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AUTOMATIC MANAGEMENT SYSTEMS FOR THE OPERATION OF THE CRYOGENIC TEST FACILITIES FOR LHC SERIES SUPERCONDUCTING MAGNETS

A. Tovar-Gonzalez, J. Axensalva, L. Herblin, J.P. Lamboy, and B. Vullierme

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ABSTRACT

Prior to their final preparation before installation in the tunnel, the ~1800 series superconducting magnets of the LHC machine shall be entirely tested at reception on modular test facilities. The operation 24 hours per day of the cryogenic test facilities is conducted in turn by 3-operator teams, assisted in real time by the use of the Test Bench Priorities Handling System, a process control application enforcing the optimum use of cryogenic utilities and of the “Tasks Tracking System”, a web-based e-traveller application handling 12 parallel 38-task test sequences. This paper describes how such computer-based management systems can be used to optimize operation of concurrent test benches within technical boundary conditions given by the cryogenic capacity, and how they can be used to study the efficiency of the automatic steering of all individual cryogenic sub-systems. Finally, this paper presents the overall performance of the cryomagnet test station for the first complete year of operation at high production rate.

KEYWORDS: LHC, superconducting magnet, cryogenic test, process control, quench.
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INTRODUCTION

The 1248 arc dipoles, the 474 short straight section quadrupoles and the 82 special short straight sections of the LHC machine, hereafter called cryomagnets, undergo a series of tests at cryogenic conditions, mainly at 1.9 K, performed within the constrains of the cryomagnet design parameters, of the cryogenic infrastructure capacity and in a 3-year period. Tests of cryomagnets are carried out in a dedicated 12-bench test facility [1] [2], installed at LHC Point 18 and using the 18 kW at 4.5 K refrigerator, part of the refrigeration system for the LHC, and its associated infrastructure [3].

Each test bench includes a Cryogenic Feed Box (CFB), which is the complex interface between the infrastructure and the cryomagnet under test. The share of all the necessary cryogenic utilities by the 12 CFB complies with a set of rules defined in order to obtain the minimum bench occupancy for individual tests of cryomagnets. This process is orchestrated by a program running on a programmable logic controller (PLC), and is operated thanks to dedicated industrial supervision and web-based applications.

LAYOUT OF THE TEST FACILITY

The cryogenic infrastructure dedicated to the cryomagnet test facility is shown in FIGURE 1. The 12 CFB are connected to the following cryogenic utilities:

- The cryomagnet Cooldown Warmup System (CWS) which includes the function of gaseous helium forced circulation with two twin 150 g/s @ 0.3 MPa screw compressors running in parallel, the pre-cooling function of the forced gaseous helium flow with 2 twin liquid nitrogen vaporizers/heat exchangers in parallel (CWU1 and CWU2) of a nominal cooling power of 130 kW@ 80 K and the warming function up to 300 K with two electrical heaters for gaseous helium with a nominal electrical power of 200 kW and 30 kW, respectively. CWS also includes the liquid nitrogen storage (two 50’000-litre liquid nitrogen tanks) and the distribution lines to CWU1 and CWU2.

- The Cryogenic Compound Line (CCL) which includes three headers. The 30-mm diameter header distributes saturated helium @ 0.14 MPa from a 25’000-litre dewar to the CFBs. The 86-mm diameter header collects @ 0.13 MPa the cold gaseous helium returned from the 12 CFBs. The 150-mm diameter header collects the cold helium @ 1.2 kPa from the CFB pumping ports.

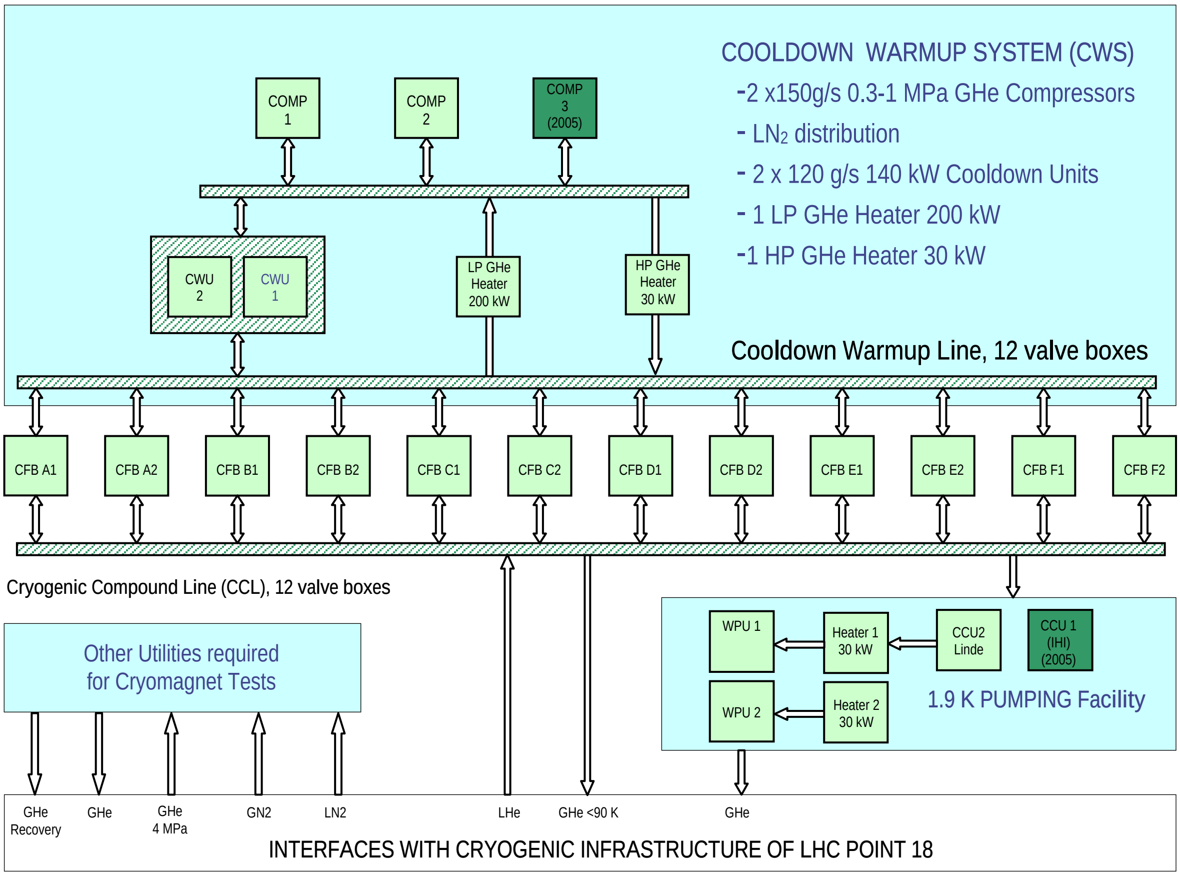


FIGURE 1. General layout of the cryogenic test facility.

- The 1.9 K Pumping Facility which allows obtaining cryomagnet temperatures in the range of 1.9 K. It consists of two branches in parallel, the suction side of both connected to the 150-mm diameter header of the CCL. Branch 1 has a capacity of 18 g/s @ 1.2 kPa. It includes a cold centrifugal pre-compression stage (CCU), a 30 kW electrical heater and the Warm Pumping Unit 1 (WPU1). Branch 2 has a capacity of 7.2 g/s @ 1.2 kPa. It includes a 30 kW electrical heater and the Warm Pumping Unit 2 (WPU2).

PROCESS CONTROL

The process control is handled by 16 PLCs from Siemens (13 CPU S7-414-3DP, 1 CPU S7-300, 2 CPU S5-115).

One of them is dedicated to all cryogenic utilities, three to the 1.9K pumping facility (WPU1, WPU2 and CCU) and one to each CFB. Communications between PLCs are made via Ethernet, while nearly all instrumentation (see TABLE 1) is connected to remote Input-Outputs via Profibus DP.

CLOSED-LOOP CONTROLS

Closed-loop controls are implemented using the PID (Proportional, Integral and Derivative) algorithm. Most of the control loops actually use dual/triple PID in selective control configuration, where a main PID controls the output variable while any of the others may limit it.

Control loops working in such a configuration act like a unique PID having several set points and measured values, changing its operation mode accordingly. The saturation of the integral terms is avoided by disabling their calculation in the PIDs whose output variable is higher than the actual global output.

MANAGEMENT OF CRYOGENIC UTILITIES

Each CFB is independent, that is, it has its own functioning parameters and modes (cooling from room temperature down to 80 K, filling with liquid helium…) and asks for the cryogenic utility required for its functioning mode (see TABLE 2) in order to perform its present and specific task.

However, when similar requests are issued by several test benches concurrently, the resulting amount of the cryogenic utility may not be sufficient.

The Cryogenic Test Handling (CTH) PLC limits operational parameters of CFBs requests in a way that the total amount of the required utility matches the present available capacity, thus avoiding any system stop due to overload.

TABLE 1. Instrumentation per PLC.

Instrumentation	CTH	CFB (x12)	WPU (x2)	CCU	Total
Analogue Inputs	208	56	24	8	936
Analogue Outputs	48	32	1	8	442
Digital Inputs	384	96	192	32	1952
Digital Outputs	288	64	128	32	1344
Closed Loop Control	37	29	1	1	388

TABLE 2. CFB functioning modes and cryogenic utilities needed.

CFB functioning mode	GHe 80 K	LHe	GHe Return	1.9 K Pumping	GHe Heating
Cooling down (300 K to 80 K)	X	-	-	-	-
Cooling down (80 K to 4.5 K)	-	X	X	-	-
Cooling down (4.5 K to 1.9 K)	-	X	X	X	-
Depressurization after quench	-	-	X	-	-
Warming Up (30 K to 300 K)	-	-	-	-	X
Cryomagnet (de) mounting	-	-	-	-	-

For CWS, the theoretical available gas flow rate is set by CTH as the sum of the nominal capacity of the compressors in operation. A first control loop tracks the compressors suction pressure, thus limiting the CWS available gas flow rate when the pressure reaches the maximum allowed value. The resulting CWS available gas flow rate is shared into warm-up gas and cool-down gas flows. A second control loop is used to limit the warm-up gas available flow rate when the heating power of the return gas reaches 200 kW. Cool-down available gas flow rate is calculated by CTH depending on the respective status of CWU1 and 2 (operational, regeneration, cool-down, stand-by, off).

For other cryogenic utilities, i.e. liquid helium supply, gaseous helium return and 1.9 K pumping, CTH calculates so-called availability factors (range 0-100%) by the means of selective control PIDs:

- the liquid helium supply availability factor: tracking, with respect to limit set points, of the pressure in the supply line and its variation rate,
- the gaseous helium return pressure availability factor: tracking, with respect to limit set points, of the pressure in the return line and its variation rate,
- the 1.9 K pumping availability factor: tracking, with respect to limit set points, of the pressure in the pumping line, of the CCU drive frequency and of the maximum theoretical pumping flow, the limit set point of which being adjusted dynamically by CTH depending on the respective status (operational, off) of WPU1 and WPU2.

PRIORITY LISTS

A Main Table is actualized by cryogenic operators to set in the simplest way the test priorities according to the expected cryomagnet test flow. The Main Table allocates to every CFB a relative priority (1^{st} up to 12^{th}). CTH computes data cyclically as follows.

Every CFB may accumulate points (true: 12 pts, false: 0 pts) by applying the rules listed in TABLE 3, to reflect its status according to up to five possible concurrently achieved conditions with respect to the three main cryogenic utilities, and to the cryomagnet powering, plus the number points resulting from its position in the Main Table (11 pts down to 0 pts for 1^{st} up to 12^{th}, respectively). Every CFB present conditions and priority is reflected by its three scores which are used by CTH to generate three 12-position priority lists, in order to rank CFBs with respect to each cryogenic utility, according to their corresponding score, sorted downward (1^{st} up to 12^{th}).

The “CWS list” ranks the 12 CFBs according to their requirement for circulation of cold or warm helium gas with CWS.

The “LHe list” ranks the 12 CFBs according to their requirement for liquid helium while their gaseous helium return has to be sent back to the refrigerator.

The “1.9 K list” ranks the 12 CFBs according to their requirement for the 1.9 K pumping.

TABLE 3. Attributions of points to each CFB according to its status.

CFB achieved conditions (True or False)	CWS (pts)	LHe (pts)	1.9 K (pts)
CFB is operational	True: 12	True: 12	True: 12
CFB requires cold or warm GHe circulation	True: 12	0	0
CFB requires LHe or in GHe depressurization	0	True: 12	0
CFB requires 1.9 K	0	0	True: 12
CFB requires powering conditions @ 1.9K	0	True: 12	True: 12
CFB is powered @ 1.9 K or ready to be	0	True: 12	True: 12

The three lists are updated cyclically and are used by CTH to set dynamically the limitations for each cryogenic utility for each CFB.

SHARING OF CRYOGENIC UTILITIES

For CWS, the values of available warm and cold gas flow rates (typically 300 g/s total), are divided by CTH into maxima values (typically 85 g/s for cool-down, 90 g/s for warmup) shared out according to the present CFB demands (warm-up or cool-down) and to the CWS priority list. As gas flow rates are eventually controlled by the CFB PLCs, actual values of CFBs cold and warm gas flow rates actualize the value of CWS available flow rates accordingly. CFBs with reduced or no allocated flow because of a lower priority simply wait until the completion of another CFB cool down or warm up sequence.

For liquid helium supply and gaseous helium return together, and 1.9 K gaseous helium pumping, respectively, CTH calculates in real time according to equation (1) the corresponding set points to be sent to CFBs, each set point to be internally used by the CFB control system as individual limitation setting for the use of this cryogenic utility.

$$S = \{R - [(100 \div n)(N - 1)]\} n \,, \qquad (1)$$

where S is the set point limited to 100 % when the result is higher than 100 %, *R* is the value of the cryogenic utility availability factor (range 0-100 %), *N* is the CFB ordinal number (range 1^{st}-12^{th}) in the priority list and *n* is the number (range 1-12) of CFB's using the cryogenic utility of that priority list.

As an example, if 3 CFB are presently requiring liquid helium, e.g. CFB_{C1}, CFB_{A1} and CFB_{D1} with, respectively, 1^{st}, 2^{nd} and 3^{rd} priority in LHe list, and if the liquid helium availability factor calculated by CTH is 75%, then the liquid helium limitation settings sent to CFB_{C1}, CFB_{A1}, and are: 100 %, 100 %, 25.2 %, respectively. For this example, if set at 12 g/s, the CFB_{A1} LHe flow rate set point will be brought down to 3.02 g/s.

This key process results in a major simplification of the supervision tasks, by letting operators off the continuous adjustment of number of interleaved parameters. In addition, as it suppresses the need for any contingency margin, the actual capacity of the cryogenic test station can be really close to maximum.

CRYOGENIC TEST BENCH TOP-LEVEL SOFTWARE

Two main softwares were designed to operate the LHC cryomagnet test bench facilities in accordance to the LHC quality control procedures: the process supervision system and the production database system.

To interact with the 16 PLCs controlling processes and equipments, a standard commercial supervision system is used for the man-machine interface. Applications of supervision for the 12 CFBs and the ones for the cryogenic utilities run on this standard kernel. They were totally built from scratch to meet the specific requirements of the activity. They deal with all relevant data for the operation of the test facility. Components, equipment and process information are displayed as much as possible in a graphical style (simplified Process & Instrumentation Diagrams with animated symbols, trends, etc…). Special attention was given to the implementation of warnings, alarms and messages.

Improved data archiving was also implemented. Data not older than 2 weeks can be visualized locally from the supervision workstation while older events can be retrieved off-line from an Oracle database via a web-based interface, in order to give an universal access to data for any further test data analysis since the start of the test activities. The database archiving occurs once a day as a batch process. Redundancy of the supervision systems is achieved by deploying the same application over several workstations.

While the supervision system is mainly focused on human interface with process control, the production data base allows organizing the production of independent test benches with interleaved tasks involving distinct operation teams. It is a kind of common reference and coordination system to follow-up on test sequences in a way that “hidden times” are used the most efficient way.

An audit of the whole cryogenic test was performed with all the involved teams to agree on a common standard well-defined test sequence. This led to the birth of the “Tasks Tracking System” (TTS). It consists on a web-based database which organizes the production in block sequences of tasks to be completed by the 3 operation teams on shift.

The TTS can be summarized for each team as “what you have to do, when and where”. This motto is translated graphically on a web page symbolizing the 12 test benches as 12 tiles (FIGURE 2) displaying the following information: the tag of the test bench, the designation of the cryomagnet on which the test sequence is running, the team involved in the current operation and a short sentence explaining which task the team has to do.

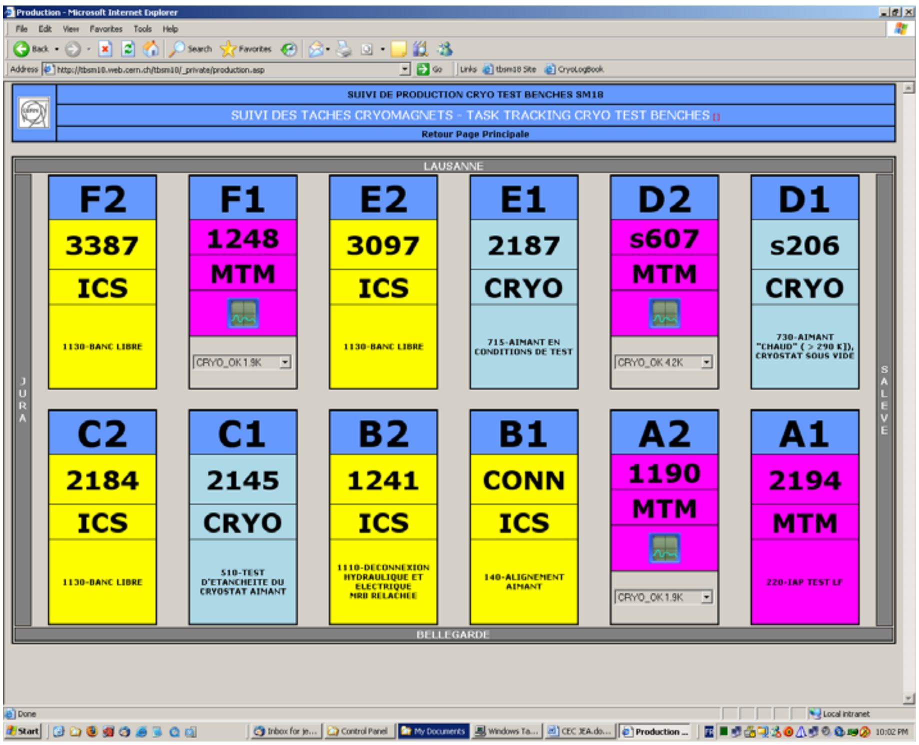
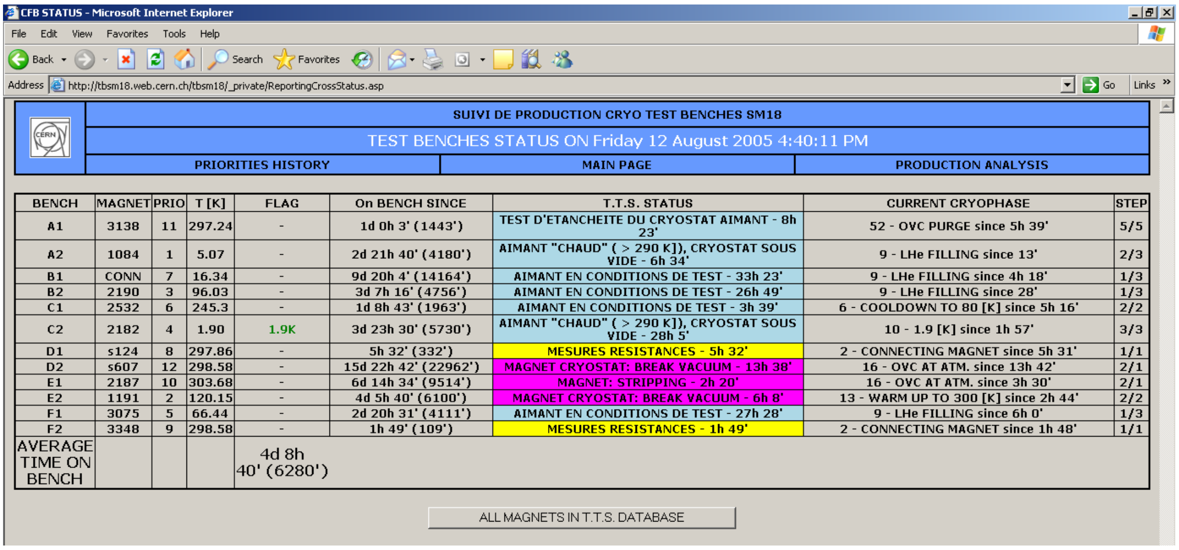


FIGURE 2. Screenshot of the main TTS window.

Once its current task is completed, the team has to acknowledge it by signing it. Then the TTS database increments to the next task. If the next task has to be performed by the same team, the web page is just refreshed with the new task. If the next task must be completed by another team, the database increments to the next task and notifies the next team by SMS and e-mail that it's time to do a specific action on a specific bench. By this mean, every team receives automatically what it has to do and where. Finer processes are also implemented: some task signatures trigger additional or pre-warning messages and special SMS are dispatched to team managers to help them to optimize production.

The TTS database includes reporting capabilities. Each week production reports, e.g. FIGURE 3, are extracted. Task times are compared with standard ones and deviations are examined carefully. This helps to predict equipment failure or malfunction, to improve operation procedures and to reduce bottleneck states.


CFB STATUS - Microsoft Internet Explorer

Address http://tbsm18.web.cern.ch/tbsm18/_private/ReportingCrossStatus.asp

SUIVI DE PRODUCTION CRYO TEST BENCHES SM18

TEST BENCHES STATUS ON Friday 12 August 2005 4:40:11 PM

PRIORITIES HISTORY | MAIN PAGE | PRODUCTION ANALYSIS

BENCH	MAGNET	PRIO	T [K]	FLAG	On BENCH SINCE	T.T.S. STATUS	CURRENT CRYOPHASE	STEP
A1	3138	11	297.24	-	1d 0h 3' (1443')	TEST D'ETANCHEITE DU CRYOSTAT AIMANT - 8h 23'	52 - OVC PURGE since 5h 39'	5/5
A2	1084	1	5.07	-	2d 21h 40' (4180')	AIMANT "CHAUD" (> 290 K]), CRYOSTAT SOUS VIDE - 6h 34'	9 - LHe FILLING since 13'	2/3
B1	CONN	7	16.34	-	9d 20h 4' (14164')	AIMANT EN CONDITIONS DE TEST - 33h 23'	9 - LHe FILLING since 4h 18'	1/3
B2	2190	3	96.03	-	3d 7h 16' (4756')	AIMANT EN CONDITIONS DE TEST - 26h 49'	9 - LHe FILLING since 28'	1/3
C1	2532	6	245.3	-	1d 8h 43' (1963')	AIMANT EN CONDITIONS DE TEST - 3h 39'	6 - COOLDOWN TO 80 [K] since 5h 16'	2/2
C2	2182	4	1.90	1.9K	3d 23h 30' (5730')	AIMANT "CHAUD" (> 290 K]), CRYOSTAT SOUS VIDE - 28h 5'	10 - 1.9 [K] since 1h 57'	3/3
D1	s124	8	297.86	-	5h 32' (332')	MESURES RESISTANCES - 5h 32'	2 - CONNECTING MAGNET since 5h 31'	1/1
D2	s607	12	298.58	-	15d 22h 42' (22962')	MAGNET CRYOSTAT: BREAK VACUUM - 13h 38'	16 - OVC AT ATM. since 13h 42'	2/1
E1	2187	10	303.68	-	6d 14h 34' (9514')	MAGNET: STRIPPING - 2h 20'	16 - OVC AT ATM. since 3h 30'	2/1
E2	1191	2	120.15	-	4d 5h 40' (6100')	MAGNET CRYOSTAT: BREAK VACUUM - 6h 8'	13 - WARM UP TO 300 [K] since 2h 44'	2/2
F1	3075	5	66.44	-	2d 20h 31' (4111')	AIMANT EN CONDITIONS DE TEST - 27h 28'	9 - LHe FILLING since 6h 0'	1/3
F2	3348	9	298.58	-	1h 49' (109')	MESURES RESISTANCES - 1h 49'	2 - CONNECTING MAGNET since 1h 48'	1/1
AVERAGE TIME ON BENCH				4d 8h 40' (6280')				

ALL MAGNETS IN T.T.S. DATABASE

FIGURE 3. Screenshot of the test bench status window.

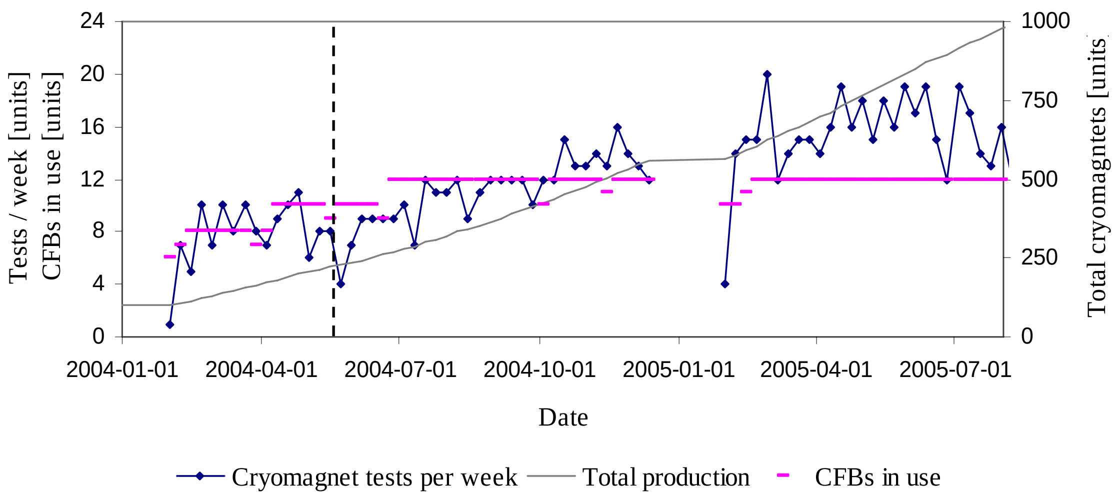


FIGURE 4. Cryomagnet test production over the past 18 months.

OVERALL PERFORMANCE OF THE CRYOMAGNET TEST STATION

See FIGURE 4. The automatic management system for the operation of the cryogenic test facilities was intrduced in May 2004 (dotted line), while the last four CFB were coming into operation and with a CWS circulation capacity of 170 g/s, known at this time as a limiting utility for the test capacity.

For the first few weeks, the update of the Main Table according to the expected test flow and extremely simple rules was not done properly by operators. There was no significant improvement compared to the previous situation, the “human” test priority handling.

Subsequently, even with a larger number of benches in operation and a limited capacity for CWS, the production per bench gradually increased without additional human intervention, by better anticipation of the needs, reduction of dead times and of overcapacity situations, and by the handling in a complete automatic mode of all the recovery phases related to resistive transitions (quenches) which occur during the cryomagnet test and training processes (~ 2000 quenches in 2004).

Early 2005, CWS capacity has been upgraded to 300 g/s. The production trend shows that the automatic management systems are able to take advantage of the upgraded CWS capacity while handling the corresponding additional needs for the other cryogenic utilities.

CONCLUSION

The Test Bench Priorities Handling System has demonstrated its perfect capability to optimize the use of installed cryogenic utilities with respect to concurrent test sequences on 12 test benches, in order to get the highest cryomagnet test flow while keeping a sufficient training capacity for weak cryomagnets.

The Tasks Tracking System is perfectly tailored for a formal communication between the 3 operating teams on shift. It minimizes the occurrence of human errors and reduces all previously encountered kind of dead times down to minimum.

So far, thanks to the introduction these management systems (among other concomitant improvements not described in this paper), the achieved peak production rate of the 12 installed LHC cryomagnet test benches reached 20 cryomagnets per week.

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