ASC, 10-15 August 2014, Charlotte, NC, USA

Advances in MgB_2 Conductors

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Outline

I. The system MgB_2
II. MgB_2 wires: fabrication and properties
III. Future perspectives: performance and costs
IV. Applications
  A. Magnetic Resonance Imaging at 20K
  B. High current cables: LINK project (CERN
  C. Applications of ultra-thin MgB_2 wires
  D. Development of special magnets
  E. Wind generators
  F. Renewable energy applications
  G. Persistent mode bulk magnets (levitation)
  H. Space applications
Conclusions

I. The system MgB_2

Present situation

- **Today, applications based on Superconductivity include MRI,**
  NMR,
  R&D laboratory magnets,
  Current leads and
  Large magnets (accelerators and fusion)

In future, HTS materials are increasingly expected to enter in this scenario

- **So far, high costs and fabrication complexity are still delaying their introduction in large industrial markets. But: Situation is improving.**
- **What is the importance of MgB_2 in the future superconducting applications?**

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Advantages of MgB_2 in view of applications

MgB_2 has to be considered a niche material, for special purposes. However, recent developments show: its application range is gradually increasing.

MgB_2 conductors present the following advantages:

- **Low material cost**
- **Multifilamentary wires (low losses)**
- **No weak pinning effects**
- **Low mass density**
- **Operation in the persistent mode**

For selected applications, the combined advantages of MgB_2 may be decisive with respect to HTS superconductors

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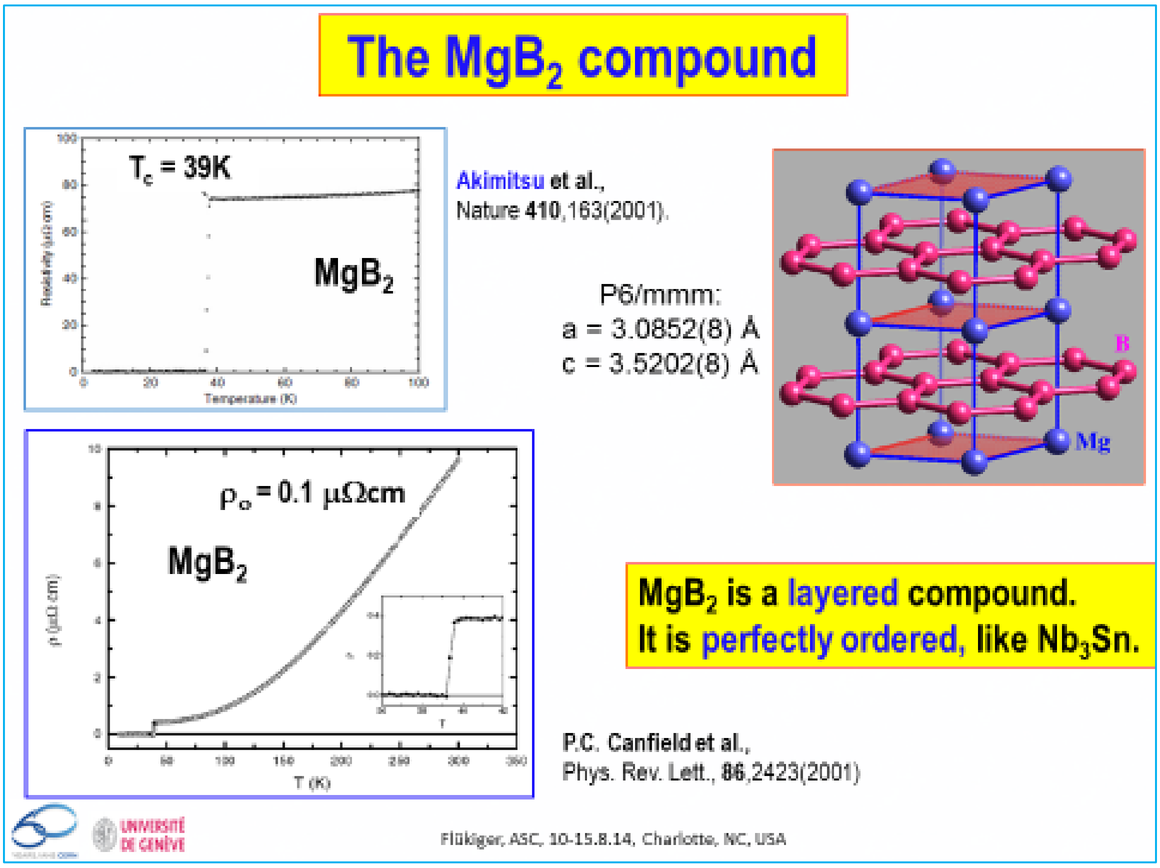

The MgB_2 compound

Akimitsu et al.,
Nature **410**,163(2001).

P6/mmm:
a = 3.0852(8) Å
c = 3.5202(8) Å

MgB_2 is a layered compound.
It is perfectly ordered, like Nb_3Sn.

P.C. Canfield et al.,
Phys. Rev. Lett., **86**,2423(2001)

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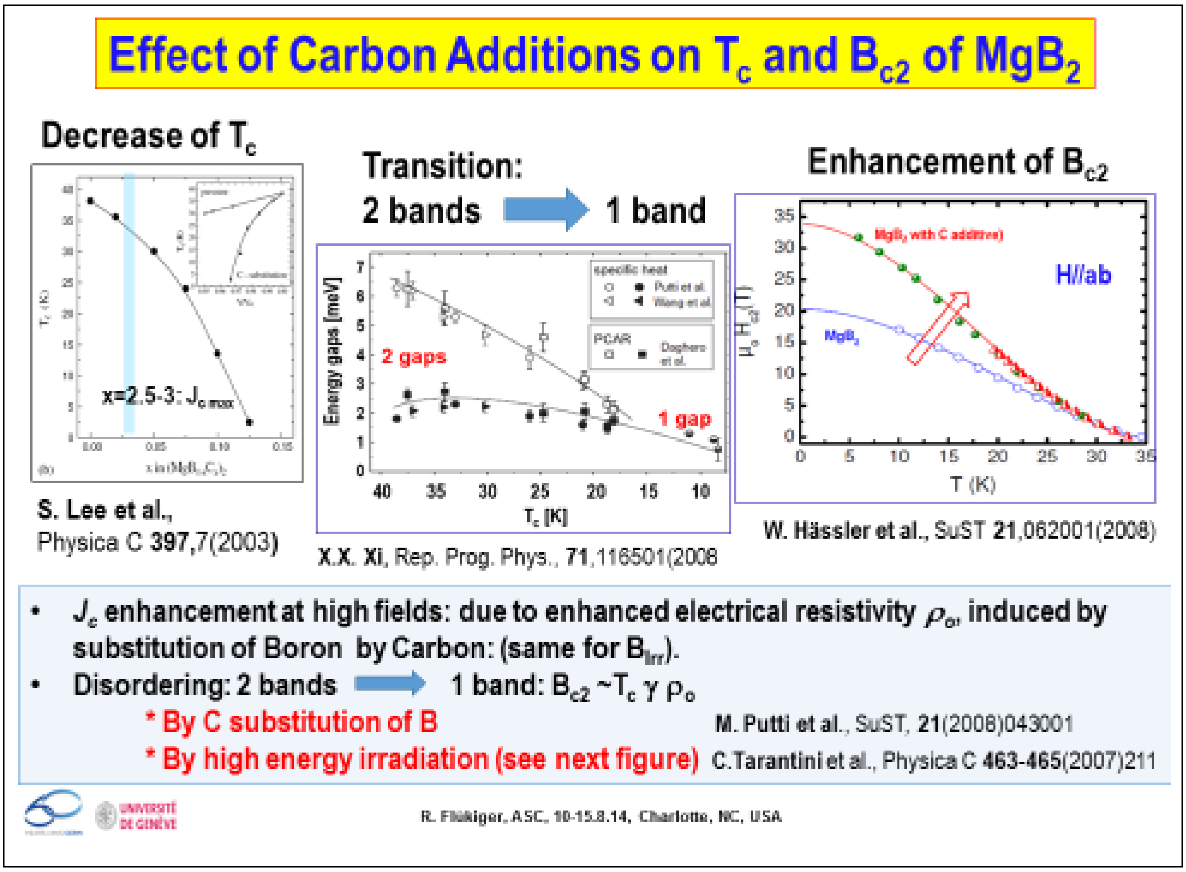
Perfect order and stoichiometry

The ***perfectly ordered*** compound MgB_2 is also ***stoichiometric*****.** It has a very narrow equilibrium phase field: no deviation from the ideal composition has been reported so far. The value of T_c for bulk samples and single crystals is very close to **39 K.**

However, this value can be influenced by impurities and by mechanical stress. It has been shown by ***X.X. Xi*** *et al. in Physica C 456,22(2007)* that on high quality 770 nm thick films produced by Hybrid physical-chemical vapor deposition (HPCVD) on sapphire substrates, T_c can even reach **40.3 K.** The corresponding value for the normal state electrical resistivity ρ_o was as low as **0.1 μΩcm** (RRR=80).

This is the lowest reported value of ρ_o of all known superconductors. Only the A15 type compound V_3Si - also ***stoichiometric and perfectly ordered* -** has a similarly low value: ρ_o = 1 μΩcm (for comparison, the lowest value for Nb_3Sn single crystals is close to ρ_o = 4 μΩcm).



Effect of Carbon Additions on T_c and B_{c2} of MgB_2

Decrease of T_c

S. Lee et al.,
Physica C **397**,7(2003)

Transition:
2 bands → 1 band

X.X. Xi, Rep. Prog. Phys., **71**,116501(2008

Enhancement of B_{c2}

W. Hässler et al., SuST **21**,062001(2008)

- J_c enhancement at high fields: due to enhanced electrical resistivity ρ_o, induced by substitution of Boron by Carbon: (same for B_{irr}).
- Disordering: 2 bands → 1 band: $B_{c2} \sim T_c\,\gamma\,\rho_o$
  - * By C substitution of B — M. Putti et al., SuST, **21**(2008)043001
  - * By high energy irradiation (see next figure) — C.Tarantini et al., Physica C **463-465**(2007)211

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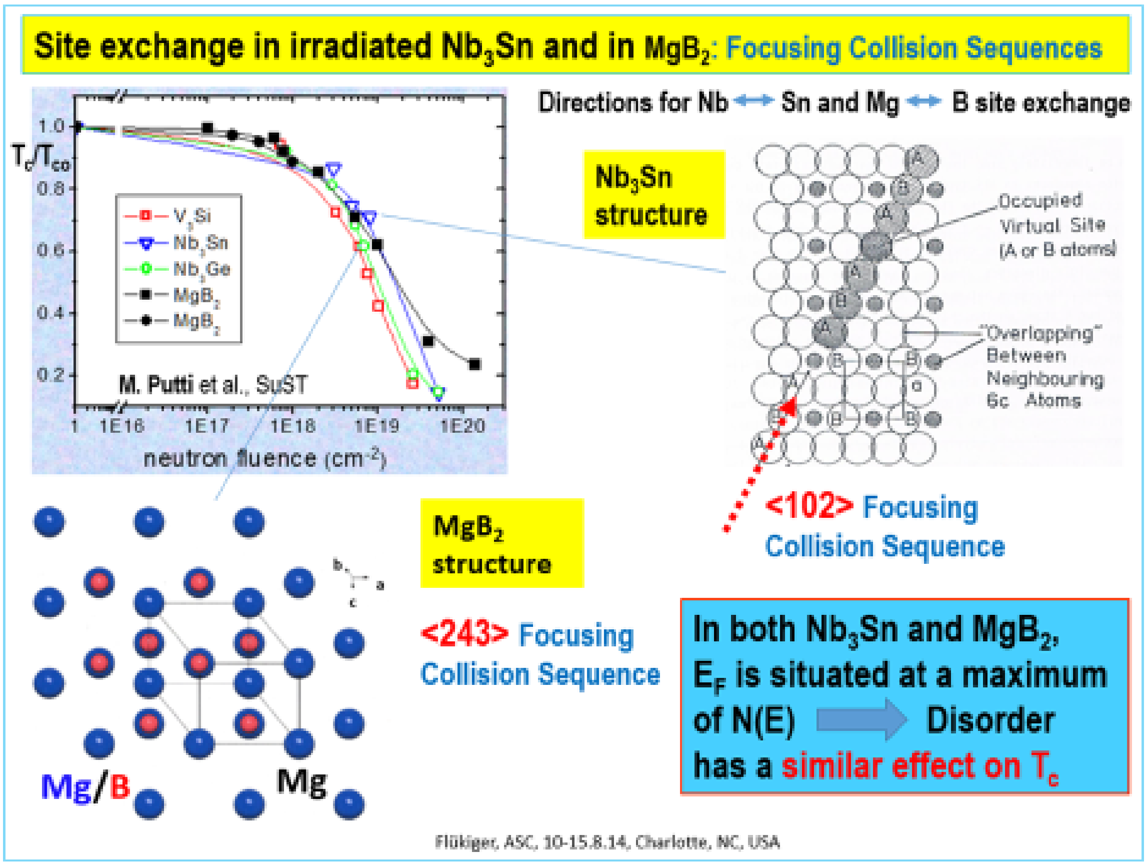
The effect of Carbon addition on T_c and B_{c2}

Carbon was found to substitute B in the MgB_2 lattice, inducing a decrease of T_c and a lowering of the electronic mean free path. As a consequence, the value B_{c2} increases considerably, by almost a factor 2.

Hässler et al. (2008) found a value of 34 T for $B_{c2}(0)$; slightly higher values were found by M. Susner (PhD work, 2012). The maximum of J_c is observed for x ~ 0.12 in the formula ($MgB_{2-x}C_x$), corresponding to ~ 6.5 % Carbon in Boron (W. Hässler et al, 2008). At this composition, T_c is close to 30K.

As shown by X.X. Xi (2008) and also by specific heat measurements (M. Putti, 2008): substitution of B by C leads from 2-band to 1-band behavior. This is also observed after high energy neutron irradiation (C. Tarantini, 2007): Generally, one can say that atomic disorder causes a gradual transition from 2-band to 1-band.



Site exchange in irradiated Nb_3Sn and in MgB_2: Focusing Collision Sequences

Directions for Nb ↔ Sn and Mg ↔ B site exchange

Nb_3Sn structure

Occupied Virtual Site (A or B atoms)

"Overlapping" Between Neighbouring 6c Atoms

<102> Focusing Collision Sequence

MgB_2 structure

<243> Focusing Collision Sequence

In both Nb_3Sn and MgB_2, E_F is situated at a maximum of N(E) ⇒ Disorder has a similar effect on T_c

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Disorder mechanism in the Nb_3Sn and in MgB_2 structures

The variation of T_c vs. neutron fluence (1 MeV neutrons) is very similar for Nb_3Sn and MgB_2. Both are highly ordered structures; in addition, the Fermi energy E_F is in both cases situated close to a maximum of N(E).

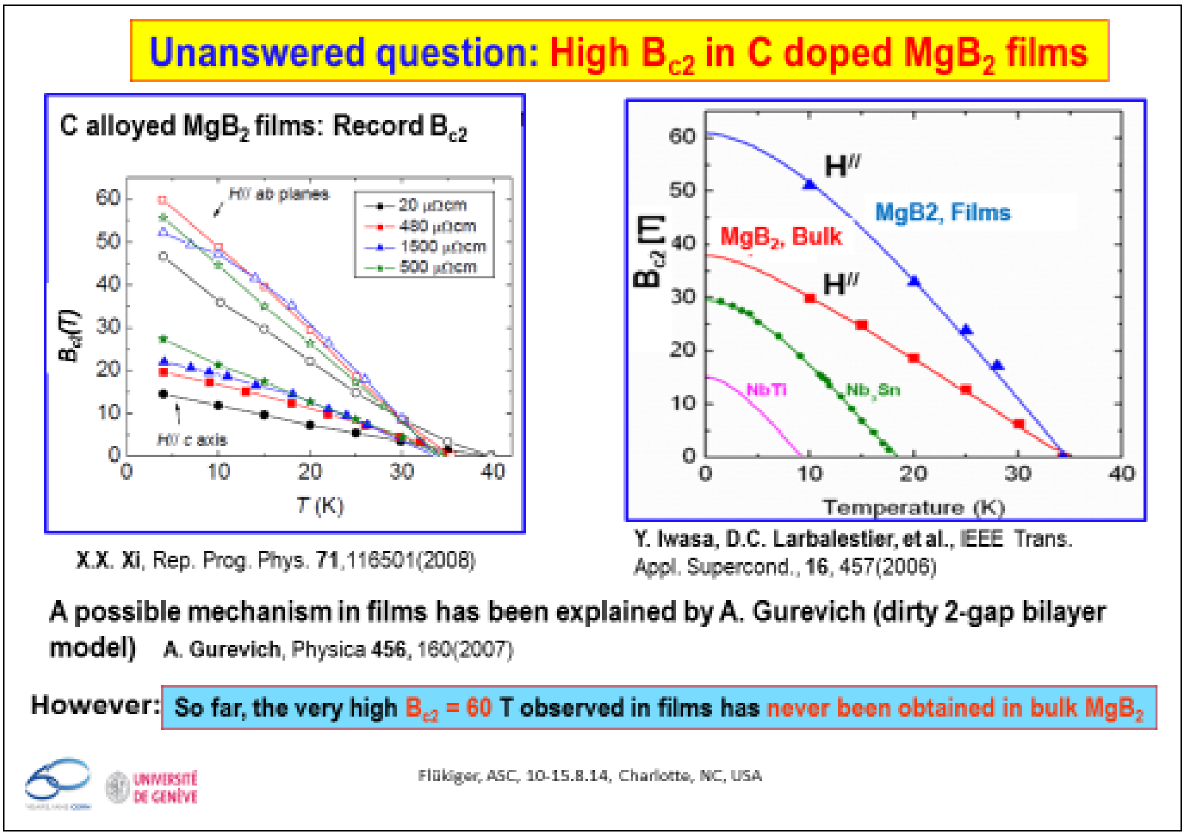
Hypothesis:

In both Nb_3Sn and MgB_2, high energy irradiation induces a lowering of the atomic order parameter, causing a similar decrease of T_c. How does a site exchange occur?

The Focusing Displacement Collision Sequences

In **A15 type** compounds, the Nb ←→ Sn site exchange leading to higher disorder occurs along the **<102>** direction, at the end of the collision process.

In **MgB_2**, no measurement of the degree of atomic ordering after irradiation is available yet. However, such a focusing direction in the lattice exists where Mg ←→ B site exchanges are possible: the **<243>** (shown above) could act as a focusing collision sequence.



Unanswered question: High B_{c2} in C doped MgB_2 films

C alloyed MgB_2 films: Record B_{c2}

X.X. Xi, Rep. Prog. Phys. 71,116501(2008)

Y. Iwasa, D.C. Larbalestier, et al., IEEE Trans. Appl. Supercond., 16, 457(2006)

A possible mechanism in films has been explained by A. Gurevich (dirty 2-gap bilayer model) A. Gurevich, Physica 456, 160(2007)

However: So far, the very high B_{c2} = 60 T observed in films has never been obtained in bulk MgB_2

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Very high critical fields in thin MgB_2 films

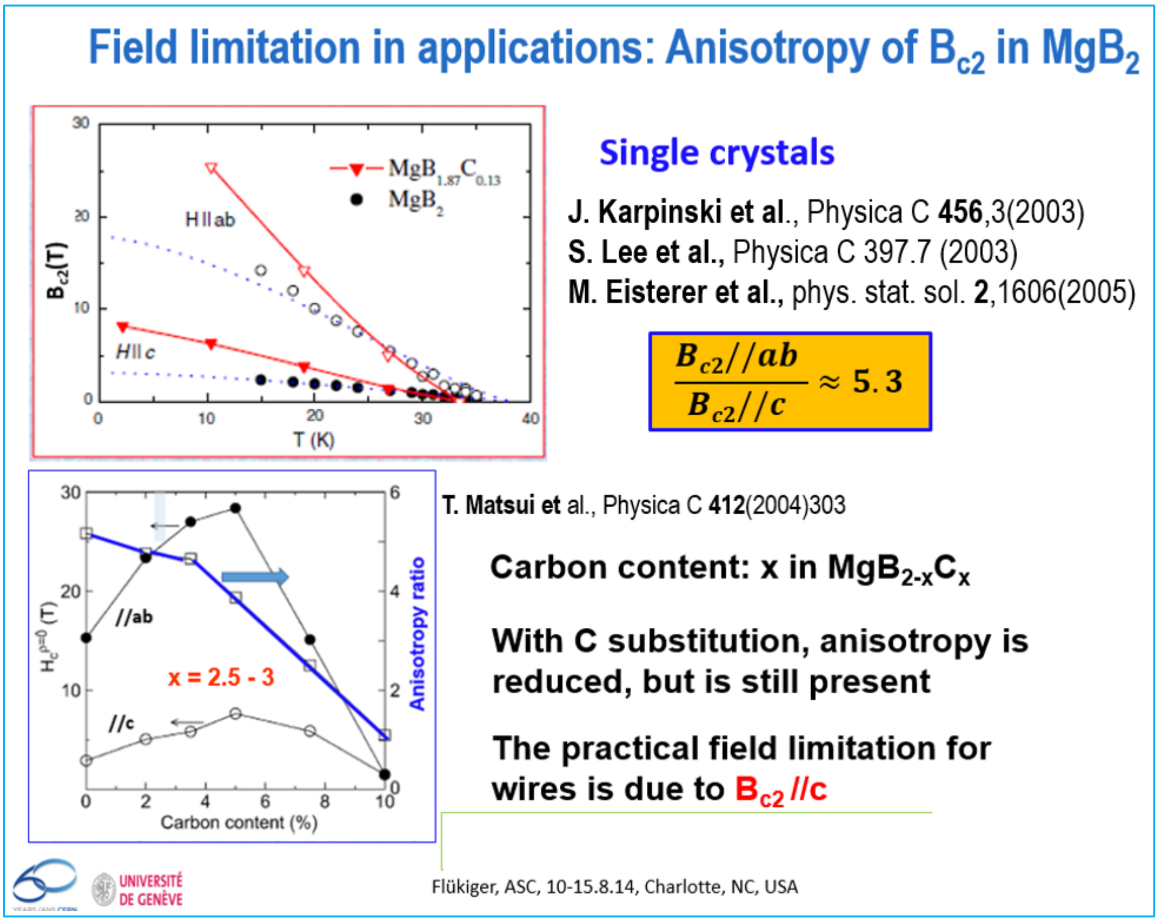
* Very high values of B_{c2} (> 60T) have been reported for MgB_2 thin films prepared by Hybrid physical-chemical vapor deposition (HPCVD):

X.X. Xi et al. Rep. Prog. Phys. 71,116501(2008), Y. Iwasa, D.C. Larbalestier, et al. IEEE Trans. Appl. Supercond., 16, 457(2006), V. Ferrando et al. Appl. Phys. Lett., 87, 252509(2005), C. Ferdeghini et al. IEEE Trans. Appl. Supercond. 15, 3234 (2005) and others.

- Ferrando et al. (2005) have reported carbon alloyed MgB_2 HPCVD films with **B_{c2} ~ 55T** and **B_{irr}** ~ 40T and high J_c values at high fields. These values have so far never been reproduced in bulk or filamentary MgB_2.

- The **very high B_{c2}** values of thin flms have been theoretically studied by Gurevich (2007), who recognized the 2-band structure as the main reason. There are still questions about the fundamental mechanism leading to these extreme values.

- The reasons for the **very high J_c values** in films are attributed to their particular microstructure, combining very small grains (10-20 nm) and possibly oxygen doping. Since they do not have an influence on filamentary MgB_2 conductors, the thin films results will not be further discussed in the present talk.



Field limitation in applications: Anisotropy of B_{c2} in MgB_2

Single crystals

J. Karpinski et al., Physica C **456**,3(2003)
S. Lee et al., Physica C 397.7 (2003)
M. Eisterer et al., phys. stat. sol. **2**,1606(2005)

$$\frac{B_{c2}//ab}{B_{c2}//c} \approx 5.3$$

T. Matsui et al., Physica C **412**(2004)303

Carbon content: x in $MgB_{2-x}C_x$

With C substitution, anisotropy is reduced, but is still present

The practical field limitation for wires is due to B_{c2} //c

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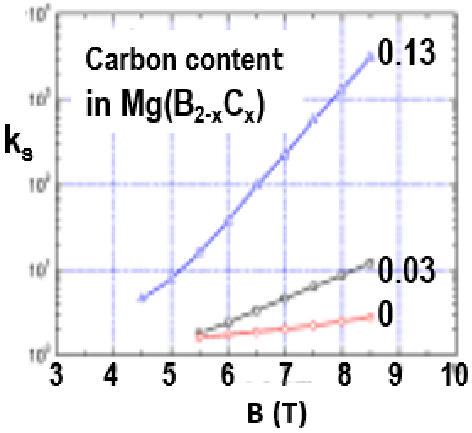
Anisotropy of B_{c2} in MgB_2

Anisotropy of B_{c2} in MgB_2: smaller than in HTS materials, but is still a limiting factor for J_c in conductors. Anisotropy is strongest in highly textured binary thin films, but is reduced in tapes. The addition of Carbon has a limiting effect on the anisotropy factor **$k_s = I_{c\text{-}par}/I_{c\text{-}perp}$:**

Binary films → Binary tapes → C alloyed tapes → C alloyed wires

In round C alloyed wires the anisotropy Factor is smallest, the measured values representing an average over all grain orientations in the filament: its value lies between the values for H//ab and H//c.

P. Kovac et al. J. Physics, **153** 012019(2009);
W. Hässler et al. SuST **21**, 062001(2009).



The anisotropy factor k_s increases with applied field.

II. MgB_2 wires: fabrication and properties

Key to high J_c values in MgB_2 wires:

High quality Boron powder:

- > 98% purity
- Amorphous
- Particle size < 100 nm

Two manufacturers:
SMI (Specialty Materials, Inc). (USA)
Pavezyum (Turkey)

Different Boron powders
- Pure Boron powder
- Boron encapsulated in a thin Carbon layer

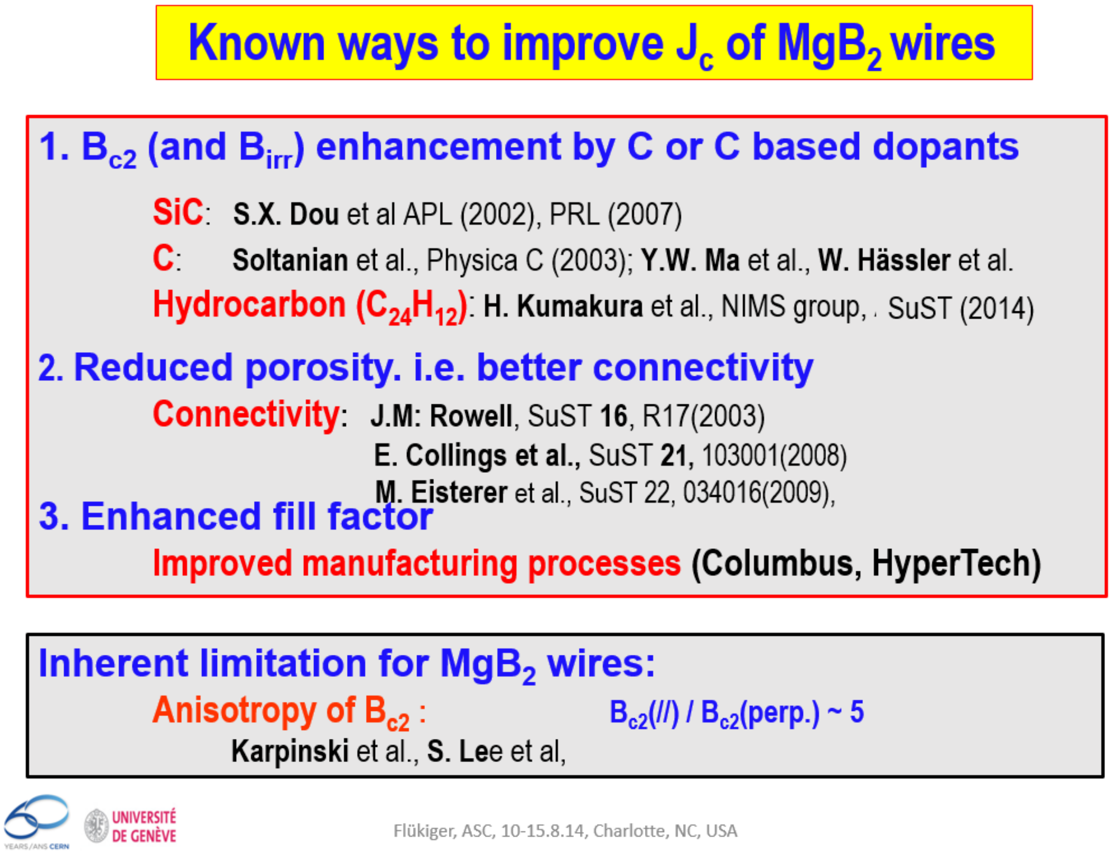
Industrial production of MgB_2 multifilamentary wires

Columbus Superconductors, Genoa, Italy

Hypertech Research Inc., Columbus, Ohio, USA

Laboratory production of long prototype wire lengths:

- OSU, Columbus, OH, USA
- NIMS, Tsukuba, Japan
- EEL, Bratislawa, Slowakia
- KIT, Karlsruhe (D)
- IEE, Beijing, China
- IFW, Dresden (D)
- University of Cambridge (GB)
- DPMC, Geneva, Switzerland
- ....



Known ways to improve J_c of MgB_2 wires

1. B_{c2} (and B_{irr}) enhancement by C or C based dopants

SiC: **S.X. Dou** et al APL (2002), PRL (2007)
C: **Soltanian** et al., Physica C (2003); **Y.W. Ma** et al., **W. Hässler** et al.
Hydrocarbon ($C_{24}H_{12}$): **H. Kumakura** et al., NIMS group, . SuST (2014)

2. Reduced porosity. i.e. better connectivity

Connectivity: **J.M: Rowell**, SuST **16**, R17(2003)
E. Collings et al., SuST **21**, 103001(2008)
M. Eisterer et al., SuST 22, 034016(2009),

3. Enhanced fill factor

Improved manufacturing processes (Columbus, HyperTech)

Inherent limitation for MgB_2 wires:

Anisotropy of B_{c2} : $B_{c2}(//) / B_{c2}(perp.) \sim 5$
Karpinski et al., **S. Lee** et al,

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Enhancement of J_c in MgB_2 wires

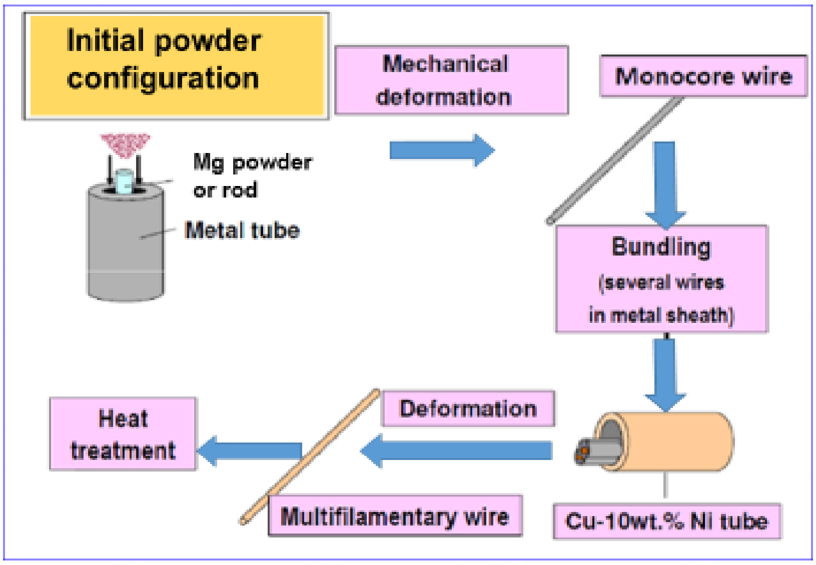
Intense work has been performed in the last years to improve the **J_c** and the **J_e** values (**J_e** is the «engineering» critical current density: the critical current is divided through the entire wire core section).

A review of a large number of other additives was published by E. Collings et al. (2008). The first successful way to add Carbon to MgB_2 was found by Dou et al. (2002) who added **SiC**, which was found to decompose during the reaction process, thus allowing the substitution of B by the free Carbon. Today, pure C is mostly added to MgB_2 wires.

Further progress was reached by enhancing the connectivity between grains. The importance of connectivity was first recognized by J. M. Rowell (2003). The mass density ratio inside the reacted MgB_2 filaments varies between 50% (*in situ* wires) to almost 100% (*second generation* wires, see later).

Finally, the fill factor inside the wire was recently raised to values well above 20%**,** thus extending the competitivity of MgB_2 wires.

Common steps for MgB_2 multifilamentary wires and tapes



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Processing routes for multifilamentary MgB_2 wires

All known processing routes follow a similar sequence:
A given initial powder configuration inside a metallic sheath.

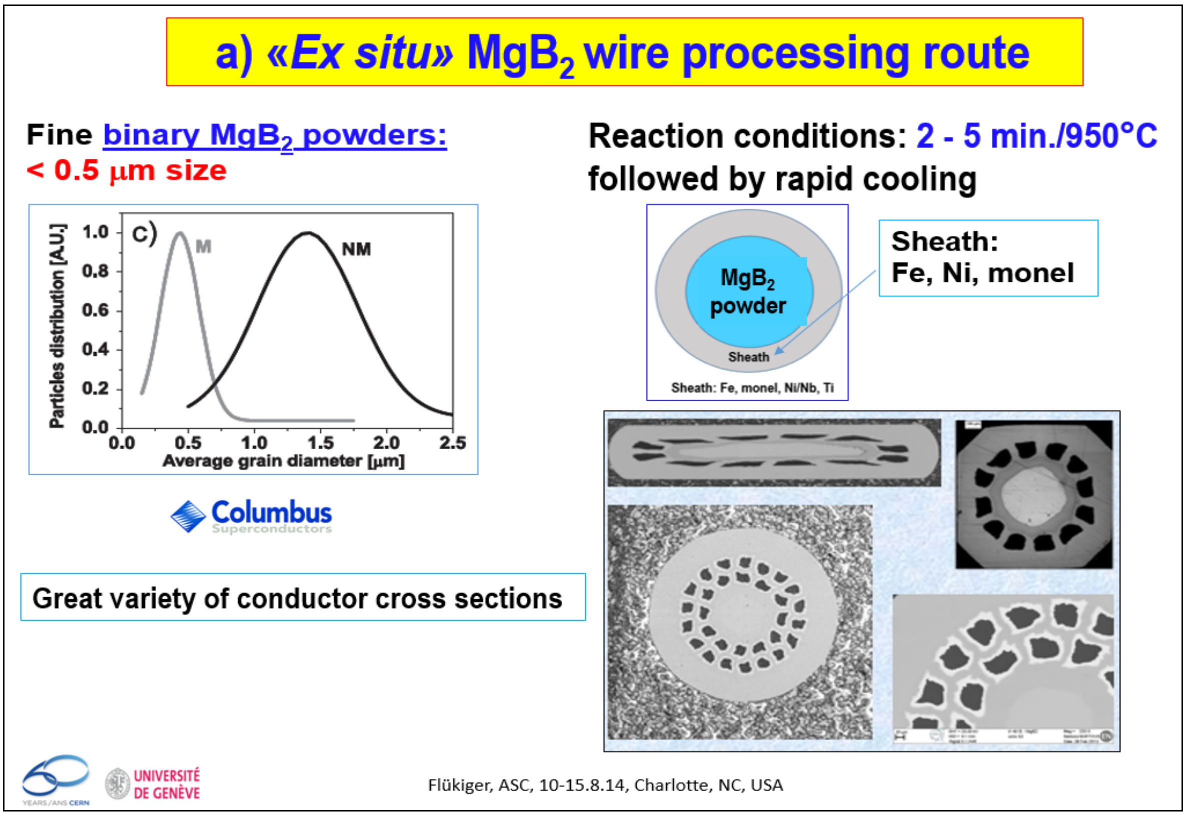
1. After mechanical deformation by drawing, a monofilamentary wire is obtained.
2. After bundling, a multifilamentary configuration is obtained; deformation to final diameter.
3. Final heat treatment

The main difference between resides in the **initial powder configuration**.

**Main difference:
Powder distribution
in the metal sheath**

MgB_2 powders	Ex situ (I)
Mg + B powders (+ C additive)	In situ (Eu, USA, ….) PIT (J) *First generation*
Mg rod, surrounded by B powders (+ C additives)	IMD (J), IMD-PIT (J) AIMI (USA) *Second generation*

IMD: Internal Mg Diffusion
AIMI: Advanced Internal Mg Infiltration



a) «*Ex situ*» MgB_2 wire processing route

Fine binary MgB_2 powders:
< 0.5 µm size

Great variety of conductor cross sections

Reaction conditions: 2 - 5 min./950°C followed by rapid cooling

Sheath: Fe, Ni, monel

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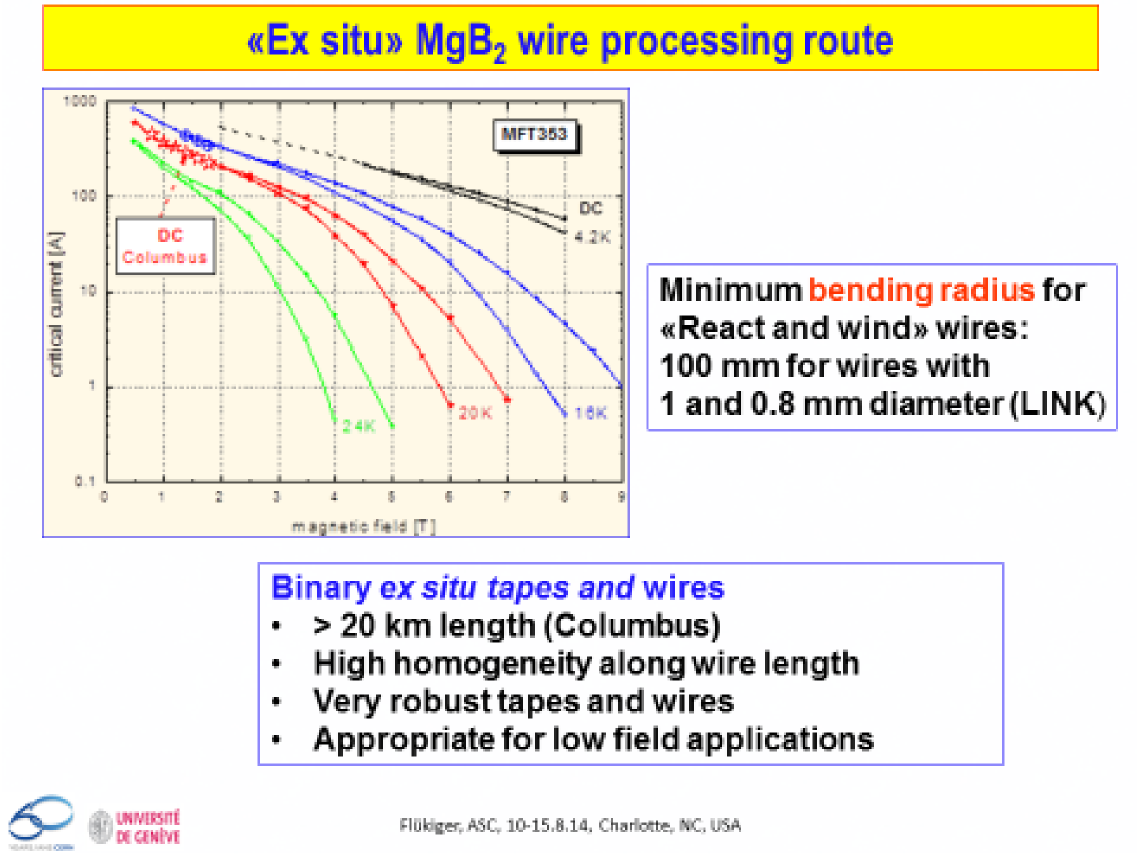

«Ex situ» MgB_2 wire processing route

Minimum bending radius for «React and wind» wires: 100 mm for wires with 1 and 0.8 mm diameter (LINK)

Binary *ex situ* tapes and wires
- > 20 km length (Columbus)
- High homogeneity along wire length
- Very robust tapes and wires
- Appropriate for low field applications

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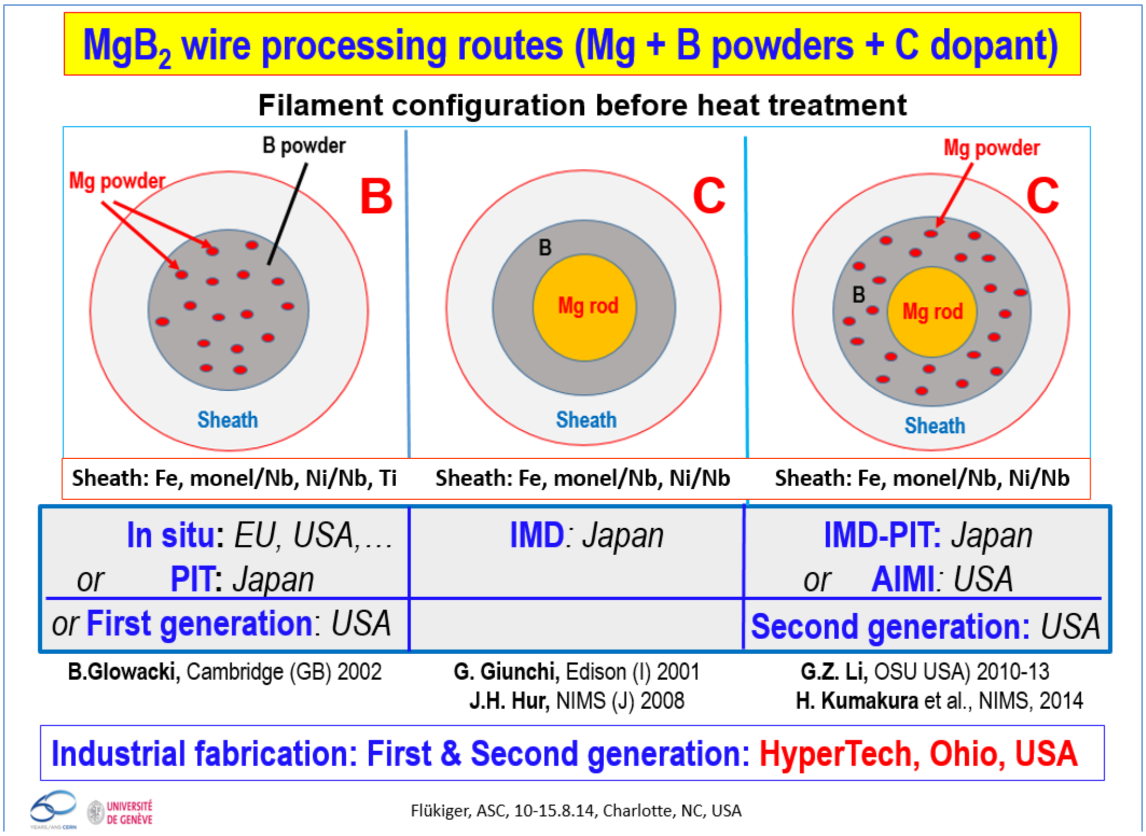

MgB$_2$ wire processing routes (Mg + B powders + C dopant)

Filament configuration before heat treatment

Sheath: Fe, monel/Nb, Ni/Nb, Ti	Sheath: Fe, monel/Nb, Ni/Nb	Sheath: Fe, monel/Nb, Ni/Nb
In situ: *EU, USA,…* *or* **PIT**: *Japan*	**IMD**: *Japan*	**IMD-PIT:** *Japan* *or* **AIMI**: *USA*
or **First generation**: *USA*		**Second generation:** *USA*
B.Glowacki, Cambridge (GB) 2002	**G. Giunchi,** Edison (I) 2001 **J.H. Hur,** NIMS (J) 2008	**G.Z. Li,** OSU USA) 2010-13 **H. Kumakura** et al., NIMS, 2014

Industrial fabrication: First & Second generation: HyperTech, Ohio, USA

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The initial powder configuration

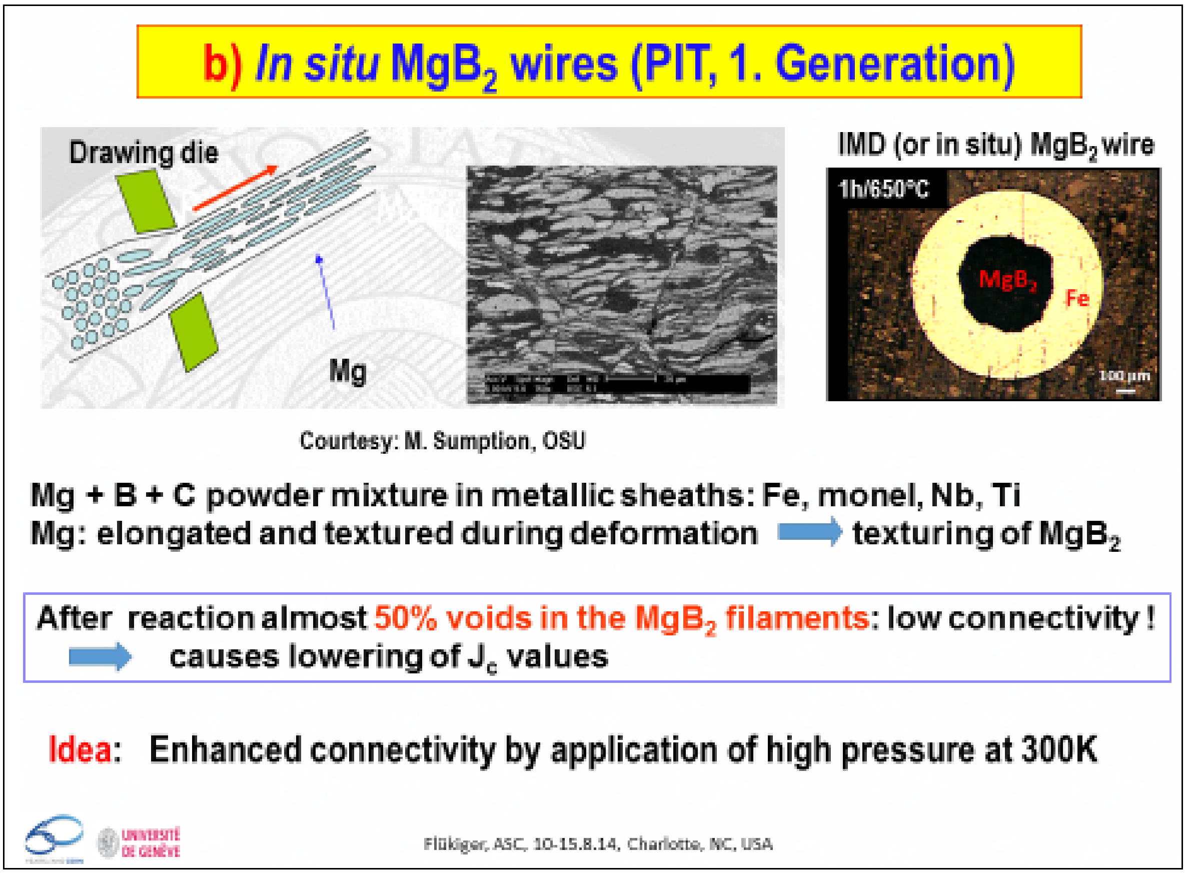
In contrast to «ex situ» processing, which starts with already formed MgB$_2$ powder, there are other routes which start with elemental powder mixtures: roughly, they can be summarized by

1st generation and **2nd generation** wires.

The difference between the US and Japanese 2nd generation wires is small, but substantial.

Compared to the “ex situ” wires (presently, only binary wires are produced), the heat treatment conditions are markedly different, and so are the properties:

Mass density inside the MgB$_2$ filament (between 50 and ~ 100%)
Grain size
Fill factor
Mechanical stability
Critical current density, in particular at high fields (due to C alloying)



b) *In situ* MgB_2 wires (PIT, 1. Generation)

Courtesy: M. Sumption, OSU

Mg + B + C powder mixture in metallic sheaths: Fe, monel, Nb, Ti
Mg: elongated and textured during deformation ⇒ texturing of MgB_2

After reaction almost 50% voids in the MgB_2 filaments: low connectivity !
⇒ causes lowering of J_c values

Idea: Enhanced connectivity by application of high pressure at 300K

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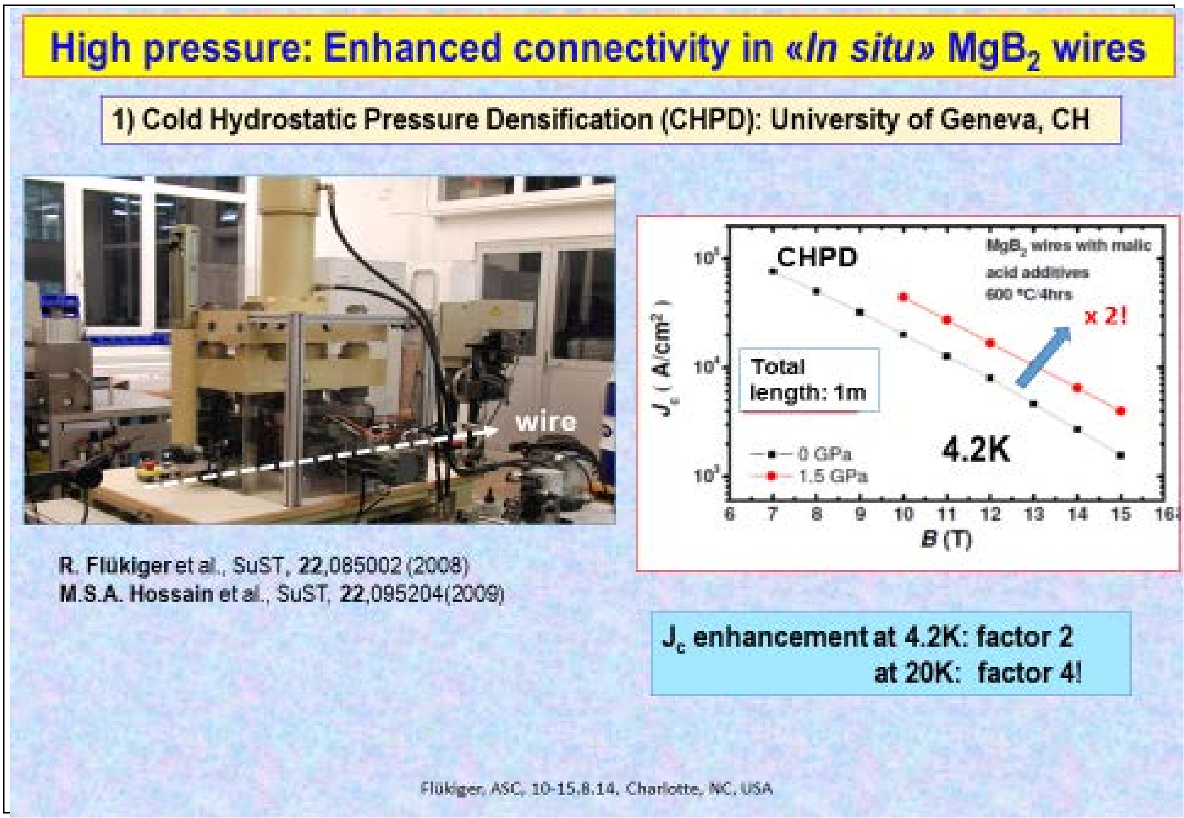
Cold Hydrostatic Pressure Densification

Regardless of the crystal structure, an inherent problem for fabrication of powdermetallurgically produced wires due to voids between powder particles:
Mass density inside filaments after deformation : well below 100%
⇒ **Mass density** inside filaments **after reaction: well below 100%.**

Problem: How to introduce a hydrostatic pressure inside the filaments?

Possibilities: 1) Reaction under HIP conditions
Available pressures: $p < 0.2$ GPa ⇒ little effect on J_c
2) **Cold hydrostatic pressure densification**
Available pressures: $p < 5$ GPa.

First experiments have shown that cold pressures > 1 GPa are necessary **R. Flükiger** et al. SuST **22**, 085002(2008) to get an enhancement of mass density inside MgB_2 filaments and thus a marked enhancement at J_c at 4.2 and 20K.



High pressure: Enhanced connectivity in «*In situ*» MgB_2 wires

1) Cold Hydrostatic Pressure Densification (CHPD): University of Geneva, CH

R. Flükiger et al., SuST, **22**,085002 (2008)
M.S.A. Hossain et al., SuST, **22**,095204(2009)

J_c enhancement at 4.2K: factor 2
at 20K: factor 4!

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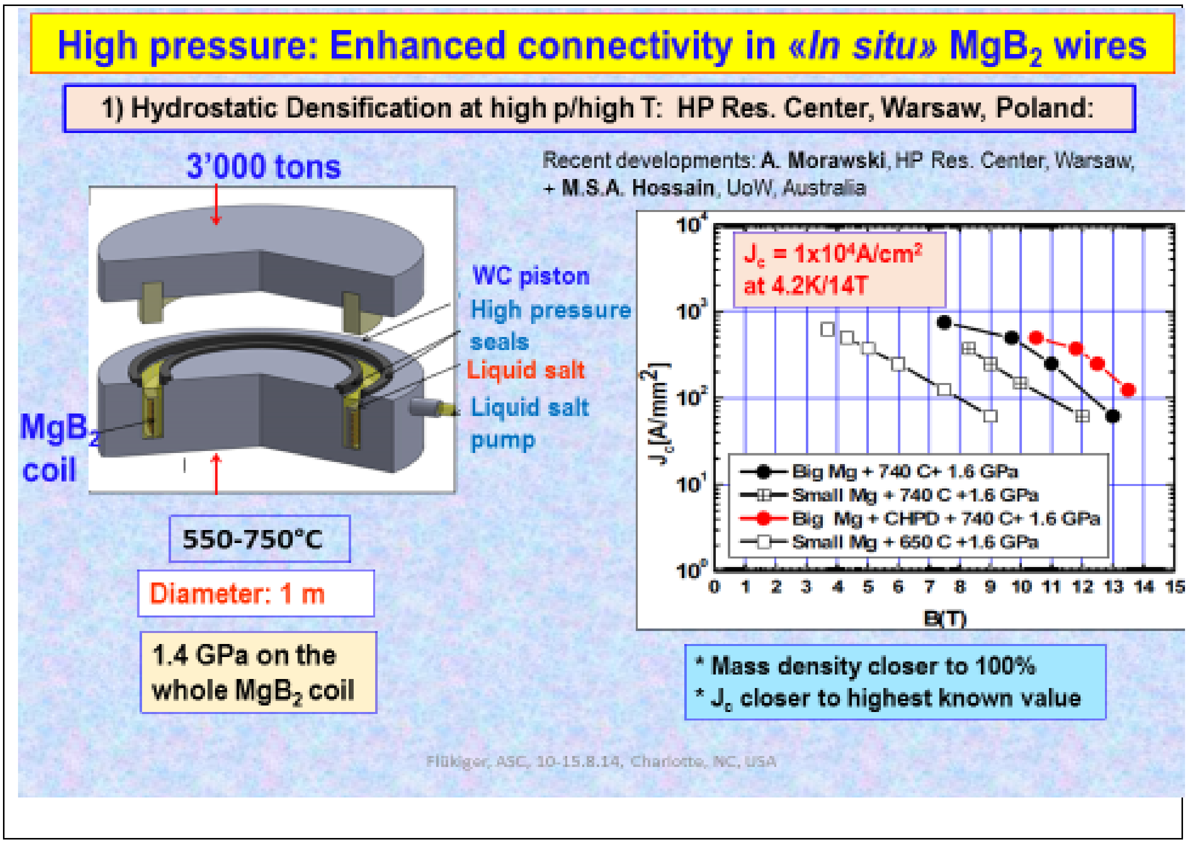

High pressure: Enhanced connectivity in «*In situ*» MgB_2 wires

1) Hydrostatic Densification at high p/high T: HP Res. Center, Warsaw, Poland:

Recent developments: **A. Morawski**, HP Res. Center, Warsaw, + **M.S.A. Hossain**, UoW, Australia

550-750°C

Diameter: 1 m

1.4 GPa on the whole MgB_2 coil

* Mass density closer to 100%
* J_c closer to highest known value

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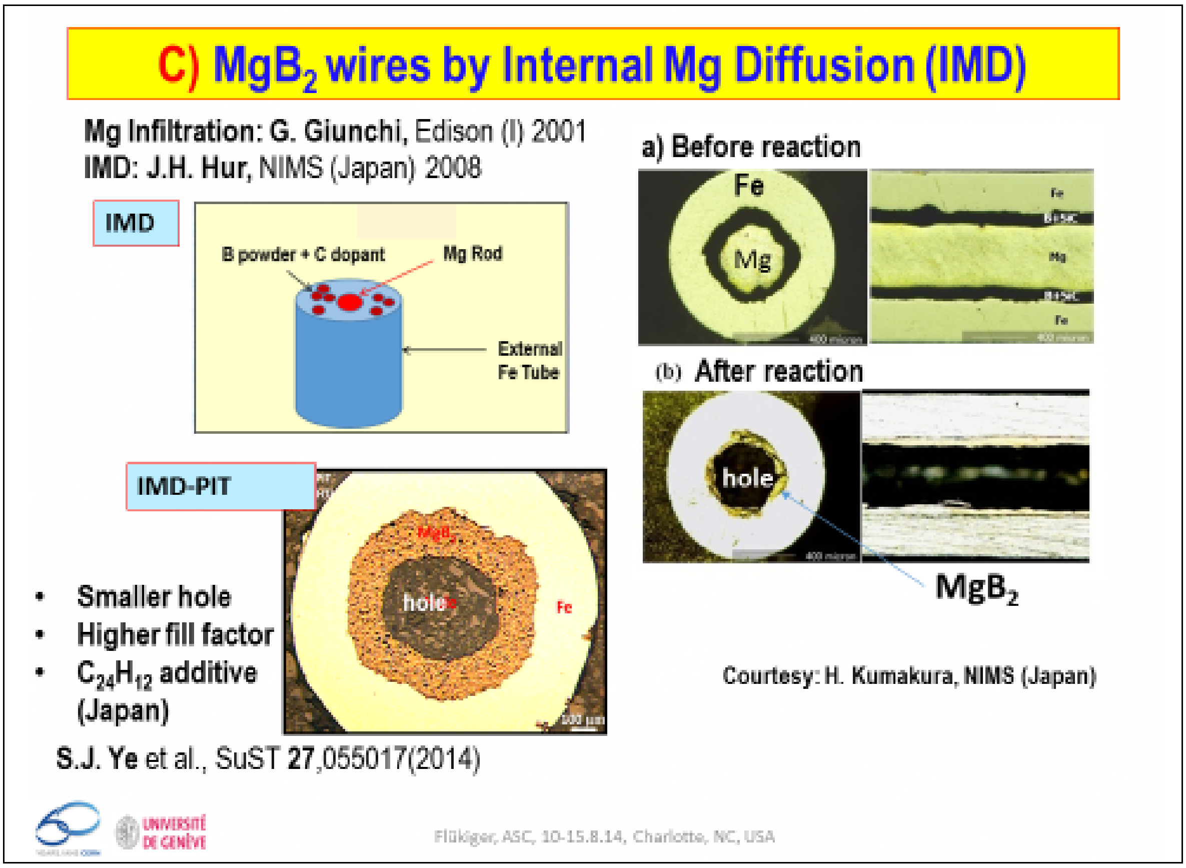


C) MgB_2 wires by Internal Mg Diffusion (IMD)

Mg Infiltration: G. Giunchi, Edison (I) 2001
IMD: J.H. Hur, NIMS (Japan) 2008

IMD

IMD-PIT

- **Smaller hole**
- **Higher fill factor**
- **$C_{24}H_{12}$ additive (Japan)**

S.J. Ye et al., SuST **27**,055017(2014)

a) Before reaction

(b) After reaction

Courtesy: H. Kumakura, NIMS (Japan)

C') Latest developments in USA and in Japan

At Ohio State University (USA) and at NIMS (Japan): advanced developments, based on the IMD process.
In both cases, the reaction kinetics has been taken into account.
Various improvements have been obtained:

➡ enhancement of MgB_2 layer and thus of the fill factor (>20%)

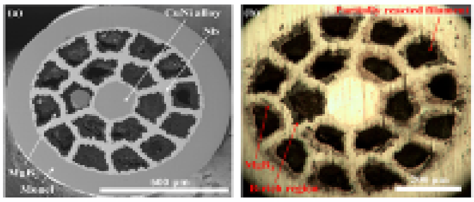
➡ enhancement of J_c.

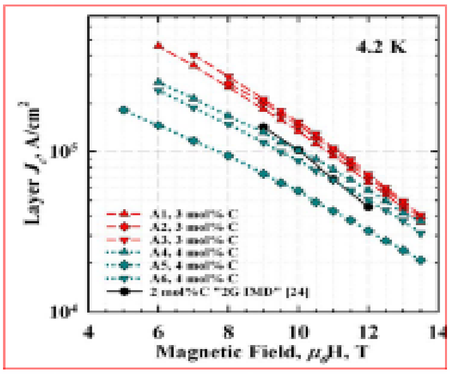
The two new wire types are denominated:
IMD-PIT (NIMS): *Internal Mg Diffusion/Powder-in-Tube* and
AIMI (OSU, Hypertech): *Advanced Internal Mg Infiltration*
Both types of wires belong to the **"second generation"**

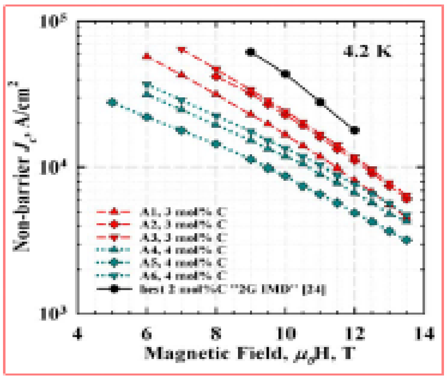
Both IMD-PIT and AIMI wires: J_c(layer) >10^5 A/cm^2 at 4.2K/10T

Latest J_c values in multifilamentary AIMI MgB_2 wires

G.Z. Li et al, preprint (2014)
Presented at ASC 2014







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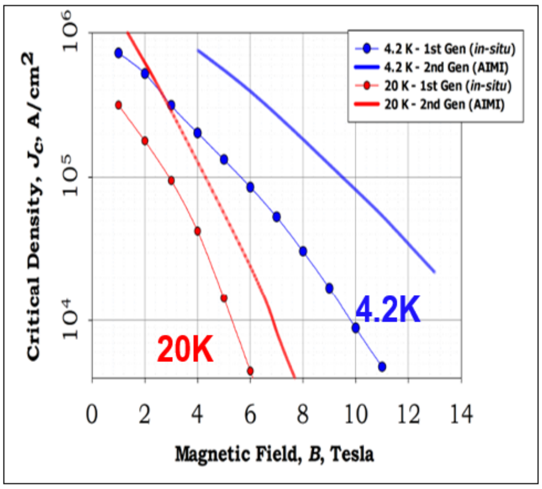
Industrial 1G (in situ) and 2G(AIMI) MgB_2 wires

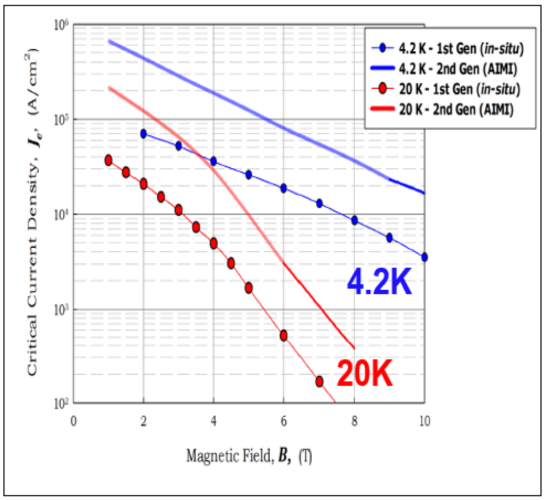
AIMI = Advanced Internal Mg Infiltration

Hyper Tech

J_c



J_e



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III. Future Expectations – performance and costs

The present J_e values of industrial MgB2 wires (AIME) suggest:
MgB_2 solenoids could be constructed producing magnetic fields of

≤ **11 T at 4.2K** and
≤ **5 T at 20K**

Some improvement is possible, but there is an inherent limitation, due to anisotropy.
This can be deduced from a comparison with the J_c data on thin films

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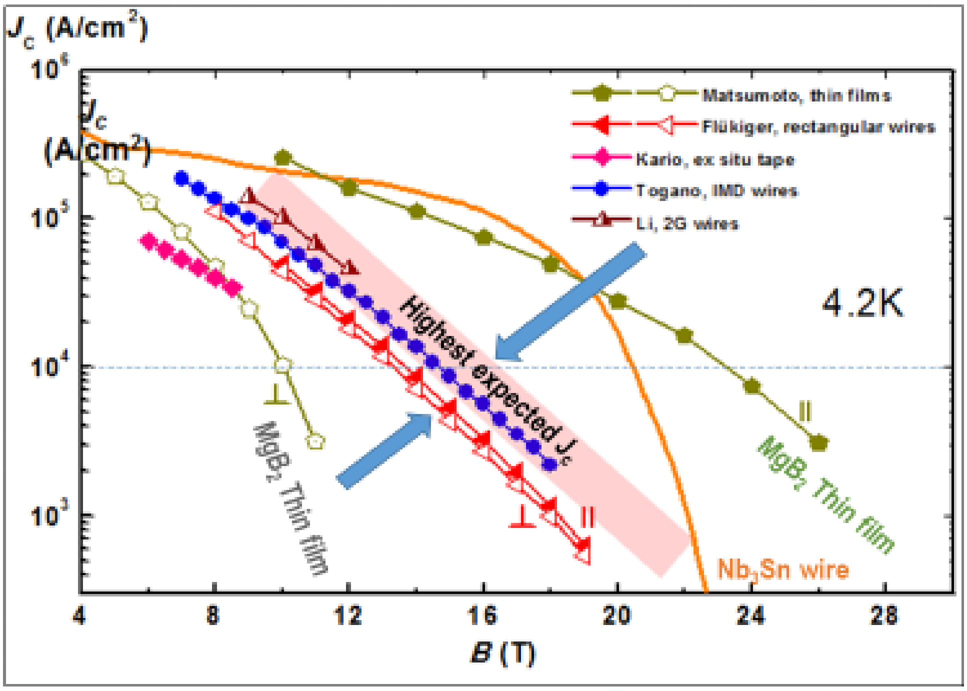
Inherent limitation of J_c in MgB_2 wires



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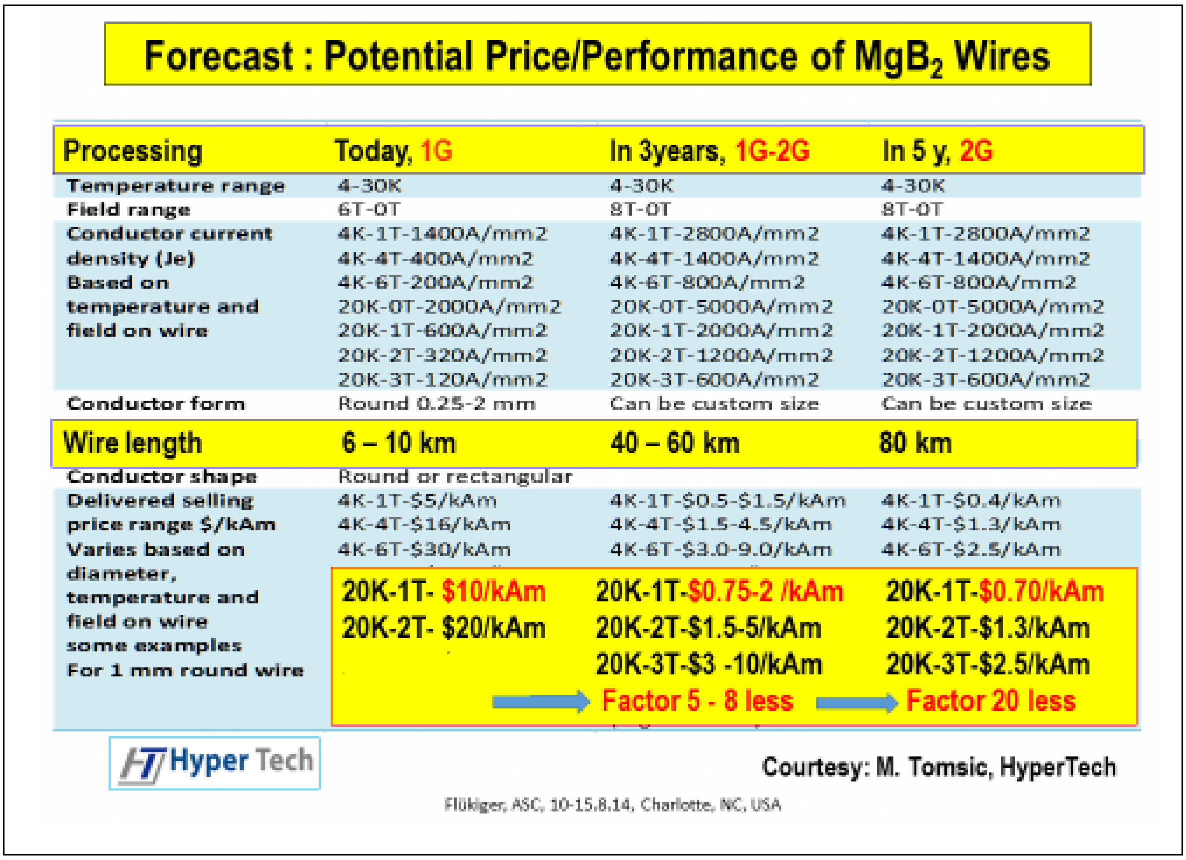


Forecast : Potential Price/Performance of MgB_2 Wires

Processing	Today, 1G	In 3years, 1G-2G	In 5 y, 2G
Temperature range	4-30K	4-30K	4-30K
Field range	6T-0T	8T-0T	8T-0T
Conductor current density (Je) Based on temperature and field on wire	4K-1T-1400A/mm2 4K-4T-400A/mm2 4K-6T-200A/mm2 20K-0T-2000A/mm2 20K-1T-600A/mm2 20K-2T-320A/mm2 20K-3T-120A/mm2	4K-1T-2800A/mm2 4K-4T-1400A/mm2 4K-6T-800A/mm2 20K-0T-5000A/mm2 20K-1T-2000A/mm2 20K-2T-1200A/mm2 20K-3T-600A/mm2	4K-1T-2800A/mm2 4K-4T-1400A/mm2 4K-6T-800A/mm2 20K-0T-5000A/mm2 20K-1T-2000A/mm2 20K-2T-1200A/mm2 20K-3T-600A/mm2
Conductor form	Round 0.25-2 mm	Can be custom size	Can be custom size
Wire length	6 – 10 km	40 – 60 km	80 km
Conductor shape	Round or rectangular		
Delivered selling price range $/kAm Varies based on diameter, temperature and field on wire some examples For 1 mm round wire	4K-1T-$5/kAm 4K-4T-$16/kAm 4K-6T-$30/kAm 20K-1T- $10/kAm 20K-2T- $20/kAm	4K-1T-$0.5-$1.5/kAm 4K-4T-$1.5-4.5/kAm 4K-6T-$3.0-9.0/kAm 20K-1T-$0.75-2 /kAm 20K-2T-$1.5-5/kAm 20K-3T-$3 -10/kAm → Factor 5 - 8 less	4K-1T-$0.4/kAm 4K-4T-$1.3/kAm 4K-6T-$2.5/kAm 20K-1T-$0.70/kAm 20K-2T-$1.3/kAm 20K-3T-$2.5/kAm → Factor 20 less

Courtesy: M. Tomsic, HyperTech

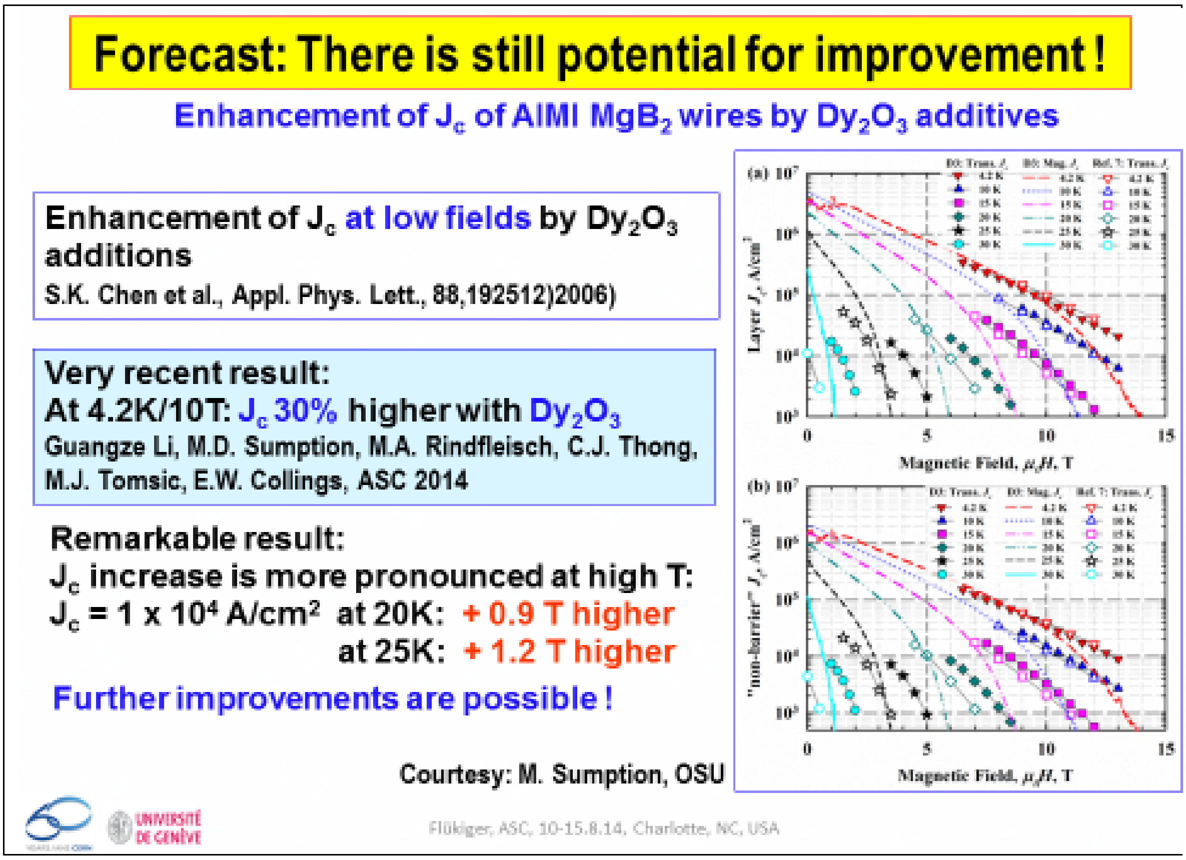
Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA

Forecast: Potential Price/Performance of MgB_2 Wires

Today, the processing route for MgB_2 wires with the largest distribution is the “ex situ” technique, followed by the 1st generation or “in situ” wires. It may be noted that “ex situ” as well as “in situ” wires have a common feature: only **one initial constituent is a powder.**

MgB_2 wires of the 2nd generation are still under development. Inherent difficulty in the development of 2nd generation wires (AIMI or IMD-PIT): **two concentric powder constituents** (see schematic representation at page 13). To produce long lengths of wire with such a configuration, particular deformation precedures had to be developed. The future effort will be concentrated in extending these lengths to > 40 km and later, to 80 km. The transition to longer lengths will require the development of extended facilities, but will also mean a lowering of production costs to an unprecedented level (see the above Table).

For applications at <1 T, e.g. in cables, the costs will be **< 1 $/kAm (10 $/kAm today)**, while for MRI magnets **(~ 3 T)**, the expected costs are as low as **2.5 $/kAm**.



Forecast: There is still potential for improvement !

Enhancement of J_c of AIMI MgB_2 wires by Dy_2O_3 additives

Enhancement of J_c at low fields by Dy_2O_3 additions
S.K. Chen et al., Appl. Phys. Lett., 88,192512)2006)

Very recent result:
At 4.2K/10T: J_c 30% higher with Dy_2O_3
Guangze Li, M.D. Sumption, M.A. Rindfleisch, C.J. Thong, M.J. Tomsic, E.W. Collings, ASC 2014

Remarkable result:
J_c increase is more pronounced at high T:
$J_c = 1 \times 10^4$ A/cm² at 20K: + 0.9 T higher
at 25K: + 1.2 T higher

Further improvements are possible !

Courtesy: M. Sumption, OSU

Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA

The search for artificial pinning in MgB_2

S.K. Chen et al. (2006) published an enhancement of J_c of MgB_2 bulk samples at low magnetic fields after mixing Dy_2O_3 powders before the final reaction. The size of the some Dy_2O_3 powders, a few µm, was reduced to several nm during reaction. The result was interpreted as being the effect of artificial pinning.

G.Z. Li et al (2014) introduced Dy_2O_3 powders of the same initial size in AIMI MgB_2 wires and obtained a slightly different result:

1. No enhancement of J_c at low fields at 4.2K
2. Enhancement of J_c at 4.2/10T.
3. A surprising enhancement of J_c at T = 20 and 25K.

This would mean that a solenoid at 20K could enhance its produced field by 0.9 T. The pinning mechanism is not clear yet, but the effect is worthwhile to be further investigated.

IV. Various MgB_2 Applications

- A. Magnetic Resonance Imaging at 20K
- B. High current cables: LINK project (CERN
- C. Applications of ultra-thin MgB_2 wires
- D. Development of special magnets
- E. Wind generators
- F. Renewable energy applications
- G. Persistent mode bulk magnets (levitation)
- H. Space applications

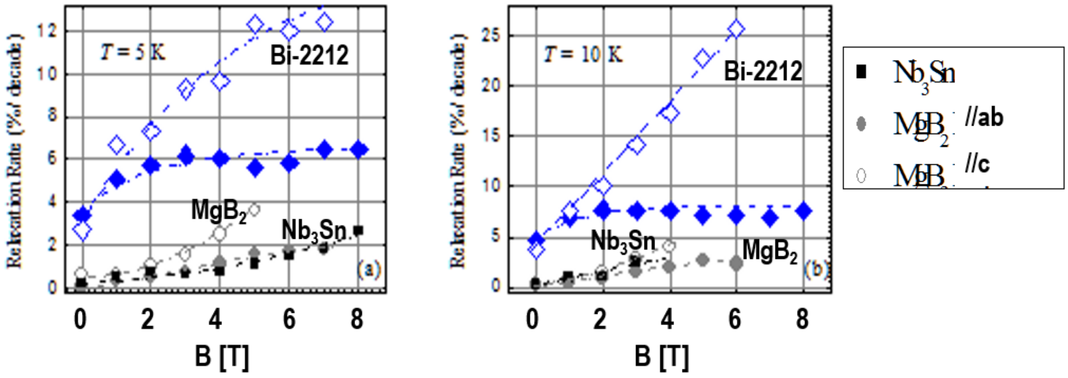
Applied activities based on MgB_2 are rapidly growing worldwide. In the following, examples for all these applications are given.

A. Magnetic Resonance Imaging (MRI)

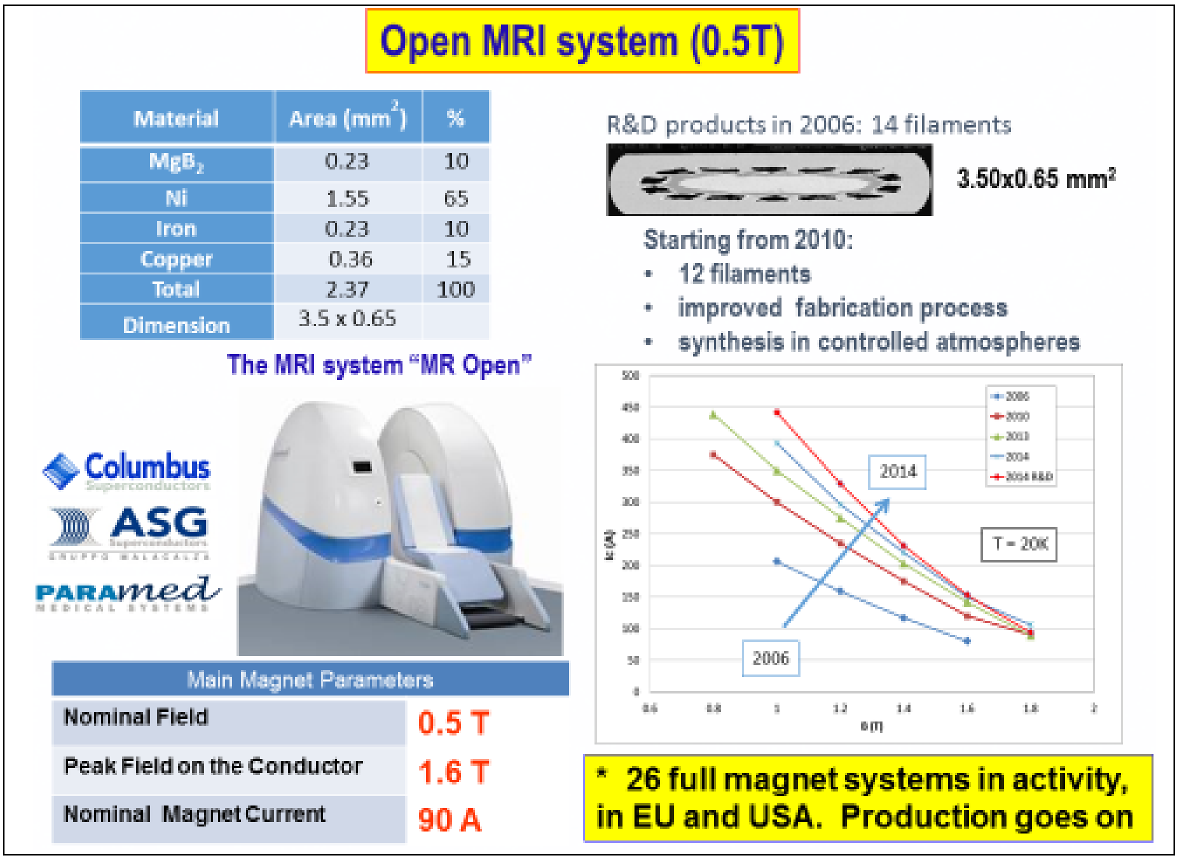
Persistent mode operation

Relaxation rate comparable to that of Nb_3Sn

C. Senatore et al., Adv. Cryo. Eng.,2005



MgB_2 joint development for MRI: Siemens (D), G.E., Hitachi (J),……..



Open MRI system (0.5T)

Material	Area (mm^2)	%
MgB_2	0.23	10
Ni	1.55	65
Iron	0.23	10
Copper	0.36	15
Total	2.37	100
Dimension	3.5 x 0.65	

R&D products in 2006: 14 filaments

3.50x0.65 mm^2

Starting from 2010:

- 12 filaments
- improved fabrication process
- synthesis in controlled atmospheres

The MRI system "MR Open"

Main Magnet Parameters	
Nominal Field	0.5 T
Peak Field on the Conductor	1.6 T
Nominal Magnet Current	90 A

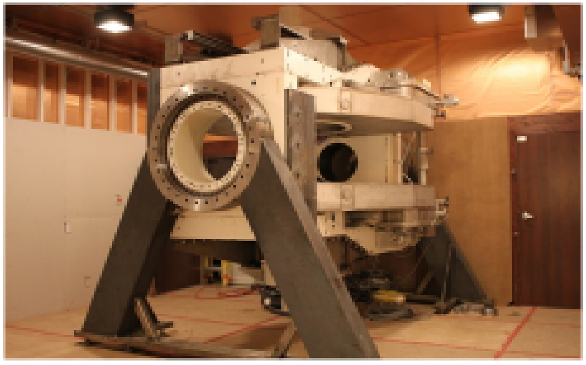
* 26 full magnet systems in activity, in EU and USA. Production goes on

Open MRI Systems

Soon after the discovery of superconductivity in MgB_2, the team at the University of Genova in Italy, together with the newly founded company Columbus (also in Genova) started a strong development program for taking profit of the particular properties of this material.

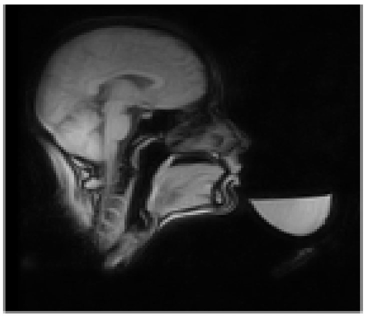
In the meantime, a collaboration between Columbus, ASG and Paramed (all Italy) have succeeded in constructing Open MRI systems. Today largest application for MgB_2 wires. The production at a steady production rate has led to a reduction of the MgB_2 production costs.

Guided Cancer Treatment



Courtesy of prof. Fallone, Cross Cancer Istitute, Edmonton

Cinematic Imaging



Courtesy of A. Phillips, Centre for Hip Health and Mobility

Projected: Conduction-cooled 1.5 T full-body MRI system

Collaboration: HyperTech, Case Western Reserve University and Ohio State University. Project Funded by the State of Ohio.

Based on 2nd generation MgB_2 wire performance

Strength	1.5 T
Type of Superconductor	MgB_2 design
Operating Temperature (K)	10 K
Length (m)	1.40
Inner Diameter (m)	1.00
Outer Diameter (m)	1.97

Stored Energy (MJ)	3.74
Maximum Hoop Stress (MPa)	76.10
Peak Magnetic Field (T)	5.40 T
Current Density(A/mm²)	175.88
Amp-length (kA-km)	18.00

Hyper Tech

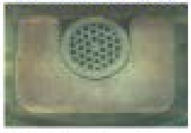
A photograph of the winding of with a Wire-in-Channel (WIC) MgB_2 conductor for this MRI magnet is shown in the next page.

UNIVERSITÉ DE GENÈVE

Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA

MgB_2 Coil, 100 m of WIC MgB_2 Conductor

WIC: Wire-in-channel



HTR: MgB_2 strand, Wire-in-channel Conductor

HTR: Coil wound, coil epoxy impregnated by HTR

OSU: Coil with > 30 voltage taps, > 18 thermocouples, , other sensors

OSU: Cool down and Test

Single Layer, 34-Turn (~100m) WIC MgB_2 Coil

Courtesy: M. Sumption, OSU

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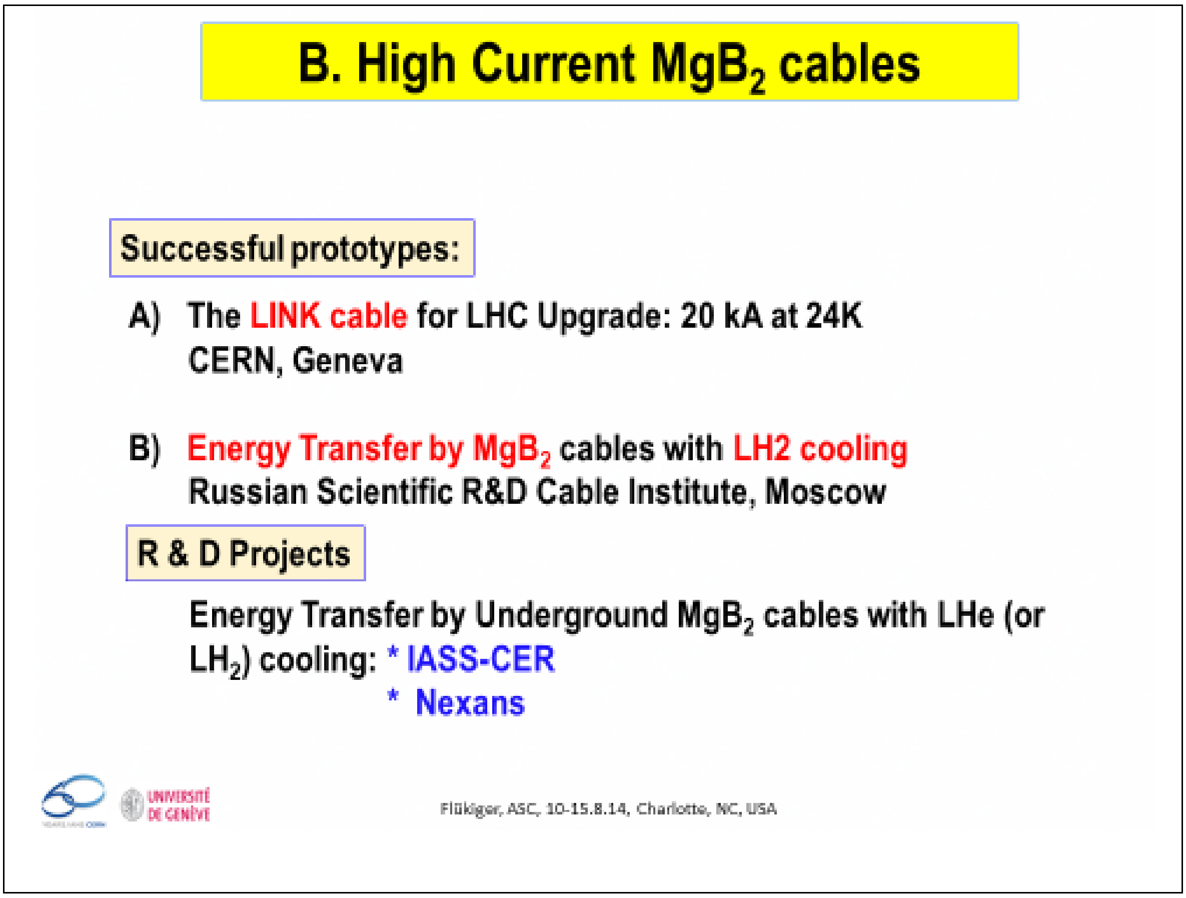


B. High Current MgB_2 cables

Successful prototypes:

A) The LINK cable for LHC Upgrade: 20 kA at 24K
CERN, Geneva

B) Energy Transfer by MgB_2 cables with LH2 cooling
Russian Scientific R&D Cable Institute, Moscow

R & D Projects

Energy Transfer by Underground MgB_2 cables with LHe (or LH_2) cooling: * IASS-CER
* Nexans

Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA

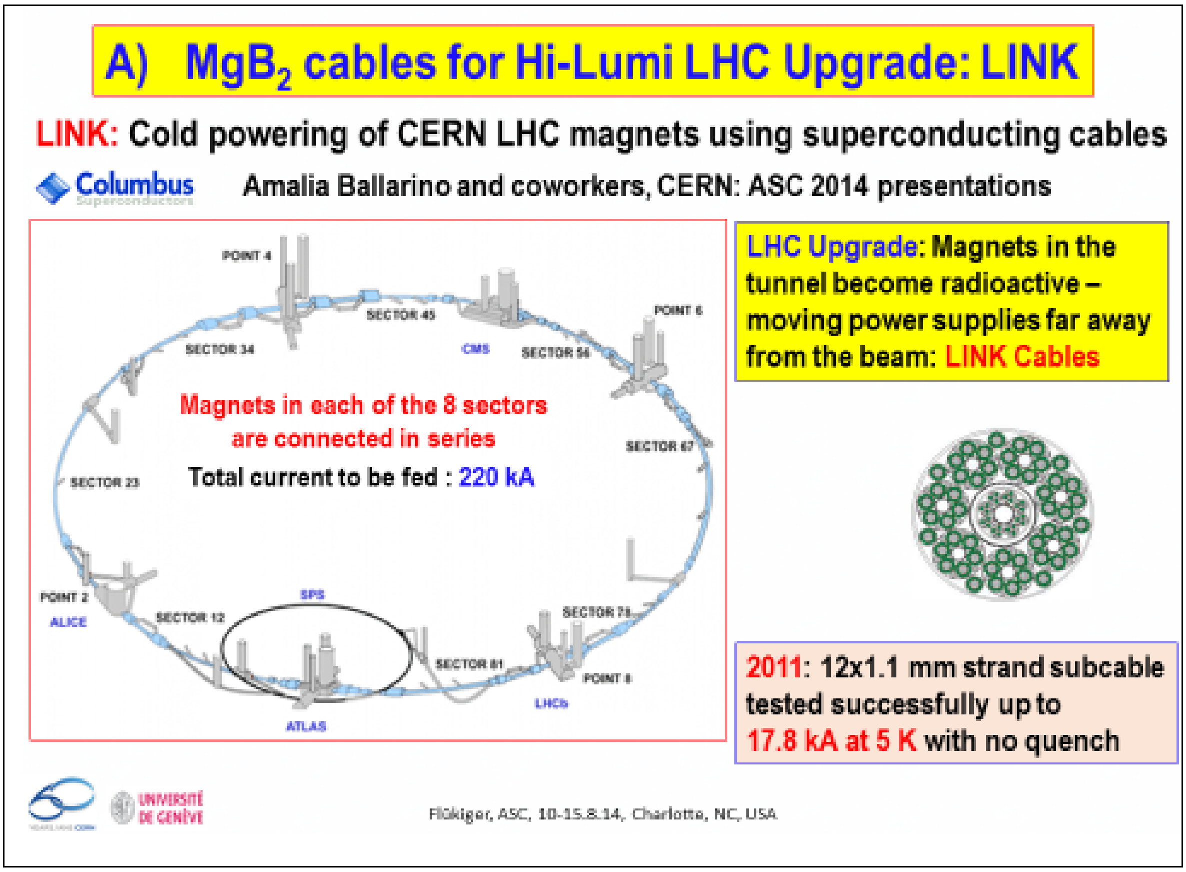
In addition to MRI magnets, the most promising applications for MgB_2 wires are Cables and Motors.

MgB_2 cables

The inherent properties of MgB_2 render it particularly efficient for low field applications, at temperatures **between 4.2 and 25K.**

This opens the possibilities of cooling by He vapour or even by liquid hydrogen. In view of the foreseeable shortage of liquid He in the next decade, this enhances the chances of MgB_2 applications.

There have been quite recently strong improvements of the current capability of MgB_2 cables. A series of cables are presented in the following.



A) MgB_2 cables for Hi-Lumi LHC Upgrade: LINK

LINK: Cold powering of CERN LHC magnets using superconducting cables

Columbus Superconductors

Amalia Ballarino and coworkers, CERN: ASC 2014 presentations

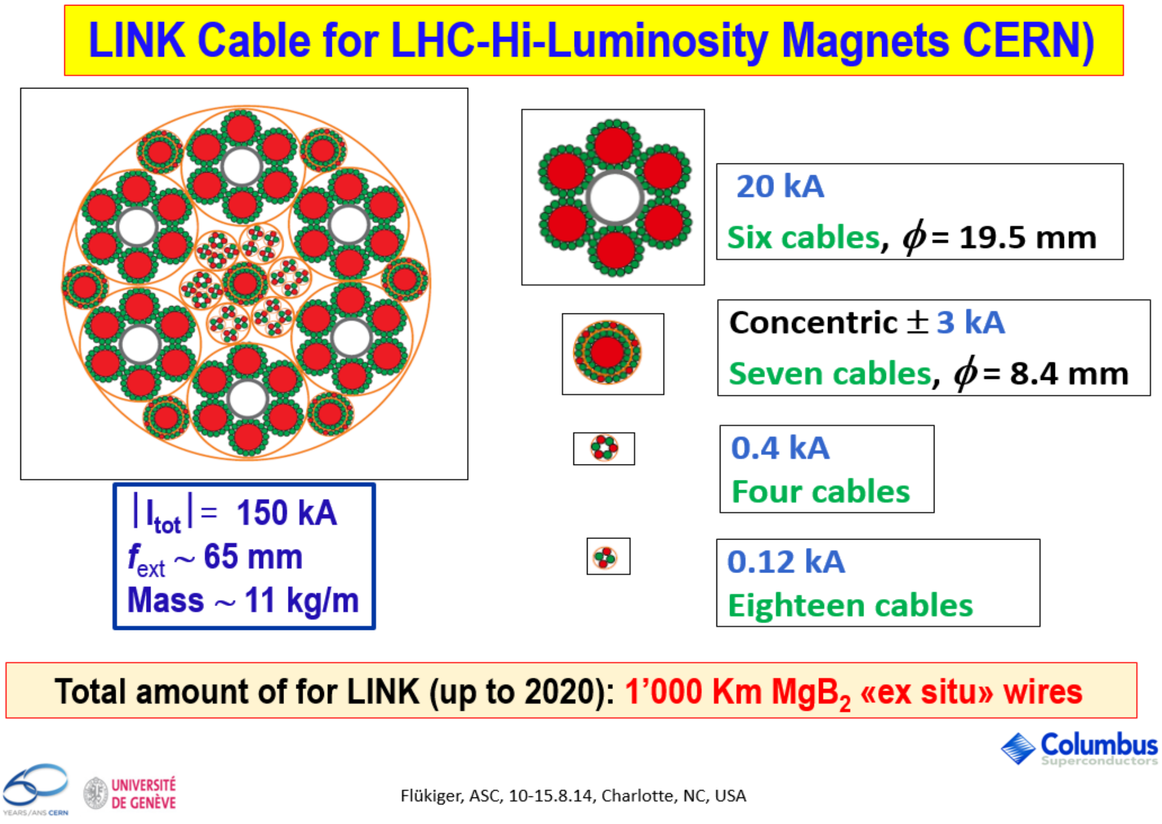
Magnets in each of the 8 sectors are connected in series

Total current to be fed : 220 kA

LHC Upgrade: Magnets in the tunnel become radioactive – moving power supplies far away from the beam: LINK Cables

2011: 12x1.1 mm strand subcable tested successfully up to 17.8 kA at 5 K with no quench

Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA



LINK Cable for LHC-Hi-Luminosity Magnets CERN)

$|I_{tot}|$ = 150 kA
f_{ext} ~ 65 mm
Mass ~ 11 kg/m

20 kA
Six cables, ϕ = 19.5 mm

Concentric ± 3 kA
Seven cables, ϕ = 8.4 mm

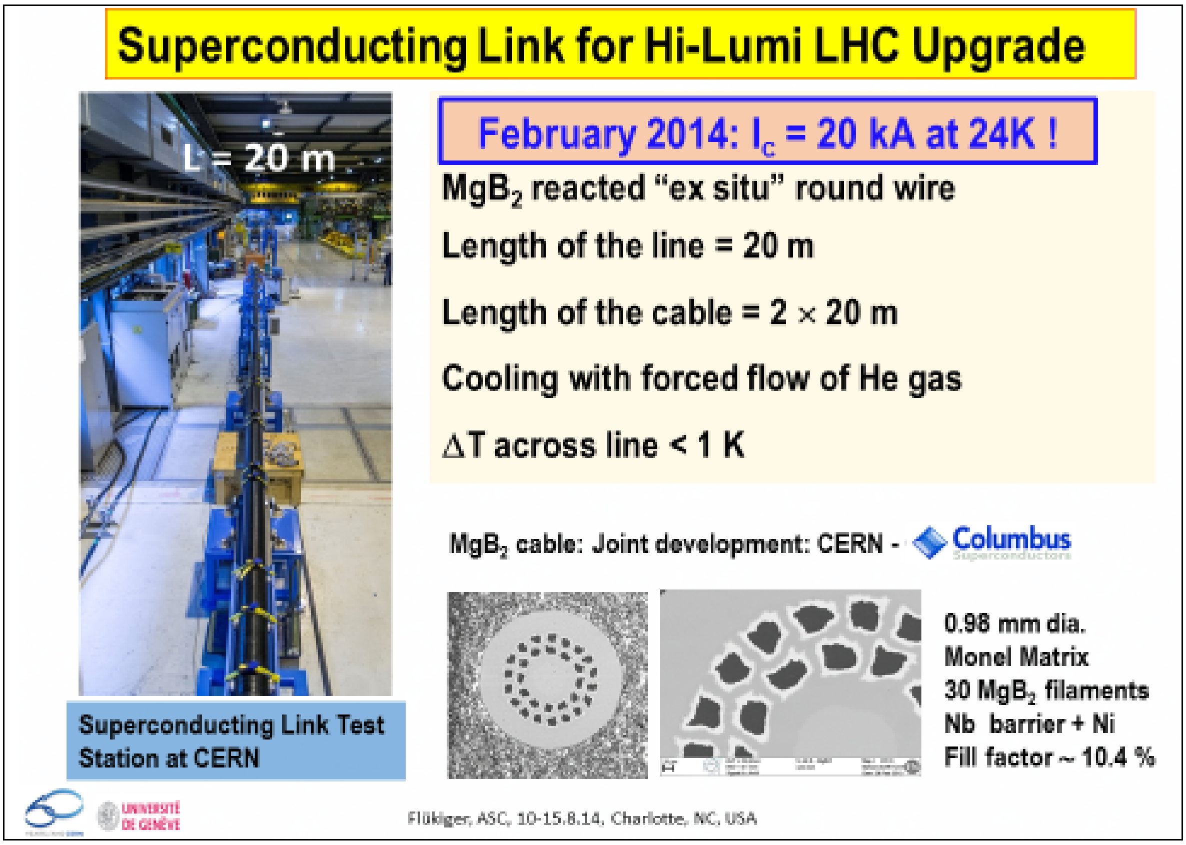
0.4 kA
Four cables

0.12 kA
Eighteen cables

Total amount of for LINK (up to 2020): 1'000 Km MgB_2 «ex situ» wires

Columbus Superconductors

Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA



Superconducting Link for Hi-Lumi LHC Upgrade

Superconducting Link Test Station at CERN

February 2014: I_c = 20 kA at 24K !

MgB_2 reacted "ex situ" round wire

Length of the line = 20 m

Length of the cable = 2 × 20 m

Cooling with forced flow of He gas

ΔT across line < 1 K

MgB_2 cable: Joint development: CERN - Columbus Superconductors

0.98 mm dia.
Monel Matrix
30 MgB_2 filaments
Nb barrier + Ni
Fill factor ~ 10.4 %

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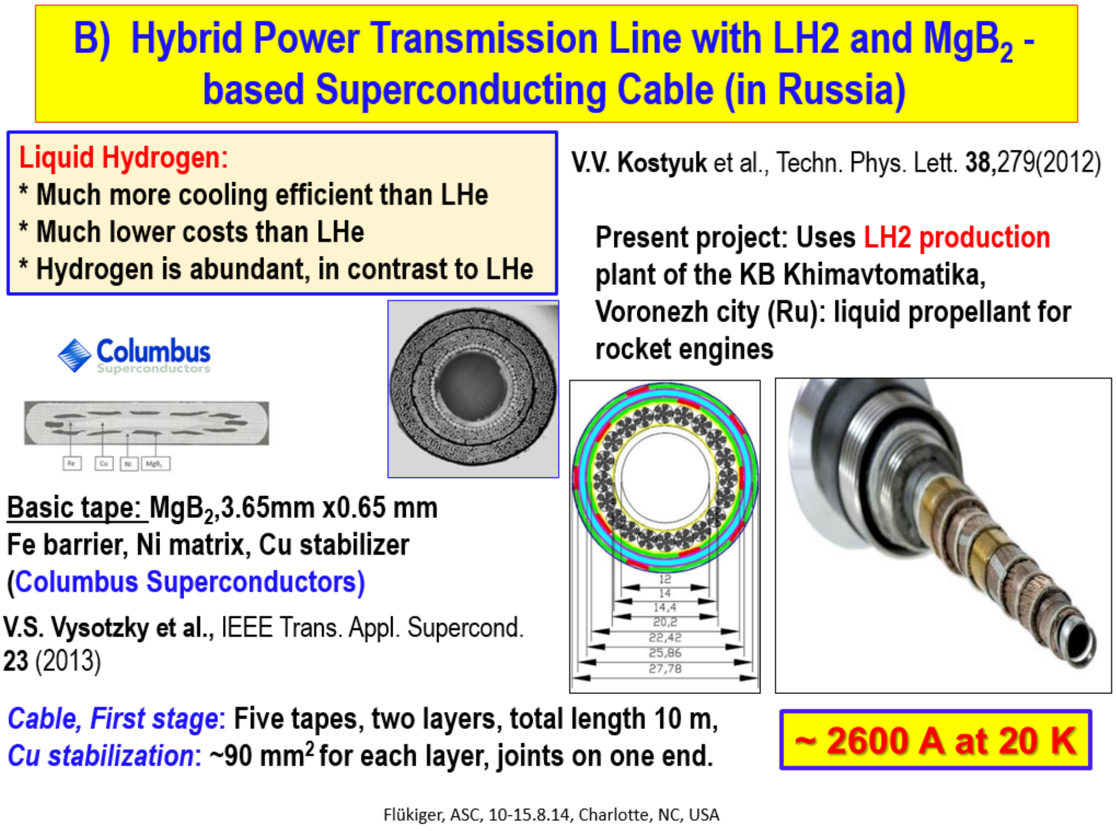

B) Hybrid Power Transmission Line with LH2 and MgB_2 - based Superconducting Cable (in Russia)

Liquid Hydrogen:
* Much more cooling efficient than LHe
* Much lower costs than LHe
* Hydrogen is abundant, in contrast to LHe

V.V. Kostyuk et al., Techn. Phys. Lett. **38**,279(2012)

Present project: Uses LH2 production plant of the KB Khimavtomatika, Voronezh city (Ru): liquid propellant for rocket engines

Columbus Superconductors

Basic tape: MgB_2,3.65mm x0.65 mm
Fe barrier, Ni matrix, Cu stabilizer
(Columbus Superconductors)

V.S. Vysotzky et al., IEEE Trans. Appl. Supercond. **23** (2013)

Cable, First stage: Five tapes, two layers, total length 10 m,
Cu stabilization: ~90 mm^2 for each layer, joints on one end.

~ 2600 A at 20 K

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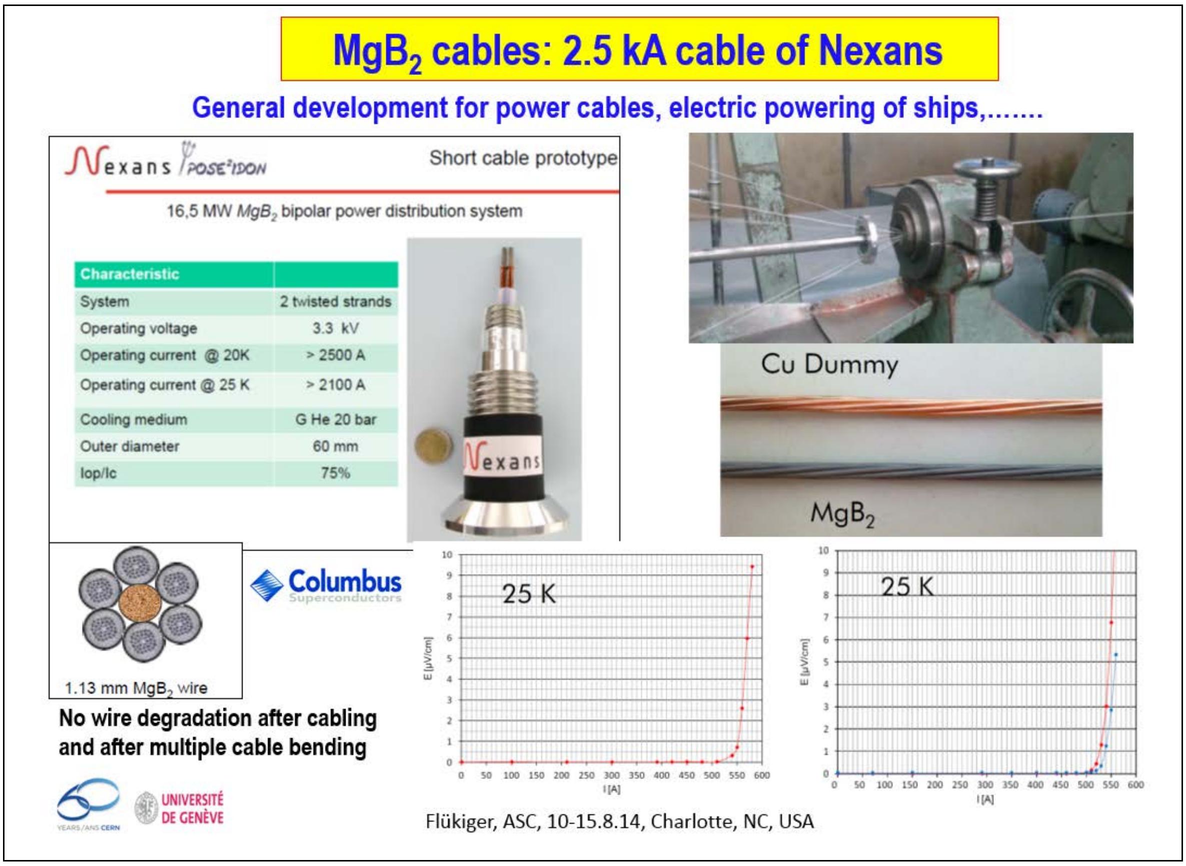

MgB_2 cables: 2.5 kA cable of Nexans

General development for power cables, electric powering of ships,…….

Nexans POSE²IDON

Short cable prototype

16,5 MW MgB_2 bipolar power distribution system

Characteristic	
System	2 twisted strands
Operating voltage	3.3 kV
Operating current @ 20K	> 2500 A
Operating current @ 25 K	> 2100 A
Cooling medium	G He 20 bar
Outer diameter	60 mm
Iop/Ic	75%

1.13 mm MgB_2 wire

No wire degradation after cabling and after multiple cable bending

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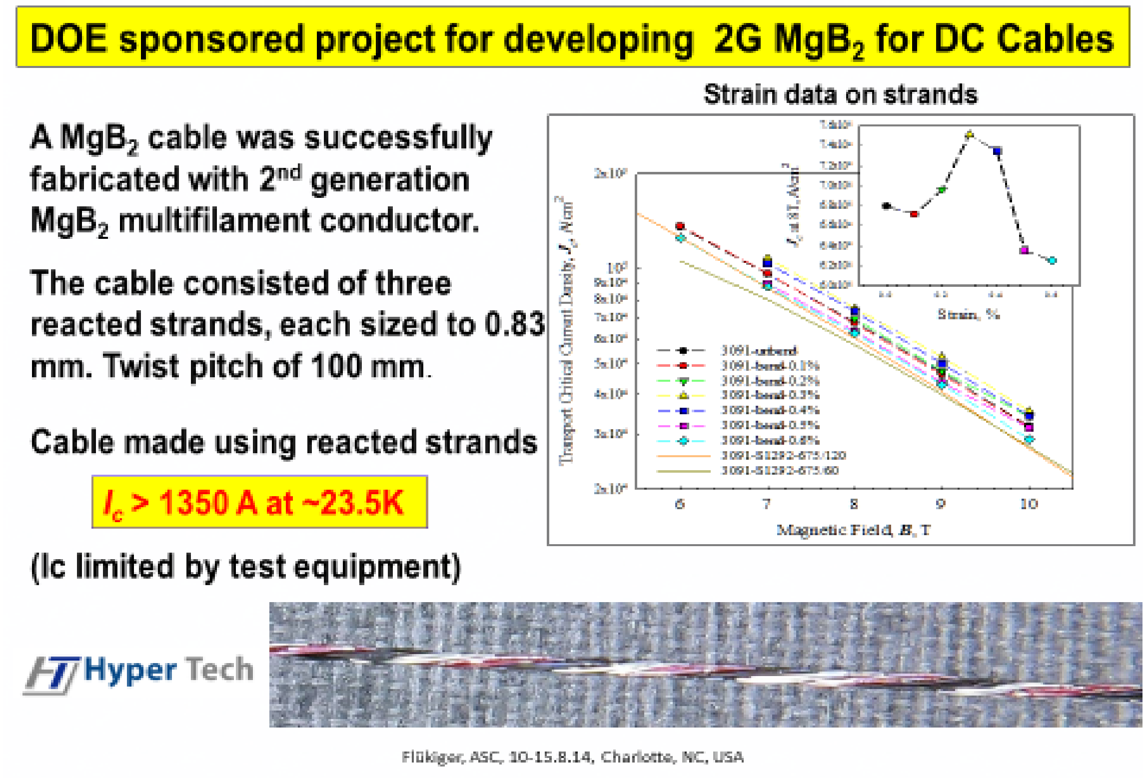


DOE sponsored project for developing 2G MgB_2 for DC Cables

A MgB_2 cable was successfully fabricated with 2nd generation MgB_2 multifilament conductor.

The cable consisted of three reacted strands, each sized to 0.83 mm. Twist pitch of 100 mm.

Cable made using reacted strands

I_c > 1350 A at ~23.5K

(Ic limited by test equipment)

Strain data on strands

Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA

R&D Study: Underground 4 GW MgB_2 transmission line

Collaboration:
IASS Potsdam (Prof. C. Rubbia)- CERN (A. Ballarino)

Subject: 800 km Power Transmission line from the North Sea wind generators to the industrial centers in South Germany.

320kV HVDC bipolar
Underground Cable
Present goal: 4 GW

2032: extension to 12 GW foreseen

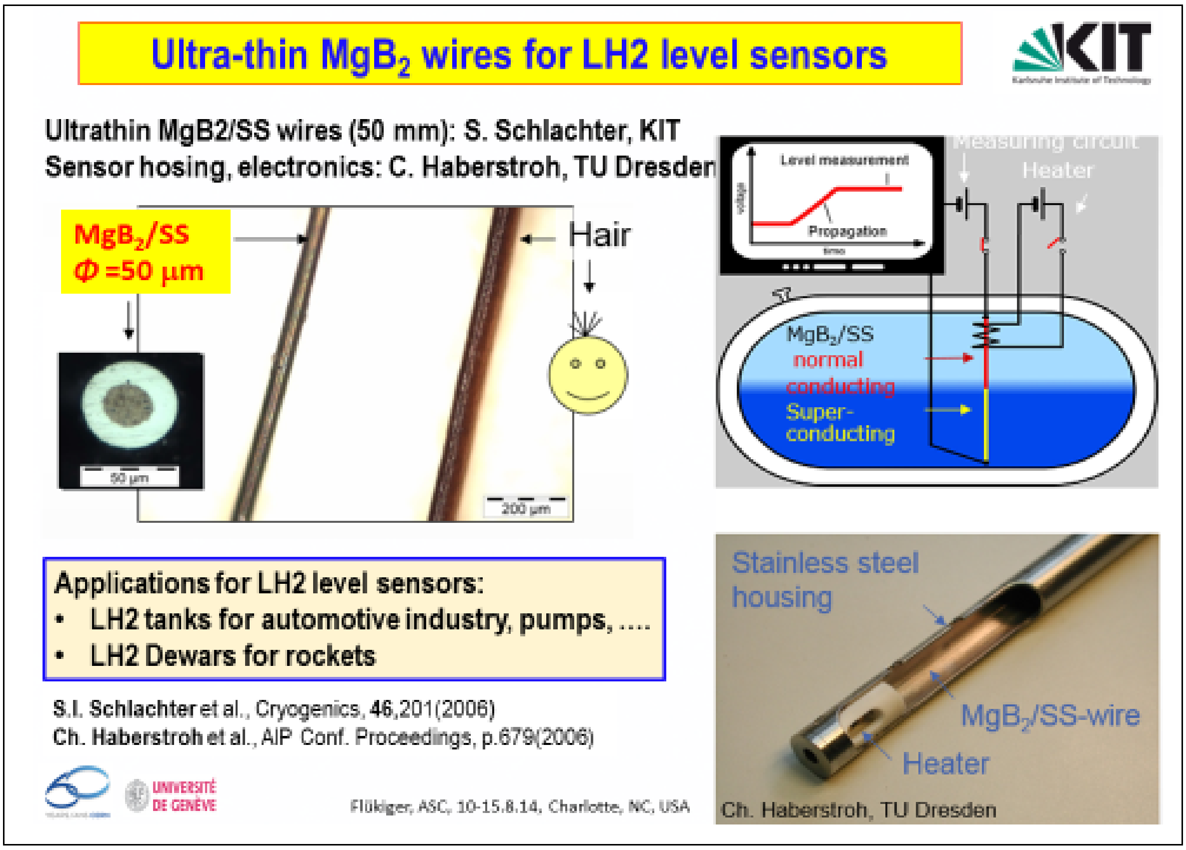
Benefits:
*** Transition through heavily populated areas possible**
*** Societal arguments: Shielded eletromagnetic fields.**
→ No opposition against environmentally harmful overhead lines
No safety corridor needed (20 m for overhead 10 GW line)

After the present breakthrough obtained at CERN, it appears that both, LHe or LH2 cooling could be envisaged.

C) Applications of ultra-thin MgB_2 wires

1. Sensors for LH2 Level
2. Current leads in satellites (NASA)
3. Finer filament MgB_2 wires for s.c. stators in all-electric aircraft (NASA)

Particular Benefits of MgB_2: * low mass density
* available in diameters < 0.1 mm



Ultra-thin MgB_2 wires for LH2 level sensors

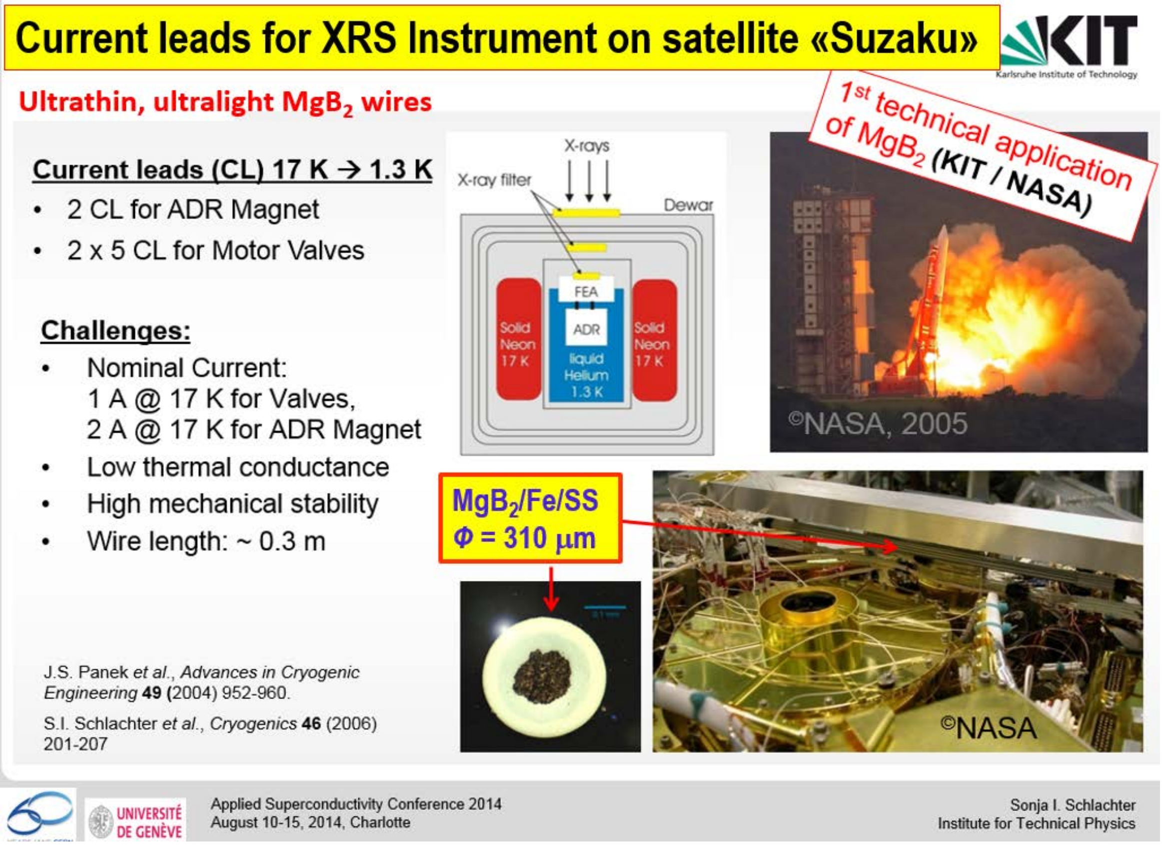
Ultrathin MgB2/SS wires (50 mm): S. Schlachter, KIT
Sensor hosing, electronics: C. Haberstroh, TU Dresden

Applications for LH2 level sensors:
- LH2 tanks for automotive industry, pumps, ...
- LH2 Dewars for rockets

S.I. Schlachter et al., Cryogenics, 46,201(2006)
Ch. Haberstroh et al., AIP Conf. Proceedings, p.679(2006)

Ch. Haberstroh, TU Dresden

Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA



Current leads for XRS Instrument on satellite «Suzaku»

Ultrathin, ultralight MgB_2 wires

1st technical application of MgB_2 (KIT / NASA)

Current leads (CL) 17 K → 1.3 K
- 2 CL for ADR Magnet
- 2 x 5 CL for Motor Valves

Challenges:
- Nominal Current:
  1 A @ 17 K for Valves,
  2 A @ 17 K for ADR Magnet
- Low thermal conductance
- High mechanical stability
- Wire length: ~ 0.3 m

©NASA, 2005

MgB_2/Fe/SS
Φ = 310 µm

©NASA

J.S. Panek *et al.*, *Advances in Cryogenic Engineering* **49** (2004) 952-960.

S.I. Schlachter *et al.*, *Cryogenics* **46** (2006) 201-207

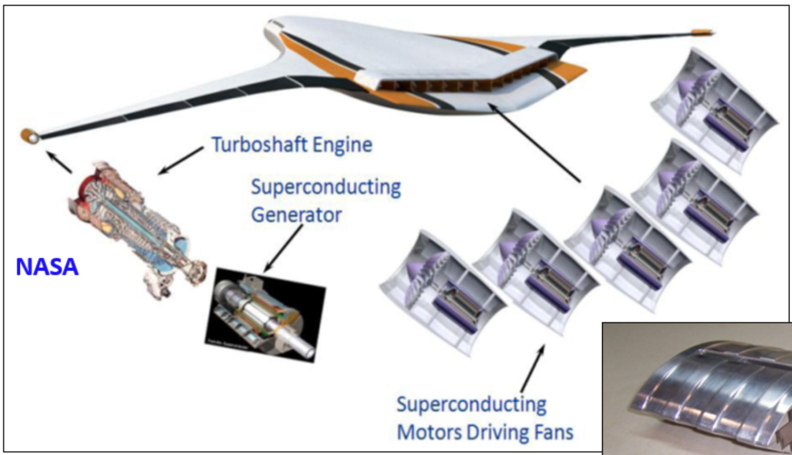
Applied Superconductivity Conference 2014
August 10-15, 2014, Charlotte

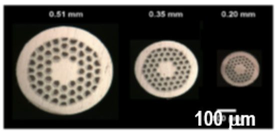
Sonja I. Schlachter
Institute for Technical Physics

Finer filament MgB_2 wires for s.c. stators in all-electric aircraft

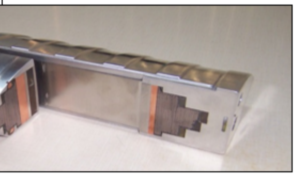
NASA, Goal: all-electric aircraft with cryogenic motors and generators

Filament sizes of ≤10 μm would yield low AC losses in the 50-200 Hz range for the stator





Hyper Tech



Present status: 20 μm filaments. J_c maintained with twist pitches ~ 10 mm.
Goal: ≤ 10 μm filaments.

MgB_2 rotor coils have been made for NASA 2MW 15,000 rpm generator

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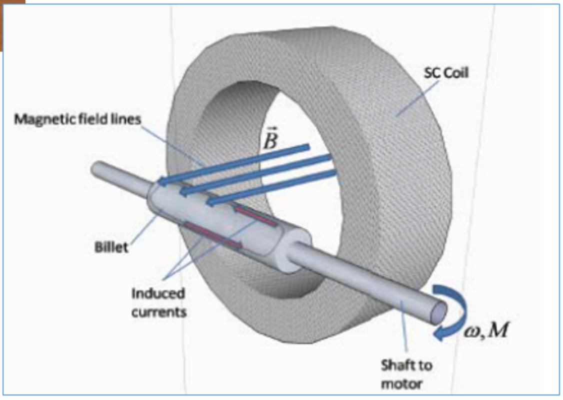
D) Development of special magnets

Various Superconducting MgB_2 coils

MgB_2 solenoid:
1 T at 16K,
wound with react and wind wires

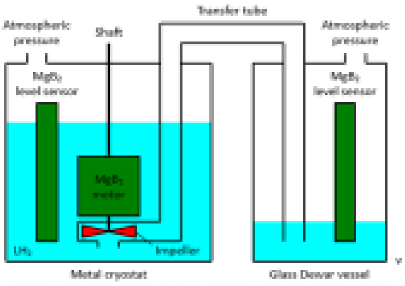


Rotating Al extrusion billet:
200kW system: billet heated by superconducting induction (energy saving)
0.5 T MgB_2 magnet of 100 cm dia.
SINTEF, Energy Res., Norway, 2010

Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA

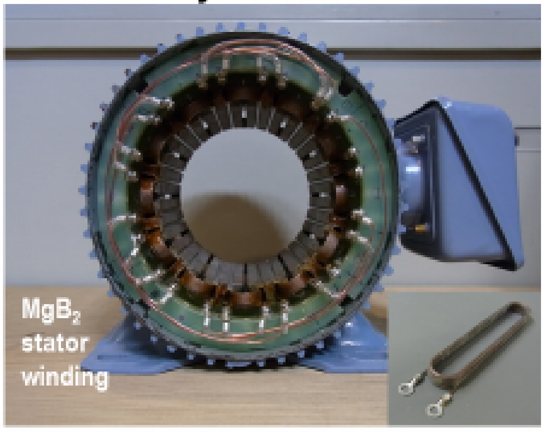
Liquid Hydrogen Transfer Pump System with MgB_2 Wires

Pump system for liquid hydrogen transfer:
MgB_2 motor and MgB_2 level sensors
MgB_2 level sensors were used * to detect the liquid level and
* to control the MgB_2 motor.
A maximum flow rate of 6.5 liters per minute is obtained at 1800 rpm.
Transfers of the liquid hydrogen: were successfully carried out



Pump system

K. Kajikawa et al.: Cryogenics **52**,615(2012)



Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA

E) Wind generators

Various 10 MW studies are presently under work

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10 MW offshore wind turbine generator - Suprapower

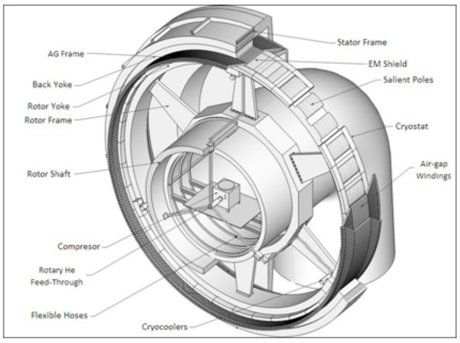
This project has received funding from European Union's FP7 Programme, under grant agreement No 308793

suprapower
Superconducting light generator
for large offshore wind turbines

Columbus Superconductors

Develop a new concept of innovative, lightweight, robust and reliable superconducting **10MW offshore wind turbine generator**

Validation of generator concept through a scale machine (coils and cryostat at real scale)



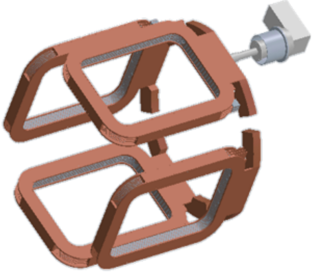
SC wind generator according to TECNALIA's concept (EP2521252A1)

tecnalia Inspiring Business

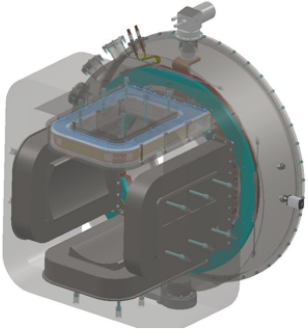
2013	2014	2015	2016
MgB2 wire design, characterization and Manufacture	First MgB2 coil construction and test	Full scale generator design and integration	Scale machine Validation
Cryostat Concept Design	Scale machine Design	Cryostat first module test	Industrialization Studies
	Rotary joint	Scale machine construction	Business Plan

Suprapower: scale machine demonstrator

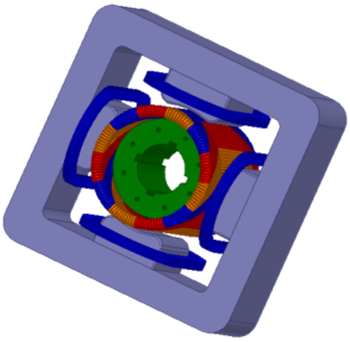
suprapower
Superconducting light generator
for large offshore wind turbines



Double pancakes MgB_2 coils of the scale machine (Tecnalia)



Scaled machine cryostat
Design, Source: TECNALIA



Scaled generator
Source: TECNALIA

tecnalia Inspiring Business · Columbus Superconductors · oerlikon leybold vacuum · acciona Windpower · KIT Karlsruhe Institute of Technology
ELÚ · d2m · d2m Engineering KNOWLEDGE, INNOVATION, SERVICE · UNIVERSITY OF Southampton · acciona Energy

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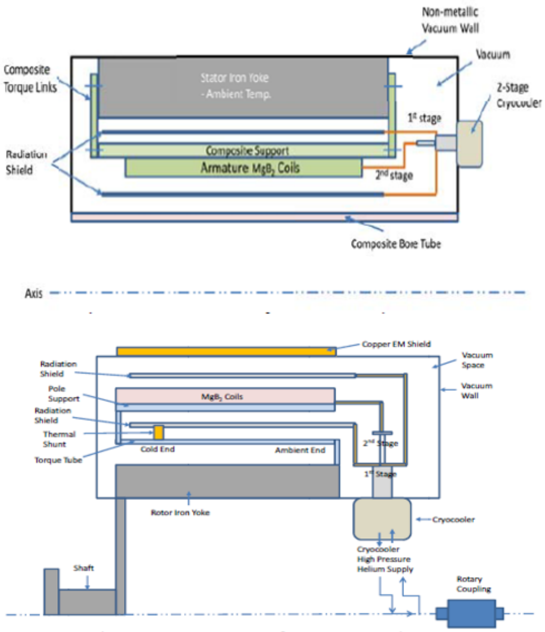
All Cryogenic 10 MW Superconducting Rotor and Stator



Conceptual Design of <u>all cryogenic</u> MgB_2 10 MW with superconducting rotor and stator operating at 15-20K using projected 2nd generation MgB_2 wire performance.

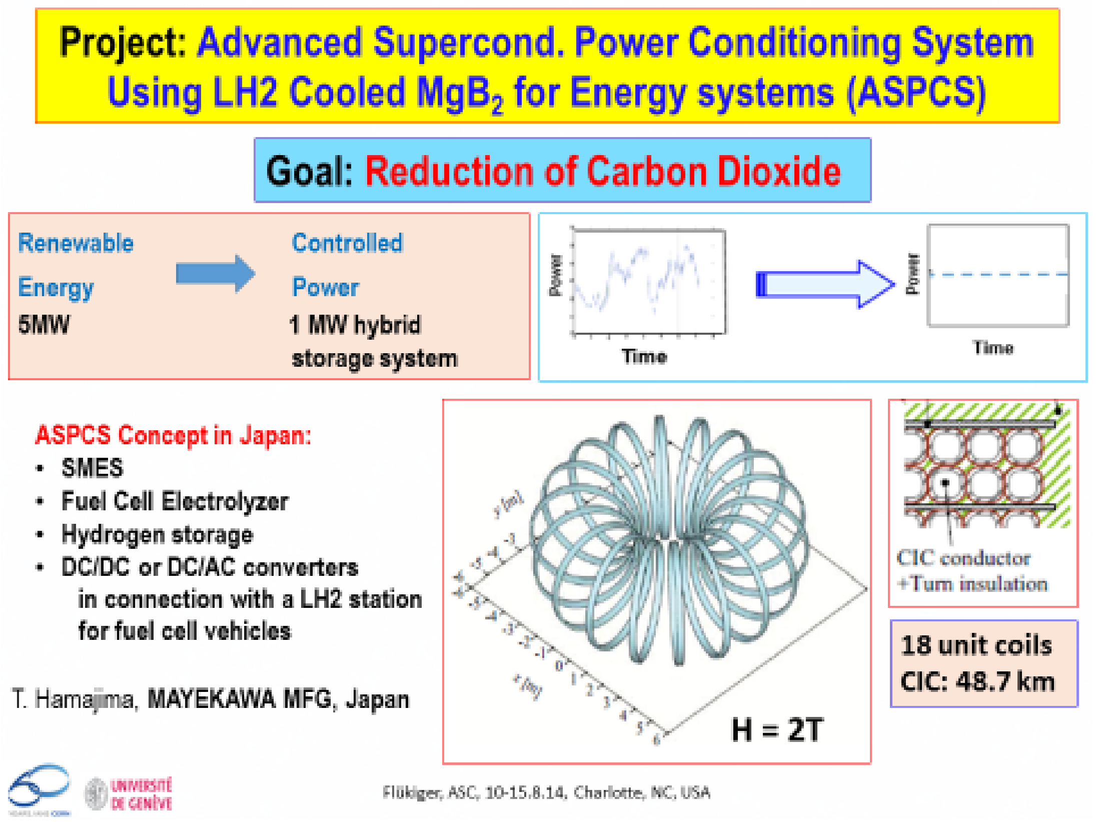
Paper by Swarn S. Kalsi
http://dx.doi.org/10.1109/TASC.2013.229125

Estimated total weight for 10 MW system is 50 metric tons. Estimated cost in for 12 or more per year is \$3.2 million. See ASC paper for details.

Hyper Tech

F) Renewable energy applications

Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA



Project: Advanced Supercond. Power Conditioning System Using LH2 Cooled MgB_2 for Energy systems (ASPCS)

Goal: Reduction of Carbon Dioxide

Renewable Energy 5MW → Controlled Power 1 MW hybrid storage system

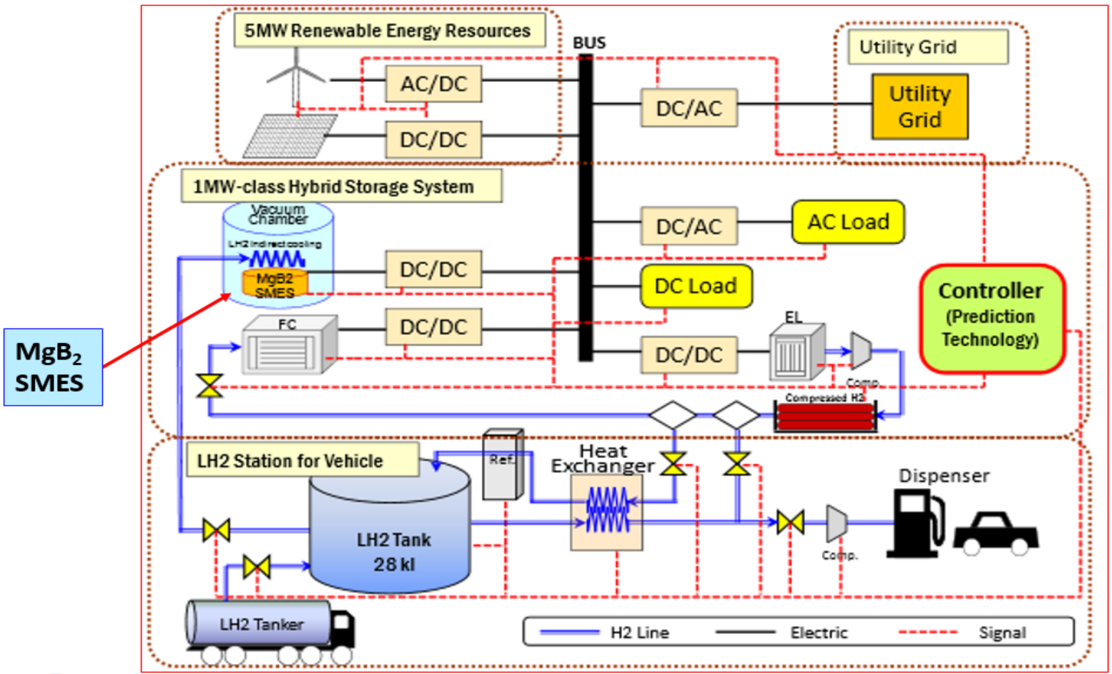
ASPCS Concept in Japan:
- SMES
- Fuel Cell Electrolyzer
- Hydrogen storage
- DC/DC or DC/AC converters in connection with a LH2 station for fuel cell vehicles

T. Hamajima, **MAYEKAWA MFG, Japan**

18 unit coils
CIC: 48.7 km

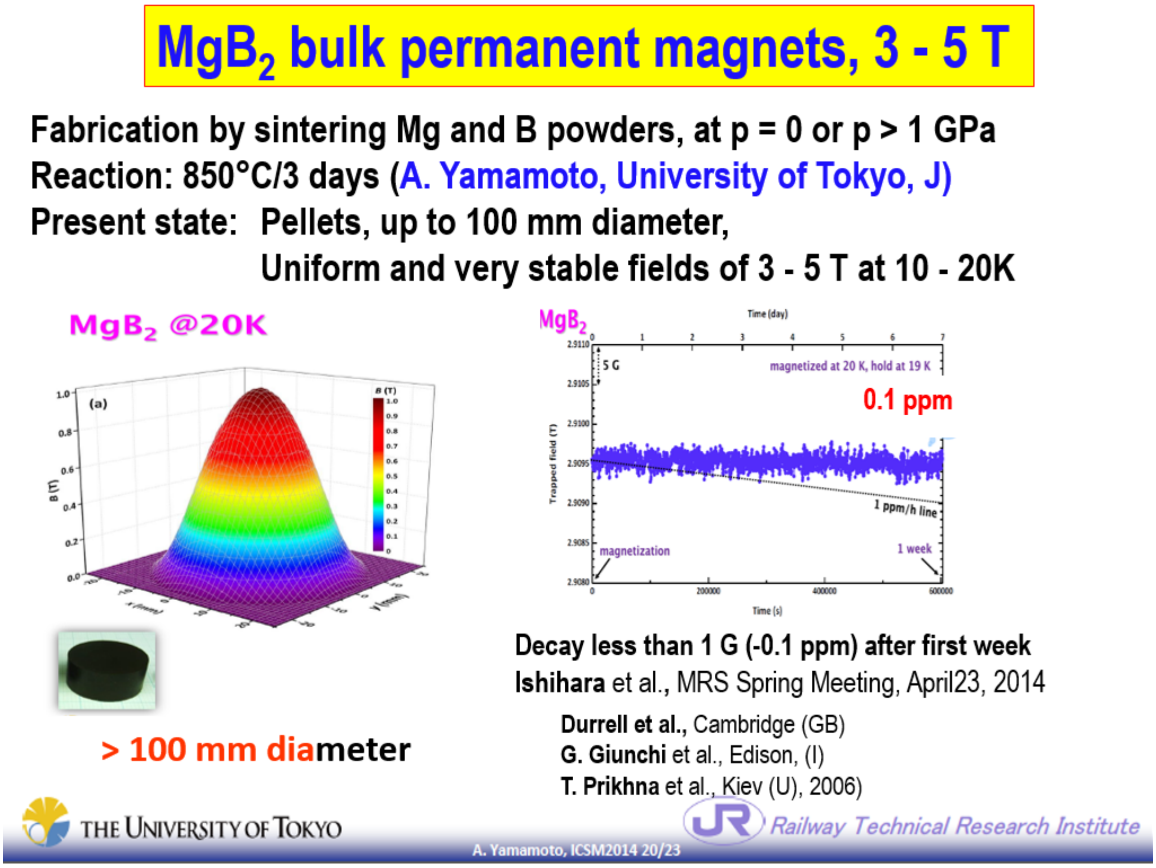
Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA

Control of fluctuating renewable power (ASPCS)



G) MgB_2 persistent mode magnets

Goal: Levitation for transportation



MgB_2 bulk permanent magnets, 3 - 5 T

Fabrication by sintering Mg and B powders, at p = 0 or p > 1 GPa
Reaction: 850°C/3 days (A. Yamamoto, University of Tokyo, J)
Present state: Pellets, up to 100 mm diameter,
Uniform and very stable fields of 3 - 5 T at 10 - 20K

> 100 mm diameter

Decay less than 1 G (-0.1 ppm) after first week
Ishihara et al., MRS Spring Meeting, April23, 2014

Durrell et al., Cambridge (GB)
G. Giunchi et al., Edison, (I)
T. Prikhna et al., Kiev (U), 2006)

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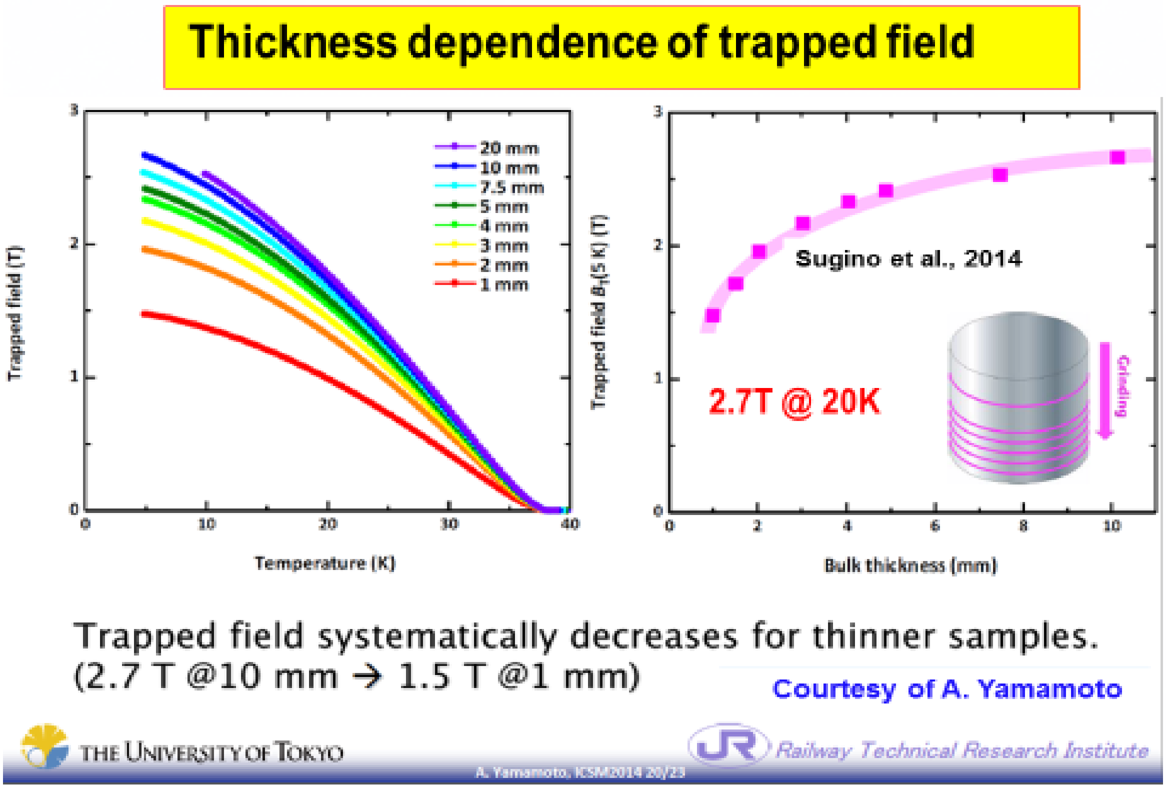
Railway Technical Research Institute
A. Yamamoto, ICSM2014 20/23



Thickness dependence of trapped field

Trapped field systematically decreases for thinner samples.
(2.7 T @10 mm → 1.5 T @1 mm)

Courtesy of A. Yamamoto

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Railway Technical Research Institute
A. Yamamoto, ICSM2014 20/23

H) Space applications

Flükiger, ASC, 10-15.8.14, Charlotte, NC, USA

SR2S: Space Radiation Superconducting Shield

This project has received funding from
European Union's FP7 Programme,
under grant agreement No 313224

Project : to protect the health of the astronaut during long duration space missions (e.g. Mars), by magnetic shielding.

Main Radiation source: protons

Active shielding

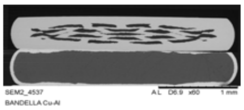
↓

**Static magnetic field using a SC coil
How to reduce the averall weight
for reducing the launching load?**

FROM:

3x0,5 nickel clad wire
3x0,2 copper stabilization

→

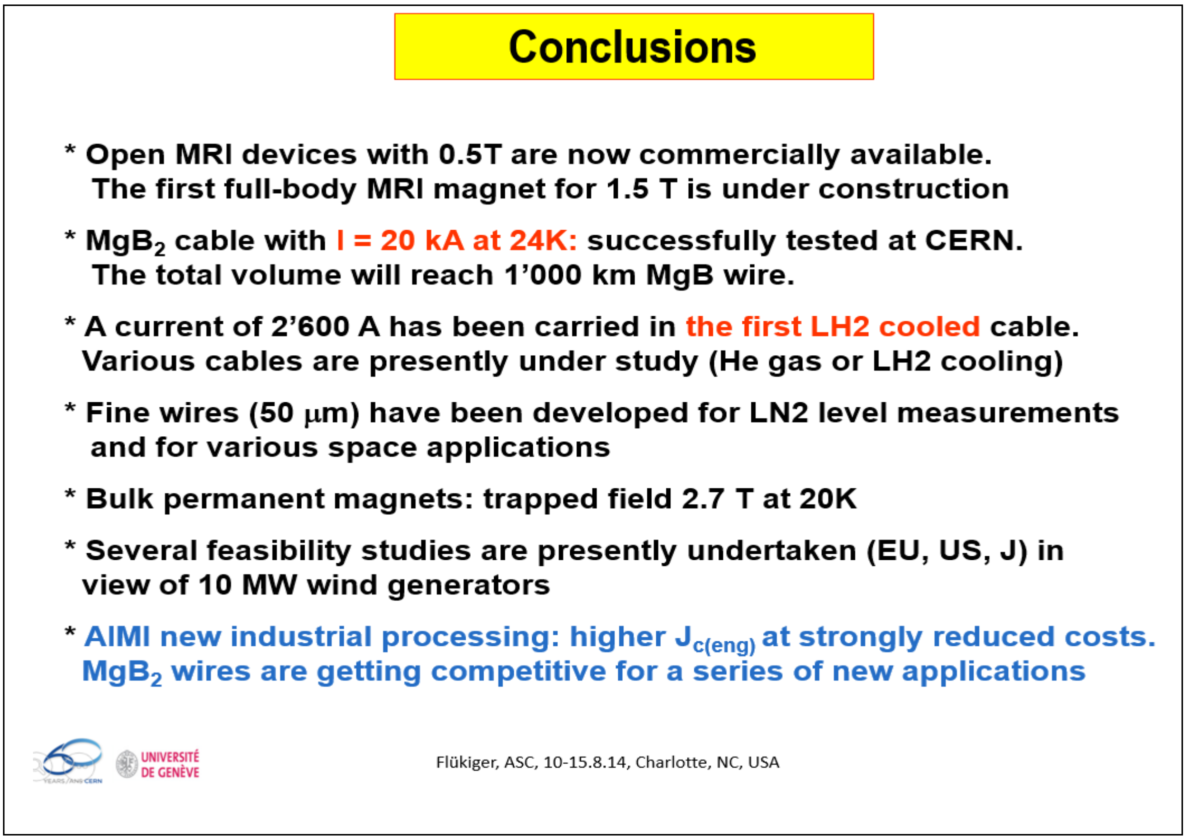


TO:

3x0,5 Ti clad wire
3x0,5 Al stabilization

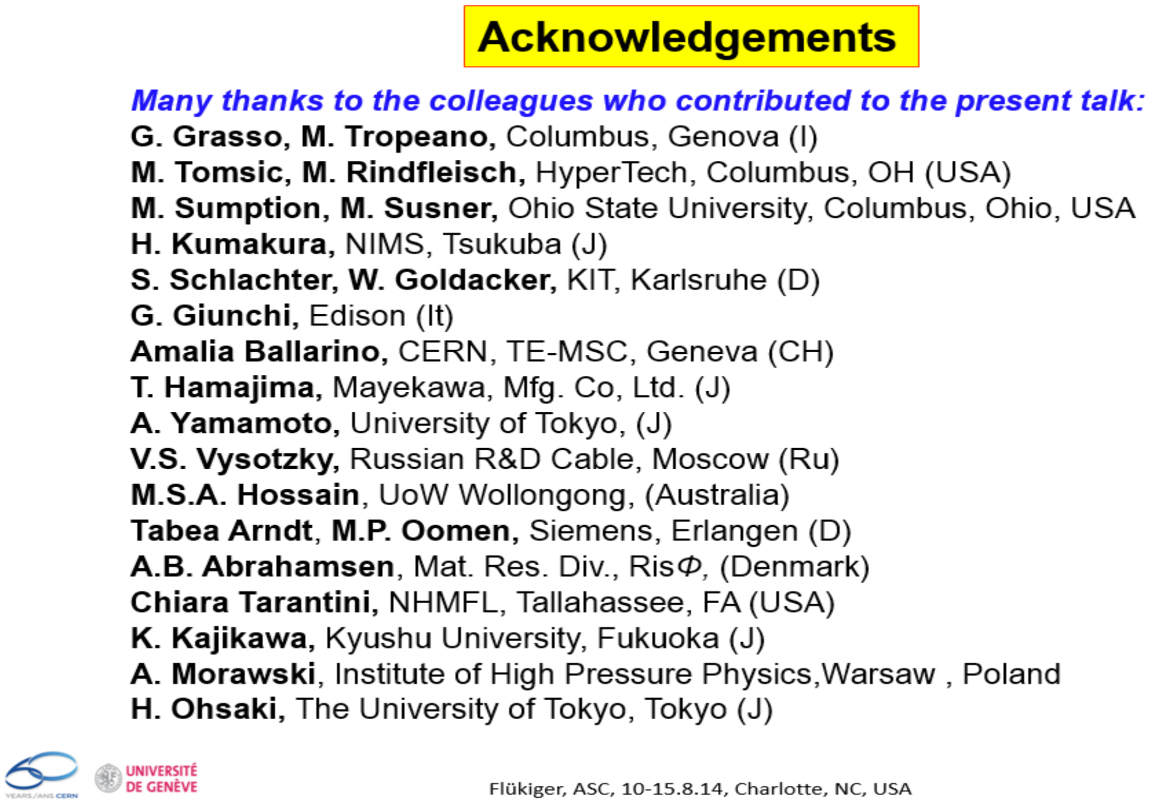
From 17grams to 10.2 grams, 40% weight reduction

Light MgB_2 wires are the answer



Conclusions

- **Open MRI devices with 0.5T are now commercially available. The first full-body MRI magnet for 1.5 T is under construction**
- **MgB_2 cable with I = 20 kA at 24K: successfully tested at CERN. The total volume will reach 1’000 km MgB wire.**
- **A current of 2’600 A has been carried in the first LH2 cooled cable. Various cables are presently under study (He gas or LH2 cooling)**
- **Fine wires (50 μm) have been developed for LN2 level measurements and for various space applications**
- **Bulk permanent magnets: trapped field 2.7 T at 20K**
- **Several feasibility studies are presently undertaken (EU, US, J) in view of 10 MW wind generators**
- **AIMI new industrial processing: higher $J_{c(eng)}$ at strongly reduced costs. MgB_2 wires are getting competitive for a series of new applications**



Acknowledgements

Many thanks to the colleagues who contributed to the present talk:

G. Grasso, M. Tropeano, Columbus, Genova (I)
M. Tomsic, M. Rindfleisch, HyperTech, Columbus, OH (USA)
M. Sumption, M. Susner, Ohio State University, Columbus, Ohio, USA
H. Kumakura, NIMS, Tsukuba (J)
S. Schlachter, W. Goldacker, KIT, Karlsruhe (D)
G. Giunchi, Edison (It)
Amalia Ballarino, CERN, TE-MSC, Geneva (CH)
T. Hamajima, Mayekawa, Mfg. Co, Ltd. (J)
A. Yamamoto, University of Tokyo, (J)
V.S. Vysotzky, Russian R&D Cable, Moscow (Ru)
M.S.A. Hossain, UoW Wollongong, (Australia)
Tabea Arndt, **M.P. Oomen,** Siemens, Erlangen (D)
A.B. Abrahamsen, Mat. Res. Div., RisΦ, (Denmark)
Chiara Tarantini, NHMFL, Tallahassee, FA (USA)
K. Kajikawa, Kyushu University, Fukuoka (J)
A. Morawski, Institute of High Pressure Physics,Warsaw , Poland
H. Ohsaki, The University of Tokyo, Tokyo (J)