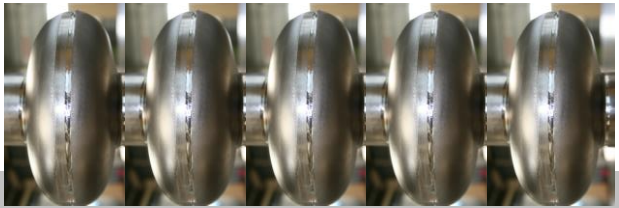
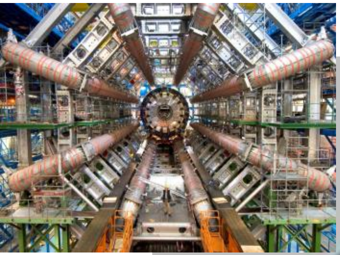
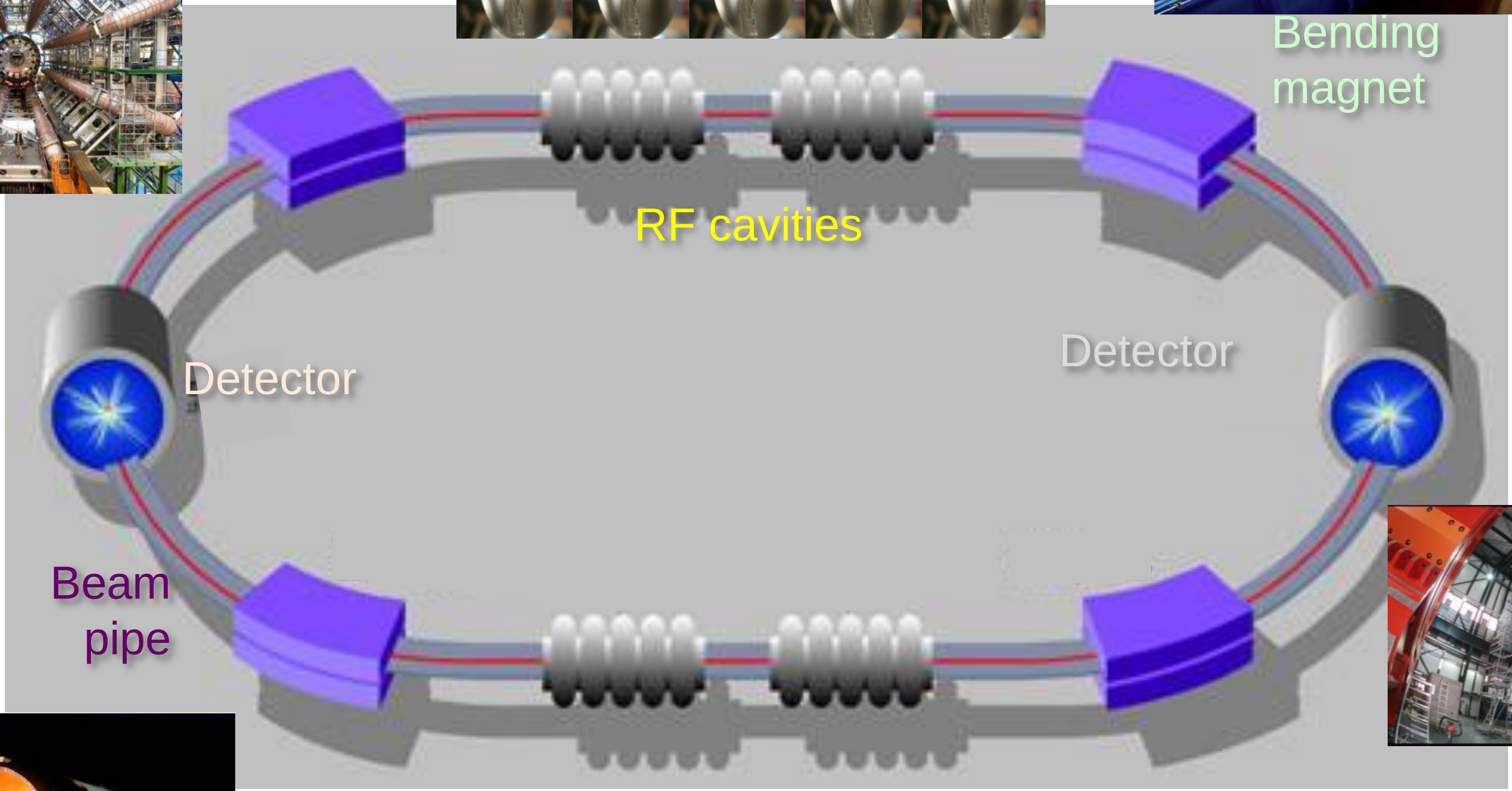
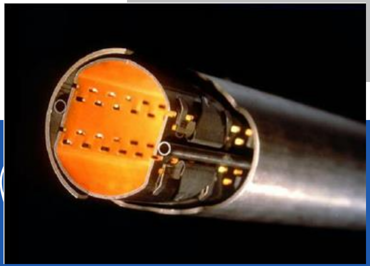
Superconductors:
Why do we need them ?

A modern circular collider





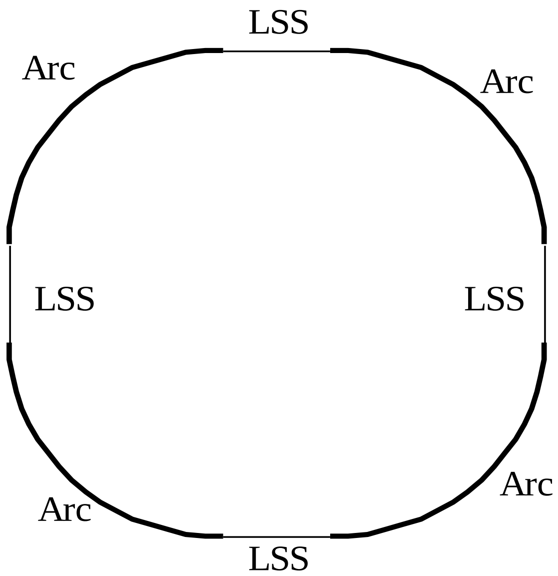




The LHC

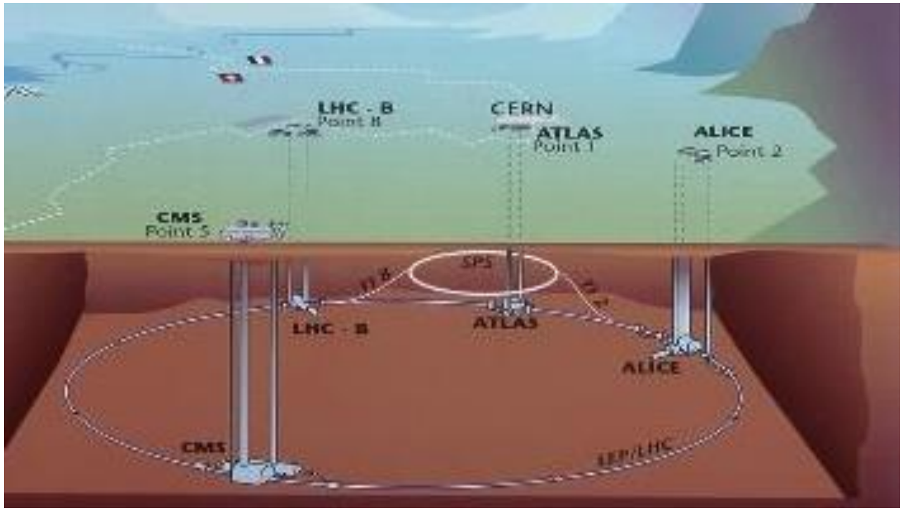
"The Arc"

- **Dipoles**: magnetic field steers (bends) the particles in a ~circular orbit
- **Quadrupoles**: magnetic field provides the force necessary to stabilize linear motion.
  - They act as a spring: **focus the beam**
  - Prevent protons from **falling** to the bottom of the aperture due to the **gravitational force (**it would happen in less than 60 ms!)
- **Correctors**

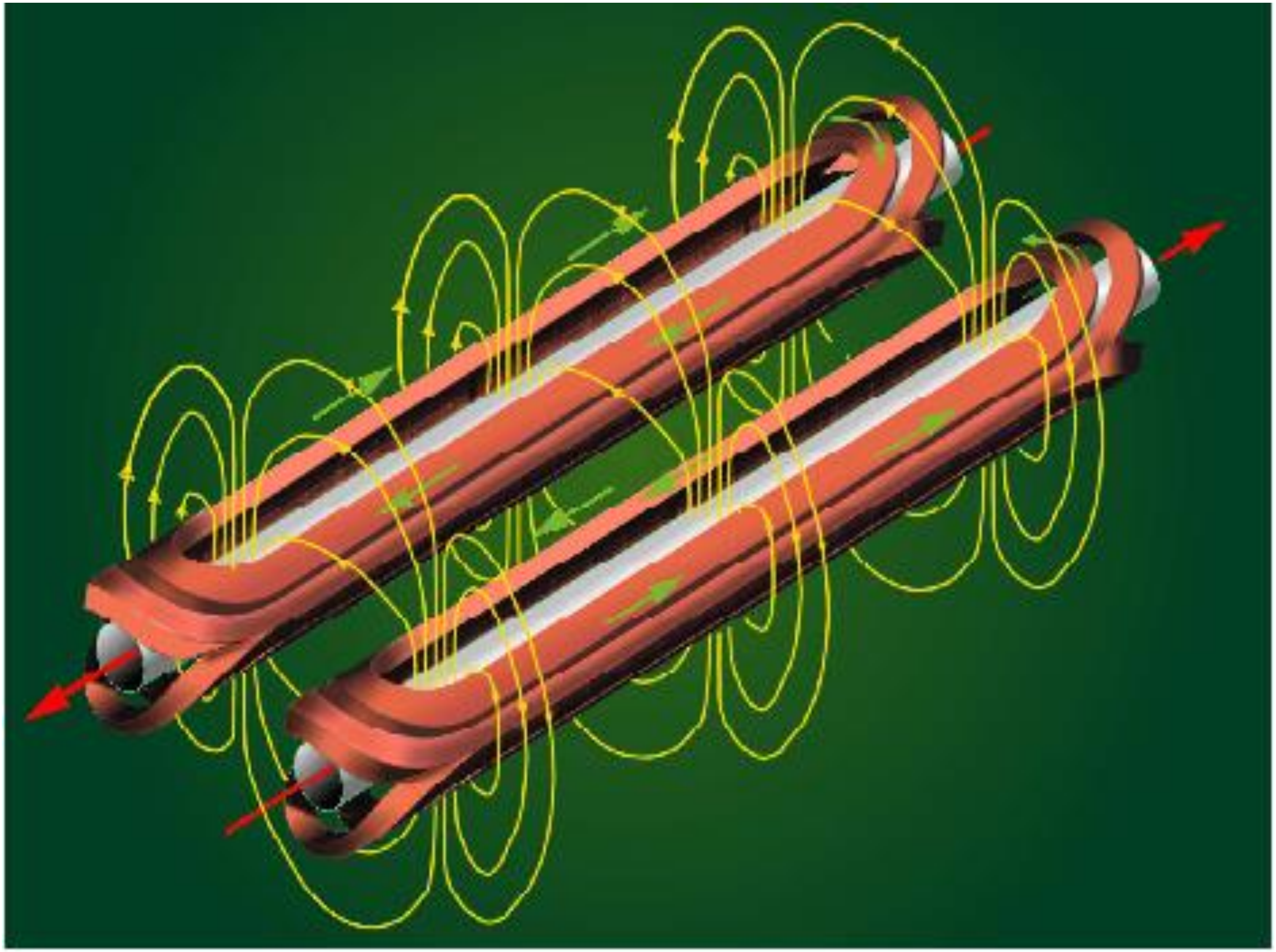


"Long straight sections (LSS)"

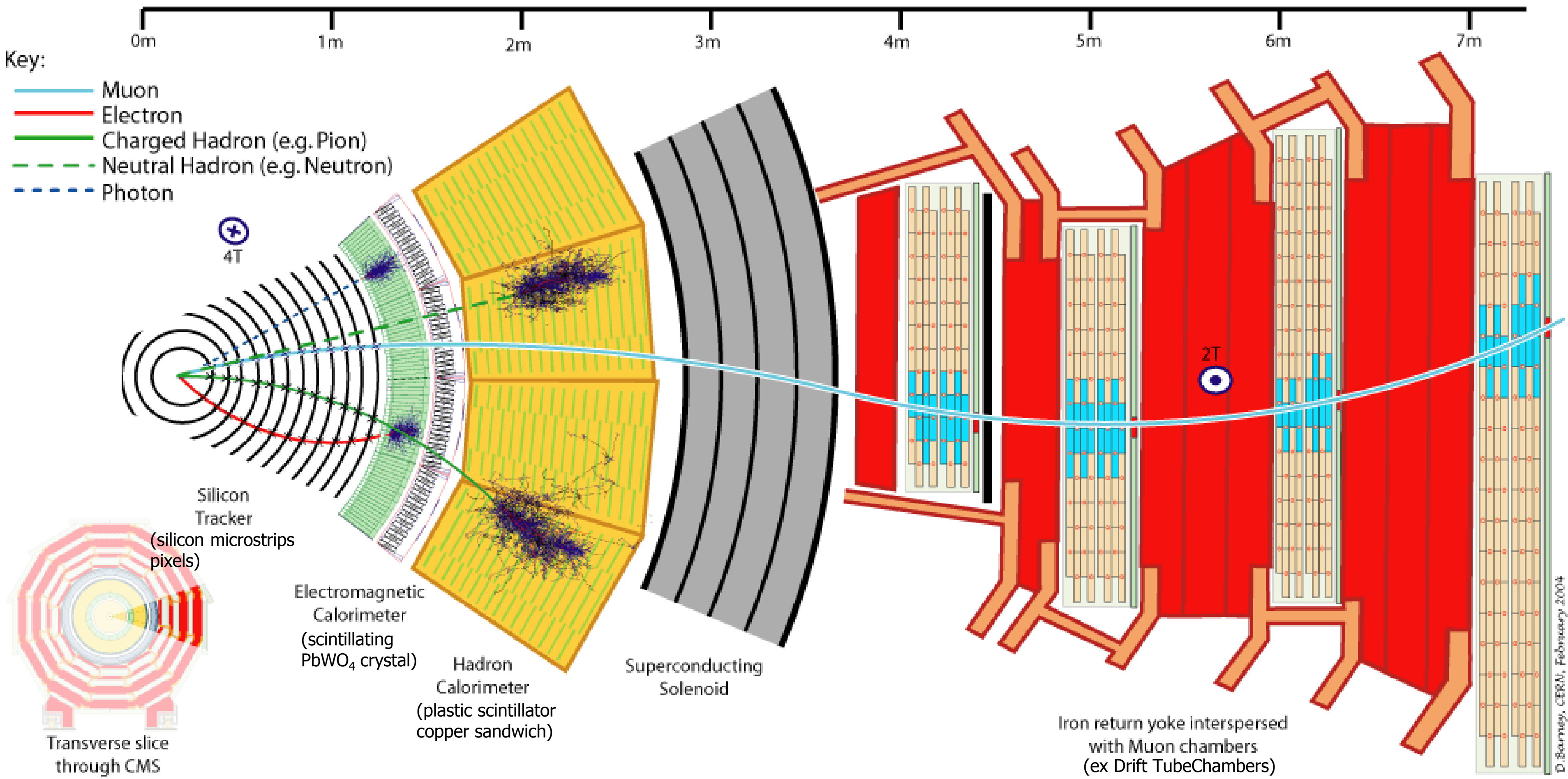
- Interaction regions (IR) where the experiments are housed
  - Quadrupoles for strong focusing in interaction point
  - Dipoles for beam crossing in two-ring machines
- Regions for other services
  - Beam injection (dipole kickers)
  - Accelerating structure (RF cavities)
  - Beam dump (dipole kickers)
  - Beam cleaning (collimators)



A dipole magnet

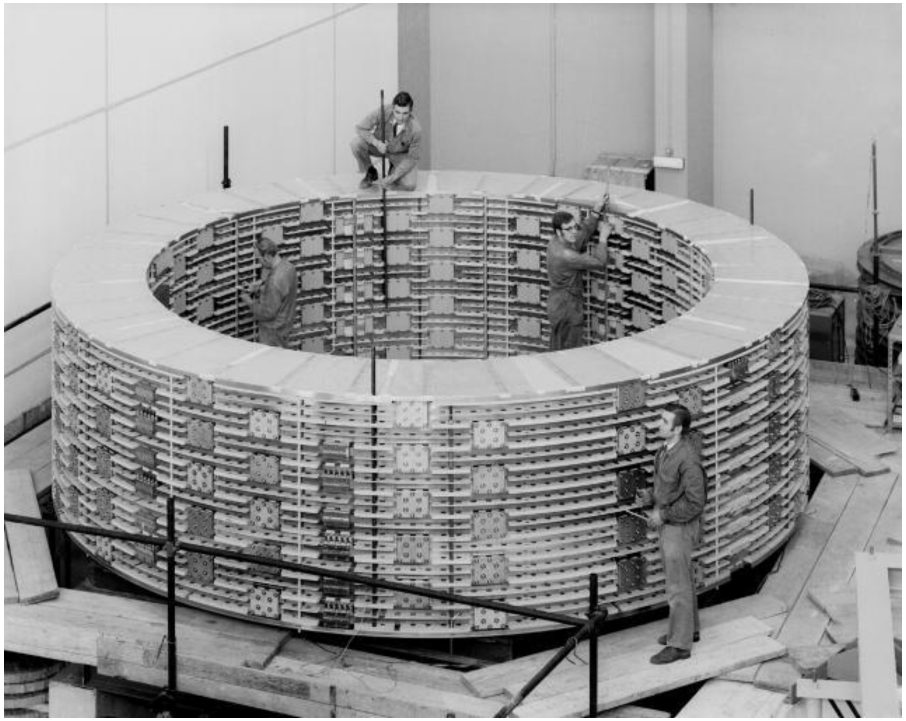


Working principle of a detector



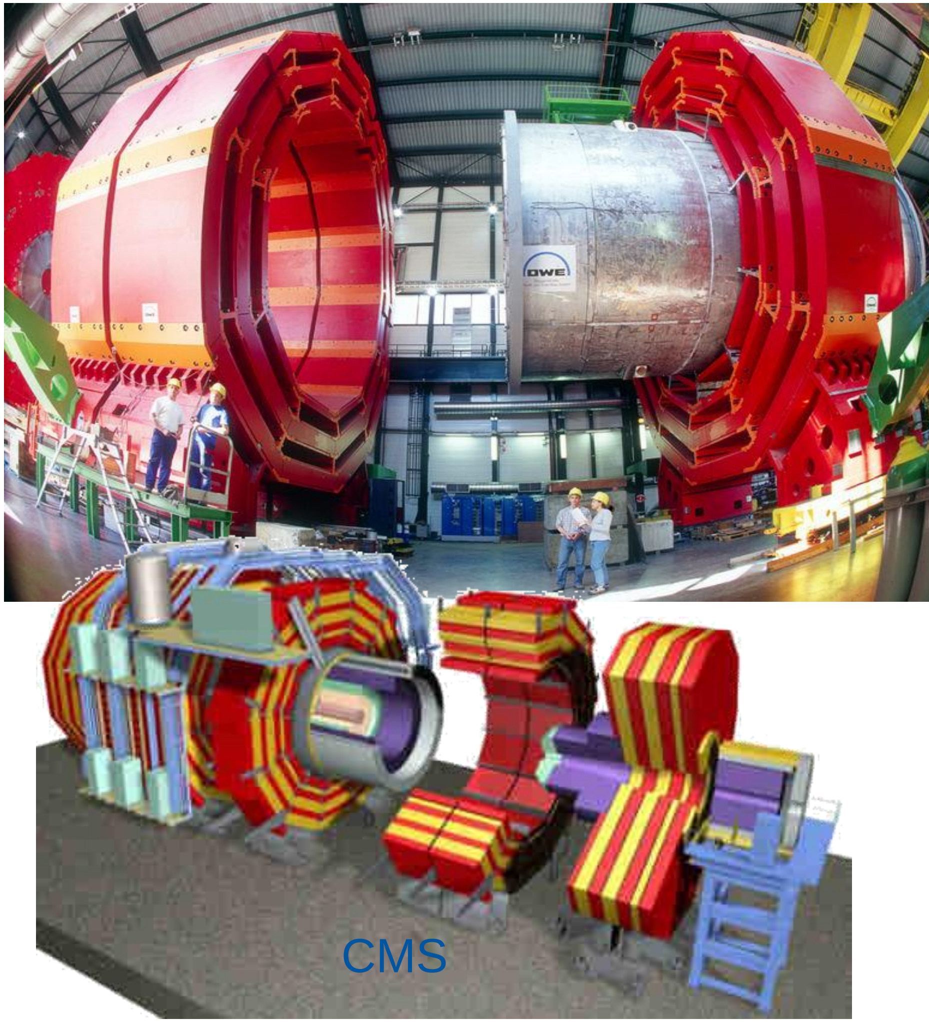
HEP detectors of the past...

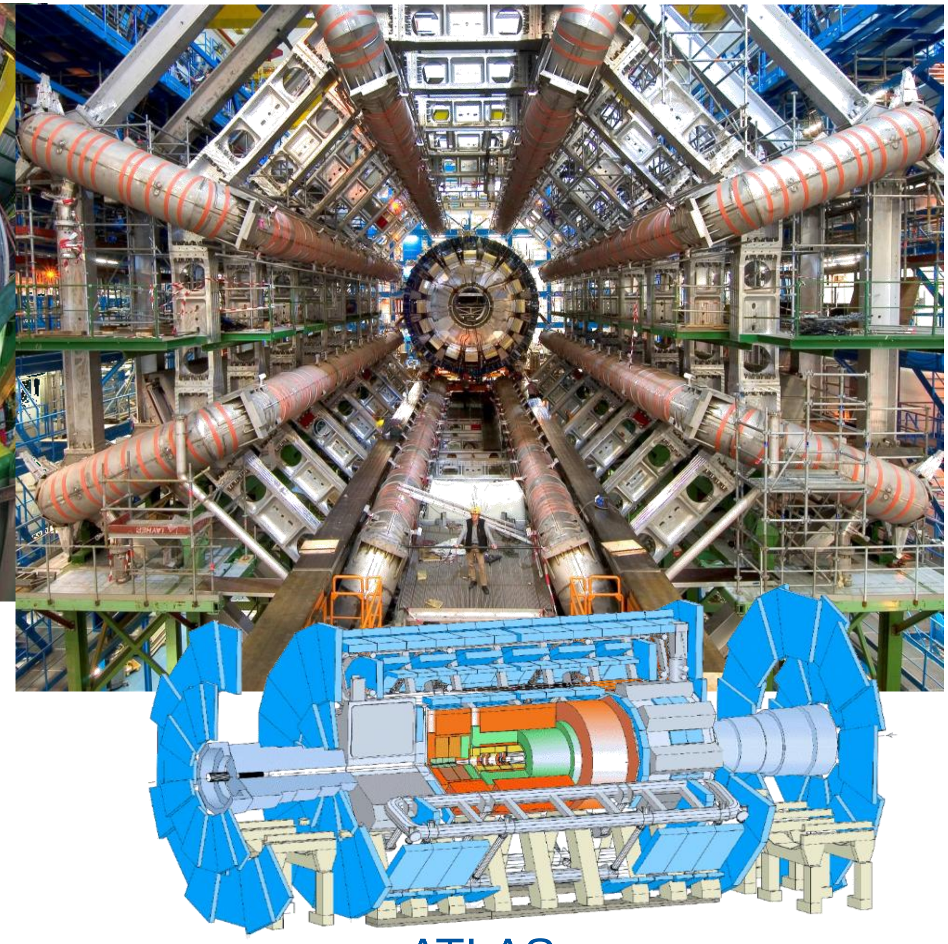
Omega
Commissioned in 1971



BEBC
Commissioned in 1973

… and HEP of the present





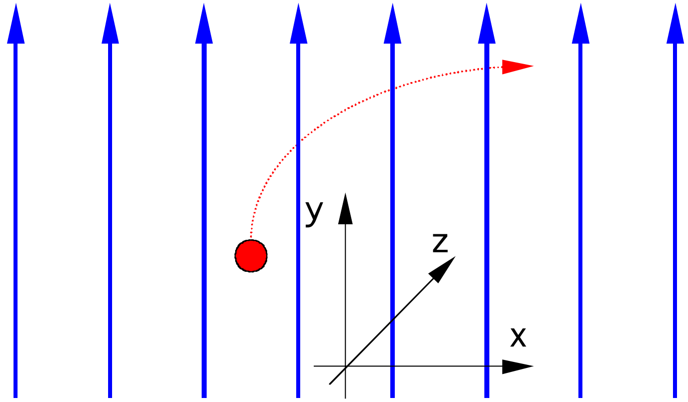
The need for high fields

Beam energy

$$E[GeV] = 0.3\, B[T]\, r[m]$$

Bending radius

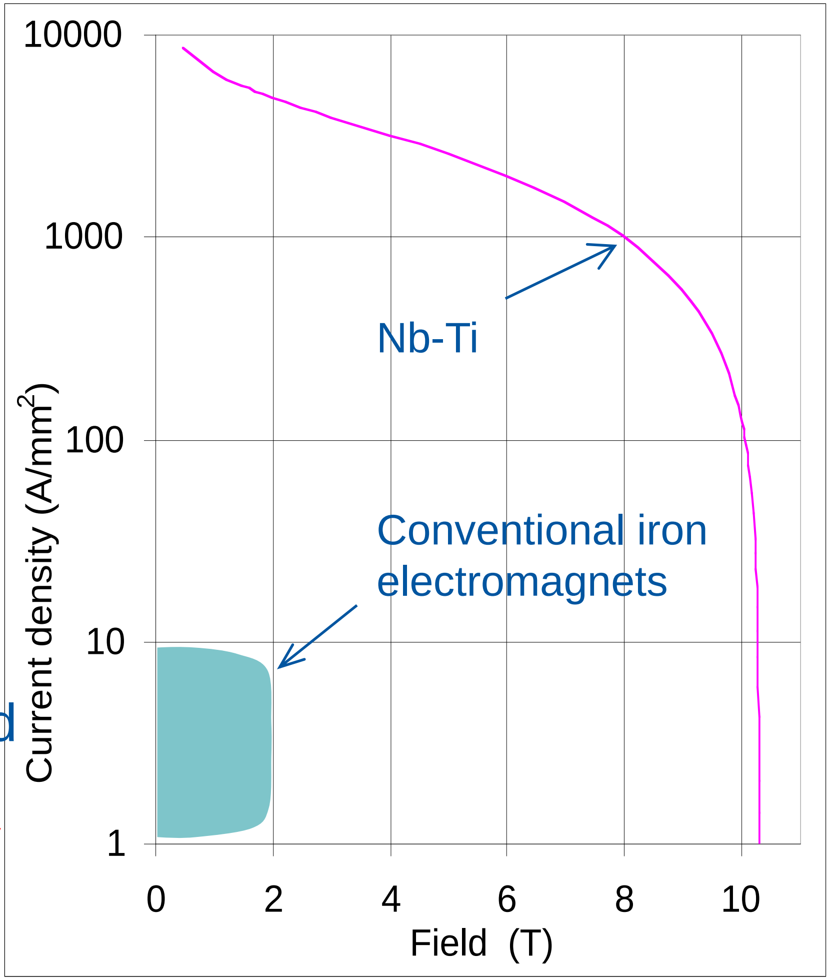
Dipole field



The stronger the field, the smaller the machine

Why superconductivity anyhow ?

- **Abolish Ohm's law !**
  - no power consumption (although need refrigeration power)
  - high current density
  - ampere turns are cheap, so don't need iron (although often use it for shielding)
- Consequences
  - lower running cost $\Rightarrow$ new commercial possibilities
  - energy savings
  - high current density $\Rightarrow$ smaller, lighter, cheaper magnets $\Rightarrow$ reduced capital cost
  - higher magnetic fields economically feasible $\Rightarrow$ new research possibilities (LHC)



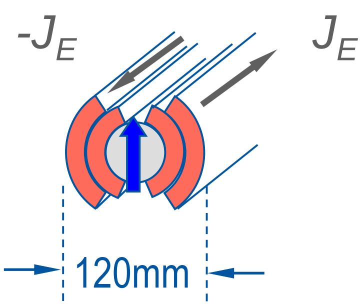
High current density dipoles

- The field produced by an ideal dipole is:

$$B = \mu_o J_e \frac{t}{2}$$

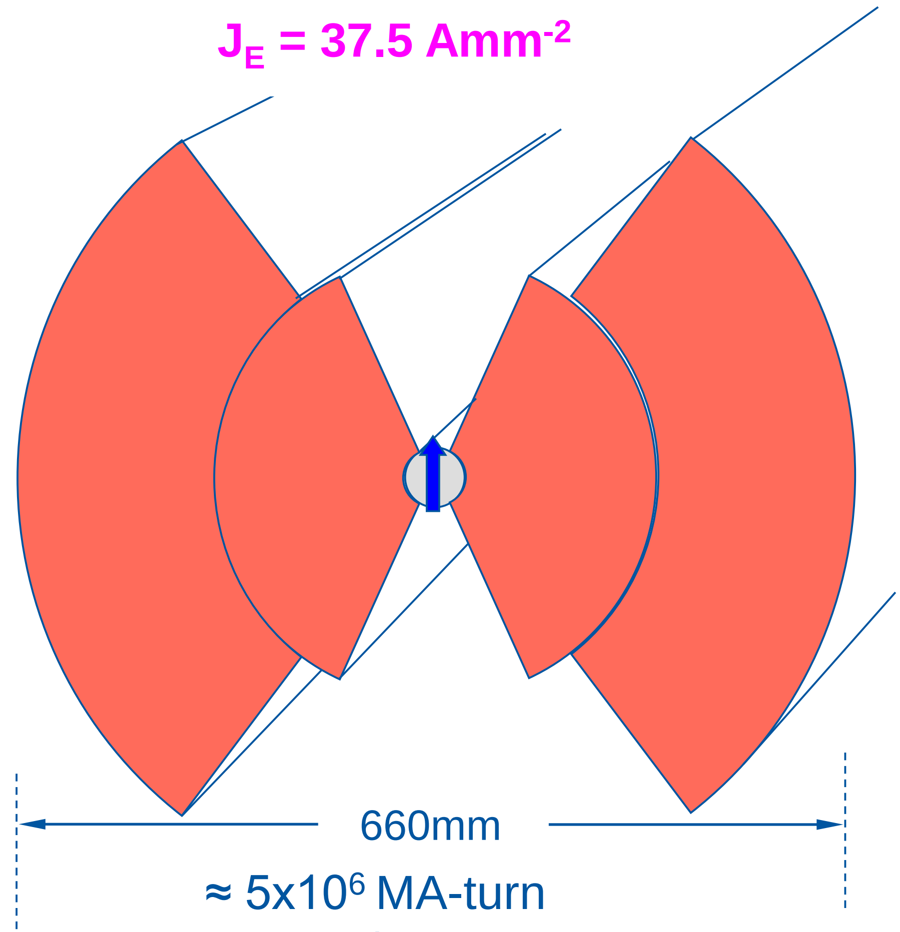
J_E = 375 Amm^{-2}

LHC dipole



≈ 1x10^6 MA-turn

J_E = 37.5 Amm^{-2}

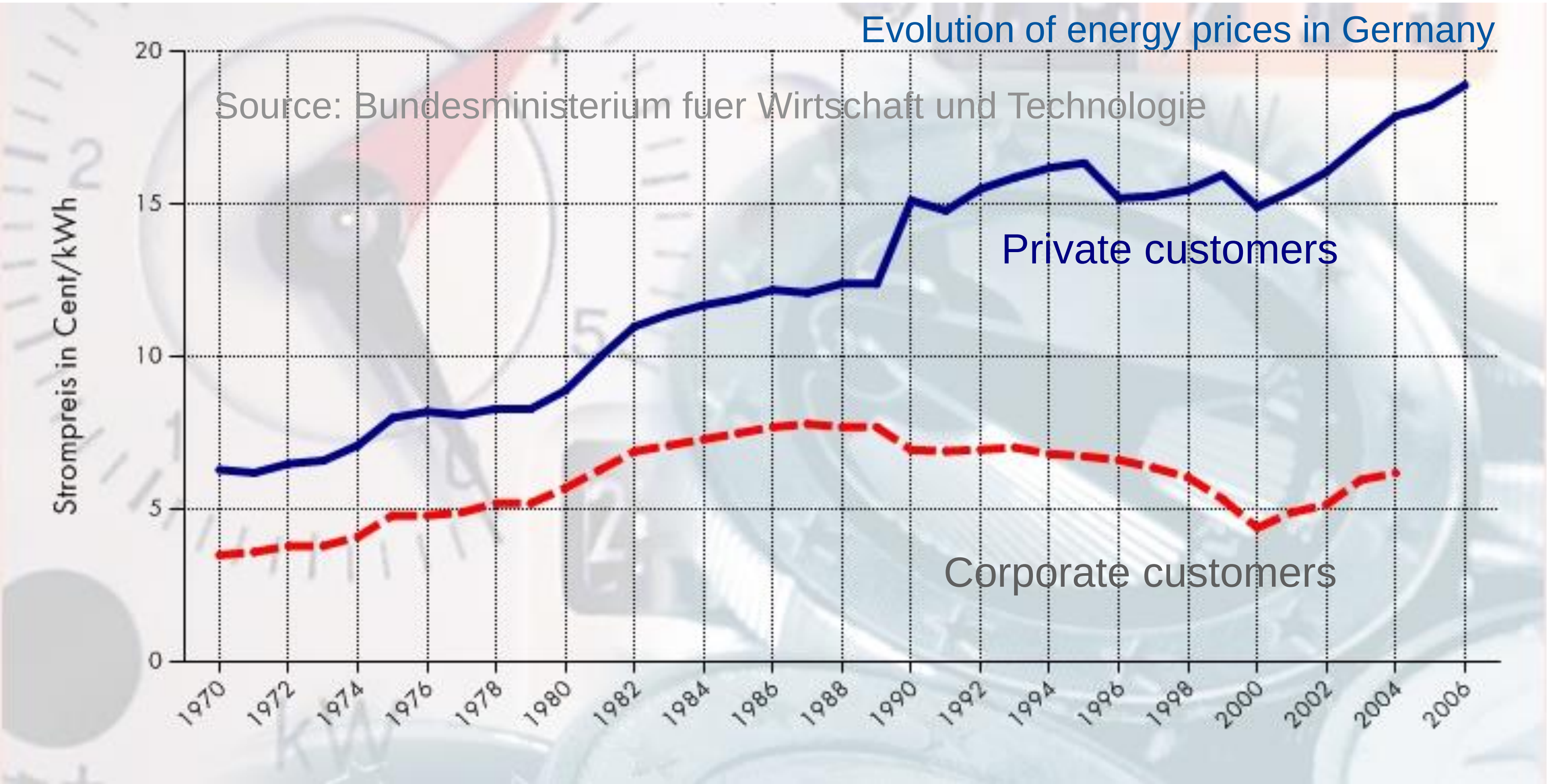


≈ 5x10^6 MA-turn

≈ 6 MW/m

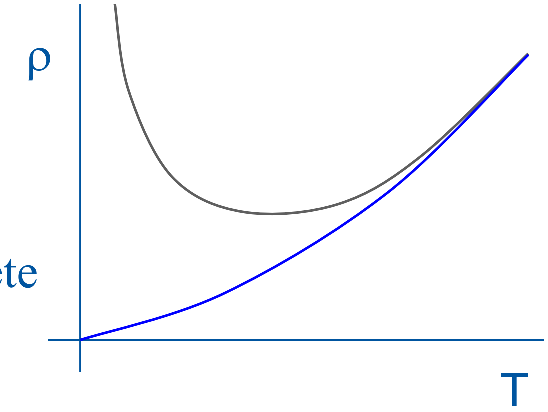
all-SC dipole record field: 16 T (LBNL, 2003 and CERN, 2015)

Cost of energy (electricity)



A great physics problem in 1900

- What is the limit of electrical resistivity at the absolute zero ?



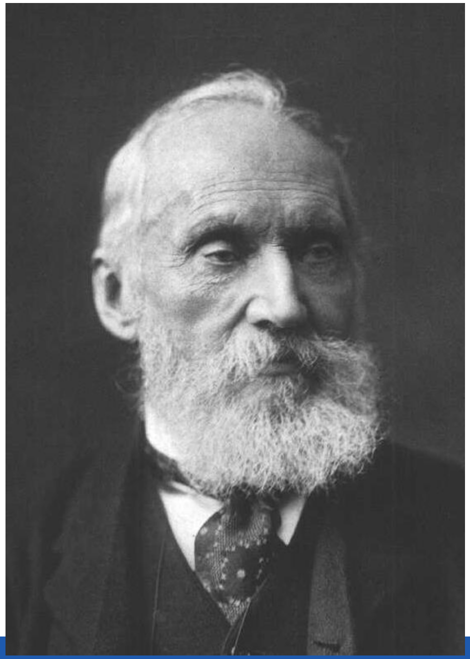
… electrons flowing through a conductor would come to a complete halt or, in other words, metal resistivity will become infinity at absolute zero.

"*X-rays are an hoax*"

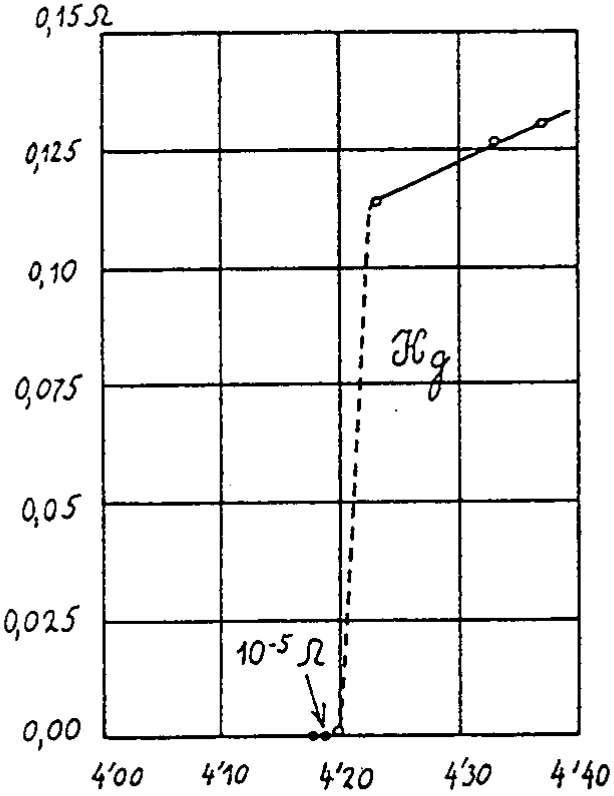
"*I have not the smallest molecule of faith in aerial navigation other than ballooning or of expectation of good results from any of the trials we hear of*"

"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"

W. Thomson (Lord Kelvin)



Superconductors Pre-history



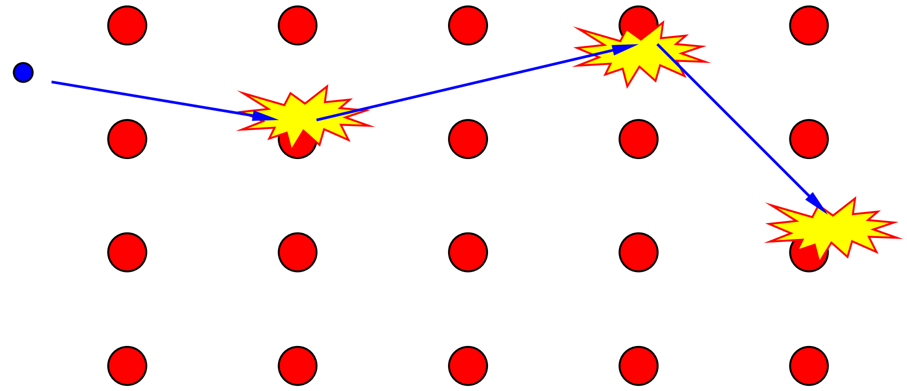
… thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*…

H. Kamerlingh-Onnes (1911)

Cooper Pairs

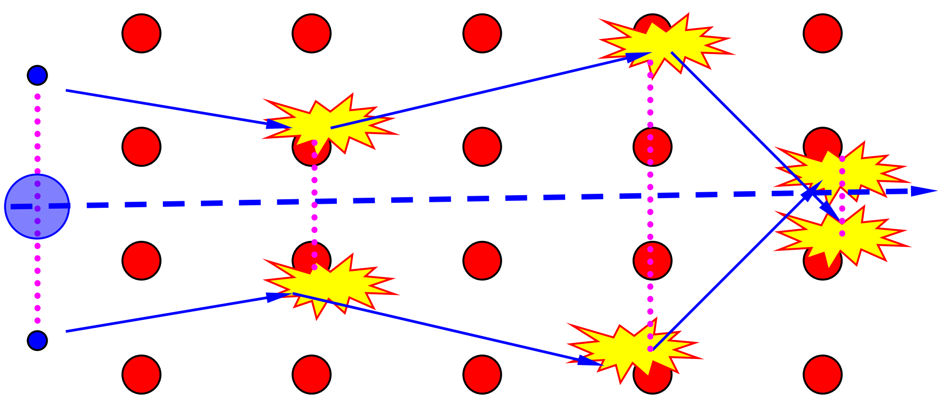
Bardeen, Cooper and Schrieffer

- Normal conductor
  - scattering of e-
  - finite resistance due to energy dissipation



Proper physics: a gas of Fermions. The conduction electrons at the Fermi surface have large energy (few eV) and interact with lattice defects, displacements or thermal excitations (hence $\rho(T)$)

- Superconductor
  - paired electrons forming a quasi particle in *condensed* state
  - zero resistance because the scattering does not excite the quasi-particle



Proper physics: paired electrons in the vicinity of the Fermi surface, with opposite momentum and spin (bosons with zero spin). The binding energy introduces a small energy gap between paired and unpaired state. An external electric field makes the pair drift.

Pairing mechanism

Lattice displacement

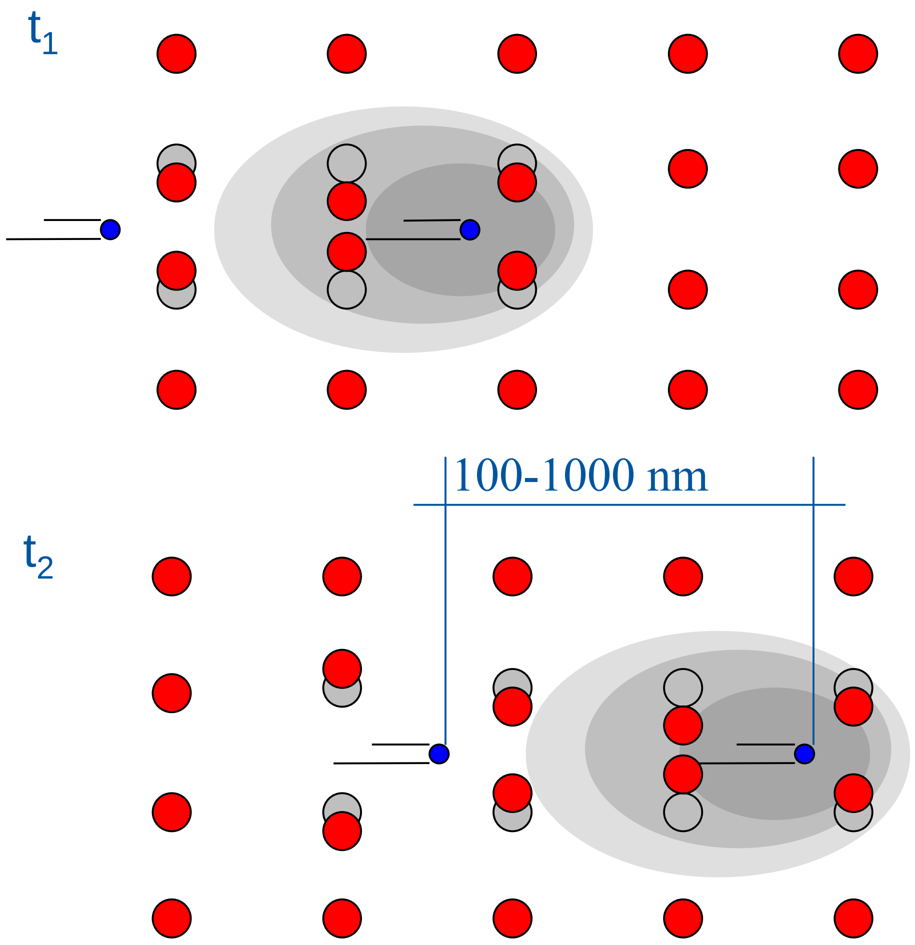
⇓

phonons (sound)

⇓

coupling of charge carriers

Only works at low temperature

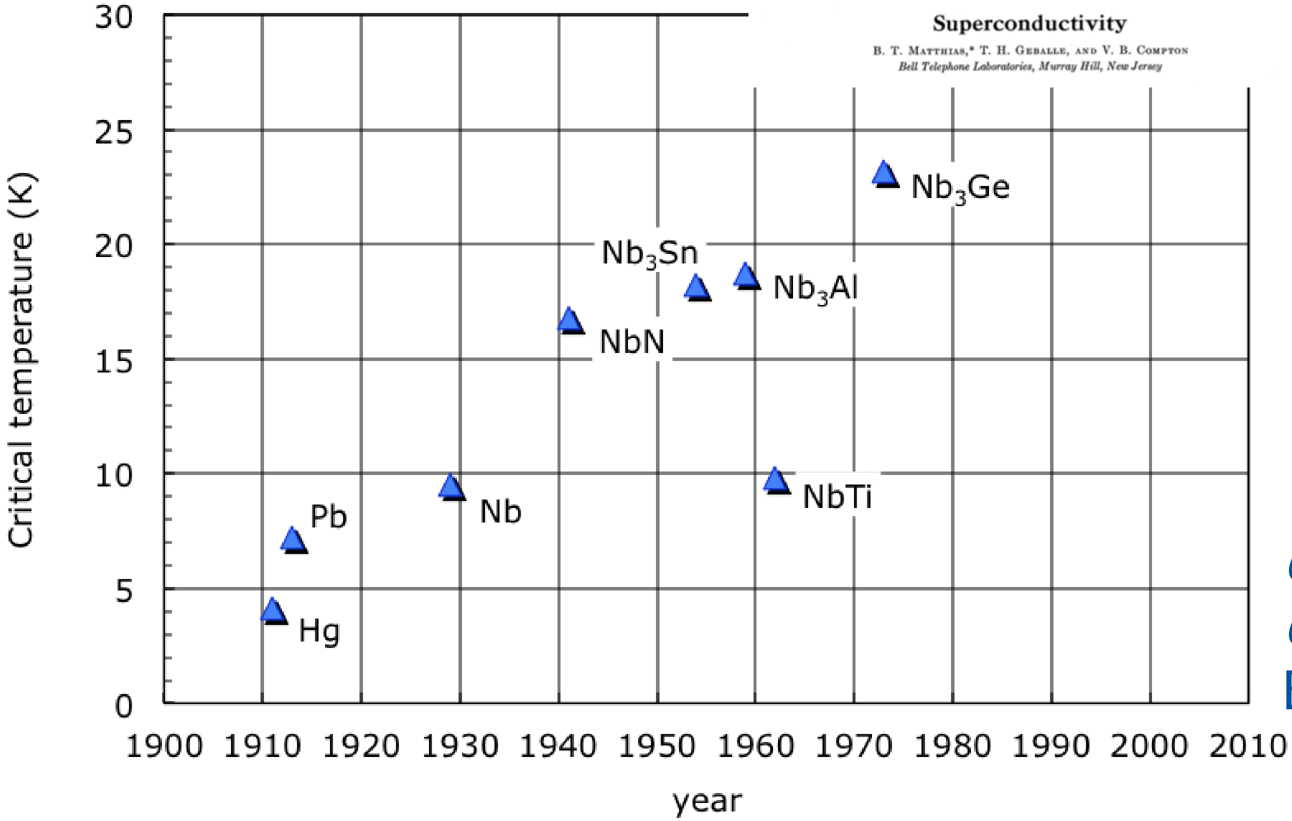


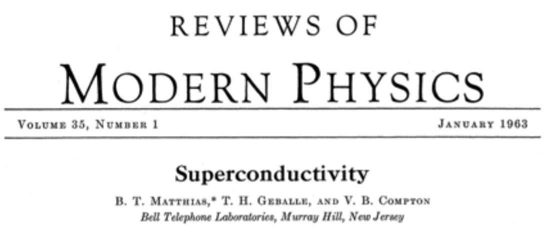
Bardeen, Cooper, Schrieffer (BCS) - 1957

Proper physics: the binding energy is small, of the order of 10^{-3} eV. Pairs can be broken easily by thermal energy. The interaction is long range, and Cooper pairs overlap and can exchange electrons

Flourishing of materials, but depressing Tc…

Theoretical limit
around **30 K**




REVIEWS OF
MODERN PHYSICS
VOLUME 35, NUMBER 1 JANUARY 1963

Superconductivity

B. T. MATTHIAS,* T. H. GEBALLE, AND V. B. COMPTON
Bell Telephone Laboratories, Murray Hill, New Jersey

One Thousand and One Superconductors
B. Matthias (1918-1980)

Superconductivity was a *physicist playground* till the late 1950's

Practical superconductors

Cu

J_e ~ 5 A/mm^2

I ~ 3 A

B = 2 T

Nb-Ti

J_e ~ 600-700 A/mm^2

I ~ 300-400 A

B = 8-9 T

Nb_3Sn

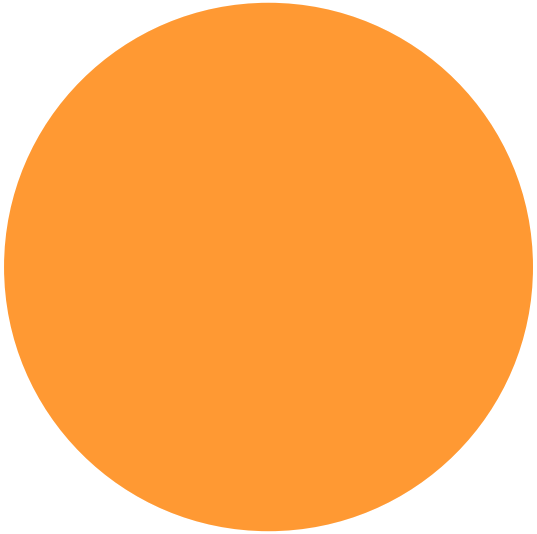
J_e ~ 600-700 A/mm^2

I ~ 300-400 A

B = 12-13 T

Practical superconductors

Cu



J_e ~ 5 A/mm²

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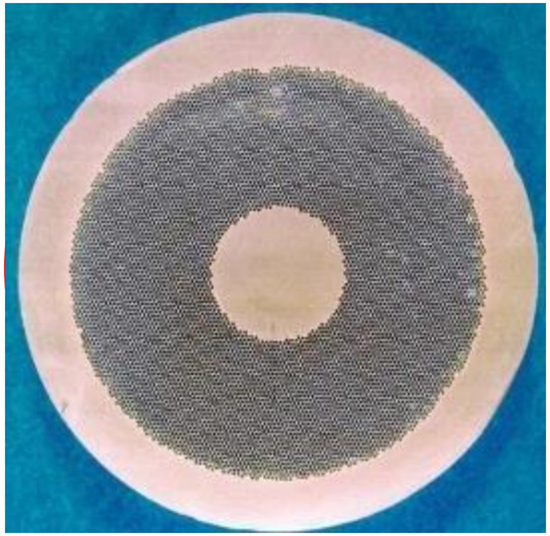
Nb-Ti

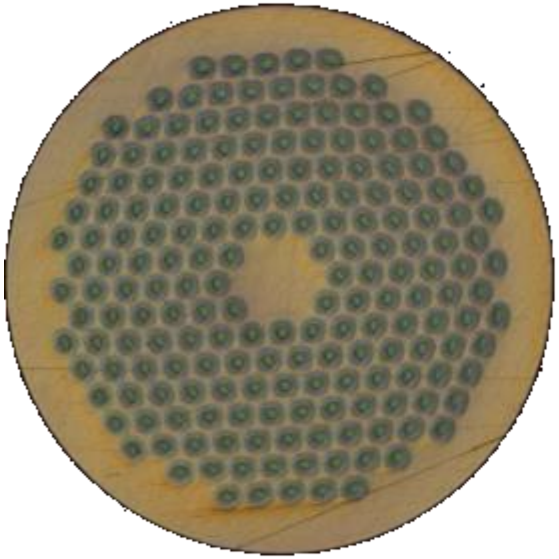


J_e ~ 600-700 A/mm²

I ~ 300-400 A

B = 8-9 T

Nb_3Sn



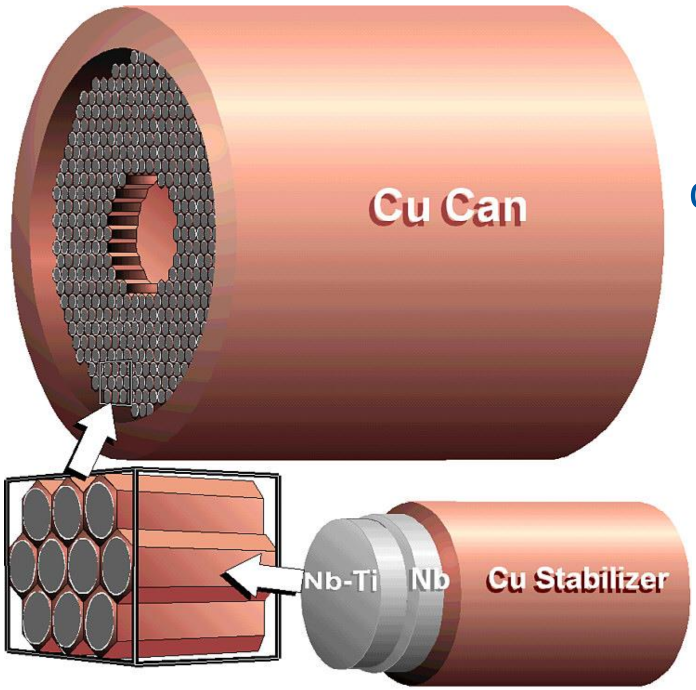
J_e ~ 600-700 A/mm²

I ~ 300-400 A

B = 12-13 T

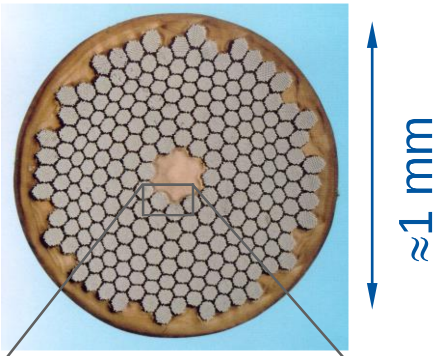
Nb-Ti manufacturing

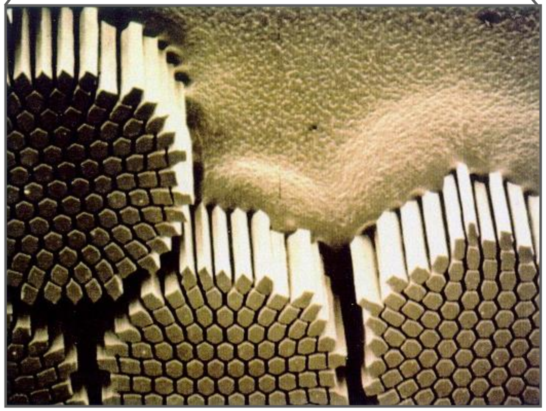
NbTi billet



extrusion
cold drawing
heat
treatments

$I_C(5\ T, 4.2\ K) \approx 1\ kA$

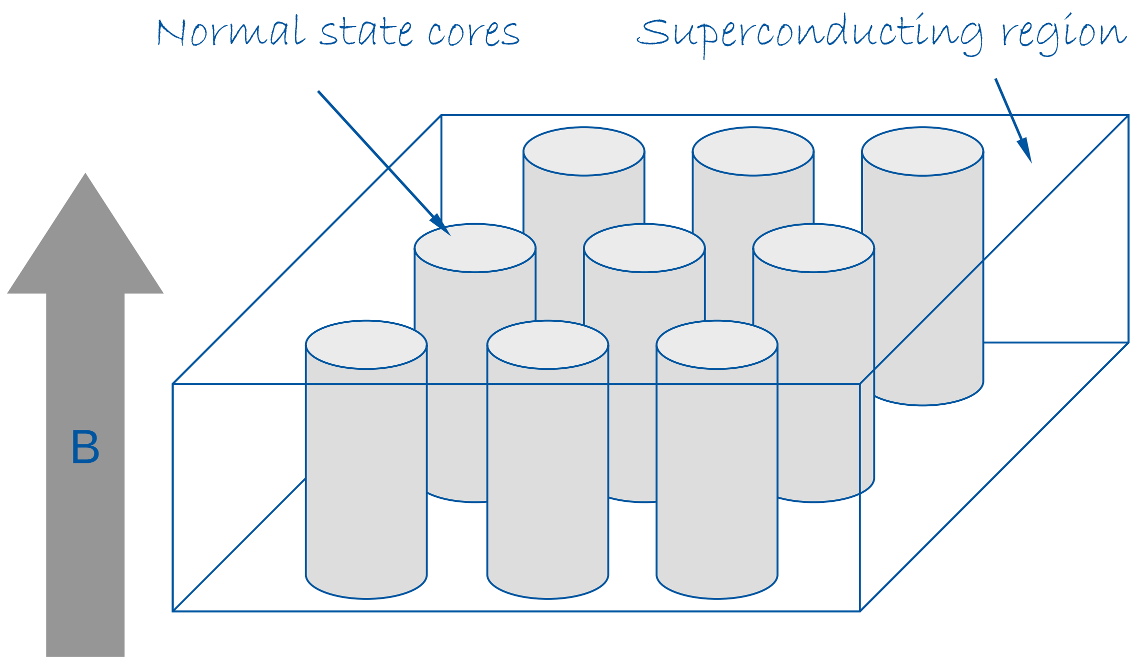


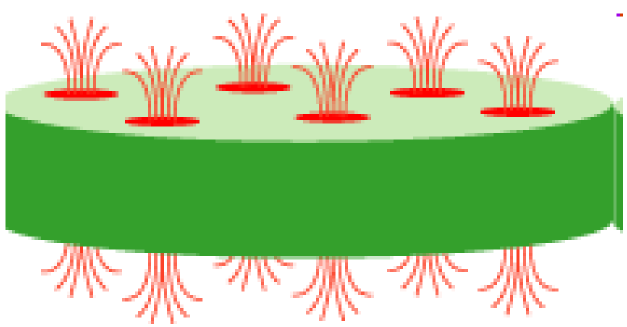


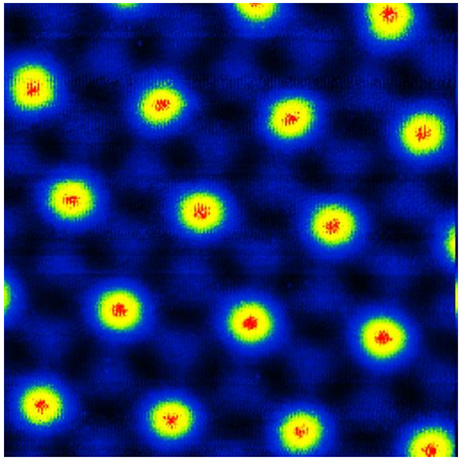
LHC wire

NbTi is a ductile alloy that can sustain large deformations

Type II Superconductors ($\xi < \lambda$)







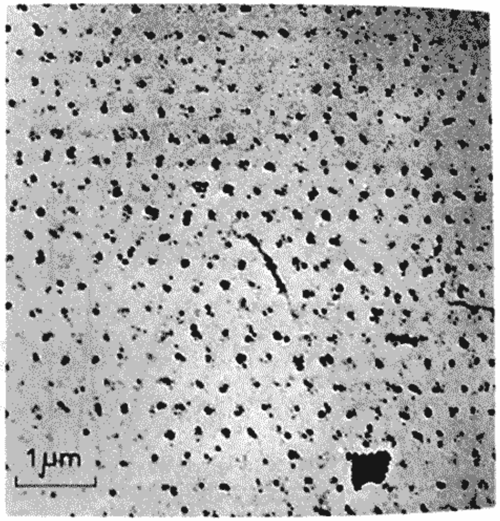


Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

Hey, what about current ?

- A current flowing in a magnetic field is subject to the Lorentz force that deviates the charge carriers:

$$\mathbf{F} = \mathbf{J} \times \mathbf{B}$$

- This translates into a *motion of the fluxoids* across the superconductor $\Rightarrow$ energy dissipation $\Rightarrow$ loss of superconductivity
- To carry a significant current we need to *lock the fluxoids* so to resist the Lorentz force. For this we mess-up the material and create **pinning centers** that exert a pinning force F_P

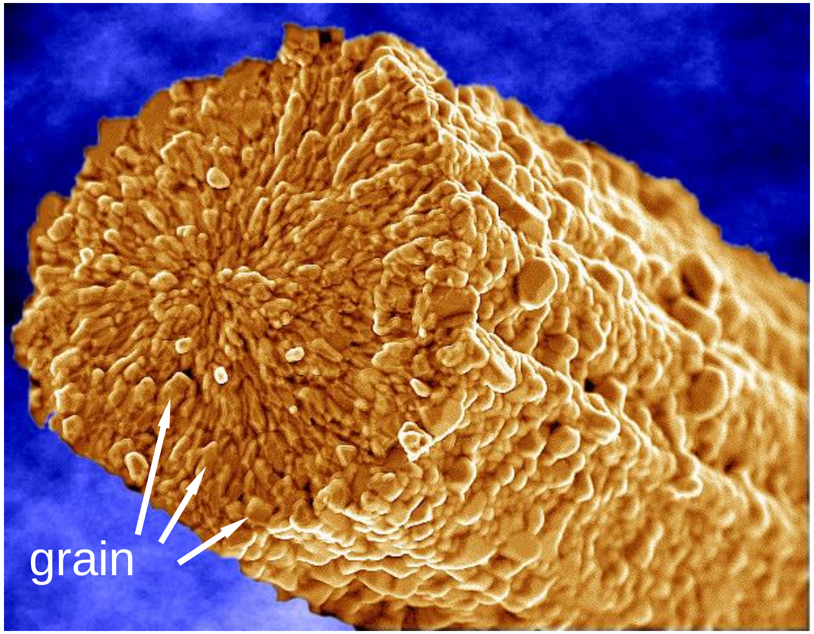
Graphics by courtesy of Applied Superconductivity Center at NHMFL

Pinning centers

Precipitates in alloys

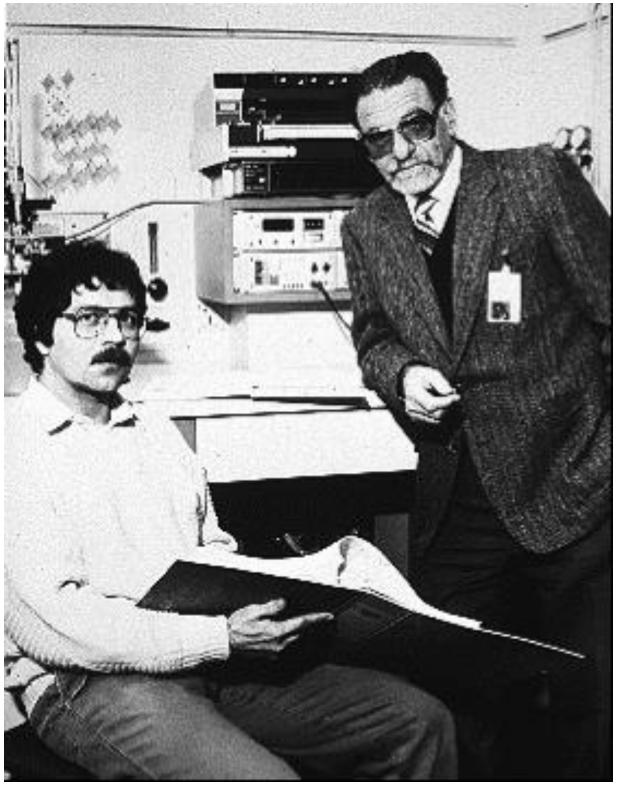
Grain boundaries in inter-metallic compounds

Microstructure of Nb-Ti

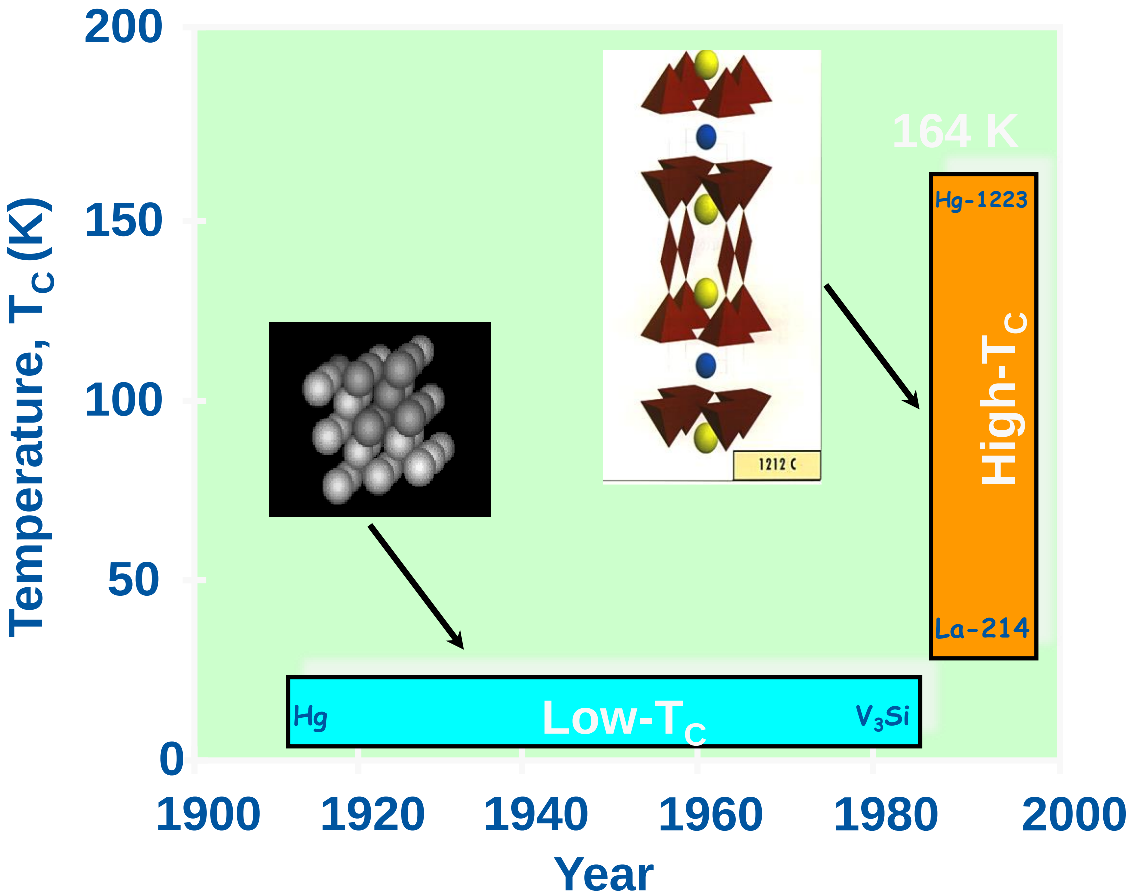


Microstructure of Nb_3Sn

1986 - A Big Surprise



Bednorz and Mueller
IBM Zuerich, 1986



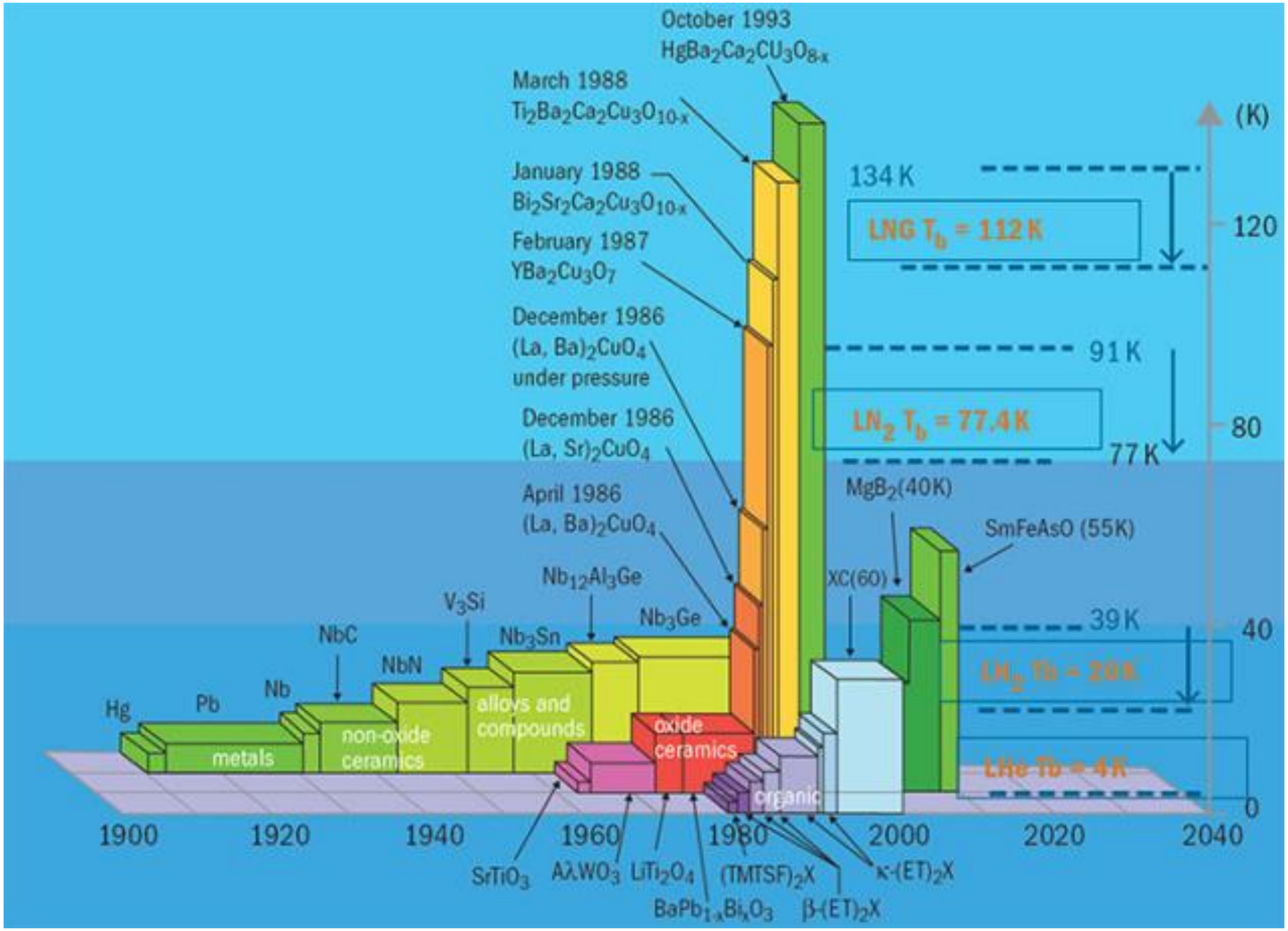
1987 - The prize !

Associated Press

J. Georg Bednorz, left, and K. Alex Müller after learning they had won the Nobel Prize in physics.

2 Get Nobel for Unlocking Superconductor Secret

High-Tc timeline – not over yet !



A summary of technical materials

HE-LHC
FCC

		LTS				HTS	
Material		Nb-Ti	Nb_3Sn	Nb_3Al	MgB_2	YBCO	BSCCO
Year of discovery		1961	1954	1958	2001	1987	1988
Tc	(K)	9.2	18.2	19.1	39	≈93	95(*) 108(#)
Bc	(T)	14.5	≈30	33	36…74	120(†) 250(‡)	≈200

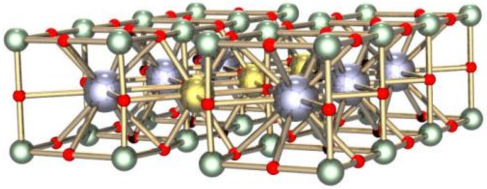
HL-LHC

Superconducting power cables

NOTES:
(†) B parallel to *c*-axis
(‡) B parallel to *ab*-axes
(*) BSCCO-2212
(#) BSCCO-2223

Tevatron
HERA
RHIC
LHC

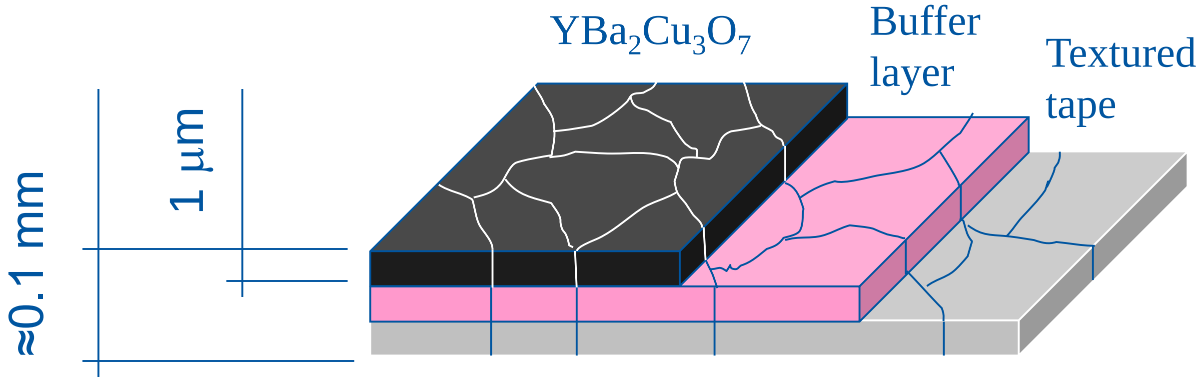
YBCO manufacturing ro



YBCO has excellent critical properties, but grains do not align during processing. If grains are not aligned the supercurrent cannot jump between the grains. All manufacturing processes force a certain degree of alignment in the microstructure

- produce a tape with an aligned texture
- coat the tape with a buffer layer
- coat the buffer with a layer $YBa_2Cu_3O_7$ such that the texture of the YBCO follows that of the buffer and substrate

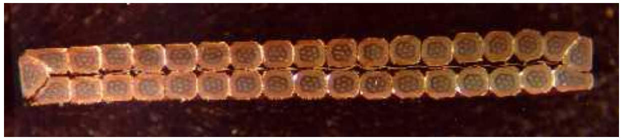
All routes use ion deposition techniques (laser, plasma) in vacuum (cost, length)

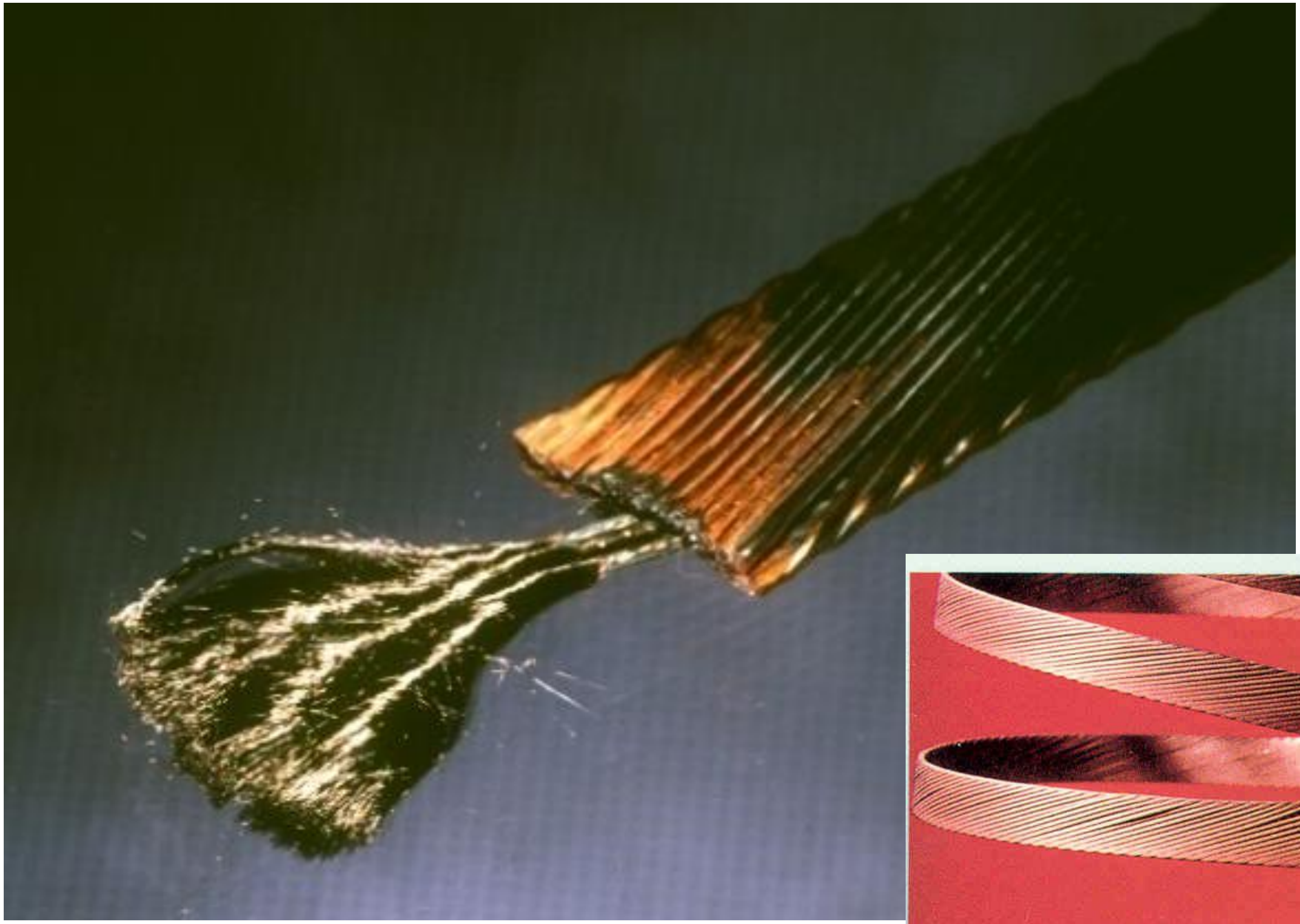


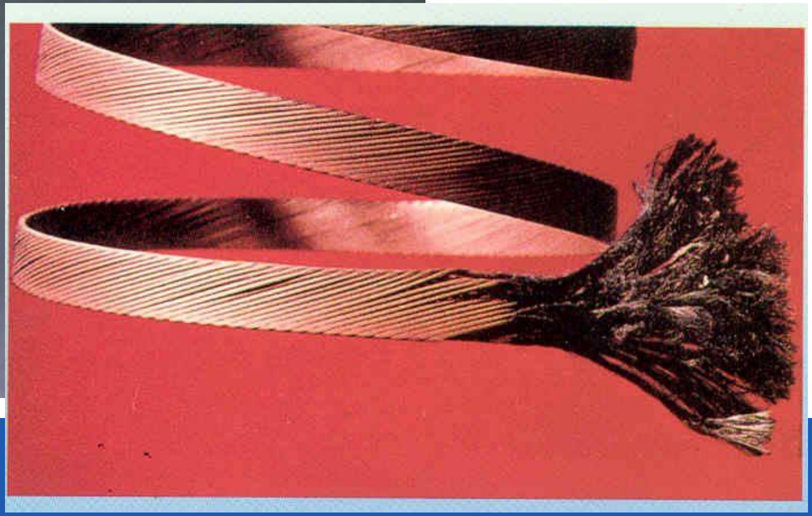
YBCO production: high-tech

Work in clean-room conditions, costly processing of long lengths

Rutherford cable



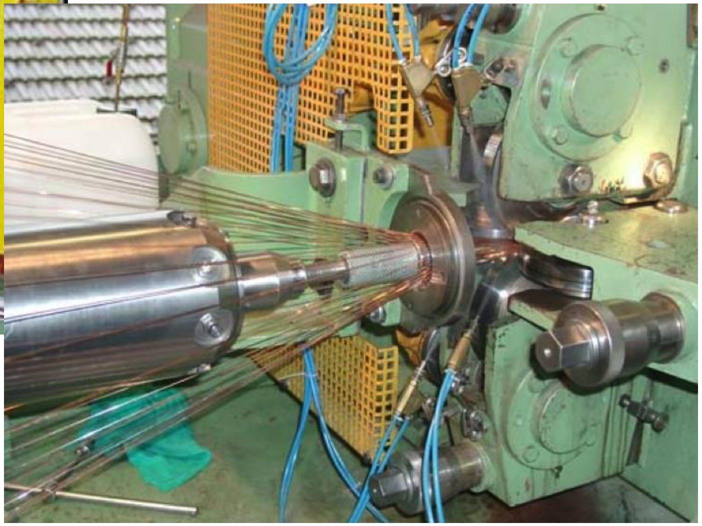




Rutherford cable machine @ CERN

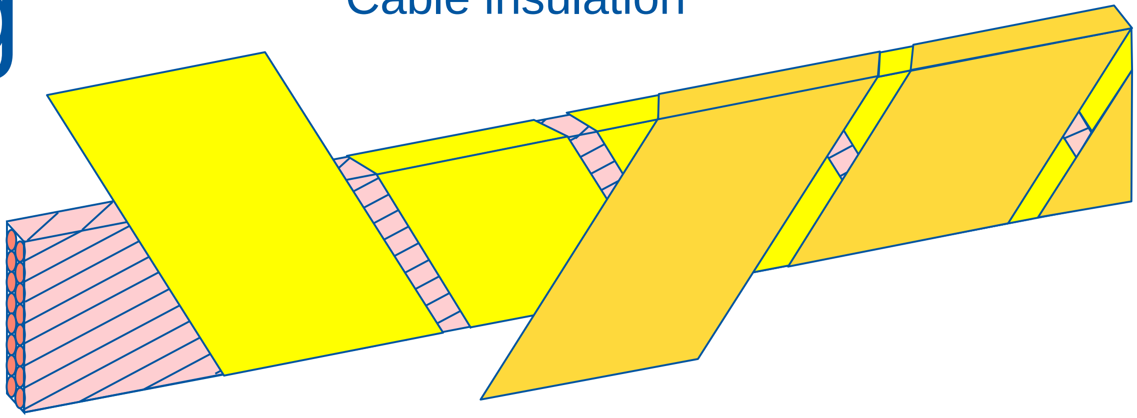
Strand spools on rotating tables

Strands fed through a cabling tongue to shaping rollers

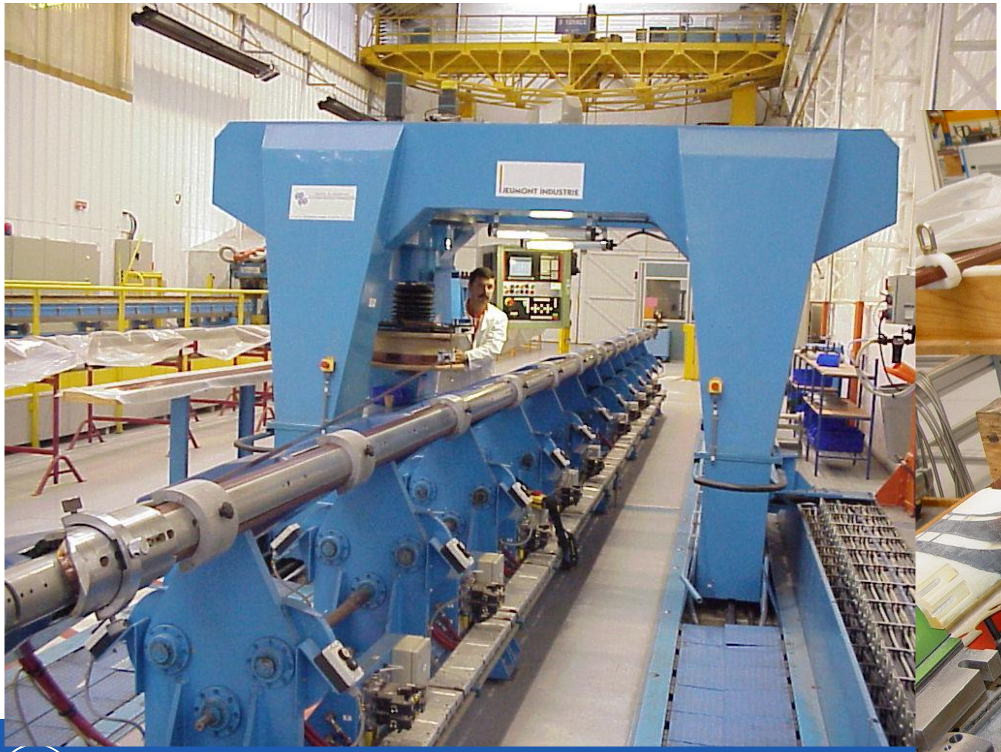


Coil winding

Cable insulation



10 μm precision !



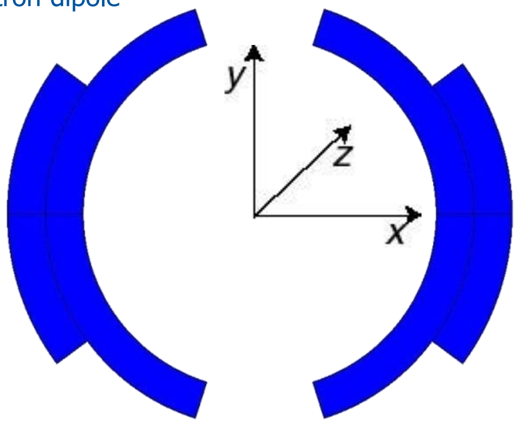
Coil winding machine

Stored coils

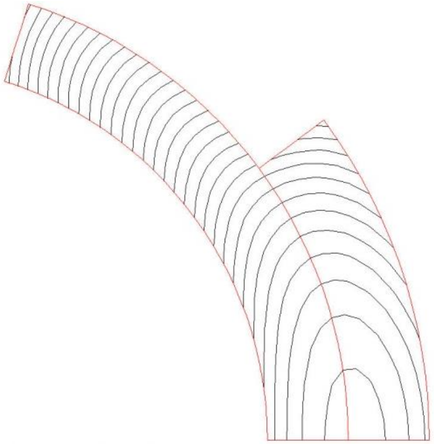
Electromagnetic forces - dipole

- The electromagnetic forces in a dipole magnet tend to push the coil:
  - Vertically, towards the mid plane (Fy < 0)
  - Horizontally, outwards (Fx > 0)

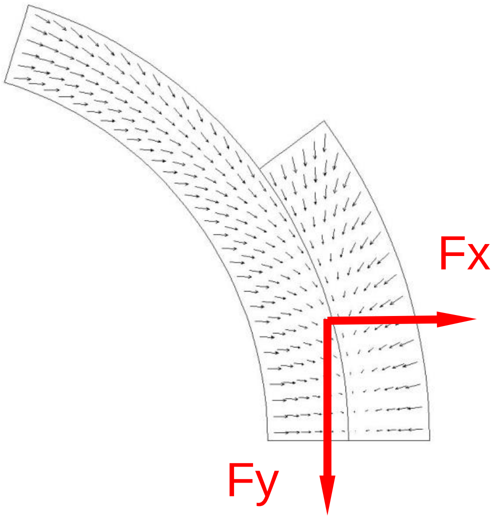
Tevatron dipole



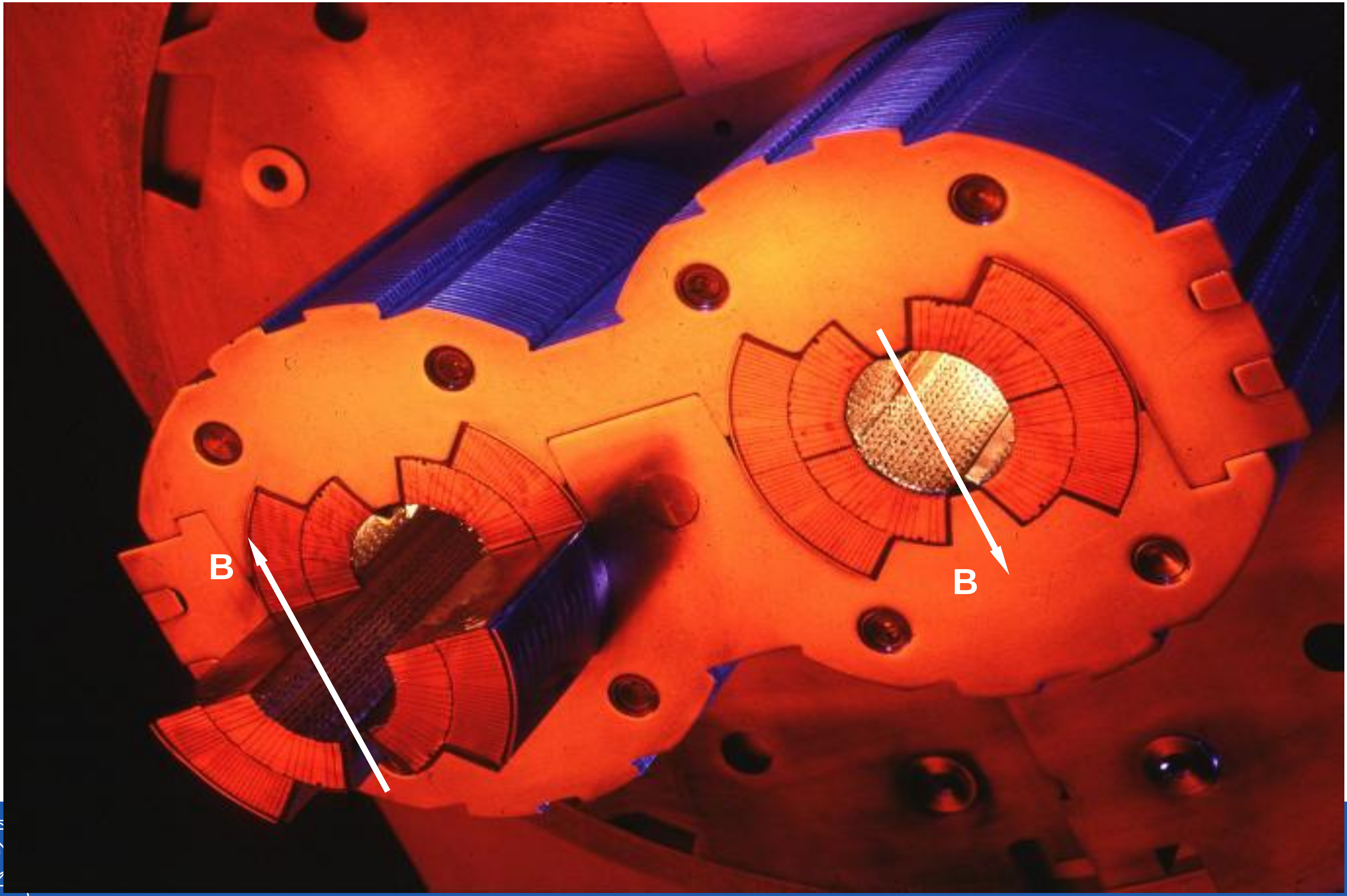
Field



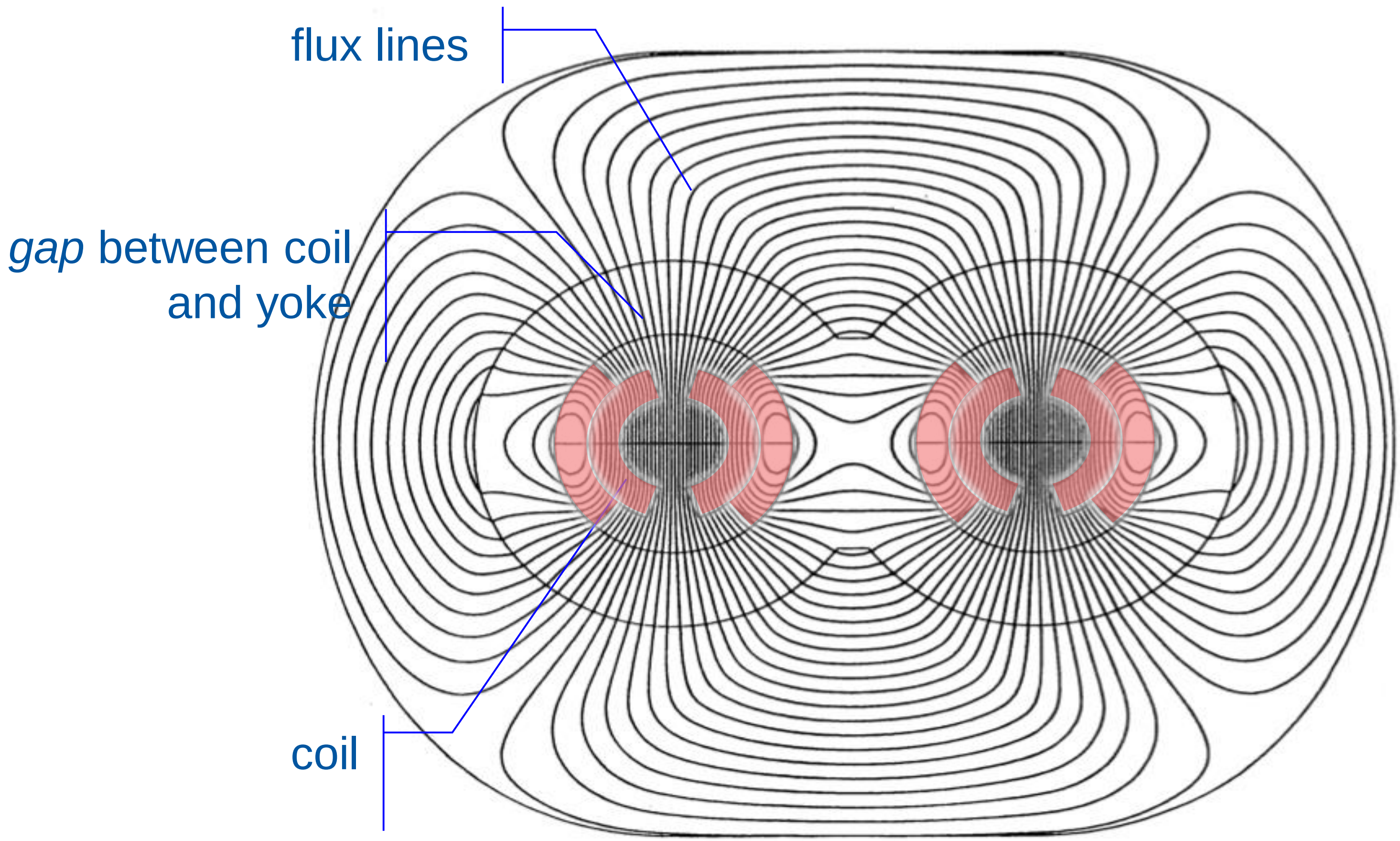
Force



LHC dipole coils



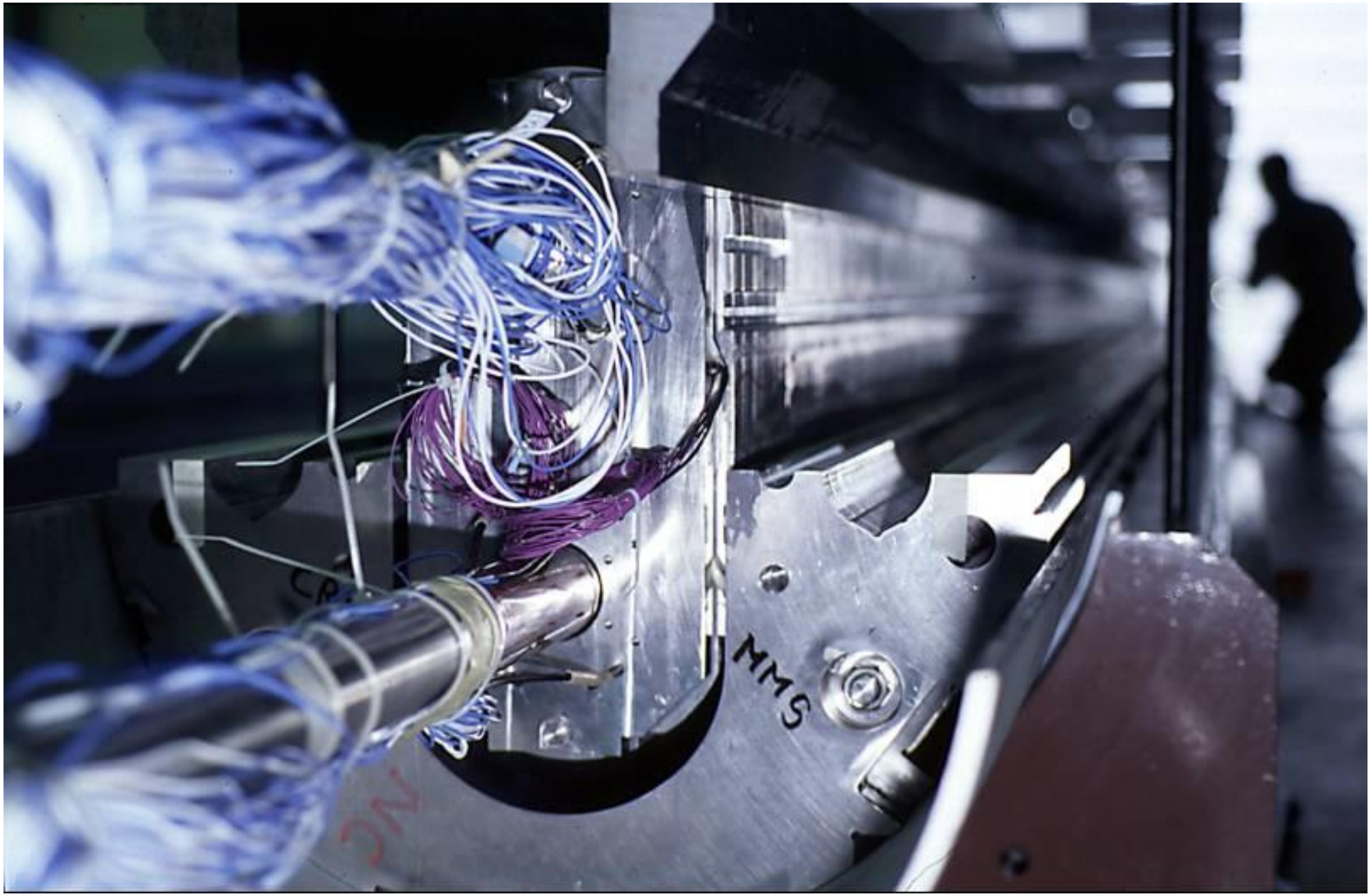
Iron to close the magnetic circuit



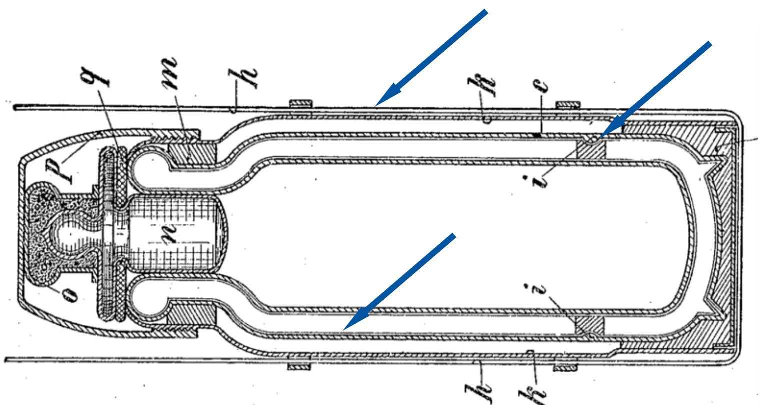
CERN 87-05, G. Brianti and K. Hubner Ed.

G. Brianti

LHC Iron yoke

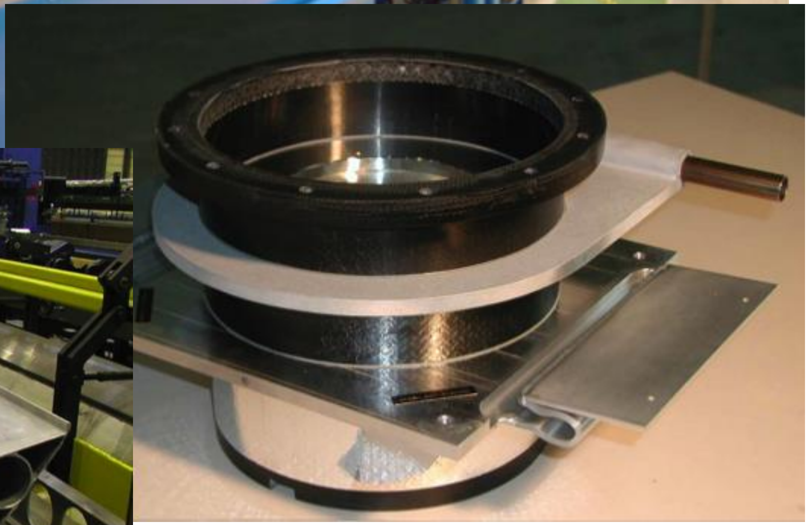


Cryostat



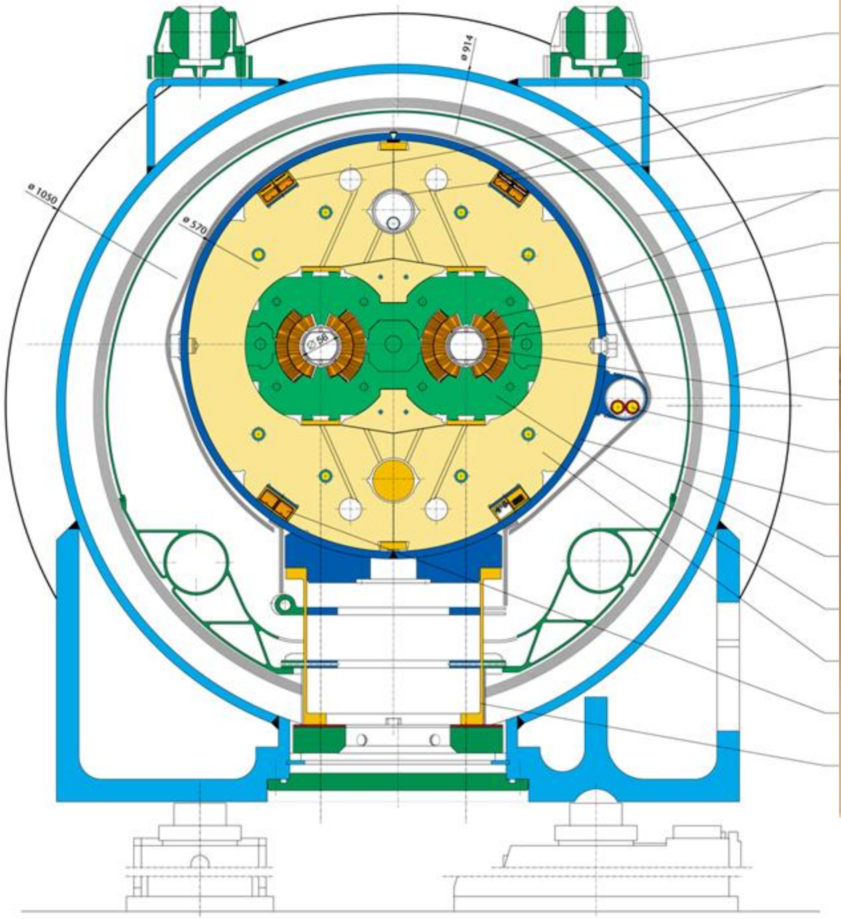
Vacuum enclosure

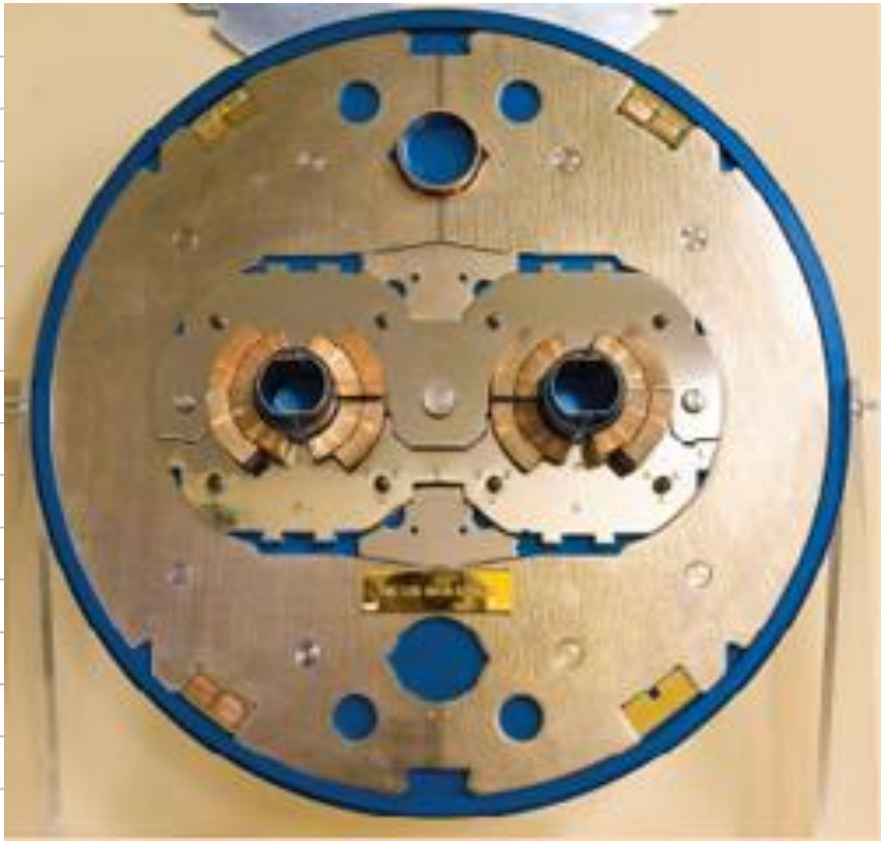
Thermal screens



Low conduction foot

The LHC dipole





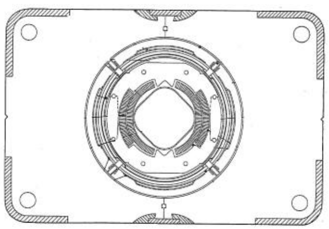
CERN AC/DI/MM - HE107 - 30 04 1999

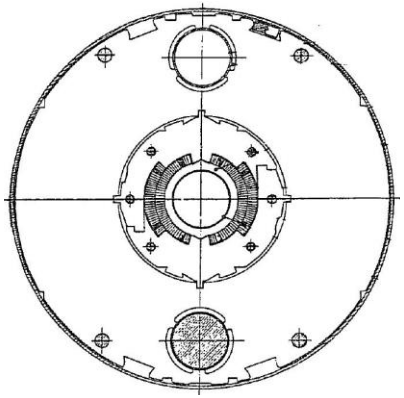
The *Hall of Fame* of SC colliders

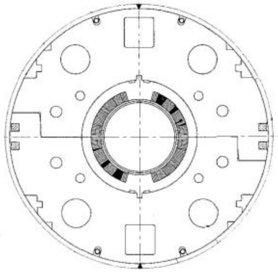
		Tevatron	HERA	RHIC	LHC
Maximum energy	(GeV)	980	920(1)	250(2) 100/n(3)	7000
Injection energy	(GeV)	151	45	12	450
Ring length	(km)	6.3	6.3	3.8	26.7
Dipole field	(T)	4.3	5.0	3.5	8.3
Aperture	(mm)	76	75	80	56
Configuration		Single bore	Single bore	Single bore	Twin bore
Operating temperature	(K)	4.2	4.5	4.3-4.6	1.9
First beam		7-1983	4-1991	6-2000	9-2008

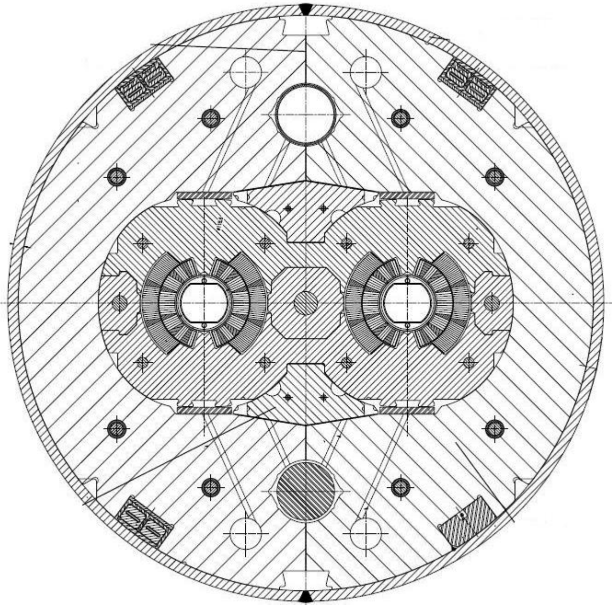
(1) energy of the proton beam, colliding with the 27.5 GeV electron beam
(2) energy for proton beams
(3) energy per nucleon, for ion beams (Au)

Champion dipoles cross sections









Tevatron
Bore: 76 mm
Field: 4.3 T

HERA
Bore: 75 mm
Field: 5.0 T

RHIC
Bore: 80 mm
Field: 3.5 T

LHC
Bore: 56 mm
Field: 8.3 T

Tevatron at FNAL (Chicago, USA)

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

HERA at DESY (Hamburg, D)

Image by courtesy of Deutsches Elektronen Synchrotron

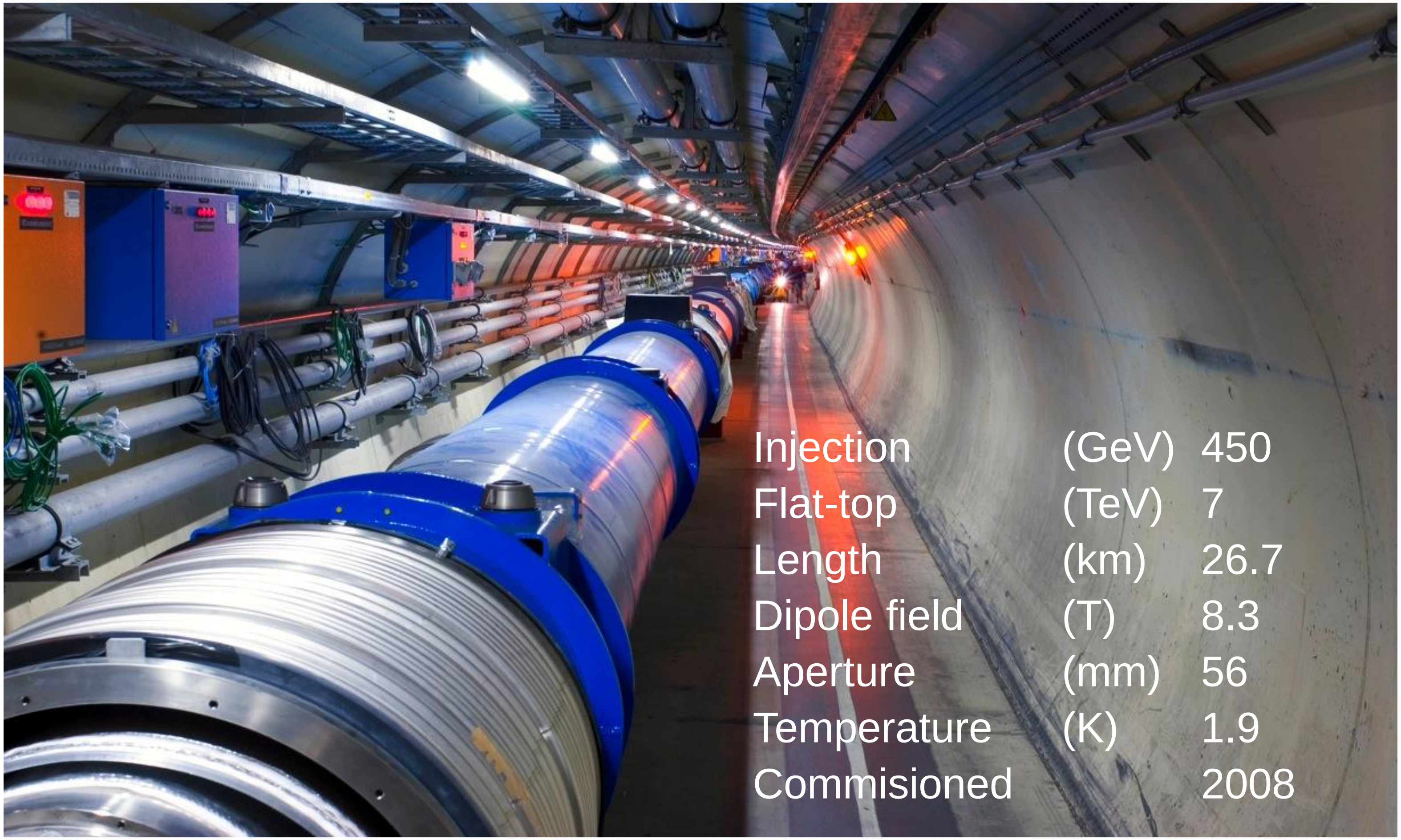
Injection	(GeV)	45
Flat-top	(GeV)	920
Length	(km)	6.3
Dipole field	(T)	4.7
Aperture	(mm)	75
Temperature	(K)	4.5
Commisioned		1991
Closed		2007

RHIC at BNL (Upton, NY, USA)

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

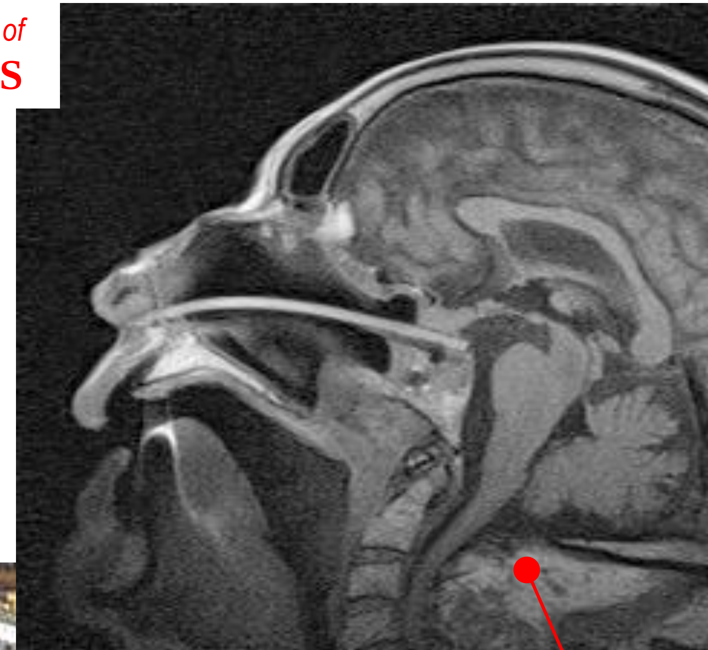
LHC at CERN (Geneva, CH)

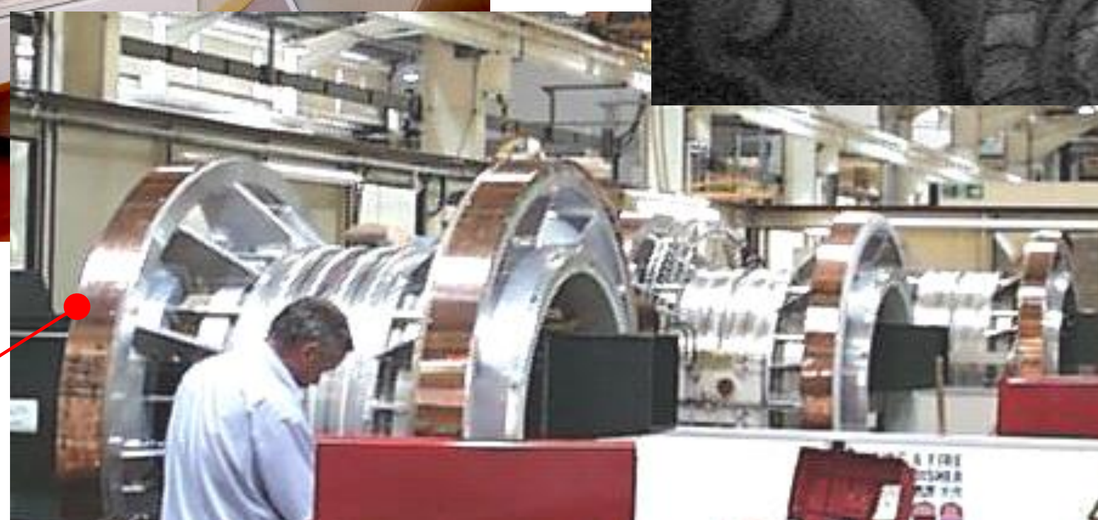


Injection	(GeV)	450
Flat-top	(TeV)	7
Length	(km)	26.7
Dipole field	(T)	8.3
Aperture	(mm)	56
Temperature	(K)	1.9
Commisioned		2008

Magnetic Resonance Imaging

photos courtesy of
SIEMENS





patient's view

engineer's view

surgeon's view

photo courtesy of
OXFORD
Magnet Technology

NMR spectroscopy

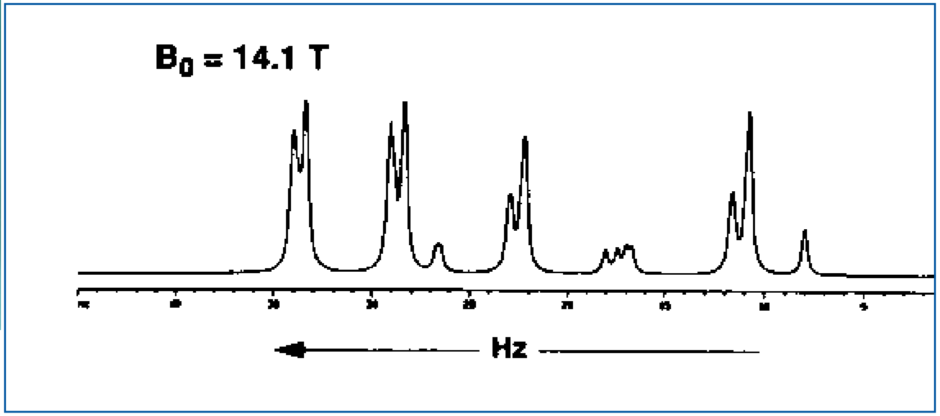
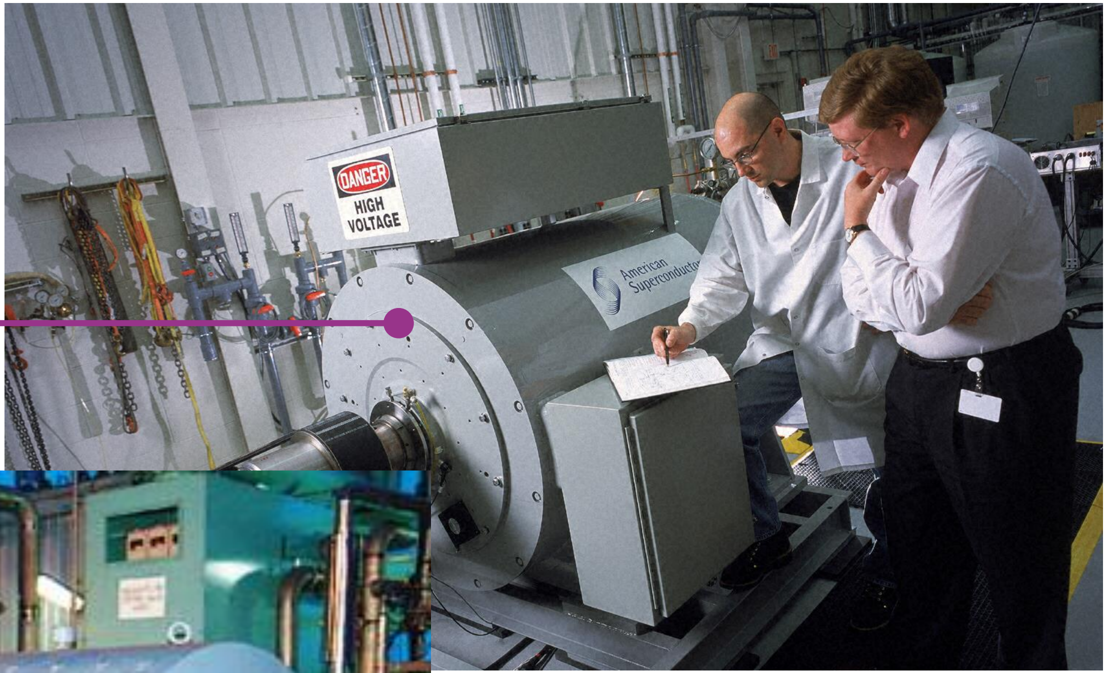


photo courtesy of
OXFORD
Magnet Technology

Motors & generators



Motor with HTS rotor

American Superconductor and Reliance

700 MW generator

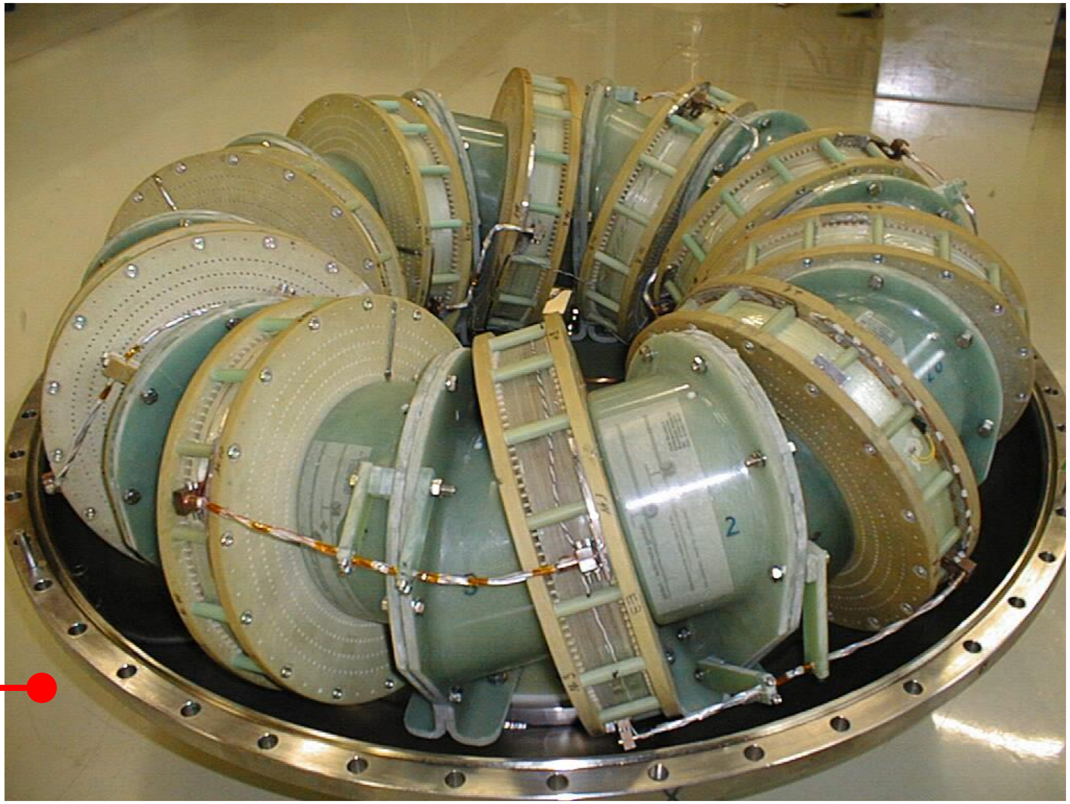
NbTi rotor

Hitachi, Toshiba, Mitsubishi

Transformers & energy storage

HTS Transformer
630 kVA,   18.7kV to 0.42 kV

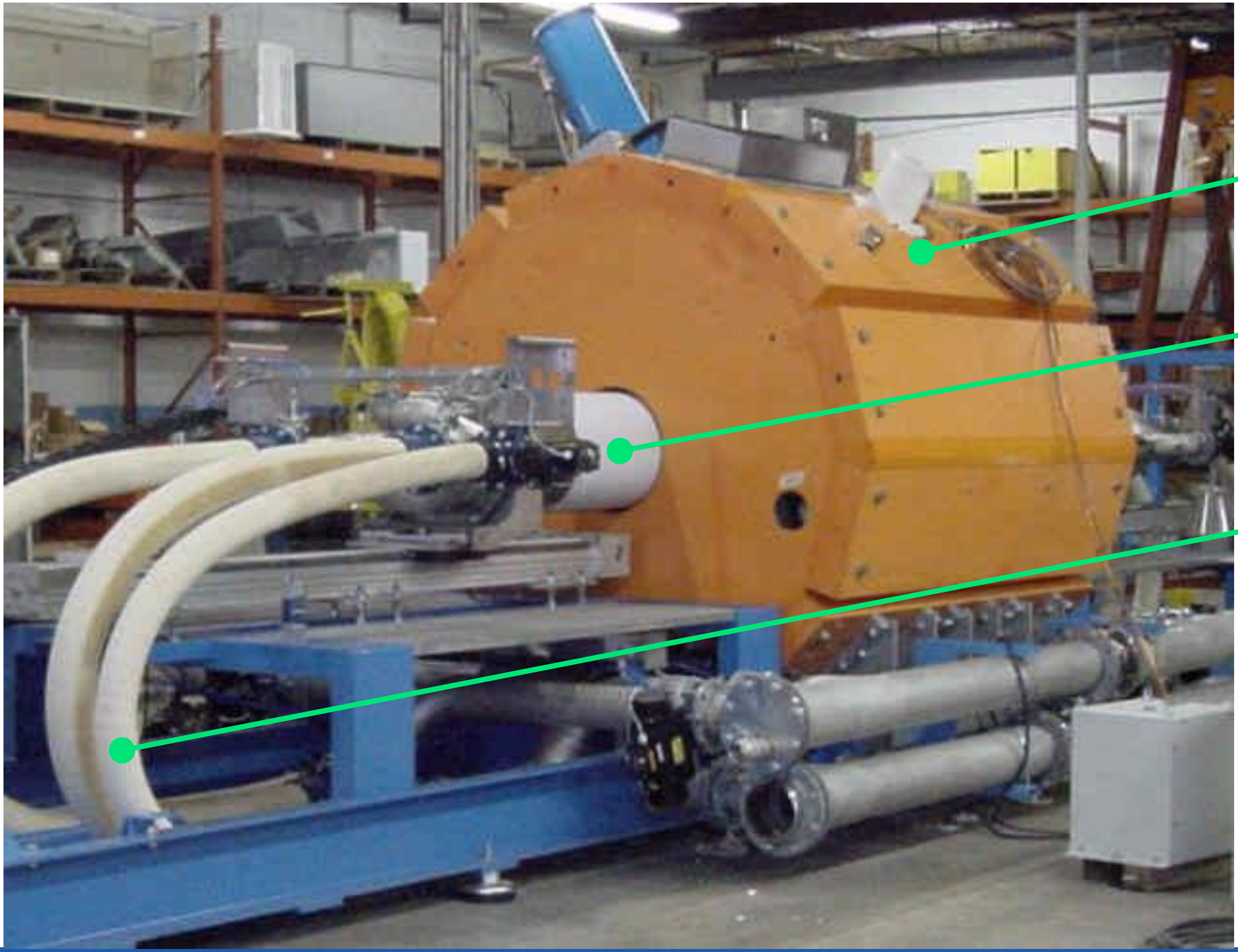
ABB



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

KfZ Karlsruhe

Magnetic separation

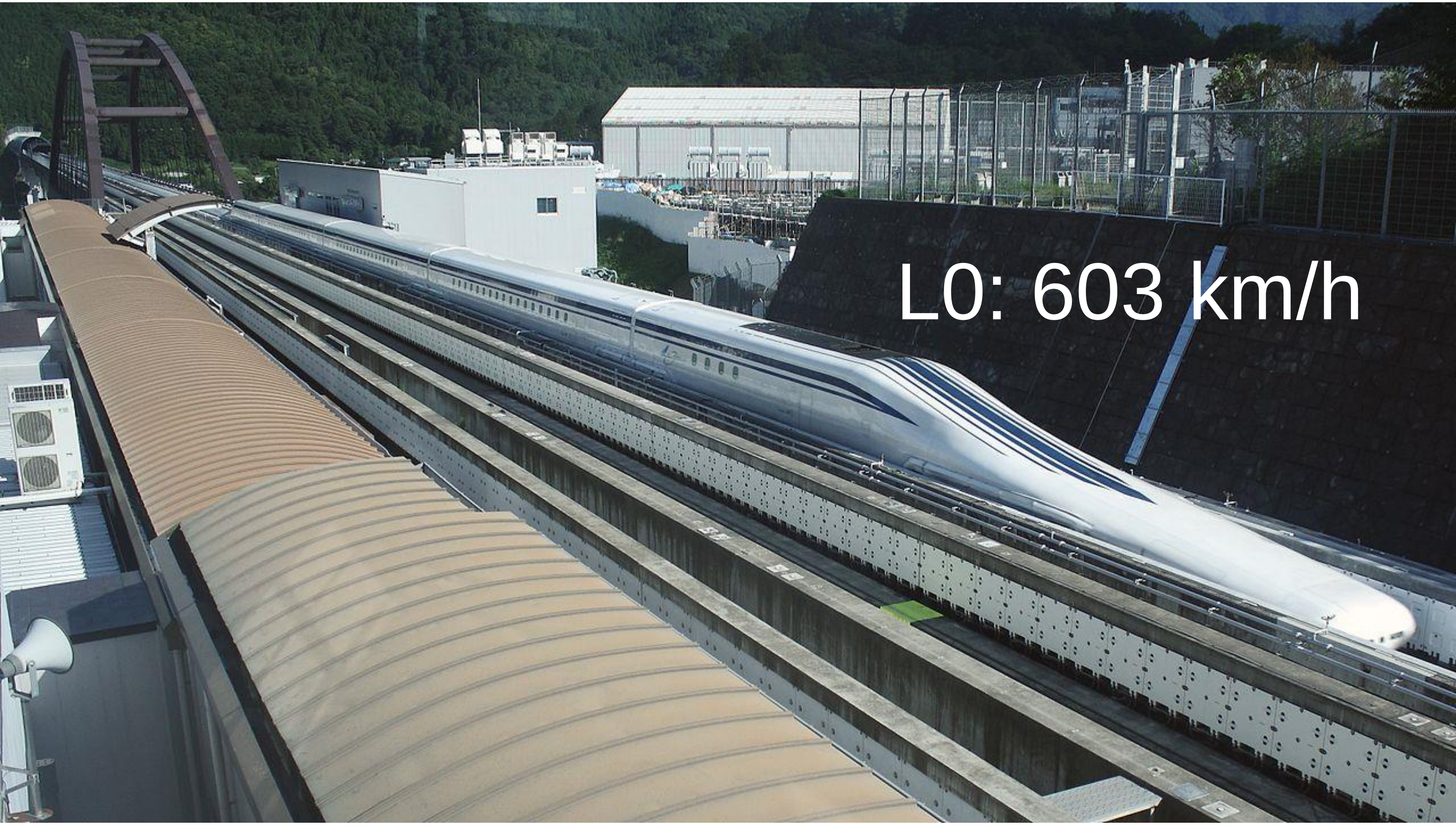


superconducting solenoid, enclosed within iron shield

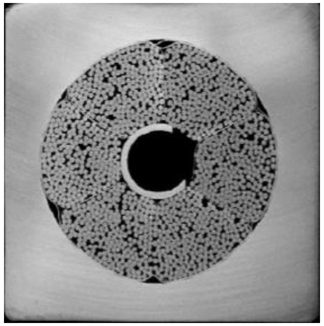
stainless steel canister containing ferromagnetic mesh

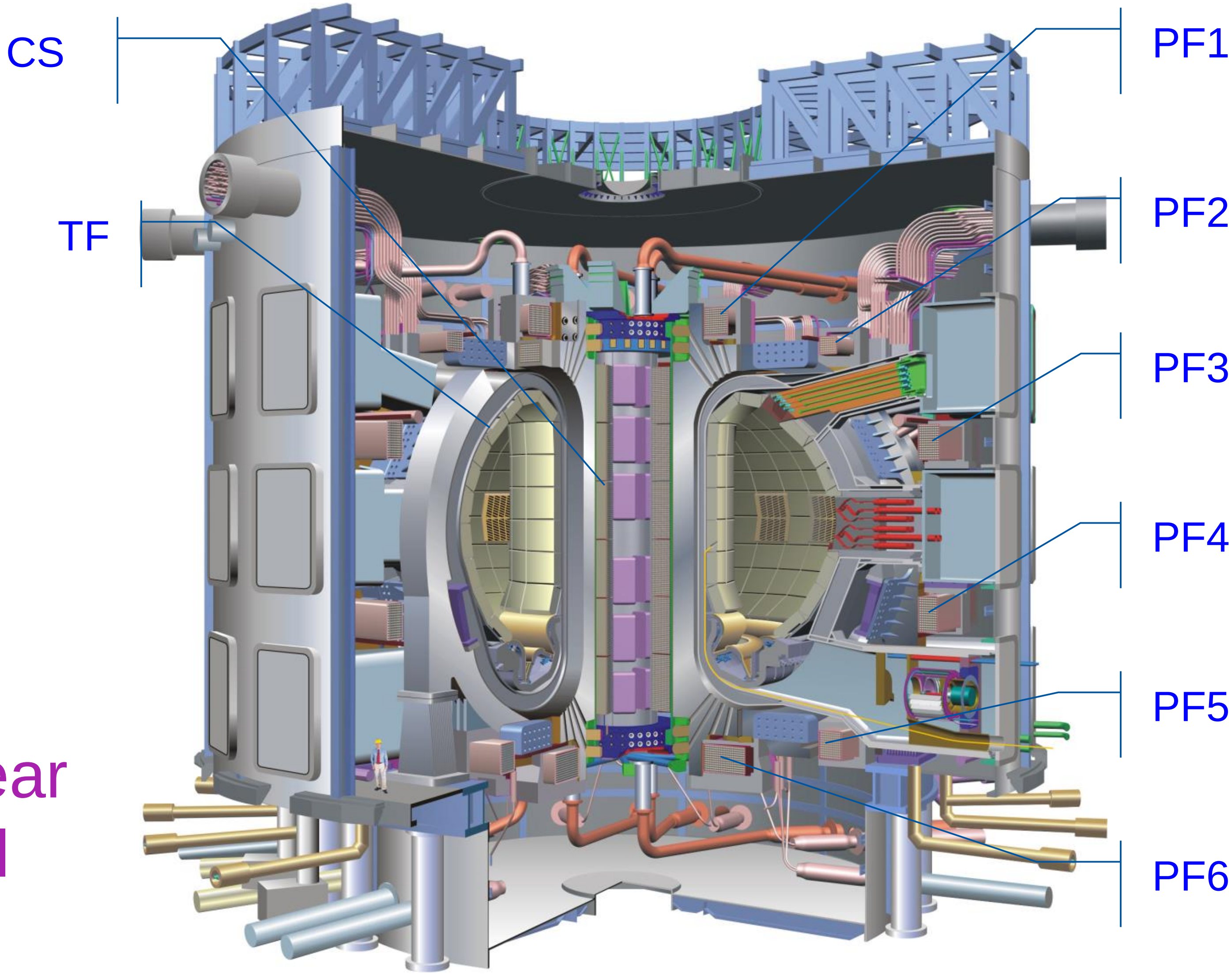
pipes feeding the kaolin slurry for separation

Transportation



Thermonuclear fusion





ITER

International
Thermonuclear
Experimental
Reactor

Other uses of superconductivity

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
it merely just hokum
this question, but yo
oil, like in the Joh

We have a big intere
subsequently, but fi

(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.

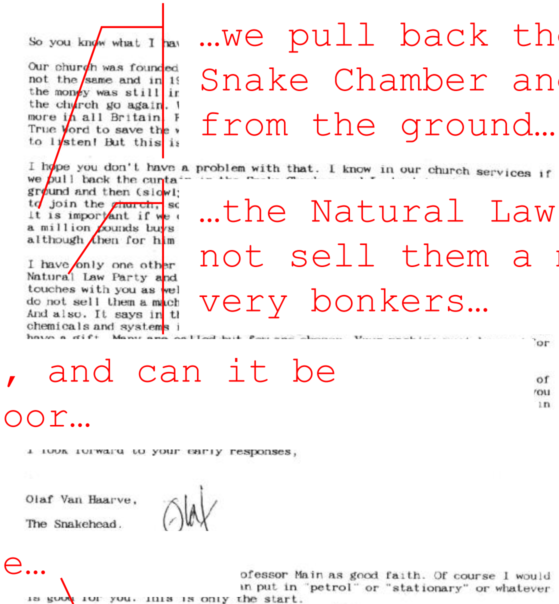
(3) We are intereste
bodies, or can t
down but that wo

(3a) Does it hurt, an
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 intenti

We have a big interest in this machine…



So you know what I hav

Our church was founded
not the same and in 19
the money was still in
the church go again.
more in all Britain.
True Word to save the
to listen! But this is

I hope you don't have a problem with that. I know in our church services if
we pull back the curta
ground and then (slowly
to join the church, so
it is important if we
a million pounds buys
although then for him

I have only one other
Natural Law Party and
touches with you as wel
do not sell them a mach
And also. It says in th
chemicals and systems

I look forward to your early responses,

Olaf Van Haarve,

The Snakehead.

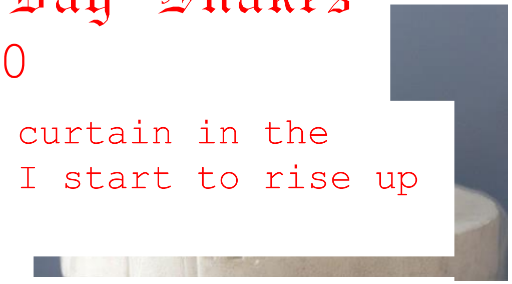
ofessor Main as good faith. Of course I would
in put in "petrol" or "stationary" or whatever
is good for you. This is only the start.

…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…



g

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

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

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