MgB_2 ten years after: present state and perspectives for superconducting wires

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Columbus Superconductors

May 13th, 2011

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 MgB_2 products

2003

Columbus Superconductors srl

75% CNR+Researchers
25% ASG

Once a targeted R&D result achieved

→

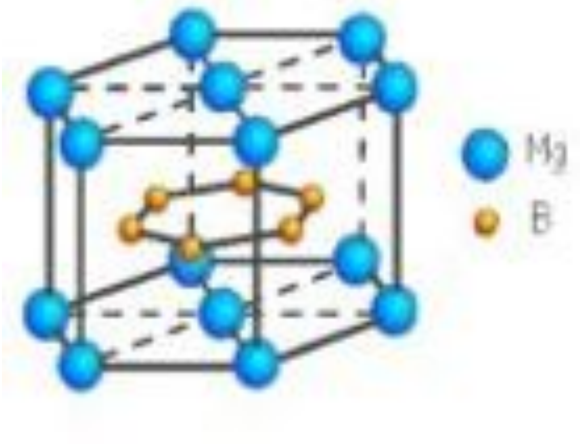
1st superconducting wire in MgB_2 longer than 1 Km

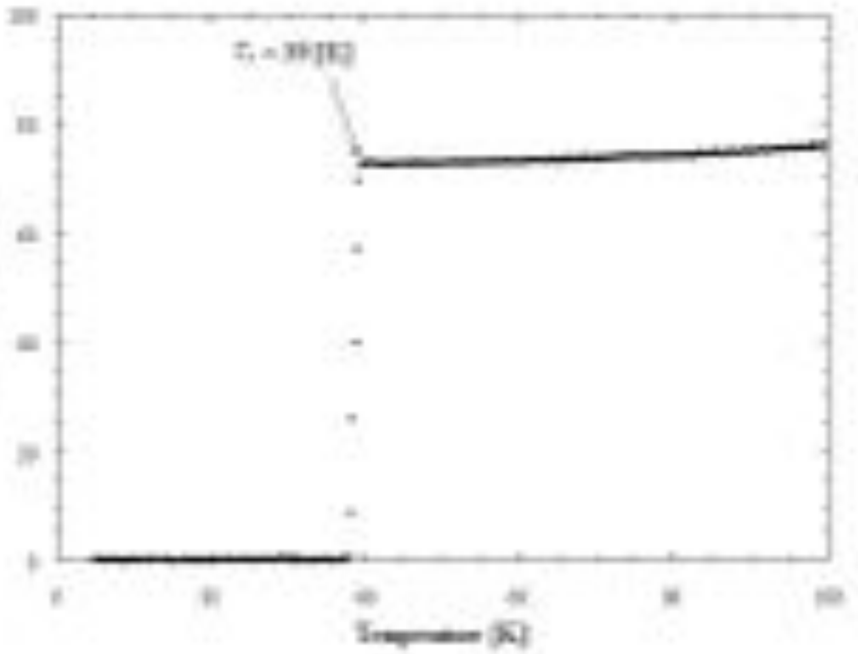
2006

Columbus Superconductors spa

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

In January 2001 superconductivity at 40K in MgB_2 was unexpectedly announced





I invested about 200 € from my own pocket to buy 100 grams of MgB_2 powders online from Alfa-Aesar the night after the day I knew..

Does it make any sense to develop wires looking at the basic MgB_2 properties?

	Composition	MgB_2
High enough for 20K operation →	Critical temperature	39 K
High enough to reduce weak links →	Coherence length	5 nm
Nanoparticles are propedeutic for high $j_c(B)$ →	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+

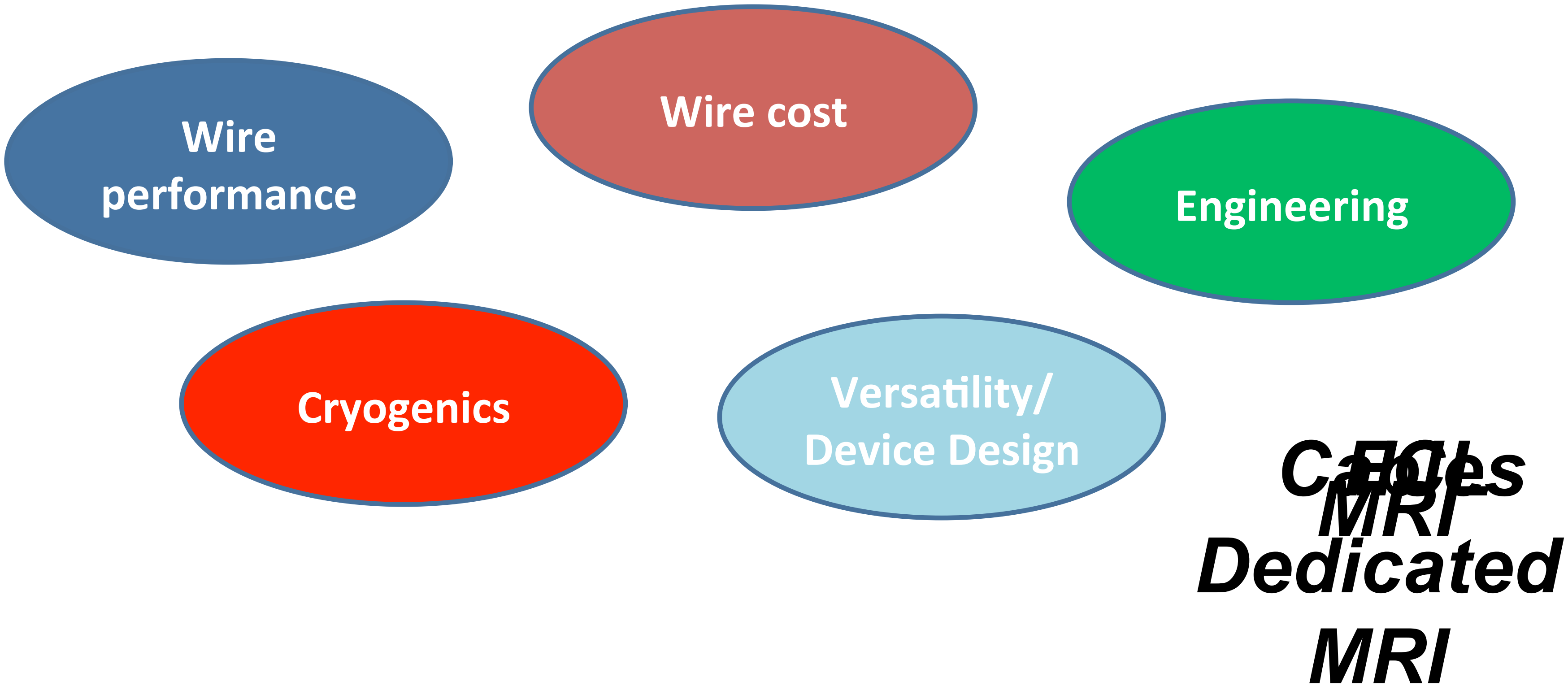
Is there a real good reason to develop MgB_2 then?

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 Nb_3Sn)

While **HTS** may allow for some applications at LN_2 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 **MgB_2** can be mostly done on a **similar cooling penalty basis** than **LTS**
1.Cost / 2.Strength / 3.Performance

Applications demand

- Making **ONE** single good superconducting product **that fits all** is a formidable interdisciplinary problem possibly with no solution



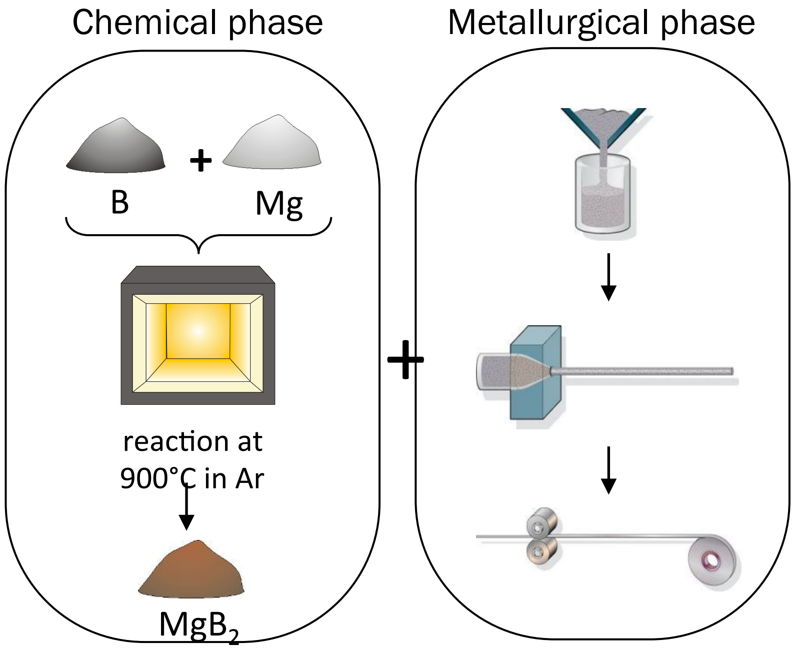
MgB_2 Production into Wires

Columbus plant in Genoa

Manufacturing of MgB_2 wires

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

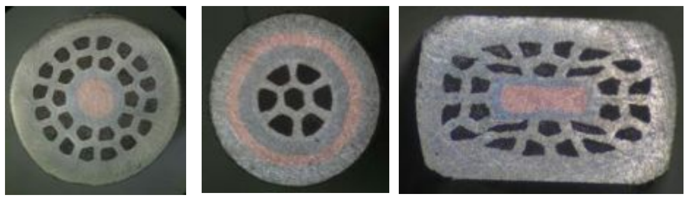
Ex-situ PIT process



Has its own production facilities in Genoa with leading capability to produce and supply MgB_2 wires on a commercial basis since three years – mostly used for MRI so far

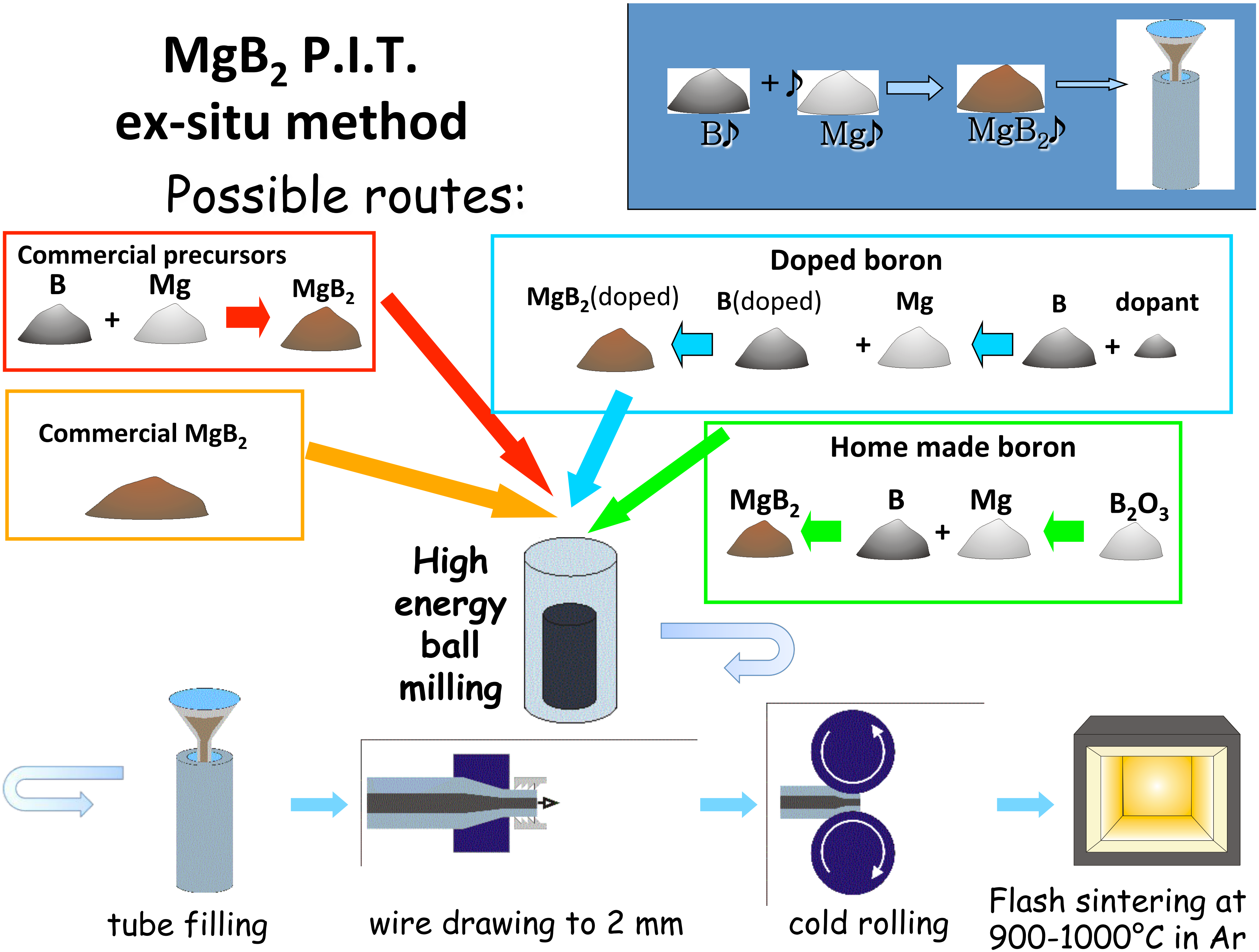
- The present plant is fully operational for MgB_2 wire production with a throughput of 2 Km/day, and is under scaling up to 3'000 Km/year according to our new market forecast with an investment > 5M€
- Wire unit length today up to 4 Km in a single piece, easily scalable by increasing billet size/length
- Total plant area 3'400 m^2 – 60% of it in use today, to be increased by further 1'000 m^2 becoming available by end of 2011
- Production for MRI so far exceeded 700 Km of fully tested wires
- MgB_2 compound production now also fully implemented
- Increased interest from developing power applications

More flexibility on wire design than HTS



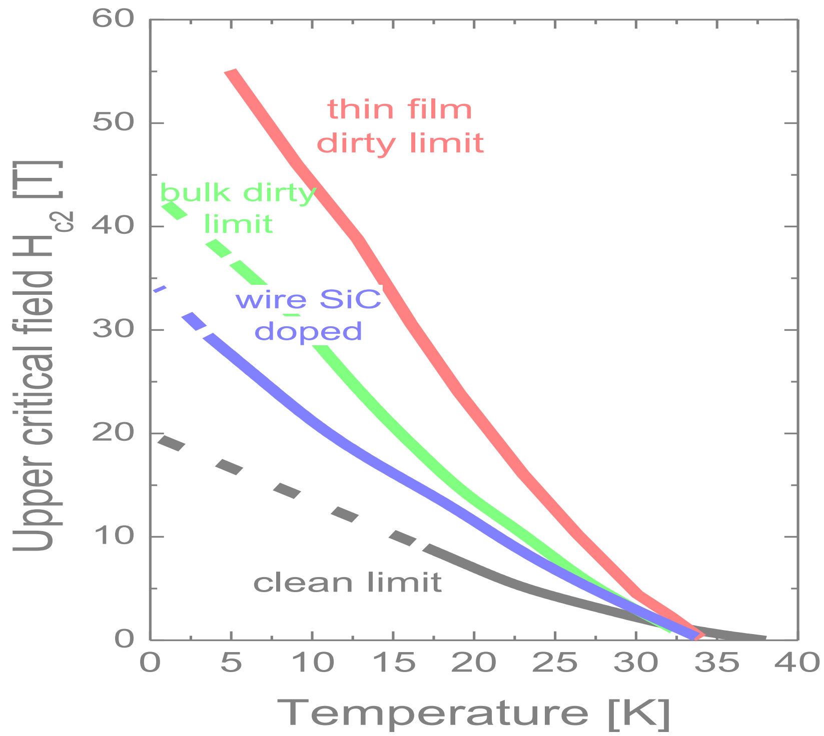
MgB_2 P.I.T.
ex-situ method

Possible routes:



Will **MgB_2** become **soon** a material for production of **very high** magnetic fields?

- Initial results of very high H_c^2 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



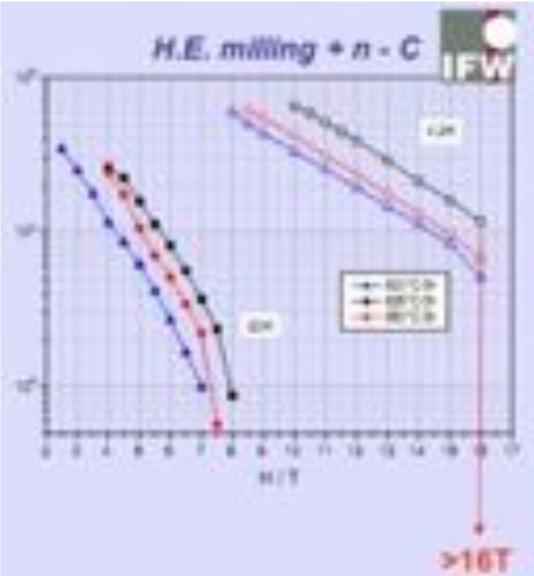
Requirements for applications

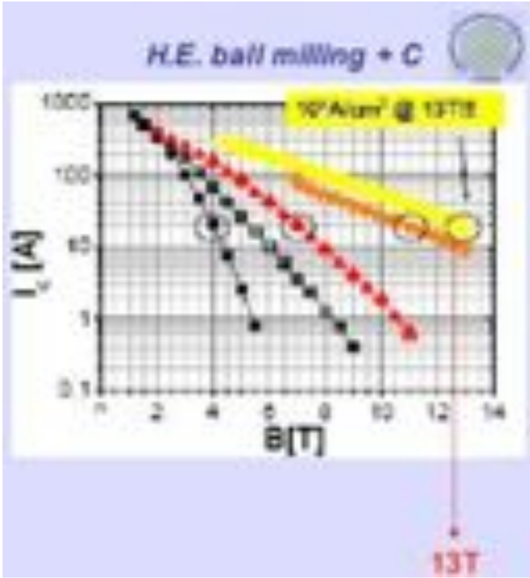
Cost vs. performance targeted figures

	Required current density	Operating temperature	Operating field	Required Cost
NMR (outer coil)	$10^4 - 10^5$ A/cm^2	4.2 K	5 – 10 T	< 5 €/kA m
MRI solenoid	$10^4 - 10^5$ A/cm^2	20 K	1 – 6 T	< 5 €/kA m
Transformers	> 10^4 A/cm^2	20 K	1 – 2 T	< 15 €/kA m
Generators/motors	> 10^4 A/cm^2	20 K	2 – 4 T	< 5 €/kA m

There might be some room for 10-12 Tesla magnets if mechanical properties exceed Nb_3Sn ones appreciably

Real potential is for cryogenic-free magnets up to 3-6 Tesla – enough for MRI and perhaps SMES energy storage



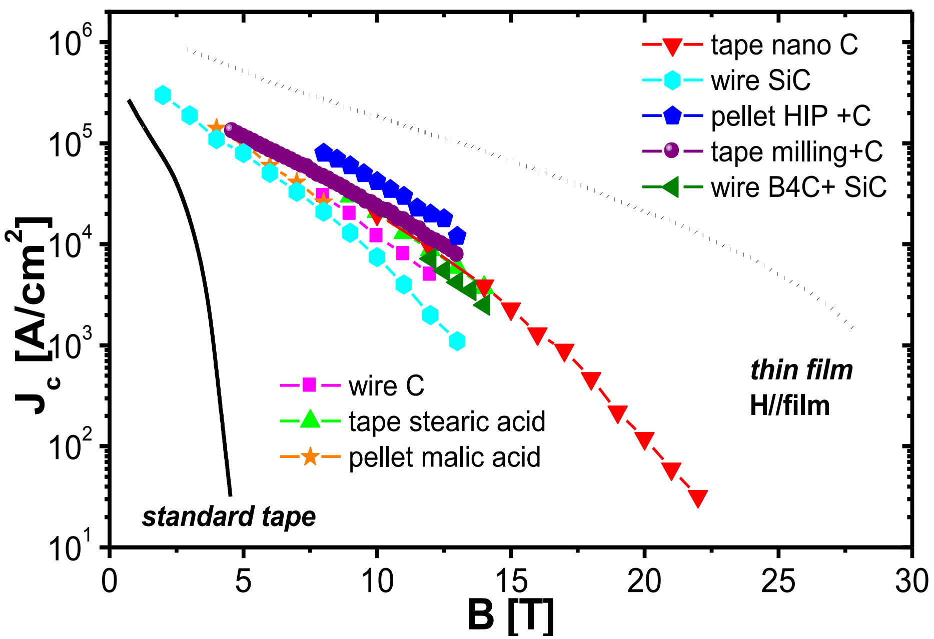


Critical current density larger than 100 A/mm^2 at fields >> 10T already demonstrated
Significant results achieved at 20K as well, while optimal properties in high magnetic field have been achieved at 12 K

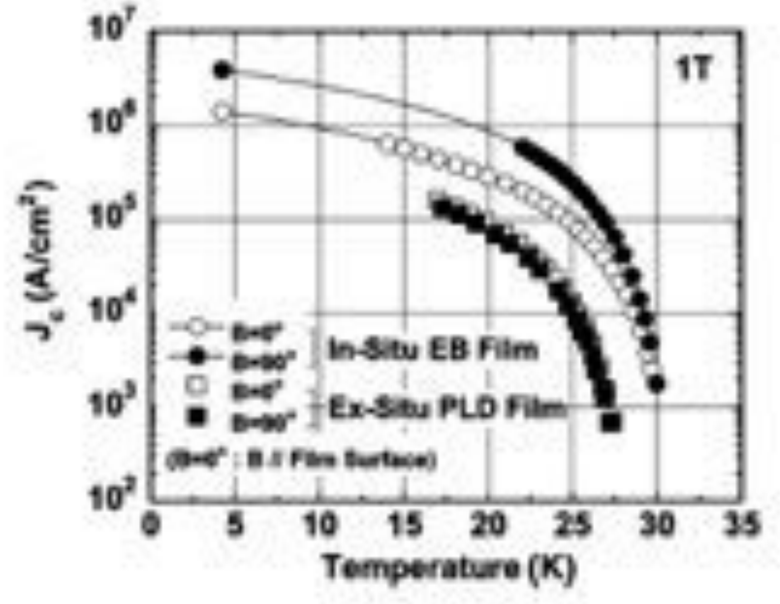
High field performance demonstrated in MgB_2 R&D wires by many groups
Much more progress yet to come

Even MgB_2 as HTS may need some degree of texturing to achieve maximum performance

i.e. j_c > 100’000 A/mm²



MgB₂ thin films

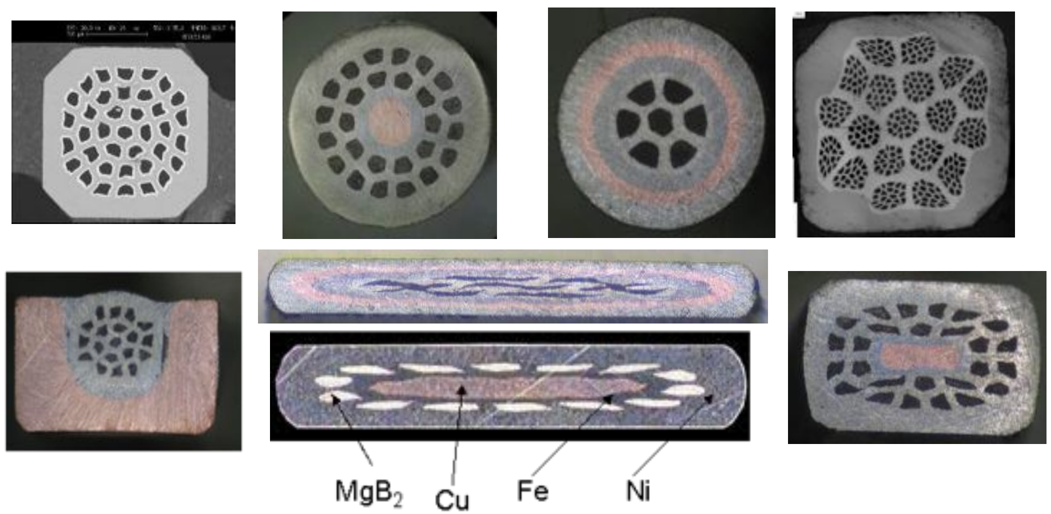


Connectivity as low as **5%** as extracted from Rowell analysis of electrical resistivity cannot explain systematically **low j_c** values in the **best bulk and wire** materials - lack of texture reduces superconducting coupling capability because of the 2-band nature of superconductivity in MgB_2

An **improvement** by at least an **order of magnitude** is still feasible by focusing on microstructure optimization

Looking at the various wire architectures possible

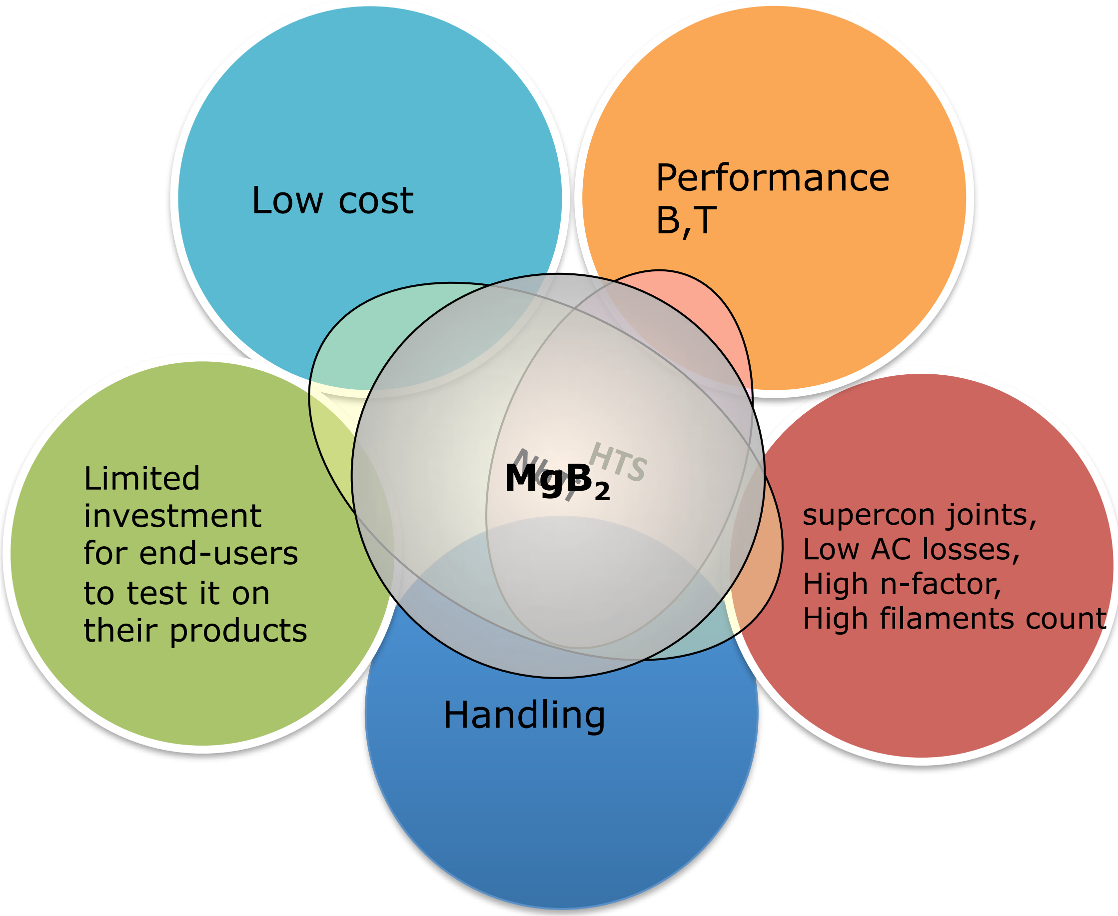
- Significant flexibility in wire architecture due to chemical compatibility with most ductile metals (Nickel, Iron, Titanium, etc.)
- No necessity for texture allows for any wire shape
- Different wire designs can be produced according to customers request (low AC-losses, high filaments count, wire-in-channel,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



Sandwich conductor is becoming our best proposal for a magnet wire – f.f. of 30%, adjustable Copper fraction, lower cost, higher overall j_e, easier than WIC for MgB_2

Driving forces for MgB_2

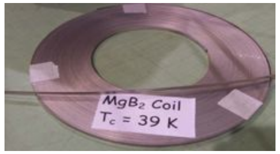
- Low cost and wide availability of the raw materials, particularly in Europe
- Excellent chemical and mechanical compatibility with various elements (Ni, Fe, Ti, Nb, Ta, Cr, although not with Cu)
- Potential for very good performance at high fields (thin films show H_{c2}>60 T!)
- Low anisotropy and potential for persistent mode operation (high n-value, low current decay at medium magnetic fields)



Is the MgB_2 wire technology already available? Very active MgB_2 device development is ongoing

Texas Center for Superconductivity
1 Tesla cryogenic-free solenoid magnet

Brookhaven National Laboratory
Cryogenic-free pancake magnet

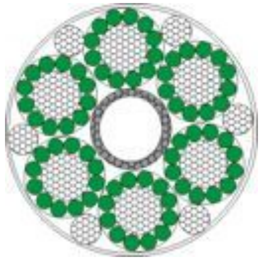


INFN-Genova
2.35 Tesla dipole magnet for particle physics

Ansaldo Breda CRIS
1 Tesla cryogenic-free solenoid magnet

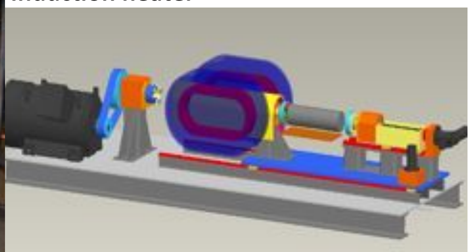
ASG Superconductors
Open-Sky MRI

Some of the devices recently realized employing W&R Columbus MgB_2 wires



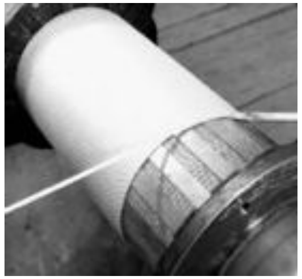
CERN
MgB_2 cable with Ic>17 kA, 6 mm in diameter
Scaled up to 125 kA on a 62 mm cable

SINTEF Norway
Induction 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

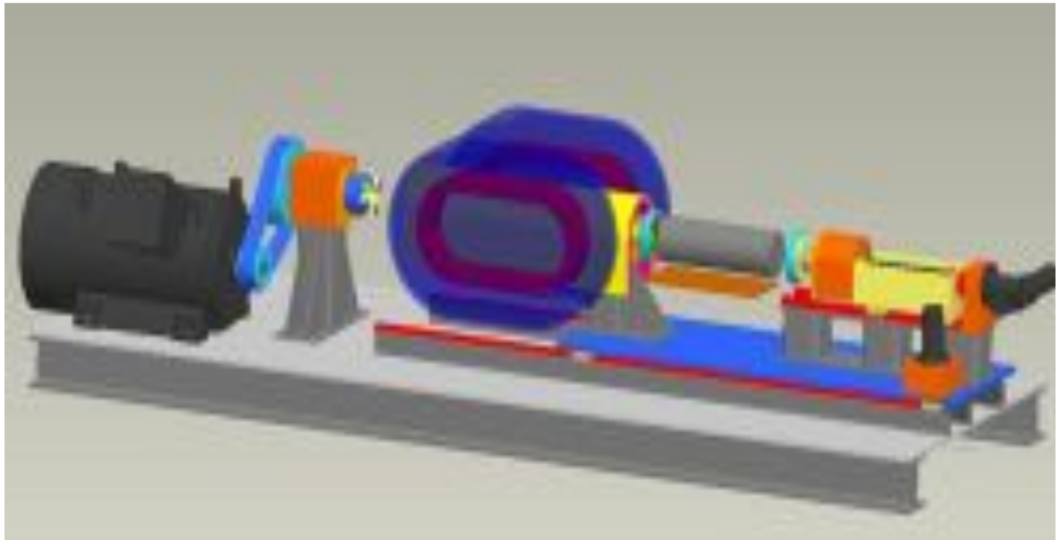
ASG Superconductors GRUPPO MALACALZA

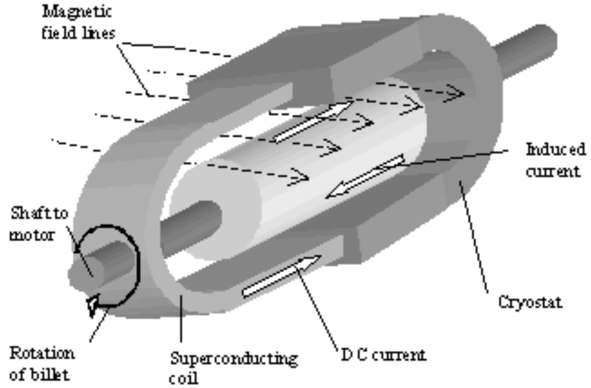
PARAmed MEDICAL SYSTEMS

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





η=90%

Assembly of MgB_2 DC induction heater

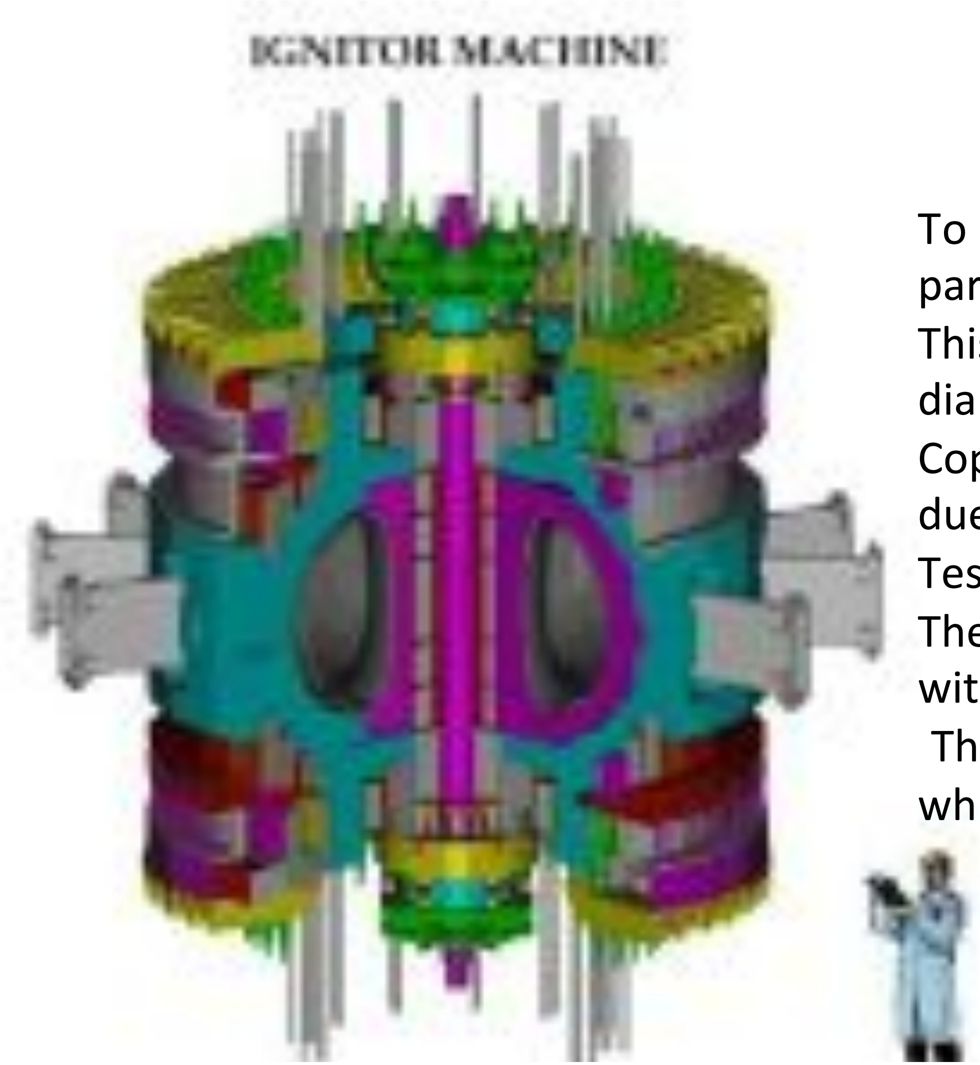
O**bjectives** of the project are:

•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 MgB_2** wires, and it has been **successfully tested** at design specs (200A, about 2 Tesla)

The IGNITOR nuclear fusion project



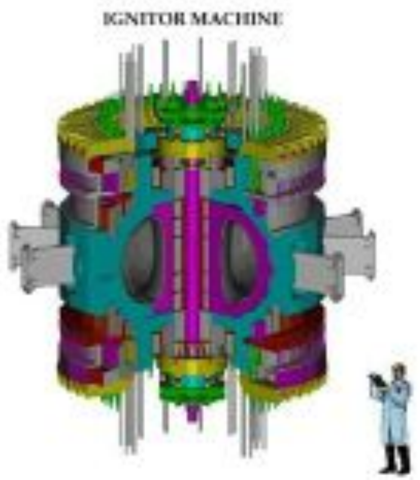
To be installed in Russia within a close partnership with Italy

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 MgB_2

The outer poloidal field coils experience a field which is compatible with today's MgB_2

Ignitor – nuclear fusion project



30K He gas cooled copper conductors are currently expected to be used in this machine – MgB_2 coils will be cooled down to 12 K

Main Ignitor system parameters

Parameters	Symbol	Value	Unit
Major Radius	R_0	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	B_T	13	T
Toroidal current	I_p	11	MA
Maximum poloidal field	$B_{p,max}$	6.5	T
Mean poloidal field		3.44	T
Poloidal current	I_q	9	MA
Edge safety factor (@11MA)	q_y	3.6	
Confinement strenght		38	MA T
Plasma Surface	S_0	34	m^2
Plasma Volume	V_0	10	m^3
ICRF heating (140 MHZ)	P_{RF}	6 (*)	MW

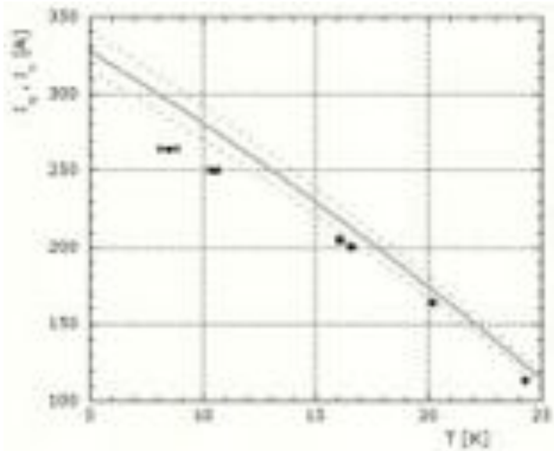
MgB_2 cable for outer poloidal field coils

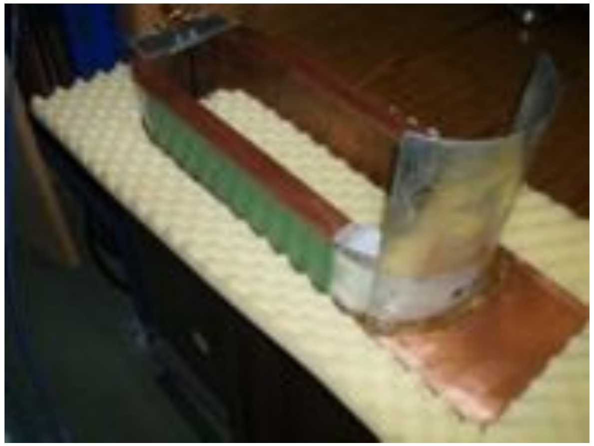
J_{cs} of a single MgB_2 strand @ 4T, 15K	1000 A/mm^2
Possible filling factor	20%
Single Strand diameter	1mm
Total cross section	0.784mm^2
SC cross section in a single strand	0.784*0.2= 0.15 mm^2
I_c of a single MgB_2 strand @ 4T, 15K	0.15*1000= 152 A
Number of strand to have 35kA	35000A/152A=230
Total amount of wire	> 500 Km per coil

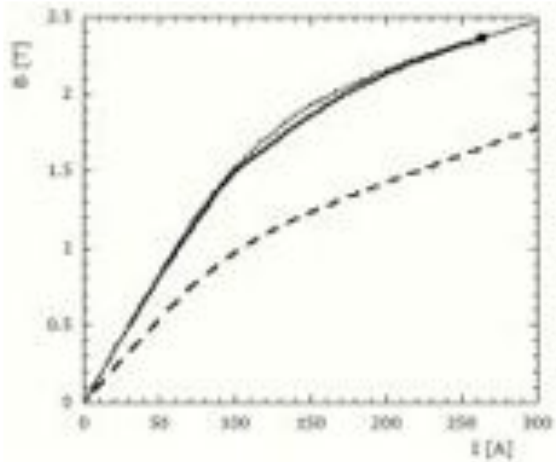
Why MgB_2 in this machine?

To prove feasibility of future systems with much higher repetition rate

Racetrack magnet for particle accelerators INFN MARIMBO project

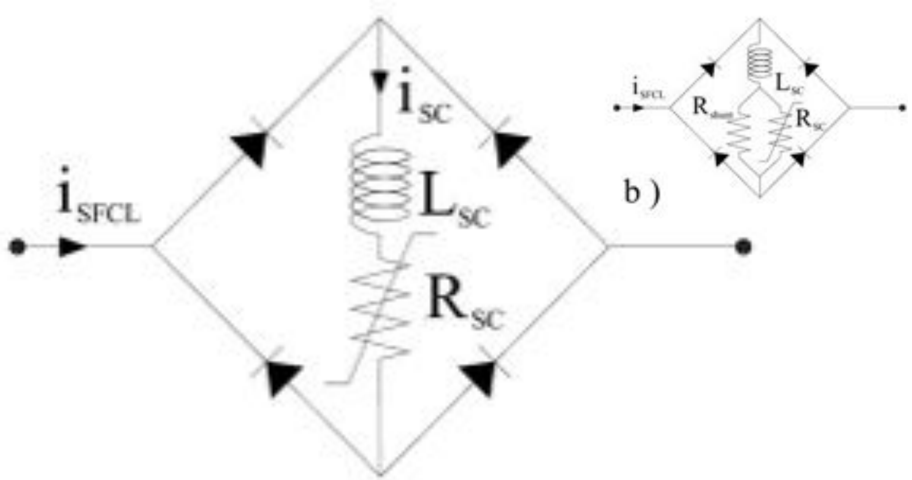


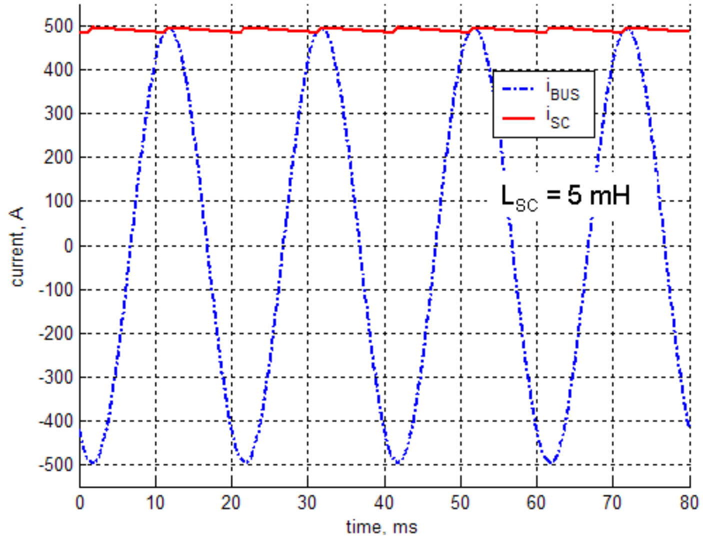




The magnet reached about 2.5 Tesla in cryogenic-free conditions
Magnet was R&W with a layer by layer structure

20kV distribution system DC resistive FCL design based on MgB_2





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

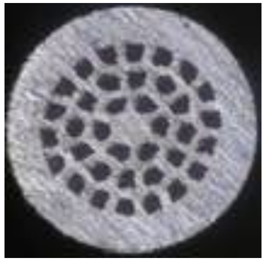
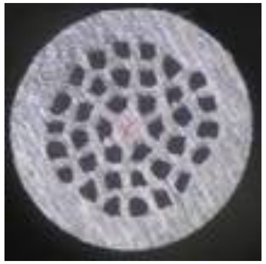
Cross section	2.30 × 1.10 mm^2
Number of MgB_2 filaments	8
Superconducting section	19.1 mm^2
Stabilization material	Cu
Sheath material	Steel
Quenched resistance per unit length	0.1 Ω/m

A rectifier bridge and a small inductance are used to operate an antinductive MgB_2 coil in almost DC mode, reducing losses and therefore cryogenic load

University of Bologna development

Conductor manufacturing for cable applications

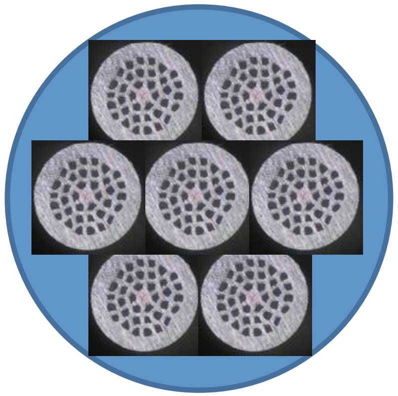
We are in the advanced development phase of MgB_2 round wires for cable applications

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

1.6 mm wire	**Today**	**In 3 years time**
MgB_2 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
Conductor cost **at 20K, 1T**	**1.5 €/kAm**	**0.5 €/kAm**

MgB_2 for cable applications



By using round 1.6 mm strands with 1-2 kA x strand capability, it should be possible to be able to carry very large DC currents by a reasonably compact cable

Unit length for this strand is limited by our billet size, of about 40 Kg today, but R&D to go up to 90 Kg is currently ongoing, and a further step to 300 Kg has been already planned

Conclusions..

- We expect a bright future for MgB_2 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 MgB_2 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