Present status of MgB$_2$ wire manufacturing
29$^{th}$ November 2012
Summary

• Why MgB$_2$
• Where we are today at Columbus
• What we are producing
• For what we are producing
• Hopes for the near future
MgB$_2$ has opened a new frontier in the physical properties and application of SC. The limit of Tc in metallic superconductors was considered equal to 30 K and this unexpected discovery of high Tc in this simple binary intermetallic compound has caused huge interest around the world.
**Low Temperature Superconductors**

- Nb – NbTi – Nb₃Sn
  - Produced from the seventies
  - Low price (1-10 €/m)
  - Operable mainly in Liquid Helium
  - Commodity – 5-10 companies competing with similar products and know-how
  - Mostly employed in MRI/NMR and ‘big physics’
  - Revenues derived: 4 B€/anno

**High Temperature Superconductors**

- Bi-2223 (1G) – YBCO-123 (2G)
  - Produced from the nineties
  - Higher price (10-100 €/m)
  - Operable also in liquid nitrogen
  - R&D – 5-10 companies active
  - Commercial outcomes somewhat limited so far by cost/difficulty of the processing

**MgB₂**

- Discovered as SC in 2001
- Low cost (1-10 €/m)
- Operable up to 30K
- Product already matured – 5 companies active
- Commercial outcomes achieved
<table>
<thead>
<tr>
<th>Wire type</th>
<th>MgB$_2$</th>
<th>BSCCO</th>
<th>YBCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round wire or tape with SS sheath</td>
<td>![MgB2 image]</td>
<td>Silver sheathed tape</td>
<td>Thin film on metallic substrate with biaxial texture</td>
</tr>
<tr>
<td>T$_c$ (K)</td>
<td>39 K</td>
<td>108 K</td>
<td>90 K</td>
</tr>
<tr>
<td>Current carrying capability at 20 K</td>
<td>1000 A</td>
<td>1000 A</td>
<td>1000 A</td>
</tr>
<tr>
<td>Superconducting splices</td>
<td>YES</td>
<td>NO</td>
<td>NOT YET</td>
</tr>
<tr>
<td>Low cost (&lt; 5 $/m)</td>
<td>YES</td>
<td>NO</td>
<td>NOT YET (likely within 5 years)</td>
</tr>
<tr>
<td>Long lengths (&gt;5 Km)</td>
<td>YES</td>
<td>NO</td>
<td>NOT YET (likely within 5 years)</td>
</tr>
</tbody>
</table>
Columbus has been founded in 2003 as a start-up originated from the Italian National Research Council (CNR)

- The actual plant is fully operational for MgB$_2$ wire production and is completing scaling up
- MgB$_2$ compound production is now also fully implemented
- Wire unit length today up to 2-4 Km in a single piece -length
- It is scaled up to 20 Km together with the full scale up of the plant with capacity exceeding 4’000 Km/year
- Columbus MgB$_2$ production for MRI has exceeded 700 Km of fully tested and qualified wires
- Total plant area 4’400 m$^2$ after being increased by further 1’000 m$^2$ in September 2012
• 39 macchine nuove, di cui 20 principali e 19 ausiliarie
• 15 macchine riutilizzate su 21, di cui 9 da modificare
• 10 principali interventi per l'infrastruttura tecnica
• 1 nuovo capannone a 2 piani
• Interventi di risanamento esterno
• Realizzazione dei magazzini separati materia prima e prodotto finito
• 2.280m² di area produttiva coperta
• 3 reparti a turnazione differenziata
• Impianto elettrico completamente rifatto (1,2 MW) con gruppo Diesel di continuità
• Reti IT e rete gas tecnici completamente distribuite
• 20 unità di manodopera diretta

Floor 0 Billet assembly
Floor -1 Finishing

New building - ready since August 2012

Finished products
Powders production
Services
R&D

Offices

Actual building
Expansion of our production

- 39 new machines, of which 20 main and 19 auxiliaries
- 15 existing machines will be still used over 21, of which 9 need upgrades
- 10 main upgrades to the technical infrastructures
- 1 new 2 floors building
- 2,280m² of covered workshop area
- 20 direct production units
PHOTOGALLERY
CLEAN SYNTHESIS OF MgB$_2$
PHOTOGALLERY
HIGH POWER STRAIGHT BENCH N1
PHOTOGALLERY
MULTISTEP DRAWING N1 & N2
PHOTOGALLERY
20-METER LONG IN-LINE FURNACE
PHOTOGALLERY
4-METER FURNACE FOR WIRE ANNEALING N1
PHOTOGALLERY
THREE LARGE ROLLING MILLS
Quality control methods we are implementing

- Hitachi SEM with EDX
- Bruker ultra fast XRD
- Fritsch Analisette 22 laser particle size analyzer
- Forster radiofrequency defect detector
- Optical stereomicroscopes
- Laser wire size and shape online monitor
- Industrial video cameras for surface defect detection
- Additional cryo-free critical current testing system under construction
Production Process

**Chemical Phase**

- **Mixing**
- **Reaction**
  - 700-1000°C in Ar
- **MgB₂**
- **Planetary Ball Milling**

**Metallurgical Phase**

- **Filling tube**
  - 1.3 g/cm³
- **Drawing**
- **Cold rolling**
- **Reaction**
  - 900-1000°C in Ar
There are **3 different wire formats**: Round, Flat and Sandwich

**Flat tape**

• The flat tape architecture has been the work-horse for Columbus in the past years and it has been the preliminary choice of our customers to start to understand the potential of our material.

• Flat tape conductor is mainly used in small bore magnets and low current devices.

**Sandwich conductor**

• This architecture is our solution for future magnet and winding applications.

• It allows the maximum flexibility in the control of the wire absolute performance and in the amount of Cu stabilization.

• Being the Cu stabilizer not subjected to the thermomechanical treatment of the MgB₂ conductor, it’s soldered to it in its optimal mechanical and electrical condition.

**Round wire**

• MgB₂ is currently the only no low-Tc superconductor that can be easily produced in round wire shape with significant transport properties, multifilamentary structure and excellent reliability over long lengths.

• Round wires present several advantages, particularly concerning easier solenoid and more complex magnet winding, and absence of anisotropy.
Outer sheath of Nickel surrounding 12 MgB$_2$ filaments protected by a Nickel barrier and stabilized with Copper core with Iron barrier

The unit piece is already 1.6 Km

Wire Design : Flat Tape
Outer sheath of Nickel surrounding 19 MgB₂ filaments protected by a Nickel barrier and Copper external stabilization.

The unit piece is already 2.5 Km. The scaling up of the production process will lead to a 15 Km unit piece length.

- The data reported in the figure below are relative to a conductor optimized for 10 K behaviour, i.e., with some light C doping.
- Because the C doping is slightly depressing the Tc, data are not representing the best conductor for use at about 20 K.

<table>
<thead>
<tr>
<th>Material</th>
<th>Area (mm²)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgB₂</td>
<td>0.36</td>
<td>24.1</td>
</tr>
<tr>
<td>Ni</td>
<td>1.14</td>
<td>75.9</td>
</tr>
<tr>
<td>Total</td>
<td>1.5</td>
<td>100</td>
</tr>
<tr>
<td>Dimension</td>
<td>3.0 x 0.5</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Dimension</td>
<td>3.0 x 0.2</td>
<td></td>
</tr>
</tbody>
</table>
Outer sheath of Monel 400 surrounding 37 MgB2 filaments protected by a Nb barrier and embedded in a Ni 201 alloy matrix.
The unit piece is already 3.5 Km.
The scaling up will lead to a 20 Km unit piece length.

### Table: Material Details

<table>
<thead>
<tr>
<th>Material</th>
<th>Area (mm²)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgB₂</td>
<td>0.16</td>
<td>16.5</td>
</tr>
<tr>
<td>Nb</td>
<td>0.15</td>
<td>14.6</td>
</tr>
<tr>
<td>Ni</td>
<td>0.16</td>
<td>15.5</td>
</tr>
<tr>
<td>Monel</td>
<td>0.53</td>
<td>53.4</td>
</tr>
<tr>
<td>Copper</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.00</strong></td>
<td><strong>100</strong></td>
</tr>
<tr>
<td><strong>Diameter</strong></td>
<td><strong>1.13</strong></td>
<td></td>
</tr>
</tbody>
</table>
• MEDICAL FIELD
  Cooperation between Columbus, ASG and Paramed has brought to life a new generation of cryogen-free, “open-sky” MRI system. Use of MgB$_2$-based magnets bypasses the need of a cryogenic coolant, reducing encumbrance, servicing cost and refill time.

• ENERGY PRODUCTION
  Superconducting motors and generators, especially into hydroelectric and wind energy field, to improve efficiency and reduce encumbrance and weight.

• POWER QUALITY & STORAGE
  SFCL for a more protected network and SMES to make the distribution of energy generated by alternative sources more stable over time.

• TRANSPORTATION
  Marine Superconducting Motors, which allows for a considerable improvement from both the weight and efficiency point of view.

• HIGH ENERGY PHYSICS
  Superconducting magnets for particle accelerator and nuclear fusion experiments mean power saving and dimension reduction of the facilities, together with great efficiency improvement.
The MRI system MROpen

MROpen has been developed employing the flat tape architecture

- Unique fully dry superconducting MRI system currently on the market
- Based on Columbus MgB$_2$ technology
- Unique superconducting open-sky MRI system currently on the market
- Very attractive because of its features (scanning with/no load, children, no claustrophobia, very easy installation and running, ..)
- More than a dozen systems produced so far
- Also highly suitable for remote installation because electricity is the only requirement to setup/start/run the system – not suffering from scattered power outages though

First commercial systems already installed and fully operational in hospitals and private clinics in EU and North America
Objectives of the ALUHEAT project are:

- To validate from a technical and economical point of view a new concept by building a 200-300 kW aluminium billet induction heater and test it in an industrial aluminium extrusion plant.

- 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.

- The magnet uses about 20 Km of MgB\textsubscript{2} wires, and it has been successfully tested at design specs (200A, about 2 Tesla).

System under advanced testing at TUT University laboratory in Finland, with SINTEF - Trondheim.
Failures of gearboxes have been reducing the reliability of offshore turbines and there have been a trend in the industry towards omitting the gearbox, introducing direct drive technologies based on copper field windings or permanent magnets.

However, the usage of the magnets based on rare earth elements is of the order of 600 Kg/MW and will impose a considerable increase in the worldwide demand. China is producing 95% of the rare earth elements and has imposed export quotas.

Advantages of a superconducting generator (1)
Superconducting Generators

- could offer several cost and reliability improvements over conventional wind turbine drivetrains when scaled up to high capacity (5 MW and larger) and when used in direct drive systems: they do not require a gearbox
- less mass and less volume than PM generators, resulting in an overall reduction in turbine capital costs
- cost advantages produced by such weight savings are most likely to be realized initially in large turbines
- should increase drivetrain reliability by allowing a larger air gap tolerance between rotor and stator as compared to PM generators
- hold the potential of providing high torques in a smaller size and with smaller weight than conventional technologies, but there are two critical points:
  1. demonstrate the reliability of the technology
  2. choose superconducting wires with a low price

Superconducting Generators
150 t
Two large frontier projects will help boost our production and quality in the upcoming years.

Cern and the fusion community are implementing MgB$_2$ critical components in their devices in order to profit from the high operating temperature of the superconductor, and the high current carrying capability without incurring in the extra costs and technical risks of complex and delicate HTS materials.
**Cold powering of CERN LHC magnets using superconducting cables**

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

Magnets in each of the 8 sectors are series connected.

Problem to be addressed: reliability of the magnets feed boxes placed in the tunnel that need constant maintenance while becoming heavily radioactive – moving them to the power supply caves far from the beam.
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$_2$.

**MgB$_2$ cable for outer poloidal field coils**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{cs}$ of a single MgB$_2$ strand @ 4T, 15K</td>
<td>1000 A/mm$^2$</td>
</tr>
<tr>
<td>Superconducting filling factor</td>
<td>20%</td>
</tr>
<tr>
<td>Single Strand diameter</td>
<td>1mm</td>
</tr>
<tr>
<td>Total cross section</td>
<td>0.784 mm$^2$</td>
</tr>
<tr>
<td>SC cross section in a single strand</td>
<td>0.784*0.2= 0.15 mm$^2$</td>
</tr>
<tr>
<td>$I_c$ of a single MgB$_2$ strand @ 4T, 15K</td>
<td>0.15*1000= 152 A</td>
</tr>
<tr>
<td>Number of strand to have 35kA</td>
<td>35000A/152A=230</td>
</tr>
<tr>
<td>Total amount of wire</td>
<td>&gt; 500 Km per coil</td>
</tr>
</tbody>
</table>

**Why MgB$_2$ in this machine?**

To prove feasibility of future nuclear fusion systems with much higher duty cycle.
MgB₂ development and production is progressing well.

We believe that MgB₂ cables will represent a very important development for our products.

Dedicated MRI projects are ongoing in several countries.

Total body MRI companies are also starting the implementation of MgB₂ in future commercial systems in order to move to cryogenic-free systems.

New industrial products and research related applications will further help to boost MgB₂ production.
Thanks for your attention