High Performance Magnesium Diboride (MgB₂) Superconductors: Towards the Prospect for Commercialization

M.S.A. Hossain (ARC DECRA Fellow)
It’s easy to see why global & Australian companies are making the move to the University of Wollongong’s Innovation Campus
ISEM STAFF
DIRECTORS

Professor Shi Xue Dou
Director

Professor Shi Xue Dou is the Director of the Institute for Superconducting and Electronic Materials. Professor Dou holds four patents; has published more than 300 refereed papers and presented at more than 40 international conferences. His publications have attracted more than 9200 citations.

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Research Programs at ISEM/AIIM Faculty

- Applied Superconductivity Group
  - Bulk
  - Wire
  - Tape
  - Cable
  - Thin Film

- Energy Storage Group

- Spintronics and Electronic Materials Group

- Thin Film Technology Group

- Terahertz Science, Solid State Physics Group

- Nanostructure Materials Group

- Advanced Photovoltaic Materials Group
ISEM Performance Profile highlight

- ISEM Team: 40 research staff (12 ARC fellows) and more than 80 PhD
- Seven research program centred on energy and electronics
- Electrification Program leader in Automotive CRC 2020
- More than 50% citations in Li ion battery and superconductivity from ISEM in Australia
- ISEM is ranked at first place in magnesium diboride superconductors and eighth place in Li ion battery research in terms of outputs since 2001
- 105 PhD graduates widely spread across five continents since 1994
- 50 ARC fellowship awards to ISEM since 1995
- 80 ARC projects since 2000
- 12% publications, 15% ARC funding and 24% citations of UoW are from ISEM
- $80m for building & $20m for facilities for research infrastructure
- Member of CoE, ANFF and Flagship
- Bao Steel Joint Centre with other 3 Universities;
- Network with more than 50 institutions world-wide
- Strong links with more than 10 industry partners
- ERA assessment ranked at 5 for materials engineering, materials chemistry, physical chemistry and interdisciplinary engineering of UOW
Our Industry Partners

Bao Steel Research Center - Li ion battery producer

Charger Company

Hypres Co Ltd USA

Zenergy Power Ltd - Image courtesy of Zenergy Power

Hyper Tech - Superconductors for Medical and Energy Products

Ningbo Jansen Mechanism Ltd

Charge Stations

EV made by Australian Blade Electric Vehicle Ltd

NiPRESS - UN WOLLONGONG
Devices Applications

- UoW and Zenergy Power design and construct MgB$_2$ Fault Current Limiter (FCL) at UoW Innovation campus for power grid security
- UoW- Ningbo Jansen set up LP to design and construct an 0.7 T open MgB$_2$ MRI
- Huge MRI market in China. MRI alone will be $2 billion market per year in China

MgB$_2$ coil for MRI by our partner Hyper Tech Research Inc

Open MgB$_2$ MRI to be built by UoW, NJS and IEE in 2012

Fault Current Limiter for electric power grid based on UoW model and installed at Southern California Image courtesy of Zenergy Power
Superconductivity?
The few ultra-thin HTS wires on the right carry as much power as all the copper shown on the left. Superconductor wire carries 150 times the current the copper wire with the same cross section. (Courtesy to American Superconductors Co.)
Applications

- Making a good superconducting product is a formidable interdisciplinary problem.
Three Main classes of Superconductors

- Low Temperature Superconductors (LTC)
- High Temperature Superconductors (HTS)
  - BPSCCO/Ag wire – 1G
  - Coated YBCO conductors – 2G
- Intermediate Temperature Superconductors: MgB$_2$
**MgB\textsubscript{2}**

- **Very simple crystal structure**
- **Polycrystalline materials carry large currents**
- **Moderately high T\textsubscript{c}**
- **Good mechanical properties**
- **Very high current densities observed in films**
- **Potentially high critical field**

**MgB\textsubscript{2} presents very promising features**

- Low cost – low weight
- MgB\textsubscript{2} precursors: 150 €/Kg today
- MgB\textsubscript{2} mass density: 2.5 kg/dm\textsuperscript{3}

- Factor of 10 larger than in bulks; room for large improvement in wires still available from R&D
- Larger than 60 Tesla at low T
Current situation

• Superconductivity is a wonderful phenomenon, but its today’s applications are still confined to MRI-NMR, R&D, current leads and ‘big physics’

• 2G HTS material is expected to modify soon this scenario, but its complexity and limitation is currently delaying its positive effect on the industrial market of superconductivity

• What can we expect more from MgB₂?
Why MgB₂ is Special for application?

- MgB₂ is technologically and economically viable conductor than LTs and HTS, HTS > MgB₂ > LTS
- Soaring He price is a serious threat to LTS i.e. NbTi (11 K), NBSn₃ (18 K)
- Cryogen-free operation can be easily achievable in the temperature range of 10-20 K.
- More than 20 years of efforts did not reduce the production cost of HTS i.e YBCO (93K), BSSCO (110 K) even if it operates at liquid N₂
- MgB₂ is of particular interest because of its
  - low material cost,
  - simple crystalline structure,
  - ease of manufacture
  - larger coherence length
  - lower anisotropy
  Which make MgB₂ competitive with HTS.

The MgB₂ superconductor, therefore, has significant potential for industrial applications.
Superconducting wires presently available on the market

<table>
<thead>
<tr>
<th>Wire type</th>
<th>NbTi</th>
<th>Nb$_3$Sn</th>
<th>MgB$_2$</th>
<th>Bscco</th>
<th>YBCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>T$_c$ (K)</td>
<td>9 K</td>
<td>18 K</td>
<td>39 K</td>
<td>108 K</td>
<td>90 K</td>
</tr>
<tr>
<td>B$_{c2}$ (T)</td>
<td>10 T</td>
<td>28 T</td>
<td>&lt;70 T</td>
<td>&gt;100 T</td>
<td>&gt;100 T</td>
</tr>
<tr>
<td>Operation in LN$_2$</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>&lt; 1T</td>
<td>&lt;2T</td>
</tr>
<tr>
<td>Ductile compound</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Flexible wires</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Superconducting splices</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Low cost</td>
<td>YES</td>
<td>≈YES</td>
<td>YES</td>
<td>NO</td>
<td>Not yet</td>
</tr>
</tbody>
</table>
$3 billion MRI market at risk
• Rising liquid helium cost
• Tripled in price the last 5 years
• Predicted to increase over the next 5 years.

All MRIs use liquid helium bath cooling
• Liquid helium in the field can be $100K over the life cycle of the MRI system (depends on number of quenches)
• Helium is unavailable in some locations
  MRIs cost prohibitive
Q&A

A life in magnets

Industry giant General Electric has a long history of making superconducting magnets for magnetic resonance imaging. Michael Banks talks to Kathleen Amm, GE’s head of MRI technology, about the challenges ahead.

How long have you been involved in superconductivity?
For more than 16 years, now. I did my PhD at the National High Magnetic Field Laboratory in Florida, where I worked on the thermal properties of high-temperature superconductors, particularly HgBa$_2$Ca$_2$Cu$_3$O$_x$, which at 133 K had the highest transition temperature of any other material.

What attracted you to work for a company attempting to commercialize superconductivity, instead of pursuing an academic career?
My father had a long career as a geophysicist in the oil industry, and I always wanted to go into industry rather than staying in academia. GE was working on products utilizing superconductors—particularly magnets for magnetic resonance imaging (MRI)—and driving new innovations in the area, so it seemed like a good firm to join. When I joined, I was initially...

Looking ahead
Kathleen Amm sees opportunities for superconductors in power generation and renewable energy, but is uncertain where the demand is that it has many years of research behind it and it is easy to wind the material for magnets. But we are certainly looking at the potential of using magnesium diboride in our magnets, which is cheaper and has a higher transition temperature of about 40 K...
Possible applications

Transportation
  Maglev trains

Medical
  MRI imagers

Energy
  Wind turbine
  Superconducting Magnets
  Josephson Devices
  Power transmission
  Fault-current limiters
  Electric motors
  Fusion
**MgB$_2$ strand recipe: critical current**

- **4 K, 4 T:**
  - $J_c = 200,000$ A/cm$^2$
  - $I_c = 245$ A (0.83 mm)

- **20 K, 1 T:**
  - $J_c = 300,000$ A/cm$^2$
  - $I_c = 350$ A (1 mm)
Possible routes:

- Commercial precursors
  - Commercial MgB$_2$
  - Doped boron
  - Home made boron
  - Doped boron

High energy ball milling

Possible routes:

- P.I.T. In/Ex-situ method
HyperTech CTFF for MgB$_2$

CONTINUOUS TUBE FORMING AND FILLING (CTFF)
Internal Mg Diffusion

IMD

B powder + dopant

Mg Rod

Tube
## MgB$_2$ wire fabrication

<table>
<thead>
<tr>
<th>Fabrication process</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMD</td>
<td>Higher layer Jc</td>
<td>Brittle</td>
</tr>
<tr>
<td></td>
<td>Better connectivity</td>
<td>Hollow in middle</td>
</tr>
<tr>
<td>PIT</td>
<td>solid structure</td>
<td>Lower Jc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Less connectivity</td>
</tr>
<tr>
<td>CTFF</td>
<td>Multi layer sheaths</td>
<td>Lower Jc</td>
</tr>
<tr>
<td></td>
<td>Fast fabrication speed</td>
<td>Less connectivity</td>
</tr>
<tr>
<td></td>
<td>solid structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suitable for longer length</td>
<td></td>
</tr>
</tbody>
</table>
(1) Mg reacts with melting $\text{B}_2\text{O}_3$ to form MgO

(2) MgB$_2$ formation

(3) Curie temp. of bare Fe

(4) Fe$_2$B formation between bare Fe and MgB$_2$
MgB2 conductors from various designs:

HyperTech Research Inc., USA

IEE, Bratislava

Columbus Superconductors srl, Genoa:

Karlsruhe Institute of Technology
Both High field and low field performance is crucial for various magnet application:

Many research has been successfully done to improve high field properties by carbon doping but low field performance is still poor..(refs…)

How to improve low field properties:

Reduction of porosity ?

by improving fabrication process..??
mechanical deformation..??
2 ways to improve the properties of MgB2 superconductors:

1. **Intrinsic** (homogeneous dopant induced Hc2 enhancement)
2. **Extrinsic** (reduced porosity i.e better connectivity between grains)

Collings *et al.* Sust 21 (2008) 103001
Enhancement of both low and high field $J_c$

Enhancement of low field $J_c$ is due to the reduction of porosity.

Enhancement of high field $J_c$ is due to the defects by C-doping.

NPG Asia Materials (2011)

Malic acid – (European Patent 2011)
Chemical doping—the most effective means for enhancing $J_c$, $H_{c2}$ and $H_{irr}$ in MgB$_2$

6. Graphene: X Xu et al. SUST (2010),
Nano doping in MgB₂ – significant breakthrough $J_c$

Nano SiC doped MgB₂ wire:

Malic acid doped MgB₂ wire
Kim et al APL 89 (2006) 142505; European patent
“Dual Reaction Model: Parent compound formation and doping reaction takes place at the same time”

--Explain, classify and predict dopants that follow the dual reaction mechanism

<table>
<thead>
<tr>
<th>Type</th>
<th>Examples</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>C containing dopants</td>
<td>SiC, Carbohydrates, Hydrocarbon</td>
<td>Reaction and substitution at low T</td>
</tr>
<tr>
<td>C containing dopants</td>
<td>B₄C, C, CNT</td>
<td>Reaction and substitution at high T</td>
</tr>
<tr>
<td>Non-C containing dopants: Silicides</td>
<td>Si, ZrSi₂, WSi₂, MgSi₂, ZrB₂</td>
<td>Reaction at low T without substitution</td>
</tr>
<tr>
<td>C containing dopants</td>
<td>TiC</td>
<td>Stable till 1000°C and little effect</td>
</tr>
<tr>
<td>Non-C containing dopants</td>
<td>Ti, Zr, W, BN, Y₂O₃, SiO₂, MgO, Ga, Ag, Pb etc</td>
<td>Limited effect by addition, if not negative</td>
</tr>
<tr>
<td>Magnetic dopants</td>
<td>Fe, Ni, Co</td>
<td>Negative effect</td>
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Reducing Porosity:

Low field enhancement:

3D X-ray Tomogram Analysis: **Voids are removed significantly** after doping with malic acid using chemical solution route.

<table>
<thead>
<tr>
<th></th>
<th>Area ($\mu m^2$)</th>
<th>Major diameter ($\mu m$)</th>
<th>Minor diameter ($\mu m$)</th>
<th>Void fraction (%)</th>
<th>Number of voids</th>
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<tbody>
<tr>
<td><strong>Malic acid doped</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x axis</td>
<td>0.34</td>
<td>0.73</td>
<td>0.37</td>
<td>41.24</td>
<td>17611</td>
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<tr>
<td>y axis</td>
<td>0.28</td>
<td>0.68</td>
<td>0.34</td>
<td>40.61</td>
<td>21442</td>
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<tr>
<td>z axis</td>
<td>0.32</td>
<td>0.70</td>
<td>0.32</td>
<td>40.48</td>
<td>18869</td>
</tr>
<tr>
<td><strong>Un-doped</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x axis</td>
<td>1.53</td>
<td>1.23</td>
<td>0.63</td>
<td>50.87</td>
<td>7496</td>
</tr>
<tr>
<td>y axis</td>
<td>1.29</td>
<td>1.26</td>
<td>0.64</td>
<td>50.38</td>
<td>8819</td>
</tr>
<tr>
<td>z axis</td>
<td>1.41</td>
<td>1.20</td>
<td>0.63</td>
<td>50.33</td>
<td>8009</td>
</tr>
</tbody>
</table>
Lattice distortion due to boron vacancy:

- Boron vacancies $\rightarrow$ stacking faults $\rightarrow$ lattice distortion within the MgB$_2$ grains $\rightarrow$ increase the impurity scattering rate $\rightarrow$ enhances the upper critical field and high field critical current density.

Undoped   C-doped
\[
\begin{array}{cc}
 a\text{-axis}: & 3.0832 & 3.0758 \\
 c\text{-axis}: & 3.5221 & 3.5237 \\
\end{array}
\]
Role of carbon for the void reduction
Improvement by extrinsic properties
Cold High Pressure Densification:
Binary MgB$_2$: Applying Pressures from 4 sides on square wires.

0 GPa  2 GPa

Not pressed  Pressed, 1.0 GPa

Fig. 4. Schematic figures of the automatic press.
Binary 18-filament MgB$_2$ wire: CHPD applied

A. 

B.
Binary MgB$_2$: Higher mass density due to volume contraction
$J_c$ vs. $B$ at 4.2, 20 and 25 K for 18-filament binary MgB$_2$ wires densified at 1.5 Gpa on short and 15 cm long samples

Hossain et al, SUST (2011)
MgB$_2$ wires, doped with 10 wt.% C$_4$H$_6$O$_5$

NbTi: $J_c = 1 \times 10^5$ A/cm$^2$ at 8T/4.2K

$J_c$ (A/cm$^2$)

$B$ (T)

Square Wire (0 GPa)

$J_c^{\parallel}$ (2 GPa)

$J_c^{\perp}$ (2 GPa)

Almost isotropic behavior

OSU measurement: MgB$_2$ wires, after 1.8 Gpa, Alloyed with 10 wt.% C$_4$H$_6$O$_5$

At 20K, $J_c = 10^4$ A/cm$^2$ at >7T!!!
CHPD improves the homogeneity of $J_c$ in the s/c layer

... as a consequence, also the n value of I-V curve is increased
$n$-factor improves in both binary and alloyed MgB$_2$ sample after CHPD:
First test on densification of longer wire lengths (1 meter) by means of an automatic press/release/advance mechanism
Learning how to improve connectivity

**CTFF-1 1st Generation Wire**

(a) monel

Nb

MgB$_2$

---

**CTFF-2 2nd Generation Wire**

(c) monel

Nb

MgB$_2$

The $J_{ct}$ of the **CTFF-1** strand is the critical transport current, $I_{ct}$, divided by the area within the Nb chemical barrier.

The $J_{ct}$ of the **CTFF-2** strand is $I_{ct}$ divided by the area of the annular MgB$_2$ layer (generally known as the “layer $J_c$”).

For comparison purposes a “non-barrier $J_{ct}$”, viz. $J_{cte}$” (an engineering $J_{ct}$) can also be defined for the **CTFF-2** strand, as the $I_{ct}$ divided by the *whole* area inside the chemical barrier.
2nd Generation MgB₂ Under Development

Critical Density, \( J_c \), A/cm²

Magnetic Field, \( B \), Tesla

4.2 K

2nd Generation MgB₂

1st Generation MgB₂

4-5 times improvement

CHPD

Hyper Tech
IMD (NIMS Group, 2009) and Modified IMD (OSU Group, 2012)
Issues involved in IMD

Very high densed MgB$_2$ layer with high $J_c$ But:

1. Hollow in the middle

2. Lower filling factor and comparatively lower Engineering current density ($J_e$)
Results: LIMD + CHPD
Using large size Mg as an alternative of Mg rod


**Schematic Concept:**

- Mg coarse powder
- C encapsulated B

**Filling**

**Drawing**

LIMD + CHPD

\[ P = 1.5 \text{ GPa} \]

600 °C/16 hrs

Mg is locally diffused

Using the ductility of Mg

Carbon treated boron

Elongated magnesium
Advantages

1. We can control the shape, size and direction of voids. If we know the mechanism of void formation, it will be easier to find solution to minimize.

2. Formation of perfectly aligned fibrous structure along the direction of transport current path.

3. Aligned fibrous structure can increase the effective area fraction of MgB$_2$ wires.

4. Voids cannot be completely eliminated but size and volume of the voids can be reduced by further CHPD or HIP or combination which can improve the grain linkage.
Comparison of sintered wires using 20-50 mesh Mg before and after CHPD

Fig. 4: SEM images of cores of sintered wires prepared from Mg powder with the large particle size of 20-50 mesh (a) before and (b) after CHPD.

The yellow surrounding areas indicate elongated voids along the wire direction and some of those are eliminated by CHPD.
High performance MgB2 Cables for power application
Microstructure #960 Cable

Cable
Swaged Cable
2-axial Rolled Cable
CHPD Cable

As it is: #960 cable

Densified #960 cable
Mechanically Deformed Cable Improves Critical Current
Cables with different twist pitch

- Twist pitch 11.3 mm
- Twist pitch 12.9 mm
- Twist pitch 17.3 mm
- Twist pitch 20.3 mm
Long length samples measurements set-up

- Up to 13 T
- LH₂
- 8 cm bore
- Up to 680 A (DC)
- Sample after HT: 700 C/1h Ar

G10

MgB₂ cable

voltage taps

5 mm
10 mm
75 mm

70 mm
Long length samples with electroplated copper

- Electrolyte: a water based mixture of 160 g/l CuSO₄, 70 g/l H₂SO₄ (95 - 97%)
- The thickness was controlled by the deposition time (400 nm/min)
- 50 – 65 cm long samples
Electroplated copper stabilize cables

- The same cable with different level of stabilization
- Twist pitch: 13 mm
- Wire fill factor: 12.5%, cable: 10%
- $J_c = 10^4 \text{ A/cm}^2$ at 10.5 T
Potential of Isotope ($^{11}$B) Based High Performance Superconductor ($\text{Mg}^{11}\text{B}_2$) for The Next Generation Fusion Reactor
Outline:

Performance: compared to conventional Nb-based superconductor

Material Properties Suitable for Fusion:
- Induced radio-activity properties
- The decay times of the induced radio-activity on fusion reactor components (this will contribute to the sustainable scenarios from construction to the shutdown phases including the maintenance and material recycle schedules)

Design, Test and Development:
- Material Design and Test
- Superconducting conductor Design and Test
- CICC cable design

How to reduce the overall cost:

Experimental Proof of Concept:
Next Generation MgB2 wires: 4-5 times $J_c$ improvement

4.2 K

Critical Density, $J_c$, A/cm$^2$

Magnetic Field, $B$, Tesla

20 K

Critical Density, $J_c$, A/cm$^2$

Magnetic Field, $B$, Tesla
2nd Generation MgB$_2$ wire
18% Superconductor Fraction
Engineering Current Density

Engineering Current Density, $J_e$, 5 T, 4.2 K:

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>$J_e$ (A/cm$^2$)</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTFF-1 (best of class 36 filament)</td>
<td>26,000</td>
<td></td>
</tr>
<tr>
<td>CTFF-2 (18 filament)</td>
<td>58,000</td>
<td>2.2x</td>
</tr>
<tr>
<td>CTFF-2 (monofilament, extrapolated)</td>
<td>122,000</td>
<td>4.7x</td>
</tr>
</tbody>
</table>
Latest MgB2 development compared to Nb-based superconductor?
The fusion reactor has many large ports to connect with plasma heating and diagnostics equipments, and D-T reaction will form 14 MeV neutrons & alpha particles that will stream and penetrate superconducting magnet through these large ports.

The amount of the streamed and penetrated neutron is estimated to be order of $10^{11}$ n/m²/s on the ITER design by Monte-Carlo simulation [1], the total amount of these neutron will be increased with increasing the operation time and fusion power.

Nb-based compound superconductors require a longer cooling time until the remote handling recycling level. The longer cooling time will be affected to maintenance and shutdown schedules, and the total cost of the fusion power plant will be increased remarkably.

MgB₂ and V based superconductors have remarkably shorter decay time than Nb-based superconducting wires and their half-life are within 1 year.

V-based and MgB₂ compounds will be promising candidate and alternative materials of the “Low activation superconducting magnet system”
Comparative advantages:

The merits of MgB2 superconducting wire in an advanced nuclear fusion power plant system are:

- lower induced radioactivity

- The higher critical temperature (40 K) of MgB₂ offers a larger thermal margin than low temperature superconductors, e.g., Nb-Ti and Nb₃Sn, and makes low refrigeration load on the cryogenic system due to the higher $T_c$ property. MgB₂ has big possibility to the liquid hydrogen cooling application due to the higher $T_c$ property (39K). (Power cable, Current Feeder)

- Acceptable properties for low- to mid-field magnets operating at temperatures as high as 20 K,
- MgB₂ wire manufacturing is not much more difficult than that of Nb-Ti wire,

- MgB₂ has one third the density of Nb-Ti, so the same mass of raw materials will yield three times the piece length,

- MgB₂ has a faster charging rate than a Nb-Ti based magnet

In the magnetic confinement fusion reactor, the Poloidal field (PF) and magnetic field correction coils require a larger coil radius to adjust the position of the plasma, and they are mainly constructed by Nb-Ti alloy in the present fusion experiment devices. It can be easily replaced by MgB₂.
Material Design: Selecting right precursor for developing low activation material

The elemental boron and $^{10}$B isotope pellets are mainly used to the neutron absorption material of nuclear fission reactor plant because it has large nuclear reaction cross-section.

- In the conventional *in-situ* process, MgB$_2$ is formed by the reaction between metal Mg (MgH$_2$) and commercial natural boron powder.

\[
(Mg (MgH_2) + 2 \text{ B} \rightarrow MgB_2 + \text{(H}_2\text{)})
\]

- In the case of “Low activation MgB$_2$ wire”, MgB$_2$ is formed by the reaction between Mg (MgH$_2$) and $^{11}$B isotope powder.

\[
(Mg (MgH_2) + 2 \, ^{11}\text{B} \rightarrow Mg^{11}B_2 + \text{(H}_2\text{)})
\]
Why $^{11}$B?

The features of boron element (isotope)

- The commercial natural Boron powder consists of two kinds of isotopes powder, which are boron-10 ($^{10}$B; 19.78%) and boron-11 ($^{11}$B; 80.22%).

- The $^{10}$B isotope powder (bulk) is usually used as a neutron absorber in nuclear power plants such as a radiation shield and control rod. ($^{10}$B has large neutron absorption cross section)

- The $^{10}$B is easy to transform to $^7$Li and He by the (n, $\alpha$) reaction. ($^{10}$B + n $\rightarrow$ $^7$Li + He (gas))
  $\Rightarrow$ Decrease of MgB$_2$ volume fraction

- The $^{11}$B is stable for the neutron irradiation without (n, $\alpha$) reaction and can reduce nuclear heating. (2.58 $\Rightarrow$ 0.13 W/cm$^3$) $\Rightarrow$ Large $T_c$ margin, 1/20 reduction

- The $^{11}$B isotope powder is desirable material as the boron source for "low activation MgB$_2$ wire".

- $T_c$ value of MgB$_2$ using $^{10}$B isotope (Mg$^{10}$B$_2$) showed 40.2 K. (D. K. Finnemore et al. Phys. Rev. Let., 86, (2001), 2420-2422.)

Boron-11 isotope powder as the boron source is suitable material for low activation MgB$_2$ wires.
Conductor design

Metal **Cu** will become the one of the promising metal sheath material on PIT wire and tape.
Cable Design for PF/TF coil

CERN LHC Busbar

Configuration \[\{(5+1)x2+6x2\}x4x6+\{(6+1)x4\}x4\]
Ignitor – italian fusion project

30K He gas cooled copper conductors are currently expected to be used in this machine.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius</td>
<td>$R_0$</td>
<td>1.32</td>
<td>m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>$a_b$</td>
<td>0.47, 0.86</td>
<td>m</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>$A$</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>Elongation</td>
<td>$k$</td>
<td>1.83</td>
<td></td>
</tr>
<tr>
<td>Triangularity</td>
<td>$d$</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Toroidal magnetic field</td>
<td>$B_T$</td>
<td>13</td>
<td>T</td>
</tr>
<tr>
<td>Toroidal current</td>
<td>$I_p$</td>
<td>11</td>
<td>MA</td>
</tr>
<tr>
<td>Maximum poloidal field</td>
<td>$B_{p,\text{max}}$</td>
<td>6.5</td>
<td>T</td>
</tr>
<tr>
<td>Mean poloidal field</td>
<td></td>
<td>3.44</td>
<td>T</td>
</tr>
<tr>
<td>Poloidal current</td>
<td>$I_q$</td>
<td>9</td>
<td>MA</td>
</tr>
<tr>
<td>Edge safety factor (@11MA)</td>
<td>$q_y$</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>Confinement strength</td>
<td></td>
<td>38</td>
<td>MA T</td>
</tr>
<tr>
<td>Plasma Surface</td>
<td>$S_0$</td>
<td>34</td>
<td>m²</td>
</tr>
<tr>
<td>Plasma Volume</td>
<td>$V_0$</td>
<td>10</td>
<td>m³</td>
</tr>
<tr>
<td>ICRF heating (140 MHZ)</td>
<td>$P_{RF}$</td>
<td>6 (*)</td>
<td>MW</td>
</tr>
</tbody>
</table>
MgB\textsubscript{2} cable conductor for Ignitor

Superconducting cabling option for a 34.7kA@ 4T, 10K conductor

Different cable configurations have been analysed in order to find the best compromise between an efficient cooling of the MgB\textsubscript{2} conductors over times, the cable cost and the feasibility from the manufacturing point of view. The basic wire is the same (shown in Fig. 1) for each configuration. An AISI 316 LN stainless steel jacket is also foreseen in each configuration. This large jacket is necessary to underpin the big stress in the coil.

- Epoxy resin (filling void spaces between cables during the coil impregnation)
- AISI 316LN SS jacket
- Spot welding
- Copper Tube
- Cable
- Sub-cable
- MgB\textsubscript{2}-based wire
- He gas

It's the simplest and cheapest to manufacture, with a limited risk of wire degradation during the assembly. With its 294 MgB\textsubscript{2}-based wire, it guarantees a good \( I_c \) margin (22%) but the helium heat-exchange perimeter is limited (even if sufficient) and the pure resin percentage into the total cross section is quite high, with a consequent risk of cracks, that should not invalidate the coil performance. This aspect has to be verified experimentally (mock-up production and testing).

Some additional sub-cables (from 294 to 330) reduce the resin percentage but the helium exchange perimeter is still the same (28 mm).

\( I_c \) margin further increases (from 22% to 25%). The cooling of the MgB\textsubscript{2} conductors over the time is really improved (helium exchange perimeter raises from 28 mm to 66 mm), but this solution is really expensive difficult to manufacture.

Continuous welding replace the spot welding and He fills all void spaced between cables and sub-cables. This is the best configuration from the stability and the heat-exchange point of view but it's neither cheap nor so simple to manufacture.
Experimental Hybrid Power Transmission Line with Liquid Hydrogen and MgB$_2$-Based Superconducting Cable

V. V. Kostyuk, I. V. Antyukhov, E. V. Blagov*, V. S. Vysotsky, B. I. Katorgin, A. A. Nosov, S. S. Fetisov, and V. P. Firsov

Institute of Nanotechnology for Microelectronics, Russian Academy of Sciences, Moscow, 119991 Russia

*e-mail: blagov@im.gov.ru

Received November 23, 2011
## Cost comparison:

### TABLE I

**Properties of Most Common Superconductors**

<table>
<thead>
<tr>
<th>Type - Wire technology</th>
<th>Basic material, $T_c$</th>
<th>Cryogen and typical temperature</th>
<th>Approximate prices US$ per 1kA·m (as of mid-2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTS – metallurgy</td>
<td>NbTi - alloy ~ 10 K</td>
<td>Liquid helium at 4.2 K and below</td>
<td>Up to 3-5$ @ 4.2 K</td>
</tr>
<tr>
<td>LTS – metallurgy</td>
<td>Nb$_3$Sn – compound</td>
<td>Helium up to 8-10 K and below</td>
<td>Up to 15$ @ 4.2K</td>
</tr>
<tr>
<td></td>
<td>~ 18 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HTS 1 Generation</td>
<td>Ceramic Bi$_2$Sr$_2$Ca$_n$-1Cu$<em>n$O$</em>{2n+4}$ (Bi-2223,Bi-2212)</td>
<td>Liquid nitrogen at 77 K and below (with other cryogens)</td>
<td>About 120-150$ @ 77 K</td>
</tr>
<tr>
<td>(Powder in tube – metallurgy)</td>
<td>~90-110 K</td>
<td></td>
<td>About 40-50$ @ 20 K</td>
</tr>
<tr>
<td>HTS 2 Generation</td>
<td>Ceramic YBa$_2$Cu$<em>3$O$</em>{7-d}$</td>
<td>Liquid nitrogen at 77 K and below (with other cryogens)</td>
<td>About 300-500$ @ 77 K</td>
</tr>
<tr>
<td>(Long coated conductors - electronics)</td>
<td>~90 K</td>
<td></td>
<td>About 80-150$ @ 20 K</td>
</tr>
<tr>
<td>Magnesium diboride - (Powder in tube – metallurgy)</td>
<td>MgB$_2$ – compound</td>
<td>Liquid hydrogen and below (with other cryogens)</td>
<td>About 5$ @ 20 K</td>
</tr>
<tr>
<td></td>
<td>~39 K</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
$/KAm of 2nd Generation even lower (even considering with Nb barrier and monel sheath)

<table>
<thead>
<tr>
<th>Material</th>
<th>Capacity (not sales)</th>
<th>Price 2013 1st Gen</th>
<th>Projected price 2014-2015 2nd Gen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyper Tech</td>
<td>MgB2</td>
<td>-$6-12/meter depending on size and quantity</td>
<td>$1-3/meter depending on size</td>
</tr>
<tr>
<td></td>
<td>500 km/yr in 2012 5,000 km/yr - by end of 2013</td>
<td>$30-40/kAm-20K-1T</td>
<td>$1-3/kAm-20K-1T</td>
</tr>
<tr>
<td></td>
<td>10,000 km/yr by end of 2014</td>
<td>$30-40/kAm-4K-4T</td>
<td>$1-3/kAm-4K-4T</td>
</tr>
<tr>
<td>Lengths</td>
<td></td>
<td>6-60 km</td>
<td>60 km plus</td>
</tr>
</tbody>
</table>
Mg$^{11}\text{B}_2$ based superconductor with state-of-the-art design can significantly reduce the overall cost ....
Experimental Proof of Concept:
**Collaboration program**

**University of Wollongong**

- Boron powders analysis
  - XRD
  - Particle size
  - SEM
  - TEM
  - Carbon content analysis

- Wire fabrication
- Ic-B measurement
- Wire analysis

**PAVEZYUM**

- Boron fabrications
  - Crystalline boron with 89, 91, 95, and 97% purity
  - Amorphous boron with > 98% purity
  - Carbon capping amorphous boron

- $^{11}$B and $^{10}$B isotopes from $\text{B}_2\text{O}_3$
- Scale-up for production
Preparation of elemental amorphous Boron-11 powders suitable for Mg\(^{11}\)B\(_2\) Synthesis

The Problem is:

Elemental boron isotopes \(^{10}\)B and \(^{11}\)B are commercially available from very few companies in the world and only in crystalline form. However, for the synthesis of high performance MgB\(_2\) one needs NOT the crystalline but the more reactive amorphous boron.

The solution came from the collaboration program with Pavezyum (Turkey has world’s 72% boron source):

In this project amorphous boron will be produced by two techniques:
1. Magnesothermal Reduction (Moisson method)
2. Thermal decomposition of Diborane gas (\(B_2H_6\))

It is important to note the boron source for the synthesis of amorphous B-11 will be in both methods the commercial easily available boric acid-11, \(^{11}\)B(OH)\(_3\).
1) Magnesothermal Reduction

STEP 1: Conversion of boric acid to oxide: $2^{11}\text{B(OH)}_3 \rightarrow ^{11}\text{B}_2\text{O}_3 + 3\text{H}_2\text{O}; \Delta = \text{heat}$

STEP 2: Magnesothermal reaction

$$3\text{Mg} + ^{11}\text{B}_2\text{O}_3 \rightarrow 3\text{MgO} + 2^{11}\text{B} + \text{impurities}$$

STEP 3: Acid leaching

$^{11}\text{B}: 86-88\%, \text{ Mg}^*: 10-12\%$

STEP 4: Chemical Purification (Chlorination)

$^{11}\text{B}: 95-97\%, \text{ Mg} < 0.8\%$
Properties of $^{11}$B (95-97%)

- It is not amorphous to X-ray, meaning at least partial crystalline

- Particle size (DLS) $d_{50} = 1.0 - 2.5 \mu$. 

- BET < 10 m$^2$g$^{-1}$. 
2) Thermal Decomposition of Diborane

**STEP 1:** Conversion of boric acid to Trimethoxy borate, B(OCH₃)₃

\[
{^{11}\text{B(OH)}}_3(\text{s}) + 3\text{CH}_3\text{OH(l)} \rightarrow {^{11}\text{B(OCH}}_3)_3(\text{l}) + 3\text{H}_2\text{O(l)}
\]

**STEP 2:** Distillation of B(OCH₃)₃ from the reaction mixture

**STEP 3** Reaction of B(OCH₃)₃ with sodium hydride, NaH

\[
{^{11}\text{B(OCH}}_3)_3(\text{l}) + 4\text{NaH(s)} \rightarrow \text{Na}^{^{11}\text{BH}}_4(\text{s}) + 3\text{Na(OCH}}_3)_3(\text{s})
\]

\[\Delta = 250-270 \, ^\circ\text{C}\]

**STEP 4:** Solvent extraction of Na^{11}BH₄ from the raw reaction product of STEP 3

pure Na^{11}BH₄; yield 95%

This process (steps 3 + 4) is called Schlesinger method
STEP 5: *in-situ* Production of Diborane gas ($^{11}\text{B}_2\text{H}_6$) by thermolysis ($\Delta$) of Na$^{11}\text{BH}_4$

\[ \text{Na}^{11}\text{BH}_4 + \text{Ar} \rightarrow \text{Furnace} > 300 \, ^\circ\text{C} \rightarrow \text{B} \]

- Spherical: $\varnothing = 50-200\text{nm}$
- Properties:
  - Purity: $>98.5\%$
  - Very reactive
  - BET $>35 \text{m}^2/\text{g}$
• Using 11B from 1\textsuperscript{st} process

• No Tc degradation

• Jc will be improved though doping and mechanical processing.

Much improved results expected from the nano size 11 B
THANKS FOR YOUR ATTENTION