Compact cryogenic test stand for superconducting magnets characterization

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Abstract. A new compact experimental facility for testing compact superconducting magnets down to 4.2 K using cryogenic fluids has been developed at CEA Paris-Saclay. This facility has been constructed to test the solenoid magnets for the next Soreq particle accelerator (SARAF) project. The magnets are cooled with liquid helium at 4.2 K and the liquid bath can be pressurized up to 2 bars to regulate the temperature of the magnet during operating conditions. In this facility, it is possible to measure and dissociate the heat loads coming from the magnet and the current leads by flow-metry. The voltage of the solenoids and their current leads are measured using National Instrument devices and monitored with a Labview program to identify and analyze eventual quenches. The magnetic performance of the magnets are also monitored dynamically with 3D hall probes. Numerous cryogenic temperature sensors are used to characterize the thermal evolution of the magnet and its current leads during the test. In the present paper, the compact facility is described and the first results obtained on the current leads of the magnet prototype are presented.

1. Introduction
A new accelerator facility, SARAF (Soreq Applied Research Accelerator Facility) will be soon installed in the Soreq Nuclear Research Centre. This facility will be used for the development and production of radio-isotopes for medical and biological research. SARAF is designed as a continuous wave (CW), proton and deuteron accelerator based on superconducting RF cavity technology. The CEA of Paris-Saclay is committed to deliver a Superconducting Linac (SCL) for the SARAF accelerator (see Figure 1)[1]. The 20.1 m long SCL is made of 4 cryomodules with a total of 20 superconducting identical Solenoid Packages (SP) located between the cavities to focus the beam [2]. The maximum on-axis peak field is 5.8 T. A Beam Position Monitor (BPM) is placed upstream each solenoid package. Each solenoid package, including the BPM, the solenoids (and associated steerers), the end bellows and flanges, is 34 cm long. Including the prototype and 2 spare elements, a total of 23 solenoids and their current leads (CL) will be tested at a temperature of 4.45 K and a pressure of 1.25 bar in a cryogenic test bench at the CEA of Paris-Saclay. Six current leads (CL) placed on the same flange (CL cluster) supply the current to the solenoids. Each solenoid and its corresponding current lead are tested at nominal current and during a quench, in order to evaluate their thermal and electrical behavior. This paper presents the test stand that has been developed to characterize the 22 solenoids of the SARAF accelerator facility and their current leads. This test facility monitors the temperature, the voltage of the different solenoids and the magnetic field at different positions.
2. The Cryostat of the Solenoid test bench

An experimental test bench has been designed and prepared to test all the 23 solenoids of the SARAF accelerator facility manufactured by Elytt Company and their corresponding current leads individually.

2.1. Overview of the cryostat insert

To test the solenoids, a specific insert made of 304 L stainless steel has been designed and manufactured by Cryodiffusion company. For the zones close to the solenoid, 316L non-magnetic stainless steel has been used to avoid any interaction with the leakage field. On the top, the main flange seals the cryostat (1.7 m height and 410 mm internal diameter) and the bottom part is connected to the helium tank of the solenoid package. A nitrogen tank surrounding the cryostat act as a thermal shield. The helium circuit of the insert is composed of a CL tank, a phase separator and several connections to fill it with liquid helium at 4.45 K and regulate its pressure at 1.25 bar. Figure 3 shows the main elements surrounding the mechanical parts with, the CL cluster composed of 6 current leads, the helium transfer line and the stainless steel rods which are attached to the upper main flange and supports the solenoid screw to Norcan© part. The CL cluster and the phase separator tank (about 5 liters) are connected to the Y-shaped helium circuit on the top of the solenoid. A 100 mm height retracted below is soldered at the bottom of the CL cluster tank. This part is designed to simplify the brazing between the current lead extension and the solenoid superconducting wires. Five horizontal thermal shields are installed between the top of the phase separator and the main flange. These thermal shields with a thickness of 1 mm and a diameter of 380 mm, they reduce the radiative heat fluxes arriving in the facility core. The closest thermal shield to the main flange is made of copper, welded to the CL cluster tank and to the outlet helium tube.

2.2. Cryogenic, vacuum and safety system

The pressure of the helium bath is regulated using a Burkert© automatic valve (Type 8692). A solenoid valve, attached to this circuit, opens completely if the pressure of the bath reaches 1.5 bar. These two valves are connected to the helium recovery line of the laboratory. In addition, a manual safety valve has been installed to release the helium directly outside above a pressure of 1.8 bar. The level of liquid helium is monitored using a 20 cm active sensing length sensor placed in the phase separator. Two cernox temperature sensors are fixed with copper charged epoxy.
glue at the surface of the phase separator and the current lead helium tank in the cryostat, to
monitor their temperature using a Lakeshore\textsuperscript{\textregistered} 336 temperature controller. Two other cernox
temperature sensors are screwed at the surface of the helium tank of the solenoid package, close
to the inlet and the outlet of the helium circuit, respectively. The mass flow in the different pairs
of current leads is controlled with LabVIEW\textsuperscript{\textregistered} regulation loops using Burkert\textsuperscript{\textregistered} solenoid valves
(Type 2871), connected to a National Instrument NI9265 card, and a Red-Y mass-flow-meter
(GSC-B9KA-BB23). The mass-flow-meter has been calibrated between 0.06 and 600 ml/min
using helium gas at room temperature. Two Pfeiffer\textsuperscript{\textregistered} turbo vacuum pumps with a primary vacuum system are installed to maintain a vacuum environment at the beam tube and the
cryostat lower than $10^{-5}$mbar.

![Figure 3. Schematic illustration of the test bench (left) and schematic illustration of the
cryogenic and vacuum system (right).](image)

3. Current leads cluster
This section presents the instrumentation to monitor the thermodynamic and electric behavior
of the current lead cluster.

3.1. Voltage measurements
The current leads manufactured by Criotec Impianti are connected to three CAEN\textsuperscript{\textregistered} power
supplies. One delivers a maximum current of 100 A and the other two deliver a maximum
current of 25 A. To perform the different acceptance tests, the CL pairs are connected each
other using the superconducting wire and the copper braid at the bottom of the extension of
the current lead (see Fig. 3). As long as the bottom of the CL extensions are in contact with
the LHe, the current goes through the superconducting wire and no resistance is added to the
electrical circuit. Otherwise, if the superconducting wire becomes resistant, the current goes
through the copper braid. The section of the copper braid is thick enough to prevent any high
voltage increase in the CL electrical system when the CL extension is no longer in contact with
liquid helium. Voltage taps are tin soldered on the copper parts located at the helium inlet
and the outlet of each current lead. Furthermore, other voltage taps are located surrounding the superconducting wire and the copper braid to monitor their electrical behavior during the tests. The voltage taps are connected to the Ni Card 9239 and monitored using the LabVIEW software.

3.2. Temperature and control mass flow system

Ten platinum temperature sensors (PT100) are glued at the 25 and 100 A CL to monitor their thermal behavior during tests. Five PT100 are placed along one 100 A CL at different positions. Four of them are inside the helium tank at cryogenic temperature and one is placed outside at room temperature, close to the helium outlet. One 25 A CL is also instrumented with 5 PT100 placed exactly at the same position. These sensors monitor possible temperature variations (‘hot spot’) of the current leads and these temperature variations are compared with simulation results. Fig. 4 shows the position of the temperature sensors along the CL with real dimensions along the brass braid. The brass braid composing the current lead ensures the heat exchange with helium gas flowing in the CL pipes. This material is retracted to improve the heat exchange between the copper brass and the helium gas. The positions of the sensors before the length reduction is indicated in red in Fig. 4. In addition, holes in the G10 electrical insulation have been done to install the temperature sensors at the external surface of the CL stainless tube using epoxy glue charged with copper powder. Those holes are covered with Kapton® tapes (see Fig. 4).

Figure 4. Photo of the current lead cluster (left) and temperature sensor positions along the current lead (right).
4. Solenoid
The tool that connects the superconducting wires between the solenoid package and the current leads cluster and the magnetic measurement system are presented in this section.

4.1. Brazing tool
To connect the superconducting wires coming from the solenoid package with their current leads, a special tool has been designed to silver braze each of the 6 wires at 5 to 8 cm length at the surface of the current lead extensions. All the 23 solenoids will be tested for the SARAF particle accelerator facility and the brazing process requires a special tool. This tool is composed of a Peek support and 6 aluminum blocks with a ceramic heater (Fig. 5). The peek support maintains the 6 current lead extensions and isolates electrically each current lead. The aluminum block are screwed at the surface of each current leads. Vertical grooves have been machined on each of these elements to maintain the superconducting wires coming from the solenoids. The ceramic heater, placed on the top, increases the temperature of the aluminum block up to 250 K. The temperature is regulated during the brazing process using one platinum temperature sensor placed inside one of the aluminum parts. The gaps between the aluminum block and the Peek support are sealed using Silicomet glue, except at the top of the assembly, around the superconducting wire. This allows to insert the silver tin inside the superconducting groove and to prevent the hot liquid silver tin to flow out of the brazing tool.

![Figure 5. Superconducting cable joints with current leads.](image)

4.2. Magnetic measurements
Heigh 3D Hall effect probe have been used to monitor the magnetic field of the solenoid package. Six probes are inside the beam tube of the solenoid package, along the axis. Four of them are Aeropoc Axis-3 with a sensibility around 100 mV/T at field up to 5T. They have a simple cylindrical shape with an outer diameter of 7 mm and a length of 18 mm. These probes can be used in higher fields at temperature range between 1.5 K and 350 K. Nevertheless, the non-linearity of the probes due to the Shubnikov-de Haas effect (quantum oscillations) increases
above 5T. The 2 other 3D Hall effect sensors are both made of three 1D Arepoc® HHP-VU probes. Their overall dimensions are 5 x 4 x 1 mm with an active area of 50 x 50 mm and a center located by around 1.8 mm from the front edge of the probe. They have lower sensitivity (around 20 – 30 mV/T) and present a linear evolution in fields above 5T. Two other 3D Hall effect probes, composed also of 1D sensors, are placed outside the helium tank of the solenoid package, close to the horizontal and vertical steerer coils. The position of those sensors is presented in Fig. 6. All the sensors are connected to Aeropoc® USB2AD-modules which are composed of 8 analog inputs (voltmeters) with a programmable resolution 20-24 bits and a single programmable DC current source controlled by a 16bit DAC. The USB2AD module is controlled using the LabVIEW software.

Figure 6. Magnetic measurements system.

5. First results with the current lead cluster
The 25 A and 100 A CL have been tested with nominal +10% current, which correspond respectively to 21 A and 91 A. The level of helium is 10 cm higher than the inlet of Current lead at the beginning of the experiment and decreases slowly during the entire test. At the end of the test, the current lead extensions are no longer in contact with liquid helium. This section presents the voltage and temperature results with the 100 A current lead. The optimum or nominal helium mass flow circulating inside the current leads has been estimated at standard temperature before performing the tests in order to reduce the energy consumption of the overall system [3-5]. This cooling method achieves better thermal performance than conduction-cooled current leads [6].

5.1. Mass flow versus voltage
The measurements of the 100 A current leads are shown in Fig. 7 with a current of 91 A on each of them from 14h20 to 15h45. The mass flow through both current leads is controlled by the LabVIEW® software and set to the optimum mass flow, half and quarter of the optimum mass flow which represent 3.94, 1.97 and 0.985 normal liter per minutes, respectively (NL/mn in SI units). At 15h15, all the current lead valves are closed and the helium no longer flows inside the CL until the end of the experiment. The experiment has been stopped when the LHe has been entirely vaporized in the tank. The voltage slightly increases (few mV difference) when
the helium mass flow is reduced. With the nominal helium mass flow, the voltage is about 60 mV in both current leads and, at the end of the experiment, the maximum voltage is 72 mV (about 15% higher) with no liquid helium in contact with the current leads for at least one hour. In the simulation with the bottom of the current lead in contact with liquid helium at 4.45 K, the maximum voltage without helium flow in the current leads is 84 mV. Furthermore, the voltage difference between the two 100 A CL is less than 5%. The fluid circulation is equivalent in the two current leads. Fig. 7 shows the test results between 14h24 and 15h40 with the simulation results at nominal current and mass flow. This simulation does not take into account the surrounding cryogenic environment. The voltage measured with the nominal mass flow is lower than the simulation (about 5% lower). The voltage is still lower than the simulation results with half of the nominal mass flow.

5.2. Temperature measurements

Fig. 8 shows the evolution of the four temperatures along the 100 A current lead in the helium tank. The 4 temperatures along the 100 A current leads increase slowly during the entire test, even if cold helium gas does not flow inside them. There is a high increase of the temperature when liquid helium is not in contact with the CL extension at the end of the test. The thermal characteristics of the brass braid composing the current lead and the cryogenic environment surrounding them are responsible of slow thermal variation. Those tests show that the temperature along the current lead never reach a temperature higher than the ambient temperature, even after two and a half hours working with a nominal current of 91 A and without any helium circulation. The simulation performed considers the bottom of the CL at 4.45 K and different mass flow values have been tested (Fig. 8). The comparison between the temperature profile of those calculations and the experimental results shows that all the temperatures are below the calculated temperature profile with 62% of the nominal mass flow. After more than two hours with no helium circulation, the temperature exceeds this last profile. Nevertheless, those values are lower than the temperature expected in the simulation without helium circulation in the current leads. The electrical and thermal behaviors of the 100 A CL prove that their characteristics are better than expected in the simulations and that they can
even work with no helium circulation inside them during several hours without any safety issues.

**Figure 8.** Temperature along the 100 A current lead compared with the simulations.

6. Conclusion
This paper has described the compact test bench that has been created to characterize the 23 solenoid packages and their current leads cluster that will focus the beam between cavities of the future SARAF accelerator facility. The entire helium circuit at 4.45 K and the instrumentation that measures the voltage, the temperature and the magnetic field surrounding the magnet have been described. The first experimental results on the prototype current leads cluster have shown a better thermal and electrical behavior than expected with simulation results. Furthermore, the test bench is ready for the next tests on the prototype solenoid package.

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