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The set up of a cryogenic test facility for large magnets and superconducting lines at INFN

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Abstract. A new cryogenic test facility for large magnets and superconducting lines is under development and construction in a challenging 30-months based project. The facility, however, will extend its activities well beyond the term of the project, being open for future test projects and collaborations. The facility will host two cryogenic plants, each dedicated to a test program. The superconducting power transmission line testing hall is under construction, while the accelerator magnet test activities are already running with the site acceptance tests of the superconducting quadrupole doublet modules (QDM) of the SIS100 synchrotron. A review of the facility is given in this work, together with some data on the refrigeration of the QDMs.

1. Introduction

In 2022 the Italian Ministry for University and Research approved the Innovative Research Infrastructure on applied Superconductivity (IRIS) program, involving four laboratories of the National Institute for Nuclear Physics (INFN, laboratories in Frascati, Genoa, Milan and Salerno), SPIN institute of the National Research Council (CNR) in three different cities (Genoa, Naples and Salerno) and five Italian Universities (Genoa, Milan, Naples, Salento and Salerno) [1,2]. The program is funded under the National Recovery and Resilience Plan (PNRR) and benefits from the experience of the partners in the field of applied superconductivity. Among its targets, the program aims at setting up a new Test Facility for large Magnets and superconducting Lines (TFML). The TFML will be set up in two buildings. The building hosting the tests of a medium voltage (MV) superconducting cable for sustainable energy transmission (or green superconducting line, GSL) will be built, while the second one for accelerator superconducting magnet tests (Test in HORizontal facility, THOR) is already existing, equipped and set in operation under a former joint test program by INFN, Facility for Antiproton and Ion Research (FAIR) and Gesellschaft für Schwerionenforschung (GSI). The Department of Physics of the University of Salerno (UNISA) is strongly committed in erecting the new building of the TFML for the GSL test program (we will refer to this building as GTF) and providing all of the technical services, while INFN Salerno is in charge of equipping the laboratory with required testing systems.

THOR will be consolidated under IRIS and it is currently involved in the site acceptance tests (SAT) of the Quadrupole Doublet Modules (QDM) of the new synchrotron SIS100 under construction by FAIR at GSI in Darmstadt, Germany. Nowadays, five QDMs plus the first of series (FoS) have been tested at THOR since the first half of 2022. The GTF, on the other hand, will be equipped with an independent cryogenic system, allowing to run the tests of the GSL, and with a set of electronics, and monitor and control systems (MCS) for high voltage/current tests.

The TFML is unique in the panorama of the Italian research infrastructure due to its scopes, equipment and know-how. The TFML design will allow for future expansion and developments, ensuring the sustainability of the TFML beyond the end of the IRIS program.

The first part of this work will focus on the new laboratory of the TFML for GSL testing and progress in designing it. A preliminary design of the cryogenic system will be also discussed. On the other hand, THOR cryogenic system, operation and first results will be presented, together with few recurrent issues and their mitigations.

2. Superconducting power transmission line test program

The first cable to be tested at the TFML will be a GSL demonstrator. It is a superconducting cable in its cryostat, 130 m long, based on MgB_2, with nominal 40 kA/25 kV rating, and working temperature of 20 K (full specification available in [3]). It is developed and procured in a work package of the IRIS project led by INFN Milan.

The GTF will have an independent cooling system with respect to THOR, enabling the cooling of the GSL with 500 W of cooling power at 20 K and ~22 g/s of gaseous helium (GHe) stream at 7-10 bar. The laboratory will be equipped with a vertical tank for the pure GHe inventory (30 m^3 at 15 bar maximum pressure) and four horizontal tanks (4.5 m^3 at 200 bar, each) for the recovered gas. Indeed, the test facility will be able to produce liquid helium (LHe) with maximum rate of 72 l/h without precooling option, as well as recover evaporated He with a classic balloon-compressor-tank scheme. A sketch of the preliminary refrigeration scheme is reported in Figure 1.

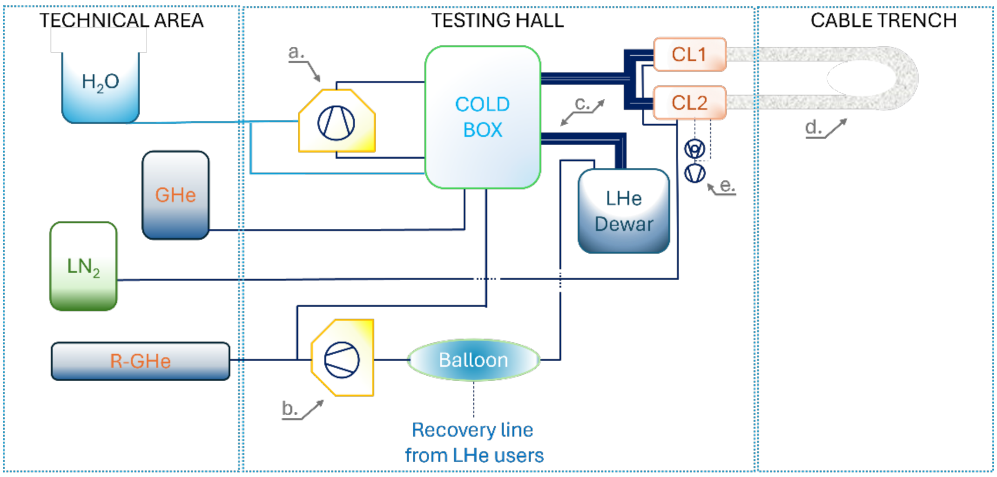

Figure 1. Preliminary scheme of the refrigeration system for the GSL test program. **a.** is the He compressor for the refrigerator (cold box in the scheme), while **b.** is the high pressure compressor for the He gas recovery to the impure He tanks (R-GHe). The cold GHe at 20 K from the refrigerator will be injected into

the GSL (**d.**) from one of the current lead (e.g., CL1) and recovered by the other (e.g., CL2). **c.** are the transfer lines to the GSL and the liquid He dewar. **e.** is the pumping system for the insulation vacuum of the GSL.

The new refrigerator is a gas bearing turbine based cold box, with separate cold ends for gas stream and LHe. The mass flow at the output is measured by means of two Coriolis effect based cryogenic mass flow meters, together with temperature and pressure parameters. The LHe will be stored in a buffer dewar of 2000 l and will serve future application or the other laboratories hosted in the building. On the other hand, the cold GHe stream will be sent to the GSL thanks to a cryogenic transfer line. The current leads of the GSL will act as an interface/feedtrhough between the transfer line and the GSL itself, allowing the refrigeration of the superconductor.

3. Superconducting accelerator magnet test program

3.1 THOR facility details

THOR is equipped with instrumentation able to cover the entire range of checks to be carried out on a QDM [4-6]. The tests are performed in different conditions: from ambient to operating temperature ~5 K and pressure ranging from ambient to ~$10^{-7\,(12)}$ mbar for insulation (beam pipe) vacuum. Most demanding requirements, however, are those referred to the refrigeration system and the power supply for nominal ramp rate test of corrector magnets. The refrigeration system at THOR is shown in Figure 2.

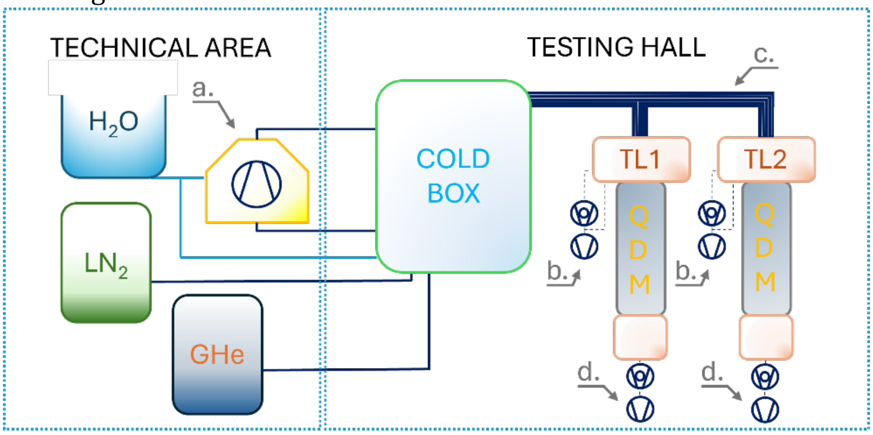

Figure 2. The He compressor (**a.**) of the refrigerator is hosted in a technical area outside the main shed, or testing hall (~450 m^2). The cold box supplies and recovers the supercritical Helium to the QDM under test (on the testing lines, TL1 or TL2) thanks to a transfer line (**c.**). A set of pumping systems generate the required vacuum for the cryostat insulation (**b.**) and for the beam pipe (**d.**).

The required cooling capacity is 120 W of single phase flow of supercritical He (SHe) in the temperature range of ~4.5K and at a pressure of 3 bar. The maximum allowed cool-down rate is 5 K/h. In addition to this, the cryogenic specifications on the thermal radiation shield require He stream at a temperature in the range 50-80 K. In order to fulfil the requirements, a Linde Kryotechnik LR280 is used. Refrigeration performances allow a stream of ~5 g/s SHe at 4.6 K and 3 bar, able to cooldown and keep a QDM (approximatively 2 tons of cold mass, including 2 quadrupoles and 2 corrector magnets, but excluding beam pipe and mechanical/electrical systems) at operating conditions. The cryogenic mass flow has to be measured independently for magnets and beam pipe cooling circuits. Two different types of mass flow meters equip the facility. An Emerson Coriolis Elite MicroMotion CMF025 is mounted on the cooling circuit of the magnets and bus-bars, while a WEKA Sense cold mass flow meter is dedicated to the beam pipe cooling

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circuit. The temperature sensors reading is performed by using Lake Shore 224, both for thermometers in the QDM and on the test equipment, as for example the interface cryostats.

The interface cryostats have been designed by replicating the GSI Series Test Facility (STF) interfaces, excluding the LHe equipment. They have to ensure the cryogenic flow distribution and the insulation vacuum required for cooldown start, i.e. in the range 10^{-4} mbar. In addition to this, an interface for beam pipe vacuum pumping is required, ensuring a vacuum level in the range of 10^{-7} mbar before cooldown can start. In this case, a UHV set up of the system is mandatory.

The required insulation vacuum is reached by using an Agilent TV501 600 l/s turbomolecular pump, together with a screw pump Varodry 100 m^3/h by Leybold for roughing/backing. The entire system of interface cryostats and QDM generally reaches $\sim 10^{-7}$ mbar in cold operation. The vacuum quality and possible real/virtual leaks are checked by a SRS100 residual gas analyzer (RGA) by Stanford Research Systems, mounted on a differential vacuum system in order to monitor the insulation vacuum from ambient to base pressure.

The demanding vacuum of beam pipe is generated by an Agilent 304FS 300 l/s, backed by a convertible system of a Agilent IDP15 and Pfeiffer ASM 340 leak detector. This room temperature equipment is mounted on the back of the “End Box” interface cryostat (EB, hosting cryogenic flow circulation) and coupled to the cold beam vacuum chamber through a cold to warm transition constituted by a 1 m long DN40 CF hose. The pumping system is able to match requirements for cooldown starting base pressure and it is isolated by means of a all-metal angle valve, allowing the beam pipe to rely on cryo-pumping effect during cold operation (gate closes below, and opens above, 20 K). A SRS100 RGA completes the equipment for the beam pipe, together with a MKS 431 cold cathode.

The software for the PXI based MCS has been developed at THOR [7], together with a series of switching boxes to automate the insulation tests and temperature sensors acquisition. Moreover, through the MCS it is possible to perform several tests, store and back up data, control gates/valves and feedback heaters along the different temperature conditions, as well as monitor the status of the facility.

3.2 THOR operation and first results

THOR started its operation during 2022, with the first cooldown of the FoS module, since April, 20th which lasted for about 6 days. This first cold run was abruptly stopped by a power grid fault on May, 26th 2022. During steady state cold conditions, several test were performed, in particular electrical (insulation and functionality) and beam instrumentation integrity.

A sequence of three QDMs (short CID 27, 42 and 44) was tested after the FoS until the end of 2023. All of them experienced several interruption due to power grid faults. The first module to use an uninterruptible power supply (UPS) for continuous cryogenic operation was QDM with short CID 49, followed by the 48.

Module 49 (48) has been cooled down since March, 7th (May, 3rd) and it reached desired cold conditions (~5 K) in about 8 (10) days. Then it remained cold for 7 (17) days, allowing cold tests. Figure 3 presents a representative cooldown, monitored on the module short CID 48.

While the module was at cold conditions, a standard test sequence has been performed, including High Voltage (HV) and Low Voltage (LV) insulation, functionality/integrity for sensors and beam instrumentation, corrector magnets powering and static heat load.

The static heat load test is performed by acquiring temperatures, pressures and mass flow values at certain indicative points of the module and of the refrigeration system. The inlet and outlet temperature and pressure of the SHe at refrigerator cold end (SHe supply and return port) are acquired, together with temperature of sensors at the forward and return side of both magnets and beam pipe cooling circuits. Finally, the mass flow of cryogenic fluid is measured separately for the two cooling circuits, as described in Section 3.1. QDMs tested at THOR present a static heat load of 6-8 W at 4.5 K, while at STF a static heat load of 10 W at 5.3 K is measured.

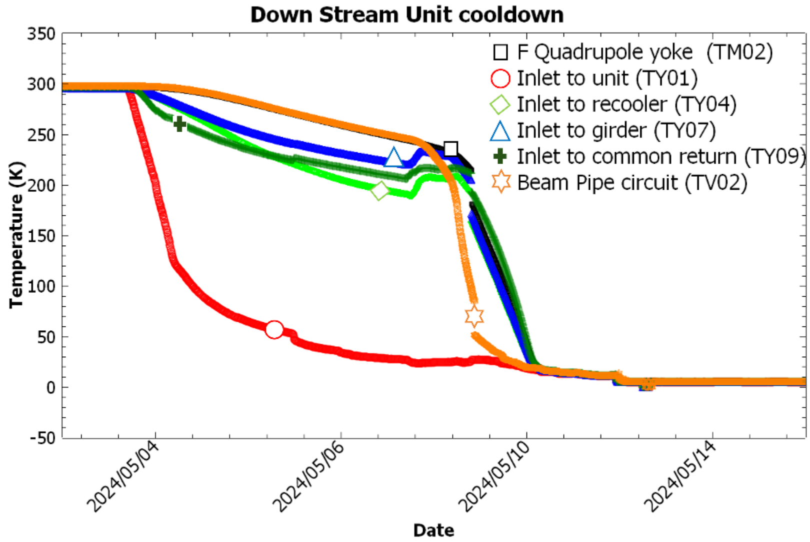

Figure 3. Representative cooldown carried out on a QDM. Reported thermometers are located on a unit, i.e. a complete assembly of superconducting quadrupole, its cooling circuit and mechanical supports.

3.3 General THOR improvements and problem mitigation

The major improvement for THOR will be the doubling of the test lines. The second test line will be equipped with a MCS and sensors similar to the already existing line. The only change in the cryogenic equipment is the use of a Emerson Coriolis Elite MicroMotion CMF010 instead of the Weka Sense on the beam pipe cooling circuit.

During the test of the 6 QDMs delivered to THOR, a consistent number of issues have been found. Two recurrent problems are related to the power grid and the cooling tower.

The first problem has to be attributed to unstable power grid performances. During the test facility operations we experienced a significant number of brownout. These events, even if very short in time, cause the triggering of the interlock for the compressor protection, shutting down the refrigerator. In some cases, they were responsible also of MCS shut down. As a result, fragmented cooldown and cold operation were carried out for FoS, and following 3 QDMs. At the beginning of 2024, a UPS has been delivered and the refrigerator, including compressor electrical supply and motor protection system, its controls and the MCS are now backed up. QDM with short CID 48 and 49 were tested in this uninterruptible power supply environment.

The second recurrent problem was caused by limestone in the heat exchanger of the cooling tower. The tower is expected to cool the water for the refrigerator warm side, turbines and power supplies. It has two independent water circuits, one closed-cycle (on the services to be cooled) and the other open-cycle (on the evaporation end of the cooling tower). The open circuit is frequently refilled by water distribution of the University of Salerno and it is equipped with a water softener. However, the huge amount of water to be substituted (estimate 1000 liters per day) made the accumulation of calcium significant. The heat exchanger acts as an accumulation point for calcium and it had to be cleaned several times in the last 3 years. The cooling tower was switched off during cleaning operations. To overcome this problem, a second heat exchanger has been bought and it will be mounted in parallel to the already existing one. The two exchangers will work separately thanks to switching valves, allowing cleaning operations on one, while continuing to use the other.

Among minor problems, it is worth citing a condensation effect at the exhaust of the insulation vacuum main pump, indicating the presence of water vapour in the insulation volume. Indeed, the large amount of multi-layer insulation (MLI), spacers, clamp and mechanical structures made by composite material and other materials able to attract and retain water vapour are used in the QDM manufacturing and cannot be avoided due to their functions. A mitigation to the risk of pump faults is the use of the gas ballast and the ball bearings gas barrier, both built into the pump.

4. Conclusion

The new cryogenic Test Facility for large Magnets and superconducting Lines, funded under PNRR IRIS, is under construction. The facility will host two large cryogenic plants working in refrigeration or liquefaction/recovery mode, allowing long term operation of the test programs, and of associated research laboratories. This is of strategic importance in the present times of He shortage and related expensive price. Improvements on THOR, such as the UPS and a dedicated design for water quality, will be replicated for the new building hosting the GSL tests. In general, the facility has been designed to be as flexible as possible for future test requirements and external facility access, ensuring the sustainability of the facility itself.

Acknowledgments

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