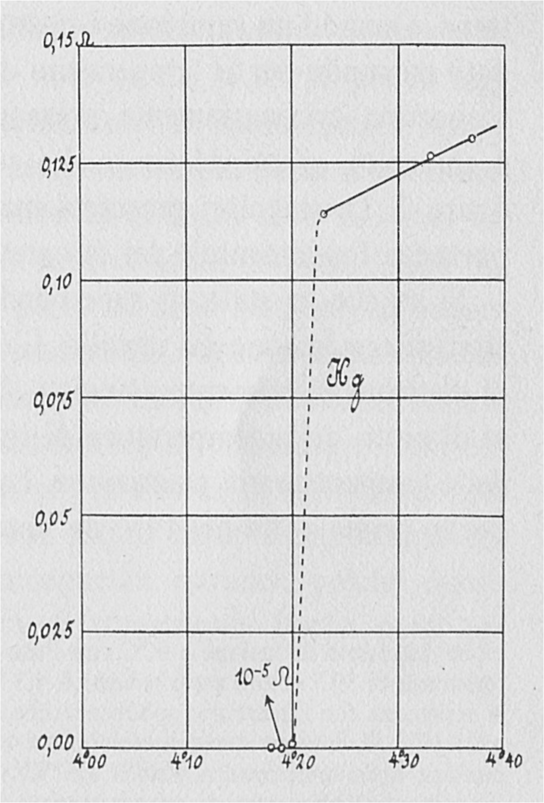
Stato attuale dei materiali superconduttori e loro prospettive applicative

Giovanni Grasso

Columbus Superconductors
GRUPPO MALACALZA

June 17th, 2011

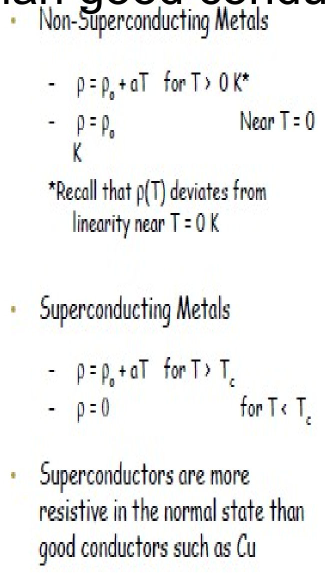
100-years old discovery of Superconductivity



In 1908, Kamerlingh Onnes succedeed to liquify He for the first time in Leiden (NL)
In 1911, as a result of routine experiments, he discovered superconductivity in pure Mercury just above 4.2 K

Non-Superconducting Metals
– ρ = ρo + aT for T > 0 K*
– ρ = ρo near T = 0 K
*Recall that ρ(T) deviates from linearity near T = 0 K

- Superconducting Metals
– ρ = ρo + aT for T > Tc
– ρ = 0 for T < Tc
- Superconductors are more resistive in the normal state than good conductors such as Cu



- Non-Superconducting Metals
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  - $\rho = \rho_o$ Near T = 0 K

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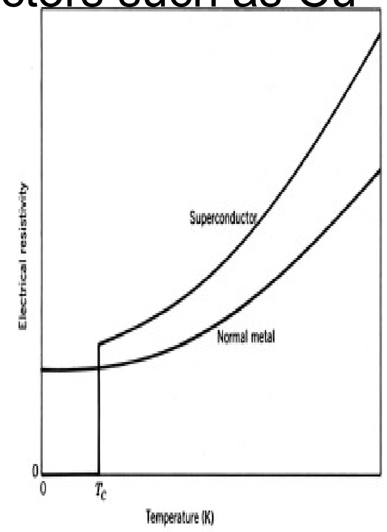
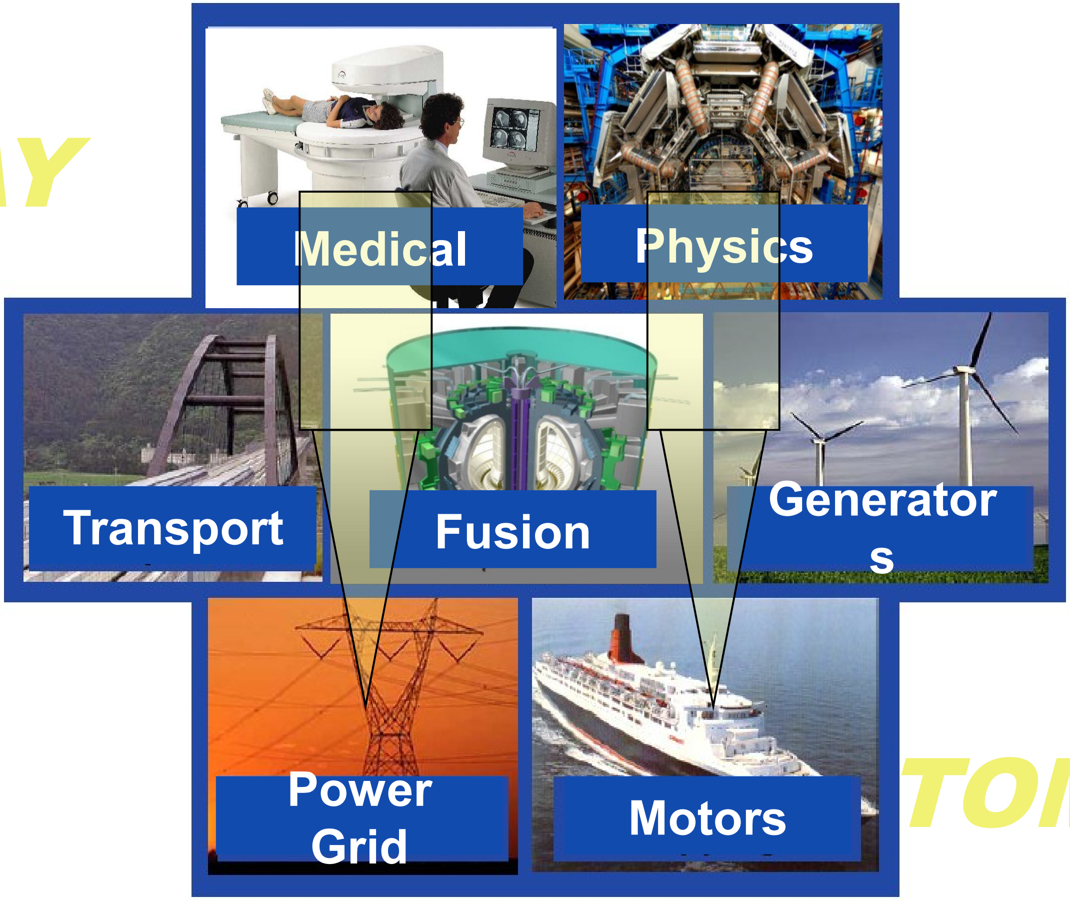
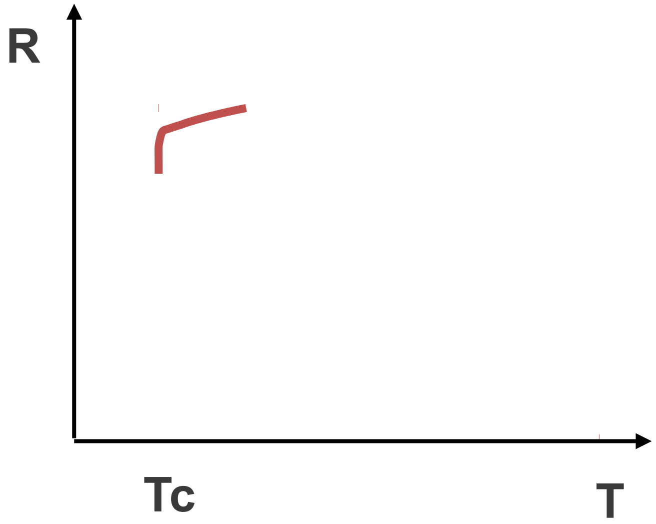
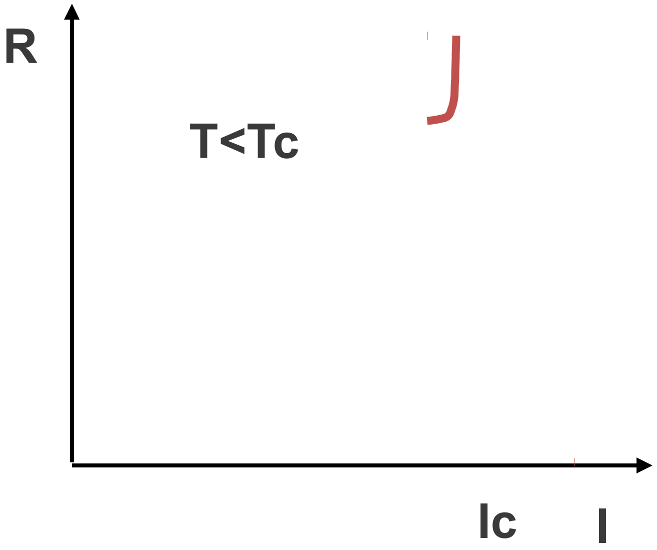


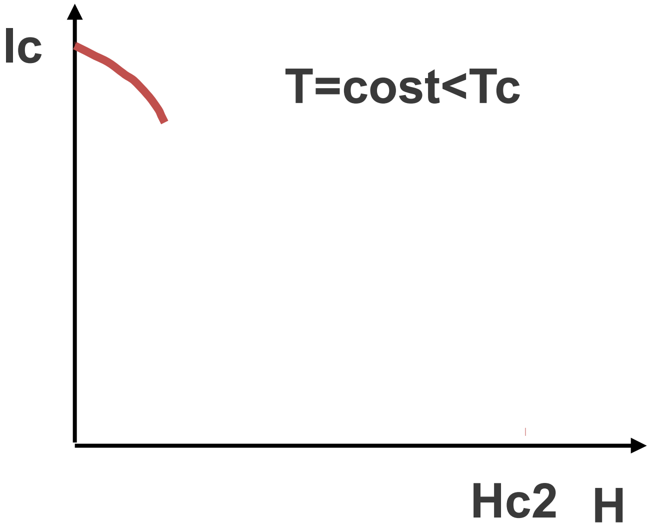
Applied Superconductivity

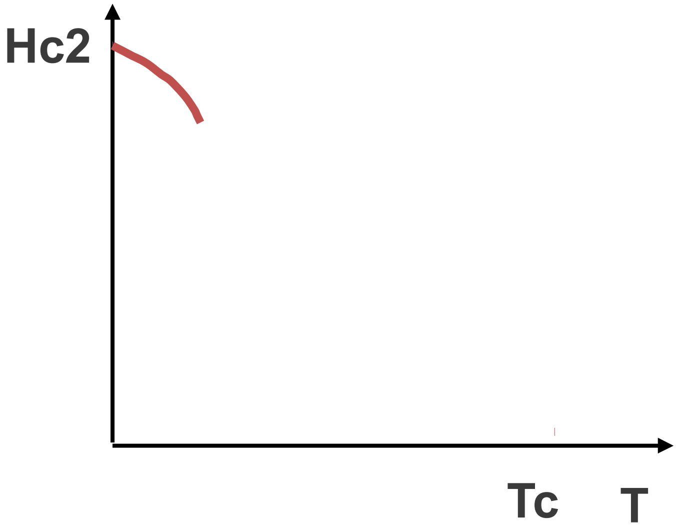


Proprietà caratterizzanti un superconduttore





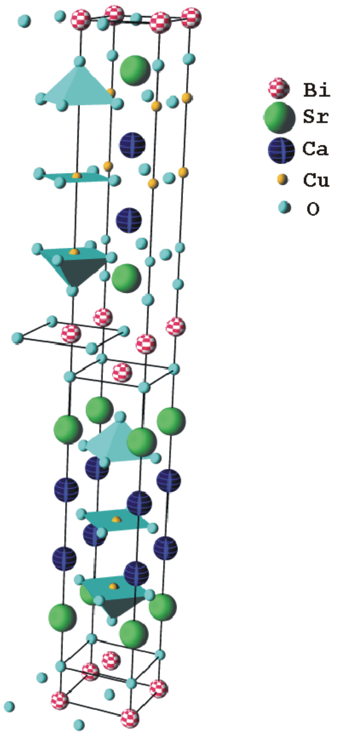


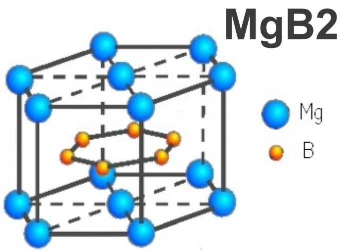


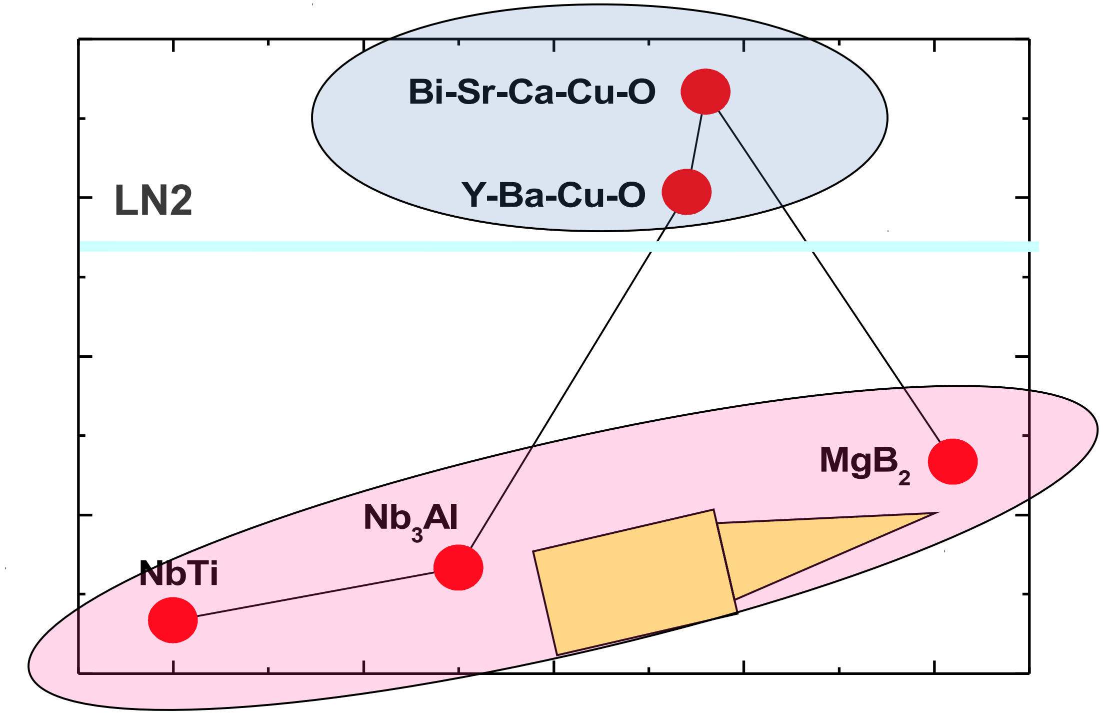
Requisiti di un filo superconduttore per applicazioni di potenza

Alta temperatura di esercizio
Elevata densità di corrente critica
Basse perdite in corrente alternata
Capacità di sopportare elevati campi magnetici
Disponibilità in grandi lunghezze
Buone proprietà meccaniche
Prezzo competitivo

Cronologia dei materiali superconduttori

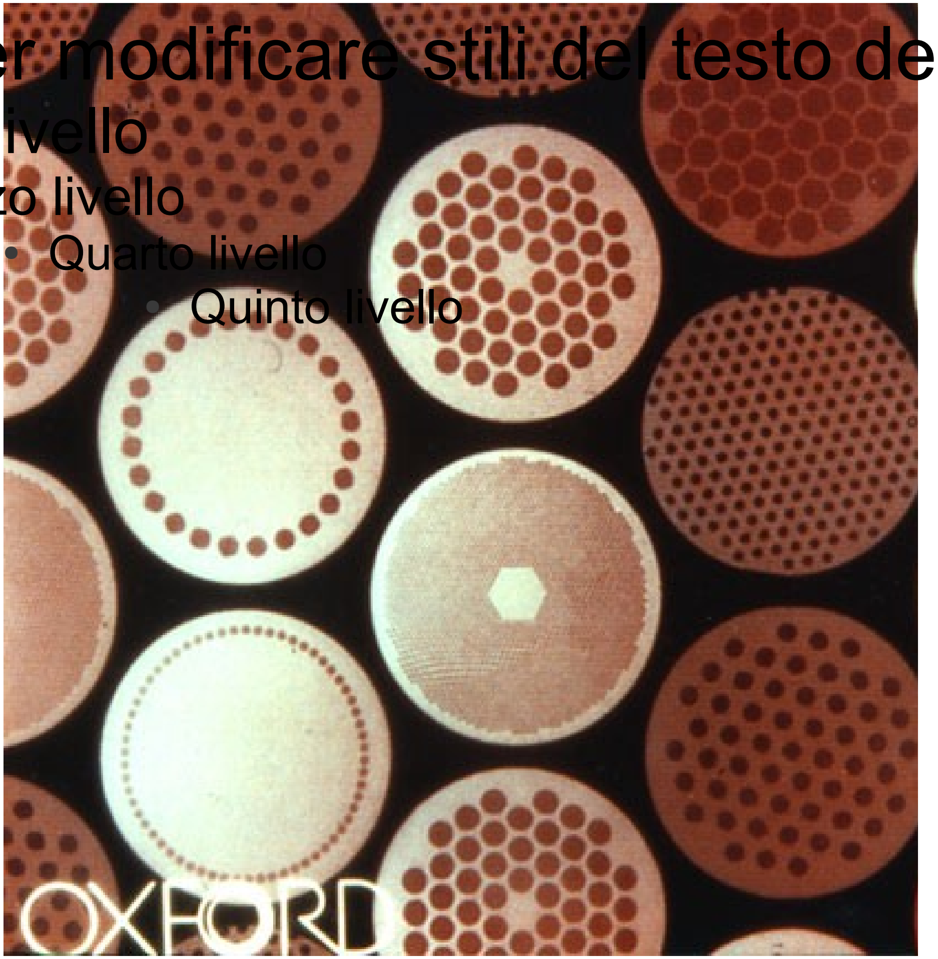






2 famiglie distinte di materiali superconduttori sono distinguibili

Nb-Ti filamentary composite wires



per modificare stili del testo dello schema

o livello

erzo livello

- Quarto livello
  - Quinto livello

superconducting materials are always used in combination with a good normal conductor such as copper for protection purposes

to ensure intimate mixing between the two, the superconductor is made in the form of fine filaments embedded in a matrix of copper

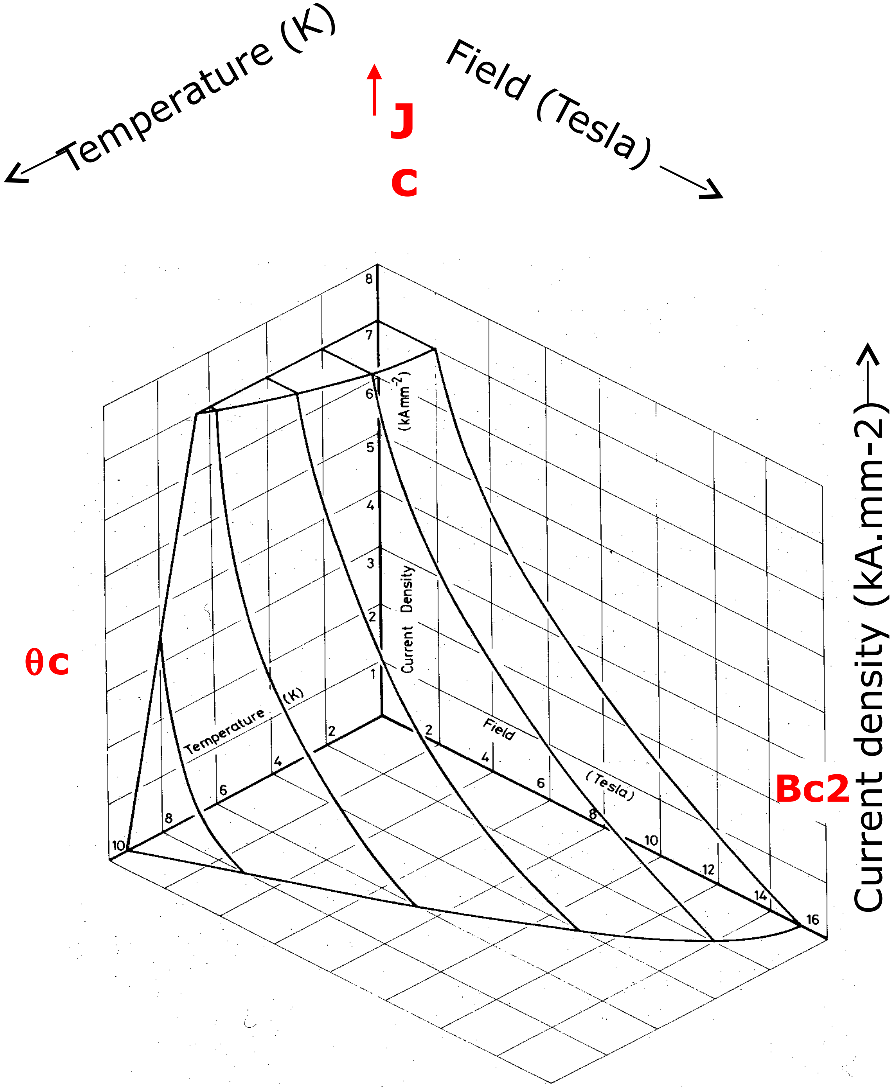
typical dimensions are:

wire diameter = 0.3 - 1.0mm

filament diameter = 10 - 60mm

for electromagnetic reasons, the composite wires are twisted so that the filaments look like a rope (see Lecture 3 on cables)

The critical surface of niobium titanium



Niobium titanium **NbTi** is the standard 'work horse' of the superconducting magnet business

it is a ductile alloy

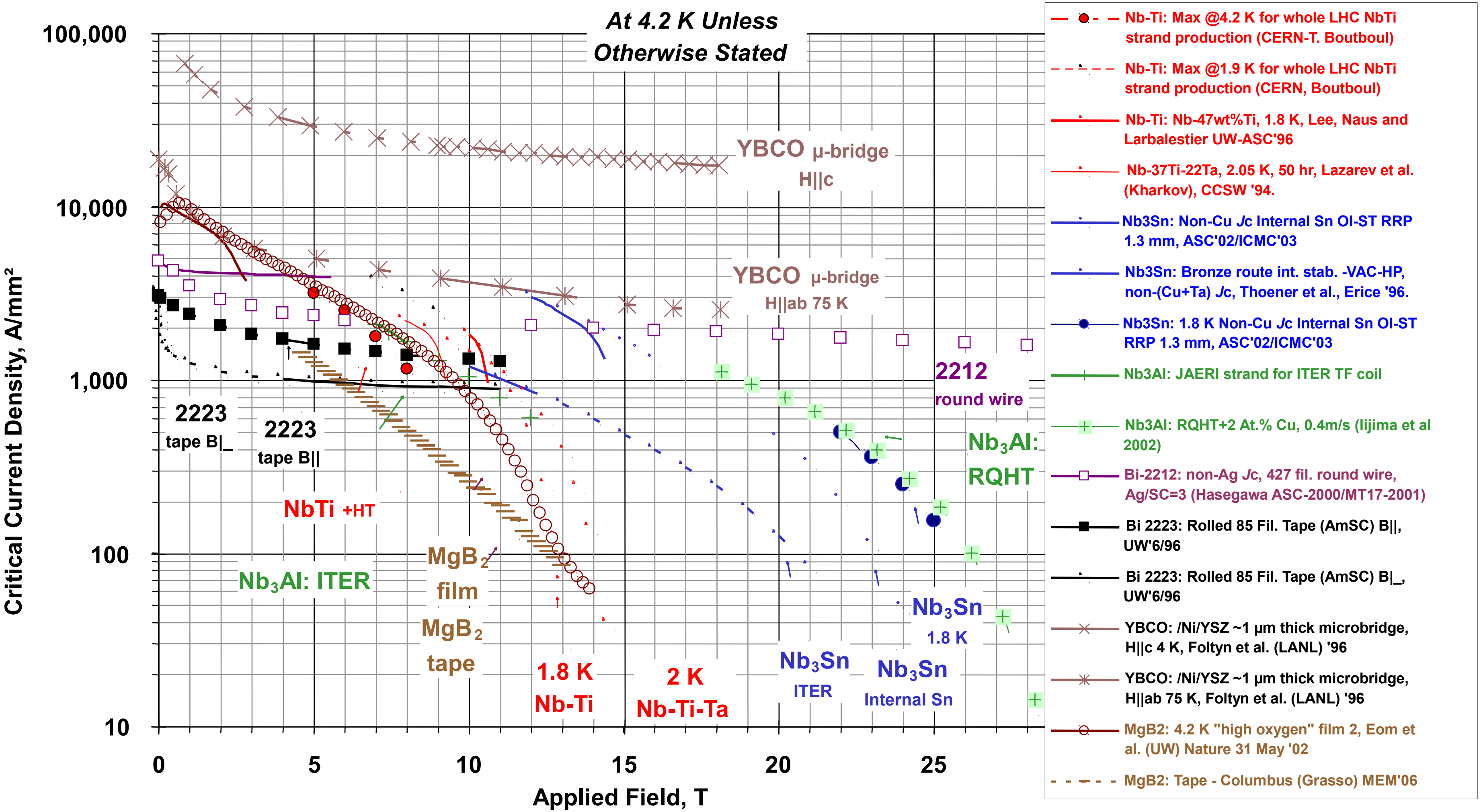
picture shows the **critical surface**, which is the boundary between superconductivity and normal resistivity in 3 dimensional space

superconductivity prevails everywhere below the surface, resistance everywhere above it

we define an upper critical field **Bc2** (at zero temperature and current) and critical temperature **θc** (at zero field and current) which are characteristic of the alloy composition

critical current density **Jc(B, θ)** depends on processing

Critical currents of technical superconductors at 4.2 K



Superconductors choice is ‘in principle’ quite wide, but jc is not the only important parameter for selection

Considerations

§There is a significantly growing interest towards LHe-free applications of superconductivity

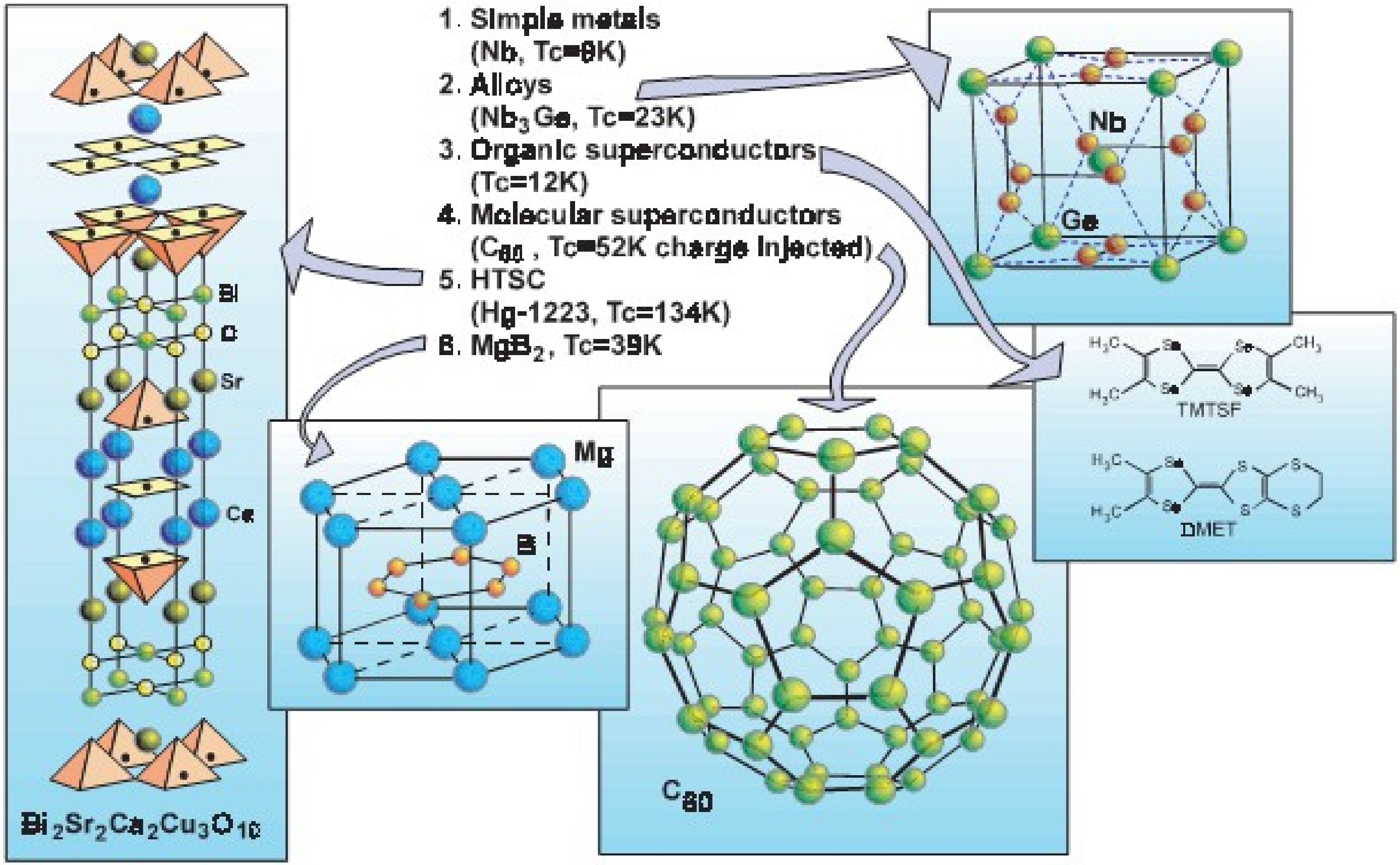
§Superconducting windings operated above 10 K will profit from a higher stability and reluctance to quench

§Easier installation and operation in a non-ideal environment are in favor of a cryogenic-free system

§Operation at higher temperatures helps making superconducting devices, particularly AC, more efficient and competitive

§Superconducting devices become more competitive on large scale devices, therefore R&D and prototyping are high risk activities

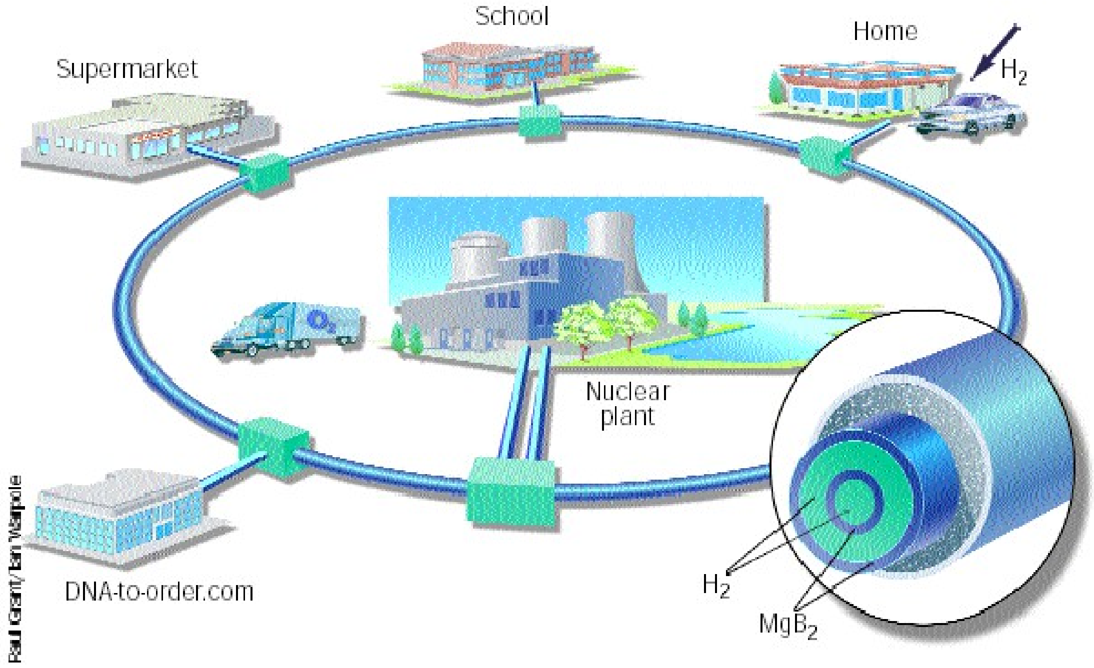
Structures of different classes of superconductors



1. Simple metals
(Nb, Tc=9K)
2. Alloys
(Nb_3Ge, Tc=23K)
3. Organic superconductors
(Tc=12K)
4. Molecular superconductors
(C_{60} , Tc=52K charge injected)
5. HTSC
(Hg-1223, Tc=134K)
6. MgB_2, Tc=39K

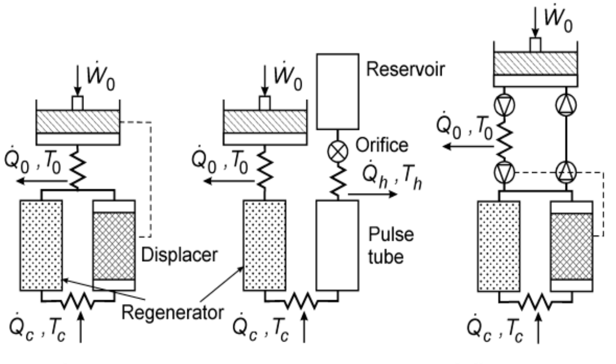
Principali liquidi criogenici

Superconduttori ed il mondo del futuro…

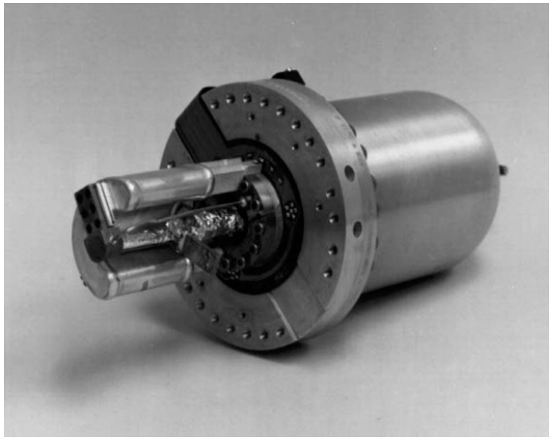


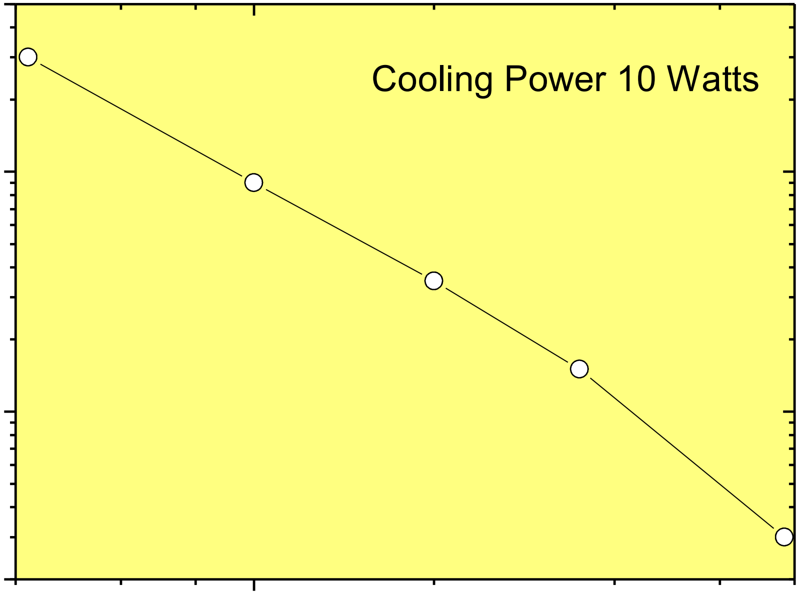
Paul Grant/ Ian Walpole

Cryocoolers: tecnologia alternativa per raffreddare i superconduttori



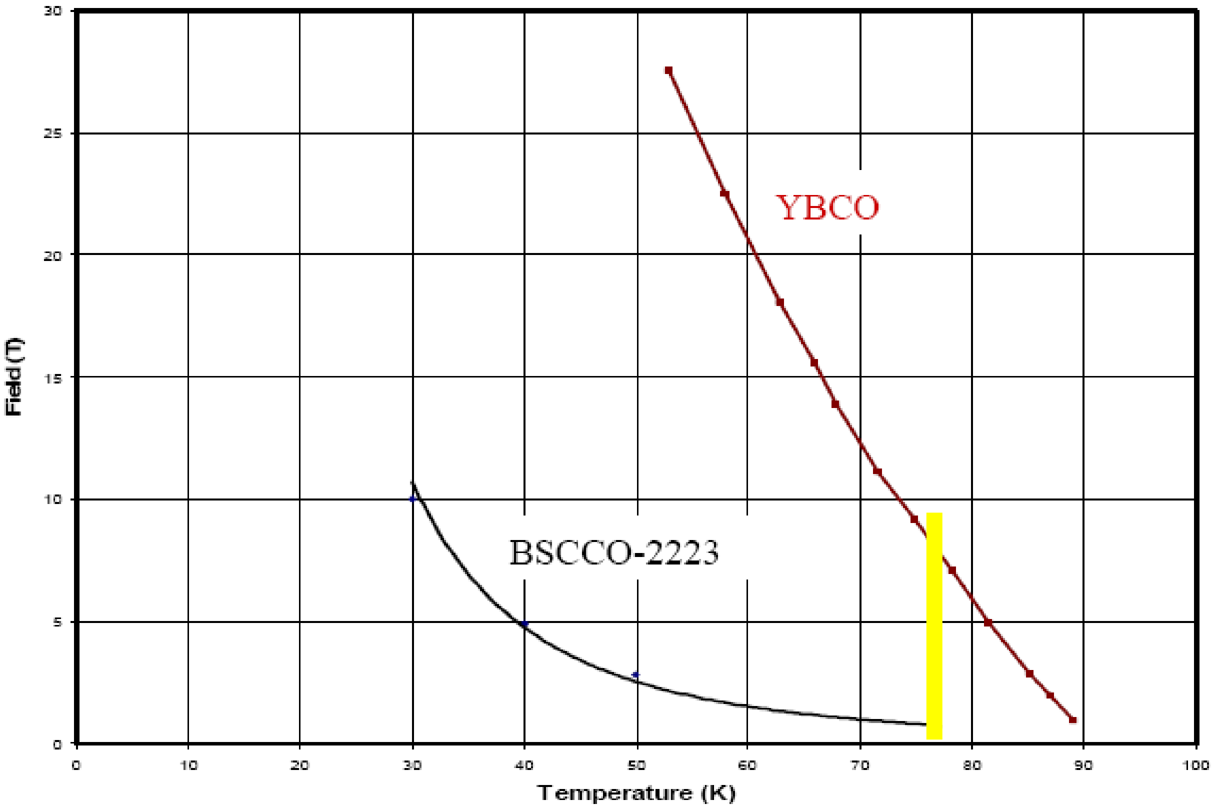
(a) Stirling (b) Pulse Tube (c) Gifford-McMahon





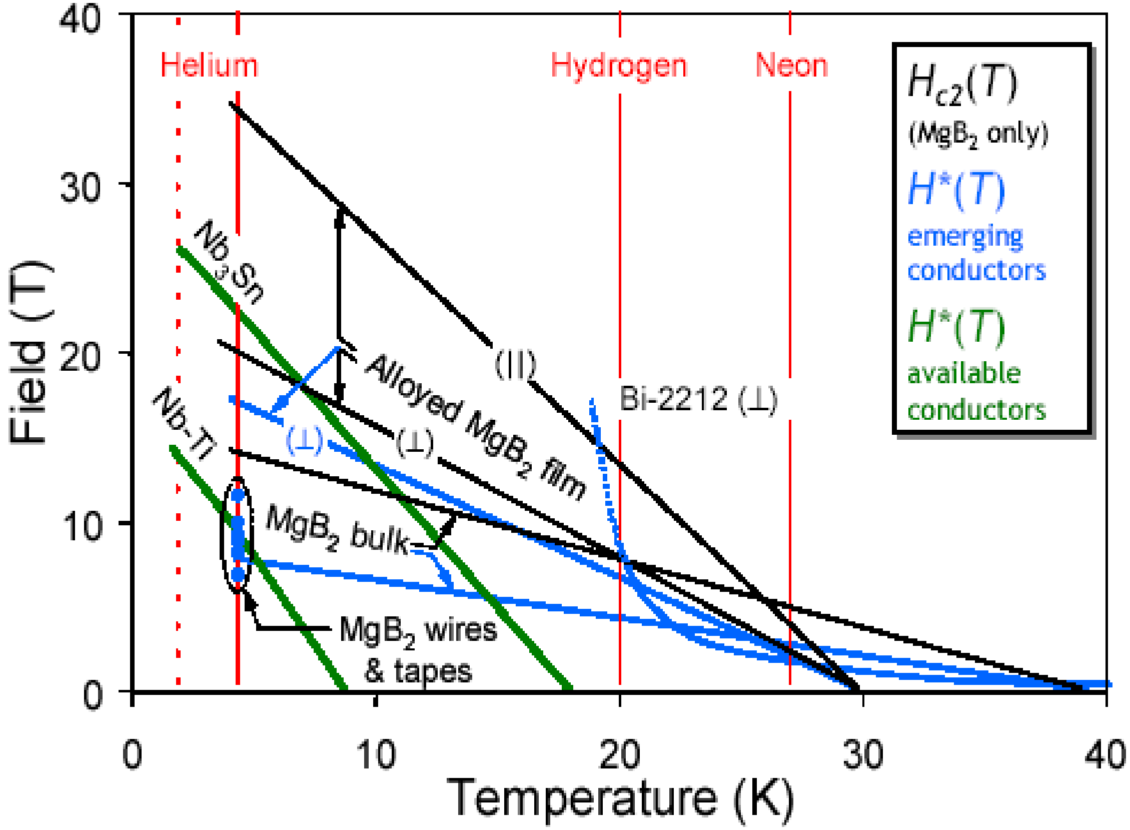
I cryocoolers risolvono solo parzialmente il problema: compatibili solo con devices molto efficienti

Comportamento a T>>4.2 K
Linee di irreversibilità per SAT



L'YBCO è al momento l'unico superconduttore che può consentire sulla carta applicazioni a 77K in campo magnetico

New Entry (2001): MgB2
Potenziale per applicazioni elettriche a temperature intermedie tra 4.2K e 77K



Il comportamento in campo magnetico dell'MgB2 è notevolmente migliorabile

Superconduttori in corrente alternata

I superconduttori in corrente alternata perdono la loro caratteristica di trasportare corrente senza dissipazione, questo a causa di:

1. isteresi magnetica superconduttiva;
2. accoppiamento elettrico tra filamenti;
3. alla guaina che li contiene

1-ISTERESI SUPERCONDUTTIVA

Nei S/C di tipo II: ‘flussoni’, quanti di flusso di campo; si ancorano nei centri di ‘pinning’, permane una magnetizzazione

CICLO DI ISTERESI MAGNETICA

Come calcolarlo?Come conoscere il campo all’interno del S/C?

MODELLO di BEAN (1962): la comparsa di un E genera una J=Jc

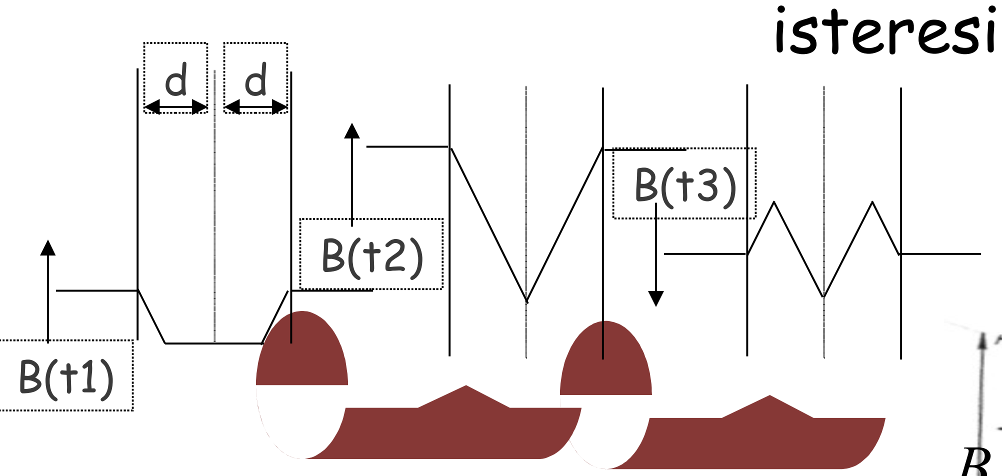
dalla 2a eq. di Maxwell: $\nabla \times B = \mu_0 J = \mu_0 J_c$ secondo Bean

conoscendo Jc si risale a B

<u>Esempio</u>: 'slab' infinito parallelo a B, semispessore d.

Problema unidimensionale : By=m0Jcx

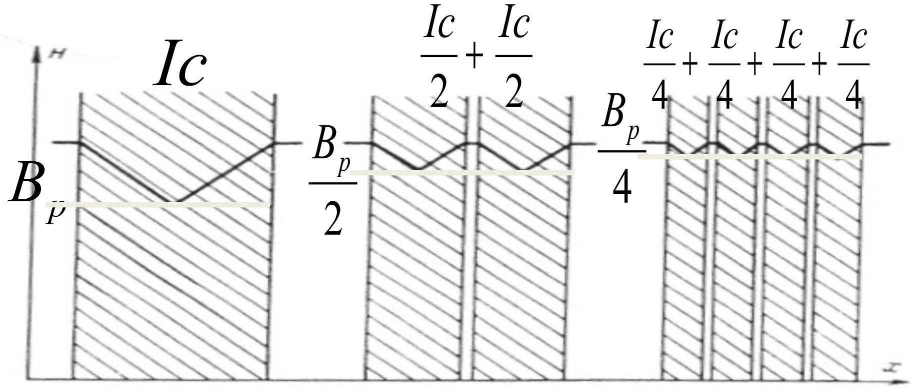
Il campo penetra fino a Bp=m0Jcd



diminuendo <u>d</u>,
diminuisce l'isteresi.

Ma per mantenere stessa corrente(sezione)…

<u>multifilamentare</u>

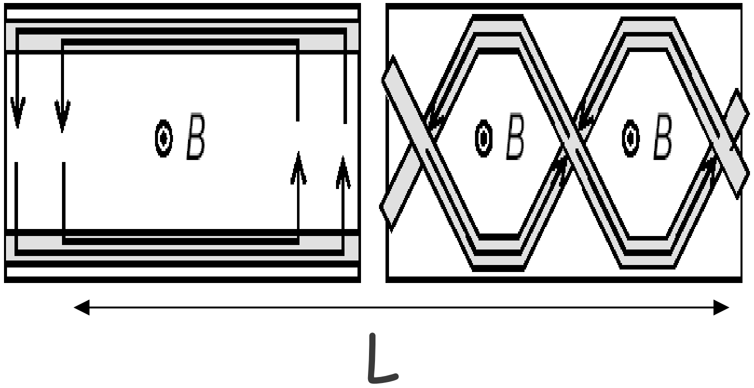


$$P_{ist} \propto \oint_{ciclo} MdB \propto B_p d \qquad \Rightarrow \qquad B_p d$$

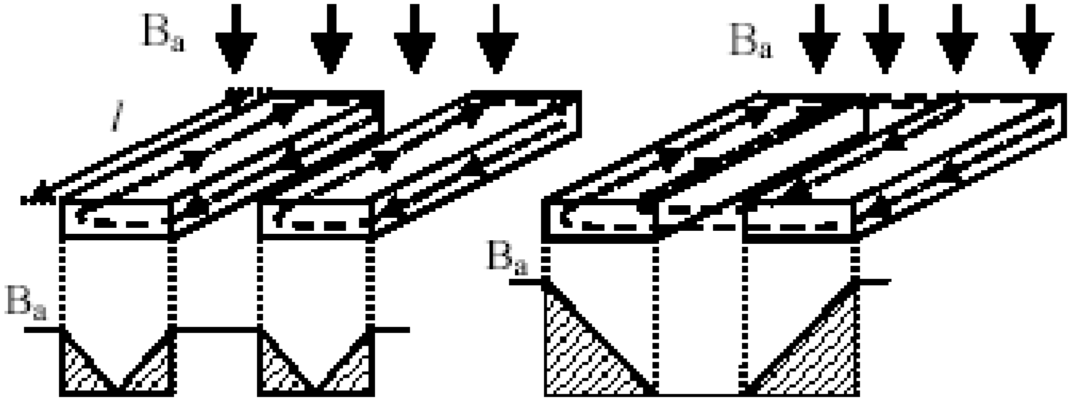
$$\left(\frac{B_p}{2}\right)\cdot\left(\frac{d}{2}\right) \qquad \left(\frac{B_p}{4}\right)\cdot\left(\frac{d}{4}\right)$$

2-ACCOPPIAMENTO TRA I FILAMENTI

Per la legge di Faraday-Neumann-Lenz:



$$L_c = 4\sqrt{\frac{\rho \cdot J_c d}{2\omega B_a}}$$

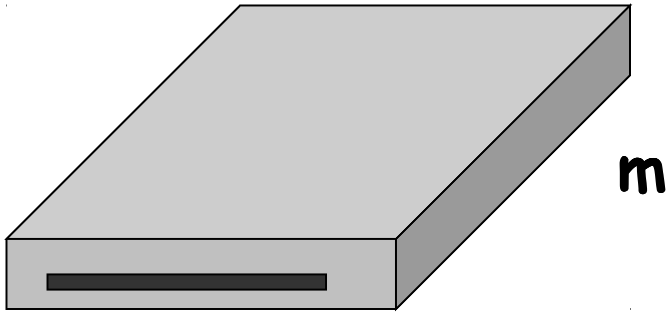


disaccoppiati

accoppiati completamente

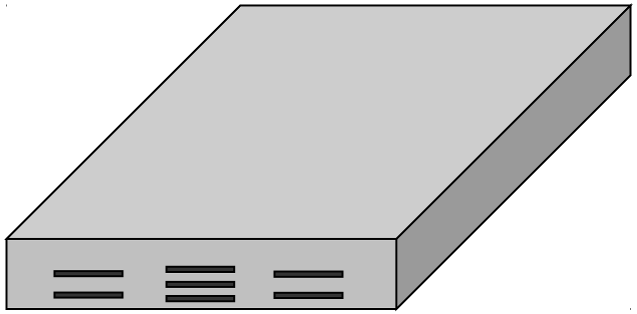
Si comportano di nuovo come un unico filamento!

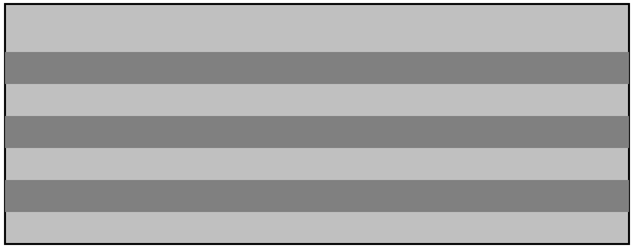
Riassumendo:



multifilamentare

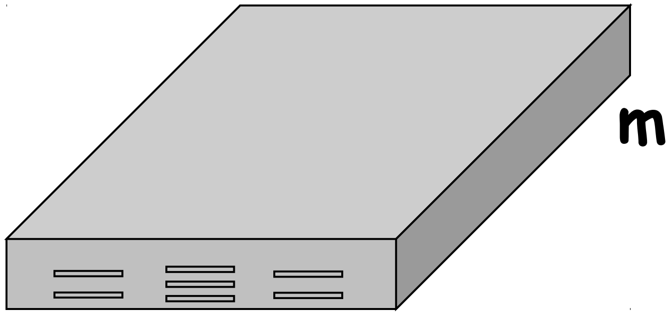
→





twistato

→



matrice metallica

→

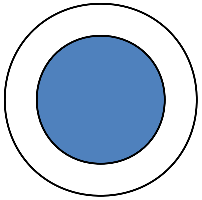
-alta resistività
(>Ag,Ni,Cu 0,1-1μΩcm)

-paramagnetica

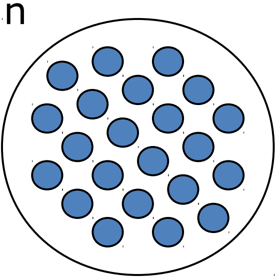
Manufacture of BSCCO HTS tapes (Bismuth Strontium Calcium Copper Oxide)

1) Oxide powder in tube OPIT

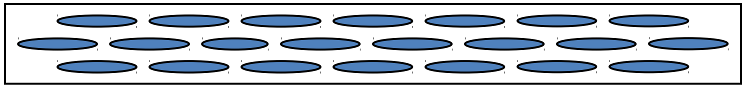
draw down
BSCCO powder
in a silver tube



stack many drawn
wires in another silver
tube and draw down
again



roll the final wire to tape and heat treat at 800 - 900C in oxygen to melt the B2212

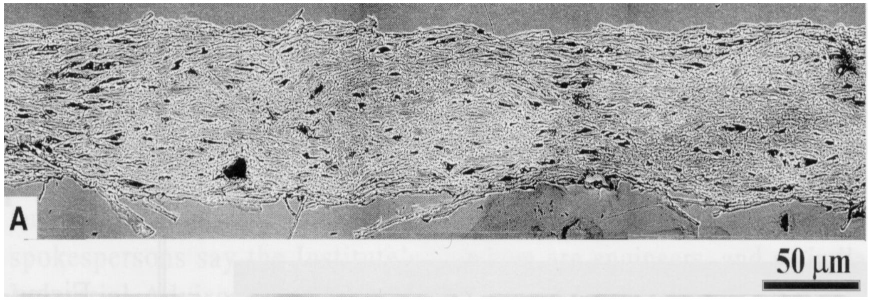


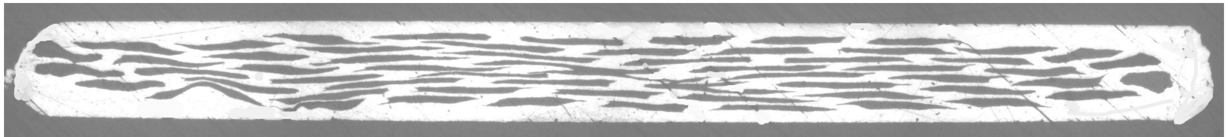
- for B2223, a special sequence of rolling and heat treatments must be used.
- the important feature of silver is that it is transparent to oxygen at high temperature, but does not react with it

2) Dip coating

coat a silver tape with B2212 powder in an organic binder
heat treat to just melt the B2212

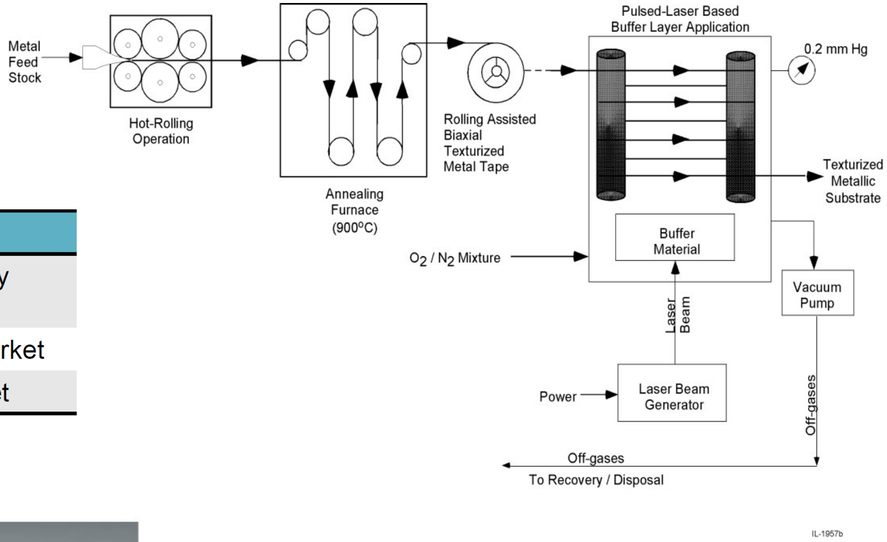
must achieve a good texture in the BSCCO layer
- silver is essential





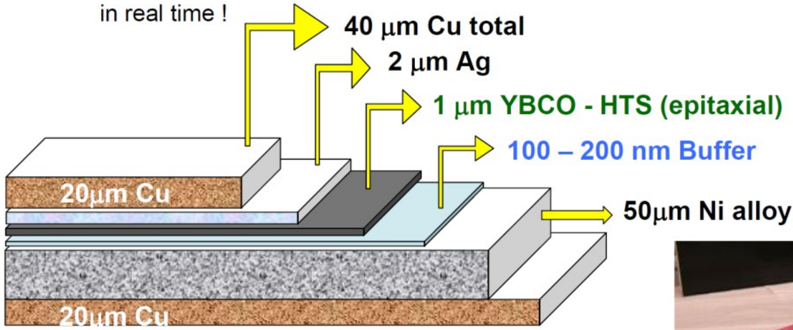
YBCO coated conductors

RABITs method



Metric	Today	Customer requirement	
Price	$ 300 - 400/kA-m	< $ 100/kA-m*	For commercial market entry (small market)
		< $ 50/kA-m*	For medium commercial market
		< $ 25/kA-m*	For large commercial market

- Only 1% of wire is the superconductor
- ~ 97% is inexpensive Ni alloy and Cu
- Automated, reel-to-reel continuous manufacturing process
- Quality of every single thin film coating can be monitored on-line in real time !



40 µm Cu total

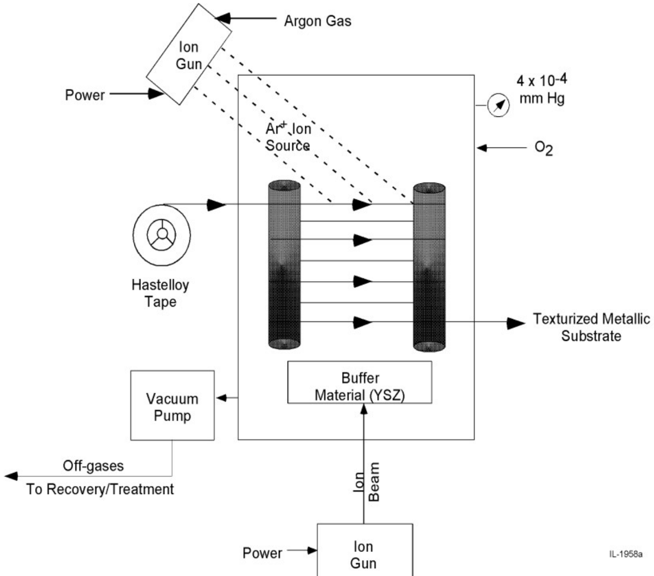
2 µm Ag

1 µm YBCO - HTS (epitaxial)

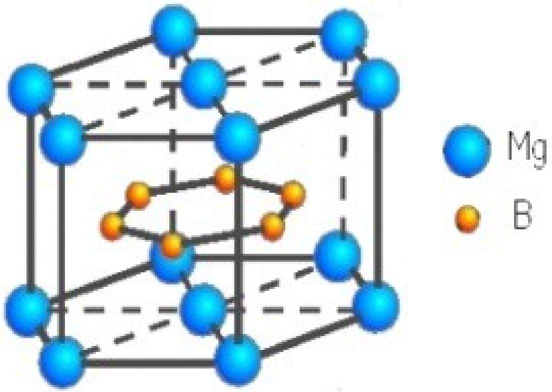
100 – 200 nm Buffer

50µm Ni alloy substrate

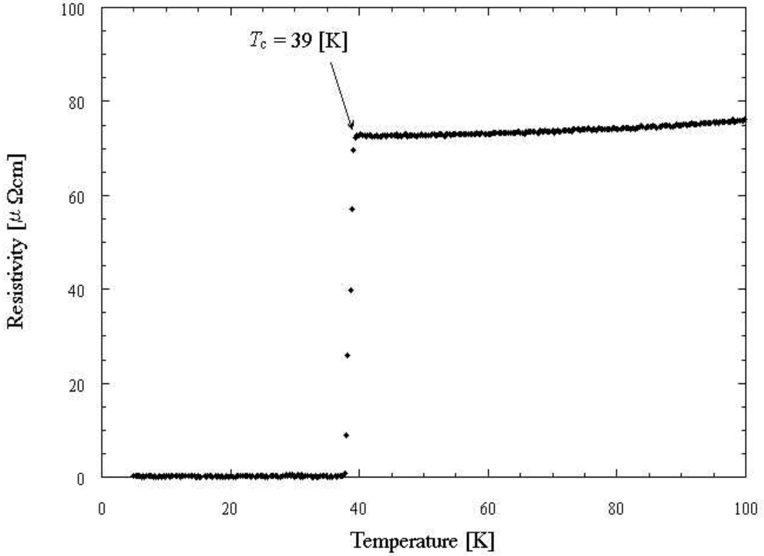
IBAD method



In January 2001 superconductivity at 40K in MgB2 was unexpectedly announced



Akimitsu_fig.4



I invested about 200 € from my own pocket to buy 100 grams of MgB2 powders online from Alfa-Aesar the night after the day I knew..

Am I a rich person now? Or shall I become one soon?

Columbus Superconductors SpA

Established in 2003 as a start-up of CNR/INFM with minro industrial participation from ASG Superconductors aiming at the development of MgB2 products

2003

Columbus Superconductors srl

75% CNR+Researchers
25% ASG

Once a targeted R&D result achieved

1st superconducting wire in MgB2 longer than 1 Km

2006

Columbus Superconductors spa

Industrial shareholders take the Company control in order to sustain investments and plant development

Does it make any sense to develop wires looking at the basic MgB2 properties?

	Composition	MgB2
High enough for 20K operation	Critical temperature	39 K
High enough to reduce weak links	Coherence length	5 nm
Nanoparticles are propedeutic for high jc(B)	Penetration depth	120 nm
High enough to produce useful fields	Upper critical field	15 – 60 T

Basic parameters are interesting enough to try making wires with an easily scalable process.. but properties are **NOT** exceeding LTS at 4.2 K nor HTS at 10 K+

Is there a real good reason to develop MgB2 then?

The **LTS lesson** tells that
1.Cost / 2.Strength / 3.Performance
often counts in this ranking when the selection of a superconducting wire is made (NbTi market share typically overwhelms Nb3Sn)

While **HTS** may allow for some applications at LN2 temperature, in most of the cases they are forced to operation in the **20-50 K** range because of the **insufficient behavior in a magnetic field** -> the comparison between HTS and **MgB2** can be mostly done on a **similar cooling penalty basis** than **LTS**
1.Cost / 2.Strength / 3.Performance

MgB2 Production into Wires

Columbus plant in Genoa

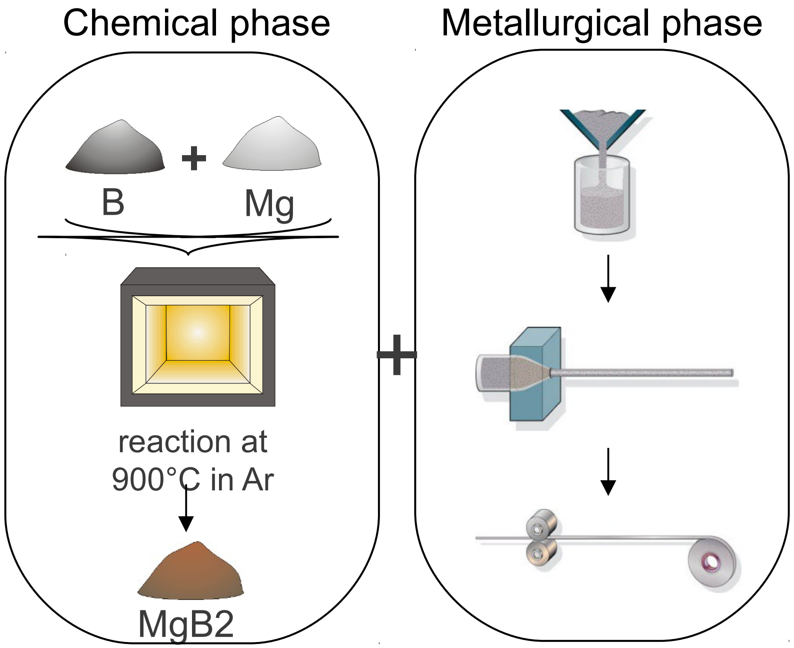
Manufacturing of MgB2 wires

by simple *ex-situ* Powder-In-Tube method

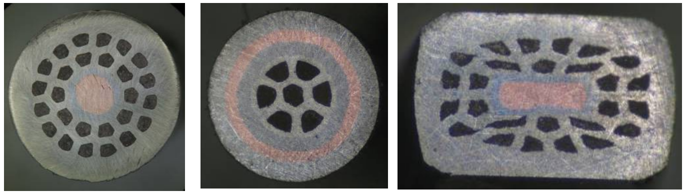
Has its own production facilities in Genoa with leading capability to produce and supply MgB2 wires on a commercial basis since three years – mostly used for MRI so far

- The present plant is fully operational for MgB2 wire production with a throughput of 2 Km/day, and is under scaling up to 3’000 Km/year according to our new market forecast with an investment > 5M€
- Wire unit length today up to 4 Km in a single piece, easily scalable by increasing billet size/length
- Total plant area 3’400 m2 – 60% of it in use today, to be increased by further 1’000 m2 becoming available by end of 2011
- Production for MRI so far exceeded 700 Km of fully tested wires
- MgB2 compound production now also fully implemented
- Increased interest from developing power applications

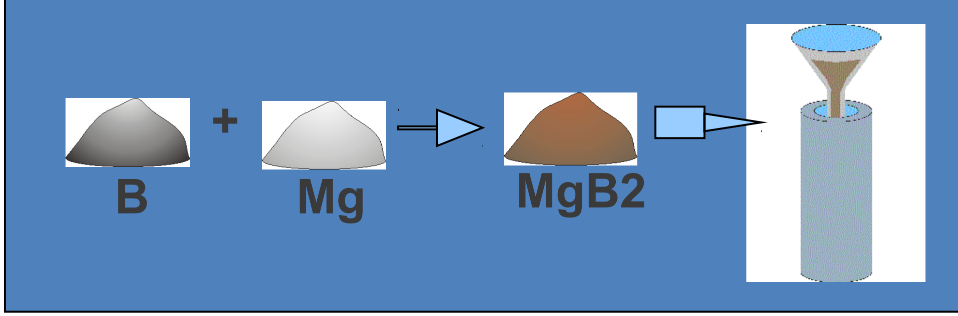
Ex-situ PIT process



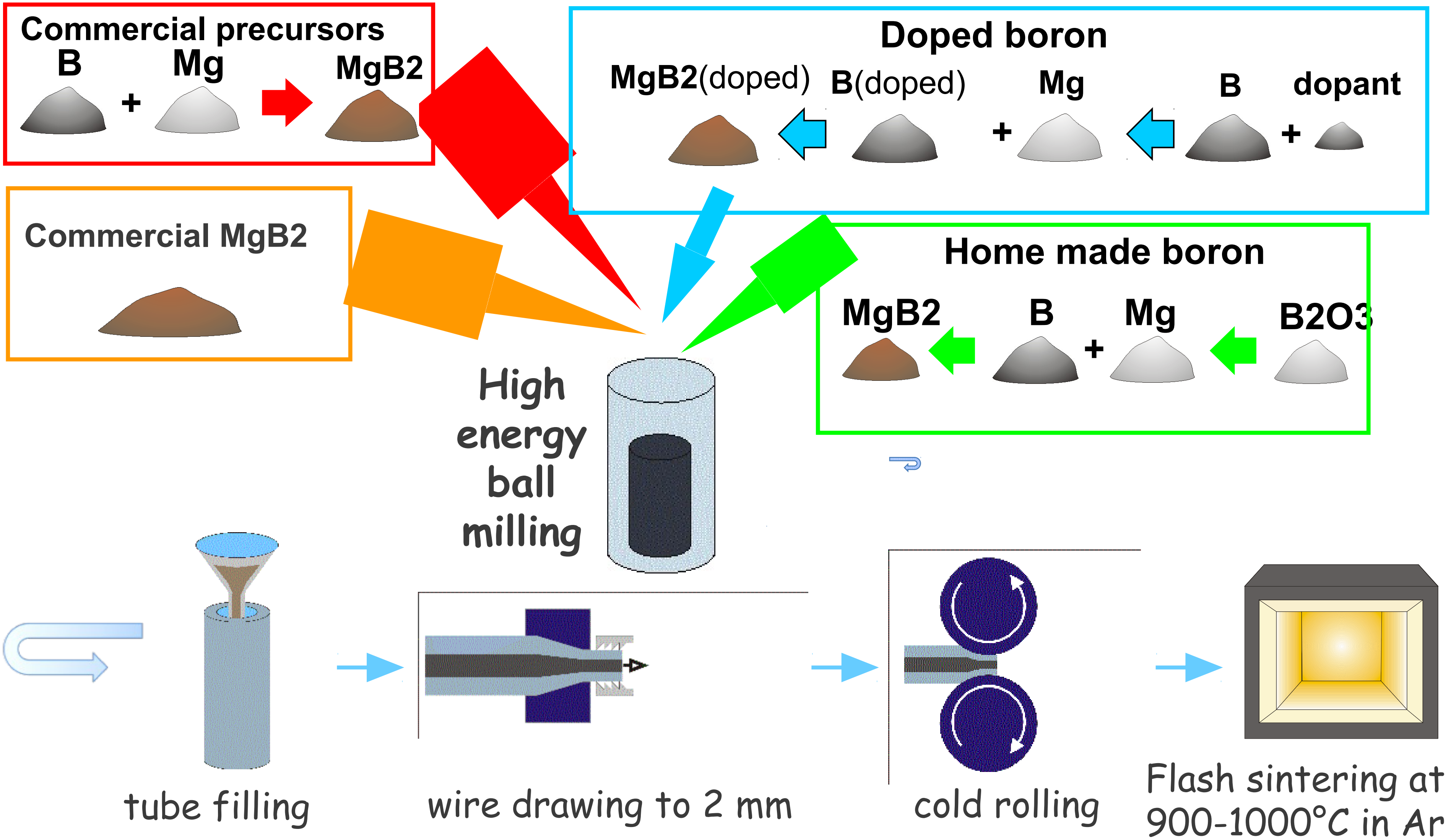
More flexibility on wire design than HTS



MgB2 P.I.T.
ex-situ method



Possible routes:



Commercial precursors

B + Mg → MgB2

Commercial MgB2

Doped boron

MgB2(doped) ← B(doped) + Mg ← B + dopant

Home made boron

MgB2 ← B + Mg ← B2O3

High energy ball milling

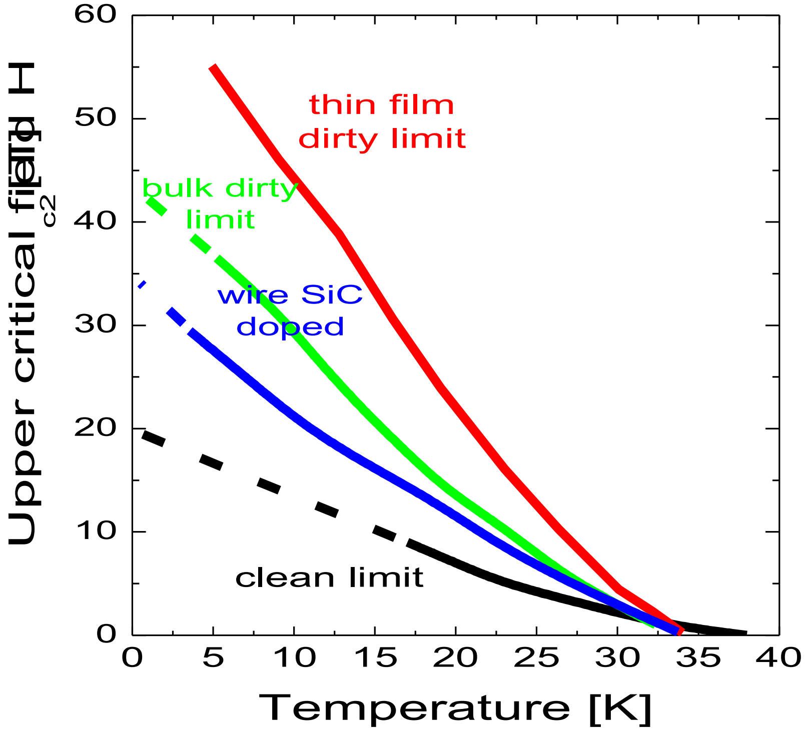
tube filling → wire drawing to 2 mm → cold rolling → Flash sintering at 900-1000°C in Ar

Will **MgB2** become **soon** a material for production of **very high** magnetic fields?

Initial results of very high Hc2 were really promising

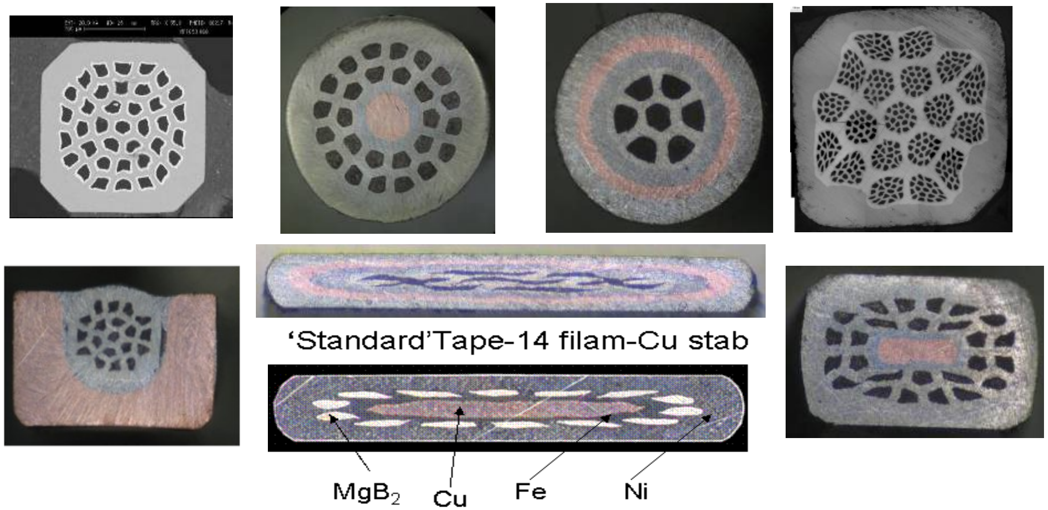
Best results easily achieved in thin films though

Grain boundary pinning, nanoprecipitates flux pinning, structural disorder and low-temperature synthesis are the combined reasons to achieve best results

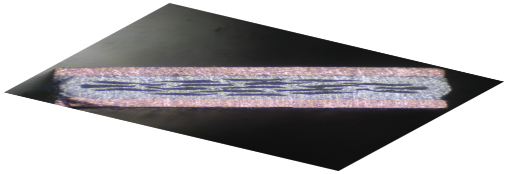


Looking at the various wire architectures possible

Significant flexibility in wire architecture due to chemical compatibility with most ductile metals (Nickel, Iron, Titanium, etc.)
No necessity for texture allows for any wire shape
Different wire designs can be produced according to customers request (low AC-losses, high filaments count, wire-in-channel, etc.)

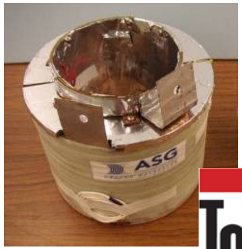

'Standard'Tape-14 filam-Cu stab

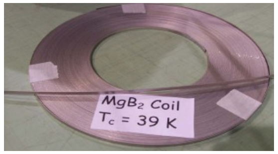
Sandwich conductor is becoming our best proposal for a magnet wire – f.f. of 30%, adjustable Copper fraction, lower cost, higher overall je, easier than WIC for MgB2



Is the MgB2 wire technology already available?
Very active MgB2 device development is ongoing

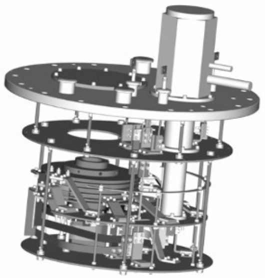
Texas Center for Superconductivity
1 Tesla cryogenic-free solenoid magnet





Brookhaven National Laboratory
Cryogenic-free pancake magnet

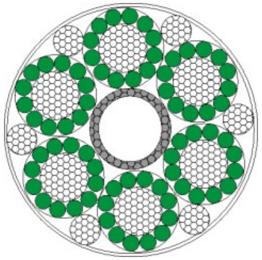
INFN-Genova
2.35 Tesla dipole magnet for particle physics



Ansaldo Breda CRIS
1 Tesla cryogenic-free solenoid magnet

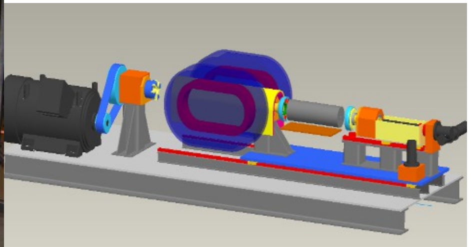
ASG Superconductors
Open-Sky MRI

Some of the devices recently realized employing W&R Columbus MgB2 wires



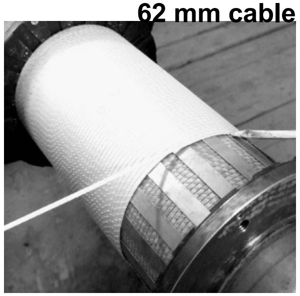
CERN
MgB2 cable with Ic>17 kA,
6 mm in diameter
Scaled up to 125 kA on a
62 mm cable

SINTEF Norway
nduction heater



Cesi Ricerca
LNe Fault current limiter

Chinese Academy of Science
1.5 Tesla cryogenic-free solenoid magnet



The MRI system “MR Open”

Main Magnet Parameters	
Nominal Field	0.5 T
Peak Field on the Conductor	1.3 T
Nominal Magnet Current	90 A
Conductor critical current at 20K, 1T	400 A
Conductor critical current at 20K, 0.5 T	1’000 A
Conductor cost/performance ratio at 20K 1 Tesla today	6.8 €/kA·m
Conductor cost/performance ratio at 20K 0.5 Tesla today	2.7 €/kA·m
Number of Pancakes	12
Conductor Length (total)	18 Km
Inductance	60 H
Overall Dimensions	2x2x2.4 m
Patient Available Gap	0.6 m
Weight	25000 Kg

MRopen

Columbus Superconductors GRUPPO MALACALZA

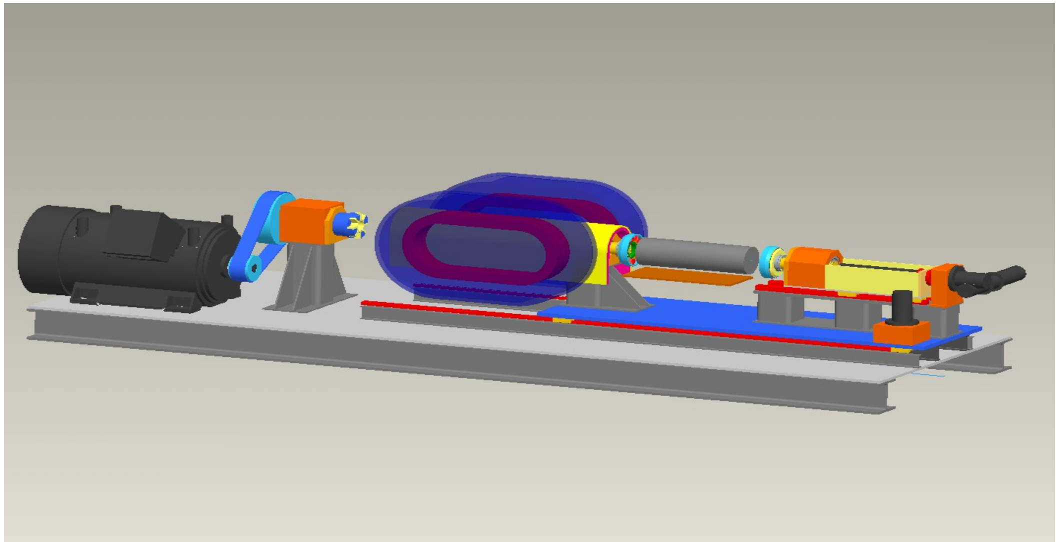
ASG Superconductors GRUPPO MALACALZA

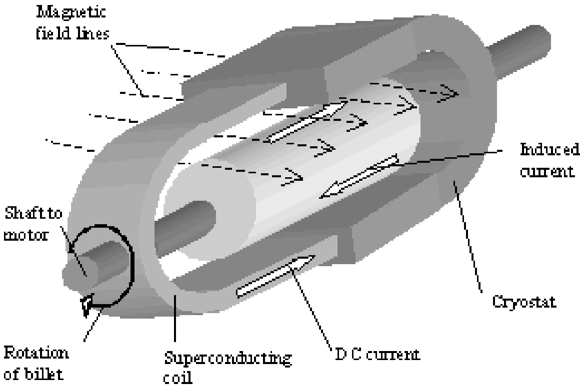
PARAmed MEDICAL SYSTEMS

First commercial systems installed in hospital in EU and North America

>10 magnet systems produced so far – 6 more systems will be shipped to customers worldwide by end of the year

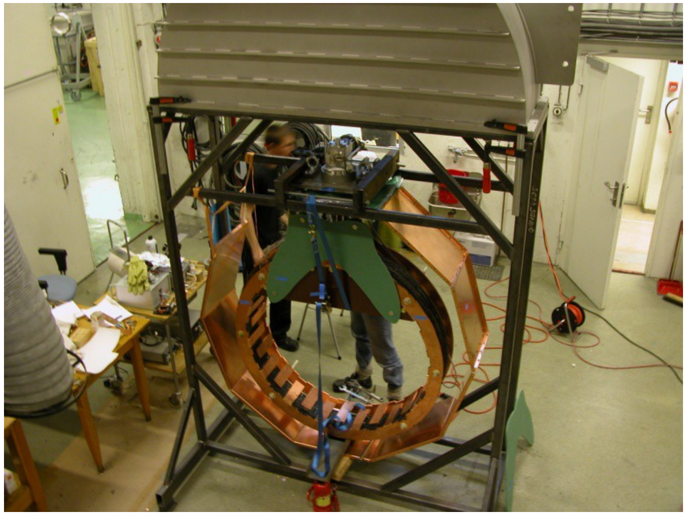
DC Induction Heater development





□=90%

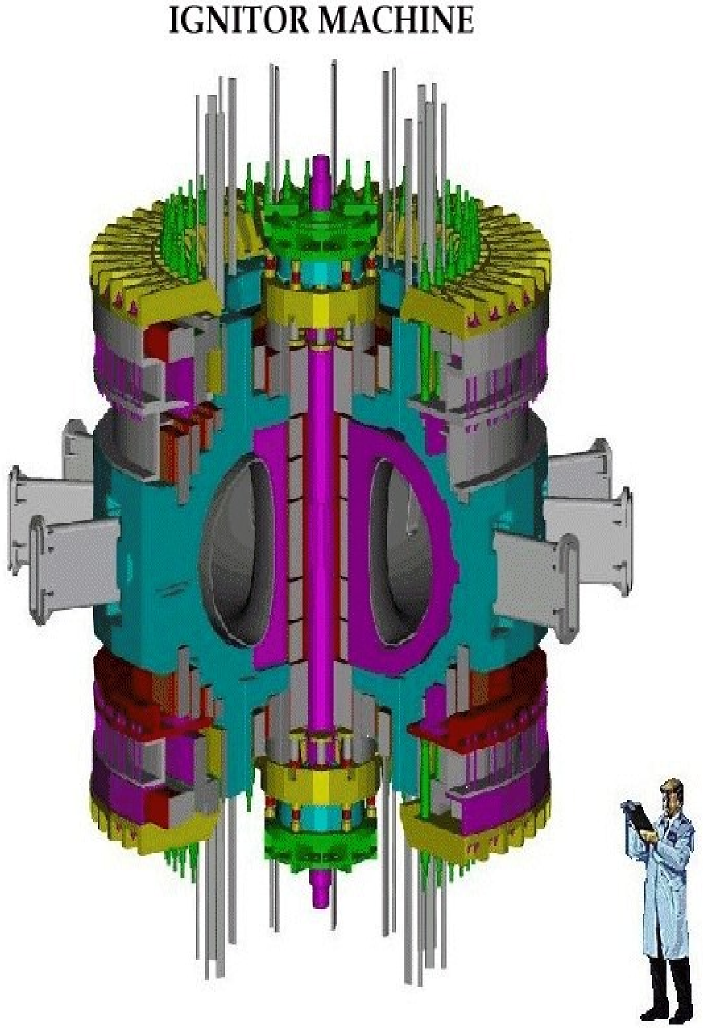
Assembly of MgB2 DC induction heate



O**bjectives** of the project are:

- to **dramatically reduce energy consumption and life-cycle costs** in one of the large-scale electrotechnical components with poorest energy efficiency and at the same time **improve** the production quality
- To **validate** the technical and economical **feasibility** of the new concept by building a 200-300 kW aluminium billet induction heater and test it in an industrial aluminium extrusion plant
- The **magnet** uses about **20 Km of MgB2** wires, and it has been **successfully tested** at design specs (200A, about 2 Tesla)

The IGNITOR nuclear fusion project



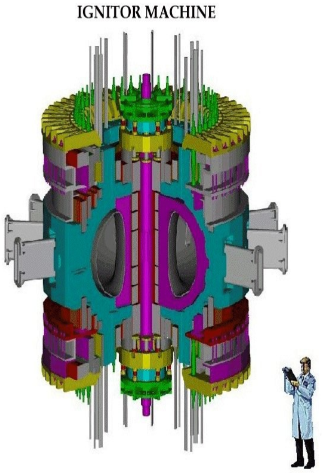
To be installed in Russia within a close partnership with Italy

This Tokamak is very compact (about 6 m diameter), and basically consists of resistive Copper coils cooled to cryogenic temperatures, due to the extremely high magnetic field (>> 20 Tesla), and operated in quasi-pulsed mode.

The helium gas cooling technology compatible with the use of MgB2

The outer poloidal field coils experience a field which is compatible with today’s MgB2

Ignitor – nuclear fusion project



30K He gas cooled copper conductors are currently expected to be used in this machine – MgB2 coils will be cooled down to 12 K

MgB2 cable for outer poloidal field coils

Jcs of a single MgB2 strand @ 4T, 15K	1000 A/mm2
Possible filling factor	20%
Single Strand diameter	1mm
Total cross section	0.784mm2
SC cross section in a single strand	0.784*0.2= 0.15 mm2
Ic of a single MgB2 strand @ 4T, 15K	0.15*1000= 152 A
Number of strand to have 35kA	35000A/152A=230
Total amount of wire	> 500 Km per coil

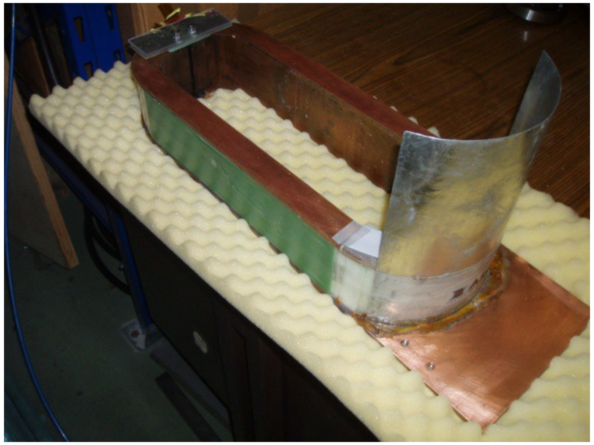
Main Ignitor system parameters

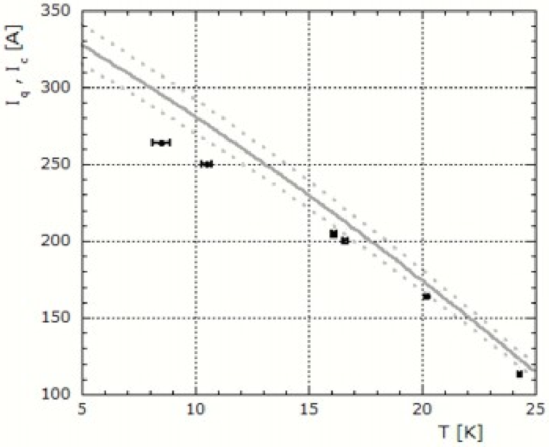
Parameters	**Symbol**	**Value**	**Unit**
Major Radius	R0	1.32	m
Minor radius	a,b	0.47, 0.86	m
Aspect ratio	A	2.8	
Elongation	k	1.83	
Triangularity	d	0.4	
Toroidal magnetic field	BT	13	T
Toroidal current	Ip	11	MA
Maximum poloidal field	Bp,max	6.5	T
Mean poloidal field		3.44	T
Poloidal current	Iq	9	MA
Edge safety factor (@11MA)	qy	3.6	
Confinement strenght		38	MA T
Plasma Surface	S0	34	m2
Plasma Volume	V0	10	m3
ICRF heating (140 MHZ)	PRF	6 (*)	MW

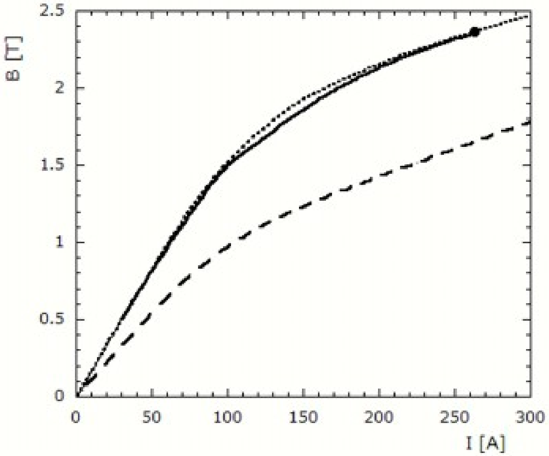
Why MgB2 in this machine?

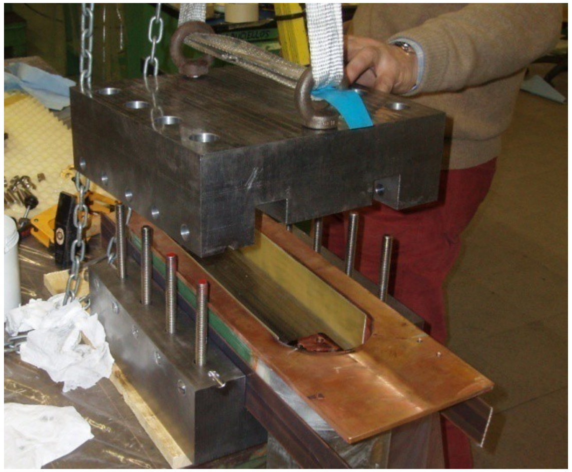
To prove feasibility of future systems with much higher repetition rate

Racetrack magnet for particle accelerators INFN MARIMBO project



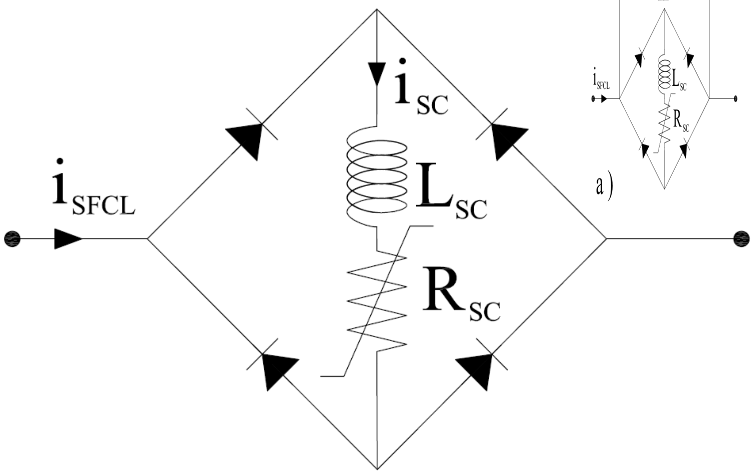


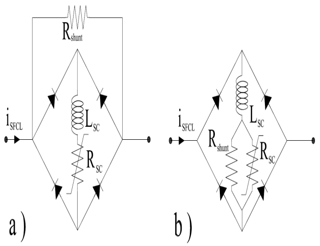


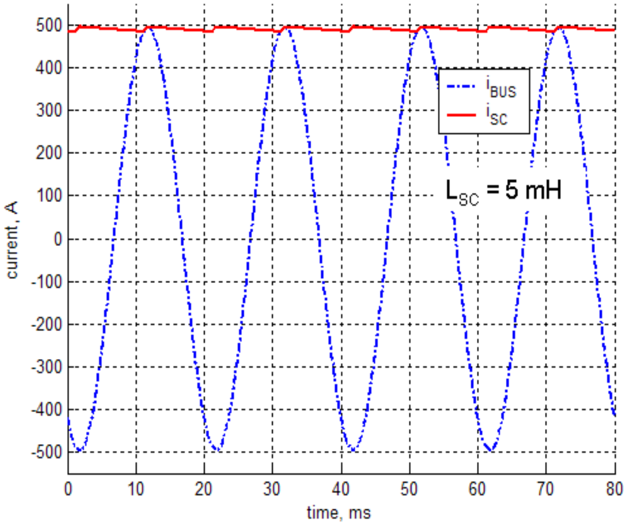


The magnet reached about 2.5 Tesla in cryogenic-free conditions
Magnet was R&W with a layer by layer structure

20kV distribution system DC resistive FCL design based on MgB2







Nominal Rate	25 MVA
Nominal Voltage	20 kV
Quenching current	1225 A
Inductance	5 mH
Quenched resistance	5

Cross section	2.30 1.10 mm2
Number of MgB2 filaments	8
Superconducting section	19.1 mm2
Stabilization material	Cu
Sheath material	Steel
Quenched resistance per unit length	0.1 □/m

A rectifier bridge and a small inductance are used to operate an antinductive MgB2 coil in almost DC mode, reducing losses and therefore cryogenic load

University of Bologna developmen

Design of an MgB2 very large current DC cable

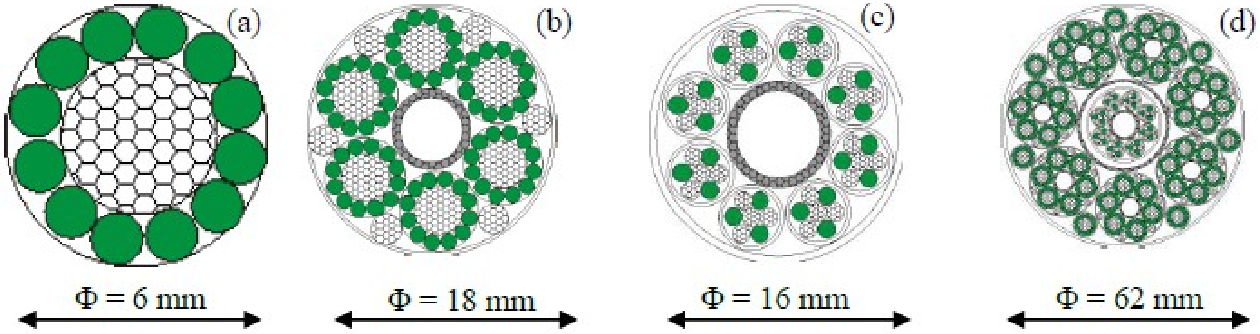


Figure 1. Layout of: 3 kA cable (a), 14 kA cable (b), group of 8 × 0.6 kA cables (c), configuration of 7 × 14 kA, 7 × 3 kA and 8 × 0.6 kA cables (d). The MgB_2 is shown solid, the copper is shown hatched.

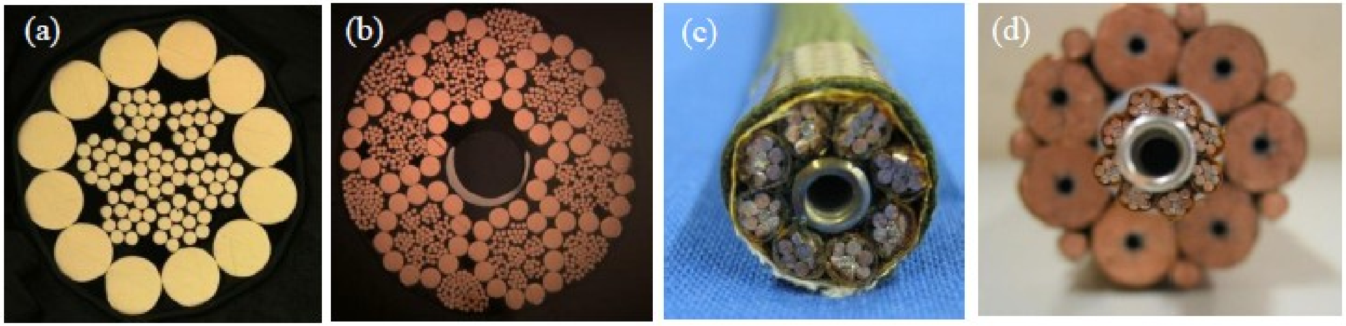


Figure 2. Mock-up of: 3 kA cable (a), 14 kA cable (b), group of 8 × 0.6 kA cables (c), configuration of 7 × 14 kA, 7 × 3 kA and 8 × 0.6 kA cables (d). The external diameter of each assembly is reported in Figure 1.

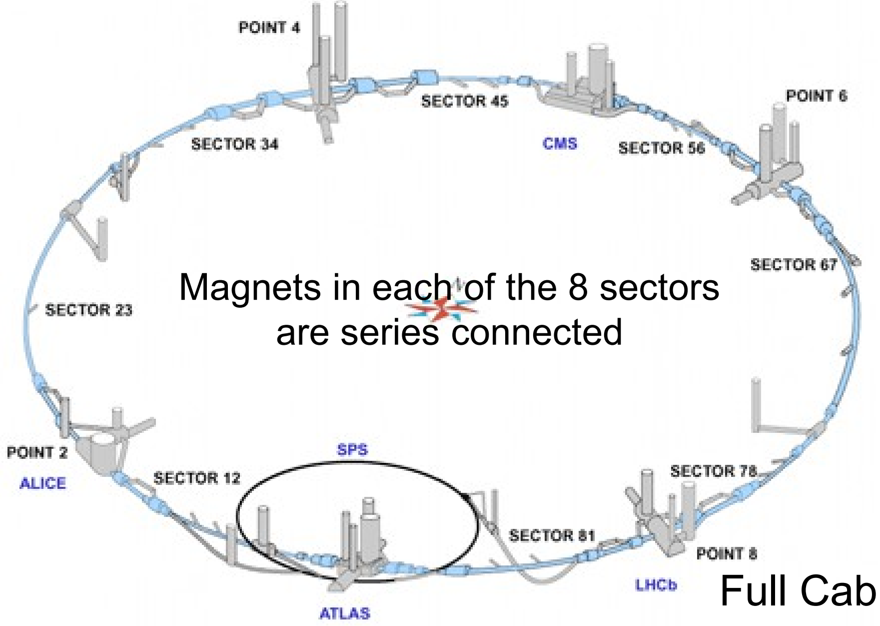
Very large current DC cables may find application in aluminium smelters, large data centers, research

MgB2 conductors for cables

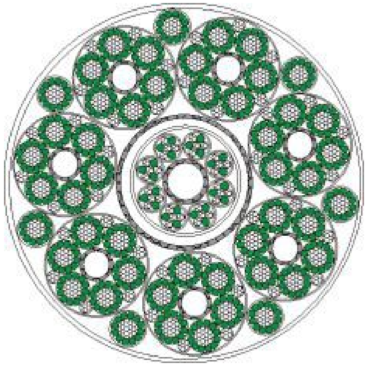
d powering of CERN LHC magnets using superconducting cables

Current has to be fed to a number of different magnet types
Total current to be fed in each sector is about 220 kA

Problem to be addressed: reliability of the magnets feed boxes placed in the tunnel that need constant maintenance while becoming heavily radioactive – moving them to the power supply caves far from the beam



Magnets in each of the 8 sectors are series connected

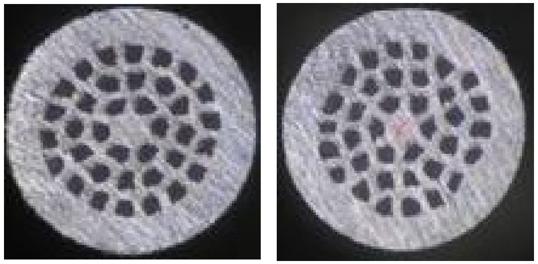


12 x 1.1 mm strand subcable tested successfully up to 17.8 kA at 5 K with no quench – it should operate up to 3 kA and 15 K

Full Cable demo of ≈20 meters (1’000 strands) to be realized and tested by end of 2011; if positive construction will be agreed and will occur during 2013-2020 for a total amount of 10’000 Km of strands

Conductor manufacturing for cable applications

We are in the advanced development phase of MgB2 round wires for cable applications



Wires are produced with different outer diameter of 1.1 (1 mm2) and 1.6 mm (2 mm2)

1.6 mm wire	Today	In 3 years time
MgB2 filling factor %	23%	35%
Critical current at 20K, 1 T	1’000 A	2’000 A
Critical current at 25K, 0.5 T	1’000 A	2’000 A
Boron purity	95-97%	99%
Boron price	0.1 €/m	0.25 €/m
Other constituents price	0.4 €/m	0.25 €/m
Manpower price	1 €/m	0.5 €/m

Conclusions..

We expect a bright future for MgB2 being a reasonable compromise between pro/cons of LTS and HTS

Having a commercial MRI product now selling with 18 Km of conductor x system and under operation from as long as 5 years flawlessy is a prof that the technology is consistent

The relatively limited effort worldwide on MgB2 has somewhat slowed down the conductor development in recent times - that should become again faster if we manage to attract more support and understanding of the potential of the material

I am not a rich person yet.. but I will definitely update you in ten years