Status of MgB₂ wire and cable applications in Europe

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Abstract. Since its discovery in 2001, MgB₂ has generated interest for practical applications. Its availability in the form of multifilamentary round wire makes it suitable for production of cables. Together with relatively high critical temperature and potential low-cost, this renders it appealing for use in superconducting devices where its limited in-field performance can be tolerated. The state-of-the-art properties of commercially available wire and the potential of MgB₂ conductors for use in superconducting systems are discussed. An overview of high-current electrical transmission projects where MgB₂ has been proposed as an alternative to conventional Nb-Ti or High Temperature Superconductors is presented.

1. Introduction
The discovery in 2001 of the superconductor MgB₂ raised high expectations in the field of fundamental and applied research. The \( T_c \) value of this compound, 39 K, is lower than those for High Temperature Superconducting (HTS) materials, but considerably above the value of Nb₃Sn (18 K). Since both Mg and B are abundant and not intrinsically expensive, it was expected that MgB₂ wires fabricated using classical deformation methods would be competitive for superconducting applications above 4.2 K in devices cooled by closed-circuit refrigerators or even in devices cooled by liquid hydrogen. A considerable effort has been made worldwide, both theoretically and experimentally, to understand this exciting material and to develop industrial conductors. In the following, research and development in the field of MgB₂ will be briefly discussed, with a focus on the activities in Europe.

2. Fundamental properties, single crystals
The simple binary, hexagonal compound MgB₂ presents in reality an unexpected complexity. As for other Low Temperature Superconductors (LTS), e.g. Nb₃Sn, MgB₂ was found to be of the BCS type, but superconductivity in MgB₂ was found to be correlated with two distinct energy bands, with energy gaps \( \Delta_\sigma \) and \( \Delta_\pi \), at 7.5 and 2.3 meV [1]. The interplay of the quasi two-dimensional \( \sigma \)-band and the almost isotropic \( \pi \)-band results in an anomalous and complex behaviour of the characteristic lengths and anisotropic critical fields, as described by Gurevich [2, 3]. The existence of two bands was experimentally confirmed calorimetrically, by tunneling and by point contact spectroscopy.

MgB₂ single crystals [4, 5] were the basis of numerous fundamental properties of this compound. Most properties are anisotropic, e.g. the coherence length \( \xi \), the penetration depth \( \lambda \), the upper critical field \( B_{c2} \) and the electrical resistivity \( \rho \). Binary and ternary MgB\(_{1-x}\)C\(_x\) crystals of a size up to 1.5 x 1 x 0.1 mm\(^3\) and of weight up to 230 \( \mu \)g were grown from flux at pressures as high as of 3 GPa by Karpinski [5] at the ETH in Zurich. Rowell [6] proposed a simple correlation between electric resistivity \( \rho_0 \) and grain connectivity, which has been verified by numerous authors. The importance of the mixed state parameters in defining the limiting conditions for loss-free currents and thus \( J_c \) in MgB₂ has been discussed in detail in a review by Eisterer et al [7] at the ATI in Vienna. The effect of high energy radiation on the electronic properties of MgB₂ has been described by Putti et al [8].

3. The effect of Carbon substitution on the properties of MgB₂
A sizeable and reproducible enhancement of \( J_c \) of MgB₂ was observed after partial substitution of B by Carbon, after the reaction with C based compounds, in particular SiC [9], malic acid (C\(_7\)H\(_6\)O\(_5\)) [10], coronene (C\(_{24}\)H\(_{12}\)) [11] or thin C layers at the surface of B particles [12]. \( T_c \) in MgB₂ decreases almost linearly with the increase of the C content: for \( x = 0.18 \) in the formula MgB\(_{2-x}\)C\(_x\) a \( T_c \) value of 30 K is...
obtained. The anisotropy ratio $\gamma$ (defined by the ratio between $B_{c2}/ab$ and $B_{c2}/c$) decreases, too, from $\gamma = 5.3$ in binary single crystals to ~ 2 in ternary MgB$_{0.87}$Cu$_{0.13}$ single crystals [5]. Both gaps $\Delta_o$ and $\Delta_e$ approach each other with increasing C content and merge at 13.5% C, only one gap being observed at higher C contents. The enhancement of the residual resistivity $\rho_0$ with lattice disorder in MgB$_2$ wires with increasing C content was clearly recognized as the dominant effect enhancing the critical current density $J_c$ at high magnetic fields. The upper critical fields $B_{c2}/c$ and $B_{c2}/ab$ as well as the irreversibility fields $B_{irr}/ab$ and $B_{irr}/c$ were found to increase, the value of $B_{c2}/ab (T=0 \text{ K})$ approaching 35 T. The vortex pinning behavior of MgB$_2$ is only little affected by the presence of C on the B sites, which was confirmed by relaxation measurements on bulk samples, which show that the pinning energy $U_p$ of SiC alloyed MgB$_2$ is unchanged with respect to that of the binary compound [13].

A review of the effect of a large number of elemental additives has been published by Collings [14], showing that C is the only substitute leading to a marked enhancement of $J_c$ in wires at high fields. The list of elements in [14] does not contain oxygen, which plays a particular role: indeed, the filaments in all wires produced by powder metallurgical procedures contain an important part of oxygen, generally attributed to the presence of MgO inclusions. Recently, Prikhna et al [15] reported that in reality, around 7 - 10 at. % oxygen is substituting B in the MgB$_2$ structure. This result, which has yet to be confirmed, would explain the strong difference between the $B_{c2}$ values in thin films and wires mentioned later in this article.

4. Fabrication methods for MgB$_2$ wires
Soon after the discovery of superconductivity in MgB$_2$, a strong activity started at the University of Genova on the fundamental properties, but also on methods for wire production. Their results were the basis for the creation of a new company, Columbus Superconductors (Genova), based on the ex situ processing method. Today, industrial MgB$_2$ wires are also produced by Hypertech. Wire developments in view of a possible industrial production are also carried out in Japan at NIMS in Tsukuba, in collaboration with Hitachi. The main requirements for optimized transport properties in MgB$_2$ wires are elemental B and Mg powders with a high purity and a small particle size. The properties in the high field range are improved by C based additives. The desired final MgB$_2$ grain sizes being of the order of 10-50 nm, the appropriate initial boron particle size should be ideally in the nanometer range, too. The commonly used matrix materials for industrial MgB$_2$ wires are Ni and Monel, with a Nb barrier for avoiding diffusion of Mg into the stabilizing Cu or reaction with the Ni in the matrix. The variation of $J_c$ vs. the applied uniaxial strain $\varepsilon$ for multi-filamentary wires shows an almost linear increase up to $\varepsilon \sim 0.4\%$, after which degradation occurs. Due to the large total surface of the nanopowders, all MgB$_2$ filaments contain several at. % of oxygen, which gives rise to MgO inclusions and to oxygen substitution of B [15]. The main processing routes for the MgB$_2$ wires are: a) ex situ, b) in situ and c) IMD (Internal Mg diffusion); they are briefly described in the following.

4.1. The “ex situ” technique
Pre-reacted MgB$_2$ powders with a molar ratio of 1:2 are inserted into a Nb tube, surrounded by a Cu$_{70}$Cu$_{30}$ tube and drawn to a wire of about 3.5 mm diameter. Several pieces of wires are then inserted in a Nickel or Monel tube, together with OFHC Cu for stabilization. This composite is groove rolled and drawn to a round wire with a diameter of 2 mm, which is twisted before to be rolled to a tape (typically 3.6 x 0.65 mm$^2$) or to a wire of about 1 mm diameter, followed by a recrystallization heat treatment of typically 4 minutes at 965°C. Industrial ex situ wires produced by Columbus Superconductors exhibit $J_c(4.2K) \sim 3 \times 10^3$ A/mm$^2$ and $5 \times 10^2$ A/mm$^2$ at 3 and 5 T, respectively, for binary wires, and $\sim 4 \times 10^2$ A/mm$^2$ at 7 T for C alloyed wires (Malagoli et al [16], Kario et al [17]), as shown in figure 1. These $J_c$ values are lower than those for the other two processing route alternatives, but ex situ wires exhibit the highest homogeneity over long lengths, in addition to availability in km lengths produced with industrial and quality-controlled methods.

4.2. The “in situ” technique
For *in situ* MgB$_2$ wires, the initial MgB$_2$ mixture consists of Mg and B powders. In Europe, *in situ* wires were developed at the University of Genova, the University of Geneva, and the ESS in Bratislava, while industrial wires using this process are developed at Ohio State University and fabricated by Hyper Tech Research. With respect to the *ex situ* route, this alternative has the advantage that the reaction to MgB$_2$ occurs at considerably lower temperatures (around 650 °C), thus reducing the reaction layer at the metallic sheath. Even at these temperatures, C can be substituted into the B plane of the MgB$_2$ lattice. The highest $J_c$ reported so far for *in situ* monofilamentary MgB$_2$ wires was obtained by Li *et al.* [12] using B powder of 100 nm size, pre-doped with various C contents by plasma spray synthesis and 99 % Mg powders of 25 μm size. Multi-filamentary wires of 0.83 mm diameter with a Nb barrier and a Monel outer sheath (MgB$_2$/Nb/Monel) were manufactured and the reaction was performed at 700°C for 40 min, the final composition in the final MgB$_2$ filament being 2.54 mol% C. In the MgB$_2$ layer this wire exhibited $J_c$(4.2 K) = 1 x 10$^2$ A/mm$^2$ at 13.2 T (see figure 1).

4.3. The Internal Mg diffusion (IMD) technique

The internal Mg diffusion process (IMD) is based on the infiltration process developed by Giunchi (Edison, Italy) [18]. The density of the MgB$_2$ phase in these wires is close to 100%, i.e. much higher than in *in situ* and *ex situ* wires (~ 45 and ~ 70 %, respectively). Hypertech and NIMS/Hitachi use similar processing routes, known as AIMI and IMD, respectively. The higher connectivity leads to considerably higher $J_c$ values in the MgB$_2$ layer (see figure 1). A pure Mg rod with a diameter of typically 2.0 mm is placed at the center of a Ta or Nb tube, and the hollow space between the metal sheath inner wall and the Mg rod is filled with a B and C, the latter as a thin carbon layer on the surface of the B particles [12] or as C$_{12}$H$_{12}$ powders [11]. A multifilamentary configuration is obtained by bundling the rods, inserting them into a Cu-Ni tube, cold deforming and reacting. During the heat treatment at 640 °C, Mg diffuses into the B and reacts to form MgB$_2$ layers of 10-30 μm thickness along the inner wall of the Ta tube.

Figure 1. $J_c$ vs. B at 4.2 K for MgB$_2$ wires, tapes and thin films. 1: $J_c$ for *ex situ* wire, binary [16], 2: $J_c$ for *ex situ* tape, C alloyed [17], 1': $J_c$ for *ex situ* wire, binary, measured at CERN on a total production of 80 km [34], 3: $J_c$ for *in situ* wire, C alloyed [10], 4: $J_c$(layer) for AIMI wire, C alloyed [12]. $J_c$ in MgB$_2$ thin films: binary: C alloyed (12.3 at % C) [19], B/ab and B//c [21]. Data of Nb-Ti and of state-of-the-art Nb$_3$Sn wires have been added for comparison.
In both AIMI and IMD wires, holes are formed at the center of each filament, where the Mg core was located before reaction. During reaction, the C based additives decompose and carbon substitutes the boron in the MgB$_2$ phase. The values of $J_c$(layer) are slightly above $1 \times 10^3$ A/mm$^2$ at 4.2 K/10 T [11,12]. At 20 K/4 T, a $J_c$(layer) value close to $3 \times 10^3$ A/mm$^2$ was reported by Ye et al [12] (see figure 2). The corresponding values of Li et al [12] (not shown here) are very similar. The layer $J_c$ of the AIMI wires [12] at 4.2 K exceeds the $J_c$ values reported so far for multifilamentary Nb-Ti wires (see figure 1).

5. Comparison of $J_c$ in MgB$_2$ wires and in thin films

The $J_c$ vs. $B$ values at 4.2 K for the three routes are shown in figure 1 ($J_c$ is normalized to the superconducting cross section, with the exception of the AIMI process for which the layer $J_c$ is reported). For comparison, the $J_c$ vs. $B$ values for C added MgB$_2$ thin films, as well those for Nb-Ti and Nb$_3$Sn wires are also shown in the same figure. At all magnetic fields, the $J_c$ values for in situ and AIMI wires are higher than those of Nb-Ti. Due to the very low values of $J_c$, even for the best thin films in the unfavorable $B//c$ orientation, MgB$_2$ is not competitive with Nb$_3$Sn at 4.2 K. It must be recognized that the present MgB$_2$ wires do not take full advantage of the inherent properties of this material. When comparing the $J_c$ values of MgB$_2$ wires with those of thin films (figure 1), it is seen that the highest $J_c$ values in AIME wires just achieve the same level as the lower $J_c(H//c)$ values for thin films [20]. Since the values of $B_{c2}$ for $B//ab$ are at least 2 times higher (the highest known value of $B_{c2//}$ is 74 T [20]), it follows that a considerable enhancement of $J_c$ in wires would be expected if its $B_{c2}$ (and $B_{ab}$) could be raised in wires too. This is also true for the properties of MgB$_2$ at temperatures in the range between 10 and 25 K, as shown by the variation of $J_c$ vs. $B$ both for AIMI wires[12] and thin films [20], see figure 2. In this temperature range, MgB$_2$ has still a series of advantages. The potential at 20 K could even be raised if the reasons for the strong discrepancy between critical fields of thin films and wires could be found. The recently reported presence of sizeable quantities of oxygen inside the MgB$_2$ structure [15] could possibly provide a source of new ideas for tackling this problem.

6. Applications of MgB$_2$

6.1. General considerations

The promised low price of MgB$_2$ conductor, in principle enabled by the low cost and wide availability of raw materials, motivated several groups to explore possibilities for use in electrical applications. The price (Euro/kA m) is not yet competitive with that of Nb-Ti at 4.2 K. Processing of ex situ and in situ wires is based on the well-known Powder-In-Tube (PIT) technology, and while the manufacture of round wire involves the mechanical deformation of alloys or metals (typically Monel® or iron) that
are harder and more difficult to draw than copper, it is reasonably expected that the supply of large quantities of conductor will lead to optimization and cost reduction. In addition, margins in state-of-art industrial conductor (filling factor, raw material purity, and density of the superconducting phase) point in the direction of a potential future enhancement of performance and lower cost per kA-m.

To date the use of MgB$_2$ is limited to demonstrators or niche applications in low (< 5 T) magnetic fields and at temperatures of up to 15 - 20 K. Operation at these higher temperatures is appealing, but MgB$_2$ is not always the natural choice when compared to HTS BSCCO 2223 and REBCO conductors – in particular when liquid nitrogen cooling is an option. If electrical performance of industrially-produced MgB$_2$ wires at 15 K - 20 K and medium and low fields, and cost, were to become comparable to those of Nb-Ti at 4.2 K, then MgB$_2$ could emerge as replacement technology for applications benefiting from higher temperature margin, and/or relying on cryogen-free, helium gas or liquid hydrogen cooling.

Winding and cabling of reacted MgB$_2$ wire must accommodate the mechanical properties of the conductor. Development wires indicate a potential for critical tensile strains of up to 0.55 % [21] and 0.67 % [22] at 4.2 K for both PIT and IMD technologies. State-of-the-art industrial *ex situ* and *in situ* PIT multi-filamentary wires exhibit critical tensile strain of ~ 0.25 % at room temperature and 0.3 % at 4.2 K, with a minimum bending radius of ~ 100 mm [23-25]. More demanding applications call for Wind & React (W&R) technology with typical reaction temperatures of about 650 °C. Both W&R and React & Wind (R&W) technologies were demonstrated by several groups with the successful assembly and test of prototype pancake and solenoid coils generating magnetic fields of up to about 5 T [26-28].

MRI cryogen-free magnets have been the first commercial application of MgB$_2$ conductor. Operation at temperatures of 15 – 20 K offers the advantage of a lower operational cost and an enhanced stability compared to Nb-Ti, and a reduction of the system, i.e. superconductor, cost if compared to HTS materials. Already in 2006, only five years after the discovery of the superconducting properties of MgB$_2$, ASG Superconductors, Columbus Superconductors and Paramed designed and commissioned an open MRI system generating a central field of 0.5 T in a free patient gap of about 60 cm. The system, that today counts 28 units operational in hospitals and clinics worldwide, uses 18 km of MgB$_2$ multi-filamentary *ex situ* tape operated at 90 A and about 20 K [29].

A racetrack coil made from reacted MgB$_2$ tape has also designed and tested in the framework of the SR2S European space project [30]. The aim was to explore the potential of MgB$_2$ in an active magnetic shield to protect astronauts from cosmic radiation during long space missions. For this application, a lightweight multifilamentary tape, with Ti matrix and Al stabilizer, was developed and tested [31].

### 6.2. High current cables and systems based on the use of MgB$_2$

Transport of high current requires cabling of MgB$_2$ tape or wire. First demonstrations of MgB$_2$ cables were done in the field of DC superconducting power transmission. The higher critical temperature and potential low-cost of MgB$_2$ triggered proposals of smart superconducting grids combining delivery of liquid hydrogen and electricity. In this context, the industrially available *ex situ* tape produced by Columbus Superconductors was assembled at the JSC VNIIKP institute, in Russia, into initially 10 m and then and 30 m long prototype cables [32]. The cables, which consisted of MgB$_2$ tapes helically wound around a central former, were measured in cryogenic transfer lines where cooling was provided by forced flow of liquid hydrogen. They reached DC currents of up to ~ 3000 A at 20 K and successfully underwent 50 kV DC electrical insulation tests. This work first demonstrated the possibility of transporting an electrical power of up to ~ 150 MW via MgB$_2$ cables based on tape superconductor.

For transmission of 1 kA range DC currents, the concept of twisted-pair cables made from tape conductor has been proposed and developed [33]. Two stacks of MgB$_2$ tapes, each electrically insulated with wrapped polyimide tape, are twisted together to form the two polarities of an electrical circuit (see figure 3). Compact twisted-pair MgB$_2$ cables were successfully measured at currents of
newly excavated underground galleries, to the LHC main tunnel. A superconducting link consists of each about 100 m long, will be used to transfer the current from the power converters, located in and Nb-Ti magnets [34]. In total eight superconducting transfer lines, called superconducting links, semi-flexible cryostat containing up to about forty MgB

The superconducting links project has been approved for integration in the LHC machine in 2024, when all hardware associated with the HL-LHC project will be installed in the LHC underground areas. The total quantity of MgB

A cabling machine able to produce kilometer lengths of this cable geometry with controlled cabling parameters has also been developed and operated [34].

An important step in the field of high-current MgB

2 superconducting transmission systems was the successfully development and commissioning, at CERN, of a helium gas-cooled transfer line incorporating 2 × 20 m long cables, made for the first time from MgB

2 round wire, and operated at a record DC current of up 20 kA at 24 K [35] (see figure 3). This work, which was performed in the framework of the LHC High Luminosity (HL-LHC) upgrade [36], has been the first demonstrator of a novel MgB

2 wire-based electrical system that is being developed for feeding the LHC HL-LHC Nb

3 and Nb-Ti magnets [34]. In total eight superconducting transfer lines, called superconducting links, each about 100 m long, will be used to transfer the current from the power converters, located in newly excavated underground galleries, to the LHC main tunnel. A superconducting link consists of a semi-flexible cryostat containing up to about forty MgB

2 cables rated at currents ranging from 0.12 kA to 18 kA, for a total current capacity of about 150 kA at 20 K. The cooling is provided by forced flow of helium gas. At the time when the HL-LHC superconducting link project started, only MgB

2 tape was industrially available, and the choice was made to develop round wires, more suitable for cable assembly. Development of MgB

2 round wire, with electrical performance and mechanical properties enabling use in high-current cables, was launched in a collaboration between CERN and Columbus Superconductors. Passing from the existing industrial tape to a round wire took a significant time and effort, and required production and measurement of several prototype wires with different layouts and composition. Today a round wire for use in cables is available in long lengths. The ex situ wire has a diameter of 1 mm. It consists of 37 superconducting filaments, each with an equivalent diameter of about 60 µm, twisted with a pitch of 100 mm. The MgB

2 filaments, made from high purity boron powder, are surrounded by a Niobium barrier and embedded in a Nickel core. The Monel matrix, around the Nickel core, is copper plated, and the copper surface is tinned. Eighty kilometer of wire have been produced by Columbus Superconductors and delivered to CERN in unit lengths of greater than 500 m. Hundreds of measurements performed at CERN and at Columbus on short wire samples confirmed homogeneity and conformity of the electrical performance, which requires a minimum critical current at 25 K and 0.9 T of 186 A. In-depth work was done at CERN to qualify the mechanical behavior of wires and cables [23, 24, 25, 37] (the cables are made from reacted wires), as well as to develop low resistance joints [38], quantify quench behavior of cables and develop associated protection strategies [39, 40]. The superconducting links project has been approved for integration in the LHC machine in 2024, when all hardware associated with the HL-LHC project will be installed in the LHC underground areas. The total quantity of MgB

2 wire required for the series production of the superconducting links is about 1000 km.

Further to the CERN initiative, MgB

2 superconducting technology was also proposed by Prof. Carlo Rubbia, scientific director of the Institute for Advanced Sustainability Studies (IASS) in Potsdam, for an innovative transmission line for long-distance transport of green power [42]. This work has generated a European initiative, the FP7 BESTPATHS (acronym for “Beyond State-of-the-art Technologies For RePowering Ac corridors and Multi-Terminal HVDC Systems”) project, presently working on the design of a full-scale 320 kV MgB

2 monopole cable system designed to transfer a current of 10 kA at 20 K for a power of up to 3.2 GW [42, 43]. The cable under study has the same geometry (18 MgB

2 strands helically wound around a copper core, see figure 3) and uses the same wire layout as those developed for the CERN HL-LHC project. In addition, it incorporates all features required for future operation in the grid. The laboratory test of the system is planned by end 2018.

Among future applications that could benefit from the on-going developments, it is worth mentioning the potential use of MgB

2 for the future IGNITOR tokamak [44]. IGNITOR is based on copper coils operated at cryogenic temperatures of about 30 K via forced flow of helium gas. The challenging aspects of the IGNITOR project are the creation of: magnetic systems with a strong field of great volume with the use of cryo-resistive conductor, a unique multipurpose power complex, a system of physical and technological diagnostics of dense thermonuclear plasma, and a system of
Figure 3. MgB$_2$ cables. From left: a) prototype power transmission cable made from MgB$_2$ tape [32] (~ 3000 A DC at 20 K, $\varnothing_{\text{ext}}$ ~ 30 mm); b) twisted-pair cable made from MgB$_2$ tape[33] (~ 4000 A DC at 4.2 K, $\varnothing_{\text{ext}}$~5 mm); c) top: prototype cable (consisting of six sub-cables) made from round MgB$_2$ wire [34,35] (20000 A DC at 24 K, $\varnothing_{\text{ext}}$~20 mm); bottom: one of the six sub-cables each made from 18 MgB$_2$ wires, of 1 mm diameter, helically wound around a copper core; d) prototype cable made from 18 MgB$_2$ round wires, of 1.5 mm diameter, helically wound around a copper core (10000 DC at 20 K, $\varnothing_{\text{ext}}$~10 mm) [42, 43]. All quoted critical currents are in self-field conditions ($\leq$ 1 T).

intelligent control of processes in plasma. For the poloidal field coils, IGNITOR considers the use of MgB$_2$ conductor helium gas cooled at about 30 K [45]. This project could open the door to fusion technology for MgB$_2$.

7. Conclusions
Significant progress has been made in the direction of developing MgB$_2$ wire with enhanced electrical performance. R&D activity indicates promising superior performance of IDM and AIMI processed wires. Round ex situ PIT wire, with homogeneous and quality controlled properties, has been successfully developed and is being produced, in large quantity, for electrical transmission in accelerator technology (HL-LHC superconducting link project). Within the same project, significant effort is on-going for the development of high-current MgB$_2$ cables and of the associated electrical system. The potential of MgB$_2$ for future power transmission in the electrical network is also being studied within the framework of a European project (BESTPATHS) gathering together industry, laboratories, and the French transmission system operator (RTE). The first industrial application of MgB$_2$, i.e. MRI systems based on MgB$_2$ tape, boasts 28 units operational world-wide. Several demonstrators of R&W and W&R small coils have been made. R&D development is still needed to understand the strong discrepancy between critical fields of thin films and wires and potentials of MgB$_2$ as high field conductor, as well as to boost performance of MgB$_2$ at higher (~ 20 K) temperature. Successful developments in these directions could bridge the gap with Nb-Ti conductor.

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