MgB$_2$ round wires for the high power superconducting cable demonstrator in Best Paths project
**Best Paths Project:** the largest project ever supported by the European Commission RDD Framework Programs within the field of power grids

October 2014 - September 2018

Total budget (EC contribution: 57%)

62.8 M€ = M$ 70.8 = 460 M¥

Demo 5 budget: 6.7 M€
EU contribution: 4 M€
Objectives of DEMO 5

- Demonstrate full-scale 3 GW class HVDC superconducting cable system operating at 320 kV and 10 kA
- Validate the novel MgB₂ superconductor for high-power electricity transfer
- Provide guidance on technical aspects, economic viability, and environmental impact of this innovative technology
Best Paths

Transmission for sustainability

10 project partners

- Demo coordination
- Optimisation of MgB$_2$ wires and conductors
- Cable system
- Cryogenic machines
- Testing in He gas
- Integration into the grid

- Optimisation of MgB$_2$ wires and conductors
- Cable system
- Testing in He gas

- Manufacturing and optimisation of wires

- Scientific coordination
- Dissemination

- Cable system
- Liquid hydrogen management

- Cooling systems
- Cable system
- Dielectric behaviour
- Integration to the grid
- Reliability and maintenance

- Cable system
- Integration into the grid
- Socio-economical impact

BEST PATHS stands for “BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal Hvdc Systems”. It is co-funded by the European Commission under the Seventh Framework Programme for Research, Technological Development and Demonstration under the grant agreement no. 612748.
The actual plant is fully operational for MgB$_2$ wire production with about 35 employees.

- **MgB$_2$ chemical synthesis** also fully implemented.
- Wire unit length today up to **2-4 Km in a single piece** – length.
- It will be possible up to **10 Km** with the full scale up of the process.
- Columbus **MgB$_2$ tape production for MRI** has exceeded **500 Km** of fully tested and qualified wires.
- Columbus **MgB$_2$ round wires production for cable** has exceeded **100 Km** of fully tested and qualified wires (end 2015-2016).

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Conductors configuration: different shape, aspect ratio, number of filaments, materials.

Home made MgB$_2$ powders:
Precursor quality, doping, synthesis temperature, granulometry.
• 39 new machines
• 15 existing machines will be still used over 21,
• 10 main upgrades to the technical infrastructures
• 1 new 2 floors building
• 2.280m² of covered workshop area
• 20 direct production units
Defining the cable layout

The most suitable wire for cabling activities is

- a round wire with the smallest possible diameter (i.e. below or close to 1.5 mm)

The wire must have **good mechanical properties** to enable cabling operations.
An important parameter for cabling is the **critical bending radius** to prevent deterioration

- during handling or introducing the right **twist**

**Operating requirements**

**Nominal operating requirements of the cable**

- Operating 10kA DC current

**Actual operating requirements**

- Controlled quench for 35kA 100ms
- DC+AC ripples
  - Ripples at 50hz, 1% of amplitude
  - Power inversion
Wire type-1
diameter: 1.33mm
36 filaments
Materials: Monel, Ni
FF: 17%

Wire type-2
diameter: 0.99mm
37 filaments
Materials: Monel, Ni, Nb
FF: 11.5%

Type 2 is the result of a CERN-Columbus collaboration started in 2008
Samples have been characterized at CERN

Trend has been confirmed also at 4.2K
Critical bending radius has been evaluated

- No/negligible degradation down to 125 mm bending radius
- 15-20% $I_c$ degradation at 100 mm bending radius
Wire 3
diameter: 1.5 mm
37 filaments
Materials: Monel, Ni
**FF: 30%**

Wire 4
diameter: 1.5 mm
37 filaments
Materials: Monel, Ni, Nb
**FF: 12%**
Measurements performed at CERN on 1.5mm wire

No $I_c$ degradation measured for bending at high field
Negligible at low field (high current)

- Measurements at 4.2 K performed on straight and bent samples from last long-length production run
- The magnetic field was applied parallel to the longitudinal axis of the wire
Cable design, manufacturing and test

- Cable manufactured by Nexans on industrial cabling machines
- Measurements of extracted wires performed after cabling after bending on 0.8 m diameter drum by Columbus SPA show no degradation
- Validation by electrical characterization of cable prototypes at CERN: Measurements of the critical current of 2 meter long prototype cable tested in liquid (at 4.3 K)

**Benefits of Design #2 versus design #1:**
1. Higher critical current density
2. Less MgB$_2$ wires to handle
3. MgB$_2$ wire stronger
4. Higher strain resistance
5. Increase of 16% of the hydraulic diameter for the Best Paths demonstrator

**Design # 1**
- 18 MgB$_2$ wires
- $I_c = 14000$ A
- $I_{op}/I_c = 0.72$
- D = 9.6 mm

**Design # 2**
- 12 MgB$_2$ + 2 Cu wires
- $I_c = 13700$ A
- $I_{op}/I_c = 0.73$
- D = 8.6 mm

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Test results at CERN Fresca Test Station

18 strands cable with Wire 1- 1.33mm tested

Critical current - estimated boundaries vs measurements

18 MgB$_2$ wires
$I_c = 14000$ A
$I_{op}/I_c = 0.72$
$D = 9.6$ mm

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The wires proposed give enough flexibility to design the cable following different approach.

<table>
<thead>
<tr>
<th>PROPERTIES</th>
<th>Wire 1</th>
<th>Wire 2</th>
<th>Wire 3</th>
<th>Wire 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>1.3</td>
<td>1</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Materials</td>
<td>Monel</td>
<td>Monel</td>
<td>Monel</td>
<td>Monel</td>
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<tr>
<td></td>
<td>Nickel</td>
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<td>Nickel</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td>MgB2 fraction</td>
<td>17%</td>
<td>12%</td>
<td>30%</td>
<td>12%</td>
</tr>
<tr>
<td>Critical current at 20K, 1T</td>
<td>500A</td>
<td>300A</td>
<td>&gt;650A</td>
<td>&gt;650A</td>
</tr>
<tr>
<td>Critical current at 4.2K, 3T</td>
<td>280</td>
<td>400</td>
<td>&gt;700</td>
<td>600</td>
</tr>
<tr>
<td>Critical bending radius</td>
<td>125</td>
<td>100</td>
<td>200</td>
<td>150</td>
</tr>
</tbody>
</table>
Superconducting wires

MgB₂

1.1 mm

56 mm

Copper 2000 mm² Conductor

≈ 1 800 A

XLPE extruded cable

> 10 000 A

Demo 5 conductor

(One € coin)
Conclusion- Next steps

Four round wires have been optimized and proposed for the cabling activities within Best Paths

Different layouts provide enough flexibility to design the cable according to

Wires production is finished as well as cabling activities

A short length cable prototypes (Design #1) has been tested at CERN facilities (FRESCA test station)
A long length cable (Design #2) will be tested at CERN and Nexans facilities within the end of the project

Aging of commercial MgB2 wires in Hydrogen
Wilfried Goldaker et al

3-D Numerical Modelling of AC losses in MgB2 wires for the 10 kA demonstrator of BEST PATHS
Guillaume Escamez et al.

Development of MgB2 cable conductor for very high power HVDC transmission within Best Paths project
Christian-Eric Bruzek et al.

Update on the high-power MgB2 DC superconducting cable project within BEST PATHS
Christian Eric Bruzek, et al.
An alternative way to transmit bulk power 3-5 GW

Overhead lines

Nelson River DC line (Canada)
1600+1800 MVA (+2000 under construction)

Gas insulated lines

Geneva, Palexpo Link 2001, 470 m, 220 kV / 2 x 760 MW

XLPE cables

Raesfeld (380 kV AC, Germany)
2x 1800 MW

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Reduced space for cable installation and substations

**Significant reduction of right-of-way corridors and of excavation work**

**No thermal dependence to the environment**

*Example:* 6.4 GW DC power link with XLPE cables

Foot print = 7 m

Favourable scenario: 15°C, soil 1 K.m/W

1,30 m

2,00 m

Resistive cables (8 x 400 kV - 2 kA)

Our Best Paths Demo 5
(2 x 320 kV - 10 kA)

Foot print = 0.8 m

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Main objectives of the superconducting demonstrator

10 partners involved in the project

- Demonstrate full-scale **3 GW** class HVDC superconducting cable system operating at 320 kV and 10 kA
- Validate the novel MgB₂ superconductor for high-power electricity transfer
- Provide information for technical aspects, economic viability, and environmental impact of this innovative technology

- Process development to manufacture a large quantity of high performance MgB₂ wires at low cost
- Cable and termination development + manufacturing processes
- Validation of cable operations with laboratory experiments performed in He gas at variable temperature
- Operating demonstration of a full scale cable system transferring up to 3.2 GW
- System integration pathways for HDVC applications
- Investigation in the availability of the cable system
- Preparation of the possible use of H₂ liquid for long length power links
Two approach:

1. **Control quenching during the fault: « a fault tollerant » approach**
   - Design the cable for the 10kA operating condition and Ic 13-15KA and accept a global resistive transition
   - Smaller overall dimension and amount of SC wires
   - Need to evaluate the impact of cable heating on cryogenics enviroment, recovery time, etc etc

2. **No quench during the fault « a fault transparent » approach**
   - Design the cable for 35kA (Ic of 42kA)
   - Bigger overall dimension, larger number strands
   - No additional load on the GRID
   - Need to carefully evaluate AC losses and thermal margin during transient
Demonstrator technical specification and testing strategy

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Monopole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>Monopole</td>
</tr>
<tr>
<td>Power</td>
<td>3.2 GW</td>
</tr>
<tr>
<td>Voltage</td>
<td>320 kV</td>
</tr>
<tr>
<td>Current</td>
<td>10 kA</td>
</tr>
<tr>
<td>Length</td>
<td>~20 m</td>
</tr>
<tr>
<td>Cooling media</td>
<td>Liq N₂ for the electrical insulation</td>
</tr>
<tr>
<td></td>
<td>He gas for MgB₂ conductor</td>
</tr>
<tr>
<td>Losses of the demonstrator</td>
<td>&lt; 50 W He gas (~20 K)</td>
</tr>
<tr>
<td>Fault current</td>
<td>35 kA during 100 ms</td>
</tr>
<tr>
<td>AC Ripples on 10 kA DC current</td>
<td>&lt; 1% amplitude 50 Hz</td>
</tr>
<tr>
<td>Change of power flow direction</td>
<td>100 MW/s up to 10 GW/s</td>
</tr>
</tbody>
</table>

- Test of operating conditions on the demonstrator
- But use only modeling to check the cable behavior during faults and polarity changes
Electro-mechanical characterization of MgB$_2$ wires for the Superconducting Link Project at CERN

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$^3$High Energy Accelerator Research Organization (KEK), Japan

1mm diameter
y=0.3mm
R=100mm strain 0.3
No degradation

1.5mm diameter
y=0.65mm
R=150mm strain 0.43
40% Ic degradation

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