Assembly and Commissioning of the LHC Test String

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I. INTRODUCTION

The LHC Project incorporates novel design features which are particularly challenging: twin aperture superconducting magnets with a stored energy higher than 5 MJ per magnet and working in a bath of superfluid helium. It was therefore decided in 1991 to order several full length prototype magnets, and install them in a test string, to demonstrate the feasibility of the LHC. This paper describes the String assembly in its first phase, which consists of a short straight section with its quadrupole and of two dipoles, together with the necessary cryogenics and powering. One will then give the first commissioning results as well as future plans.

II. THE STRING PHASE 1

It was originally foreseen to build a string made of one quadrupole and four dipole magnets, which corresponded to a full LHC half-cell at that time, [1]. In fact, as the delivery of the 10 m long dipole prototypes was delayed, it was decided to install the String with first the quadrupole and only two dipoles, which are sufficient for assessing the validity of the main design choices. Similarly, the correction elements such as sextupoles, tuning quadrupoles, closed orbit correctors which are normally in the short straight section, (SSS) of the LHC lattice, were replaced by dummies in the prototype SSS.

Fig. 1 shows a schematic of the overall installation. The String starts with the String Feed Box, (SFB), which is a large tank under vacuum, containing cryostat, helium heat

Fig. 1: Axonometric view of the LHC test String

exchanger, all the valves and regulators which are necessary for feeding the superconducting magnets with the different cryogenic fluids. Several pairs of current leads are mounted on the large upper flange of the SFB, both for the dipole and quadrupole excitation (15 kA), and for powering later on the correction elements (500 and 1500 A).

The SSS is connected directly to the SFB and is followed on the other side by the dipole magnets. The String ends with the String Return Box (SRB), which closes the string cryostat vacuum and which contains the short circuits for the electrical busbars, as well as some cryogenic valves.

The SFB is also connected to the central cryogenic station as well as to an additional device, called Cooling and Warming-up Unit, (CWU), which provides gaseous helium at adjustable temperature and pressure, for both cooling and warming up of the String. An insulated reservoir installed behind the SFB is used for recuperating the gaseous helium which is ejected from the String during a magnet quench.

The power converter, (15 kA, 20 V), the two safety switches and the dump resistors are close to the SFB and interconnected with several water-cooled cables in parallel.

III. MECHANICAL ASSEMBLY

To reproduce the worst conditions one can find in the LEP tunnel, where LHC will be installed, the test String was built on a concrete beam, as wide as the LEP tunnel and with a slope of 1.4%. The support beam is 110 m long which allows future extension of the String to a full LHC lattice cell. As it was originally foreseen to install the LHC machine above the LEP collider, all the String elements are mounted on Γ shaped supports, which brings the cryostat axes at about 1.5 m above the floor level and leaves underneath sufficient free space for LEP components.

The SFB and the SRB, which are described in more details in [2], were assembled and fully tested at 1.8 K, in another hall before being installed in the String.

As compared to the original design, [3], the SSS cold mass prototype contains dummy steel masses of equivalent thermal capacity in place of the corrector magnets. Quench protection diodes for the main quadrupole and auxiliary diodes, for protecting the dipoles against overvoltages produced by quench heater delays, (see chapter 4), are also mounted inside the SSS cold mass. The SSS was built on a separate bench and tested for vacuum tightness but not cryogenically before installation, the main quadrupole having being tested before at Saclay on its own at 1.8 K.

The two dipole prototypes, [4], were produced by industry and fully tested at CERN, both cryogenically and magnetically, in the same hall as the String, and prepared there for their installation in the String which included the adjustment of the electrical busbars to the right shape and length, the welding of bellows and the cleaning of the two cold bores.
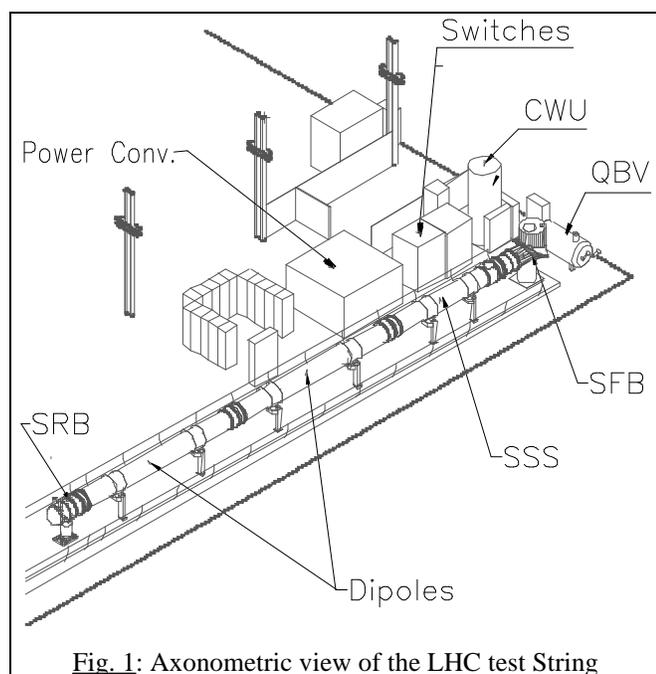
Magnet Interconnections

The String forms in fact a single cryostat, containing all the cryogenic lines necessary for its operation: a cryo-magnet must then be connected at both extremities to another one and/or to the SFB or SRB before being cooled down and powered. The magnet interconnections are very critical for LHC, because the space needed to weld together the large number of pipes must be kept as short as possible, in order to maximize the active length of the final LHC. At the same time, the magnet interconnections must cope with the mechanical tolerances and alignment errors, be designed to absorb the 30 mm magnet contraction during cool-down, while being able to withstand the 20 bars pressure rise which may be produced during a magnet quench, [5].

In the present cryostat design, see fig. 2, the 14 pipes are interconnected in a space 440 mm long, for a cryostat inner diameter of 960 mm. It should be noted however that the magnets are not yet equipped with a beam screen in each cold bore, which simplifies somewhat the junction. An all-welded construction has been chosen, as this is the best long term reliable solution against helium leaks, [6].

The interconnection is started by brazing the main and auxiliary electrical busbars, and by insulating the resulting junctions. The pipes are then TIG-welded together with one of two special orbital machines which cover the whole range of diameters (50 to 180 mm). Another orbital machine allows the pipes to be cut, if necessary.

The tightness of the junctions is insured by monitoring the welding parameters and also by visual inspection. Whenever possible, local and global leak tests are performed, in some cases by inverting the direction of the pressure. The innermost pipes are welded first and one finishes by the installation of the quench relief valve, which is not welded but bolted to the magnet cold mass, so that it can be easily changed in case of blockage. The actuator of the valve is linked to the valve body via a long rod passing through the various screens and the vacuum tank.

The magnet interconnection is completed by installing the local radiation and thermal screens, with their layers of
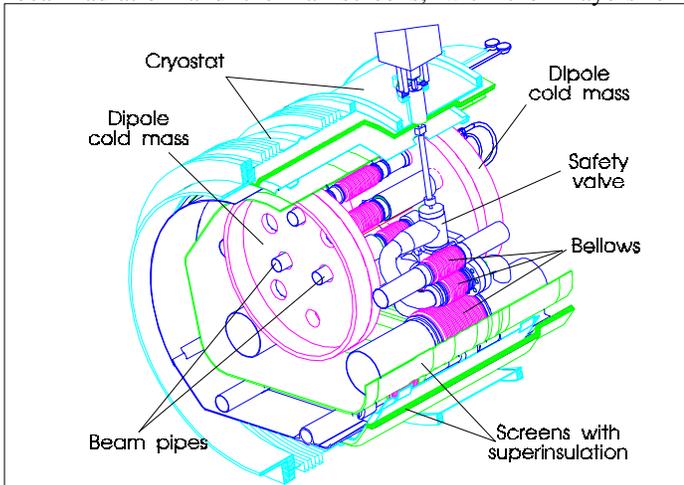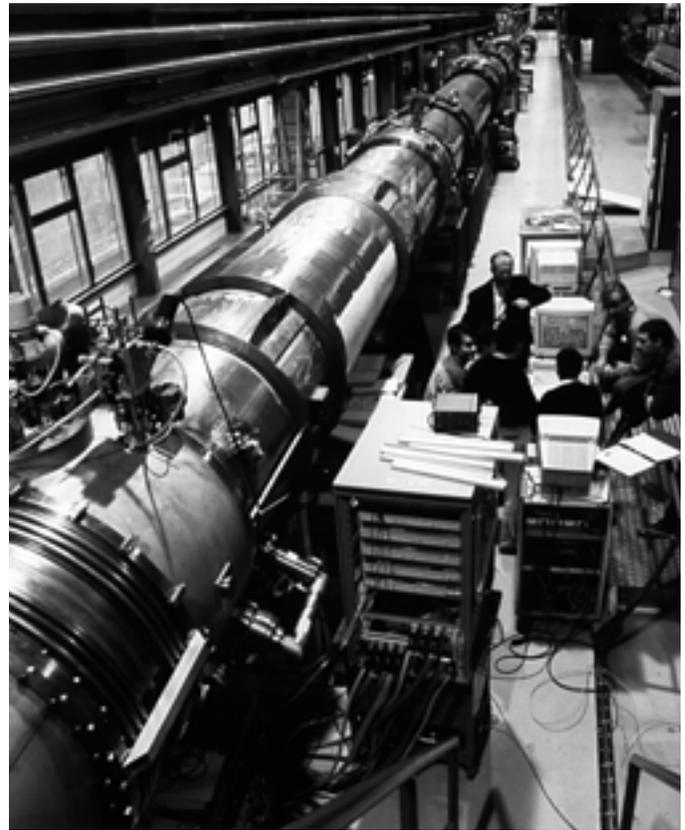

Fig. 3: Overall view of the LHC String in SM18

superinsulation, and by insuring the continuity with the neighboring screens. The outer tanks are closed by a sliding cylinder fitted with a large bellows for flexibility. Fig. 3 shows a picture of the String, seen from the top of the SFB.

Vacuum performance

The String is pumped with two large turbomolecular pumps, one attached to the SFB, the other in the middle of the String. A vacuum barrier, [3], installed at the front face of the SSS cold mass, allows separation of the SFB vacuum from the rest of the string. This has proven to be very useful when checking the whole String for helium tightness. In fact, only one leak was found between the SSS and the SFB. It was due to a corrosion problem and could be repaired in situ. Otherwise, all the welded junctions in the interconnections were perfectly leak tight.

Once the pressure of the insulation vacuum was below 10^{-2} Torr, a global leak test was performed by pressurizing all the cold masses and the internal cryogenic lines to 19 bars with gaseous helium. No leak was observed. This pressure test also served as a safety test to demonstrate the capability of the whole String to withstand the high pressures generated during a magnet quench.

When pumping down the String for the first time, it took about a week to reach a pressure in the 10^{-4} Torr range, because of the humidity accumulated in the superinsulation layers. When cooling the String to 80K, the 10^{-6} Torr range is obtained. The beam vacuum is separated from the insulation vacuum and is usually better than 10^{-9} Torr.

Fig. 2: Schematic view of magnet interconnection

III. CRYOGENIC PERFORMANCE

Cooling the string can be started when the insulation vacuum is low enough, i.e. in the 10^{-2} -10^{-3} Torr range. It is made in 3 phases, using the equipment and procedures as described in ref. [2].

The first phase implies the use of the Cooling and Warming-up Unit, (CWU), which produces gaseous cold helium at a pressure around 10 bars. This gas is injected in the pipes attached to the radiation shield and in the magnet cold masses though the SFB. Its temperature is controlled in the CWU with a liquid N_2 heat exchanger and is adjusted to 50 K below the highest temperature measured in the magnet cold masses. Fig. 4 shows the resulting magnet temperature variations. The temperature gradient limit of 50 K was chosen so as to avoid excessive mechanical stresses and possible magnet deformation during cool-down. This limit could in fact be applied to each magnet individually, as the temperature front is almost perpendicular to the string axis and propagates longitudinally. This would reduce somewhat the time required for this phase.

When the 80 K level is reached, the helium gas flow is stopped in the cold masses, but is maintained in the pipes attached to the radiation shield. The second cooling phase, from 80 K to 4.5 K, was done first by filling the large cryostat inside the SFB with liquid helium at 4.5 K and by letting this liquid vaporize at 1 bar in the magnet cold masses, until the 4.5 K level is reached and the cold masses filled with liquid. A more efficient and faster way was also used and is illustrated in the second graph of fig. 4: by suitably pressurizing the cold masses and the SFB internal cryostat, one can cool with supercritical helium, which allows 4.5 K to be reached in some 15 hours for the whole string. The internal pressure is brought back to 1 bar or less at the end of the phase, which fills all the magnet with liquid. Note that the temperature spikes at the end of this phase were due to an insufficient level of liquid helium in the large storage Dewar of the central cryogenic station and not to problems in the String. In total, about 700 l of liquid helium are needed for completely filling the String, including the SFB cryostat, which corresponds well with the calculated value of 25 l of liquid per metre of dipole.

The last cooling phase is quite fast: by lowering to 10-15 mbar the pressure in the technical service module located in front of the SSS, [3], the liquid helium inside it becomes superfluid and the HeII heat exchanger, which runs across the cold masses of the String starts to operate, [2]. The magnets are cooled down to the 1.8 K level simultaneously in 3 hours about, (see last curve of Fig. 4).

One has also verified the response of this HeII heat exchanger to an external heat load. When dissipating 9 W in each magnet, which simulates more than the heat which may be deposited by the proton beams, [1], the regulation system opens the Joule-Thomson valve which controls the primary helium flow of the heat exchanger and keeps the temperature changes in the String below 0.1 K. This clearly demonstrates the efficiency of this important system for LHC.
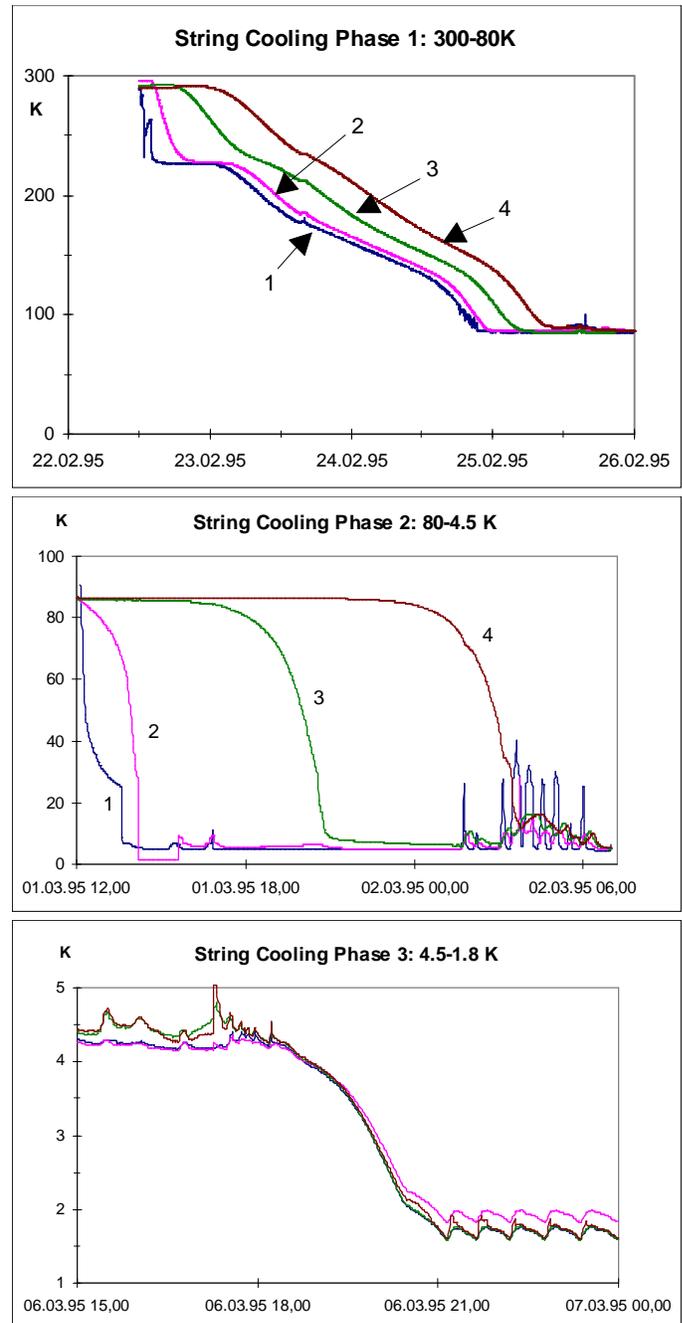
Fig. 4: LHC String Cooling Phases
Magnet Temperatures: 1- SSS entrance; 2- Dipole 1 entrance
3- Dipole 2 entrance; 4- Dipole 2 exit

In total, two complete String cooling sequences have been performed so far: with the present refrigeration capacity one needs about five days to cool down to 1.8 K from 300K, if there are no problems. The end-of-the-year shutdown was an opportunity to test also the warming-up sequence, which, with the same temperature gradient limit of 50 K, was found to take slightly less than five days. These results are important, as they allow reliable extrapolation to determine the time which will be required for cooling and warming-up a full octant of the final LHC machine, and to design accordingly the cryogenic plants.

IV. POWERING AND QUENCH PROTECTION

A simplified electrical circuit of the String is shown in Fig. 5. The power converter (20 V, 15 kA), is unipolar and has an internal current regulation loop, which allows adjustment of the current ramp rate within the voltage limits. It is paralleled by free-wheel diodes and grounded through a 1 Ω resistor. Two switches, between the power converter and the String can open the circuit, namely a fast thyristor switch and a slower mechanical circuit breaker. Each is paralleled by a resistor, which allows quick discharging the circuit in case of a quench. Water-cooled cables connect the power supply and switches to the main current leads on top of the SFB.
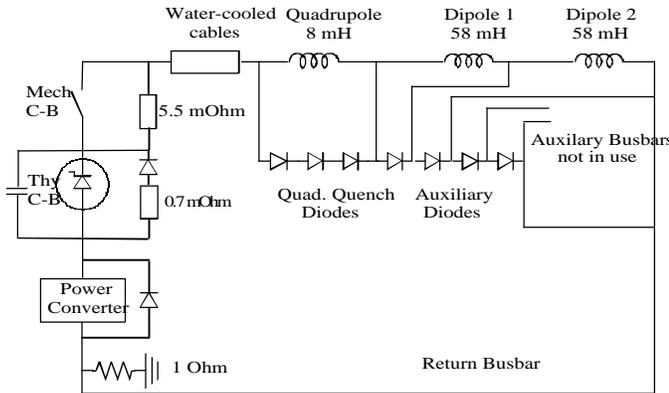

Fig. 5: Equivalent electrical circuit of the String

The principle of the quench protection system is descibed in ref. [7]. Voltage taps are used to constantly monitor the voltage across each magnet half coil. When a voltage difference exceeding a preset value appears between two half-coils or between two coils of the same magnet, or in between two magnets, the quench protection is triggered:

•capacitor banks are discharged in heaters inside all magnets, inducing a resistive transition in the whole String,

•the quench relief valves are opened,

•the two circuit-breakers are opened and the power supply is stopped.

As the whole String makes a resistive transition when the quench protection is fired, protection diodes across each magnet are not mandatory. They were nevertheless installed across the main quadrupole, to gain experience. In the case of the dipoles, it was realized lately that different delays in the resistive magnet transition when firing the quench heaters may induce excessive voltages across the magnet, [8]. The remedy was to install auxiliary diodes in the quadrupole cold mass and connect one diode across each dipole with some of the auxiliary busbars running along the String, (see fig. 5).

V. CONTROLS AND DATA ACQUISITION

The control system for the String is essentially based on industrial control technology, each subsystem having its own Programmable Logic Controller, (PLC), [9]. Whenever possible, the PLC was bought with the equipment it had to control, as for example for the CWU. Others, like the one for the SFB, which were more difficult to specify, have been designed in-house. The supervision of the String PLCs makes use of a workstation running commercial software packages, such as FactoryLink, (TM). This type of controls has been found to be very efficient and has allowed the final String commissioning, that is the first rise to the nominal current as well as the 24 hour run, to be performed entirely remotely from the String control room.

It was also realized very early that a high performance data acquisition system was essential for running the String and analyzing the experimental data. This system was entirely built by industry, [10], and is made of two parts:

• the archiver, which can monitor continously up to 450 channels at sampling rates ranging from seconds to hours,

• an externally triggered transient recorder, which can sample some of the above channels at rates of up to 100 Hz.

Both types of data are stored locally for some time, but are periodically transferred to a central Oracle (TM) data base, and can then be retrieved and analyzed on an EXCEL sheet for instance from any PC of the CERN network.

VI. GLOBAL TESTS AND EXPERIMENTS

Commissioning of the String was done in successive steps. The power converter and the two switches were tested first on a short circuit. After having checked the voltage insulation of the whole String against earth, the quench protection was fired with the String powered at 1 kA. This has allowed verification of the interlocks matrix logics and to eliminate transient voltage spikes induced by opening the thyristor switch. The same experiment was repeated at 5 kA, to verify that, when fired, the quench heaters indeed induce a resistive transition in each magnet (at this level, the dipoles are still self-protected). A global test of the system at 7 kA completed this phase.

The String was then ready to be powered up to the LHC nominal current, i.e. 12'350 A. The current was ramped at 5 A/s from 0 to 9 kA and at 2 A/s above. The first attempt was stopped by a quench in Dipole 2 at 12'200 A. Although somewhat frustrating, this clearly demonstrated the perfect functioning of the quench protection system. The String then reached the nominal LHC current on the second attempt. This was followed by a long run, (Fig. 6), in which the String was
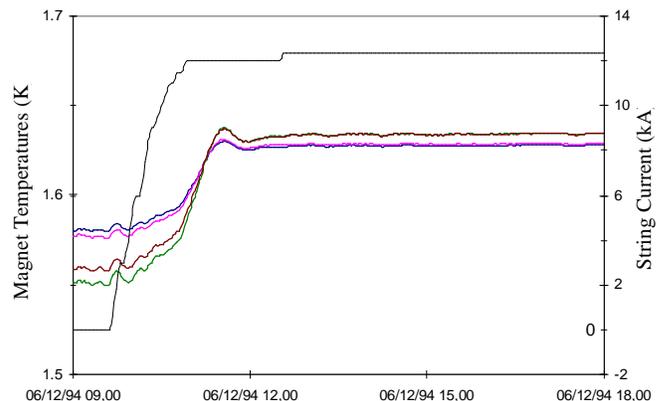

Fig. 6: First part of the 24 hour run of the String

powered for 24 hours at 12'350 A without problem. Fig. 6 shows that the magnet temperatures increase slightly when ramping the current but were stabilized quite rapidly, by the HeII heat exchanger descibed above. At that time, the thermometers had not yet been calibrated and in reality the magnet temperatures were in fact about 0.1-0.15 K higher than those shown in fig. 6.

After 24 hours at nominal current, the String current was again raised at 2 A/s until a quench occured in Dipole 1 at 13'070 A, i.e. at about 9 T, which shows that there is some safety margin in the operating field of the LHC magnets. The evolution of the voltages across the different String elements during that quench can be seen in Fig. 7, while Fig. 8 shows the evolution of the corresponding magnet internal pressures. After calibration, the maximum value recorded does not exceed 12 bars, that is less than anticipated.
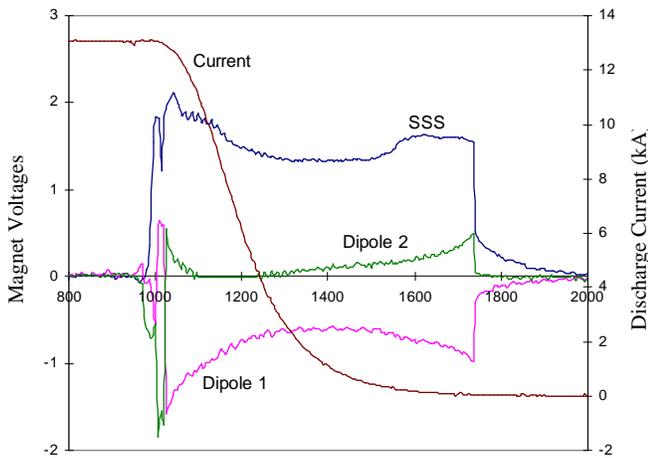

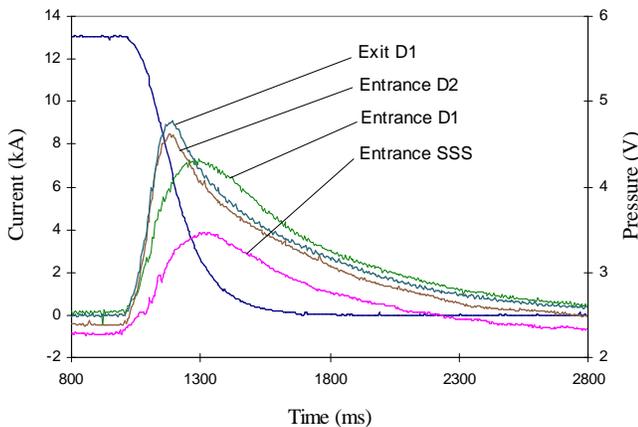Fig. 7: Magnet voltages during the quench at 13'070 A

Fig. 8: Magnet pressure during the quench at 13'070 A

The LHC String can be considered as being operational. It will now be used to validate the technical choices made for LHC and to hopefully improve the machine design. Experiments are being conducted for measuring the performance of the cryogenic system, for studying quench propagation, vacuum behaviour, etc. To this end, the String will be completed with two more magnets, as soon as they become available.

On the longer term, the SSS will be reconstructed, to incorporate all correction elements and the dipole magnets will be replaced by 14.2 m long magnets in order to have the String as close as possible to the final LHC half-cell, [11].

VII. ACKNOWLEDGEMENTS

The LHC String project has benefited from the constant support of G. Brianti and L. Evans, the former and present LHC Project Leaders. This project was launched in 1991, but the final installation and commissioning were done in a very short time, from July to December 1994, thanks to the hard work and enthusiasm of a number of people in the Accelerator and Technical Sectors of CERN. It is not possible to mention them all here but their contribution to the success of the String is gratefully acknowledged.

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