# The DRYSMES4GRID Project: Development of a 500 kJ/200 kW Cryogen-Free Cooled SMES Demonstrator Based on $MgB_2$

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***Abstract*—A three-year research project, called DRYSMES 4GRID, was recently funded by the Italian Minister of Economic Development, Italy. The project, which involves five Italian partners (companies, universities, and research institutes), is aimed to demonstrate the feasibility of cost-competitive SMES based on magnesium diboride ($MgB_2$) with a cryogen-free cooling by means of the manufacturing and the testing of a demonstrator with an objective rating of 500 kJ/200 kW. This rating is deemed suitable for disclosing the critical technological aspects of all components in view of practical applications. A further goal of the project is the assessment of the technical and economic benefits that the SMES can bring to real-world electric grids. The general outline and technical objectives of the project are presented in this paper. Preliminary design assumptions and results concerning the $MgB_2$ coil and the power condition system are also discussed.**

***Index Terms*—Energy storage, SMES, $MgB_2$, cryogen-free cooling, power conditioning system.**

## I. Introduction

ENERGY storage is a key technology for modern electric power systems, especially in the perspective of smart grids and distributed renewable energy production. Its introduction in the grid contributes to cope with the inherent imbalance between load and generation, which is becoming very acute due to increasing penetration of green distributed generation (DG) in the energy mix. Furthermore, application of energy storage at the customer site can provide immunity with respect to voltage disturbance, uninterruptible power supply (UPS) service and power modulation. A classification of energy storage technologies can be made based on the power they can provide, the duration of the delivery and the number of deep charge/discharge cycle that they can withstand. No unique storage technology exists able to span the entire range of characteristics appropriate for various applications. The most suitable storage technology must be chosen from case to case [1]. Hybrid systems, obtained by combining different storage technologies, represent a convenient option in many situations.

Superconducting magnetic energy storage (SMES) offers complementary characteristics with respect to other storage methods: high charge and discharge power, fast response, extremely high number of cycles (lifetime), high round trip efficiency. Its exploitation in combination with other storage technologies (e.g., electrochemical batteries) enables the feasibility of cost effective hybrid storage systems (Energy Intensive + Power Intensive), able to meet all the needs both at the customer and at the grid level, so as to guarantee high power quality, in particular for networks with high penetration of distributed generation (existing or planned). SMES is also suitable for the leveling of impulsive loads and can supply electric customers in islanded operating conditions, thus compensating network disturbances such as long voltage dips and interruptions [2]–[4].

SMES is an established storage technology. Real scale SMES systems, with rated power up to 10 MW, have been developed in the past based on liquid-helium cooled low-temperature superconductors and have been successful submitted to live grid installation [6]–[9]. Nevertheless, significant improvements on SMES technology, able to increase both the technical and economical attractiveness, can still be obtained by means of new high temperature superconductors (YBCO coated conductors and $MgB_2$) compatible with cryogen free cooling [10]–[13].

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In this context, a three-year national research project, called DRYSMES4GRID, has been recently funded by the Italian Minister of Economic Development (MISE). The project, which involves five Italian partners (companies, universities and research institutes), is aimed to demonstrate the feasibility of SMES based on $MgB_2$ with no use of liquid cryogens. Due to the moderate cost of the $MgB_2$ superconductor and the simplification of the cooling system, cost advantages can be expected for this technology with respect to past solutions based on LTS materials and LHe cooling. The general outline and technical objective of the project are presented in Section II. Preliminary design assumptions and results concerning the power condition system and the $MgB_2$ coil and cooling system are given in Sections III and IV respectively.

## II. Project's Outline and Technical Objectives

The aim of the project is to demonstrate the feasibility of cost-competitive SMES based on $MgB_2$ with a cryogen free cooling system. All engineering aspects needed for the practical development of the SMES technology will be dealt with within the project, including manufacturability of $MgB_2$ cable and winding, stability and loss of the winding during the fast discharge, electrical insulation of the dry coil, temperature uniformity, minimization of cooling losses and converter losses, especially during standby. Furthermore, all aspects related to the development of power and control electronics needed for the appropriate operation of the SMES in the power network will also be dealt with. All activities will converge in the manufacturing and the testing of a demonstrator with an objective rating of 500 kJ/200 kW. The demonstrator will be able to compensate harmonic currents, reactive power, current unbalances and oscillating components of active power of disturbing loads, and will be able to supply sensitive loads in island mode. Though reduced, the rating chosen in the project is deemed suitable for disclosing the critical technological aspects of all components in view of practical applications. The demonstrator will be tested in the low voltage microgrid integrating different generators, storage systems and loads that is available at one of the partner's site (RSE, Milan, Italy). The tests will be performed to evaluate the opportunity offered by this device to support the grid in terms of compensation of disturbing loads and to supply sensitive loads, also in island operation condition. A further goal of the project is the assessment of the technical and economical benefits that the SMES can bring to real world electric grids. This task will be carried out by identifying relevant case studies and by the designing the full scale SMES system and estimating the costs based on the experience gained with the development of the demonstrator cost estimates.

The DRYSMES4GRID project is coordinated by Columbus Superconductors SpA, based in Genoa, Italy. Further partners are the University of Bologna, Italy, RSE SpA (Research on Energy System, Milan, Italy), ICAS S.C. r. l. (Italian Consortium for Applied Superconductivity, Rome, Italy) and CNR – SPIN (Institute for Superconductors, oxides and other innovative materials and devices, Genoa, Italy). The expertise of the partners (coming from industry, academy and research), is complementary and covers the range of skills (materials, magnet design, power electronics and grids) needed for the development of SMES technology. The main activity, the contribution of the partners and the time-line of the project are summarized in Fig. 1.

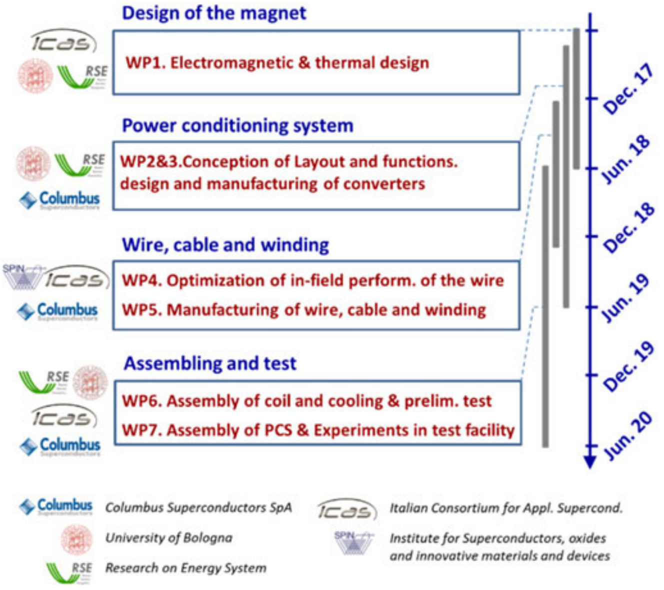

Fig. 1. Main activity and the time-line of the DRYSMES4GRID.

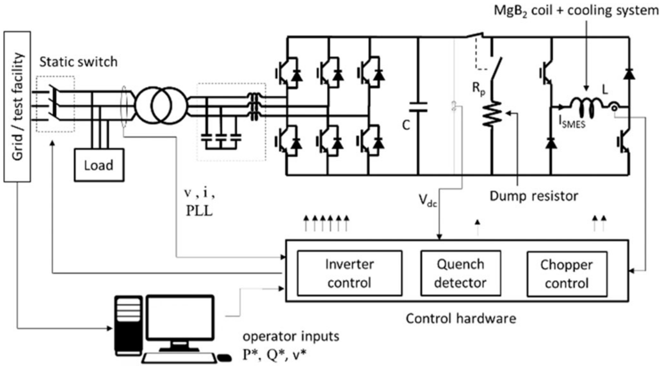

Fig. 2. Schematic of the power conditioning system and control.

TABLE I
Main Parameters of the Power Conditioning System

| | |
|---|---|
| AC voltage – grid side | 400 V rms |
| AC voltage – inverter side | 250 V rms |
| Voltage of the DC bus | 750 V |
| DC capacitance | 40 mF |

## III. Power Conditioning System and Test Facility

Power electronic converters are crucial for the full exploitation of the SMES potential for grid operators and customers [14]. The preliminary layout chosen for power conditioning system (PCS) is shown in Fig. 2. The main characteristics of the system are reported in Table I.

A controlled power is delivered/absorbed to the grid by means of the inverter. During the electric grid outage, the whole

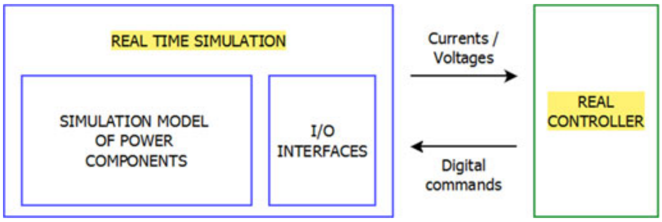

Fig. 3. CHIL principle scheme.

| Number of filaments | 6 + 1 Cu (3%) |
|---|---|
| Diameter | 1.52 mm |
| $MgB_2$ fraction | 29 % |
| Matrix material | Nickel (24 %) |
| External sheath | Monel (44 %) |
| External Copper coating | up to 50 µm |
| Critical Current @ 21 K - 2.0 T | 426 A |

Fig. 4. Picture and main characteristics of the $MgB_2$ round wire.

system is disconnected from the grid by a static switch (islanded operation) and the inverter is controlled so as to supply the loads with constant voltage (400 Vac rms–50 Hz). The magnetic energy stored in the SMES is released by the two-quadrant chopper, thus keeping constant the dc-link inverter voltage (750 Vdc). In this operating mode the system acts as an UPS. During regular healthy electric grid operation, the inverter acts as a power active filter, providing for load reactive power (power factor correction), balancing load currents and/or attenuating low-order current harmonics, smoothing (with respect to the grid) pulses of load power demands, and avoiding flickers. In this operating mode, the dc-link voltage is regulated by the inverter itself (750 Vdc), while chopper regulates the charge/discharge of the SMES according to the desired timing, and according to the power demand of load and the possible power limitations of the grid.

As a result, a controlled bidirectional power is transferred from the SMES to the grid by means of the two converters. The magnet's protection system is also integrated into the power conditioning system. A dump resistor for the discharge of the coil in case of quench is connected to the dc bus via a controlled switch for this purpose.

IGBT (Insulated Gate Bipolar Transistors) switches are considered in this preliminary stage for the design of the converters. The possibility to use Silicon Carbide (SiC) or power Mosfet technology will also be considered in the very next future in order to minimize the loss that occurs in the SMES during the idling phase due to the circulation of the current in the chopper.

An integral and relevant part of the power conditioning system is the control. The detailed definition of the control algorithms (logic, schemes, parameters) to be used during the shunt and the islanding operation and for the shift from one to the other is in progress. Selection of the suitable hardware for the implementation of the algorithms is also in progress. The quench detector is integrated into the control hardware and the logic for the management of the discharge is included in the overall control algorithm. Both the power and the control electronics will be tested in the laboratory. To evaluate the real behaviors and the performances of power electronic devices, in terms of control and automation, advanced modeling and simulation techniques, in particular, Hardware In the Loop (HIL) real-time simulations schematically described in Fig. 3, will be implemented. The use of a real time digital simulator interfaced to real hardware systems allows overcoming the physical limitation of a laboratory. In the project the control logics will be tested through Control Hardware in The loop (CHIL) simulations, thanks to a real time simulator OPAL-RT available in RSE.

Finally, the SMES demonstrator (PCS + $MgB_2$ coil and cooling system) will be assemble and tested in the test facility available at the RSE laboratory in Milan. This test facility consists of a low voltage microgrid that interconnects different generators, storage systems and loads and is currently used for testing distributed energy resources and smart grid solutions [17]. The Facility extends over an area of about 20000 $m^2$ and is interconnected to the medium voltage grid by means of a 800 kVA dedicated transformer (23 kV/400 V).

## IV. $MgB_2$ COIL

A procedure for the electromagnetic design of the $MgB_2$ coil has been established. The purpose is to select the conductor, to define the possible layout of the assembled cable and to arrive at the main characteristics of the coil fulfilling the specifics in terms of deliverable power and energy. Based on the results of this preliminary design phase, the detailed design of the cooling system and the mechanical structure will be carried out in the next future. The electromagnetic design procedure takes into account both the functional and the protection requirements of the coil. A round $MgB_2$ wire already deliverable by Columbus Superconductors SpA has been considered for the design of the coil. Possibility to use tape instead of the wire for the final design of the coil presently under discussion. This would greatly simplify the winding process (though with some additional difficulties due to the fact that more tapes are to be used in parallel in order to reach the required operating current of the coil). A picture of the wire is reported in Fig. 4 along with its main characteristics. A copper coating up to 40 $\mu$m can be applied to wire in order to improve protection during the quench. A solenoid layout is considered. In order to carry out a conservative design of the coil electromagnetic performance at 21 K are considered. This means that the designed coil is able to meet the specifics as far the operating temperature is lower or equal to 21 K. A maximum field $B_{\max}$ of 2.0 T on the conductor (at the maximum state of charge of the SMES) and an aspect ratio (length/diameter) of 2 are chosen as input parameters for the design for the solenoid. The inner diameter and the height of the coil are obtained accordingly as indicated in [16]. The thickness of the coil is obtained by intersecting the load line of the solenoid with the $J_c - B$ characteristic of the wire scaled by the assumed $J/J_c$ margin of 0.6. The main characteristics of the designed coil are reported in Table II. The geometrical layout is shown in Fig. 5 along with the field map at the maximum state of charge. The total energy stored is 569 kJ. Once the geometrical layout of the coil is arrived at, a further choice is needed between the number of turns and the current of the conductor. By choosing a cable made of three wires in parallel a total number of 2720 turns, arranged in 8 layers of 340 turns each, are

TABLE II
DESIGN PARAMETERS

| | |
|---|---|
| Operating temperature | ≤21 K |
| Inner radius | 300 mm |
| Thickness | 24.9 mm |
| Height | 1198.5 mm |
| Current of the coil at maximum state of charge | 768 A |
| Max field at the maximum state of charge | 2.0 T |
| Current of the coil at end of the discharge | 267 A |
| Number of turns | 2720 |
| Num. of wires in parallel | 3 |
| Inductance | 1.93 H |
| Total length of cable | 5340 m |
| Max voltage on the coil | 1200 V |
| Dump resistance | 1.56 Ω |
| Max hot spot temperature | 194.5 K |

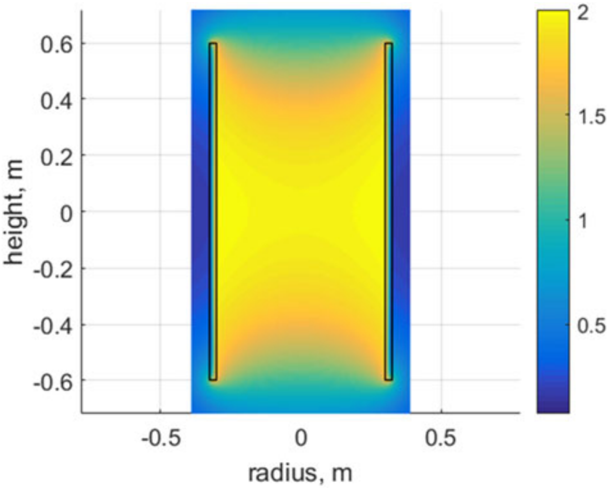

Fig. 5. Layout of the coil and field map (T) at the maximum state of charge of the SMES.

needed for filling the cross section of the coil (a filling factor of 0.646 is considered for the cable, and a filling factor of 0.907 is assumed for the winding made of hexagonal pattern of cables). The maximum current of the SMES, corresponding to the maximum state of charge, is 768 A. The current of one single wire is 256 A, which, in accordance with the design requirement, is 60% of the critical current of the wire at the corresponding field of 2.0 T and temperature of 21 K. The inductance of the coil is 1.93 H. The residual energy of the coil after a discharge at 200 kW for 3 s is 69 kJ (12% of the total), corresponding to a current of 267 A. The time evolution of the SMES current during one discharge/charge cycle at 200 kW is shown in Fig. 6. We stress that, with the chosen value of voltage of 750 V for the DC bus (see Section III), the SMES is in fact able to deliver the required power of 200 kW over the entire range of current shown in Fig. 6.

In order to evaluate the protection of the SMES we have considered a quench occurring when the coil is carrying the maximum current of 768 A. As the insulation level of the coil is 1.2 kV a dump resistor of 1.56 Ω is assumed for the emergency discharge of the coil in case of quench. The time constant of the discharge circuit is 1.24 s. The time evolution of the hot spot temperature during the discharge is shown in Fig. 7. This is calculated by means of a conservative model based on the energy balance in adiabatic condition (no diffusion is considered in the longitudinal and transverse direction). The temperature dependence of the materials parameters (resistivity of copper, specific heat of Copper, Nickel, Monel and electrical insulation) is taken into account. It can be seen from the figure that designed coil is self protected since a final temperature of 194.5 K is reached in the coil at the end of the discharge.

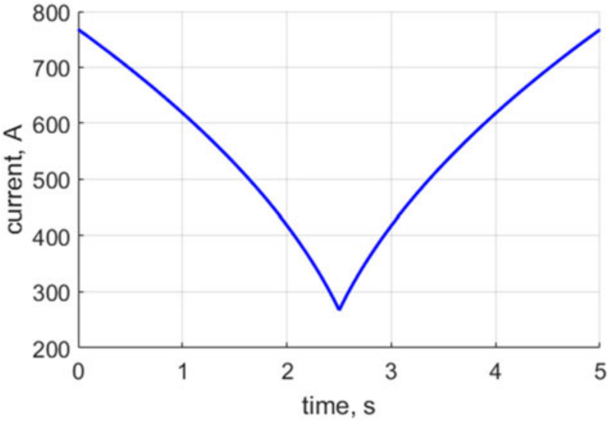

Fig. 6. Current of the SMES coil during one discharge/charge cycle (100 kW–3 s).

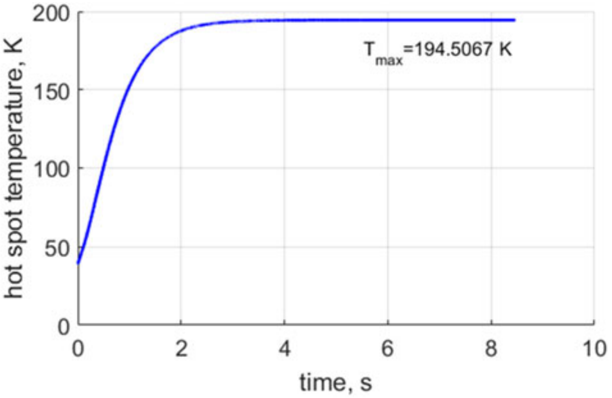

Fig. 7. Hot spot temperature during the discharge of the coil.

Further steps needed for the defining the final layout of the SMES coil are the design of the mechanical structure and the cooling system. For this purpose, numerical modelling for calculating the AC loss of the wire in assigned transport current and magnetic field and for estimating the additional heat load due to induced current on the metallic parts (cryostat walls and copper connection to the cryocooler(s)) is in progress. We report that the preliminary coil designed fulfills both the functional and the protection requirements and hence represents already a viable solution for the implementation of the prototype. Feasibility of the cable made of more wires with appropriate twisting and no degradation of the critical current was confirmed by previous works carried out on similar conductors [17]. For this purpose, the manufacturing and the test of short samples of cable will be carried out in the next future. We also report that possible optimization of the layout of the coil in terms of stored energy and/or size, length of conductor, architecture of the cable and

AC loss can be obtained after the development of a specific wire with improved $J_c - B$ performance and increased number of filaments which is one of the objective of the project (see Section II). Optimization of the granulometry of the boron powders, which is the key for improving the in-field current density and filamentarization of $MgB_2$ wires, has already started at CNR-SPIN [18].

## V. CONCLUSION

A three-year national research project (DRYSMES4GRID), funded by the Italian Minister of Economic Development, has been recently started. The aim of the project is the manufacturing and the testing of 500 kJ/200 kW SMES demonstrator with cryogen free cooling based on $MgB_2$. A procedure for the electromagnetic and thermal design has been established and the preliminary design of the coil has been completed based on $MgB_2$ wires already available. Numerical modelling for calculating the total heat load of the SMES and for designing the cooling system is started. Improvement of the $J_c - B$ performance of the wire for possible optimization of the coil is also started. Preliminary layout for power conditioning system has been completed. Definition of the control algorithms and hardware is started.

## REFERENCES

[1] M. Farhadi and O. Mohammed, “Energy storage systems for high power applications,” in *2015 IEEE Ind. Appl. Soc. Annu. Meet.*, Addison, TX, 2015, pp. 1–7, doi: 10.1109/IAS.2015.7356787.

[2] C. A. Luongo, “Superconducting storage systems: An overview,” *IEEE Trans. Magn.*, vol. 32, no. 4, pp. 2214–2223, Jul. 1996.

[3] A. Morandi, “Energy storage (SMES and flywheels),” in *Applied Superconductivity: Handbook on Devices and Applications*, P. Seidel, Ed. New York, NY, USA: Wiley, 2015, pp. 660–674.

[4] L. Ren *et al.*, “Development of a movable HTS SMES system,” *IEEE Trans. Appl. Supercond.*, vol. 25, no. 4, Aug. 2015, Art. no. 5701109.

[5] N. Amaro, J. M. Pina, J. Martins, and J. M. Ceballos, “Integration of SMES devices in power systems—Opportunities and challenges,” in *Proc. 2015 9th Int. Conf. Compat. Power Electron.*, Costa da Caparica, Portugal, 2015, pp. 482–487.

[6] H. J. Boenig and J. F. Hauer, “Commissioning tests of the Bonneville power administration 30 MJ superconducting magnetic energy storage unit,” *IEEE Trans. Power App. Syst.*, vol. PAS-104, no. 2, pp. 302–312, Feb. 1985.

[7] S. Nagaya *et al.*, “The state of the art of the development of SMES for bridging instantaneous voltage dips in Japan,” *Cryogenics*, vol. 52, no. 12, pp. 708–712, 2012.

[8] A. Morandi *et al.*, “Design, manufacturing and preliminary tests of a conduction cooled 200 kJ Nb-Ti micro-SMES,” *IEEE Trans. Appl. Supercond.*, vol. 18, no. 2, pp. 697–700, Jul. 2008. [Online]. Available: http://dx.doi.org/ 10.1109/TASC.2008.921285.

[9] L. Ottonello *et al.*, “The largest Italian SMES,” *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 602–607, Jun. 2006. [Online]. Available: http://dx.doi.org/ 10.1109/TASC.2005.869677.

[10] M. Song *et al.*, “100 kJ/50 kW HTS SMES for micro-grid,” *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Jun. 2015, Art. no. 5700506.

[11] Y. Xu *et al.*, “Numerical simulation and experimental validation of a cooling process in a 150-kJ SMES magnet,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 6, Sep. 2016, Art. no. 5700507.

[12] P. M. Leys, M. Klaeser, C. Ruf, and T. Schneider, “Characterization of commercial MgB2 conductors for magnet application in SMES,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, Apr. 2016, Art. no. 6200605.

[13] A. Morandi, A. Fiorillo, S. Pullano, and P. L. Ribani, “Development of a small cryogen-free MgB2 test coil for SMES application,” *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. no. 5700404.

[14] D. Casadei, G. Grandi, U. Reggiani, and G. Serra, “Analysis of a power conditioning system for superconducting magnetic energy storage (SMES),” in *Proc. 1998 Int. Symp. IEEE Ind. Electron.*, 1998, vol. 2, pp. 546–551.

[15] V. Prandoni, C. Sandroni, M. Verga, and A. Pegoiani, “Smart grid Lambrate project: Microgrid active management and control from a primary subsation,” in *Proc. Eur. Conf. Renew. Energy World*, Milan, Italy, 2016.

[16] A. Morandi, B. Gholizad, and M. Fabbri, “Design and performance of a 1 MW—5 s, high temperature superconductor magnetic energy storage system,” *Supercond. Sci. Technol.*, vol. 29, no. 1, 2016, Art. no. 015014.

[17] K. Konstantopoulou *et al.*, “Electro-mechanical characterization of MgB2 wires for the superconducting link project at CERN,” *Supercond. Sci. Technol.*, vol. 29, no. 1, 2016, Art. no. 084005.

[18] M. Vignolo, G. Bovone, D. Matera, D. Nardelli, C. Bernini, and A. S. Siri, “Nano-sized boron synthesis process towards the large scale production,” *Chem. Eng. J.*, vol. 256, pp. 32–38, 2014.