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Test set-up for the cooling of heavy magnets by controlled way down to 77 K

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Abstract

In the scope of the High Field Magnets work package of the European FP7-EuCARD project, the structure of the future dipole magnet RMC and FRESCA2 has been tested at liquid nitrogen temperature replacing the actual Nb_3Sn-based coils by aluminium dummy coils. Such test aims at measuring during the cooling the evolution of the mechanical stresses and the temperatures via compensated strain gauges and carbon-ceramic sensors placed at various locations on the structure (shell, rods, yokes, dummy coils). These measurements help assess the thermo-mechanical behaviour of the assembly for different applied pre-stresses and validate the finite element simulation of the magnet cooling before including the definitive brittle Nb_3Sn coils. For this purpose, a specific cool-down / warm-up nitrogen test station has been built up at CERN in order to control the required maximum temperature gradient in the magnet during both cooling and warming. In this paper, we present in detail the test facility, the instrumentation along with the automatic process control system. An analytical approach computing the expected temperature evolution during a thermal cycle is introduced and the temperature measurements related to the magnets cooling down to 77 K and warm up to room temperature are presented.

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Keywords: large scale magnet; cryogenics system, nitrogen cooling facility, high field magnet

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1. Introduction

The next generation of High Field Magnet (HFM) to be installed at CERN in the “Facility for the Reception of Superconducting Cables” (FRESCA) aims to produce thanks to an upgraded superconducting magnet, FRESCA2, a dipolar magnetic field of about 13 T in a 100 mm clear bore (9.5 T / 56 mm for FRESCA) [1]. To produce such field, Nb_3Sn conductor will be used instead of previously NbTi. But Nb_3Sn is brittle and the impregnated coils will now sustain larger mechanical pre-stress (150 MPa) after assembly and cool down [2]. For these reasons, the thermo-mechanical behavior of the magnet structure should be studied both by numerical analysis [3] and experimental measurements before setting the Nb_3Sn coils in their final assemblies.

In order to measure the properties of FRESCA2 magnet structure along its cooling to cryogenics temperature, a new Nitrogen Test Facility (NTF) has been built at CERN outside the SM18 building between December 2013 and March 2014 and so for a temporary basis of six months. For this experiment, Nitrogen coolant has been chosen as the thermal contraction coefficients of the magnet materials hardly vary below 77 K (liquid N_2). Using the new installation, FRESCA2 structure with Nb_3Sn coils replaced by bulk aluminum blocs that simulate their presence has undergone three thermal cycles from room temperature to liquid nitrogen. Different pre-stresses were applied each time to the dummy coils. The purpose of this paper is to present in detail the novel Nitrogen Test Facility, the cooling time assessment by analytical model and the measurements recorded during the thermal cycles.

a) b) c)

Fig. 1. a) Global view of the Nitrogen Test Facility at CERN; b) view of the Magnet Flushing Station; c) view of the FRESCA2 insertion.

2. A novel nitrogen test facility

2.1. Main issues of the experiment

As displayed in Fig. 1a, the Nitrogen Test Facility is composed of the main LN_2 tank that supplies liquid Nitrogen to the Magnet Flushing Station (MFS) which feeds in return the cryostat with N_2 liquid or gas at regulated temperature, Fig. 1b. The cryostat is surrounded by the magnet holding structure in blue and a scaffolding to access to the top. The experiment is driven from a dedicated room where the electrical rack and instrumentation acquisition system stand. Fig. 1c depicts the insertion of FRESCA2 hanging on its insert and suspended by the crane.

The set-up of the facility has presented several issues. The first arises from the large dimension and weight of FRESCA2 (1036 mm x 1600 mm for 8370 kg). Therefore, a truss was needed to support the magnet weight since the cryostat itself could not. Besides, since only 36 mm was available to fit the structure in the cryostat, proper mechanical alignment of the set-up was insured. A second problem comes from the differential shrinkages of the various materials that occur during cool-down. These may locally lead to stresses in the Aluminum part close to yield point (400 MPa) if the cooling process is too quick. This mechanical constrain limits the thermal gradient between any parts of the structure. To be in safe condition, a maximum value of 100 K was chosen. A consequence is that no direct liquid nitrogen could be used. The problem is solved using the MFS to perform a pre-cooling with nitrogen gas at regulated temperature then pour liquid nitrogen when the warmest area reaches 180 K. As analytical approach proves, more than 48 hours is required to reach 77 K thus an automatic process was chosen to control the experiment. The last issue concerns the intensive instrumentations installed both to monitor the structures (temperature and strain) and to control the test facility (temperature, pressure, LN_2 level, valve and heater controls). A proper Data Acquisition System was then required. These three aspects of the project are now described in details.

2.2. Nitrogen test facility set-up

The NTF is installed on a re-enforced concrete platform qualified to support the 12 t installation. As detailed in Fig. 2a, the square-shape holding structure made of steel (EN S235) is 4.95 m high and 2.22 m large with 160 mm x 165 mm feet qualified for an effective divided mass of 10 t. The magnet hangs under a re-enforced steel plate (HEA160, 40 mm thick) via three stainless-steel rods (304 L, 40 mm diameter and 2.29 m long) linking the magnet and the plate by six knuckle joints. The plate is deposed on the truss in four provided notches. The truss hosts the cryostat (4.5 m long and 1.1 m wide) which is settled and ground spited after proper alignment.

The cryostat has been recuperated from former station. It consists of a stainless steel inner and outer vessels connected by a top flange with a vacuum pump inlet, two safety relief valves (1.5 bar abs) and two rupture disks (2 bar abs). Super-insulator layers (10 LMI) stand between the vessel walls to block radiation heat whereas a vacuum of 10^{-5} bar is set in-between to stop the convective transfer. Fig. 2a shows a view of the structure, cryostat and magnet structure with relevant dimensions.

Fig. 2b displays the top-plate (304 L) that closes the cryostat. Flanges are implemented for the gas inlet (DN50), the gas outlet (DN80), the bursting disk (DN50, 2 bar abs.), the holding rods and the instrumentation path (DN200). Because of the alignment of the assembly and of the tight clearance between the magnet and the cryostat inner wall, the top plate is composed of a 3-layer sandwich (3 mm x 20 mm thick) made of three plate rings (1.16, 1.02 and 0.89 m diameter) and one main disk (1.04 m) as seen in Fig. 2c. The disk can slide in the transverse plane according to the 40 mm-interstice offered by such assembly.

When the top-plate is in contact with the cryostat flange, the bolting between the inner ring and the main disk is tighten whereas the outer ring is bolted to the cryostat flange threads. The various mechanical hermetic liaisons are insured by O-ring joints. The top plate is thermally insulated by a 150 mm thick layer of extruded polystyrene foam and three 3 mm thick polished aluminum shield disks to limit radiation.

Just as the top-plate, those allow room for the various paths. In order to bring the coolant down to the bottom of the cryostat, the female bayonet soldered to its top plate flange hosts the male bayonet that is inserted and bolt. The male bayonet is inserted in a funnel-shaped insulated pipe that runs through the magnet bore. A grill is attached at the end to create turbulence and spread the fluid. The gas goes to atmosphere through the outlet pipe that ends in a barrel to avoid freezing.

2.2. Nitrogen liquid/gas supply system

The “Magnet Flushing Station” was used to dry or “flush” LHC superconducting magnets. It has been adapted for this experiment to supply the cryostat with Nitrogen at regulated temperature ranging from 350 K to 77 K (N_2 boiling point). As schemed in Fig. 3a, the MFS is made of a vessel filled with LN_2 that contains an evaporator (H1, 5 kW). It creates a N_2 gas circulation into a 2-heater pipe (H2A, B, 3.5, 1.5 kW) that is connected to the cryostat inlet transfer line.

The LN_2 supply from the main tank to the MFS is controlled by Joule-Thompson valve (LCV700). The whole process is then driven by evaporator power to set the flow rate (up to 25 g/s) and the heater power for the gas temperature regulation (from 350 K to 77K). The valve opening is regulated according to the level in the MFS vessel.

Apart from the MFS, three heaters (H3a, b, c, 3x1.5 kW) are placed at the bottom of the main cryostat. They aim to empty the cryostat and warm-up the structure. All heaters are powered on 230 VAC lines, via static relays (on the basis of a cycle time percentage) integrated in the control rack. Mechanical switches (TCY723, 724, 725) in series with static relays (TCY702, 703, 721) cut the individual power lines under specific logical condition.

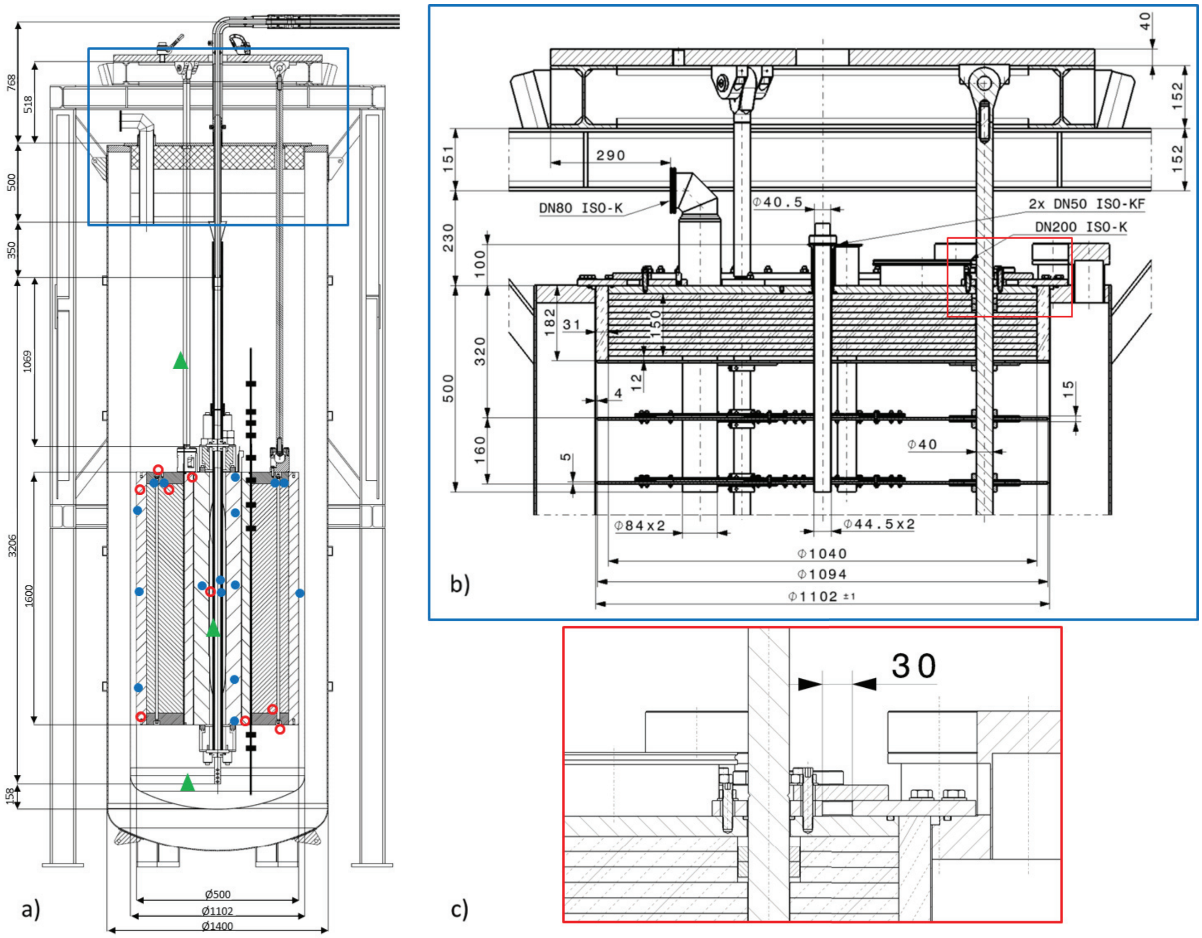


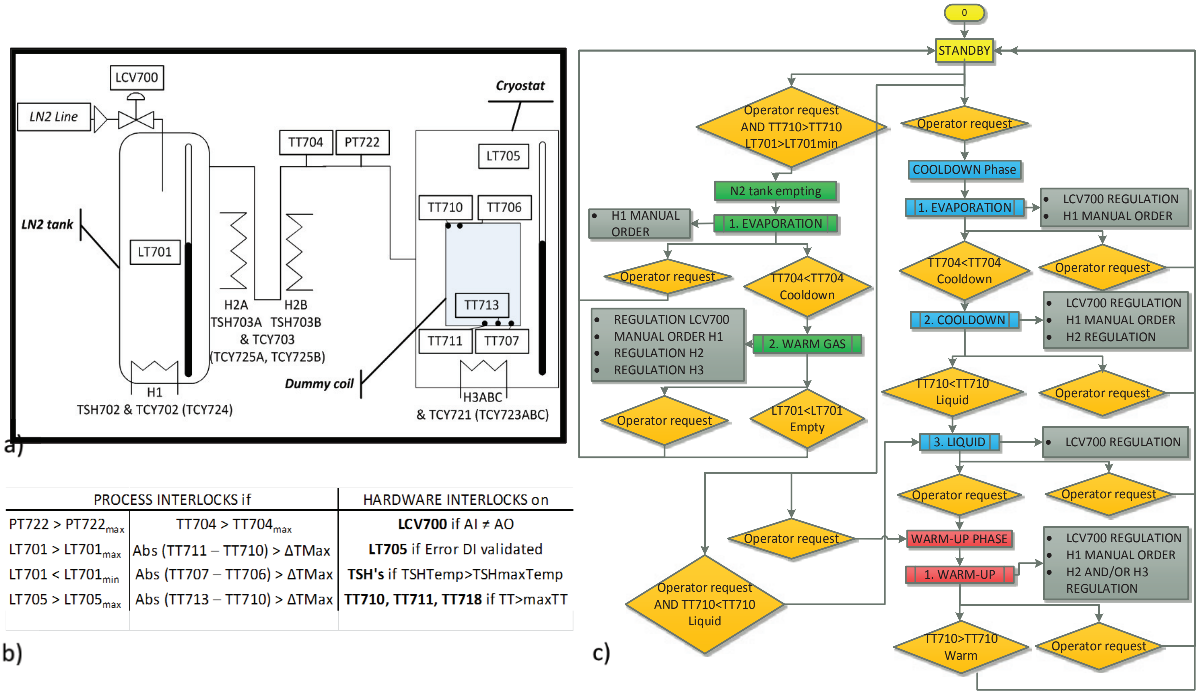
Fig. 2. a) Cross-section of the holding truss, cryostat, FRESCA2 structure and transfer-line. Full blue and open red markers point at the magnet strain gauge and temperature sensors, full square for FO, green triangles and black stroke respectively at gas temperature and the LN2 level sensors. b) Transverse view of the cryostat insert. c) Zoom-in the top plate assembly bindings to cryostat and suspension rod that allows lateral motion of the main disk to ease magnet insertion.

2.3. Instrumentation

As shown in Fig. 3a, the MFS is equipped with one pressure sensor (PT722), one temperature sensor (TT704) for the gas outlet, and 3 thermocouples (TSH702, 703A, 703B) probing the heaters.

The LN_2 level in the vessel is measured with a pressure-based level sensor (LT701). In the cryostat, three thermometers probe the gas temperature at bottom, middle and top of the structure; whereas 10 Zener diodes (LT705) regularly placed along the length detect the level of LN_2 during the cryostat fill-up. An electronic interface has been developed to verify each prove state that sends digital information output.

As shown in Fig. 2a, the magnet is instrumented by 9 carbon ceramic temperature sensors (TT7..) and 16 strain gauge sensors evenly placed on the tested structure to monitor the magnet shell, rod, yoke and dummy coils states. The mechanical measurement performed on FRESCA2 can be found in [4]. A 30 m permanent fiber optic (FO) installation is also implemented in the facility in order to perform strain and temperature monitoring during thermal cycles. Eleven Fiber Bragg Grating (FBG) sensors written in 6 fully polyimide recoated fibers are installed on the magnet shell. It reads in Wavelength Division Multiplexing (WDM) using 6 of 16 channels of the Micron Optics SM041 Channel Multiplexer and the SM125 optical interrogator. The 30 m FO can be connected between the



PROCESS INTERLOCKS if		HARDWARE INTERLOCKS on
PT722 > $PT722_{max}$	TT704 > $TT704_{max}$	**LCV700** if AI ≠ AO
LT701 > $LT701_{max}$	Abs (TT711 – TT710) > ΔTMax	**LT705** if Error DI validated
LT701 < $LT701_{min}$	Abs (TT707 – TT706) > ΔTMax	**TSH's** if TSHTemp>TSHmaxTemp
LT705 > $LT705_{max}$	Abs (TT713 – TT710) > ΔTMax	**TT710, TT711, TT718** if TT>maxTT

Fig. 3. a) Schematic of the Nitrogen Test Facility, b) Schematic of operating logic depicting the different phases of the program controlled by the operator or automatically according to probes measurements, c) Interlocks table listing the different conditions causing stop of the process.

acquisition system and the cryostat inside through 6 of the 8 leak-tight fiber optic feedthrough on the top-plate. The main results of FO measurement of this experiment are presented in [5].

3. Experiment operating principles

The UNified Industrial Control System (UNICOS) is a CERN-made framework to develop industrial control applications. It deals with the two upper layers of a classical control system: *Supervision* and *Control for automation*. All sensors and actuators described above are connected, via a control rack, to a UNICOS-designed Siemens Programmable Logic Controller (PLC), using 13 DI, 17AI (+3 thermocouple inputs), 9DO, 1AO. The PLC Supervisory Control And Data Acquisition (SCADA-PVSS) has been developed in accordance to the operating logic schematic and the Grafcet presented in Fig. 3b. PVSS allows to directly record data with short frequency configuration or threshold value per signal. Data are saved on a temporary server and on a long term database (CERN Timber) for post-mortem analysis. The automatic process is composed of 4 phases with sub-phases: i) stand-by, ii) MFS filling and evaporation start, iii) LN_2 transfer, iv) Cryostat emptying and warm up.

Static relays and mechanical switches are used to activate the heaters whereas PID regulation is applied on the JT valves according to the different phases of the process. To keep the cryogenic installation and the magnet safe, interlocks are implemented in UNICOS to act on hardware, by Full or Temporary stops. Parameters under surveillance concern the Pressure (PT722), Level in LN2 tank and cryostat (LT701, LT705), the heaters temperature (TSH700) and the thermal gradient as shown in Fig. 4c.

4. Measurement results and data analysis

The structure of FRESCA2 has undergone three thermal cycles from room temperature to liquid nitrogen (77 K) successfully maintaining a maximum temperature difference of 100 K between all sensors. In Fig. 4a, the temperature distribution in the magnet structure is shown with basically a cooling realised in the outward radial direction, from the bore to the yoke then outer shell. The cooling process last 45h 30min in total with LN_2 maintains over one night. The warm-up may take 72 hours if the process was not standby during weekend as in this third run.

In order to assess the time needed to cool-down FRESCA2, an analytical model of the convective problem was built. It is based on the mixture law (Al + Fe composite) for the nonlinear temperature dependence of the material properties and on the Biot's approximation. The latest assumes uniform temperature distribution of an infinite cylinder if the Biot number Bi of the system is below 0.1. Bi is function of the convective heat transfer coefficient h, the conductivity of the structure k_M and the characteristic length L_c equal to half the cylinder diameter as read in Eq. (1).

The main issue is about the value chosen for the coefficient h. It depends on the Nusselt number Nu of the system, the gas conductivity k_{GN2} and the hydraulic diameter D_h of the system as written in Eq. (2). Nu is largely dependent on the regime of the fluid. In the cryostat, the fluid is likely in a turbulent mode because of the various obstacles it faces. For the model, the conditions at the interface of the system gas/structure are unknown.

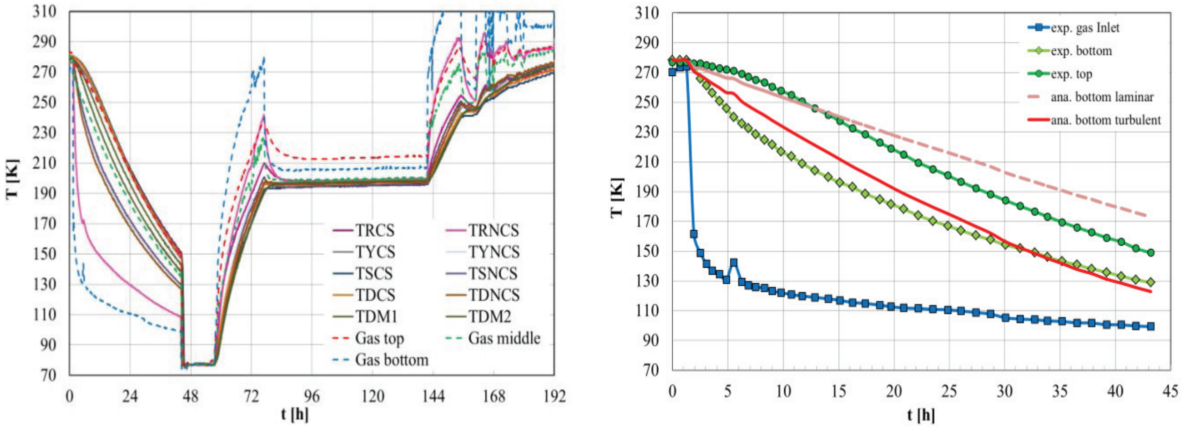
The Reynolds number Re, computed from Eq. (3) is proportional to the velocity of the fluid U_∞, D_h (0.042 m) and the viscosity of the fluid ν_{GN2} ($2.10^{-6}\ m^2 s^{-1}$). Re reads a value of 1060, below the common figure of 2300 used to define the end of the laminar flow regime. In the laminar regime, for concentric cylinder Nu reads 4.9, whereas in turbulent regime it is given by the correlation in Eq. (4) which yields to a h value of 10.5 for (Prandtl number Pr of 0.7 for GN_2). With $k_{GN2} = 0.01\ Wm^{-1} K^{-1}$, $D_h = 0.0419$ m, one get $h = 1.3$ for laminar and 2.4 for turbulent ($Re = 2300$), expressed in $Wm^{-2} K^{-1}$. At last, the Biot number with $k_M = 50\ W.m^{-2}.K^{-1}$ and $L_c = 0.515$ m gives a value of $Bi = 0.025$ for which uniform temperature can be assumed. The four relations expressed above are from [6] and reported hereafter:

$$Bi = \frac{h \cdot L_c}{k_M} < 0.1 \quad (1), \quad h = \frac{k_{GN2} \cdot Nu}{D_h} \quad (2), \quad Re = \frac{U_\infty \cdot D_h}{\nu_{GN2}} \quad (3), \quad Nu = 0.023\ Re^{4/5}\ Pr^{n} \text{ with } n = 0.3. \quad (4)$$

The lumped capacitance method defined in [6] yields to an exponential decay of the system reduced temperature θ^* with a time constant τ as written in Eq. (5) with the heat capacity $C_{p,M}$ of the structure and p_w the wetted perimeter ($p_w = 13.7\ m$):

$$\theta^*(t) = exp\left(-\frac{t}{\tau}\right), \quad \text{with,} \quad \theta^*(t) = \frac{T_M(t) - T_\infty}{T_i - T_\infty} \quad \text{and,} \quad \tau = \frac{m_M C_{p,M}}{p_w L_M \boldsymbol{h}}. \quad (5)$$

The results of the computation are plotted in Fig. 4b. The turbulent approach for the estimate of the convection coefficient seems to get closer to the experimental measurements. One may note however that the model could be refined so as to describe the observed thermal gradient dropping off the "infinite cylinder" assumption.



a) b)

Fig. 4. a) Plot of the temperature as function of time measured at the different structure and cryostat location. b) Plot of the measured and computed temperature used for the cooling time assessment.

5. Conclusion

A new Nitrogen Test Facility has recently been built at CERN-SM18 in order to perform thermal cycles from room temperature to 77 K on large size and heavy magnets. The structure of FRESCA2 dummy coil magnet has been successfully tested in the facility during a test campaign that has help tuning the applied pre-stress to the magnet and validating its Finite Element models [7]. Another magnet has also been tested twice, the RMC [6] and other magnet structure could likely be studied using this facility.

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