

The Functional Test of the SIS300 Model Dipole at INFN-LASA

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Abstract—The FAIR facility, under construction at GSI, includes the synchrotron SIS300 (300 Tm rigidity). To reach the required high intensities of protons and heavy ion beams, the bending dipole magnets (beam tube diameter aperture 100 mm) have to be pulsed from the injection magnetic field of 1.5 T to the extraction field of 4.5 T at the rate of 1 T/s. The first 3.9-m-long model dipole has been built and the functional tests have been carried out at LASA Lab. These tests have been performed inside a vertical cryostat in boiling helium at 4.2 K, and they were aimed to verify the operation of the magnet, also in pulsed regime. The paper illustrates the commissioning activities of the test station and the results of the magnet tests. The performance of the magnet with respect to quench stability and heat losses in pulsed regime will be compared with the design values.

Index Terms—Superconducting dipole, test station.

I. INTRODUCTION

THE FAIR facility at GSI (Darmstadt, Germany) in the second phase of its program, will rely on the 300 Tm synchrotron SIS300. The dipoles of this synchrotron have a maximum field of 4.5 T, in a 100 mm bore, and are fast ramped at 1 T/s. The 7.8 m long dipole has a curvature radius of 66.67 m. In a R&D collaboration between GSI and INFN, the INFN sections of Milano (LASA), of Genova and the Frascati Laboratory have agreed to design, build and test a model dipole of half length (3.9 m).

The main goal of the model is to demonstrate the feasibility of a curved superconducting dipole, working in pulsed condition, with good field quality and reasonable heat losses in the cold mass.

A general description of the project and of the magnet is given in [1], [2]. The 2-D design of the magnet is described in

Manuscript received October 17, 2012; accepted November 19, 2012. Date of publication November 21, 2012; date of current version January 3, 2013.

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Digital Object Identifier 10.1109/TASC.2012.2229771

TABLE I
MAIN PARAMETERS OF THE MODEL MAGNET

Nominal field	1.5 T – 4.5 T
Nominal ramp rate	1 T/s
Maximum current	8926 A
Nominal current rate	1983 A/s
Cable critical current @ T=4.2 K & B=5 T	18540 A
Voltage during ramp rate	22.6 V
Maximum magnetic energy	459 kJ
Coil aperture diameter	100 mm
Magnetic length	3.878 m
Curvature radius	66.667 m
Bending angle	6 2/3 deg
Yoke inner / outer radius @ 300 K	96.85 mm / 240 mm
Reference radius for field quality	35 mm

[3], where the main losses in the conductors are also reported. The mechanical calculation is presented in [4], whereas the description of the NbTi conductor is given in [5]. Table I reports the characteristics of the model magnet.

The magnet is designed to be operated in forced-flow (100 g/s) supercritical helium at 4.7 K, 3 bar absolute, and will be tested in this condition at GSI Lab. However, before the cold mass is inserted in the horizontal cryostat, a functional test was foreseen in the INFN-LASA Lab. to verify the performance of the magnet close to the final conditions.

The magnet has been tested in boiling LHe (4.2 K) in a vertical cryostat, because in the LASA facility there is no availability of supercritical helium. Moreover, a particular electrical circuit for the magnet discharge has been designed and realized in order to use the existing power supplies which can be operated only for the charge of the magnet and not for the discharge (first quadrant only of the voltage-current diagram). The description of the design of the electrical circuit which allowed to test the magnet also in the pulsed conditions, even if with some limitations, has been given in [6], together with the main description of the test station. The following paragraphs will describe the activities of the assembling of the magnet in the test station and the results of first campaign of measurements, performed in July 2012.

II. ASSEMBLING OF MAGNET IN THE TEST STATION

The magnet cold mass initially has been located horizontally in the specific movement tool necessary for the rotation of the system in vertical position. When still in horizontal position, all the assembling operation were performed, i.e.

- Position of the upper flange of the vertical cryostat. The flange has been aligned respect to barycenter of the cold mass and fixed in the movement tool. For the alignment a laser tracker with the position reconstruction of the cold mass has been used.



Fig. 1. Magnet and movement tool just rotated in the vertical position (left) and insertion of the magnet in the vertical cryostat (right).

- Position of the three XX mm long and YY mm diameter stainless steel rods for the coil mass suspension in the cryostat upper flange. The final regulation of the tension and positioning of the rods for a correct repartition of the cold mass weight has been executed after the vertical rotation of the cold mass.
- Horizontal insertion of the two 1.5 m long current leads, ap-positely designed and custom built for this test station [6].
- Assembling of the 950 mm long superconducting bus bars on the cold heads of the current leads. These bus bars have the double function to feed the current in the magnet from the current leads and keep the temperature of the current lead cold heads inside the designed values (4.2–6.5 K, depending by the maximum-minimum level of LHe in the cryostat). The superconducting bus bars have been realized with samples of ATLAS-Barrel Toroid conductor [7] (Rutherford NbTi 40 strands cable core, stabilized with a 12 mm \times 57 mm ultra-pure aluminum). Per each current leads, five bus bars have been used: between them, only one is used to feed the current, so the other four have the function of “cold finger” to cold the current leads heads. The aluminum contact surface of the bus bars respect the current leads head, was previously treated with indium deposition to enhance the electrical/thermal exchange properties.
- Soldering of the magnet Rutherford cables to the bus bar Rutherford cables.
- Connection of the diagnostic cables to the connectors in the upper flange.

After all the assembling, the magnet and the movement tool has been rotated in vertical position, using the main crane of the laboratory (Fig. 1, left). During this operation the magnet was kept tight to the movement tool with belts, and when in vertical position the weight was transferred to a special cradle at the bottom of the magnet, because the three suspension in the flange had not been regulated. When in vertical position, a “IMPALCATO” was built around the movement tool, in order to allow an easy and safe work around the upper flange for the final regulations.

The calibration of the length of the suspension has been performed by partially lowering the flange with the crane and measuring with strain-gauges the load on each rods. In this way it was assured that the total mass of the magnet was equally distributed on the suspensions.

Finally the flange with the cold mass was lowered with the crane and inserted inside the vertical cryostat (Fig. 2, right).

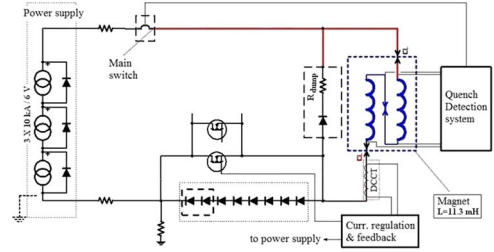


Fig. 2. Electrical scheme of the magnet for the test at LASA.

III. TEST STATION DESCRIPTION

The electrical circuit scheme for a fast pulsed magnet would require a power supply working in the first and fourth quadrant of the voltage-current ($V-I$) diagram. In this way, the power supply can give energy to the magnet during up-ramp and to absorb energy during down-ramp. At LASA lab. we had at disposal three power supply units, each capable to provide 10 kA with an output voltage of 6 V operating in output voltage or current regulation mode. The ripple is compensated by an active compensation circuit; the residual ripple is difficult to estimate, since the operating condition (a almost pure reactive load) can hardly be simulated without the superconducting magnet in operation. Since these power supplies can operate in the first $V-I$ quadrant only, a diode bench with in parallel twenty MOSFET's has been inserted in the current circuit, to allow a controlled fast current discharge (Fig. 2).

During the ramp up of the magnet, the MOSFET are polarized to be closed, and consequently the three power supplies in series can increase the current in the magnet at the maximum voltage of about 16 V, corresponding to a magnetic ramp rate of 0.7 T/s (1400 A/s). This value is 70% of the nominal magnet ramp up, and the limitation is due to the maximum voltage of the power supplies in series (18 V, minus about 2 V for the resistive voltage drop in the bus bars). During the ramp down, the MOSFET are polarized to be open, and the current flows in the diode bench (12 diodes in series), which allows the magnet to discharge with a ramp rate of about 0.7 T/s. During the charge and discharge, the current is regulated using a DC current transformer (DCCT) in series with the magnet. In case of quench detection, the Quench Detection System (QDS) activates the fast discharge: the main switch is opened and the current is discharged through the dumping resistance ($R_{dump} = 44 \text{ m}\Omega$). In this case the maximum voltage in the magnet is 400 V.

The current leads have been optimized for the warm-to-cold transition in order to minimize the thermal load on the LHe. The length of the leads (from the maximum level of the LHe to the top of the closing flange of the cryostat) has been fixed to 1280 mm (at room temperature), as requirement of the cryostat design to have free room above the maximum level of LHe for the containment of over pressure in case of a sudden evaporate of helium. This characteristic has led to design the current leads internally, because it was not possible to find in the market products with similar length. Moreover, the fact that the current can be ramped up to 2000 A/s, discouraged the use of commercial high- T_c current leads, because their performances are reported for current ramp rate one order of magnitude lower. A more detailed description of the current leads was given in [6].

The data acquisition and control system performs different tasks involving both the magnet under test and the test station itself; in the follow sub-paragraphs they will be shortly described.

A. Slow Acquisition

It records the temperatures in the magnet and at various locations of the test cryostat, the internal pressure, the vacuum pressure, the voltage drops along the current leads and the bus bars and the overall voltage across the magnet. The acquisition rate is approximately 1 Hz. Data are shown on a console and stored, but no feedback is provided.

B. Magnet Safety System (MSS)

It manages all the faulty condition of the test station and of the magnet under test; it provides, as outputs, two logical signals which activate, respectively a slow-discharge or a fast discharge. For reliability reasons, it is hardware-implemented and it does not depend on any computer based system.

The most important part of the MSS is the Quench Detection System (QDS). QDS subtracts the voltages across the two pole coils and any absolute residual value larger than 100 mV lasting more than 20 ms is interpreted as a quench. In addition, the absolute voltage drops across the internal splice and the two external splices between the magnet's end and the current bus-bars are monitored, with the specific thresholds of 20 mV for the quench triggering. Unfortunately during the magnet cool down a voltage connection of one of the external splice (between the magnet and the bus bars) resulted broken: then the voltage drop of this splice was monitored with a different spare connection, which was very noisy in signal because not twisted to the other voltage connection. For this reason the threshold voltage of this splice was increased up to 500 mV during the fast ramped tests.

C. Fast Acquisition

It records the voltage across the two magnet coils, the internal splice, and the overall tension between the magnet ends, in case of a quench. All the signals are fed, by means of a resistive voltage divider, to an array of custom made, optoinsulated, conditioning boards [8], whose outputs are read by a 18 bit PCI-6288 National Instrument acquisition board running on a PC, with a sampling frequency of about 1 kHz.

IV. CRYOSTAT

The vertical cryostat for the test is situated in a hollow, 6.5 m deep, already present in the experimental area. The vacuum chamber cylinder has an internal length of 720 mm and an internal diameter of 700 mm. The cold mass has been inserted from the high and suspended from the upper flange of the cryostat with three stainless steel suspensions (see Fig. 3).

The maximum level of the LHe from the bottom of the cryostat is 5795 mm, in order to leave a safe minimum clearance between the upper surface of the LHe and the closing flange of 1405 mm, corresponding to a free volume of 0.51 m³. The maximum LHe volume inside the cryostat is 1.33 m³, and pessimistic calculations have shown that in case of sudden evaporation of the LHe for a quench (all the magnet energy transferred into the LHe), the maximum pressure inside of the cryostat would be 5100 hPa absolute. Consequently all the cryostat has been certificated for a maximum pressure of 5500 hPa absolute. As additional security, a pressure relief valve for over-pressure of 4200 hPa (relative) has been mounted in the cryostat. The total thermal load on the LHe for the thermal radiation and the cold mass suspensions is about 10 W.

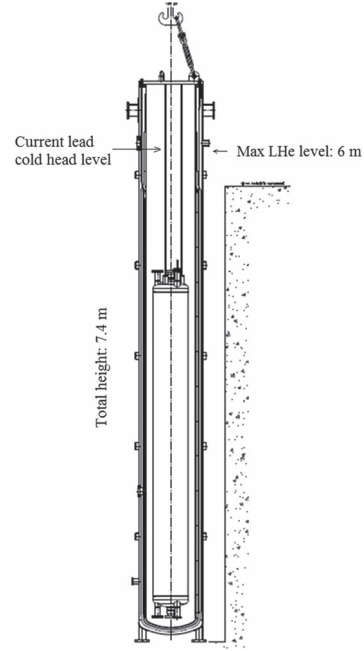


Fig. 3. Cross-section of the vertical cryostat, with the cold mass inside. The cryostat basement is in a hollow 6.5 m below the walking floor of the LASA experimental area.

V. MAGNET COOL DOWN

The magnet has been cooled from 300 K to about 90 K with GN₂ controlled in temperature: the cold gas was blown at the bottom of the magnet, in the space between the beam tube and the coils. The maximum temperature gradient allowed during the cool down was 30 K between 300 K and 150 K, and then 40 K below 150 K. It was necessary about 3 weeks to cool down the magnet up to an average temperature of 80 K. After that, the cooling with GN₂ was not efficient to decrease the large temperature gradient between the upper and lower part of the cold mass; so the cryostat was filled with LN₂, and after the time necessary for the magnet thermalization, the LN₂ was siphoned out. Heaters at the bottom of the cryostat and temperature sensors allowed to control that no residual LN₂ was present at the bottom. Finally the step from 80 K to 4.2 K was reached in about 5 days, by flowing LHe from the bottom of the cold mass.

VI. MAGNET TRAINING

The magnet was tested in two runs (July and October 2012). The first tests were aimed to check the equipment and the protection system, in particular the effectiveness of the quench heaters and the capability of the QDS to detect the quench and to activate the protection. After the positive results of these tests, the magnet was ramped up to 9000 A at low ramp rates (less than 100 A/s). A training quench was reached at 8230 A, corresponding to 92% of the nominal current. After that, the magnet reached successfully 9000 A, corresponding to 100.8% of the nominal current. In Fig. 4 the cable short sample critical current vs. the magnetic field at different temperatures (scaled from measurements at 4.2 K) is shown. The figure also shows the load line of the conductor peak field, the operating point on the load line and the training quench. The maximum temperature of the He bath considering the hydrostatic pressure at the bottom of the cryostat is 4.3 K.

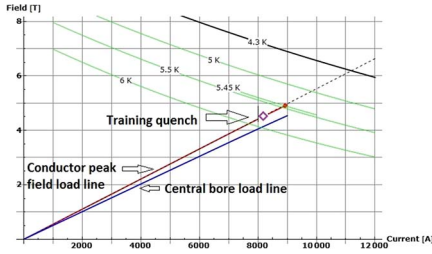


Fig. 4. Conductor short sample critical field (scaled at different temperature) versus current, conductor peak field load line and bore field load line, operating point on the load line, and training quench.

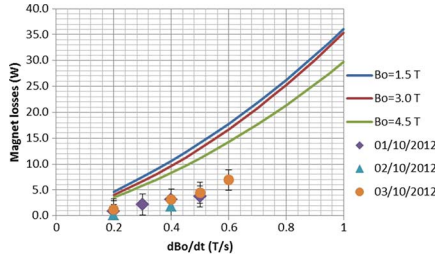


Fig. 5. Magnet losses in pulsed condition measured from the difference of the evaporative He in pulsed regime and static regime. The continuous curves represent the instantaneous estimated losses, scaled from the values at the nominal ramp rate $dB_0/dt = 1$ T/s [2], [3].

VII. PULSED REGIME

After the test in static condition, the magnet was operated under pulsed regime. Different charge-discharge cycles were applied acting on three parameters: minimum current, maximum current and ramp rate. Typically we used cycles with 1) a bottom flat of 1–2 seconds at a given minimum current, 2) a current rise to the maximum current at ramp rates up to 1400 A/s, 3) a top flat of 1–2 seconds at the maximum current, 4) a current decrease down to the minimum current with the same ramp rate used for rising the current.

These tests demonstrated that the magnet can be charged up to the maximum current at the maximum available ramp rate, but there is some limitations to the current sweep amplitude. As an example for a current sweep from 3000 A to 9000 A (corresponding to $B_0 = 1.5$ T–4.5 T), the magnet could reach the final current value with a maximum ramp rate of 300 A/s. If the minimum current is 5000 A, the maximum current can be reached with no quenches at a ramp rate of 1000 A/s. For minimum currents higher than 5000 A, ramp rates up to 1400 A/s can be used with no problem and the magnet can be cycled for an indefinite number of times.

The limitation in the maximum allowed current sweep is present not only ramping up the magnet but also ramping it down. As an example, when ramping down the magnet from 8000 A at 1000 A/s a quench occurs at 2600 A.

In order to understand if the quenches are caused by ac losses, a preliminary loss measurements have been performed in continuous pulsed conditions ($N_{\text{cycle}} > 100$). In the ramp rate range of 400–1200 A/s, the difference of the He gas flow in pulsed and static condition was measured and converted to a power loss. Fig. 5 shows the results, along with the curves of the estimated losses [2], [3]. From this preliminary measurements it appears that in this range of ramp rates the experimental losses are at least 50% lower than the estimated values during the design.

Because of this low values of the losses, the limitation in ramp rate seems not to be ascribed to unexpected volume of dissipations; a possible reason could come from saturation of critical current in some parts of the conductor, where a number of strands can act as loops, inductively coupled with the rest of the magnet. If such a zone is located in a low field region, the local magnetic field is not too much different at low and high current. This could justify why the limit in ramp rate is equally present both in ramp up and ramp down, i.e. almost independent of the final value of the field and is largely dependent on the amplitude of current sweeping ΔI . These loops may be located in the conductor ends, where the Rutherford cable is brazed to high pure copper to enhance the conductor stability. Other possible causes may be taken in consideration, as localized large losses, bad thermal conduction of boiling LHe in some zones, current redistribution between cable strands and mechanical instability more critical in the pulsed regime. A future more deep analysis will have to show what of these possibilities are more likely.

VIII. CONCLUSION

The first preliminary test of the SIS300 model dipole has been carried out at LASA. The test station worked properly, in particular the novel scheme of the electrical circuit with the controlled discharge in diodes benches was reliable. The magnet reached the maximum field with only one training quench at 92% of the design operating current. The tests in pulsed regime showed that the magnet can work up to 1400 A/s (the limit of the test station capability), but with some limitations in the maximum sweeping of the current. The first data show the losses are lower than the estimated values. The limitation in the maximum current sweeping could be due to some localized large current loops inside the cable. A more precise characterization will come in the next months, and the final test in all the operating conditions will prosecute at GSI.

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