PRISMAC: A R&D Program and a New Dedicated Laboratory for Very High Field Superconducting Magnets

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***Abstract*—For the development at CERN (European Center for Nuclear Research) of the post-LHC accelerator infrastructures, HL-LHC (High Luminosity Large Hadron Collider) and FCC (Future Circular Collider), a new generation of energy-efficient magnets with extreme mechanical constraints, capable of generating high-quality magnetic fields up to 14 T (operational) will be required. These magnets will be based on technological knowledge currently under development and new superconducting materials. To foster the Spanish efforts to contribute to these strategic goals, CIEMAT (Research Center for Energy, Environment and Technology), CDTI (Center for Technological Development and Innovation), and CERN signed three collaboration agreements in 2019 within the framework of PRISMAC (Very High Field Superconducting Magnets Program). This paper depicts the progress of the PRISMAC program activities and the tasks foreseen to achieve its goals. PRISMAC is based on three work packages: i) the delivery of the nested orbit correctors MCBXF for the HL-LHC, ii) the construction of a dedicated laboratory at CIEMAT for prototyping and testing high-field magnets, and iii) the development and assembly of Nb_3Sn demonstrator magnets for the FCC study. There is an extension of the program for the design and development of High-Temperature Superconducting (HTS) magnets for future needs. The PRISMAC program is outlined, focusing on the commissioning of the new laboratory.**

***Index Terms*—Accelerator magnets, high field magnets, superconducting laboratory, superconducting magnets.**

I. Introduction

The next accelerator infrastructures foreseen at CERN are the upgrade of the Large Hadron Collider, called HiLumi or HL-LHC [1], and the FCC [2]. CERN studies for these post-LHC stage infrastructures concluded that a new generation of high-quality and high-field magnets, up to 14 T operational field, will be required. To develop these magnets, it is essential to have a strong understanding of the design, prototyping, testing and the industrial development of high-field superconductor technology. In general, a solid knowledge in magnetic engineering, manufacturing and testing is necessary.

For this purpose, three agreements within the framework of the PRISMAC program [3] were signed by CERN, CDTI, and CIEMAT, in coordination with the Spanish Ministry of Science, Innovation and Universities. PRISMAC stands for “PRograma de Imanes Superconductores de Muy Alto Campo” (Very High Field Superconducting Magnets Program in Spanish). The objectives of the PRISMAC program are:

- To develop and commission a laboratory for prototyping and testing high-field superconducting magnets up to 2 m in length.
- To develop and manufacture a small series of the nested orbit correctors called MCBXF for HL-LHC.
- To develop and manufacture superconducting magnet prototypes for the HFM (High Field Magnet) program [4] coordinated by CERN.
- To develop an exploratory study of HTS (High Temperature Superconductor) magnet technologies for compact fusion reactor systems.

This paper outlines the progress of the PRISMAC program activities, focusing on the new high-field magnets laboratory.

II. The SMART-Lab

One goal of the PRISMAC program is the design, construction, and commissioning of a new magnet development facility at CIEMAT premises in Madrid. The facility must have the resources necessary to manufacture short model magnets up to 2 m in length. It should include equipment for winding, heat treatment, instrumentation, impregnation, assembly, handling, and quality assurance of the magnets. This objective has been achieved with the new laboratory called SMART-Lab, which stands for Superconducting MAgnet Research and Technology Laboratory. There are similar laboratories in the United States (Fermilab, LBNL and BNL), Europe (CEA, CERN, PSI and INFN), and Asia (KEK).

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A. SMART-Lab Targets

With the SMART-Lab, CIEMAT aims to develop and manufacture magnets and magnetic components for scientific facilities and scientific instrumentation, i.e., high energy physics accelerators, and also for social applications, including:

- Medical applications: i.e., compact accelerators for PET (Positron Emission Tomography), reducing the footprint, size and power consumption [6];
- Energy generation: i.e., coils for new fusion facilities (ITER [5], IFMIF DONES [7]);
- Energy transmission and energy storage: i.e., SMES (Superconducting Magnetic Energy Storage) [8];
- Transportation: i.e., Magnetic Levitation [9] and propulsion trains; Hyperloop [10] with HTS levitation;
- Aerospace and Defense: i.e., superconducting motors for aircrafts.

The PRISMAC program aims to increase the industrial capacity, particularly in Spain. To this end, SMART-Lab is expected to be a reference and support facility for those companies interested in developing magnetic components.

This program also supports the participation of Spanish companies in big scientific facilities, i.e., in the manufacturing of the main dipoles for the FCC-hh, the hadron-hadron FCC.

The Spanish industry is currently involved in several PRISMAC activities, including the supply of equipment for the SMART-Lab, the manufacturing of tooling for coil and magnet components production, the production of tooling for magnet assembly, and the production of magnet components.

B. SMART-Lab Commissioning

SMART-Lab is inspired by the laboratory in building 927 at CERN. The Superconducting Magnets Technology Section at CERN gave significant support in defining the concept of the facilities and the specifications for the necessary equipment. They also helped with the purchase and contract follow-up for large equipment.

The building where the laboratory is located was completely refurbished, the renovation finished in June 2023. The activities in the SMART-Lab started gradually in January 2024, and it is foreseen to be fully operational before the end of 2025.

C. SMART-Lab Layout and Equipment

The laboratory is almost one thousand square meters:

- In the first floor there are offices and a meeting room with a total surface area of 120 m^2.
- In the ground floor, it has 400 m^2 in Hall 4 and 150 m^2 in Hall 3 (Fig. 1). Each hall has a 10 tons bridge crane.
- In the underground floor, it has 300 m^2 (Fig. 2).

1) Ground Floor. Hall 4: In Hall 4 at the ground floor there are two separate rooms (*A* and *B* in Fig. 1), and some open areas (from *C* to *H* in Fig. 1).

The area dedicated to winding and binding activities (*A* in Fig. 1), is in a separate room to minimize coil contamination with undesired particles during these activities. It has two winding machines, now dedicated to the short and the long MCBXF coils. They have two different rotation movements: one around the vertical axis, and another around the cylinder (mandrel) axis, where the winding is made. The speed of both turns can be adjusted to suit different needs. These machines can also be adapted to wind straight CCT (Canted Cos-Theta) coils (see Fig. 3). Over each winding machine there is an electric chain hoist for tooling assembly during winding and binding activities, and also to host the spool with cable in case it is needed for a second layer in the coil. Each winding line has a pay-off machine for the closed-loop control of the pulling tension, up to 100 N, given to the cable during the winding. A new winding machine for curved CCT coils up to 1.2 m long and 300 kg, and a pay-off machine for HTS cables are being commissioned.

The separate room for measurements (*B* in Fig. 1) has a more accurate temperature and humidity control compared to the one in the rest of the facilities. This allows to carry out geometric and electrical measurements with safety and control. This room is equipped with a precision granite table and a CMM (Coordinate Measurement Machine) capable of measuring parts up to 700x700x500 mm (length, width, height) and 750 kg, with

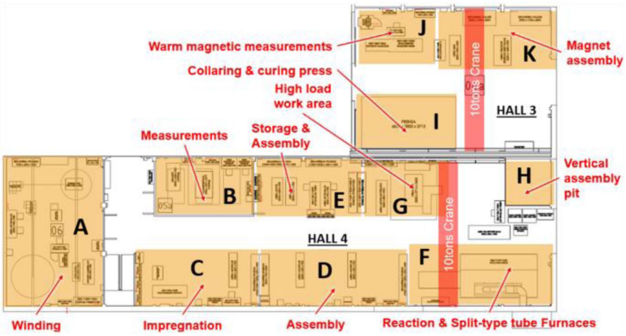

Fig. 1. SMART-Lab ground floor.

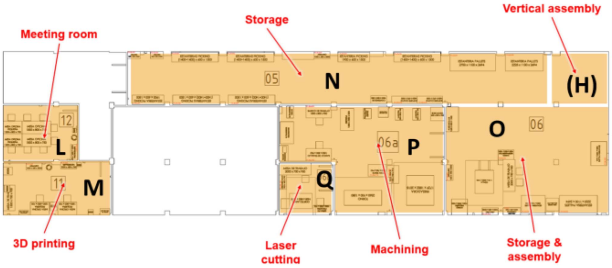

Fig. 2. SMART-Lab underground floor.

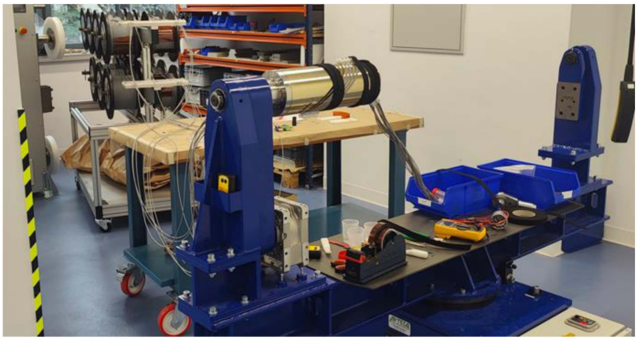

Fig. 3. Winding machine with a CCT coil.

Fig. 4. Reaction furnace.

an accuracy better than 5 µm. It is also equipped with devices for electric measurements, and several small measurement equipment to control tooling and components parts, and to check that the assemblies are carried out properly. The purchase of a multisensor measurement system has been launched. It will allow to measure parts up to 320x175 mm using an image, a laser or a probing sensor.

There is an area dedicated to impregnation (*C* in Fig. 1). We can impregnate with epoxy resins, cyanate ester resins, and wax (pure, with alumina), among others. Each coil is enclosed in a mould that precisely confines it in its final geometry. The mould is then introduced into a vacuum chamber to facilitate the sealing. The heating is done with electrical resistances, and the control systems are equipped with the necessary components to regulate the thermal cycle, supporting up to six independent heating circuits. A leak detector is used to check the sealing of the impregnation mould prior to impregnation.

The two areas for storage and assembly activities (*D* and *E* in Fig. 1) have shelves to store tooling and components, and wheeled worktables that can be used throughout the laboratory to prepare components or perform assembly tasks.

The commissioning of a heat treatment furnace (see Fig. 4) to be used for Nb_3Sn coils is being finishing (*F* in Fig. 1). Typically, the thermal cycle for reacting the Nb_3Sn alloy takes up to two weeks, needing a stable temperature of 650 °C for approximately four days. This process requires a controlled atmosphere to eliminate the presence of oxygen. The furnace use argon gas, the most cost-effective option, with a flow up to 15 liters per minute in the furnace chamber, and 5 liter per minute for the reaction mould. This configuration allows to maintain an overpressure of 50 mbar, ensuring the exclusion of external air. The maximum temperature dispersion while maintaining constant setpoint temperature is +/- 3 °C. The system is also equipped with an uninterruptible power supply (UPS) based on batteries that enables the control system to remain operational for 3 to 4 hours during power outages. The furnace is equipped with a water-cooling system, and can host a mould up to 2.5 m in length and 3 tons in weight.

In the same area (*F* in Fig. 1) there is a split-type tube furnace to be used for small cable and coil samples. It is based on a quartz tube that is heated from the outside by radiation. The useful volume is 500 mm long and 150 mm in diameter.

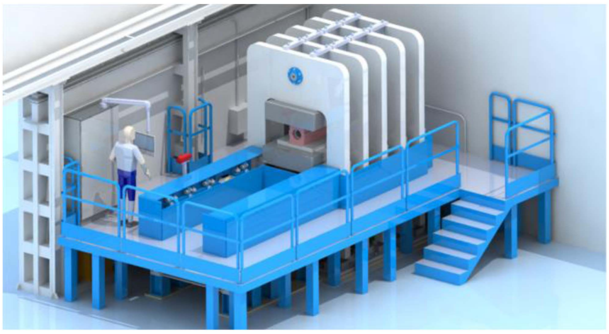

Fig. 5. 3D model of the collaring and curing press.

Fig. 6. Warm magnetic measurement bench.

A tilting device to change the position of magnets up to 2 m long, 1 m diameter and 10 tons from horizontal to vertical and vice versa is in the high load work activities area (*G* in Fig. 1).

There is a pit for vertical magnet assembly (*H* in Fig. 1) and to transfer loads between the underground and the ground floor. A small vertical press for mechanical characterization of superconductor cable samples and small mechanical models of magnet support structures will be soon installed in this area.

2) Ground Floor. Hall 3: The activities on assembled magnets will mostly take place in Hall 3. It will have a multipurpose collaring and curing press (*I* in Fig. 1) to allow the assembly of magnets with collars. It will generate a force of 3700 tons with 10 cylinders arranged in pairs (see Fig. 5). To allow compensating possible variations of the rigidity along the mould, each pair of cylinders can be operated individually. The loss of pressure will be less than 5% per hour at full load. During the collaring process, the error of parallelism between the movable plate upper surface and the top plate lower surface will be lower than 200 µm in the transverse direction and less than 1 mm/m in the longitudinal direction. It will accommodate moulds up to 2 tons, 2.5 m long, 1 m wide and 400 mm high. It will also be used to polymerize coils made with wires insulated with polyimide tape pre-impregnated with an adhesive. These coils require heat and pressure to adapt their geometry to the mould as they polymerize. The heating system will operate up to 250 °C with a precision of ±2 °C.

One area will be dedicated to warm magnetic measurements (*J* in Fig. 1), enabling the quality control of finished magnets, as the final position of the wires is not accessible. The warm magnetic measurement system is now being used for the MCBXF magnets at CERN (see Fig. 6).

The last area in the ground floor is for final magnet assembly activities (*K* in Fig. 1). One of the benches will be capable of rotating the magnets to ease the access during the final electrical connections between coils. A hydraulic system for bladder & key assemblies with ten independent circuits capable to pressurize water up to 1100 bar has been also commissioned.

3) Underground Floor: In the underground there are two separate rooms: one is a meeting room (*L* in Fig. 2), and in the other there are two plastic 3D printers, one uses plastic powder and the other plastic filaments (*M* in Fig. 2). They are used to produce test and practice parts, and also for rapid prototyping. The hallway (*N* in Fig. 2) is a storage area with several shelves and cabinets.

The storage and assembly area (*O* in Fig. 2) is used for assemblies and preparation of tooling and components. There is a chemical storage cabinet for solvents and chemical products, i.e., resins, binders, adhesives. Two small furnaces are used for heating resin components before mixing them, to cure silicone parts and adhesive products applied to bonded parts. The shearing machine is outside the machining area due to lack of space, but it is a relatively clean machine. A vacuum chamber for degassing is also being purchased.

The machining area (*P* in Fig. 2) is in this separate room to avoid contaminating the rest of the areas with shavings or metallic dust. It is used for minor modifications and final adjustments in tooling or components. It has a lathe, two tool tracks, two foldable cranes, two workbenches, a bandsaw, machines for drilling, grinding and two for sanding, a threading machine and a TIG welding machine. Two ultrasonic cleaning machines allow the removal of any metal debris and grease from pieces. A milling machine will complete the workshop.

Inside the machining area there is a dedicated room with a CO_2 laser cutting machine (*Q* in Fig. 2) with a working area of 1000x610 mm. It is used for insulation material, such as polyimide and fibreglass sheets.

D. SMART-Lab Technical Capabilities

Magnets up to 10 tons and 2 m long can be produced in the SMART-Lab. Several superconducting materials can be used: LTS (i.e., NbTi, Nb_3Sn) and HTS (i.e., MgB_2, REBCO, BISCO).

Different cable configurations: flat cables, as the Rutherford, round cables, as CORC, or tape cables, as Roebel, can be wound in different coil configurations: flat coils called racetrack, used in block and common coil configurations; coils in cylindrical shape known as CT (Cos-Theta coils); CCTs, where the cable is placed in a groove machined around a tube in tilted position.

III. MCBXF FOR HL-LHC

The second objective defined in the PRISMAC program is the development [11], [12], [13] and manufacture of 12 short MCBXFB and 6 long MCBXFA magnets for HL-LHC at CERN. These correctors are the first nested superconducting magnets with mechanical torque locking to be installed in an accelerator facility.

The production of the last 6 short and 5 long magnets coils is taking place in the SMART-Lab. CIEMAT is responsible for all the magnets components manufacturing, and the quality control is done at the SMART-Lab before sending them to CERN, where the magnets are assembled and tested (electric and magnetic tests at warm and at cold) [14] to [25].

Coils and components for MCBXFB09 and MCBXFA4 are under production. It is foreseen to finish the coil and components production in March 2026 [26], and to finish all magnets, up to MCBXFB10 and MCBXFA5, in May 2026 [27].

IV. 14T COMMON COIL DEMONSTRATOR FOR HFM

The third PRISMAC program goal is the design and fabrication of a Nb_3Sn 14 T magnet demonstrator in common coil configuration, in the framework of the HFM program. As a first step, two Racetrack Model Coils (RMC) already produced at CERN will be assembled in common coil configuration in a model magnet called ISAAC (Investigating Superconducting Assembly to Address Common coil mechanics), [28], [29], to validate the mechanical design strategy before the design and manufacture of the 14 T common coil demonstrator magnet called DAISY (Demonstrator for Assembly Innovations in Superconducting common coil technologY). ISAAC will be assembled and tested at cold before the end of 2025.

DAISY will be the first magnet with Nb_3Sn coils manufactured in the SMART-Lab. It is a hybrid magnet, with a single layer coil of Nb_3Sn in the high-field region, and a double pancake coil with NbTi cables in the low-field region [30], [31]. It will be assembled and tested at cold by the beginning of 2027.

V. HTS MAGNET TECHNOLOGIES STUDY

The objective is to initiate a preparation phase to provide a comprehensive response, including its industrial scope, to the HTS needs of the Spanish national Fusion program, within the framework of the European strategy [32].

The activities on the design and construction of an HTS magnet with flat coils for a gyrotron at CIEMAT, and on the analysis of the development of an HTS cable have started.

These activities would enable an analysis of potential interest in opening a program similar to PRISMAC, with a greater focus on applying superconducting magnets to develop pre-industrial fusion power generation equipment.

VI. CONCLUSION

The four goals of the PRISMAC program are described, focusing on the new magnet laboratory SMART-Lab, a unique facility in Spain, with strong links with industry.

SMART-Lab is intended to produce magnets up to 10 tons and 2 m long, using any kind of superconducting material, cable type or coil configuration. 80% of the necessary equipment has been installed, and the lab shall be fully operational by the end of 2025.

The MCBXF magnets production for HL-LHC is progressing very satisfactorily. All the tasks will be completed by May 2026.

Activities for the HFM program are well advanced: ISAAC is under fabrication, and DAISY is under design, based on a hybrid concept using NbTi in the magnet low field region.

The activities related to the HTS study are being launched.

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