The build up of a test station facility for the SIS100 superconducting modules

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Abstract. More than eighty quadrupole modules, especially designed and fabricated at JNIR in Dubna, will be used at the FAIR facility in Darmstadt. Prior the installation in the new accelerator SIS 100 tunnel, the modules need to be tested by an independent laboratory. The required test have to be the same for all the modules and the answer will be the benchmark for the final decision on accepting or rejecting the module. With this target in mind, a system with as much as possible automatisms will be realized. Three kinds of tests will be performed: mechanical, thermal and electrical. The mechanical test will concern on the search of vacuum leaks, if present, and on the measurement of the limit pressure reached in the vessel. The thermal test will have to check that the various thermometer, scattered inside the modules, will be correctly working and that the heaters are able to deliver the generated heat. The electrical tests will verify the insulation to ground of both the devices and the superconducting coils and bus-bars. All tests will be done in a thermal sequence: at room temperature, at the cryogenic working temperature of 4.5 K, and finally at room temperature again.

1. Introduction
The GSI (Helmholtzzentrum für Schwerionenforschung GmbH) is a company associated with the German Federal Government based near Darmstadt in the region of Hesse, in Germany. This laboratory performs basic and applied research in physics and related natural science disciplines using the heavy ion accelerator facility. Within the GSI, the new FAIR (Facility for Antiproton and Ion Research) accelerator complex is under construction. The FAIR facility is a new unique international accelerator complex for the research with the antiprotons and heavy ions. From the construction point of view, the realization of this accelerator is quite different than the other large particles accelerators, e.g. the CERN (European Organization for Nuclear Research) LHC (Large Hadron Collider) accelerator ring. In fact, this accelerator complex is based on magnets ramped up to 4 T/s, fast respect to the corresponding LHC magnets that are ramped at only 0.01 T/s.

In the framework of the collaboration with GSI, the INFN (Istituto Nazionale di Fisica Nucleare) is involved with an activity concerning the final tests of the accelerator QDM (Quadrupole Doublets Modules) to be installed in the SIS100 synchrotron ring. There are 81 QDM to be tested, where 54 are arc type, and the other 27 are straight type modules.

Each QDM contains two superconducting quadrupoles and up to five superconducting corrector magnets, both individually tested before their assembly in the modules. Within each QDM there is
also room for cold masses with ancillaries like the CL (Current Leads) and the BMP (Beam Position Monitor). Several other devices are needed to keep the temperature and vacuum of the QDM under control. Bilfinger Noell GmbH in Würzburg, a company selected by GSI-FAIR, assembles the cryostat containing all this stuff.

In this paper we first describe the laboratory facilities already present, analyzing the degree of commissioning of various parts. These will include the cryogenic system, part of the ancillary cryogenics, vacuum systems and, spare electronics. Then we summarize the test list agreed with GSI, and according to this list, we describe the equipment we are procuring to be integrated into the test facility. Part of the work in progress concerns the realization of a global control system to achieve a fully functional testing facility, with the required reliability for performing all the tests.

2. Laboratory layout and main instruments
The laboratory has its own building realized at University of Salerno in the campus area, in the southern of Italy. The laboratory spans a length of over 30 meters, a width of 15 meters, and 9 meters height, thus it has an indoor available surface of 450 square meters. Two additional side rooms, each one of about 40 square meters and 3 m ceiling, are also available. The main shed is equipped with a 20 tons crane to allow movement of heavy weight inside the building. In addition a large front gate allows the access of trucks inside.

On the backside of the shed there is an external area where technical services have been installed, like the cooling water evaporation tower, the pure helium gas storage, the helium main screw compressor of the cryogenic refrigerator. A layout of these technical services inside and outside the shed is shown on Fig. 1 where, the space around has been left available for future expansions or needs.

Figure 1. Layout of the laboratory with the main equipment required for testing the QDM magnet. On the right outside, there are: the cooling water evaporation tower, the tall pure helium gas storage and near the shed the main screw compressor. Inside the shed, the QDM cryostat is horizontally fixed to the refrigeration plant through a Feed-Box, connected to the Cold-Box with a cryogenic transfer line.
The total electrical power available to the laboratory is 1.2 MW and is provided by a dedicated 16 kV medium voltage substation, located near the main shed. In the future, if necessary, this power substation may be upgraded up to 2.5 MW.

In order to comply with all the GSI requests, new certified instruments have been bought and for the others, already in use, a quality certification has to be obtained.

The core of the cryogenic plant is the LR280R one of the largest refrigerator, manufactured by Linde Kryotechnik Group. Our configuration has been customized for present need and future expansions. The cryogenic plant is composed by the following items:

1. Supercritical He (with pressures in the range 3÷7 bar)
2. Liquefactor (with cryogenic turbine expansion box and gas purifier)
3. Cryogenic Shield flow
4. Screw Compressor (with a 196 kW SFC, Static Frequency Converter)

In particular the Linde LR280R refrigerator is equipped with a helium subcooler stage for single phase stream at 4.5 K up to 7 bar, a separate J-T liquid port, an internal purifier and a 80 K adsorber. In refrigeration mode the maximum 4.5 K helium flow is about 15 g/s, thus the refrigerator can deliver an isobaric power of 200 W (between 4.5K÷6K), plus additional 500 W (60K÷80K) in refrigeration mode, while providing 1.5 g/s of helium at 4.6K (used for cooling the current leads) and returning to the warm side at low pressure suction (i.e. not through the cold box internal heat exchangers). In liquefaction mode the cold box is able to produce up to 120 l/h of liquid helium. The refrigerator controller is a Linde standard rack whose management is based on Siemens software WINCC.

The cryoplant has been tested either at the Linde factory and on site. The test on site has been performed in pure refrigeration mode on a dummy load. At regime, the Cold Box was able to achieve about 220 W @ 4.5 K and 500 W @ 65 K.

The helium inventory available is in the external storage vessel, whose capacity is of 30 cubic meters at a pressure of 10 bar, corresponding to a total of 300 cubic meters of pure helium gas.

The SFC screw compressor of 196 kW can deliver about 70 g/s of helium at the pressure of 11 bar with the full speed of 1500 rpm. The SFC electronics, controls the compressor flow through its speed: at low flow (i.e. at low cryogenic power) the speed can be dropped up to 750 rpm, reducing the compressor input power to about 50% of the full power.

External liquid nitrogen cryoabsorber has been recently added in the helium process lines. This item allows a more efficient removal of the gas contaminant from the helium lines during the purging procedure. A dedicated Multi Component Detector gas analyser will monitor the presence of helium contaminants (mostly moisture and nitrogen) in selected places of the He lines.

The QDM module is fixed into its horizontal cryostat, and, as shown in Fig. 1, is connected to the refrigeration plant through a Feed-Box, which is connected to Cold-Box by a cryogenic transfer line. The Feed-Box is the place where hydraulic and electrical connections converge at low temperature. In fact on the top flange of the Feed-Box two current leads may be fitted, to deliver the electrical power at low temperature [1]. For the foreseen tests the high current leads are not required, so the corresponding flanges are temporary closed with blind flanges. The Feed-Box will also provide the vacuum pumping system and analysis, and will contain also the cold flow meters. In addition also an End-Box has to be realized to close the other termination of QDM cryostat. The electrical connections of all the electronic devices installed inside the module are routed on a flange placed on the center of the module. Besides the two ends and the central flange, there is no other access inside the module.

Following the GSI design and instructions, a railway system, that simplifies the alignment of the QDM cryostat with the Feed-Box and End-Box has been designed and is actually under construction.

A detailed three-dimensional model of these units is shown in Fig. 2 where, on the left of the figure there is the feed box with, on its top, the two cryogenic high current leads and the cooling pipes needed to cool down the superconducting coils. The other termination box, on the right side of the same figure, plays the role of both module mechanical support and vacuum-tight closure.
It has to be noticed the important role, played by the vacuum pumping groups. In fact, a very good insulation vacuum is needed in order to cool down quickly and efficiently the module under test. Actually, not shown in the previous figures, the Feed-Box is equipped with a pumping group, that make the insulation vacuum of the whole cryogenic system, including the QDM module shares which shares the same insulation vacuum of the Feed-Box.

An additional pumping group is needed for maintaining the vacuum within the beam pipe. Due to the specific needs, it is required that the beam pipe has to be maintained as clean as possible and with the highest vacuum achievable. In order to fulfill this request a specific pumping system completely oil free is installed on the End-Box with the scope of maintaining the solely vacuum of this beam pipe.

Figure 2. Scaled 3D model of the test assembly unit that will be realized for the SIS100 module, shown on the center. The frontend boxes are on both sides of the image while the rail support is shown under the quadrupole module. (Model realized by A Buonora of the Buonora Engineering Studio©)

As a final implementation of the vacuum quality control within the cryostat, there is a leak detector and two RGA (Residual Gas Analyzer) that will permits to quickly identify the origin and the nature of the residual gas and act accordingly.

3. Modules testing procedure

After the installation and before starting to work on the real modules, all the instruments and apparatus have to be designed, manufactured, and tested. The quality tests, required by the GSI for all modules, are essentially vacuum-tight, electrical and thermal both at room and at the cryogenic working temperature. The order of the test steps has been organized in such a way that an early failure may lead to an abort all the tests that will follow. However, the decision to stop or proceed in case of a test failure will be done on a case-by-case basis and, will be done in agreement with the GSI engineers in
charge evaluating, among other considerations, the economical convenience in saving both time and economic resources with an early reject.

A first visual test is done at the arrival. The QDM are assembled by Bilfinger&Noell in Germany, and shipped to Salerno by truck. The QDM is accepted if do not have any visual damage and the enclosed documents contain the factory test report with all the right thermometer calibration curves.

After the inspection the QDM is mounted on the test assembly unit and all pipes and wires are connected. The pumping groups are activated and the insulation vacuum slowly restored. Within few hours large leaks can be detected, while smaller leaks require the activation of the leak detector and some helium gas to be insufflated into the module pipes. Anyway, either large or small leaks need to be found and if possible closed, until the final vacuum pressure is reached.

After the module is vacuum tight mounted, the control electronic, mainly thermometers and heaters, may be connected to the computer controlled relay box. Table 1 will summarize the device and the number of connections needed in order to verify the low voltage devices. The high voltage test points, about ten points, depending on the particular module under test, are not reported in the Table 1.

A computer controlled Relay Switchboard will manage all the wires from the connections reported on Table 1 and will connect all the termination to the instruments in order to execute the wire connection test, electrical functionality test and high or low voltage insulation tests.

| N. Devices | Device description | Terminals | Connections | Notes |
|------------|--------------------|-----------|-------------|-------|
| 20         | Cernox/CCS CLTS    | 4         | 80          | Only wires and readings |
| 13         | PT100 Resistors    | 2         | 26          | Wires and Resistance readings |
| 5          | Thermocouples      | 2         | 10          | Only Voltage readings |
| 18         | Heaters            | 2         | 36          | Power test and thermal coupling |
| 1          | Cryocatcher        | 1         | 1           | Only Insulation |

**Total number of required connections** 153

*Table 1.* List of the devices present inside one of the cryostat module, mainly thermometers and heaters for monitoring and temperature control. The connections column reports the total number of wires needed. The last column reports the kind of tests that can be done on that type of device.

The wire connection tests apply to the four-contact thermometers, where it is not possible to prove the device, usually a doped semiconductor with unknown resistance. The test measure the electrical resistance of the two couple of wires joined together on the same sensor terminal ensuring that both couples of wires are connected together on their extremity. On the thermocouples, with only two-contact connections and negligible intrinsic resistance, this measure is applied to the two contacts. The test may be considered passed if the measured resistance values are compatible with the expected value of resistance of the wires. The connection test on the two-contact heaters and PT100 sensors is the same as thermocouples. In this case, the test may be considered passed if the measured value is compatible with the sum of the resistance of the wires and the sensor.

The electrical functionality test on the thermometers is obtained with the reading the temperature values. At room temperature, in isothermal condition, within the variation of about a degree, all thermometers should report the room temperature value. After the cool down, the same measure is less meaningful and may be omitted. The heater functionality requires a thermal coupling test. This test may be considered passed if after pouring some power into the heater, the corresponding thermometer shows a significant rise in its temperature value.

The high voltage insulation tests apply only to the superconducting taps on coils and bus-bars [2]. The tests must be done above the Dew Point with a temperature below 40 °C. Three voltage steps of 200, 500 and 1000 Volts, with respect to ground, are applied on each voltage tap for 120 s with a 120 s discharge pause before and between them [3]. Alternatively, a voltage ladder with five linear steps
from 200 to 1000 Volts with 120 s duration of each step may be used. A time interval of 240 s for
discharge is required before reversing the polarity and at the end of the test. If while increasing the
voltage the resistance falls below 100 Mega Ohm the test will be interrupted. The test is considered
passed if the insulation resistance is greater than 1 Giga Ohm for any voltage step.

The low voltage insulation tests, apply to the electronic devices, mainly thermometers and heaters
by measuring the leakage current to ground. In order to protect the low voltage device, during the
measure, all terminal have to be joined together. Two voltage steps of 20 and 100 Volts with respect to
ground are applied, each for 120 s, with both polarities. This test is considered passed if the resistance
toward the ground is higher than 100 Mega Ohm.

During the execution of all tests, room temperature and humidity are recorded together with the
atmospheric pressure. While pumping down the cryostat the value of the vacuum is monitored and the
spectra of residual gases recorded. Resistances and leakage currents will be acquired during the whole
duration of all insulation tests with a rate of 2 sample/s. All graphs will be added to the final report.

After the room temperature tests, the cooling helium gas provided by the Linde LR280R
refrigerator will chill the superconducting quadrupole within the cryostat from room temperature to
about 4.5 K. During the cool down of the QDM, besides the control of the residual vacuum pressure,
and temperatures, there will be a careful registration of some relevant signals extracted from the Cold
Box. The mass flow and the differential pressure of the in/out cooling helium gas will be measured
and monitored. The module will be considered cooled down when the designed working cryogenic
temperatures are reached and carefully stabilized.

While the QDM is kept at this temperature value, the room temperature electrical tests have to be
repeated almost identically. In this state, the tests of the superconducting sextupoles now may be
executed. The coils will be powered with a current ramp, with increasing value of intensity and rate,
up to the working values are reached and slightly overcome. During this test, a highly sensitive quench
detector, inside the power supply, will work in order to avoid damages to the superconducting coils
and to the high-temperature superconducting current leads [4].

At the end of all cryogenic temperature electrical tests, the module under test, will naturally return
toward room temperature. Because of the large masses involved this may require several days. The
circulation of warm helium gas, within the cooling pipes, may significantly accelerate the warming up
process. The control of the helium flux and its temperature, may significantly and safely shorter the
warming times. When, finally, the module is warmed up and stabilized at room temperature, the room
temperature electrical tests are repeated again. This test repetition will ensure that the thermal cycle
has not caused damages to the module coils and on the devices within it.

Through all the tests the collected data are stored locally. The decision of accepting or rejecting the
tested module will be done after the evaluation of the information contained in this file. A dedicated
Report Generator program will construct the final report by using the log and data files, written during
the test procedures and monitoring activities. All log files and data file, as soon as they are created,
will be stored in a folder as text files in order to be always readable on any computer. While reading
the information contained in the log files, the Report Generator will control the acquired values and
create the required graphics. Finally, data, text, and pictures will be merged into a single unalterable
pdf document. The log and data files used by the Report Generator program, in order to save their
integrity, will be compressed into a single password-protected archive and stored in multiple copies
into dedicated storage sites.

4. Final remarks and conclusions

The INFN group within the University of Salerno is involved into the setting up of a laboratory for
testing part of the superconducting magnets to be installed in the SIS100 synchrotron ring.
Since the tests are required on about eighty almost identical modules, a testing procedure has been created with the highest possible automation level. This will reduce the operator errors and will speed up the time needed in some repetitive measurements. This procedure at its end will generate a report that constitutes the most important document on which the decision of accepting or rejecting the quadrupole module will be taken. In this paper the procedure of quality verification of the quadrupole modules is presented in some details with a description on how the proposed steps will operate.

Nowadays this type of facility is not yet present in Italy and in Europe only few, very specialized research centers, are able to carry out testing procedure of such complexity with the needed expertise. The buildup of this laboratory for the complexity and the efforts required and the technological breakthrough represents a challenge for the Italian physics community. The presence of this scientific facility would also contribute to expand the competence of firms located on the surroundings.

References
[1] Saggese A, Iannone G, Gambardella U, Califano N and Ferrentino A 2015 IEEE Trans. On Applied Supercond. 25 4801304.
[2] Rahimzadeh-Kalaleh S, Ambrosio G, Chlachidze G, Donnelly C and Tartaglia M 2009 IEEE Trans. On Applied Supercond. 19 2442-2445.
[3] Zhang Z, Song Y, Wu H, Xie Y, Yang Z, Shen G, Wu W, Lu K and Wei J 2017 IEEE Trans. On Applied Supercond. 27 4900804.
[4] Kamby P and Elkiær A 2012 Test Procedure 501717-201 4x855 20kA/±25V and 10kA/±50V Danfysik Factory.