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SuperRail – World-first HTS cable to be installed on a railway network in France

Arnaud Allais, Jean-Maxime Saugrain, Beate West, Nicolas Lallouet, Hervé Caron, David Ferandelle, Louise Terrien, Grégory Bouvier, Ghazi Hajiri, Kévin Berger and Loïc Quéval

Abstract— The SuperRail project consists in the development, manufacturing, installation and long-term operation of a high temperature superconducting (HTS) DC cable system for railway applications. The objectives of the project are to reinforce the power supply of the Montparnasse railway station in Paris, to increase the traffic and to participate to the reduction of CO₂ emission. The saturated underground in the center of Paris does not allow to create new right of ways and only the HTS cable technology allows to carry the required power to railway tracks using the few available 100 mm conduits left. The HTS cable system must answer to a load chart with a high level of requirements corresponding to the connection of a substation to a set of railways tracks in very constraints areas. In the case of SuperRail, two 60-meter long 1.5 kV-3.5 kA HTS DC cables made of second-generation (2G) conductors will be installed in parallel. They need to sustain a 67 kA-200 ms short-circuit current. The cryogenic system is specifically designed for this project. It is based on a Reverse Turbo-Brayton cycle producing cooling power of about 1700 W at 67 K. This system intends to ensure low maintenance during life cycle, high reliability and would be scalable for future application (not limited to railways). In parallel, prospective studies are being carried out to simulate superconducting cables in railway networks, and to find original solutions to replace the current leads. SuperRail is a landmark project, as it is the first time that a DC HTS cable system is installed on a commercially operated railway network. The technologies developed have the potential to be reproduced in similar cases existing in large cities.

Index Terms—Cooling system, railway network, superconducting cables, Turbo Brayton technology.

I. INTRODUCTION

THE French rail network supplied with direct current at a voltage of 1500 V is 5904 km long. This represents around a quarter of the national rail electrification [1]. A major disadvantage of this low-voltage configuration is the voltage drops along the lines, which necessitate the installation of substations close together. The French railway network is also subject to a number of constraints, notably linked to the 60% increase in traffic between 1998 and 2008, which is set to

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multiply by a factor of 4 by 2030. In addition, it is becoming increasingly difficult to install substations in densely populated urban areas. Superconducting power cables make it possible to avoid major construction work, particularly on civil engineering structures, while improving the quality of the power supply and reducing energy losses. This is the choice made by SNCF as part of the SuperRail project, launched in February 2022, which involves the development, manufacture, installation and long-term operation of two 60-meter long 1.5 kV-3.5 kA high-temperature superconducting (HTS) DC cables to reinforce the power supply to the Montparnasse station in Paris, France.

This project follows on from several superconducting cable projects and demonstrators around the world. Since 2000, we have pinpointed no less than 35 superconducting cable projects: 26 for AC [2]–[27] and 9 for DC [28]–[36].

II. MONTPARNASSE-VOUILLÉ DEMONSTRATOR

A. Motivation

The Montparnasse railway station in Paris, shown in Fig. 1, offers 28 tracks and a daily throughput of 200,000 passengers on 750 trains. But recent electrical failures [37], [38] underscore the urgent need for reinforced electrical infrastructure. In this context, SNCF needs to bring additional power from the Ouest-Ceinture Vouillé traction substation to a railway tracks platform 60 meters away at Montparnasse station (Fig. 2). The requirement is for 4.5 MW of nominal power (3000 A), and 10.5 MW of inrush power (7000 A) during the train's acceleration phases.

The existing connection between the substation and the tracks relies on 400 mm² copper cables, installed in a cable duct bank integrated into an aging bridge. However, with only two unoccupied conduits remaining (Fig. 3), there is insufficient capacity to accommodate the six copper cables required to carry the nominal 3000 A at 1500 V. Reinforcing with copper cable would have required the installation of a new cable duct bank, which would have necessitated substantial civil engineering work, estimated at over 10 million euros.

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Fig. 1. Montparnasse railway station in Paris, 28 tracks and a daily throughput of 200,000 passengers on 750 trains.

The SuperRail project aims to perform the electrical reinforcement using two HTS cables laid in the two existing conduits, thus avoiding major civil engineering work. This could have been done with only one HTS cable but, for operational reasons, it has been decided to install two 1500 A DC HTS cables. This is an excellent example of how the high energy density of HTS cables can be leveraged to reinforce the electric grid in dense urban areas.

B. Cable and termination layout

A 3D digital twin of the installation site was created using LiDAR (Light Detection And Ranging) analysis. It enables the virtual integration of the HTS cable system into its future environment. This is useful to estimate the length of the HTS cable to be manufactured, confirm the design of the various components, and anticipate problems.

Fig. 4 shows the planned cable path. Each of the two 60-meter HTS cables will be pulled inside one empty 100 mm diameter conduit. Cable pulling requires adapting to the geometry of the existing conduits, installed several decades ago, and to the presence of the copper cables. One of the first tasks carried out was to check that the HTS cables could be

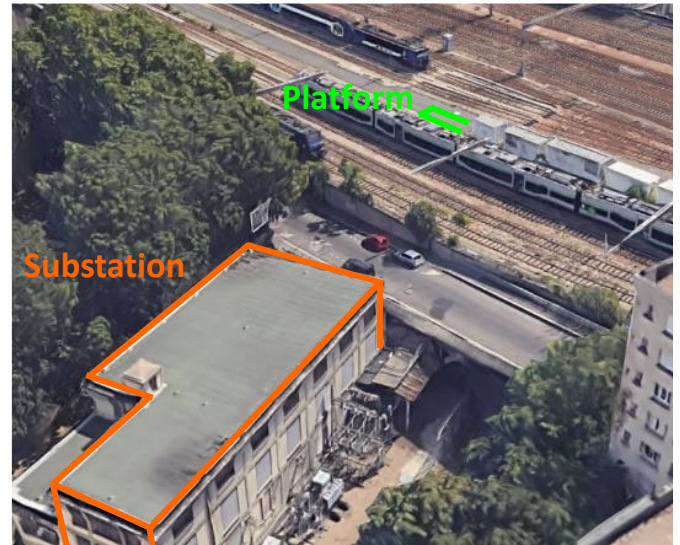


Fig. 2. The Vouillé traction substation (in orange) in the heart of Paris and the railway tracks platform (in green) that will house the HTS cable terminations at Montparnasse station.



Fig. 3. Existing cable duct bank between the substation and the platform. Each conduit is filled with one 400 mm² copper cable (500 A each).

correctly pulled into the conduits, taking advantage of two newly built manholes. The investigations identified strong

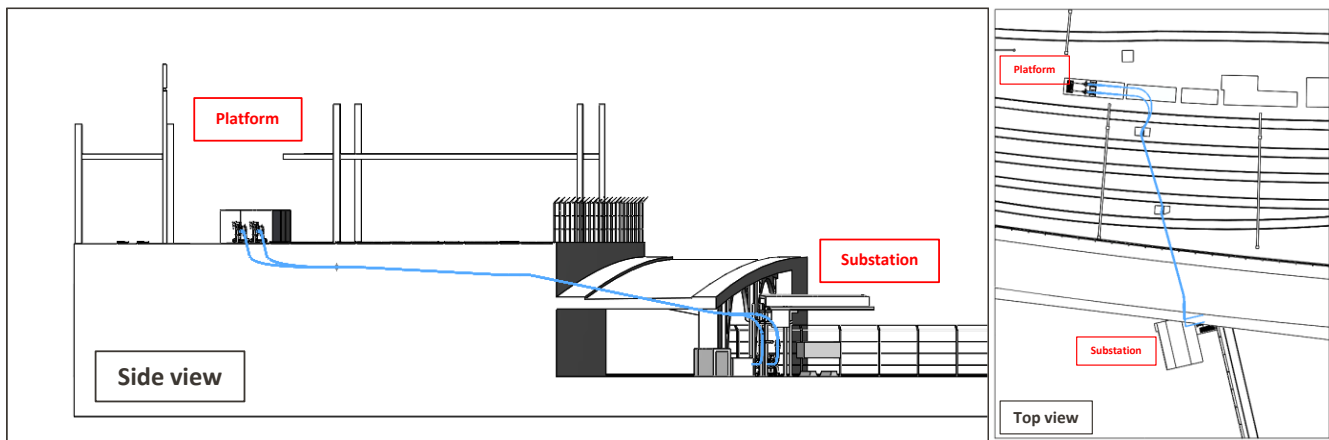


Fig. 4. Cable path in Montparnasse-Vouillé. The rectangles on the cable path are the two newly built manholes.



Fig. 5. Pulling of a dummy cable in Montparnasse-Vouillé.

gradients and two critical areas with bending radii of 1.7 m and 2.1 m. The pulling of a dummy cable was then carried out on-site to ensure that the pulling of the real cable would be successful (Fig. 5). It gives an insight into the installation of an HTS cable on a railway network.

Two terminations will be installed in the substation and two on a platform as shown in Fig. 6. Each termination has two current leads: one for the conductor layer and one for the screen layer. The conductor is connected to the positive pole of the AC/DC converter on the substation side and to the feeder on the platform side. The screen is connected to the neutral pole of the AC/DC converter on the substation side only. The screens of both cables are connected to each other on the platform side.

III. SUPERRAIL PROJECT INNOVATIONS

The HTS cable system is subjected to several operating constraints which have influenced its design. Table I summarizes all the figures provided in this section.

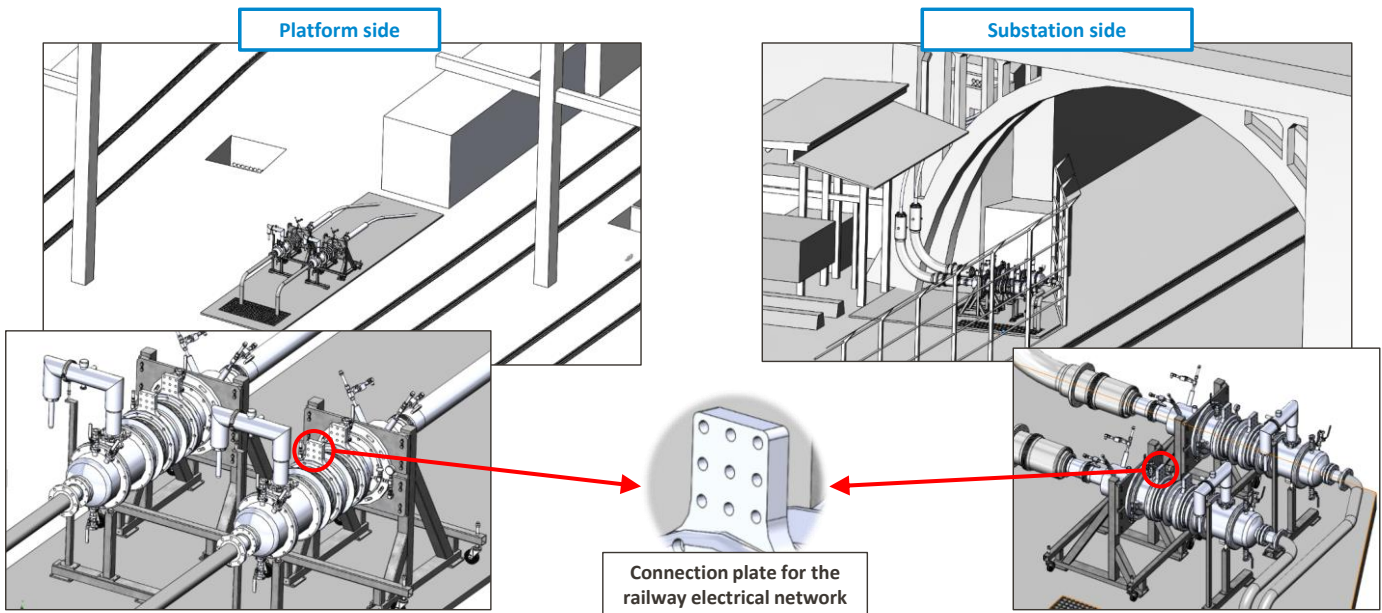


Fig. 6. Termination integration on the platform and substation sides in Montparnasse-Vouillé.

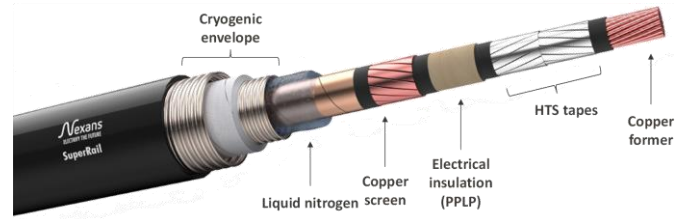


Fig. 7. Overview of SuperRail HTS DC cable in Montparnasse.

A. HTS cables

Each cable must carry a nominal current of 1500 A (maximum 3% harmonics below 5 kHz) and sustain repetitive inrush currents of up to 3500 A during train acceleration. Even more demanding, each cable must withstand a short-circuit current of 67 kA for 200 ms, corresponding to a fault power of 100 MW.

Fig. 7 illustrates the cable that has been developed by Nexans. The cable core is made of several layers. The copper former has a diameter of approximately 18 mm. This figure is relatively high to withstand the fault current. The HTS conductor consists of 25 4.4 mm wide second-generation (2G) HTS tapes arranged in two layers. It has a minimum critical current of 4000 A to withstand inrush currents of 3500 A for a few seconds. Two different manufacturers of HTS tapes have been selected: SuNAM [39] and AMSC [40]. The electric insulation is a 1-mm thick Polypropylene Laminated Paper (PPLP) that is impregnated by liquid nitrogen which contributes to the dielectric strength. The cable insulation is designed for 3000 V, but it will operate at 1500 V for the SuperRail installation. The 1.8-mm thick copper screen is made up of several copper tapes.

The cable core is inserted into a linear cryostat. This is a vacuum-insulated flexible cryostat made of corrugated stainless-steel tube that provides the thermal insulation to maintain the cable core around 70 K while minimizing thermal

TABLE I
SUPERRAIL CABLE SYSTEM IN SUMMARY

Component	Parameters	Value
<i>Electrical parameters</i>		
	Number of cables	2
	Nominal voltage	1500 V
	Inrush current	3500 A
	Nominal current	1500 A
	Critical current	4000 A
	Fault current	67 kA - 200 ms
<i>Tape parameters</i>		
HTS Cable	Tape manufacturers	SuNAM & AMSC
	Tape width	4.4 mm
<i>Geometric parameters</i>		
	Copper core diameter	18 mm
	Number of tapes	12 + 13
	PPLP thickness	1 mm
	Copper screen thickness	1.8 mm
	Cryostat outer diameter	74 mm
	Length	60 m
	Minimum bending radius	1.5 m
<i>Cooling system parameters</i>		
Reverse Turbo-Brayton	Overall cooling capacity	1700 W @ 67 K
	Available power for the cables	1200 W @ 67 K
Cooling system	Cable inlet temperature	> 64 K
	Cable outlet temperature	< 74 K
	Inlet pressure	< 14 bar
	Outlet pressure	> 7.5 bar

losses. The outer diameter of the cryostat is 74 mm, and the cable has a minimum bending radius of 1.5 m, in line with the site constraints.

As part of the SuperRail project, an HTS cable production line has been assembled at the Nexans' Bourg-en-Bresse factory in France.

B. Terminations

In a project such as SuperRail, where the cable length is short, the design of the terminations plays an important role, as it is the element that contributes most to the losses that must be extracted by the cooling system. In this project, terminations account for around 70% of the system total losses at nominal current. The terminations developed by Nexans for this project were adapted from earlier designs made for the REG project in Chicago [41]. These are specialized components that still need to be standardized, so that they can be supplied and installed easily and reliably.

C. Cooling system

Absolut System designed the cooling system, working with all the partners to define the system requirements:

- Cooling capacity of 1700 W at 67 K for the cables and terminations (1200 W) and other cryogenic losses (500 W);
- Closed loop cooling system;
- Low maintenance.

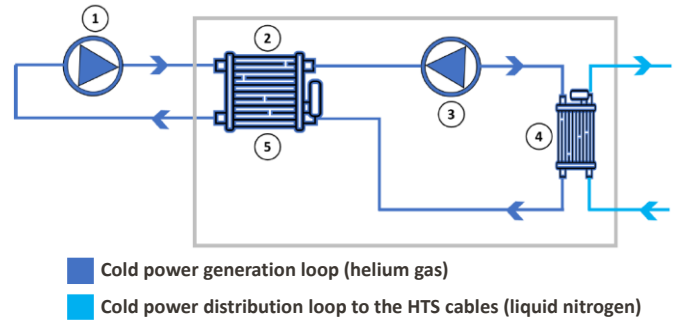


Fig. 8. RTB cooling machine operating principle.

These requirements rule out Pulse Tube and Gifford-McMahon technologies. A Stirling machine was initially envisaged, but it has three major drawbacks: no cold power regulation to adapt to load variations, high maintenance needs due to the piston, and need to import key elements. Internal R&D was unable to find solutions to these problems. The decision was therefore taken to develop a Reverse Turbo-Brayton (RTB) machine, the main sub-assemblies of which are manufactured in France.

The 5 stages of the RTB closed cycle are shown in Fig. 8:

- ① Compression of helium gas with centrifugal compressors operating at ambient temperature: increasing the pressure and temperature of the gas;
- ② Pre-cooling in the first branch of the recuperative heat exchanger;
- ③ Expansion in the centripetal turbine: pressure and temperature are reduced to the target cryogenic temperature;
- ④ Extraction of cold power from the helium gas in the cold generation cycle and recovery by the liquid nitrogen in the cables loop in the application exchanger;
- ⑤ Heating of the fluid in the recuperative heat exchanger.

The RTB uses high-speed turbomachines and high-efficiency recuperative heat exchangers. Hydrodynamic gas bearings are used for the turbomachine rotor, which operate at speeds ranging from 30,000 rpm for the largest to over 300,000 rpm for the smallest. These non-contact bearings guarantee reduced maintenance and high reliability. This technology is scalable for future applications (not limited to railways) and is notably proposed for future European observation satellites. The consumption of an RTB machine is typically 10 kW of electrical power for 1 kW of cold thermal power at 80 K. Moreover, the cooling capacity can be controlled from 30% to 100% of the maximum power. The overall architecture of the cooling system connected to the HTS cables is shown in Fig. 9. Note that the cooling system is one-sided: the LN₂ will flow in one cable and return in the other one. It consists of:

- A LN₂ tank used for the initial cooling of the cable and refills after maintenance;
- A skid that integrates the circulation and pressurization of LN₂ and overall cooling management. A LN₂ pump in a vacuum cryostat to circulate liquid nitrogen in the cables loop;

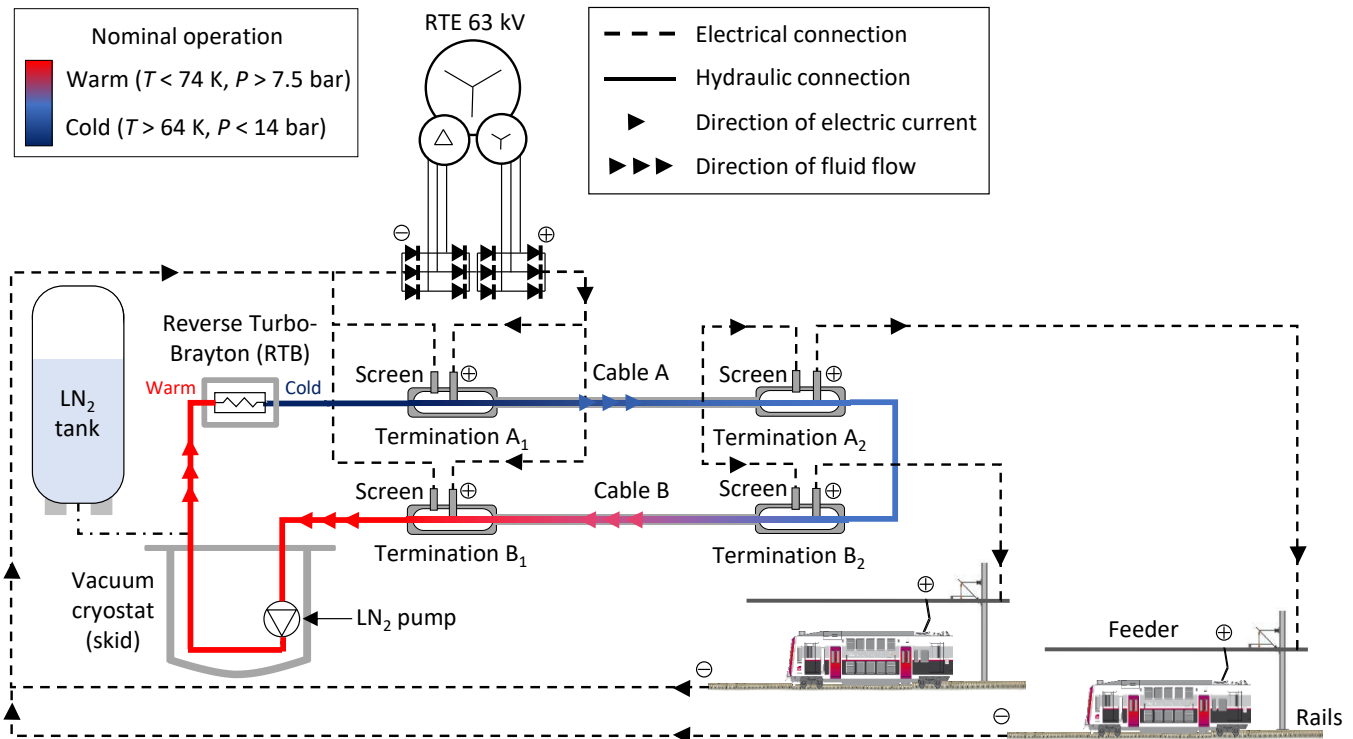


Fig. 9. Architecture of the cooling system connected to the HTS cables, in nominal operation.

- A Reverse Turbo-Brayton (RTB) machine to remove the heat from the cryogenic circuit;
- A set of valves, sensors and a programmable logic controller to control the system.

The skid has been assembled and is being tested. It is pictured in Fig. 10. A 3D CAD drawing of the RTB machine is presented in Fig. 11. It is now being manufactured by Absolut System. This cooling system will be installed right next to the Vouillé substation. Thanks to the closed loop operation, there will be almost no LN₂ consumption, except for filling or maintenance operations. This limits the number of times the LN₂ tank has to be refilled each year, greatly simplifying operation.

IV. TYPE TEST LOOP

Cable and termination designs are complete. A 35-meter cable type test loop shown in Fig. 12 is being installed at the SNCF Railway Test Agency (SNCF-AEF), starting in summer 2023. The test loop includes two terminations, one joint, and the cooling system. Although it is not needed for the installation in the Vouillé substation, a joint has been designed for future projects and will be tested. These tests will qualify cables, terminations and joints for SuperRail and similar projects, whatever the length. The results of these tests will be the subject of a specific report.

V. ANTICIPATION OF FUTURE PROJECTS

In addition to being a technology demonstrator, SuperRail aims to assess the competitiveness of using a superconducting cable versus a resistive cable solution for future railway installations. This is essential to gauge the market potential and economic prospects of superconducting cable systems. In this

regard, the GREEN laboratory at the University of Lorraine is actively developing computational tools to simulate superconducting cables in railway networks. The models take into account electromagnetism, heat transfers, hydraulics and circuit equations, including the structure of the electrical network [42]–[44]. These models will be validated using data from the SNCF-AEF type test loop and the Montparnasse-



Fig. 10. Cryogenic skid, being tested.

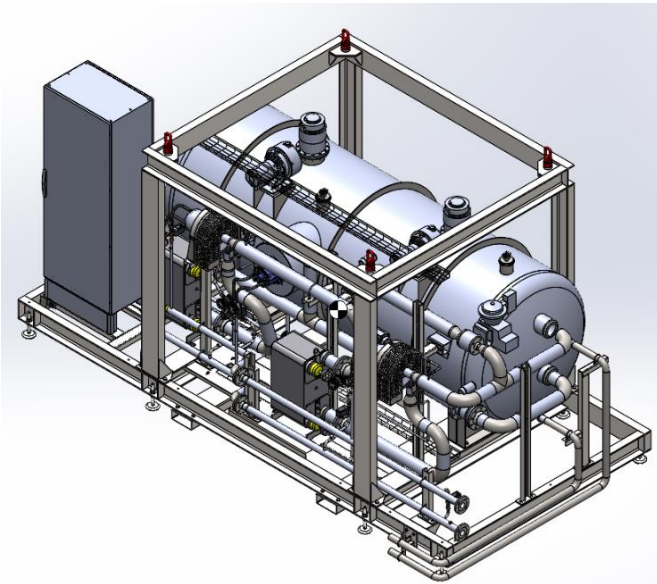


Fig. 11. 3D CAD drawing of the RTB machine, being assembled.

Vouillé demonstrator. In parallel, the GeePs laboratory at University Paris-Saclay is carrying out feasibility studies to integrate a superconducting transformer and a cryogenic power electronic converter into the cable system, as shown in Fig. 13 [45], [46]. This architecture would eliminate the need for two terminations while taking advantage of cryogenic temperatures to improve the converter's efficiency and power density. These efforts collectively contribute to estimating potential and forecasting future projects, thus playing an essential role in the advancement of the technology.

VI. CONCLUSION

The SuperRail project responds to the need to improve railway power supply in urban environments, such as the Montparnasse station in Paris. Through the use of a high-temperature superconducting DC cable system, it introduces an innovative approach to reinforcing electrical infrastructure, avoiding the need for extensive civil engineering works. SuperRail is the world-first HTS cable to be installed on a railway network, and the first HTS cable commercial installation in France.

This article described the technology adopted for the demonstrator and the first steps towards the installation. In parallel with the demonstrator, SuperRail aims to evaluate the technology for other installations and anticipate the future.

The cable will be installed and commissioned in 2024. It will then be operated by SNCF for its entire lifetime. Feedback will be provided on the commissioning and operation of this HTS cable system.

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Fig. 12. Cable type test loop installed at the SNCF Railway Test Agency (SNCF-AEF), including two terminations and a joint.

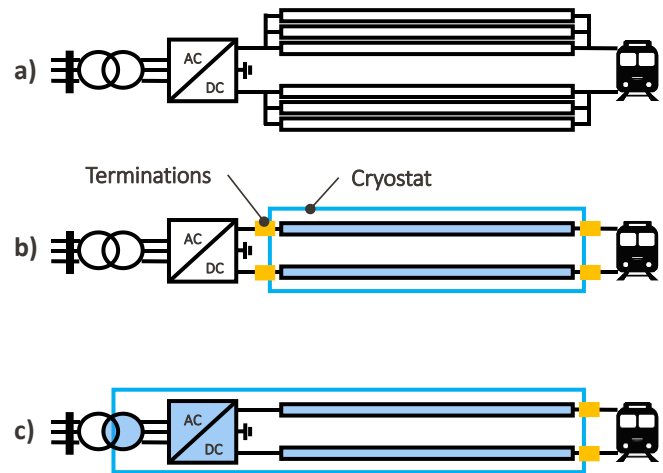


Fig. 13. a) Conventional solution, b) Montparnasse-Vouillé demonstrator (TRL 6-7), c) Lab prototype (TRL 4) with a superconducting transformer and a power electronic converter operating at cryogenic temperature.

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