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**Operational Experience and Consolidations for the Current Lead Control Valves
of the Large Hadron Collider**

A. Perin¹, K. Brodzinski¹, O. Pirotte¹, B. Krieger² and A. Widmer³

1 CERN, Geneva, Switzerland

2 Bürkert GmbH, Ingelfingen, Germany

3 Bürkert AG, Hünenberg, Switzerland

Abstract

The Large Hadron Collider superconducting magnets are powered by more than 1400 gas cooled current leads ranging from 120 A to 13000 A. The gas flow required by the leads is controlled by solenoid proportional valves with dimensions from DN 1.8 mm to DN 10 mm. During the first months of operation, signs of premature wear were found in the active parts of the valves. This created major problems for the functioning of the current leads threatening the availability of the LHC. Following the detection of the problems, a series of measures were implemented to keep the LHC running, to launch a development program to solve the premature wear problem and to prepare for a global consolidation of the gas flow control system. This article describes first the difficulties encountered and the measures taken to ensure a continuous operation of the LHC during the first year of operation. The development of new friction free valves is then presented along with the consolidation program and the test equipment developed to validate the upgraded valves prior to their installation into the LHC.

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OPERATIONAL EXPERIENCE AND CONSOLIDATIONS FOR THE CURRENT LEAD CONTROL VALVES OF THE LARGE HADRON COLLIDER

A. Perin¹, K. Brodzinski¹, O. Pirotte¹, B. Krieger² and A. Widmer³

¹CERN
CH-1211 Geneva 23, Switzerland

²Bürkert GmbH
D-74653 Ingelfingen, Germany

³Bürkert AG
CH-6331 Hünenberg, Switzerland

ABSTRACT

The Large Hadron Collider superconducting magnets are powered by more than 1400 gas cooled current leads ranging from 120 A to 13000 A. The gas flow required by the leads is controlled by solenoid proportional valves with dimensions from DN 1.8 mm to DN 10 mm. During the first months of operation, signs of premature wear were found in the active parts of the valves. This created major problems for the functioning of the current leads threatening the availability of the LHC. Following the detection of the problems, a series of measures were implemented to keep the LHC running, to launch a development program to solve the premature wear problem and to prepare for a global consolidation of the gas flow control system. This article describes first the difficulties encountered and the measures taken to ensure a continuous operation of the LHC during the first year of operation. The development of new friction free valves is then presented along with the consolidation program and the test equipment developed to validate the upgraded valves prior to their installation into the LHC.

KEYWORDS: control valve, current lead.

INTRODUCTION

The superconducting magnets of the Large Hadron Collider (LHC) are powered by more than 1400 gas cooled current leads installed in cryogenic electrical feedboxes

TABLE 1. The gas cooled current leads of the LHC.

Type of lead	Total Number	Type	Inlet flow at current lead at I_{nom}
13 kA	64	Hybrid HTS	0.7 g/s @ 20 K
6 kA	258	Hybrid HTS	0.35 g/s @ 20 K
7.5 kA	40	Hybrid HTS	0.40 g/s @ 20 K
600 A	692	Hybrid HTS	0.03 g/s @ 20 K
120A	276	Resistive (group of 2, 4 and 8)	0.006 g/s @ 4.5 K
600A	112	Resistive	0.03 g/s @ 4.5 K

installed around the accelerator [1,2]. TABLE 1 lists the types and the number of current leads found in the LHC [3,4,5]. The flow of helium through the leads is regulated by room temperature control valves installed in the vicinity of the current leads. In the LHC, the gas cooled current leads range from 120 A to 13000 A, the corresponding valves sizes and their quantity are shown in TABLE 2. The 120 A leads are cooled in pairs or in groups of 4 or 8, which results in the number of control valves listed in TABLE 2.

In the LHC, almost all magnets are needed for the correct operation of the accelerator. The functionality of all the current lead control valves has therefore a direct impact on the availability of the LHC.

DESCRIPTION OF THE VALVES

The main operational conditions common to all valves are listed in TABLE 3 [5], the sizes of the valves are listed in TABLE 2. One of the main requirements is the fact that the valves are used to control the temperature of the leads with a closed loop regulation. For this kind of regulation, it is not necessary to know the exact position of the valve. Therefore, and in order to simplify the design of the valve actuator, no feedback on the position of the valve was required in the specification. In addition to the requirements about the flow properties, a key requirement was the operation in the presence of significant radiation which precluded the usage of most standard electronic components.

After evaluating several prototypes that differed essentially by the choice of the actuator technology (electric motor, pneumatic, solenoid), solenoid proportional valves manufactured by the company Bürkert GmbH of Germany were selected for the LHC.

The selected valves are solenoid valves where the lift of a mobile part is proportional to the current applied to the valve coil. The current can be supplied by control electronics located up to 800 m away from the valves, so no active electronic component would be in

TABLE 2. The current lead control valves of LHC. The helium mass flow is given for DP = 33 mbar.

Valve type	DN (mm)	Max. flow (g/s)	Kv (m ³ /h)	Number	Current leads
A	10	1.1	1.9	64	HTS 13 kA
B	6.5	0.55	1.1	298	HTS 6 kA, HTS 7.5 kA
C	1.8	0.05	0.08	887	HTS 600 A, Res. 4 x 120 A Res. 600A (DFBX), Res. 2 x 120 A
D	2.5	0.12	0.172	13	Res. 8 x 120 A

TABLE 3. Main operational conditions and requirements of the current lead control valves.

Pressure drop		33 mbar – 250 mbar
Nominal inlet pressure		1.2 bar
Characteristic		Linear
Rangeability / resolution		1 to 10 / < 2% of full flow
Type of regulation		Closed loop
Inline leaks (DP = 500 mbar)		5 % of max flow
Temperature	nominal	293 K
	max 20 minutes	273 K
Radiation		240 Gy and neutron flux of 1200 n/cm ³ over 10 years

the radiation exposed areas. A schematic view of the valve is shown in FIGURE 1. The mobile part, the plunger, is guided by two polymer dry bearings. The advantages of this type of solenoid valve are its simplicity and small dimensions. No leak tight mechanical transmission or bellows is required for the transfer of movement. The resulting valves are very compact with dimensions of only 110 mm x 45 mm x 50 mm for the larger valves (type A and B) and 75 mm x 45 mm x 35 mm for the smaller sizes (types C and D).

In such a solenoid valve, the position of the disk is determined by the equilibrium of the magnetic force, the pre-load spring force, the differential pressure force acting on the valve disk and by friction. As the coil cannot generate a very high magnetic field, the pre-load forces are small. The direct consequence is that the valves are not perfectly leak tight even when closed and that the stroke is influenced by the differential pressure. For the larger size valves, the maximum differential pressure is about 400 mbar. A typical full stroke cycle is shown in FIGURE 2 (left). The observed hysteresis, of about 7 %, is due to the magnetic behavior of the materials and is not related to friction. In smaller loops (5 % span), the observed hysteresis was lower than 1 % of the input signal.

FIGURE 1. Schematic view of a size C solenoid proportional valve (left) and flow characteristics for several differential pressures (right).

FIGURE 2. Mass flow for size C valve for a differential pressure of 100 mbar with a nominal behaviour (left) and with friction (right, zoomed on 0% - 50%).

INITIAL OPERATION

During the early phases of the hardware commissioning of the LHC, it was observed that the valves were operating at very low opening signal, not more than 2 %. The recorded signal being only the command signal, the actual position of the valve was not known. An additional characteristic of the regulation was that all values were oscillating around 1.8 % of output signal as can be seen in FIGURE 3 (left). The regulated temperatures were, however, well within the specified values of ± 2 K. The source of the observed behavior was rapidly traced to the fact that, as there is no position feedback, the valve opening is a function not only of the input signal, but also of the differential pressure. The control electronics was set at the factory for a differential pressure of 33 mbar while the actual differential pressure in the LHC was more than 150 mbar. The result of this setting was that the valve minimum opening (about 2%) was providing about half of the nominal flow. The fact that the input signal was oscillating around 1.8 % is linked to a specific feature of the control electronics that cuts the power to the valve coil for any input signal lower than 1.8 %, this is to improve the leak tightness of the valve at 0 % input signal. In fact the valves were acting as on/off valves with the regulation being performed by modulating the time spent at value higher than 1.8 % in a de-facto pulse-width-modulation regulation mode.

Initial Valve Tuning

During the first phases of the hardware commissioning campaign, the current lead control valves were regulating in at least partial on/off operation. As the temperature of the leads could nevertheless be controlled within nominal range, this did not affect the powering campaign and all commissioning operations were carried out in this mode. However, the on/off operating mode was not satisfactory as it was extremely difficult to extract any diagnostic data from the valve positions, for example to assess the performance of a current lead by comparing with its neighbors. It was therefore decided to tune the electronics for operating the valves in the full expected range of 50 mbar to 250 mbar; this could be performed with a simple operation on the electronics by shifting the input-signal-to-output-current curve. After validating the choice of parameters on a dedicated test bench, this was performed during the shutdown in 2008–2009 for all the smaller sized valves of type C/D.

FIGURE 3. On/off regulation of a 600 A current lead temperature with a valve of type C (left) and ramp up to 10'000 A with a type A valve showing partial on/off operation mode (right).

Sensitivity to Particle Contamination

During the initial months of operation, several valves, about 10, had to be replaced as it was not possible to regulate the helium flow to obtain the correct temperature. The faulty valves were removed from LHC and measured in a dedicated test bench; they showed the presence of significant hysteresis due to internal friction with respect to nominal characteristics as can be seen in FIGURE 2. An investigation performed in the last month of 2008 showed the presence of fine particles and some signs of wear on the polymer sliding bearings that guide the mobile internal parts. Previous experience with this type of valves indicated that some wear of the bearings was normal and should not have affected the valve performance so the investigation focused on the particles. After demounting several connecting pipes, the widespread presence of significant amounts of fine particles was confirmed (the composition was found to be essentially metal oxides and fine metallic particles from the piping and LHC magnets. It also appeared that the smaller size C valves were the most affected but the problem had been hidden by the on/off mode. By September 2009, 56 totally non-functional valves were identified

Following this finding, the decision was taken to install 20 μm filters on all valves and to clean all piping directly connected to the valves by flushing them with successive cleaning solutions. The cleaning / filter installation consolidation operation started in May 2009 with priority given to the size C valves. Each valve was individually tested on a test bench before re-installation. By the end of 2009, all valves had been equipped with filters and more than 500 of the C type valves had been demounted, cleaned and reinstalled.

Degrading Bearings

When the LHC sectors were brought sequentially into nominal operation conditions at the end of 2009, the reconditioned valves showed a normal performance for the first few weeks. However, after about a month of operation, several valves failed, showing increased friction. The most affected valves were the type C/D (rate of failure 3.5 valves/week on a total of 887 valves), but sizes A/B were also increasingly affected (rate of failure 3 valves/week on a total of 362 valves).

In collaboration with Bürkert GmbH, the supplier of the valves, a detailed investigation was started to determine the causes of the increasing failures. By re-

examining each detail of the faulty valves and by comparing them with healthy ones, the cause of the problem was found to be an excessive wear of the polymer linear bearings. After a variable amount of time, an irregular deposit of the bearing material was accumulating on the metallic parts, causing excessive friction and in some cases even the complete blockage of the valve. The exact origin of the difference in lifetime between individual valves was not conclusively determined but is thought to be due to small differences in the construction tolerances. In order to exclude possible causes linked to the LHC environment, a size C valve was long-term tested on a test bench and confirmed the appearance of degradation after 4 weeks of operation.

Compensatory Measures to Operate the LHC with Degrading Valves

As a first measure to reduce the problems, the valve manufacturer proposed to replace the polymer material of the bearings, but this rapidly proved to be insufficient to cure the problem. With the restart of the LHC at the end of 2009, the constant degradation of the valves and insufficient time to replace them, a number of measures were taken to allow the operation of the current leads with degraded valves. The first measure was to tune back the valve electronics to operate in on/off mode in order to reduce the sensitivity of the valves to friction, resulting in a regulation as the one shown in FIGURE 3.

Despite the robustness of the on/off mode, the degradation of the valves was in many cases so severe that even with the adjusted parameters, the regulation was heavily affected. During 2010 this concerned on average 3.5 valves / week for types C/D valves (about 20% failure rate per year) and 2 valves/week for types A/B valves (about 25 % failure rate per year). In order to allow the operation until the next technical stop of the LHC (every 5-8 weeks), a specific procedure was defined that involved successively: tuning of the PID regulation loops, action on the loop control logic and forging a full on/off mode. The faulty valves were then replaced during the subsequent technical stop. In total, the procedure was applied to 255 valves in 2010 (about 20% of the valves) and proved very successful as no LHC stop was caused by a valve failure, but at the cost of multiple maintenance interventions. No significant evolution was seen during the year 2010 as concerns the degradation rate which was constant at about 3 valves / week.

NEWLY DEVELOPED BEARING-LESS VALVES

To the present day (May 2011), the continuous degradation of the valves has imposed a constant monitoring of the valves and frequent heavy interventions on the LHC electrical feedboxes to replace the defective units. This situation has caused significant workload and poses a continuous risk as the degradation of the valves is not predictable. The complete replacement of the original valves was estimated to be mandatory for medium and long term operation. A strong incentive was placed in finding a solution that would allow reusing the existing cabling, electronics and piping. After the tests had excluded simple solutions like replacing the materials of the bearings, Bürkert GmbH proposed to develop valves without sliding bearings, thus avoiding the friction problems.

The solution proposed to avoid friction was to replace all sliding bearings with elastic supports resembling flat springs. A similar technical solution had already been applied by Bürkert GmbH to replace sliding bearings either fully, on much smaller valves, or only partially, on similar sized valves, but this is the first time that such a technology was applied to completely replace sliding bearings in valves of this range of sizes. The specially configured springs, shown in FIGURE 4, allow an easy movement perpendicular to the

FIGURE 4. Pictures showing the flexible bearings installed on the mobile parts for size C/D valves (left) and size A/B valves (right).

plane of the spring while providing a very stiff guidance in the plane of the spring. Such springs were specifically developed for the CERN control valves.

The new valves were tested at CERN and the characteristics for a valve of size B are shown in FIGURE 5 (left). The hysteresis is essentially caused by the magnetic hysteretic behavior of the valve materials and not by friction, as can be seen on FIGURE 5 (right). The valves show an excellent sensitivity to input change, with changes as small as 0.2 % in the input signal resulting in a measurable change of the flow. For small variations, the measured hysteresis was less than 0.2%. The behavior was identical for all valve sizes.

Pre-series units of all valve sizes were installed in the LHC to confirm the long term behavior and were closely monitored during a period of several months. The new valves allowed to improve the quality of the regulation with an achieved regulation band of $50\text{ K} \pm 0.2\text{ K}$, compared to the previous regulation of $50\text{ K} \pm 1\text{ K}$.

2010 – 2011 CONSOLIDATION CAMPAIGN AND FUTURE PLANS

In parallel with the validation of the newly developed valves, plans were drafted for

FIGURE 5. Gas flow as a function of the input signal for a size B bearing-less valve. Full stroke cycle (left) and small cycle (right).

the systematic replacement of all 1262 valves of LHC. The first phase, taking place during the 6 weeks technical stop of LHC at the end of 2010, was the replacement of most of the size C (DN1.8) valves of LHC and of all the size B (DN6.5) valves of the 8 inner triplet electrical feedboxes.

All valves were individually tested prior to installation. A dedicated full automatic test bench was developed for this purpose, with a daily test capacity of up to 80 size C/D valves and up to 20 size A/B valves. This high throughput was required to cope with the limited time available before the technical stop of LHC and the necessity to reuse some of the piping for the type C valves.

Before the restart of the LHC in March 2010, 711 size C/D valves (86% of total) and 68 size A/B valves (23% of total) were replaced. During the successive technical stops of March and May 2011, these numbers increased to 865 and 104 replaced valves. During the three months of continuous operation between February and June 2011 all 969 newly installed valves showed nominal operating performance.

CONCLUSIONS

During the hardware commissioning campaign of the LHC, the proportional solenoid gas flow control valves used to regulate the temperature of the current leads showed a progressive degradation of their performances. The initial investigations focused on the presence of particles in the gas flow. However, even after cleaning and installation of filters, the problems persisted. It was later determined that the problem was intrinsic to the valves that were suffering of premature wear of their sliding bearings. This necessitated the development of new bearing-less valves, where the mobile parts are guided by flat springs. The newly developed valves are characterized by the absence of friction and provide excellent regulation characteristics. It was decided to replace all current lead valves with the new type, but before this could be done, compensatory measures have been successfully applied to allow the LHC operation despite progressively degrading valves. The consolidation plan is well advanced. By June 2011 97 % of the size C/D valves and 25% of the size A/B valves have been replaced. The consolidation operations will continue at each technical stop of LHC with the target of having replaced all valves in the first half of 2012.

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