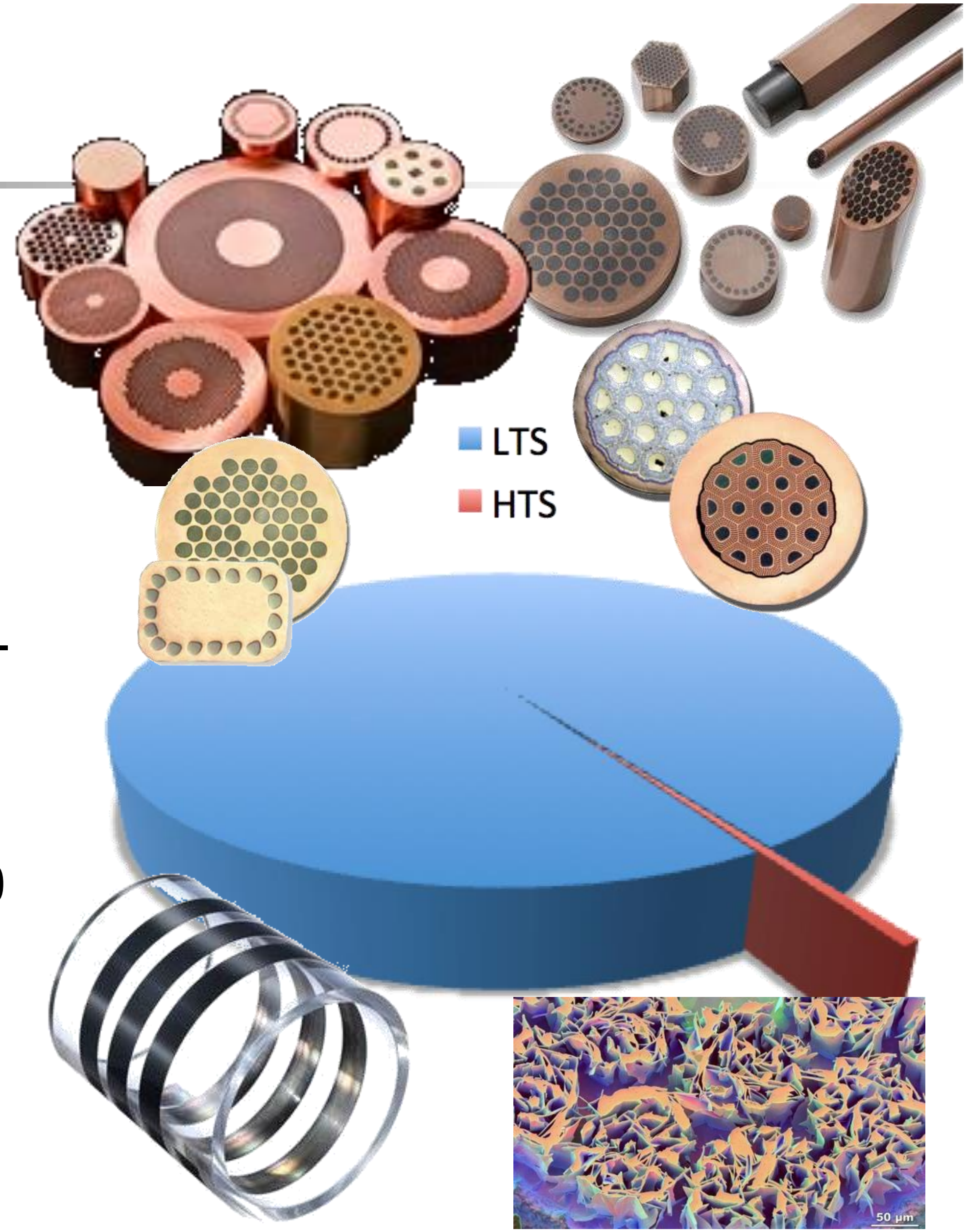




Sources: [1] from market report at Conectus.org, converted from repored 5.3 BEUR in 2013
[2] Report to the CERN Finance Committee, 2008, reported 1.7 BCHF(2008) escalated to 2013
[3] DOE Assessment of the ITER Project Cost Estimate, reported 1.09 BUSD(2002) escalated to 2013

SC materials

- Nb-Ti: 600 t/year, mostly driven by MRI
- Nb_3Sn: 10 t/year, mostly driven by NMR and laboratory systems
  - LHC required 1300 tons of Nb-Ti (300 t/year peak production)
  - ITER requires 300 tons of Nb-Ti and 600 tons of Nb_3Sn (250 t/year peak production)
- All of HTS (BSCCO, YBCO) and MgB_2 (MTS) is below 1 ton/year



Other uses of superconductivity

FOUNDED 1905
BARKING, ESSEX

The Church of The Latter Day Snakes

The Church of the Latter Day Snakes
founded 1905, revived 1950

Professor Main,
The Physics Dep
The University

14 April, 1997.

Dear Professor Main,

I and my closest associates who are good eggs in the Church of the Latter Day Snakes were very fascinated to read a reporting of your experiment with a powerful magnet and a frog in The Independent, of Saturday, 12 April, 1997. You claim that you are able to levitate a frog and even fish and plants too by means of your machine. We in the church are not scientists, we follow the spiritual path, and …

(1) How big is this magnet, and can it be concealed beneath a floor, perhaps? It is important for our ideas that it can not be seen. Will it work if there is wood there? And the floor nails. Will they mess up the magnet?

(2) Does it make much noise, and if so is it a loud noise? A quiet hum would be alright of course because we have a Hammond organ.

(3) We are …

(3a) Does it hurt, … because it will be me doing the levitating. I am quite large being 22 stone weight, but my mother says I have heavy bones! No, jokings put aside, most of me is liquid I think and I am not very dense so maybe that is good for your machine.

Please answer me first these questions and then you are my friend. I must trust you first before we do business. For you, you must be interested to know that our church is very rich. We have nearly twenty five million pounds in gilt edge securities and properties in Essex and Kent, so if everything is good we want to buy your machine for one million pounds, which would be a good price.

We have a big interest in this machine…

…we pull back the curtain in the Snake Chamber and I start to rise up from the ground…

…the Natural Law Party… please do not sell them a machine… **they** are very bonkers…

How big is this magnet, and can it be concealed beneath a floor…

Does it make much noise…

Does it hurt… because it will be me doing the levitating.

Olaf Van Haarve,
The Snakehead.

I put in five pounds for you… This is only the start.

Letter to Prof. Main, University of Nottingham, 14 April 1997

A word of closing

- Superconducting magnet design is a lot about superconductors (materials, wires, cables, and their electric and thermal properties)…
- … but not only !
  - High field & forces bear mechanical problems that are tough to solve ($B=10$ T $\Rightarrow$ $p_{mag}=400$ bar !)
  - Materials at low temperature are not what we are used to (mechanical and magnetic properties, thermal expansion, electrical insulation)
  - Cooling is an applied science by itself

Where to find out more - 1/3

- Superconducting magnets:
  - Case Studies in Superconducting Magnets: Y. Iwasa, Plenum Press, New York (1994), ISBN 0-306-44881-5.
  - Superconducting Magnets: M.N. Wilson, Oxford University Press (1983) ISBN 0-019-854805-2
  - High Field Superconducting Magnets: F.M. Asner, Oxford University Press (1999) ISBN 0 19 851764 5
  - Superconducting Accelerator Magnets: K.H. Mess, P. Schmuser, S. Wolf, World Scientific, (1996) ISBN 981-02-2790-6
  - Stability of Superconductors: L. Dresner, Plenum Press, New York (1994), ISBN 0-306-45030-5
  - Handbook of Applied Superconductivity ed. B. Seeber, UK Institute Physics 1998
  - Proc Applied Superconductivity Conference: IEEE Trans Magnetics, 1975 to 1991, and IEEE Trans Applied Superconductivity, 1993 to 2012,
  - Proc European Conference on Applied Superconductivity EUCAS, UK Institute Physics
  - Proc International Conference on Magnet Technology; MT-1 to MT-20 (2007) mainly as IEEE Trans Applied Superconductivity and IEEE Trans Magnetics

Where to find out more - 2/3

- Cryogenics
  - Helium Cryogenics S.W. Van Sciver, Plenum Press, 86 ISBN 0-0306-42335-9
  - Cryogenic Engineering, B.A. Hands, Academic Press 86 ISBN 0-012-322991-X
  - Cryogenics: published monthly by Elsevier
- Materials - Superconducting properties
  - Superconductor Science and Technology, published monthly by Institute of Physics (UK).
  - IEEE Trans Applied Superconductivity, published quarterly
  - Superconductivity of metals and Cuprates, J.R. Waldram, Institute of Physics Publishing (1996) ISBN 0 85274 337 8
  - High Temperature Superconductors: Processing and Science, A. Bourdillon and N.X. Tan Bourdillon, Academic Press, ISBN 0 12 117680 0

Where to find out more - 3/3

- Materials - Mechanical properties
  - Materials at Low Temperature, Ed. R.P. Reed and A.F. Clark, Am. Soc. Metals 1983. ISBN 0-87170-146-4
  - Handbook on Materials for Superconducting Machinery, Batelle Columbus Laboratories, 1977.
  - Nonmetallic materials and composites at low temperatures, Ed. A.F. Clark, R.P. Reed, G. Hartwig, Plenum Press
  - Nonmetallic materials and composites at low temperatures 2, Ed. G. Hartwig, D. Evans, Plenum Press, 1982