A New Cryogenic Test Facility for Large and Heavy Superconducting Magnets

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Abstract— **CERN has recently designed and constructed a new cryogenic facility for testing large and heavy superconducting magnets at liquid helium temperatures. The facility, erected in a large assembly hall with cranes capable of up to 100 t, provides a cooling capacity of 1.2 kW at 4.5 K equivalent, 15 kW LN_2 cooling and warming capabilities for up to 3 magnets in parallel. The facility provides the required technical infrastructure for continuous and reliable operation. Test capabilities comprise electrical, cryogenics, vacuum and mechanical verification and validation at ambient and liquid helium temperatures. A comprehensive survey and magnetic measurement system, comprising a hall-probe mapper, a rotating-coil magnetometer, a stretched wire, a translating fluxmeter and a laser tracker, allows the detailed measurement of the magnetic field strength and quality on a large volume. The magnetic axes of the quadrupoles can be established within ± 0.2 mm at 1 sigma accuracy. The facility has been equipped with power supplies, 3 converters of ± 500 A / 120 V and 6 converters of ± 600 A / 40 V, as well as the required energy extraction, quench protection, data acquisition and interlocks for the testing of superconducting magnets for the FAIR project, currently under construction at the GSI Research Center in Darmstadt, Germany. The versatile design of the facility, its layout and testing capabilities complements CERN's other test infrastructures for large superconducting magnets. We report on the design, construction and commissioning of the facility as well as the expected capabilities and performances for future tests of large and heavy superconducting magnets.**

***Index Terms*—cryogenics, instrumentation and measurement, magnetic field measurements, measurement techniques, superconducting magnets, test facilities, testing.**

I. Introduction

The European Organization for nuclear research (CERN) designs, develops, constructs and operates test facilities to assess and validate the performance of superconducting magnets for the needs of present and future applications required by its scientific program in the field of accelerators and particle physics.

Within the framework of a collaboration with GSI Darmstadt, a new facility for the testing at liquid helium temperature of large and heavy superconducting magnets has been constructed and will enter into operation in 2017, at first to test and validate the performances of magnets for the Super Fragment Separator (Super-FRS) of the Antiproton and Ion Research Facility (FAIR) [1] being constructed at GSI Darmstadt, and later to be integrated into the magnet testing infrastructures at cryogenic temperature at CERN.

FAIR is currently under construction to provide high intensity ion and antiproton beams to serve experimental areas in the field of atomic, nuclear and plasma physics and material science. The Super-FRS will provide separation of exotic nuclei up to relativistic energies. It will require about 180 superconducting magnets that are currently in the final design stage prior to construction in industry.

The test facility has been designed and developed to satisfy the stringent criteria and requirements [2] of the Super-FRS magnets testing while profiting and making extensive use of the existing infrastructures, competences and developments available at CERN. The infrastructure previously used for the testing of the ATLAS superconducting magnets [3] has been reviewed, refurbished and upgraded. New capabilities have been added in order to satisfy the test requirements in the most efficient way.

The most significant features of the test facility are the unprecedented capabilities to measure the characteristics of large and heavy superconducting magnets at cryogenic temperatures.

II. Facility capability and test requirements

A. Super-FRS magnets characteristics

The Super-FRS superconducting magnets [2] are of superferric type.

The dipoles which provide separation of nuclei have the coils installed in a cryostat and liquid helium bath surrounded by a warm iron yoke. The focusing quadrupole and corrector magnets are installed in a common cryostat and liquid helium bath in a common system called multiplet.

The helium inventory ranges from 50 l for the dipoles up to 1200 l for the largest of the multiplets. Their main sizes and

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The final version of record is available at http://dx.doi.org/10.1109/TASC.2016.2626270

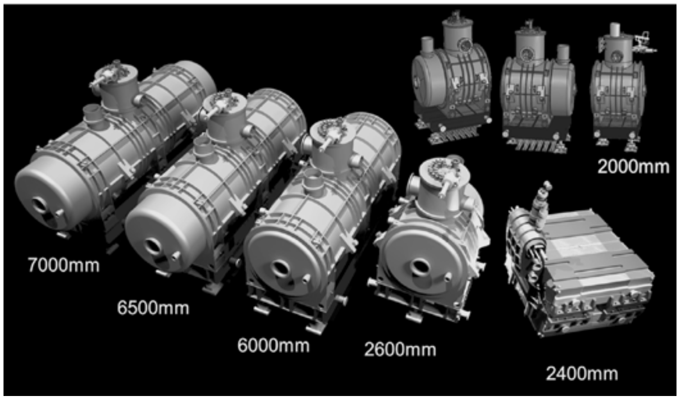

Fig. 1. Super-FRS superconducting dipole and multiplets variants and overall lengths (total height up to 5 m).

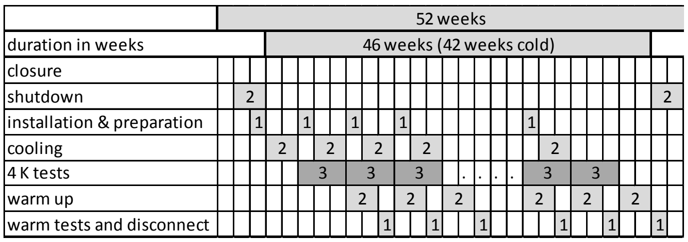

Fig. 2. Yearly sequencing of magnets testing (duration in weeks).

characteristics are summarized in Fig. 1 and Table I.

B. Test requirements

The magnets operate in a liquid helium bath at 4.5 K with a maximum pressure of 20 bar. During cooldown and warm-up the maximum allowed speed is 1 K/h with a maximum temperature variation across the magnet of 50 K. To reduce heat in-leak to the cold mass, a surrounding thermal screen is cooled between 60 and 90 K. The main cooling requirements are summarized in Table II.

The first tests are based on an extensive magnet characterization program to be performed to the pre-series dipoles and two multiplets of different lengths and magnet composition. These tests will validate the design and performances of the magnets before starting the series production.

The series magnets testing will include verification at warm conditions of the vacuum insulation, instrumentation and high voltage insulation prior to cooldown. At nominal operating conditions the instrumentation and high voltage insulation will be verified and the magnets will undergo a series of cycles of current ramping tests. This will be followed by a comprehensive magnetic measurement program to assess the integral field and field quality along the magnet as well as the magnetic axis with respect to the alignment fiducials. The evaluation of the cryogenic heat loads can be performed overnight under stable conditions with calorimetric measurements.

C. Test plan and schedule

The series of magnets must be tested during a period of about three years between 2018 and 2021 to match the industrial production and installation rates at GSI. With the constraints of

TABLE I
SUPER-FRS MAGNETS MAIN CHARACTERISTICS

Type	Qty [unit]	Mass [ton]	Field range [-]	Measur. surface [mm]	Field quality [ppm]
Dipole	24	50	0.1-1.6 T	400x140	10^2
Multiplet long	24	70	1-10 T/m	340 Ø	10^3
Multiplet short	9	25	1-10 T/m	340 Ø	10^3

TABLE II
SUPER-FRS MAGNETS MAIN COOLING REQUIREMENTS

Test Phase	Requirement
Cool-down 293 – 90 K	5.6 kW cooling power, 21.4 g/s at 10 bar
Cool-down 90 – 4.5 K	6.2 m^3 of saturated LHe at 4.5 K
Filling of magnet LHe	1.4 m^3 of saturated LHe at 4.5 K
Cold tests heat loads	30 W static at 4.5 K, 35 W dynamic (10 min) 160 W at 60 – 90 K 1.6 g/s at 4.5 K – 300 K (liquefaction load)
Warm-up 90 – 293 K	5.4 kW heating, 20 g/s at 10 bar

the existing refrigerator cooling power and the facility size and layout, an optimized testing program based on three parallel benches and a cycle of 46 days per magnet has been worked out. Using each test bench magnets can simultaneously be in preparation/cooldown, nominal operating conditions and warm-up/dismantling as per Fig. 2.

III. DESIGN AND PERFORMANCES OF THE MAIN SYSTEMS

A. General layout of the facility

The general layout of the facility is shown in Fig. 3. The testing area is divided in four zones:

a. The acceptance and preparation area for up to three magnets which comprises also the power converters and energy extraction systems;
b. The cryogenic infrastructure production area;
c. The main testing areas served by the cryogenic distribution lines where three individual test benches and magnets are accessible via a platform system;
d. The monitoring and control rooms overlooking the whole area and serving as a control, data acquisition and analysis center.

The platforms around the magnets provide access at different levels (i.e. cryogenic connections, electrical powering connections, beam pipe for magnetic measurements). They are made of permanent sections to cover the common areas and three configurable parts at the magnet's edges in order to configure the platforms to accommodate and guarantee safe access for all possible magnets configurations (lengths and shapes). These configurable parts in the proximity of the magnets are made from aluminum due to the proximity with the magnets aperture.

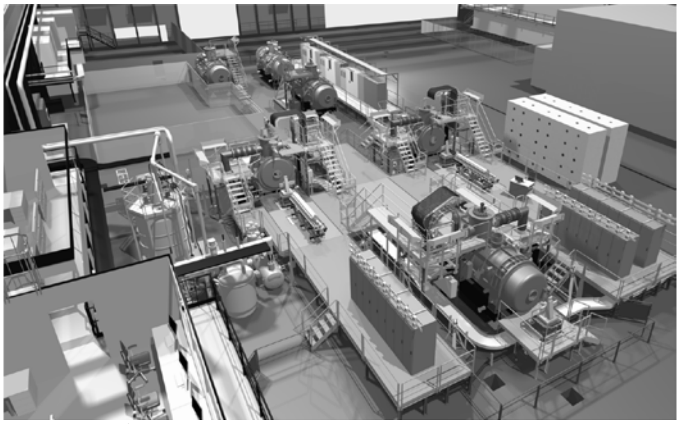

Fig. 3. Test facility layout.
Top – The magnets acceptance, preparation and power converters area.
Right – The main testing areas with the three test stations.
Left – The cryogenic production area and the monitoring and control rooms.

The magnetic measurement systems are positioned on concrete blocks for easy adaptation to the configuration and for stability. The cable trays and water piping for the converters run under the platforms and in the building underground galleries.

B. Infrastructure and general services

The building housing the facility was already equipped with two cranes that have been upgraded and coupled to obtain a lifting capacity of 100 t. Devices with heights up to 7 m and masses up to 90 t can now be handled.

A series of underground galleries are used to interconnect the different equipment with the general services. An adjacent building has been refurbished to house the compressor system for the cryogenic refrigerator.

The facility has been designed with a 1.3 MW open loop cooling power system to feed the water cooled compressors and the demineralized closed water loop (about 150 l/min) for the power converters and several small pumps.

3.3 kV and 400 V cells provide 2 MW electrical powering distribution with an uninterruptible power system for the energy extraction and cryogenic control systems.

C. Cryogenic system

The cryogenic system [4] is designed to provide cooling and warming-up capabilities at the three test benches. The overall layout is presented in Fig. 4.

An existing TCF200 1.2 kW at 4.5 K refrigerator, with a liquefaction capacity of 5.6 g/s, was refurbished and equipped with a new oil flooded compound compressor providing a helium flow of 150 g/s at 18 bar. Supercritical helium at 4 bar and 4.5 K is distributed via a distribution valve box and 3 independent transfer lines and satellite valve boxes to the individual test benches. A liquid helium dewar of 5 m^3 provides boosting to the cold box for filling with liquid helium and quench recovery as well as additional buffer capacity.

Two independent Cool-down and Warm-up Units (CWU) allow the independent cool-down and warm-up of two test benches while the third one is at nominal operating conditions and test. Two compressor stations supplying 50 g/s at a pressure of 5 bar can bring the magnets down to operating temperature

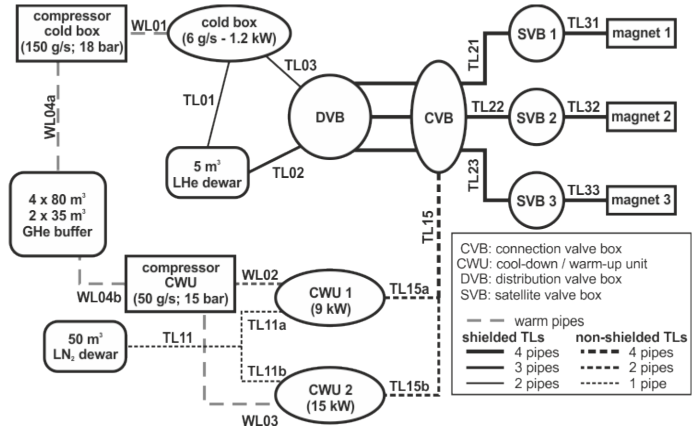

Fig. 4. Cryogenic system layout.

in less than two weeks, respecting the maximum cooling speed and gradient imposed by the design of the magnets and guaranteeing the overall test schedule.

D. Powering, energy extraction and quench protection systems

The general layout of the quadrupole powering circuit, quench detection, energy extraction, quench detection and magnet protection systems is shown in Fig. 5.

Each Super-FRS magnet can be independently powered with three converters at ± 500 A / 120 V and six at ± 600 A / 40 V. Each power circuit is equipped with load switches to select the test bench to be powered and interlocked with the overall powering interlock system. The performances of the power converter will guarantee an accuracy of ± 200 ppm or ± 100 mA, a reproducibility of ± 50 ppm or ± 25 mA and a short term stability during the tests of ± 20 ppm or ± 10 mA.

The dipole and quadrupole circuits are equipped with an energy extraction system due to the stored magnet energy of several MJ.

The quench detection and magnet protection system is based on the LHC architecture and design [5]. It is digital, FPGA based with redundant detection systems.

E. Data acquisition and interlock system

Data acquisition and interlocks are based on the systems already developed at CERN for other magnet test benches [6].

There are four main systems: a mobile and stand-alone system, the database and analysis system for the test benches area, the control and interlock systems.

The mobile stand-alone system is used to measure all the main parameters of the magnets. It is based on a Megger multiplexer system for the High Voltage measurements, a high precision PXI-DMM system for the RRR and splice measurements and a frequency analyzer for the inductance measurements.

The database and analysis system is based on the CERN general acquisition architectures and provides acquisition and data analysis via National Instruments® based equipment interfaced with CERN database infrastructure.

The control systems share a common operator interface

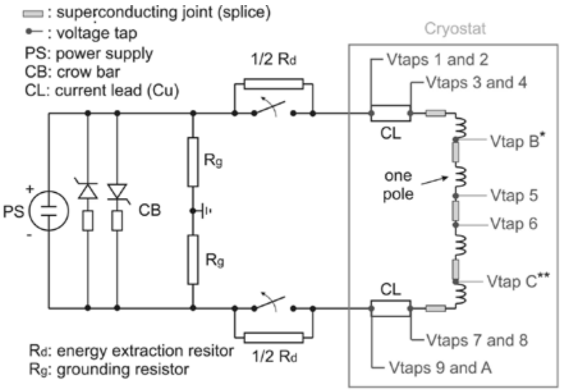

Fig. 5. Layout of the quadrupole powering, energy extraction and quench protection systems.

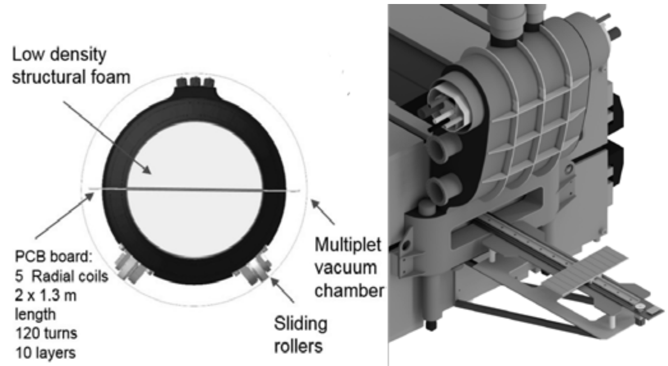

Fig. 6. The rotating array of PCB based radial coils for the multiplets and the translating induction-coils systems for the dipole magnet.

platform based on the Unified Industrial Control System framework developed at CERN [7] except for the power converter that is based on customized front end controllers and operator interfaces.

Individual systems have their own process interlocks managed within the individual control system. A global powering and safety interlock system with a dedicated PLC is designed to guarantee the overall safety operation of the test facility based on the output of a risk and Failure Mode and Effect Analysis.

F. The magnetic measurement and fiducialisation systems

The driving requirements and challenges for the development of the magnetic measurement systems are:

a. A large measurement volume;
    a. 170 mm bore radius for the multiplets;
    b. 400 x 140 mm good-field region for the dipoles;
    c. Up to 5.2 m length to be covered for the measurement of the integral field.
b. The measurement of the local field homogeneity along the dipole magnets;
c. The identification of the magnetic axis of the quadrupoles within ± 0.2 mm at 1 sigma accuracy;
d. A limitation on a maximum weight of 60 kg for the support and guiding of the system inside the multiplets bore;
e. The operation of the measurement systems at the specified accuracy in an industrial-like setting without temperature control.

The measurement methods and tools chosen are:

a. An array of induction coils translated longitudinally by means of a stepping motor and equipped with a linear encoder to translate longitudinally inside the aperture of the dipole magnets;
b. A system based on an array of printed-circuit coils supported by a carbon-fiber shaft rotating inside the multiplets, which can be displaced longitudinally inside the bore to measure the different magnet modules in the multiplets;
c. A standard stretched-wire system to measure the multiplet magnet's integral field strength and axis location.

A dedicated R&D program was established in order to develop the required measurement system and tools for the first two systems [8]. Prototypes (Fig. 6) were extensively tested and the fulfilment of the measuring requirements for the magnet characterization was validated to proceed with the construction of the final instruments.

The fiducialisation system consists in an absolute laser tracker located in four positions and a network of reference points around the magnets to measure the alignment fiducials.

IV. Construction and Commissioning

The test facility was designed in 2014 in close collaboration with colleagues from GSI Darmstadt. Its construction took place from 2015 to 2016.

The magnetic measurement R&D has been completed and the final measurement systems are ready for production.

The commissioning of the cooling system has been completed and the commissioning of the power and cryogenic system is now underway. The final commissioning of the whole facility with the pre-series magnets will start in the second half of 2017.

V. Conclusion

A new test facility for large and heavy superconducting magnets has been successfully designed and built at CERN.

Existing and newly developed techniques for the accurate measurement of the superconducting magnets characteristics will be initially used for the testing of the Super-FRS magnets and then be available to complement CERN laboratory magnet testing infrastructure capabilities.

Acknowledgment

The authors would like to thank colleagues at CERN and GSI for their contribution to the facility construction.

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