MgB$_2$ development for magnets in medical application

Matteo Tropeano, Giovanni Grasso

Superconductivity and other new Developments in Gantry Design for Particle Therapy
17-19 September 2015
• Why MgB$_2$?
• Interesting properties since its discovery in 2001
• Companies dealing with the manufacturing MgB$_2$ wires or related applications

• PIT technique
• Main critical issues
• Columbus Superconductors
• Wire formats: round wires for cable applications
• Wire formats: copper stabilized tapes for magnets applications

• Achieved results and new projects
• Medical application
• Final remarks
**Why MgB$_2$?**

1. **High critical field**
   - Iwasa Y et al. 2006
   - A round table discussion on MgB$_2$; towards a wide market or a niche production?

2. **Large critical current density**
   - Zeng et al. 2003
   - Superconducting MgB$_2$ thin film on silicon carbide substrate by HPCVD
   - APL 82 2097-9

3. **Low density**
   - **Compound** | **Mass density**
   - Copper                  | 8.96 g/cm$^3$
   - NbTi                    | 6 g/cm$^3$
   - Nb$_3$Sn                | 5.4 g/cm$^3$
   - YBCO                    | 6.35 g/cm$^3$
   - BSCCO-2223              | 6.5 g/cm$^3$
   - MgB$_2$                 | 2.6 g/cm$^3$

---

**Relatively high Tc, simple structure and common materials**

Nagamatsu et al. 2001
Superconductivity at 39K in magnesium diboride
Nature 410 63-4

**No evidence of “weak link”, no need of high degree of texturing**

D.C Larbalestrier et al. 2001
Strongly linked current flow in polycrystalline form of the superconductor MgB$_2$
Nature 410

**PIT process for the fabrication of wire**

G. Grasso et al. 2001
Large transport current in unsintered MgB$_2$ SC tapes
APL Volume 72, number 9
Early stage New York based company, granted as SME partner by UK for R&D activities on MgB₂

MgB₂ wires for Cryo-free MRI
Summer 2015 for MRI magnet 1.5T-3T magnet

Interested in the MgB₂ technology

1000 m of MgB₂ wire already demonstrated in collaboration with IFW Dresden

Patents on MgB₂ wires
Several R&D activities

Ready for industrial production
2 different manufacturing process
ex-situ and in-situ technique

Interested in commercial production of wires or wires+magnet
Columbus superconductors

2003
Columbus Superconductors srl
75% CNR+Researchers
25% ASG

2005
R&D target
First 1.6 km MgB$_2$ long wire in a single unit length

2006
Columbus Superconductors SpA
ASG became the main shareholder to sustain industrial investment and to start the business plan

Superconducting wire
Superconducting magnet
MRI
Conductors configuration:
different shape, aspect ratio, number of filaments, materials

Home made MgB$_2$ powders
Precursor quality, doping, synthesis temperature, granulometry
Powder optimization
- Purity and granulometry control
- Grain connectivity
- MgO at grain boundaries
- Pinning and/or doping control

Sheath materials
- Mechanical properties of the raw metals
- MgB$_2$ / sheath reaction

Optimization of intermediate (500-800°C) and final thermal treatment (900°C)

Application voted design
Layout of the conductor: shape, dimensions, number of filament
Magnetic, electrical, thermal and mechanical properties
• The actual plant is fully operational for MgB$_2$ wire production and is under scaling up
• MgB$_2$ chemical synthesis is now also fully implemented
• Wire unit length today up to 2-4 Km in a single piece –length
• It will be possible up to 20 Km with the full scale up of the process and of the plant with a nominal full capacity exceeding 5000Km/y
• Columbus MgB$_2$ wires production for MRI has exceeded 500 Km of fully tested and qualified wires
• Total plant area 3’400 m$^2$ increased by further 1’000 m$^2$ by September 2012
Columbus Superconductors Plant

- 39 new machines
- 15 existing machines will be still used over 21
- 10 main upgrades to the technical infrastructures
- 1 new 2 floors building
- 2.280 m² of covered workshop area
- 20 direct production units

Clean synthesis of powders

High power straight drawing machine

20 meter long in-line furnace

Multistep rolling machine

Multistep drawing machine

4 meter furnace for annealing HT
Quality Control is done through all the process area from incoming raw material to the final product.
- Defined responsibility in the control process
- Dedicated operative instructions and procedure
- Real time data collections of production and quality records
- Materials traceability

- SEM with EDX
- Optical stereomicroscopes
- Fast XRD
- Particle size analyzer
- Laser wire size and shape online monitoring during the deformation process

- Industrial video cameras for surface defect detection
- Eddy currents defect detector

100% of our products passes through these detectors.

Quality management system is in compliance with the standard ISO 9001:2008
Eddy current detector to check the product integrity

4 camera visual inspection to check the surface appearance

TEST REPORT - V66_4
Test station: DEFECTOMAT CI
Request: V66

Outer
Inner defects
Round wires are produced in different configuration at diameter even smaller than 1mm

For application in power cable
An external copper layer (30-40 μm) could also be provided through an electrodeposition process to improve the interstrand conductance and current distribution.
WORLD-RECORD CURRENT IN A SUPERCONDUCTOR

In the framework of the High-Luminosity LHC project, experts from the CERN Superconductors team recently obtained a world-record current of 20 kA at 24 K in an electrical transmission line consisting of two 20-metre long cables made of Magnesium Diboride (MgB$_2$) superconductor. This result makes the use of such technology a viable solution for long-distance power transportation.

- 20 meter line
- forced flow He gas
- 2 x 20 meter long MgB$_2$ powered to 20KAmps

Long R&D effort started in 2008 between Columbus and CERN
Short cable prototype

16.5 MW MgB₂ bipolar power distribution system

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>2 twisted strands</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>3.3 kV</td>
</tr>
<tr>
<td>Operating current @ 20K</td>
<td>&gt; 2500 A</td>
</tr>
<tr>
<td>Operating current @ 25 K</td>
<td>&gt; 2100 A</td>
</tr>
<tr>
<td>Cooling medium</td>
<td>G He 20 bar</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>60 mm</td>
</tr>
<tr>
<td>lop/lc</td>
<td>75%</td>
</tr>
</tbody>
</table>

Experimental Hybrid Power Transmission Line with Liquid Hydrogen and MgB₂-Based Superconducting Cable

V. V. Kostyuk, I. V. Antyukhov, E. V. Blagov*, V. S. Vysotsky, B. I. Kalggin, A. A. Nosov, S. S. Feltsov, and V. P. Firsov
Institute of Nanotechnology for Microelectronics, Russian Academy of Sciences, Moscow, 119991 Russia
*e-mail: blagovev@mail.ru
Received November 23, 2011
1. Best Paths project

Objectives

5 top technology demonstrations including a HVDC MgB2 superconducting link
2. Technical specifications

Conceptual design of the cable with two fluids to guarantee the safety of the operation.

- **Outer cryogenic envelope**: Liquid N\_2 at 70K and 5 bar.
- **Inner cryogenic envelope**: Helium gas at 20K and 20 bar.
- **4 walls’ cryogenic envelope**
- **HV lapped insulation in LN\_2**
- **10 kA MgB\_2 conductor in GHe**
2. Technical specifications

Principle of the testing installation with 2 parallel cooling circuits

10 kA /320 kV
Terminaison 1

4 wall cable cryogenic envelope

1~20 m

10 kA /320 kV
Terminaison 2

Cooling system #1 (He gas)
20 K - 20 Bar

Cooling system #2 (Liq N2)
70 K - 5 Bar

320 kV

Inner flow

Outer flow
R&D products in 2006: 14 filaments

Starting from 2010:
- 12 filaments
- improved fabrication process
- synthesis in controlled atmospheres

<table>
<thead>
<tr>
<th>Material</th>
<th>Area (mm²)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgB₂</td>
<td>0.23</td>
<td>10</td>
</tr>
<tr>
<td>Ni</td>
<td>1.55</td>
<td>65</td>
</tr>
<tr>
<td>Iron</td>
<td>0.23</td>
<td>10</td>
</tr>
<tr>
<td>Copper</td>
<td>0.36</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.37</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Dimension: 3.5 x 0.65

Unit length: 3.2Km
Sandwich wire: $3 \times 0.5 \text{ mm}^2$

19 filaments nickel tape can be produced in unit length up to 3Km. Lamination process is now reliable and uniform over all the length.

Perfect copper to MgB$_2$ tape alignment is confirmed by the statistical analysis of the data from laser in-line micrometers.
Performance improvements

![Graph showing performance improvements with magnetic field (B) and current (Ic) at T=20K](image)

- **Legend**:
  - MRO
  - MRO 2014
  - MRI HF
  - MRI HF 2014

- Axis labels:
  - **Y-axis**: Ic (A)
  - **X-axis**: B (T)
Starting from ASG experience, the feasibility has been already demonstrated in two different tapes, stabilized and sandwich like with high persistent current in several turns coil.
Development of superconducting joint on MRI wire. More than 30 single-joint samples realized with $I_p/I_c > 50\%$, with total resistance of $< 10^{-14}$ Ohm.

Recently built and measured a 200m long coil with single joint.
At 15 Kelvin reached:
- **280 Ampere** in Persistent Mode (I.E. $< 10^{-14}$ Ohm)
- **0.3 Tesla** on inner surface
- **0.2 Tesla** in the center of coil.

**NEXT STEP:**
1Km long magnet with switch device
UNDER CONSTRUCTION with ASG Superconductors
The aim is to 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)

- **2013**
  - MgB2 wire design, characterization and Manufacture
  - Cryostat Concept Design

- **2014**
  - First MgB2 coil construction and test
  - Scale machine Design

- **2015**
  - Full scale generator design and integration
  - Cryostat first module test
  - Scale machine construction

- **2016**
  - Scale machine Validation
  - Industrialization Studies
  - Business Plan

This project has received funding from European Union’s FP7 Programme, under grant agreement No 308793.
This project has received funding from European Union’s FP7 Programme, under grant agreement No 308793.
Double pancakes MgB2 coils of the scale machine  
Source: Tecnalia

<table>
<thead>
<tr>
<th><strong>Coil</strong></th>
<th><strong>Stack of racetrack DPs</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of DPs</td>
<td>9</td>
</tr>
<tr>
<td>Number of copper caps</td>
<td>2</td>
</tr>
<tr>
<td>Thickness of copper cap</td>
<td>8 mm</td>
</tr>
<tr>
<td>Insulation layers between DPs</td>
<td>G11</td>
</tr>
<tr>
<td>Insulation layer thickness</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Total thickness stack</td>
<td>~77.6 mm</td>
</tr>
<tr>
<td>Coil radius (curved parts coil ends) inner/outer</td>
<td>100 mm / 165 mm</td>
</tr>
<tr>
<td>Total thickness</td>
<td>~93.6 mm</td>
</tr>
<tr>
<td>Straight side length end parts</td>
<td>185</td>
</tr>
<tr>
<td>Straight side body</td>
<td>622</td>
</tr>
<tr>
<td>Total Wire length</td>
<td>~3200 m</td>
</tr>
</tbody>
</table>
Unique **fully dry** superconducting MRI system
Unique superconducting open-sky MRI system currently on the market
No liquid helium required
Also highly suitable for **remote installation** because electricity is the only requirement to setup/start/run the system

### Main Magnet Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Field</td>
<td>0.5 T</td>
</tr>
<tr>
<td>Peak Field on the Conductor</td>
<td>1.3 T</td>
</tr>
<tr>
<td>Nominal Current</td>
<td>90 A</td>
</tr>
<tr>
<td>Conductor critical current</td>
<td>400 A</td>
</tr>
<tr>
<td>Conductor price (€/kAm) at 20 K, 1 T</td>
<td>&lt; 7</td>
</tr>
<tr>
<td>Number of Pancakes</td>
<td>12</td>
</tr>
<tr>
<td>Conductor Length (total)</td>
<td>18 Km</td>
</tr>
<tr>
<td>Inductance</td>
<td>60 H</td>
</tr>
<tr>
<td>Overall Dimensions</td>
<td>2x2x2.4 m</td>
</tr>
<tr>
<td>Patient Available Gap</td>
<td>0.6 m</td>
</tr>
</tbody>
</table>
The next step will be to implement our new MgB$_2$ superconducting technology in the broad whole body market thanks to the following key factors:

- Easier operation than other superconductors
- Higher stability than other superconductors (due to the high temperature margin)
- Cost comparable to the actual solution

Liquid helium-free MgB$_2$ technology will be of particular attractiveness for installation in remote areas where the supply and handling of a cryogenics liquid is highly problematic.
The linac-MR consists of a LINAC that rotates in-unison with the biplanar 0.5 T MRI in transverse plane. The MRI's Bo field and the central axis of the 6 MV beam are parallel to each other. This parallel configuration avoids large increases in dose at tissue/air interfaces and at beam exit.

The open configuration of the systems allows real-time MRI guided radiotherapy of all tumors including peripheral tumours (eg, in breast, etc) with imaging and treatment performed concurrently.

http://www.mp.med.ualberta.ca/linac-mr/
• cryogen-free superconducting magnet not requiring a helium vent
• Possibility to turn to turn magnet off or on in a few minutes for servicing
• possibility to rotate the charged magnet

• provides high-quality MR images during irradiation
• 6 MV Linac
• can treat all tumours, including peripheral tumors (eg, in the breast)
MgB$_2$ is a new technology in comparison to the other technical SC but has been already implemented with excellent results in several prototype devices and in industrial products:

- long record of fully tested and qualified wires
- world record current in a SC at CERN
- challenging application in the framework of the High Luminosity LHC project for the development of SC link
- demonstrative activities in rotating machine (generator for a wind power application)

Medical devices:

- more than 20 magnet working in MRI MrOpen medical system
- new prototype hybrid LINAC-MRI system
- exploring the whole body MRI market

- ....... SC Gantry?
The progress in MRIs is strongly linked to the creation of new devices with always-stronger fields.

- Stronger the magnetic field
- Stronger the signal
- Better the images

The main magnetic field is created by a large superconducting electromagnet in which a current flows.

The weak resistance of superconductors allows very strong currents to flow with no heating in the material, and hence enables to get very high field values of several teslas.
This project has received funding from European Union’s FP7 Programme, under grant agreement No 313224

The aim of the project is to develop, validate and increase the Technology Readiness Level (TRL) of the most critical technologies related to a magnetic shielding system for protecting astronauts’ lives during long duration space missions.

Active shielding → Static magnetic field using a SC coil

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

TO:
3x0,5 titanium clad wire
3x0,5 alluminum stabilization

FROM 17 grams TO 10.2 grams,
40% weight reduction

How can we reduce the overall weight for reducing the launching load?
Electro-mechanical characterization performed at Institute of Electrical Engineering, Slovak Academy of Sciences Bratislava, Slovakia

Courtesy of P. Kovac

Properties related to the operations and to the implementation are required by customers.
It’s possible to operate with:
- Frequency
- Gain
- Filter
- Threshold

Results are the absolute value and phase along the wire from detectors:

DF1: 10 KHz (inner defects)
DF2: 60 KHz (outer or superficial defects)
**Boron**
- Boron of higher quality than presently used (99% and + compared to 95% of today) is known to allow for 50-100% performance improvement.
- A source of reasonably priced 99% pure Boron is under advanced evaluation, and shall be implemented in some wires during H2 2013.

**Particle size control**
- Control of particle size is fundamental to achieve high MgB$_2$ density, and increase in-field performance.
- Although R&D techniques have led to successful results, industrial methods need to be identified and introduced (expected in 2014 on mass production).

**MgB$_2$ doping**
- So far, MgB$_2$ doping in Columbus has been optimized for wire performance at 12-20 Kelvin, 2-4 Tesla.
- Optimal Carbon doping concentration (2-5%) and vehicles for it will be introduced in production wires during H1 2014.
- Complex Carbon sources with combined effects (boron AND substitution) will be implemented within H2 2014 to enhance in-field properties without depressing $T_c$.

**Connectivity**
- Lack of MgB$_2$ density, lack of texture and impurities at grain boundaries as a consequence of Boron impurities and oxygen contamination are limiting the connectivity.
- Higher MgB$_2$ density in final wire, and more clean MgB$_2$ powders thanks to the new system for their handling and treatment in controlled atmosphere will increase connectivity further during 2015.

**Superconductor filling factor**
- The know-how learned from several years of industrial MgB$_2$ wire processing will help us pushing the superconductor to matrix ratio much higher than today.
- Increasing the active fraction of the superconducting wire is essential – trials to reach 40% at R&D level were already successful – stable results over long lengths are expected in production wires from 2015.
### Boron
- Boron is currently the most important key-element to balance cost / performance ratio of MgB$_2$ wires.
- Today Columbus is employing industrial grade 95% pure Boron in its production wires to minimize cost impact & have access to large suppliers.

### Doping Source
- Doping is achieved by nanoparticles additions of carbon-containing phases (graphite, SiC, diamond, etc).
- Although being special products, our doping approach limits their use to low-cost carbon sources and in concentration below 5%, diluting the impact on wire cost at the moment.

### Nickel alloy tubes
- It is the most important raw material cost today – western suppliers are still privileged in order to guarantee the quality of supply – we currently pay this approach with an extra cost of 400% with respect to the nickel LME price – target is to bring it below 200%.
- A different long term strategy is under development with increasing volumes, by selecting lower-cost suppliers of sufficient reliability.

### Mechanical Processing (cold working)
- The new production line for significant wire quantities (>3’000 Km/y) has been completed and put in operation successfully.
- Further dedicated investments will be put in place in order to be able to exceed 5’000 Km/y beyond 2015 – single piece unit lengths exceeding 10 Km will be implemented for every wire format already within 2014.

### Heat Treatments
- Furnaces for MgB$_2$ synthesis, wire annealing during cold working, and final wire sintering have sufficient capacity and reliability.
- Optimization of the thermal processes (large batches, cheaper gas atmospheres, shorter cycles) will minimize gas and power bills.

### Quality assurance tests
- Significant investment on QA technology already in place (SEM, XRD, lasers, eddy currents, particle size analyzers, cameras, etc).
- A strategy for systematic critical current measurements with faster data acquisition, less manpower, will be implemented.

### Team training
- Manpower in the production dept are currently going through intensive training on material processing and handling.
- Manpower efficiency will dramatically improve in 2013-2015 once the new workforce skills will reach our standards.