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Superconductivity at Future Hadron Colliders

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Outline

1. Superconductivity and Energy: general applications
2. Accelerators: history
3. Requirements for Superconducting Wires and Cables
4. Superconductors and magnets: fundamentals and applications
5. Superconductors in the LHC Accelerator
6. Superconducting wires and cables: fabrication
7. Conclusions

1. Superconductivity and Energy: General Applications

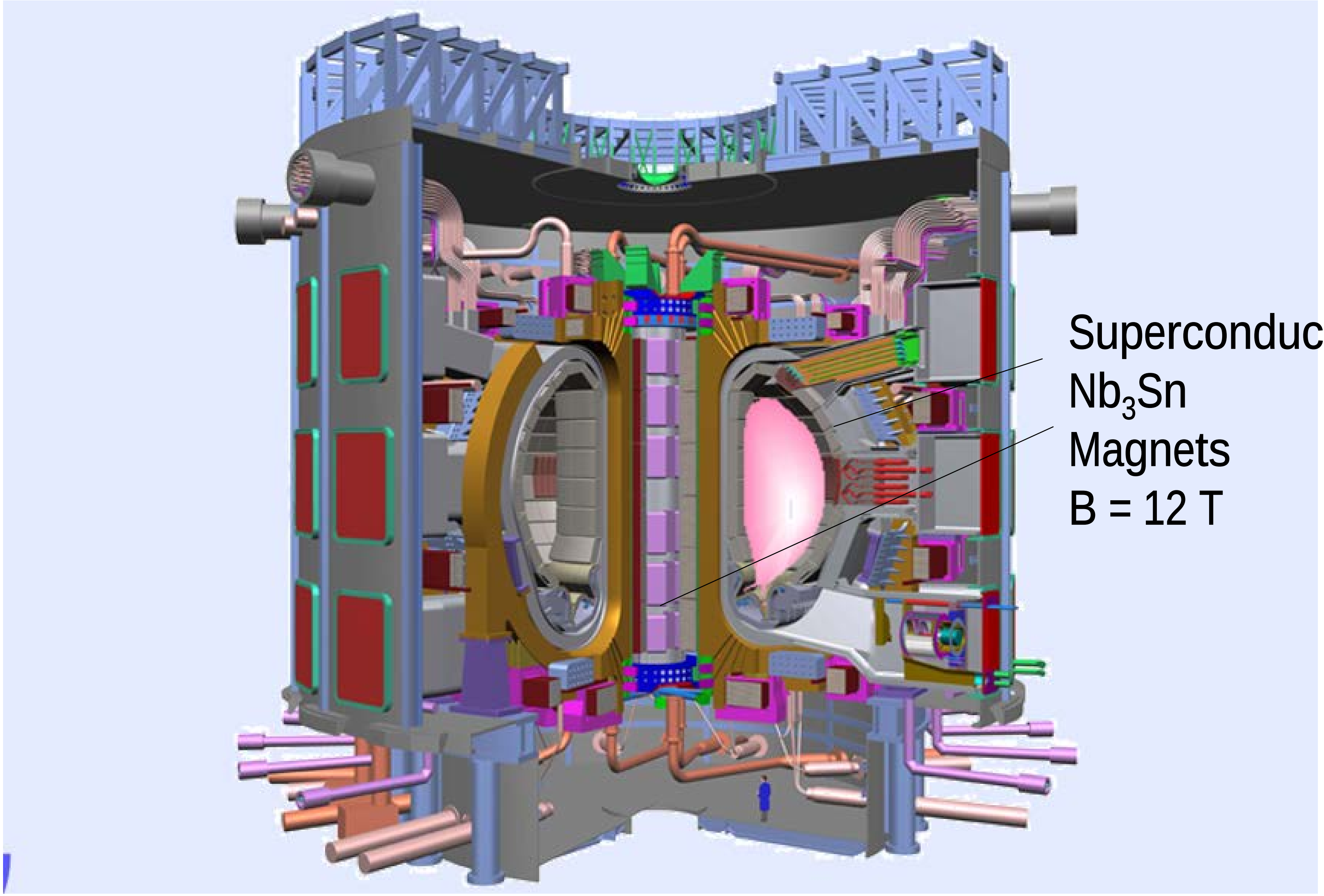
Superconductivity and Energy

Superconductivity does not produce energy, but

- Can contribute to energy saving
- Renders motors lighter and smaller
- Allows high power cables in very crowded city areas

- Levitating trains with > 500 km/h (Japan, under construction)
- MRI in hospitals and high field NMR: not without superconductors
- Thermonuclear fusion (ITER): not without superconductors
- Accelerators: LHC, FCC: not without superconductors

Largest future project: Thermonuclear fusion, ITER



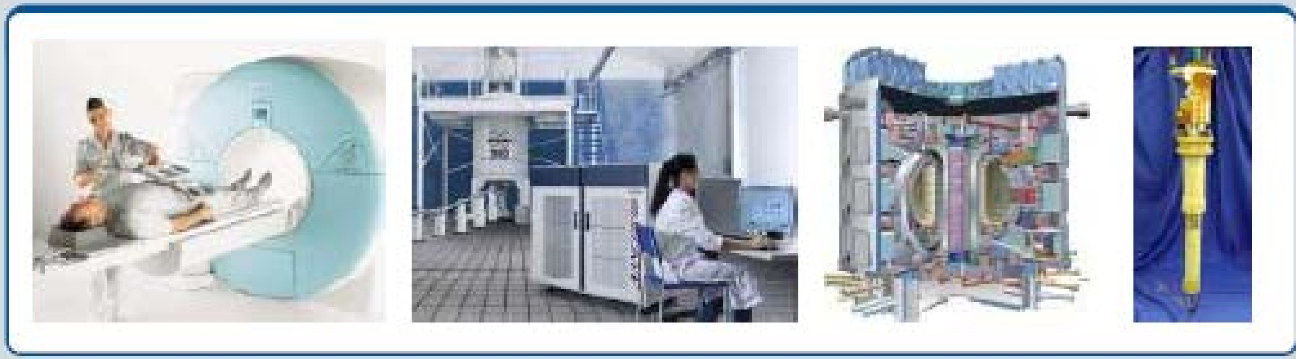
Superconducting
Nb_3Sn
Magnets
B = 12 T

Superconductivity and Energy

Magnet technology

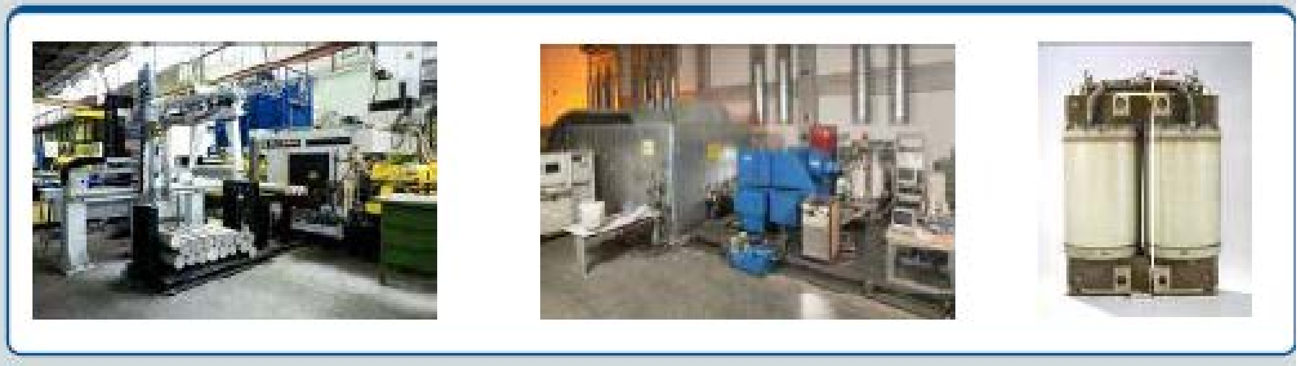
- T=4K
- Fields up to > 23 T

Fusion, Accelerators



Industry & Transportation

- T=20K – 77K
- Fields mT up to 5T



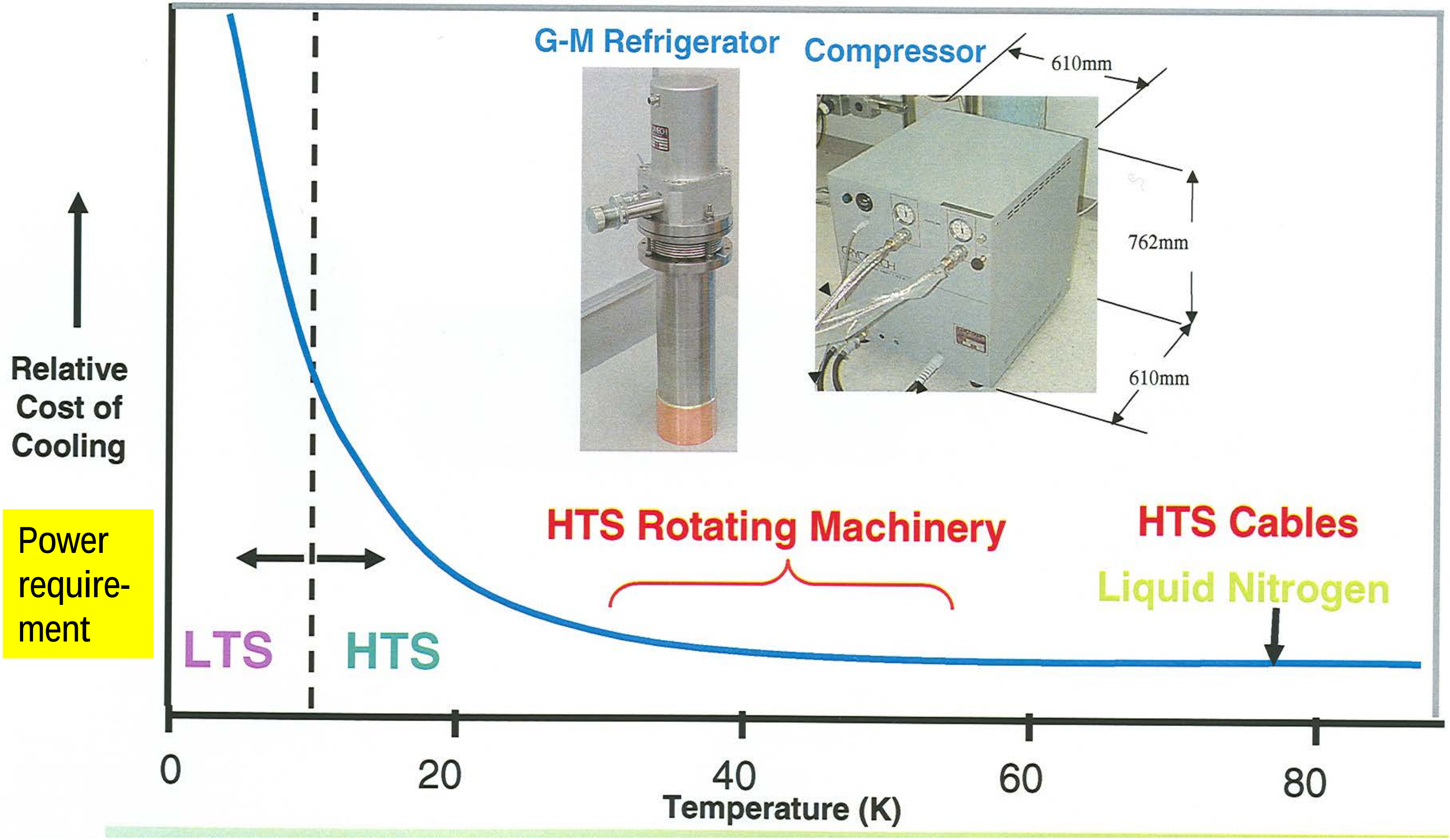
Power grid

- T=65 to 77K
- Fields mT up to 7 T

Technically interesting superconductors

Compound	Year	T_c (K)	$B_{c2}(0)$ (T)	ξ (nm)	
NbTi Nb_3Sn	1960 1953	9.5 18.3	14.6 24 - 28	~ 6 ~4	LTS
MgB_2	2001	39	39_{bulk}; 70_{films}	5	Intermediate
$Bi_2Sr_2Ca_2Cu_3O_{10}$ $YBa_2Cu_3O_7$	1989 1988	110 92	> 100 > 100	1 - 2 1 - 2	HTS

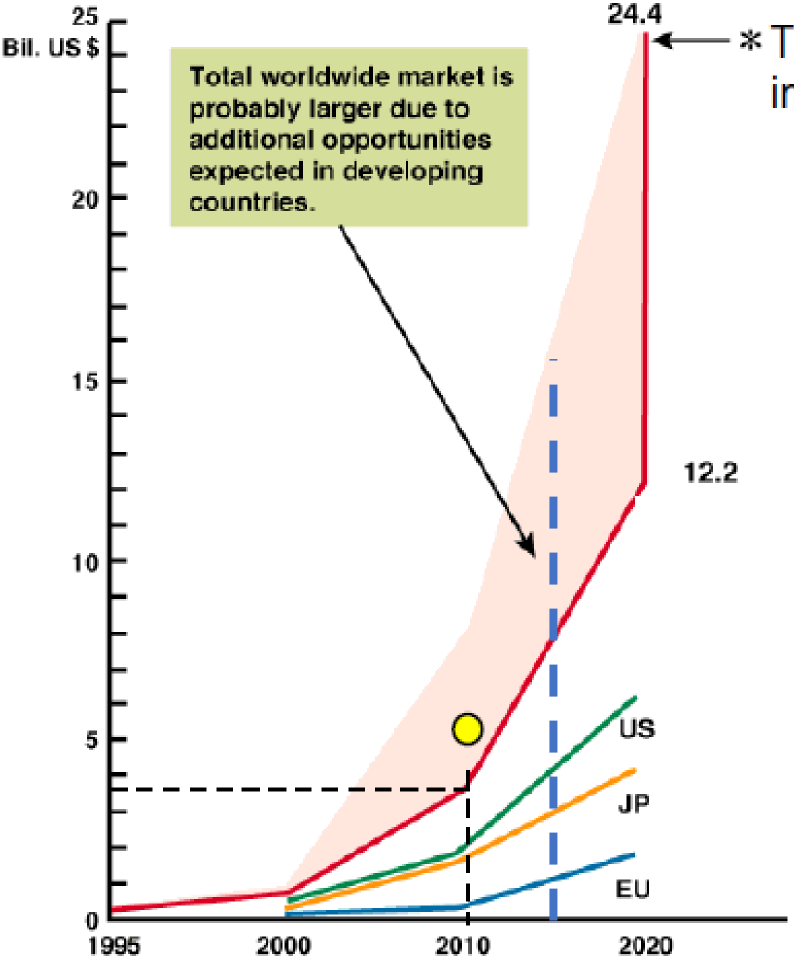
Cooling Regime for various Superconducting wires



Power requirement

Global Market for Superconductivity

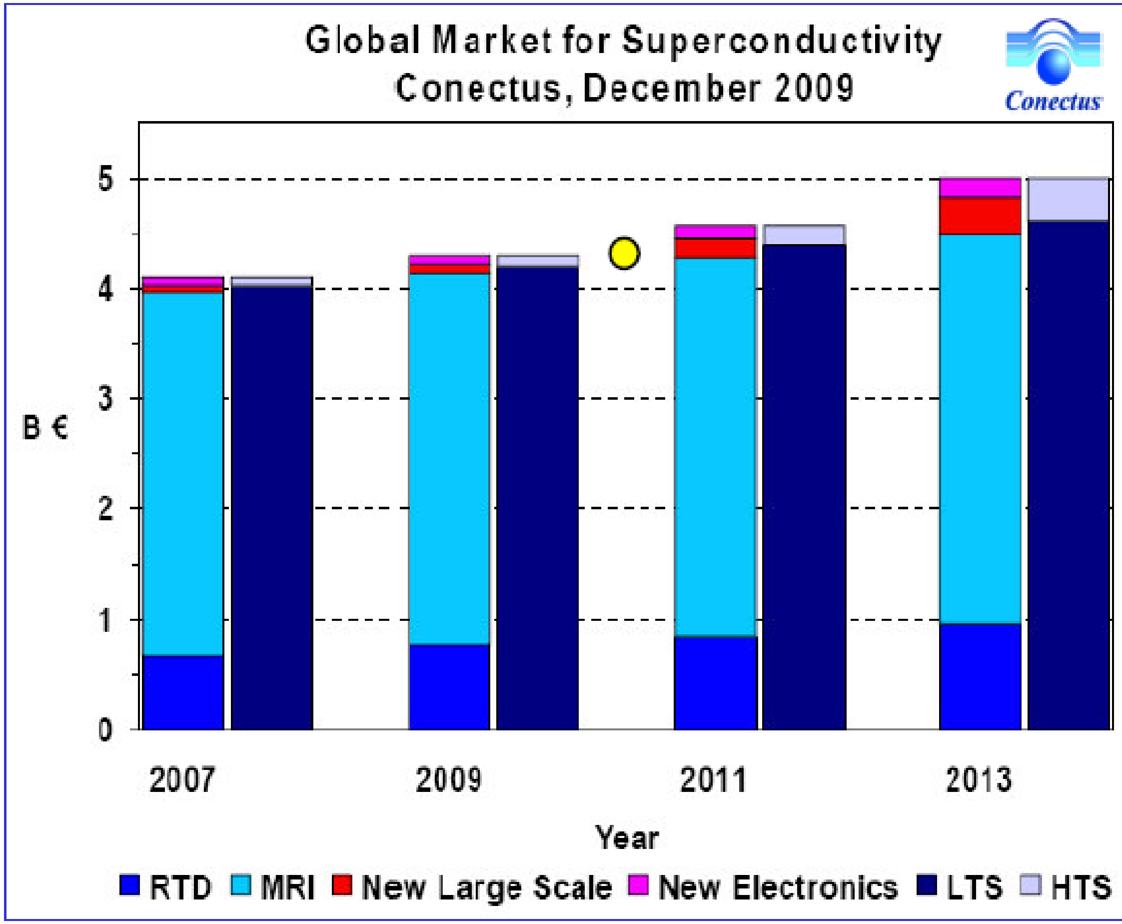
The International Superconductivity Industry Summit



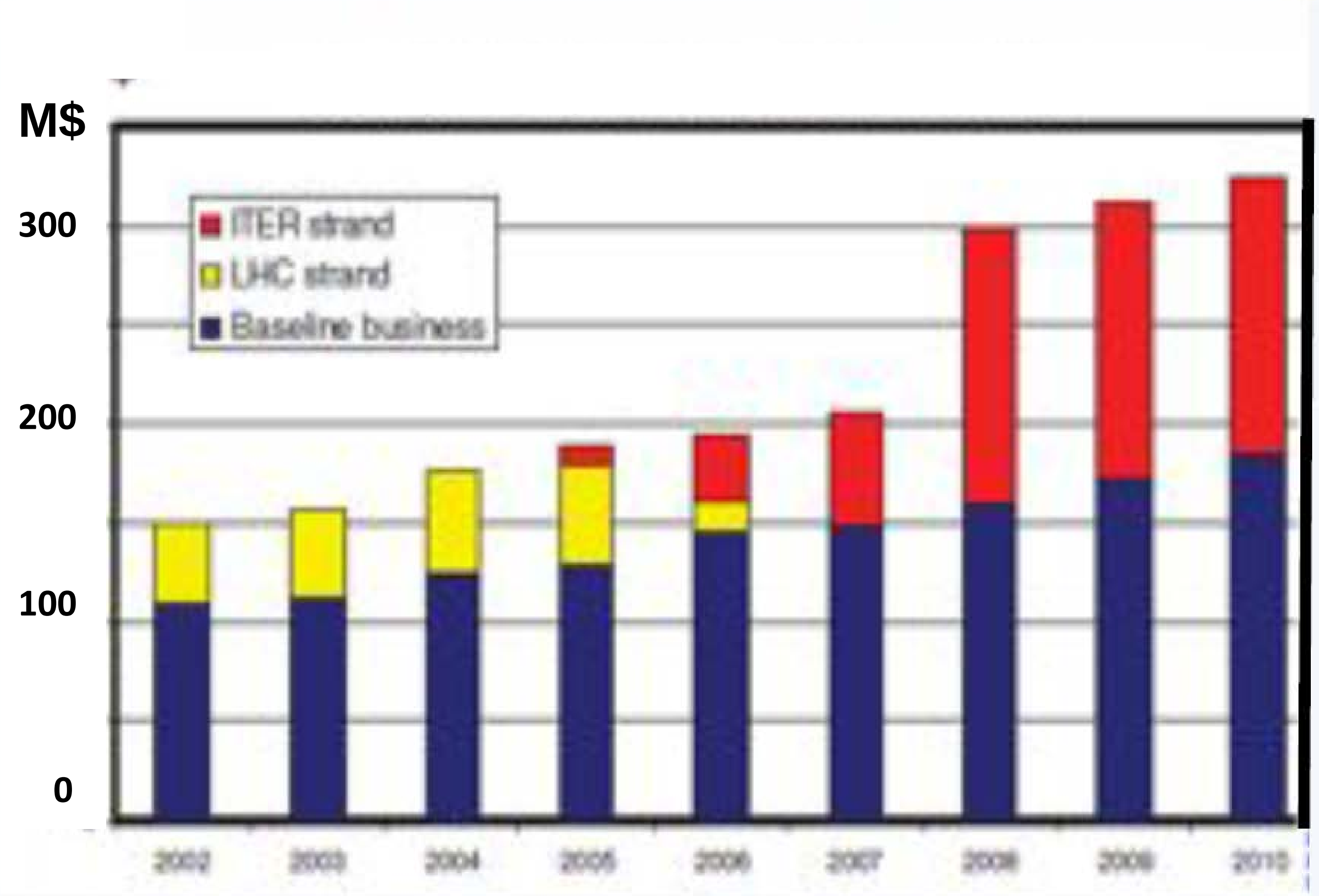
Total worldwide market is probably larger due to additional opportunities expected in developing countries.

* This forecast includes the expected expansion of sales by 100% into outside U.S., EU & JP, as predicted by the World Bank

The **5th ISIS** Market Forecast
Japan, May 14-16, 1996



Worldwide Superconducting Wire Market



Conectus: CONsortium of European Companies (determined) To Use Superconductivity

Cables
High voltage/high current

Advantages:

* 5 – 10 times the current in the same space

* less space than a normal cable *

Presently, there are more than 10 cable projects worldwide

- Long Island Cable (USA)
- Ampacity in Essen (D)
- Yokohama cable (Japan)
- Large Cable system (Korea)

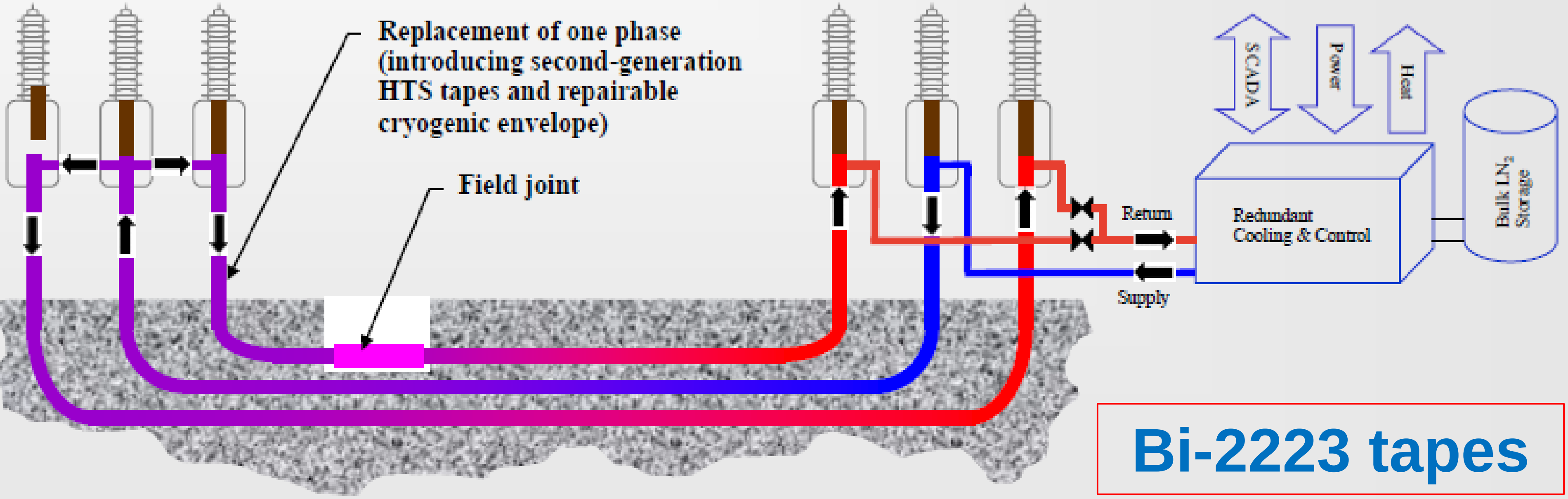
- …………………………

- 3 km cable in Chicago (envisaged)

Long Island Port Authority: LIPA 2 project

Preparing for multi-kilometer HV HTS cables

- Project funded by the U. S. Department of Energy
- Same partners (American Superconductor, Air Liquide and LIPA) and same site as for the LIPA1 project

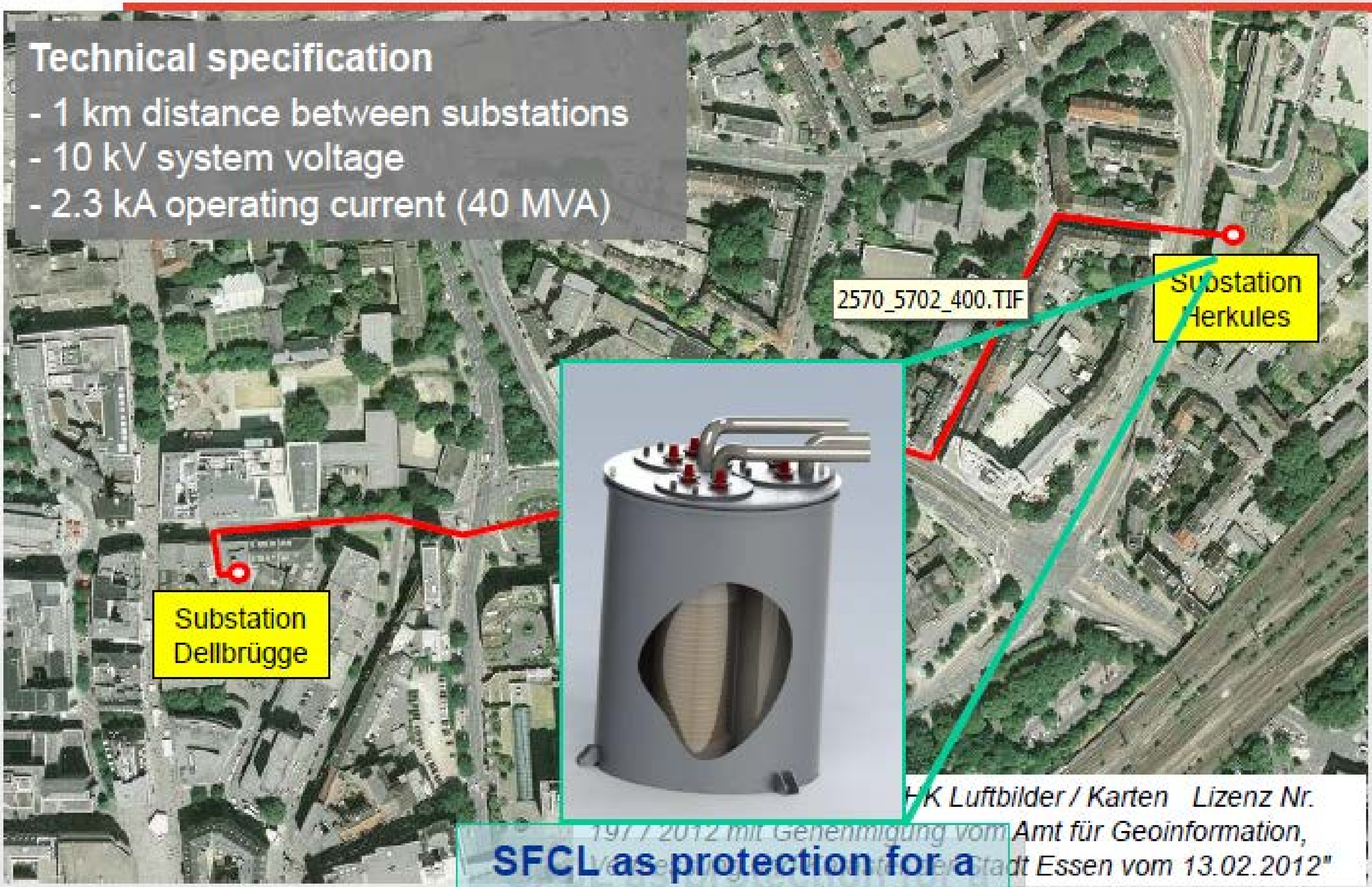

Replacement of one phase (introducing second-generation HTS tapes and repairable cryogenic envelope)

Field joint

Bi-2223 tapes

Installation and commissioning : end of II 2012

Ampacity Cable in Essen (D), 1 km long



Technical specification

- 1 km distance between substations
- 10 kV system voltage
- 2.3 kA operating current (40 MVA)

K Luftbilder / Karten Lizenz Nr.
197 / 2012 mit Genehmigung vom Amt für Geoinformation,
Stadt Essen vom 13.02.2012"

SFCL as protection for a Superconducting Cable

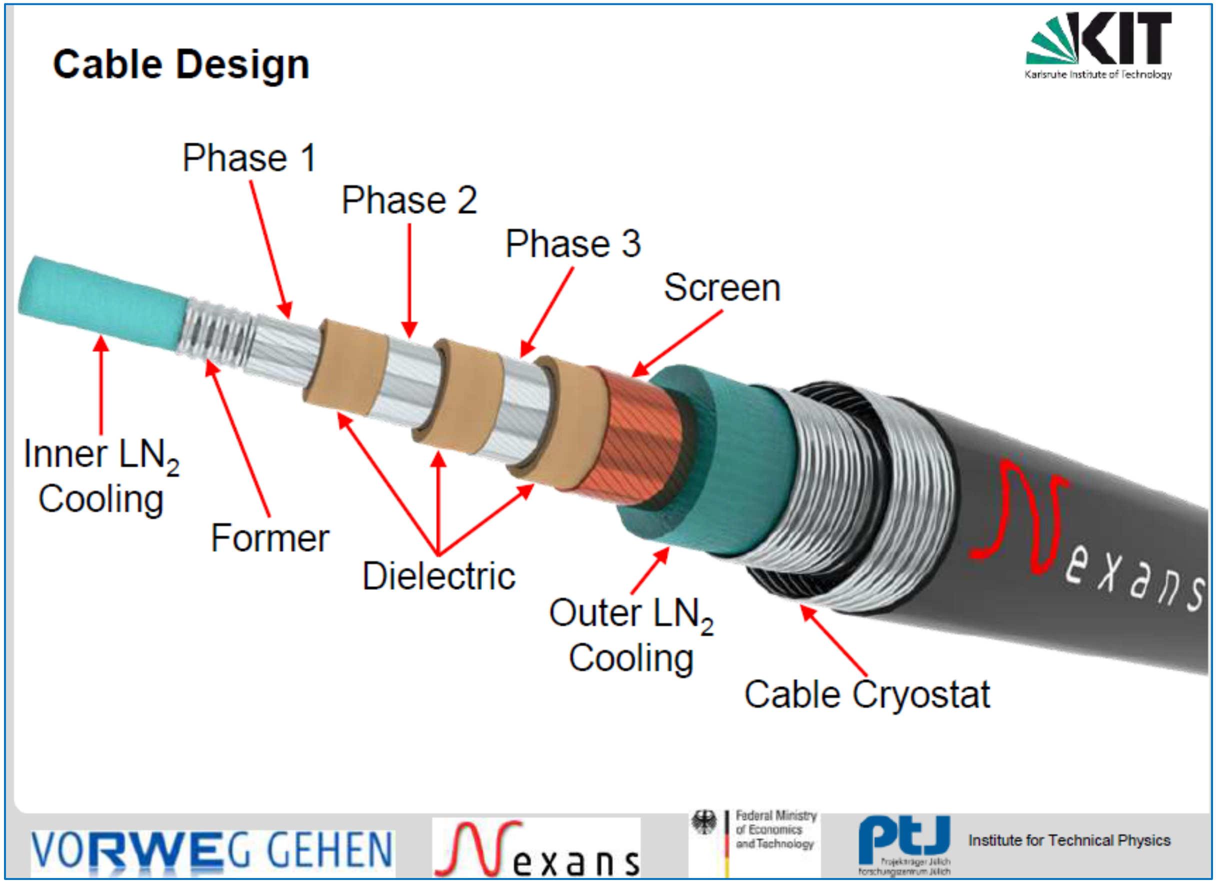
Bi-2223 tapes

Ampacity Cable Project in Essen (Germany)

Installation of 10 kV, 40 MVA HTS system in the German City of Essen

- Project started in September 2011

* **Alternative to 110 kV systems**

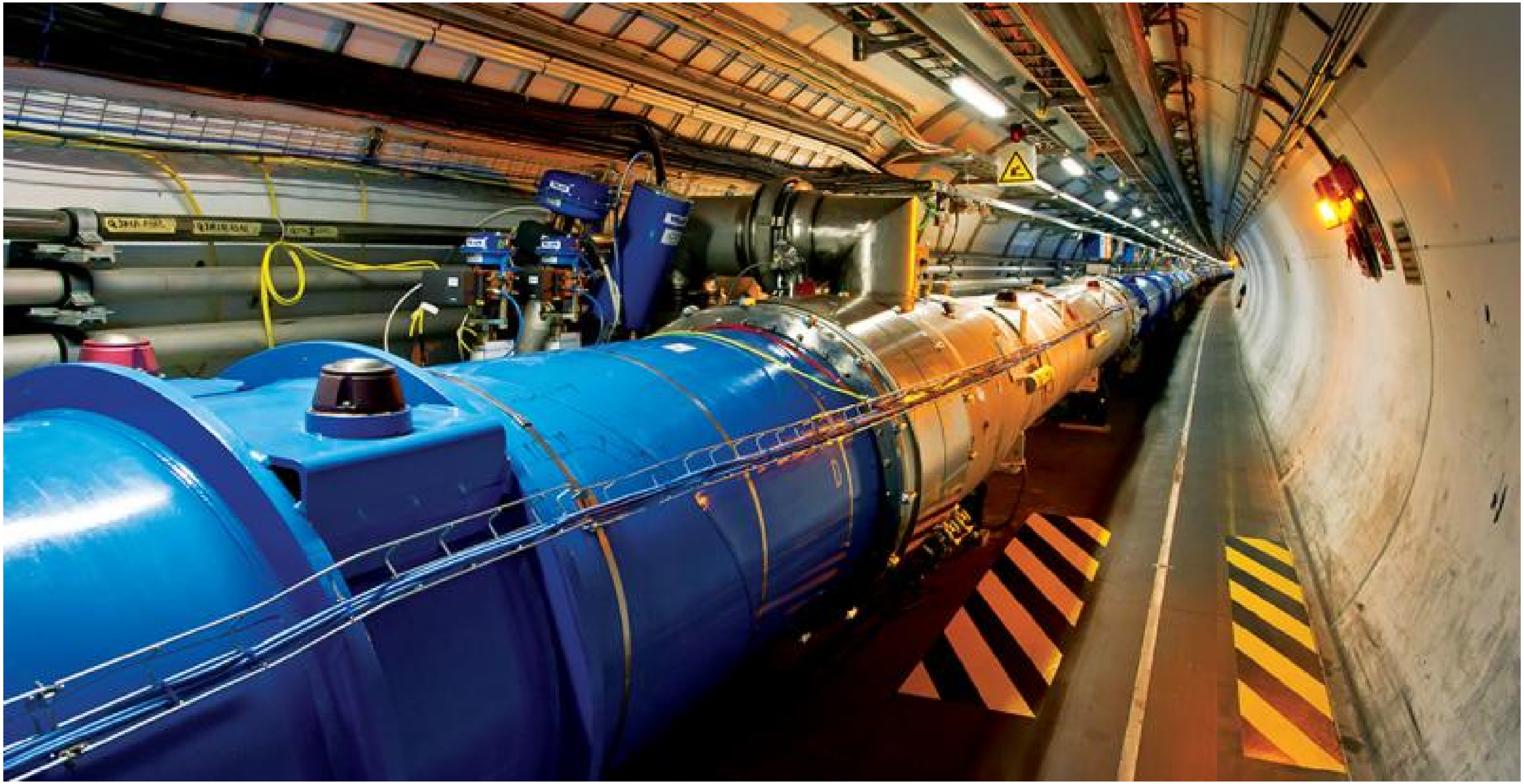


Cable Design

Bi-2223 Wires

Operational: since 2014

Dipoles in LHC Accelerator (operational since 2012)



2. Accelerators (Colliders)

History and Present State

Evolution since 1960

- Early 1960s Experiments with newly discovered type II SC material
- Mid 1960s **Recognition of application for experimental particle physics led to intense activity to understand and develop useful conductors for winding magnet coils**

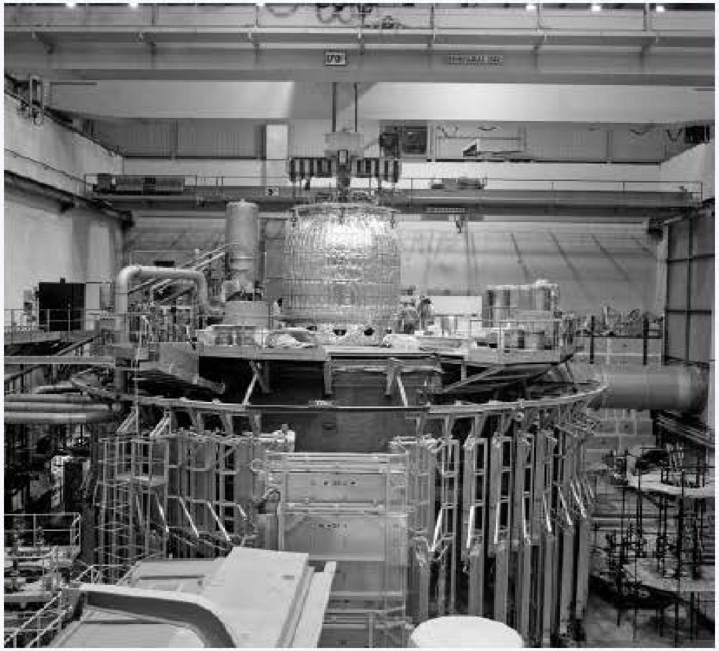
  → *Importance of filaments, stabilizers, twisting and transposition*

  Defining moment: Brookhaven Summer Study (1968)
- Late 1960s First SC magnets for experiments and beam lines

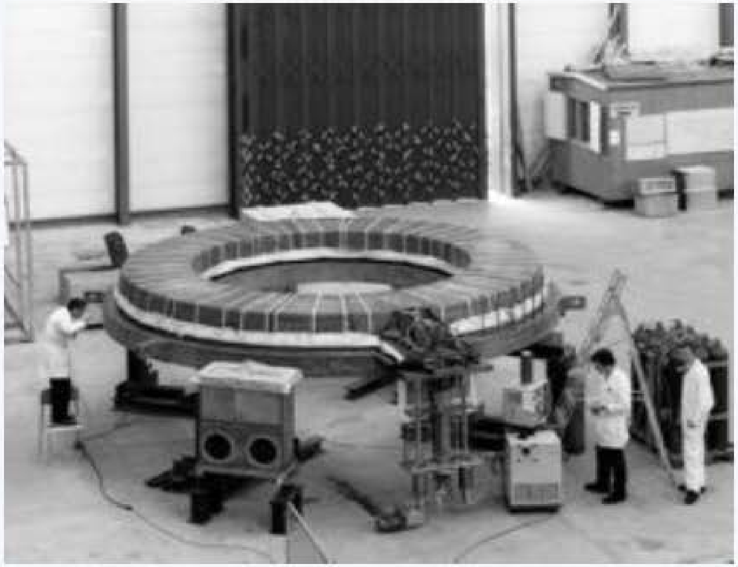
  Studies for a large SC accelerator → GESSS 1970-74

  Group for European Superconducting Synchrotron Studies

  (IEKP Karlsruhe-D, RHEL Chilton-UK, CEN Saclay-F)
- Early 1970s First SC spectrometer magnets (at CERN **BEBC, Omega**)
- Late 1970s First SC accelerator magnet sub-system (**ISR** low-β insertion at **CERN**)



BEBC magnet: 3.5 T @ 4.5 K, 5700 A
Stored energy: 800 MJ
Φext ~ 6.5 m
Nb-Ti (45 km), J ~10 A/mm^2
Flat composite strip: 61×3 mm^2
200 SC untwisted filaments
3.5 % Nb-Ti in copper matrix
Eddy currents during ramp



Omega magnet: 1.5 T @ 4.5 K, 5000 A
Stored energy: 50 MJ
Φint ~ 3 m
Hollow conductor cooled by forced flow supercritical helium
Nb-Ti (18×18 mm^2), J~14 A/mm^2
Historical milestone in the development of forced flow conductor

ISR (**I**ntersecting **S**torage **R**ing)

Eight **superconducting quadrupoles** for the high-luminosity insertion **installed in 1980** - work on design started in 1973

Gradient : 43 T/m
Inner diam. of coils: 232 mm
Operating current :1600 A @ 5.8 T and 4.5 K
Conductor : rectangular wire
$1.8 \times 3.5\ \mathrm{mm}^2$ (± 0.01 mm)
Nb-Ti with copper stabilizer
1250 filaments (50 μm)
Twist pitch: 50 mm

This has been the first **application of superconductivity in a working accelerator**

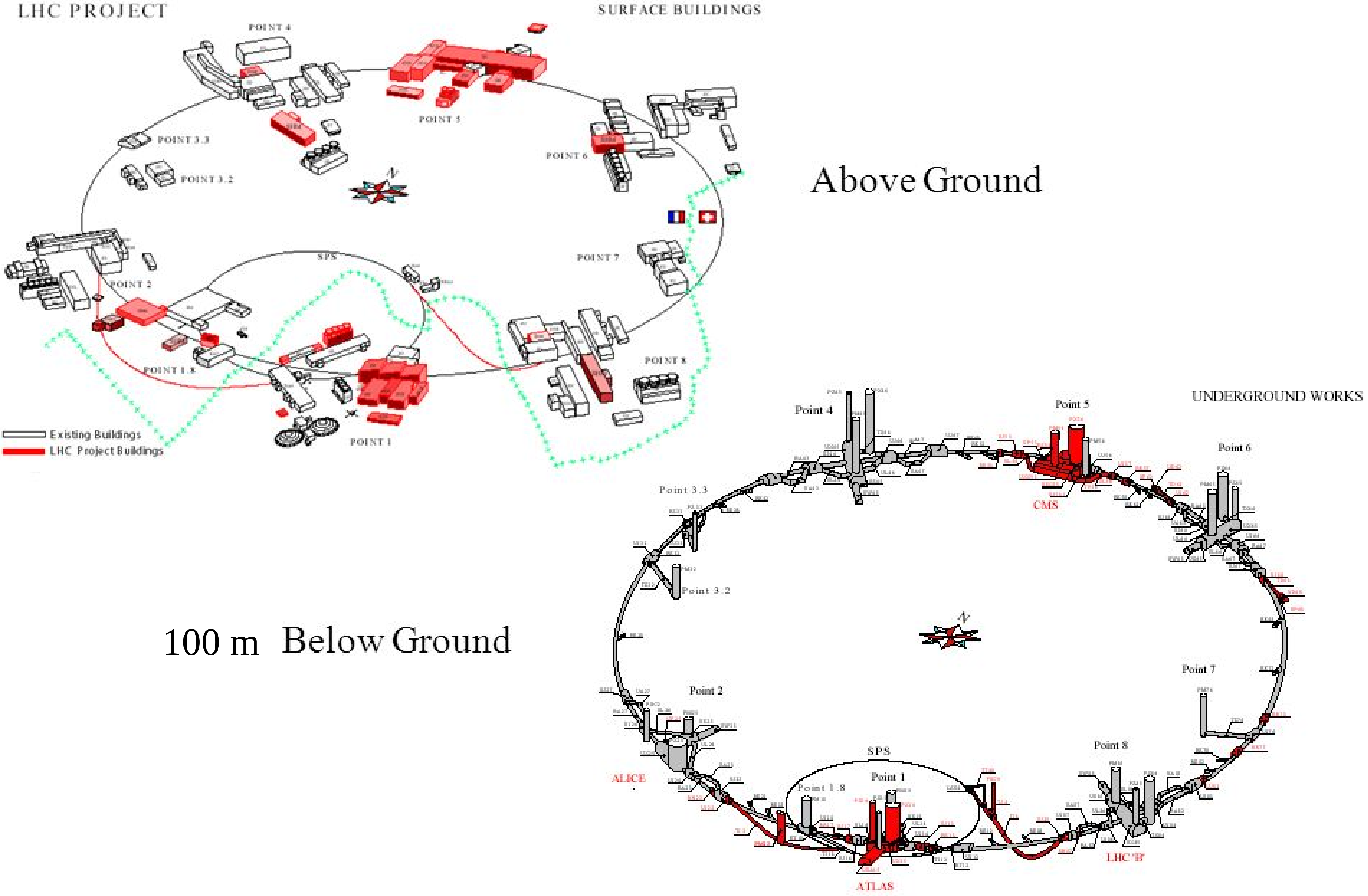
What happened after 1980 ?

- Mid 1980s Fermilab Tevatron – Ø 2 km – SC magnet system + CDF +D0
- 1980s, 90s **CERN LEP** – Ø 8.5 km – **SC RF system + ALEPH + DELPHI**
- Early 1990s DESY HERA – Ø 2 km – SC magnet system + ZEUS
- Mid 1990s Jlab – CEBAF – SC RF system (+ spectrometers)
- Early 2000s BNL RHIC – Ø 1.2 km – SC magnet system
- Late 2000s **CERN LHC** – Ø 8.5 km – **SC magnet system + ATLAS + CMS**

The LHC Collider

- The **Large Hadron Collider** (**LHC**) is the world's largest and most powerful particle collider, the largest, most complex experimental facility ever built, and the largest single machine in the world .
- It was built by the European Organization for Nuclear Research (CERN)
- It lies in a tunnel 27 kilometres (17 mi) in circumference, as deep as 175 metres (574 ft) beneath the France–Switzerland border near Geneva, Switzerland.

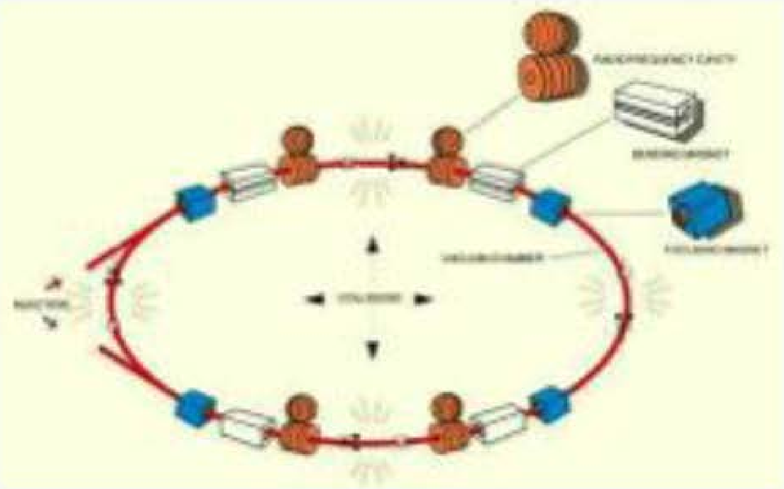
The Large Hadron Collider

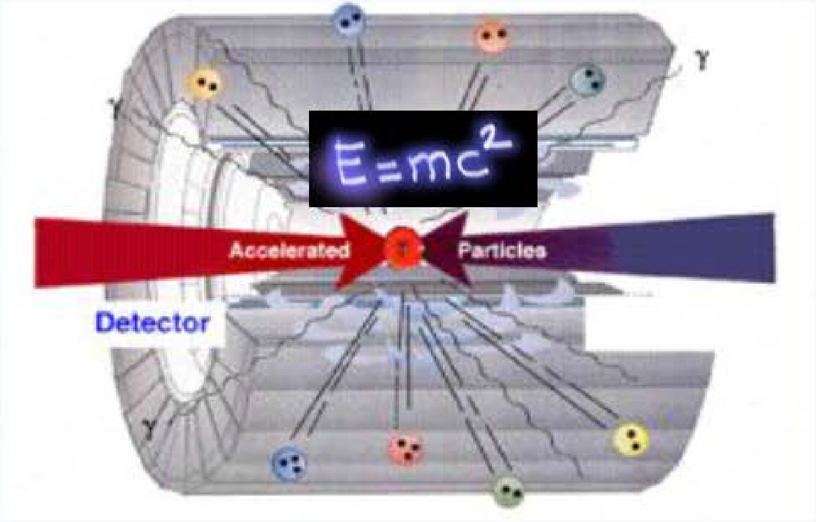


Above Ground

100 m Below Ground

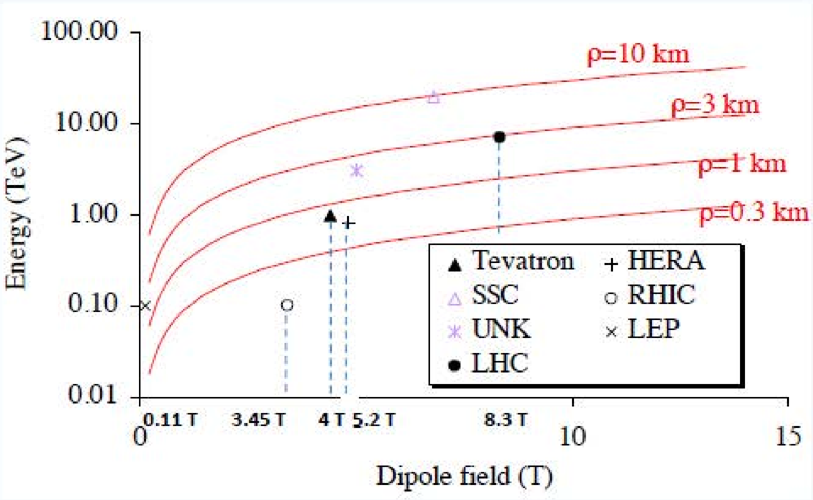
Accelerator Energy and Magnetic Fields



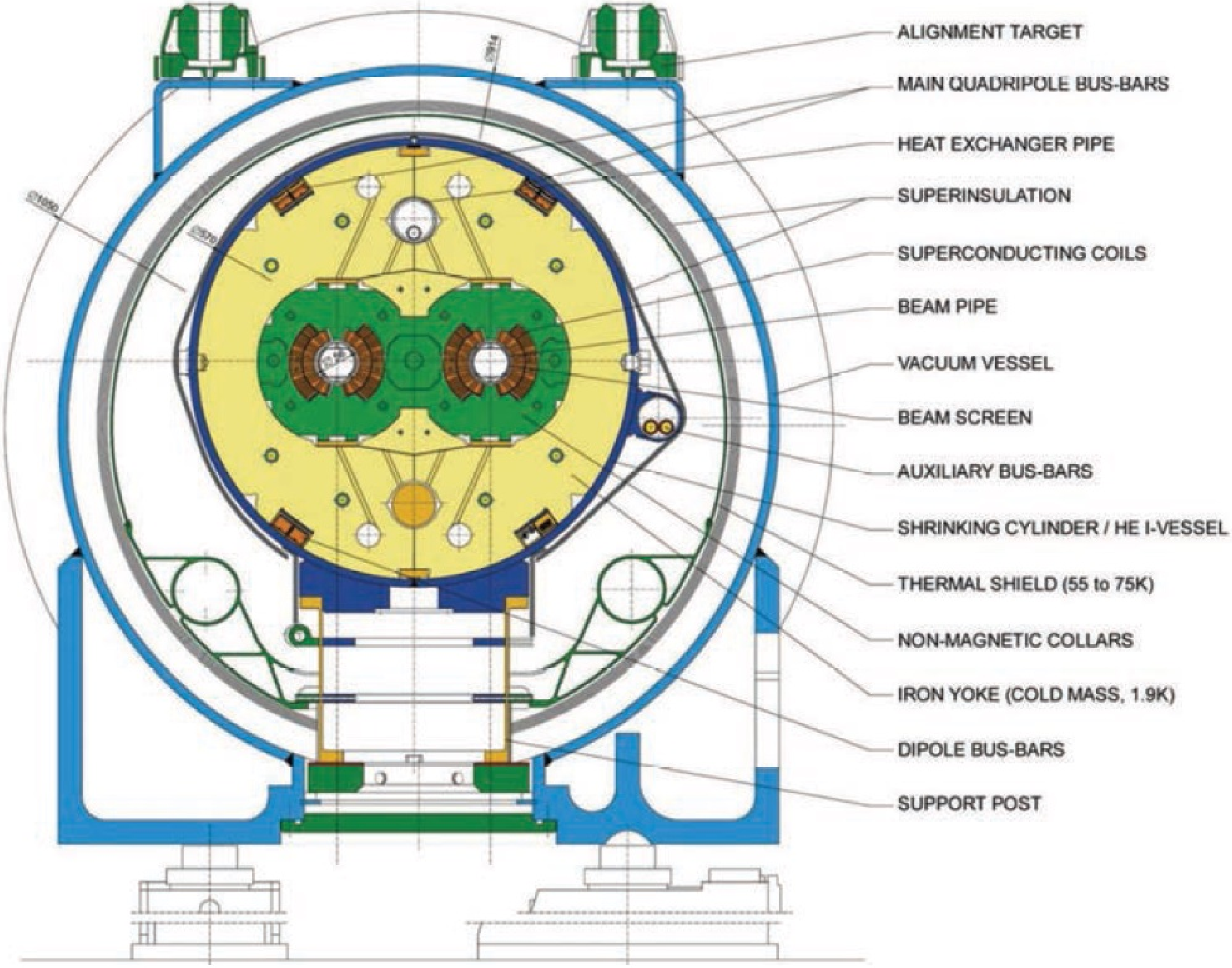


Synchrotron:
E[GeV]=0.29979 B[T] R[m]

Higher energies: Higher magnetic fields
➡ Need for high field magnets



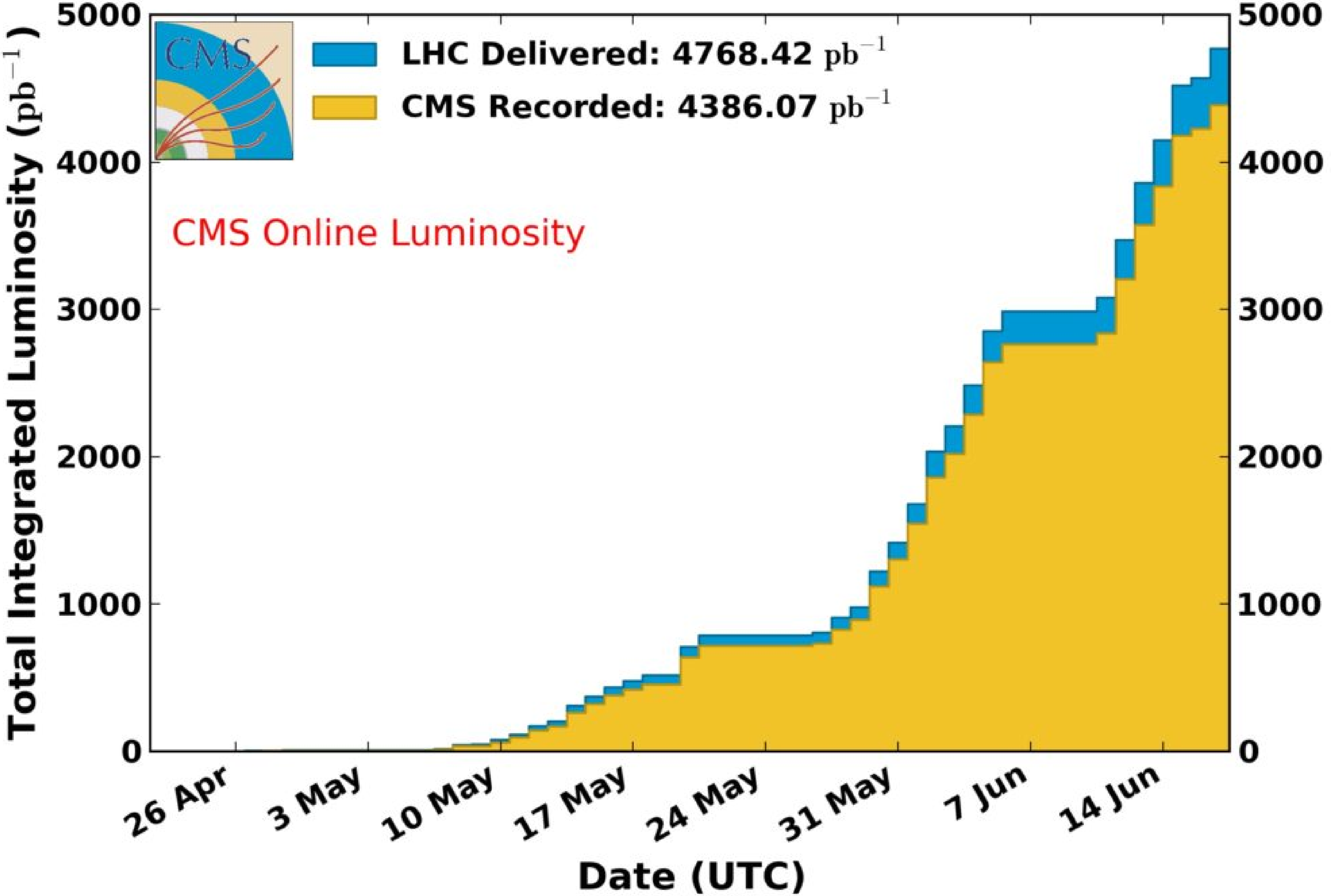
LHC Dipole Magnet, Cross Section



Dipole magnets, Test Station

In the LHC Tunnel

ATLAS Detector



CMS Integrated Luminosity, pp, 2016, $\sqrt{s} = $ 13 TeV

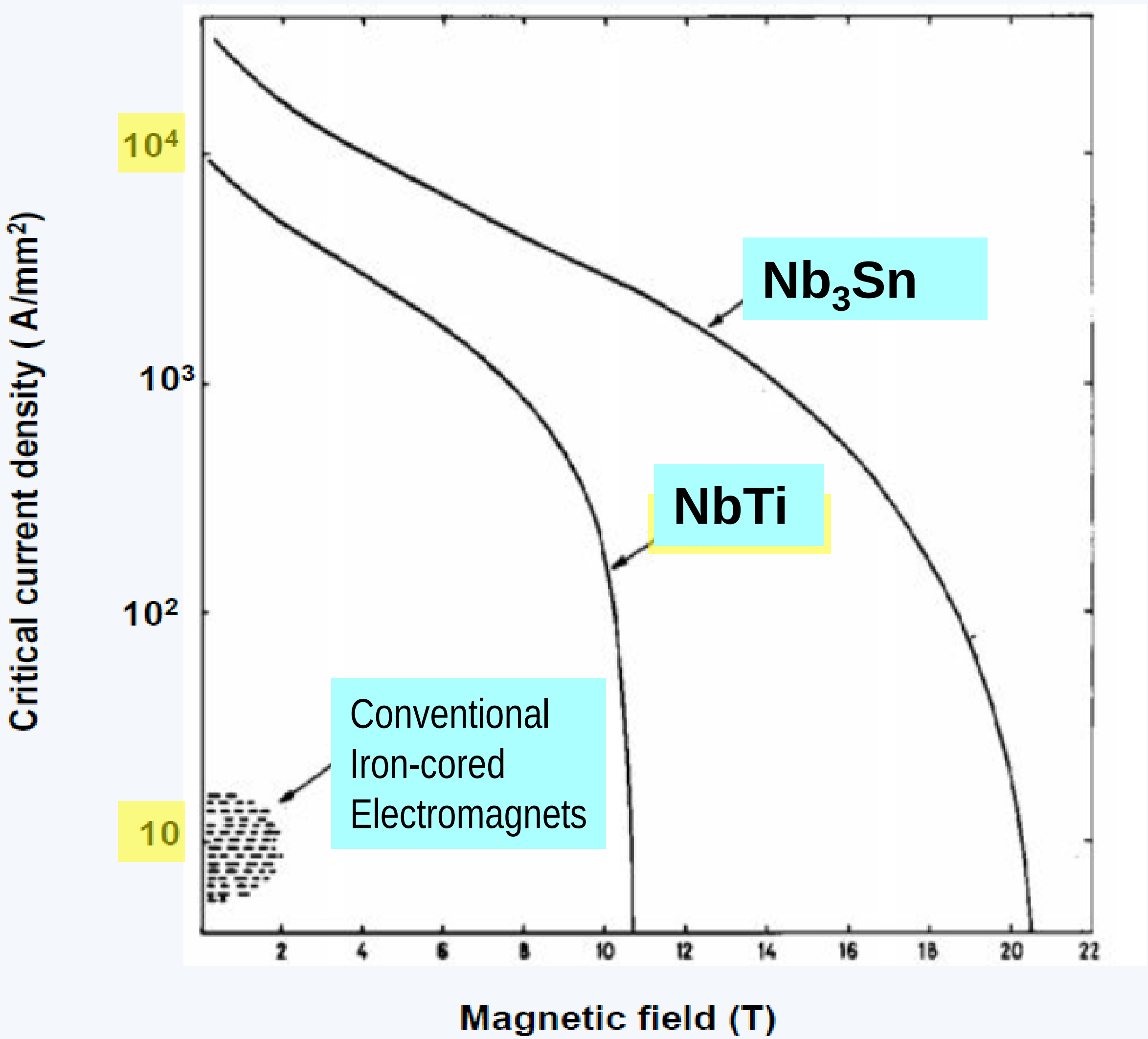
Data included from 2016-04-22 22:48 to 2016-06-17 08:55 UTC

Magnetic Fields in Colliders

LHC	**actual**	**27 km**	**8.5 T**
HiLumi LHC	**~2023**	**27 km**	**8.5T/12T**
FCC (possibly	**~2035**	**100 km** 80 km	**16T** 20T ?)

3. Requirements for Superconducting Wires and Cables

Current Density vs. Magnetic Field



Requirements: Technical Superconductors

- Long unit lengths
- Uniform characteristics (Ic,Jc)
- Good mechanical properties – for cabling and for magnet winding
- Stabilizing matrix material
- Flexible design (diameter, filament size and number, RRR…)
- Competitive cost

……….

↓

Nb-Ti for accelerator technology

Conductor Requirements - Wires

What does a conductor for accelerator magnets need to provide?

WIRE

- High and uniform **current density** to produce a large field over a small transverse aperture;
- Small **filaments size** to a) reduce magnetization and assure uniform field - mainly at injection, b) avoid flux jump;
- **Filaments twist** to minimize coupling effects during ramping (eddy currents);
- Appropriate **(Cu/non Cu) ratio** - minimum amount of copper needed for stability and protection, controlled within a strict tolerance (typically 1.5-2 ± 0.05 for accelerator magnets)

Conductor Requirements - Cables

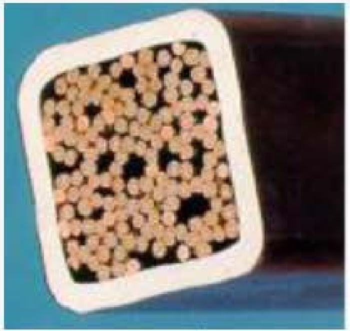
What does a conductor for accelerator magnets need to provide ?

CABLES

- High-current cables (10 - 20 kA range)
- Minimum Jc degradation with respect to virgin strands;
- Uniform current density;
- High filling factor;
- High aspect ratio;
- Precise dimensions;
- Twisted wires to minimize coupling effect during ramping;
- Controlled inter-strand resistance between crossing strands in the cable

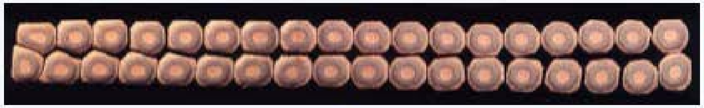
Superconducting Cable Types

CIC



ITER magnets

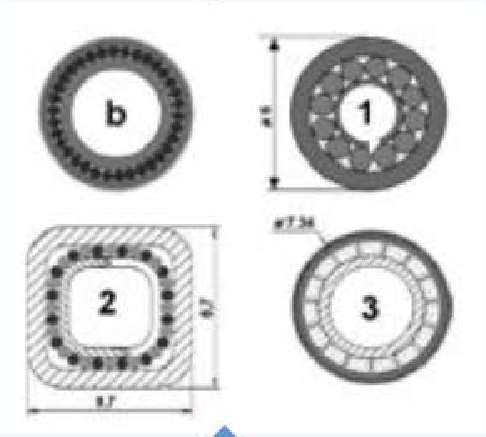
Rutherford



Accelerator magnets

Tevatron, HERA
RHIC and LHC

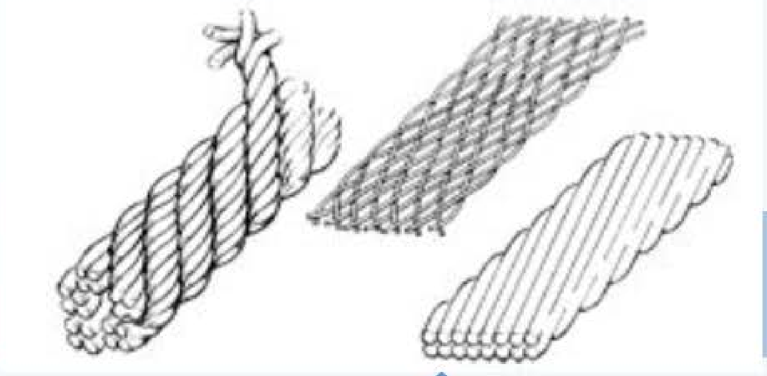
Indirectly cooled



Nuclotron Type (b)
Pulsed SIS 100 magnets

Rutherford

Detector magnets



Rope, Braid and Rutherford cables

Superconductor for the LHC Magnets

- **R&D** Program started in **1988**

- **Contracts** for the LHC cables were signed at the end of **1998** (six firms). Specification aiming at guaranteeing:

  High Technical Requirements;
  Homogeneity of the production;
  On-time cable delivery

1988 → **1998**

10 years

- **Production** of cables –including spare- **ended** in spring **2006**

1998 → **2006**

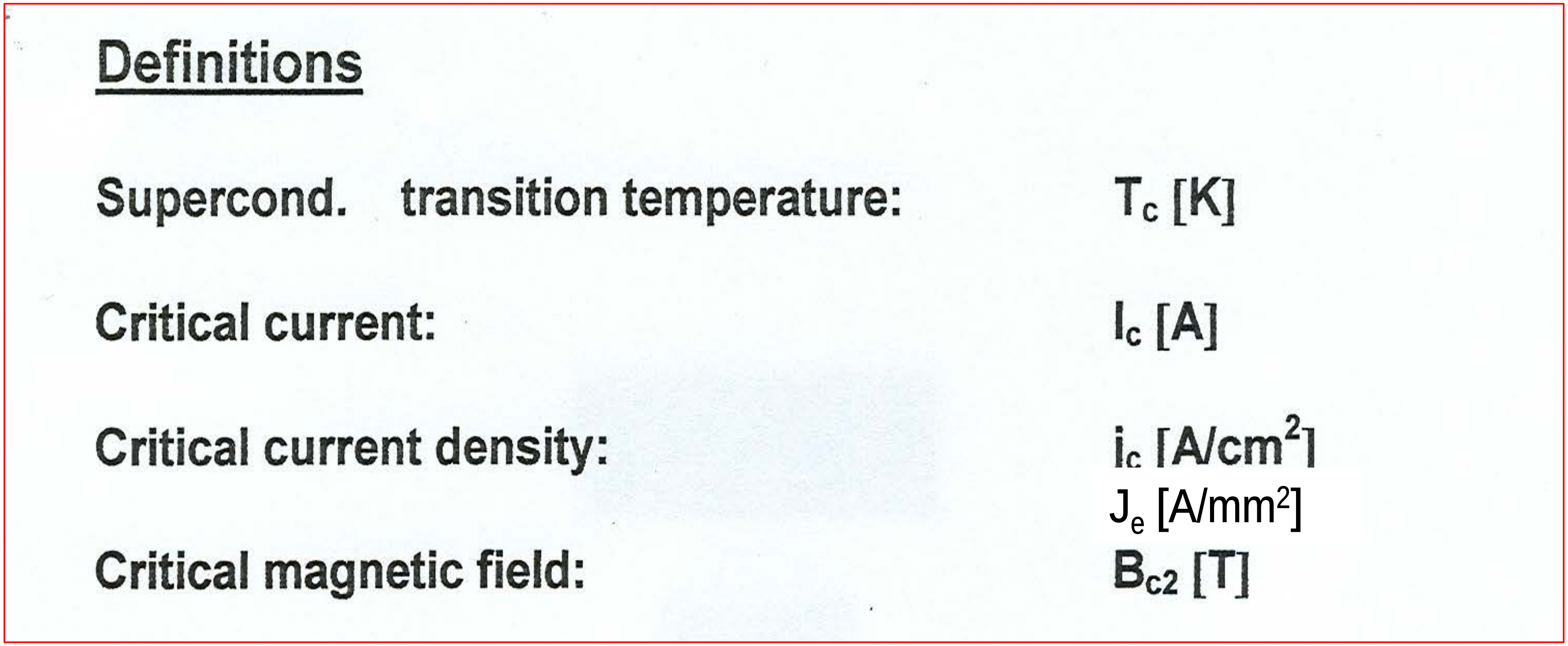
8 years

*** Same scenario since 2010 for HiLumi LHC**

*** Maybe: same scenario for FCC, starting 2015**

4. Superconducting Materials
Fundamental properties
Definitions

Applied Superconductivity, Definitions



Definitions

Supercond. transition temperature:	T_c [K]
Critical current:	I_c [A]
Critical current density:	i_c [A/cm^2] J_e [A/mm^2]
Critical magnetic field:	B_{c2} [T]

Critical parameters depend on several factors

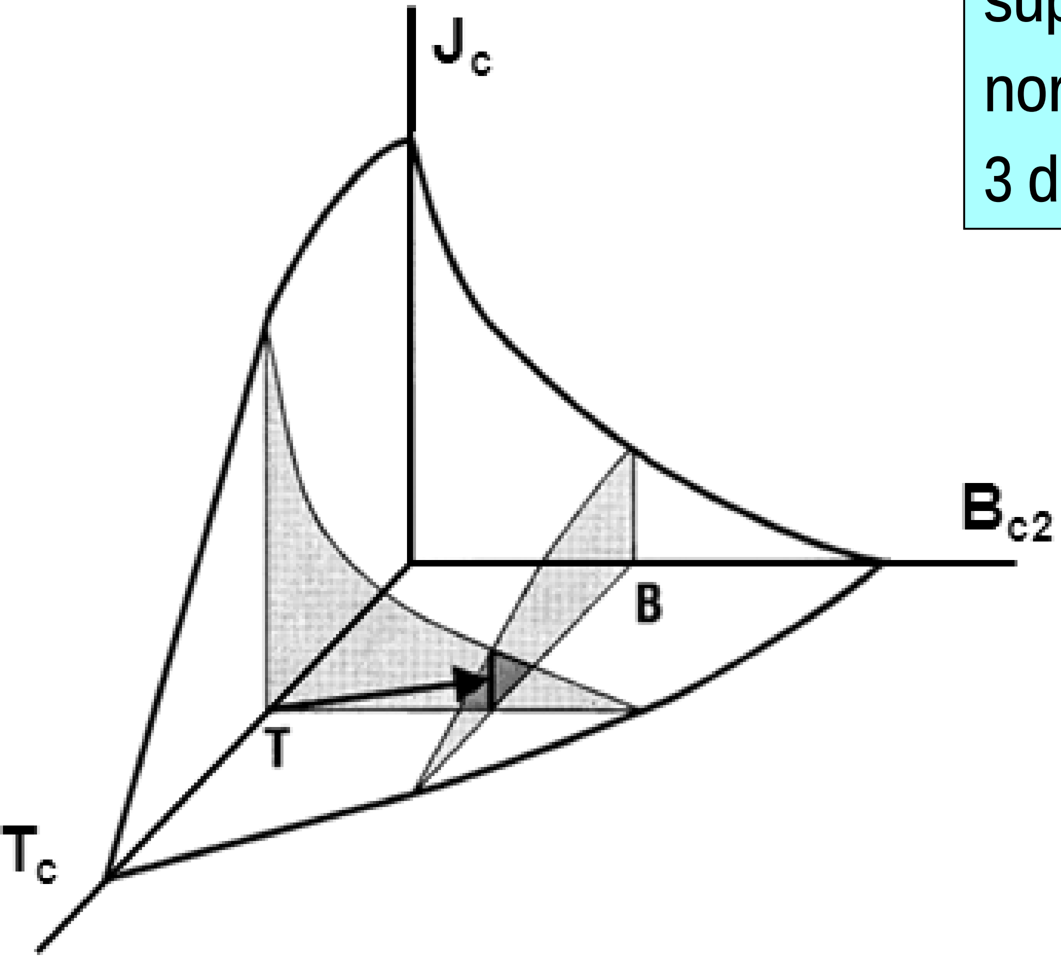
- Elements
- Crystal structure
- Microstructure (mostly affects J_c)

Technically interesting superconductors

Compound	Year	T_c (K)	$B_{c2}(0)$ (T)	ξ (nm)	
NbTi	1960	9.5	14.6	~ 6	**LTS** Low Tc Superconductors
Nb_3Sn	1953	18.3	24 - 28	~4	
MgB_2	2001	39	$39^{a}{}_{bulk}$ $60^{a}{}_{films}$	5	
$Bi_2Sr_2Ca_1Cu_2O_8$	1989	94	> 100^a	1 - 2	**HTS** High Tc Superconductors
$Bi_2Sr_2Ca_2Cu_3O_{10}$	1989	110	> 100^a	1 - 2	
$YBa_2Cu_3O_7$	1988	92	> 100^a	1 - 2	

Critical surface in type II superconductors

Critical surface: boundary between superconductivity and normal resistivity in the 3 dimensional space: T_c, B_{c2}, J_c.



Below the 3D surface: superconductivity

Above the 3D surface: normal state **(R ≠ 0)**

Critical parameters depend on :
Elements
Crystal structure
Microstructure (mostly affects J_c)

Characterization of superconductors Definitions

a. Electrical resistivity of metals and superconductors

Metallic R vs. T:

- * Electron-phonon scattering (lattice interactions) at high temperature
- * Impurities at low temperatures

Metals: finite resistance at low T

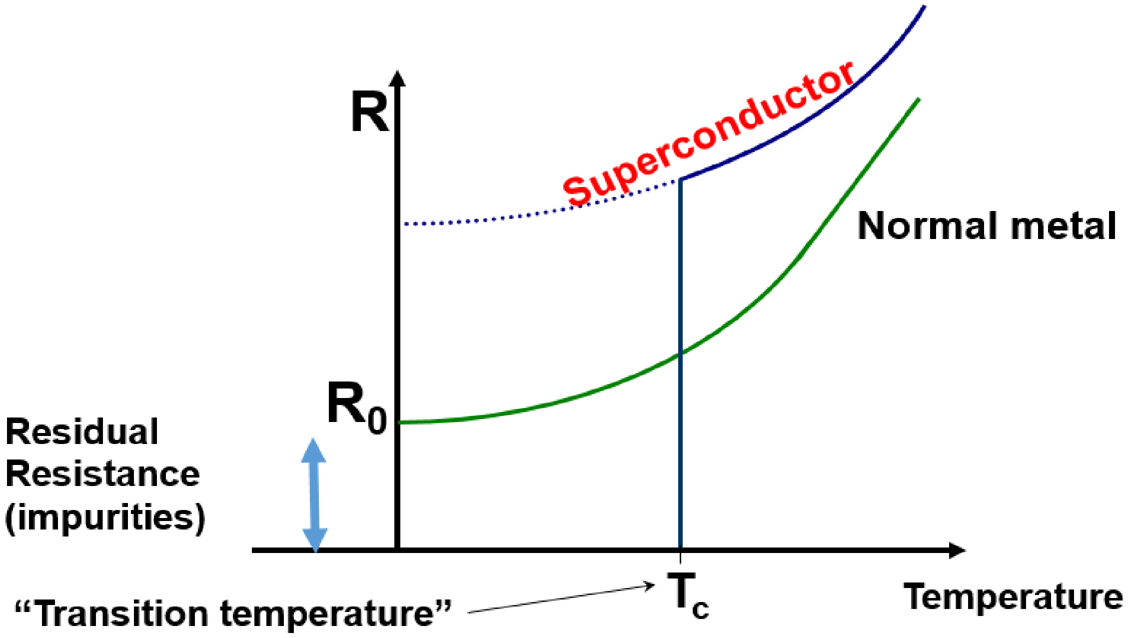
$\rho(T) = \rho_o + aT$ for $T > 0$ K

$\rho(T) = 0$ near $T = 0$ K

Superconductors:

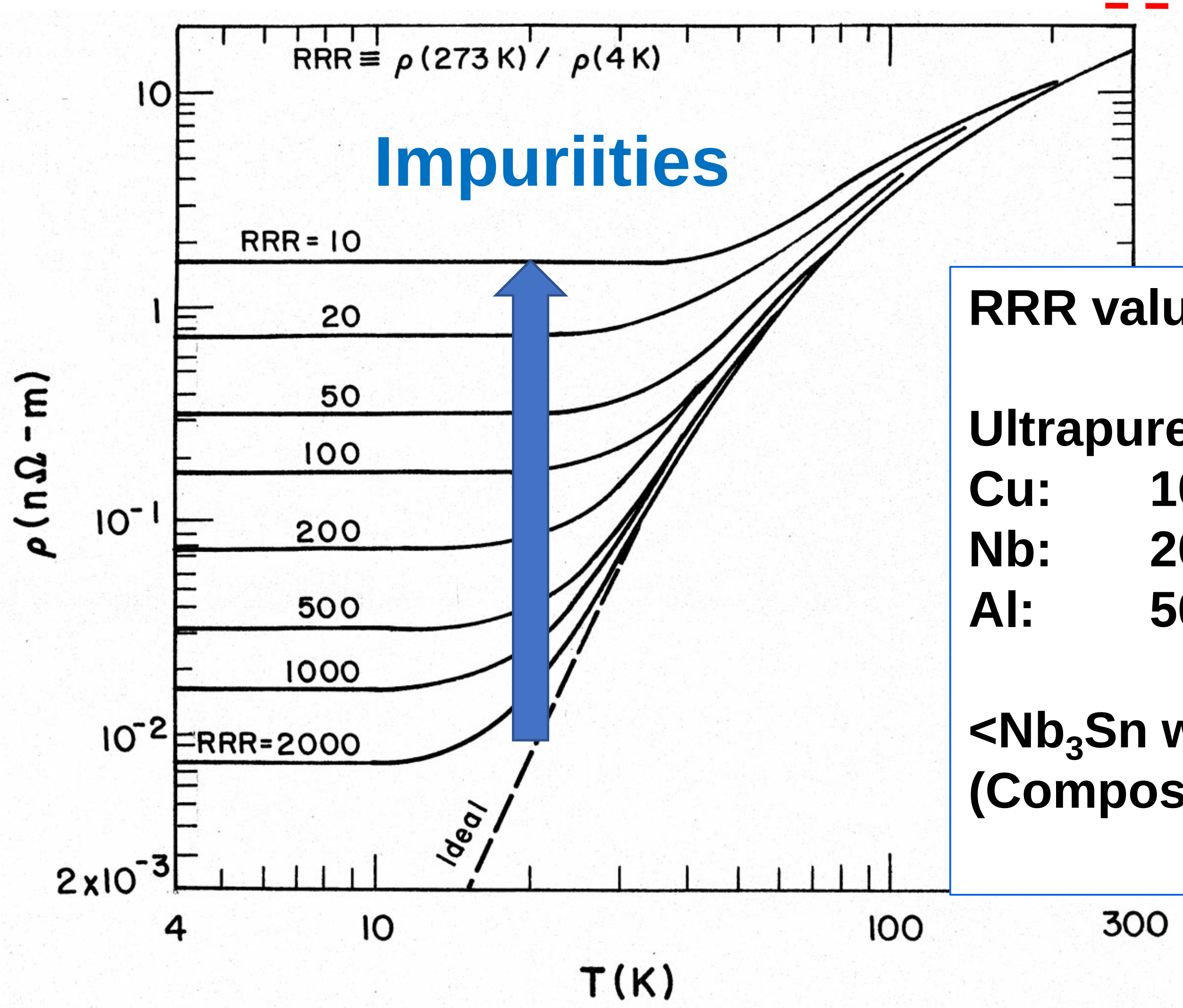
$\rho(T) = \rho_o + aT$ for $T > T$ K

$\rho(T) = 0$ at $T < T_c$



Resistivity of Metals

Resistivity increases with impurities



Mott limit

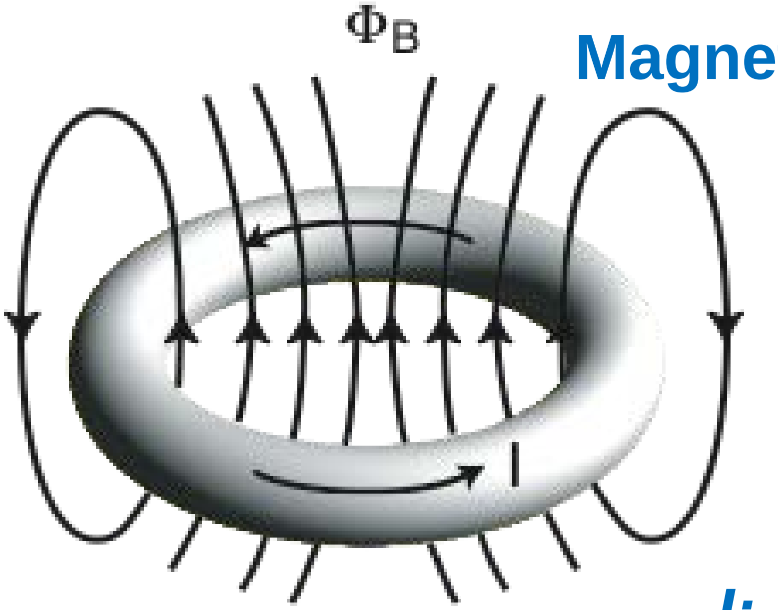
RRR values:

Ultrapure metals: >10^4
Cu: 10………> 2’000
Nb: 20……… 20’000
Al: 50 ………> 3’000

<Nb_3Sn wire> > 100…200
(Composite)

Resistivity of a superconductor: really zero or just very small?

$$I(t) = I_0 e^{-t/\tau}$$

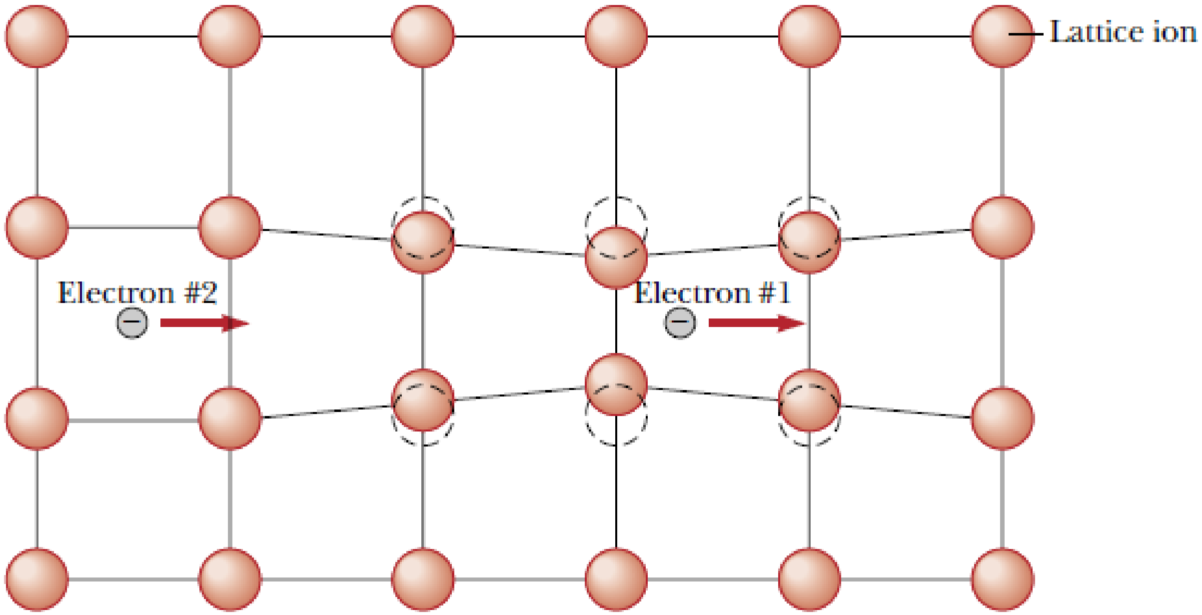


Magnetic field

I: Supercurrent

- A super-current can be induced in a superconducting ring.
- The decay of the current is given by the relaxation time (10^{-14} s for a normal metal). For a superconductor it should be infinite. Experiments suggest that it is not less than 100.000 years.

The Cooper pairs



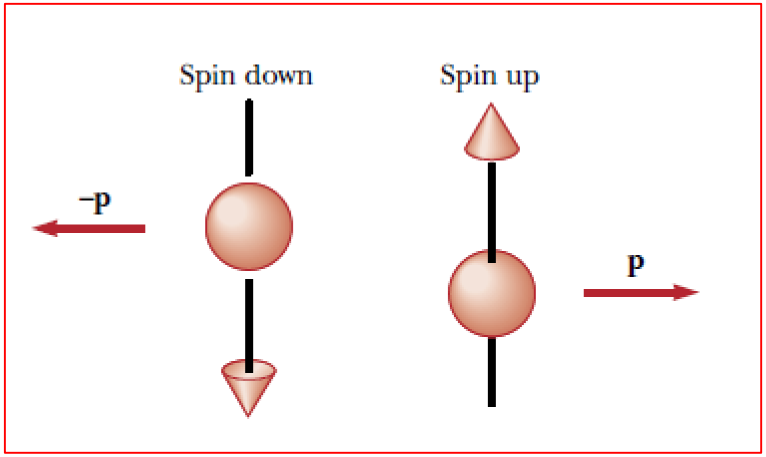
Attractive interaction between two electrons: through the lattice deformation

Electron #I attracts the positive ions, which move inward from their equilibrium position. This distorted region of the lattice has a net positive charge: electron #2 is attracted.

The Cooper pair

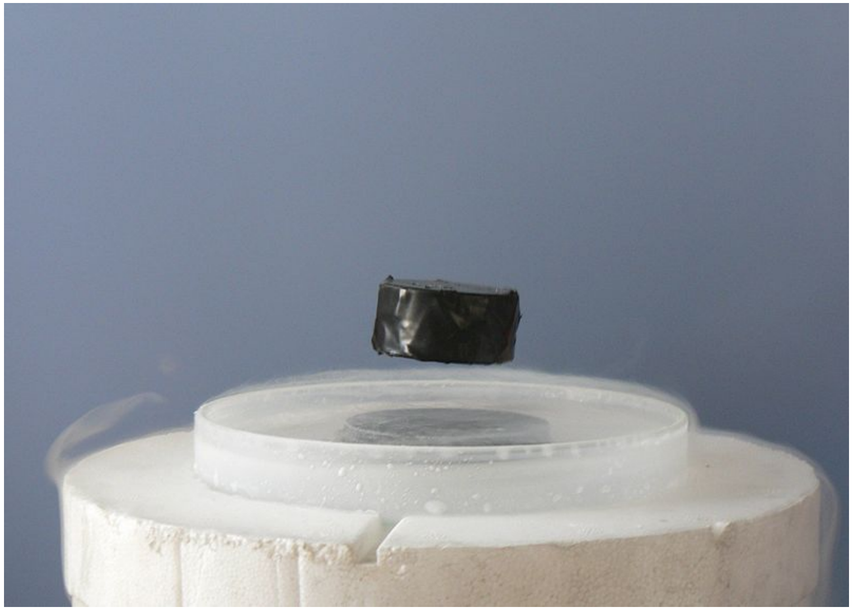
Attractive force between two Cooper electrons: interaction between electrons and lattice: electron-phonon interaction
(Phonons: quantized lattice vibrations)

Cooper pair in a superconductor:
2 electrons with opposite momentum and opposite spin



Total momentum and total spin of the system is zero.

Magnetic levitation



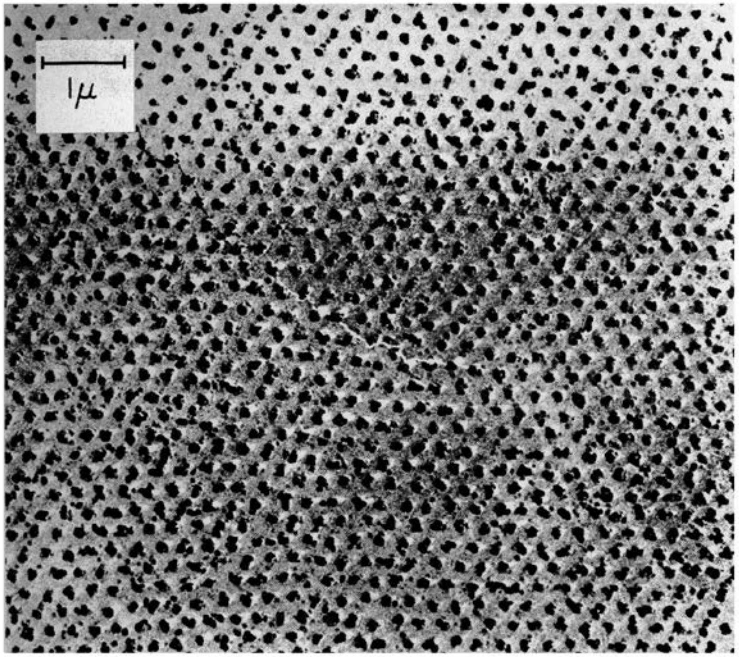
The levitation stems from the same reason as ordinary diamagnetic levitation: a combination of gravitational force and a magnetic force due to the inhomogeneous field.

Applications: *Ultrarapid Centrifuges*

Levitating high speed trains (Japan)

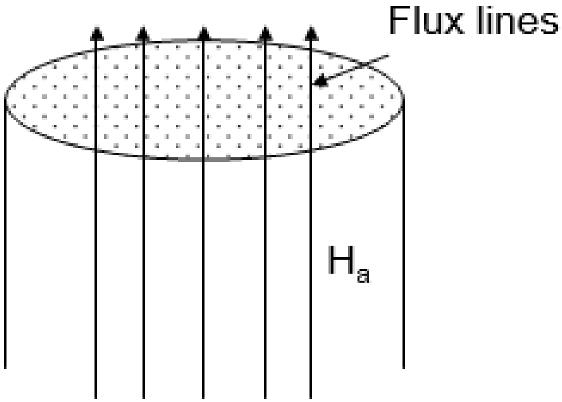
The mixed state: The vortex

Mixed state in Type II superconductors

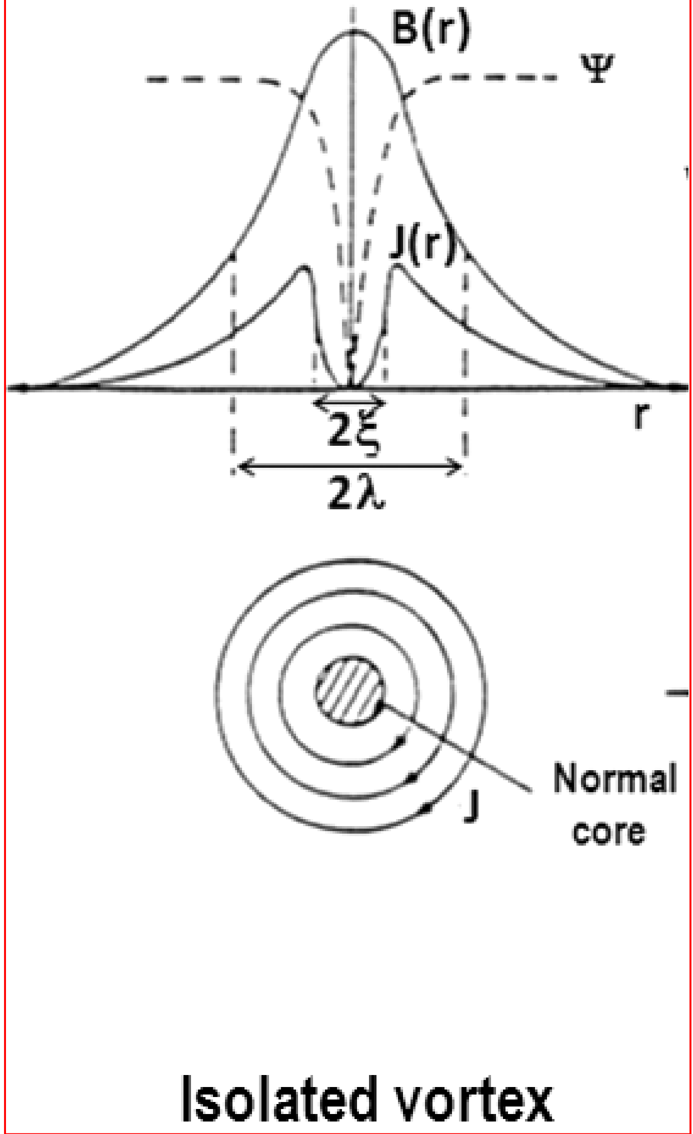


- Experimental observation
  - Magnetic particles on SC
  - Triangular pattern of "normal regions" within SC regions (islands within the superconducting background)
  - Number of lines proportional to B_a
  - $\xi < \lambda$

- One individual normal "island" is called a vortex

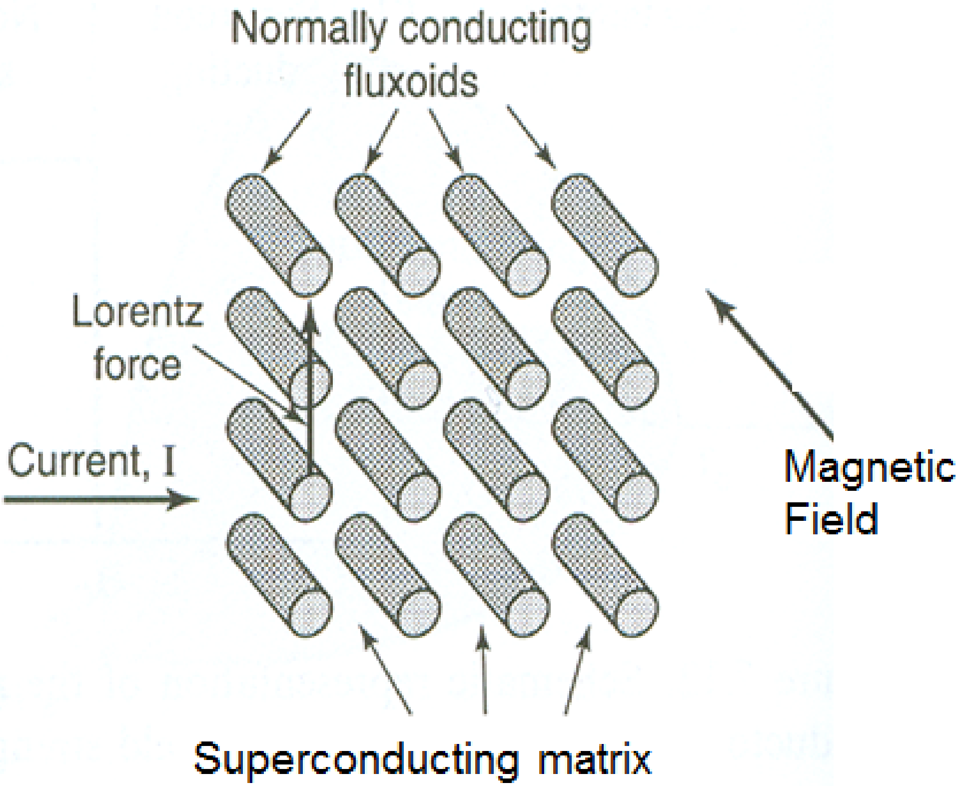


Flux pinning in superconducting wires: the vortex



Isolated vortex

How to imagine a vortex?



Tornado

* Speed zero at the center

* V_{max} outside of the tube *

Diameter: > 100 m

Vortex

* $T_c = 0$ inside (normal)

* $J_c \neq 0$ outside of the vortex

* « Diameter »: < 10 nm

Importance of a Vortex

The vortex is a normal conducting region of nanosize
It pins the magnetic flux lines

The more magnetic flux lines are pinned, the higher is the current which can pass through the superconductor without to render it normal conducting

→ A perfect superconductor does not carry supercurrent
The more local defects, the higher J_c , the critical current density

The art consists in introducing as many vortices (nanosize defects) as possible :

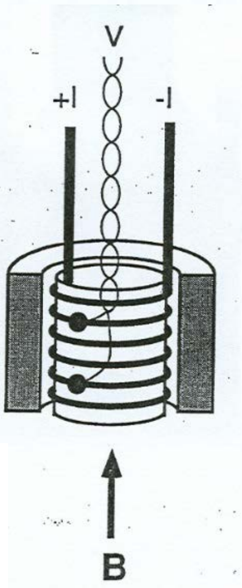
- **By nano-inclusions**
- **By high energy irradiatiom**

The critical current density J_c

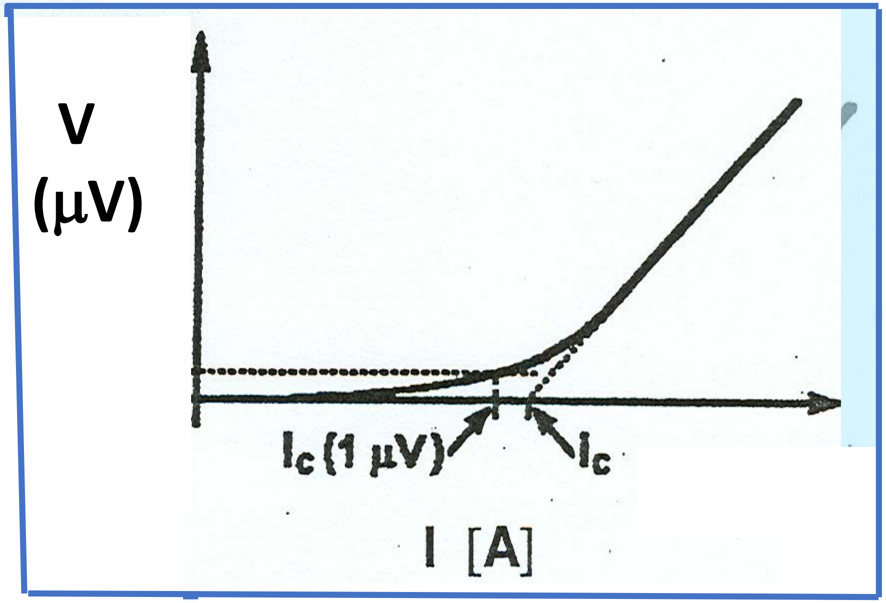
Transport Measurement of J_c

Long wires

(length: > 0.1 m)

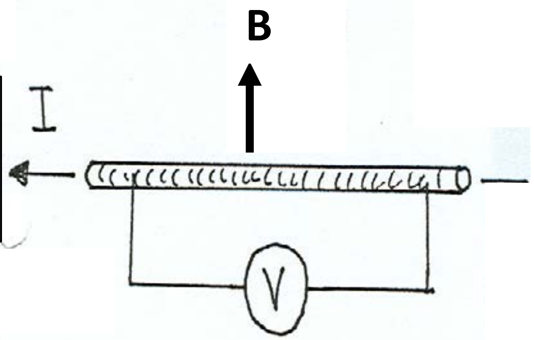


Long wires:
Criterion for J_c:
0.1 μV/cm



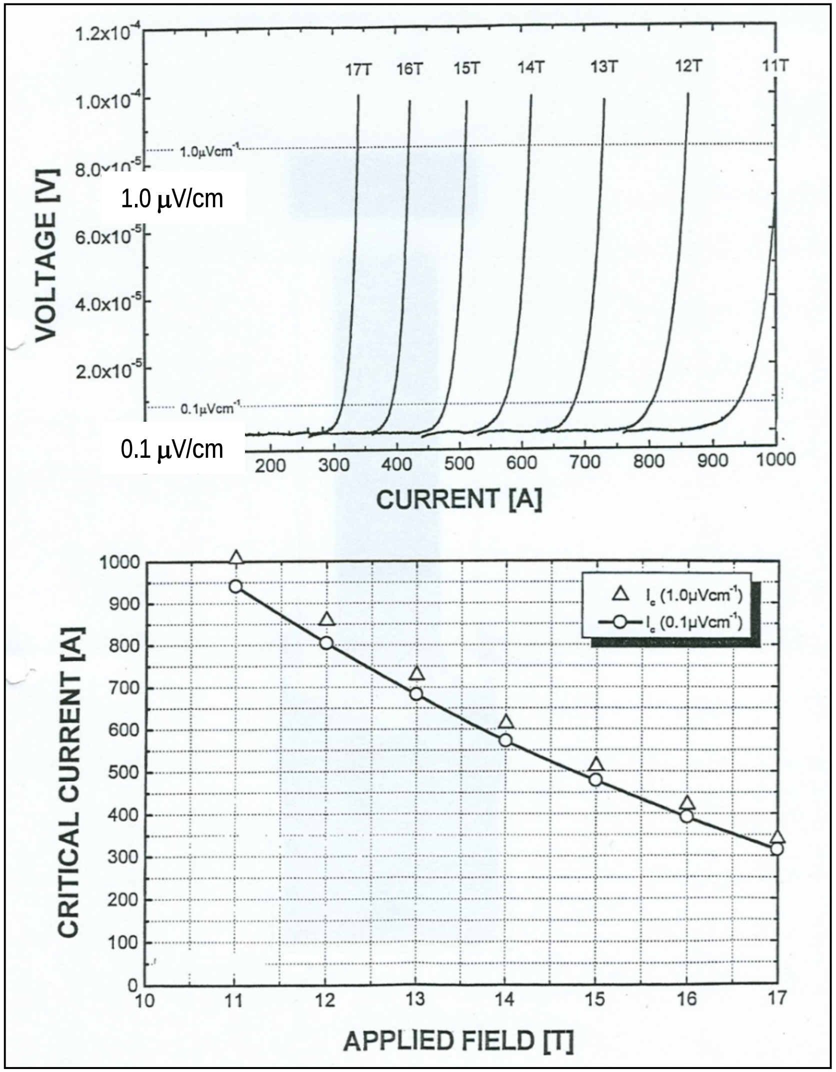
Short wires

(2-3 cm length)



Short wires: Criterion for J_c: 1 μV/cm

Measurement of Industrial Nb_3Sn wires



Resistive superconducting transition at various magnetic fields

(Industrial wire for Bruker)

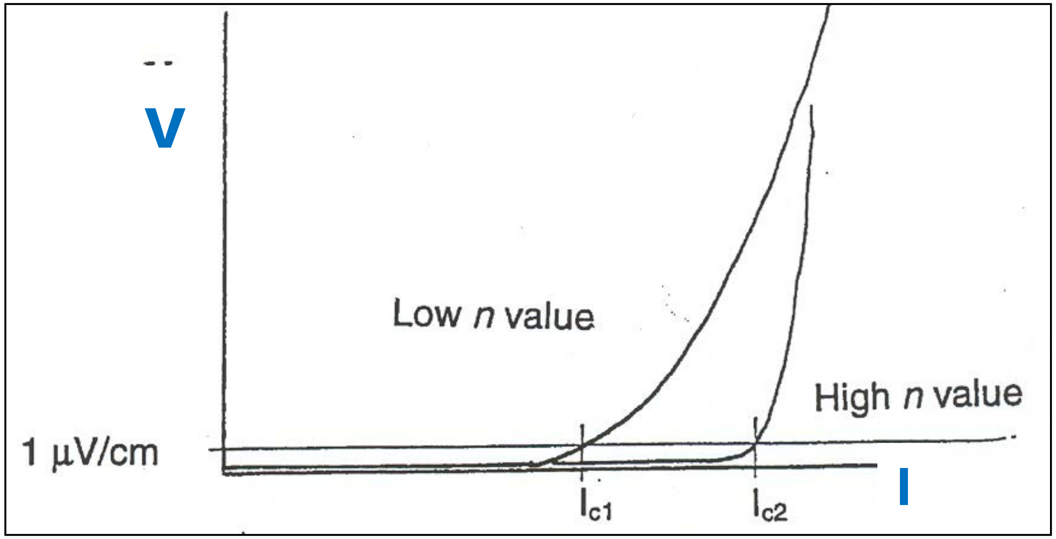
Variation of critical current vs. applied magnetic field B

The exponential *n* factor

The *n* factor is an empirical quantity describing the quality of the wire:

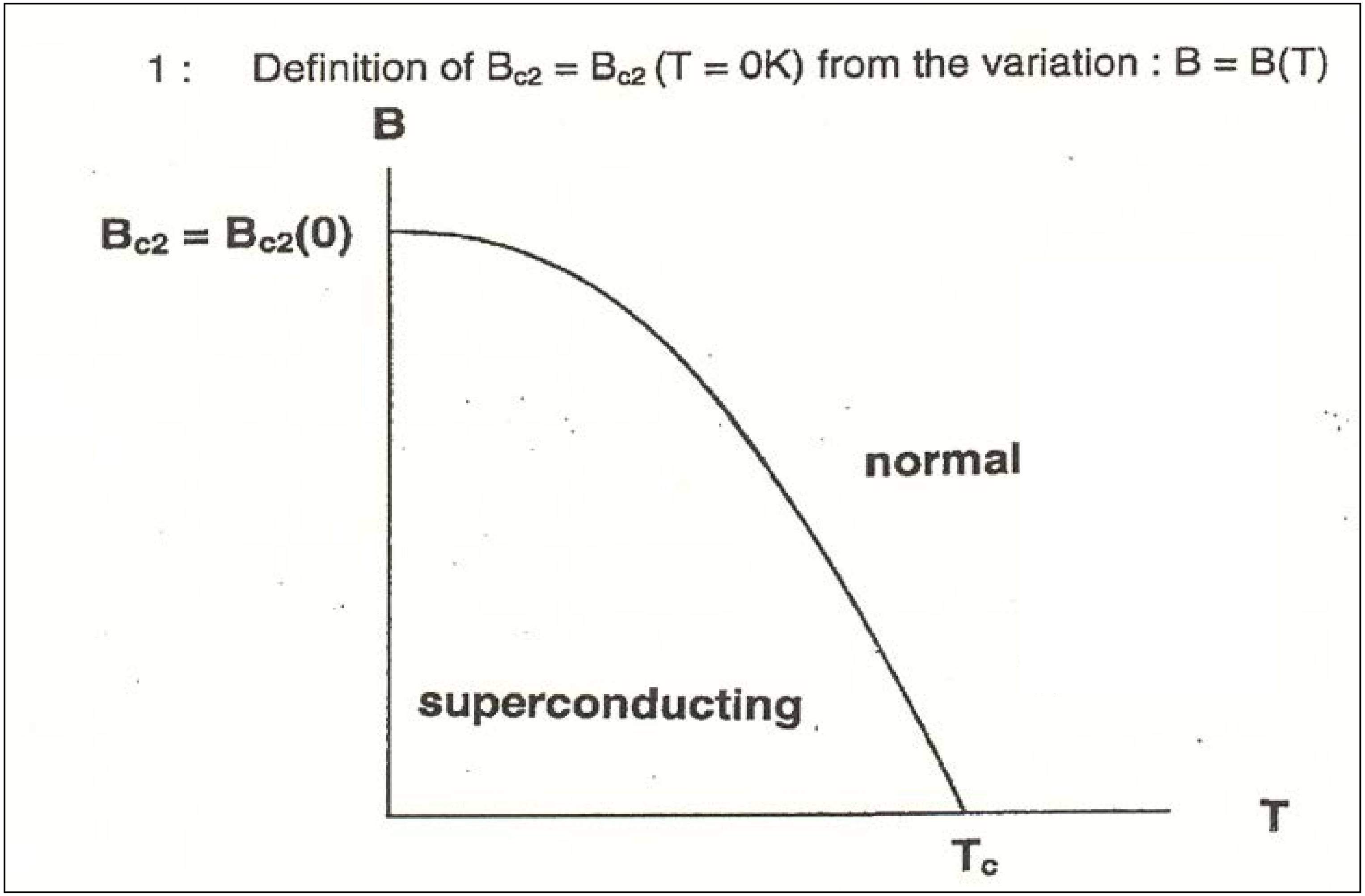
* surface state of the filaments
* homogeneity along the wire axis («sausaging»)

Definition: $V \sim I^n$ at a given operational B and T



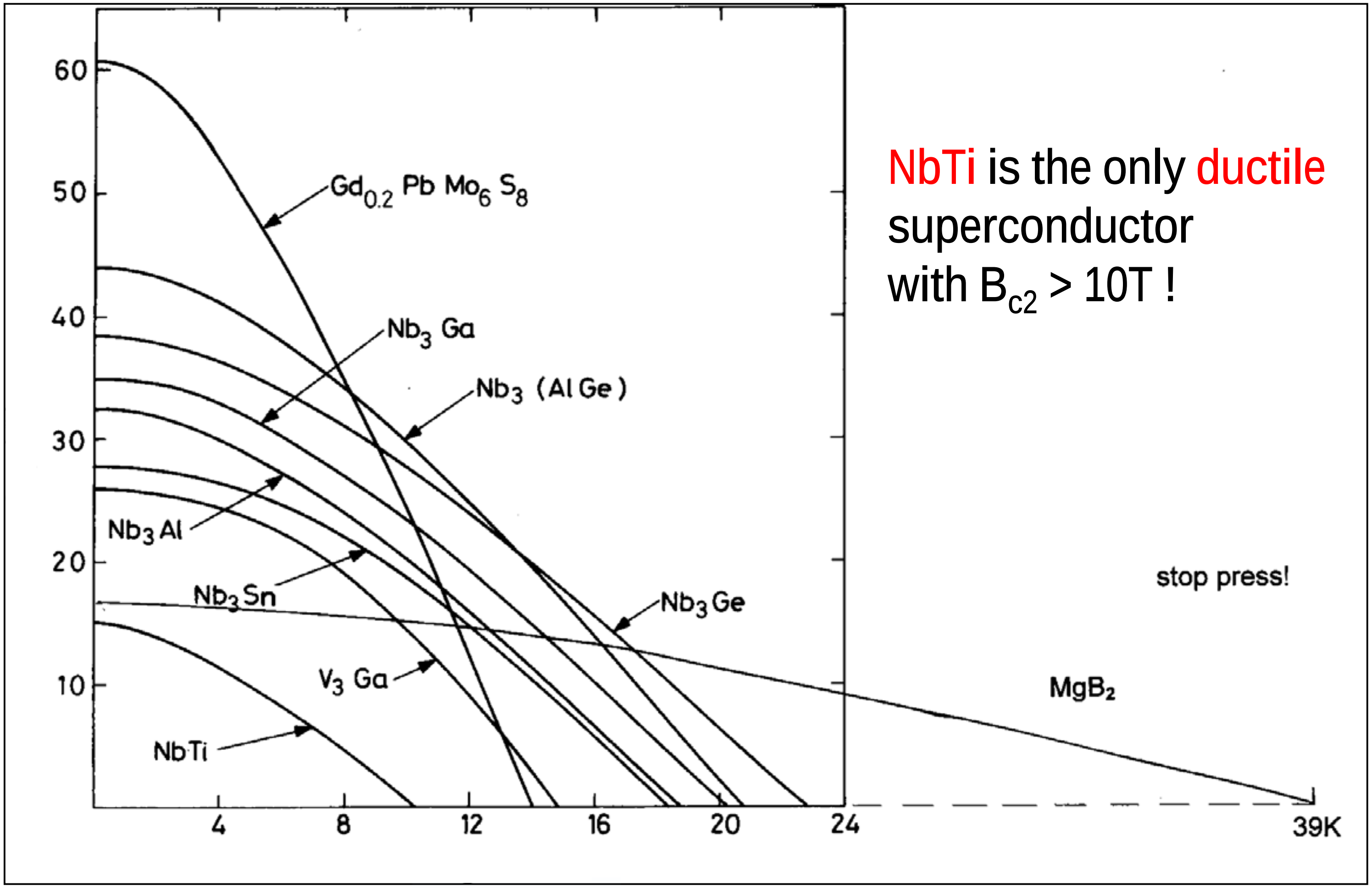
In general, a high *n* value corresponds to a wire of higher quality
Required*:* ***n* > 30** at operational B and T.
Highest *n* values for NMR magnets

The upper critical magnetic field B_{c2}



1 : Definition of $B_{c2} = B_{c2}$ (T = 0K) from the variation : B = B(T)

Upper critical fields of metallic (LTS) superconductors



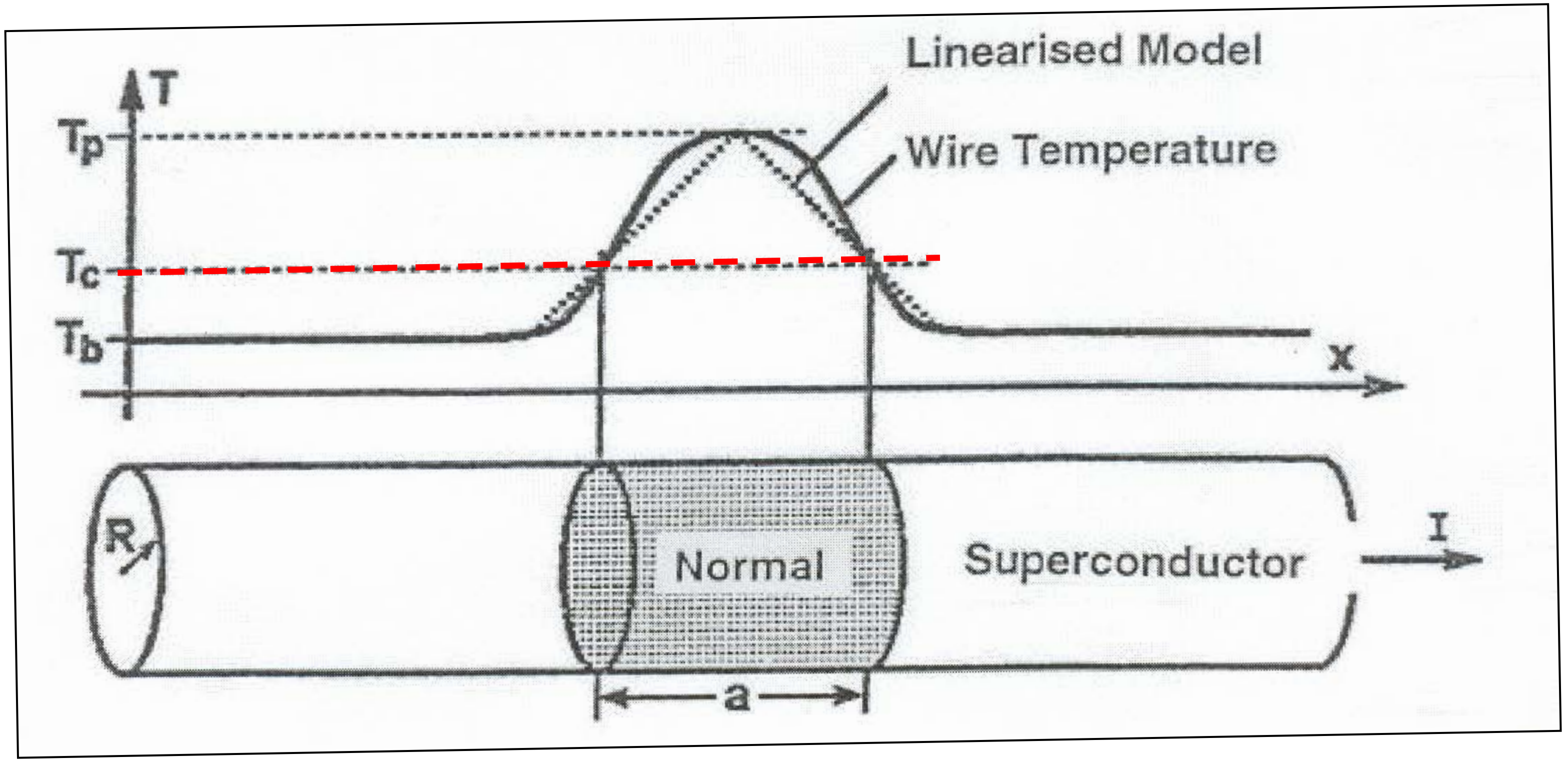
NbTi is the only ductile superconductor
with B_{c2} > 10T !

Why must the filaments in a superconducting wire be nanosized?

III. Thermal Stability of a wire submitted to a current

Local and/or temporary perturbations may lead to thermal instability and to a quench.

Consider a wire with T_c submitted to I in bath T_b. Stable operation conditions: $T_c > T_b$



Why multifilamentary superconducting wires?

Suppose a local perturbation causing : $T = T_p > T_c$

→ * a resistive zone develops in the wire

* Joule heat is built up locally.

Energy to be evacuated to restore the superconducting state comprises:

*the energy leading to the perturbation, and

*the energy produced by the Joule heat.

Three different power terms have to considered:

1: The Joule heat

$$P_{joule} = R_n I^2 = \rho_n \, a \, j^2 \, \pi R^2 ,$$

where $j = I / \pi R^2$, and ρ_n = normal resistivity.

2. Heat conduction through the wire

Heat from the resistive zone to the neighbouring superconducting region:

$$P_{conduction} = 2\pi R^2 \lambda\, dT/dx = 2\pi R^2 \lambda\, dT',$$

where λ = thermal conductivity

T' = temp. gradient in perturbed zone

$= dT/dx = 2\,(T_p - T_c)/a$

3. Heat transfer to the bath, in a slice of thickness x

$$dP_{bath} = 2\pi R h\,[\,T(x) - T_b\,]\,dx, \quad \text{and}$$

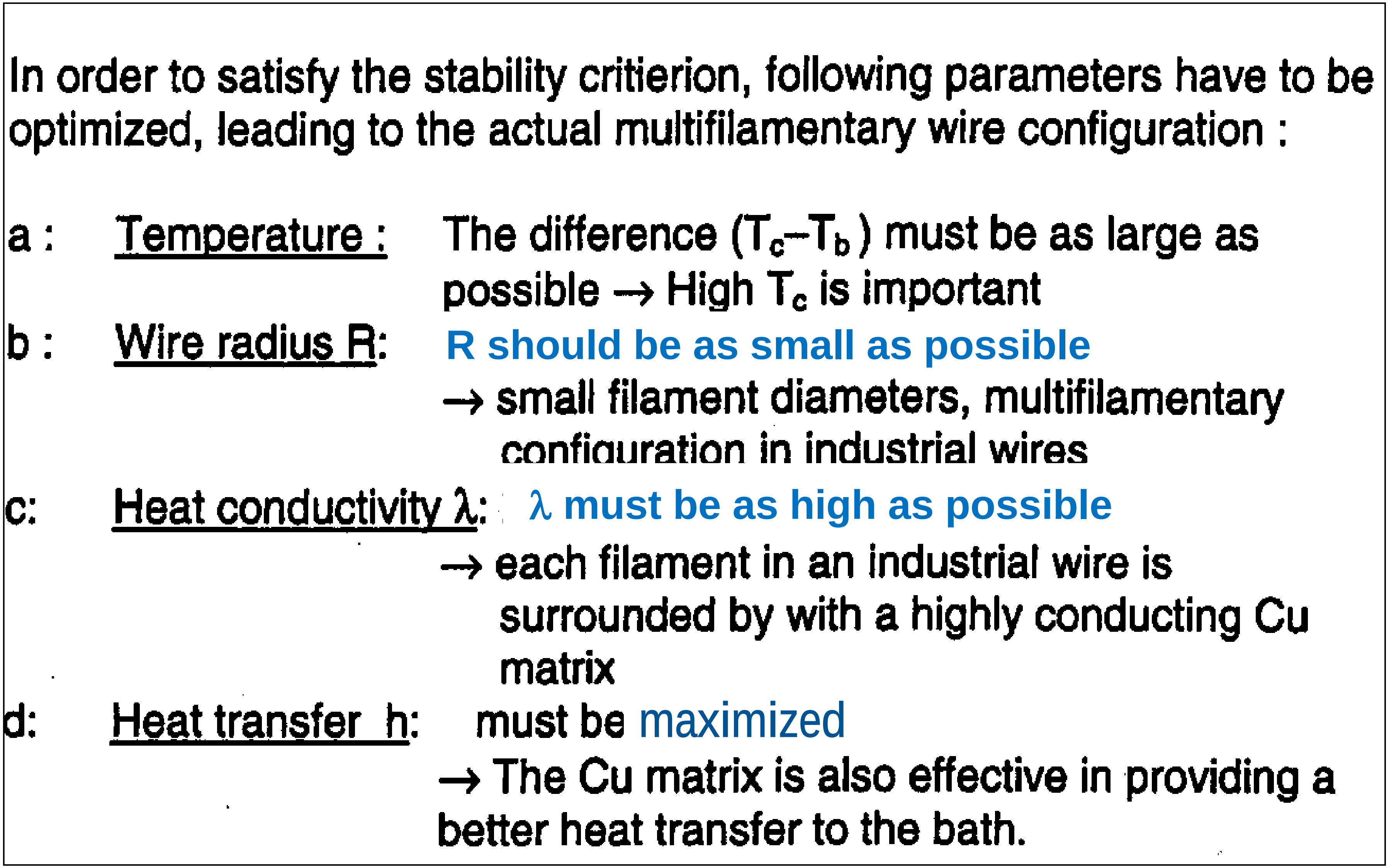
$$P_{bath} = 2\pi R a h\,[\,(T_c - T_b) + a T'\,],$$

where h = heat transfer coefficient (to the bath)

The thermal stability limit is now given by : $P_{joule} < P_{conduction} + P_{bath}$

$$\rho_n I^2 < 2\lambda\, dT'\; 1/a + hT'/2R\; a + 2h/R(T_c - T_b) \equiv f(a)$$

Stability criteria for wires



In order to satisfy the stability critierion, following parameters have to be optimized, leading to the actual multifilamentary wire configuration :

a : <u>Temperature :</u> The difference (T_c–T_b) must be as large as possible → High T_c is important

b : <u>Wire radius R:</u> **R should be as small as possible**
→ small filament diameters, multifilamentary configuration in industrial wires

c: <u>Heat conductivity λ:</u> **λ must be as high as possible**
→ each filament in an industrial wire is surrounded by with a highly conducting Cu matrix

d: <u>Heat transfer h:</u> must be maximized
→ The Cu matrix is also effective in providing a better heat transfer to the bath.

Practical criteria for stability and applicability of superconducting wires

1 : Chemical stability

2 : Mechanical stability :

Bulk superconductors (except NbTi) break at **ε <0.05 % !**

→ microcomposite (multifilamentary) configuration

Filament size: < 5 - 30 µm

Wires: Irreversible strain: $\varepsilon_{irr} > 0.4$ %

3 : Cryogenic stability : presence of Cu as stabilizer

High thermal conductivity of Cu

→ a minimum quantity of stabilizer is required (> 23% Cu)

4 : Electromagnetic stability :

Low AC coupling losses required → Twisting of wires

5 : Low material costs

6: Length: > 1 km

Typical wire configuration: 1'000 -10'000 filaments
5 - 30 µm filament size
25 cm twist pitch