Control System and Operation of the Cryogenic Test Facilities for LHC Series Superconducting Magnets

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ABSTRACT

Prior to their final preparation before installation in the tunnel, the ~1800 series superconducting magnets of the LHC machine will be entirely tested at reception on modular test facilities using dedicated control systems. The test facilities are operated by teams of high-skilled and trained operators. This paper describes the architecture of the control & supervision system of the cryogenic test facilities as well as the tools and management systems developed to help in real time all involved operation teams in order to reach the required industrial production level.

INTRODUCTION

The LHC ring consists mainly of ~1800 twin-aperture superconducting magnets made by the industry. The 1248 15-m long arc dipoles and the 474 short straight sections quadrupoles, hereafter called cryomagnets, shall pass a sequence of conformity tests. The final acceptance tests, including the cryogenic ones, are conducted at CERN by the means of a dedicated infrastructure [1], before final preparation and installation of the cryomagnets in the tunnel. The ACR group/Magnet Test section of the LHC Accelerator Technology Department is in charge of providing the cryogenic infrastructure and of running the cryogenic facilities required for such cryogenic tests.

Cryomagnets are designed in line with the LHC machine requirements, not with the test ones and apart from the constraints linked to intensive sharing of cryogenic utilities and budgetary conditions, another very strong constraint is the time allocated for these tests: most of the 1800 LHC cryomagnets have to be tested over a 3-year period. This challenging objective has lead CERN to setup industrial methods and support, the current target being to reach a peak test capacity of up to 3 cryomagnets per day. This paper describes briefly the typical test sequence and how CERN has organized and is running the concurrent operation of 12 cryogenic test benches, with the help of the control and supervision systems.

CONTEXT

For the complex and numerous jobs repeatedly required to perform the complete cryogenic test of LHC cryomagnets, CERN has taken the approach of splitting the tasks by area of expertise, i.e. mainly mechanics, magnetic & electrical measurements and cryogenics, to 3 teams. For the mechanical tasks, mostly those of (dis)connection of cryomagnet electro-mechanics interfaces, the activities are outsourced in the frame of results oriented Work Packages (WP) of an industrial contract. Each WP is described in an engineering specification document in which the details of the tasks as well as those of the quality control are exhaustively set. The operation of magnetic & electrical measurements, which has to comply with strict procedures, is conducted by CERN and supported through a collaboration program with India. Last but not least, the operation of cryogenics, which relies on predefined procedures for acting on modular or shared infrastructure, is outsourced in the frame of a dedicated resource-oriented WP of an industrial contract in the field of cryogenics, the technical management of which being closely followed-up by CERN. CERN insures the training of operators, as well as the on-the-job transfer of know-how to the 3 teams, thus leading to guarantee the accurate execution of the WP's and the correct application of the procedures, respectively. Moreover, we have setup software tools to monitor and improve, and in some extent formalize, the communication between the 3 teams involved in the execution of the interleaved tasks of the whole cryogenics tests sequence, in order to make the operators working together in the most efficient way.

CRYOMAGNET TEST SEQUENCE

The cryomagnet is equipped with a return box and, when required, with two anti-cryostats [3]. It is transported by the means of a special wire-guided transport vehicle to the selected test bench. Then it is positioned, aligned and levelled on the supporting structure of the Cryogenic Feed Box (CFB). The power cryomagnet electrical interfaces are *in-situ*-soldered and mechanically secured. The retractable sleeves housing the electrical joints are stretched out and locked in closed position. The six flanged hydraulic connections are tightly bolted. An automatic helium purge of the just-connected hydraulic circuits and a helium leak check on tightness of their double-sealed interfaces are performed. The dismountable thermal shield and the multilayer insulation (MLI) blanket surrounding the connection area are fitted. Lastly, the vacuum sleeve is pulled out and tightly bolted. At this stage, the vacuum enclosure starts and runs down to ~1 Pa, then the secondary pumping down to ~0.1 Pa and a global helium leak rate measurement is done, while instrumentation cables are plugged and electrical measurement & protection circuits checked on conformity. The cooldown to ~90 K is done by means of helium circulated at 80 K. Subsequent cooldown to ~4.5 K and filling are done through a 2-phase helium distribution, and lastly, down to superfluid helium temperature by the means of the 1.9 K pumping facility. The cryomagnet coils are maintained at 1.9 K for the duration of the electrical measurements and of the magnetic ones, if any. It is re-cooled down to 1.9 K in case of training quenches (resistive transitions) or of a thermal cycle, ramped up back to nominal current, and lastly quenched at lower energy. The so emptied cryomagnet is warmup up to 295 K and the vacuum enclosure is pressurized up to atmospheric pressure with nitrogen gas. The vacuum sleeve is pulled away, the MLI & thermal shield are removed. The helium circuits to be disconnected are automatically purged with nitrogen gas. Hydraulic and electrical interfaces are disconnected. The tested cryomagnet is then transported back for stripping off (test tooling & configuration). A typical summary of 9 concurrent test sequences running in cog wheeling over 9 test benches (TB) is given in Table 1 hereafter.

TB	Period n	n+1	n+2	n+3	n+4	n+5	n+6	n+7	n+8
1	Install	Setup	To 90 K	To 1.9K	Test 1.9 K	Test 1.9 K	Test 1.9 K	Warmup	Remove
2	Test 1.9 K	Test 1.9 K	Test 1.9 K	Warmup	Remove	Install	Setup	To 90 K	To 1.9K
3	Remove	Install	Setup	To 90 K	To 1.9K	Test 1.9 K	Test 1.9 K	Test 1.9 K	Warmup
4	To 1.9K	Test 1.9 K	Test 1.9 K	Test 1.9 K	Warmup	Remove	Install	Setup	To 90 K
5	Warmup	Remove	Install	Setup	To 90 K	To 1.9K	Test 1.9 K	Test 1.9 K	Test 1.9 K
6	To 90 K	To 1.9K	Test 1.9 K	Test 1.9 K	Test 1.9 K	Warmup	Remove	Install	Setup
7	Test 1.9 K	Warmup	Remove	Install	Setup	To 90 K	To 1.9K	Test 1.9 K	Test 1.9 K
8	Setup	To 90 K	To 1.9K	Test 1.9 K	Test 1.9 K	Test 1.9 K	Warmup	Remove	Install
9	Test 1.9 K	Test 1.9 K	Warmup	Remove	Install	Setup	To 90 K	To 1.9K	Test 1.9 K

Table 1 Typical arrangement of 9 concurrent LHC cryomagnet test sequences

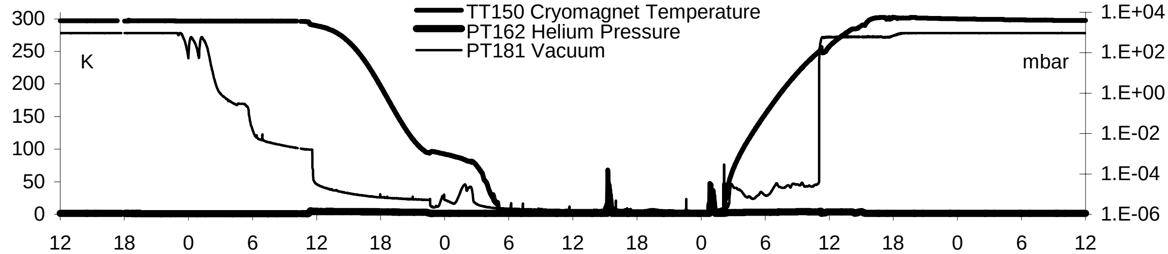

Fig 1 Real chart of a standard cryogenic test sequence

CONTROL & SUPERVISION SYSTEMS OF THE CRYOGENIC TEST FACILITIES

The control system is designed and built like any industrial one: PLC units and Supervisory Control and Data Acquisition (SCADA) applications running on PC. A network of PLC's linked together by TCP/IP and Profibus™ protocols control the processes of the test facilities. This system of PLC's hosts ~850 analog inputs, ~1650 digital inputs, ~350 analog outputs and ~1200 digital outputs. The PLC system is the first logical level of control, it handles all the real-time tasks, runs the ~380 PID's controls of all regulated objects, assure the safety and the reliability of the installation through programs sequences and background processes and transmits, using the TCP/IP protocol, the state and the physical measurements values to the second layer, the supervision system (SCADA) which by turns, displays the animated synoptics, the control, trends & alarms windows and sends back all the control parameters and the operators' commands. An exhaustive set of flags and alarms centralized and summarized by system, helps the operators in diagnosing process deviation or possible equipments malfunctioning. The majority of the program parameters are customizable through the SCADA application to allow a tuning of the process. The SCADA applications are running on 8 PC, 6 for the 6 clusters (pairs of CFB) of neighbouring test benches and 2 for the utilities of the cryogenic test station.

Whereas all the PLC hardware is made with off-the-shelf components, the software is deeply tailored for our applications and was totally designed and written by CERN. The heart of the system is a central PLC, the main tasks of which are to control the processes of the centrally available utilities (liquid helium distribution & return, circulated helium for cooldown & warmup) and to run the master software of the test facilities, the so-called Cryogenic Test Handling (CTH) software. Connected to this central PLC, 4 individual PLC control separate pumping, circulation and compression units of the test facilities, and 12 identical PLC & software control the CFB. The CFB program is structured into phases, themselves divided into steps, resulting from the test sequence of the cryomagnet. Transitions between steps and/or phases arise when predefined values and/or states are reached, some of them requiring the acknowledgement of the operator.

The numbers of benches (12), of process phases (21) and of utilities of limited capacity (4), i.e. liquid helium & return, subcooling, cooldown and warmup, have naturally introduced the concept of "priority" among the test station. It is essential that all cryomagnets are assigned, at any time, an exclusive priority value in the range [1-12] compatible with a logical and efficient production flow. Practically, the magnetic measurement team updates and transmits its priority list accordingly with its tests objectives and with its own shared resources. The cryogenic operation team then acknowledges this request by updating the present input priority list to CTH. The CTH priority module, which discriminates the present phase/step of each of the 12 CFB, e.g. CFB of cryomagnets powered at 1.9 K, so their respective requirements with respect to the 4 shared utilities, reacts instantly by recalculating the weight of the corresponding 4 utilities set points of each of the 12 CFB. As a result, the production flow can make use of the full installed capacity of the 4 above-mentioned utilities in a self-limiting way.

Like the PLC software, the development of the SCADA applications was done by CERN. Both the PLC programs and the SCADA applications were designed and developed jointly, so that we have a complete compliance between the databases, objects, etc… of the PLC and the SCADA. This conformity is very timesaving when upgrading and maintaining the overall control system.

Additional improvements to the supervision systems have been developed through a central database stored on a web server. A set of web pages gives access to the on-line information about the status of the production, anywhere on the CERN's web intranet. Reports on current or previous tests (test duration, statistics, etc…) can be queried. To achieve this, the SCADA system is used as an event generator launching a collection of scripts updating the central database. The refresh time is a few seconds, as the load on the SCADA system mainly limits this updating frequency; nevertheless the data refresh occurs at least every minute to guarantee consistent synchronization with the actual production status. This methodology (SCADA → scripts → database) allows an easy maintenance, any change or upgrade can be implemented and tested independently. A bridge with a CERN's reference database –Manufacturing and Test Folders (MTF)– has also been implemented into the SCADA application of the CFB for downloading the parameters of the anticryostats [3] in an automated way and writing them back to the dedicated PLC. An e-mailing of important events or errors is also implemented through this system of scripts.

OPERATION OF THE CRYOGENIC TEST BENCHES

The cryogenic test station is operated 24 hours per day, 7 days per week, by a team of 2 or 3 operators. In addition to its field activities, mainly to witness the liquid nitrogen deliveries, the watch patrol for installations, the follow-up of helium leak measurements, its mandate is to complete and/or check the correct execution of the concurrent test sequences from the control room by the means of the SCADA with the help of the Task Tracking System, another web database application beside the database, automatically fed by the control system. The Task Tracking System (TTS) has been implemented to standardize the communications between the 3 –mechanics, magnetic & electrical measurements and cryogenics– teams and to delegate to it the repetitive action of broadcasting information. Technically, the TTS is housed in the same web server as mentioned in the above paragraph. All the key production tasks, grouped by area of expertise, are rationally ordered in a to-do list following the test sequence. This to-do list of tasks is the backbone of the TTS. The TTS is field-oriented operator production follow-up application, it means that the data recorded in it is entered by the operators –via password protected web forms– on the field, right after the completion of their current task. Every test bench has its TTS list where the teams have to record the progress of their job.

When the "hand" passes to the next team in the to-do list, this one is automatically and immediately notified by a SMS message sent by the TTS, that its action is requested (the bench and actions are recalled in the SMS message and, of course, on the TTS main web page, accessible elsewhere on the CERN's intranet). The TTS is used from the arrival of a cryomagnet on a bench up to its removal. By this mean, the history of the tasks achieved on a bench –and on a cryomagnet– is recorded into the TTS database so that data can be later queried for statistical purpose. The TTS guarantees that the production information is automatically and always recorded and forwarded on time. The safety and quality functions are also present in the TTS, because the system requires that the tasks are strictly and chronologically executed in the way they were defined in the to-do list. For example, the opening of the cryomagnet's helium circuit by the mechanical team cannot be done while the cryogenic operators have not signed the safety and lock tasks.

CONCLUSION

Significant improvements have been implemented in the control & SCADA systems. We now have stable foundations for reliable and efficient operation of the cryogenic facilities for the test of series cryomagnets. The present production of the test plant demonstrates that a messaging system embedded in a web-based follow-up system can help the coordination of 3 teams from different area of expertise. More experience is still needed for outputting meaningful statistics and to identify hidden bottlenecks in the test production flow. For that purpose additional analysis work has to be done on the recorded data.

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