CERN LIBRARIES, GENEVA

CERN-AT-95-38

CERN AT/95-38 (CR)

LHC Note 350

84 9545

**Measurement of the Thermo Hydraulic Behaviour
of LHC Dipole Prototypes After Quench**

G. Gerin, B. Vullierme, R. van Weelden

The superconducting dipole magnets under design for the Large Hadron Collider (LHC) at CERN operate in pressurized static baths of superfluid helium at a pressure of 1 bar and at a temperature of 1.9 K. Several prototype magnets have been tested. We have measured for different quench conditions the development of pressure, temperature and helium content of the cryostat after a quench. Temperature data of the collar, yoke and the helium, both inside the cryostat and after discharge from the cryostat, were taken. Pressures were measured in the cryostat end-volumes and at three locations along the beam pipe. We present the results obtained as a function of the relevant quench parameters like energy released to the cryostat and discharge valve opening time.

Cryogenic Engineering Conference and International Cryogenic Materials
Conference,
July 17-21 1995, Columbus - Ohio, USA

Geneva, Switzerland
29 September 1995

MEASUREMENT OF THE THERMO HYDRAULIC BEHAVIOUR OF LHC DIPOLE PROTOTYPES AFTER QUENCH

G. Gerin, B. Vullierme, and R. van Weelden

Accelerator Technology Division, CERN
CH-1211 Geneva 23, Switzerland

ABSTRACT

The superconducting dipole magnets under design for the Large Hadron Collider (LHC) at CERN operate in pressurized static baths of superfluid helium at a pressure of 1 bar and at a temperature of 1.9 K¹. Several prototype magnets have been tested. We have measured for different quench conditions the development of pressure, temperature and helium content of the cryostat after a quench. Temperature data of the collar, yoke and the helium, both inside the cryostat and after discharge from the cryostat, were taken. Pressures were measured in the cryostat end-volumes and at three locations along the beam pipe. We present the results obtained as a function of the relevant quench parameters like energy released to the cryostat and discharge valve opening time.

INTRODUCTION

When a LHC dipole magnet quenches its full stored magnetic energy is dissipated by ohmic heating in the coils as they become resistive². This heat will eventually end up in the cold mass, and unless the helium contained inside the cold mass is expelled sufficiently fast it will drive the pressure an order of magnitude beyond the 2 MPa (20 bar) cryostat design pressure. Therefore after quench detection a quench relief valve (QRV) will be opened, fast enough to allow the helium to discharge and to limit the pressure rise to below this cryostat design pressure

Four prototype magnets (denoted A1, A2 and A3 for ANSALDO1 to ANSALDO3, and N1 for NOELL1)³ from two different manufactures have been tested on a specially constructed magnet test bench⁴.

We have measured the development of pressure, temperature and helium content of the cryostat after a quench, with the aim of answering the questions relating to the magnitude of the pressure rise in the bulk helium volume, the magnitude of the pressure

rise around the beam tube, the QRV sizing and the influence of QRV-opening time on maximum quench pressures.

EXPERIMENT

Installation Layout

The magnets are tested on the so called Magnet Test Bench, which is described in detail in a separate article⁴. It consists of the Magnet Feed Box, MFB, the interconnect, the dipole cryostat, and the Magnet Return Box. The superconducting dipole magnet operates in a pressurized static bath of superfluid helium at a pressure of 1 bar and at a temperature of 1.9 K. The heat load on this superfluid helium bath is extracted by conduction along the magnet length and along the interconnect to a lumped cold source inside the MFB. A 4.5 K saturated helium bath, which intercepts residual heat at the lower end of the 18 kA vapour cooled current leads, is thermally and hydraulically separated from the pressurized superfluid helium enclosure by two “ λ -plates”, which allow feedthrough of the superconducting current bus and instrumentation wiring. Emergency pressure relief and helium discharge after a magnet quench is performed through a DN50 electro-pneumatically-actuated, industrial-type, cold valve: the QRV. The helium is discharged into the 4.5 K vessel wherefrom the two-phase mixture is decanted.

Instrumentation

Figures 1 and 2 show the placement of sensors inside the magnet cryostat. Temperature sensors (Allen-Bradley 100 Ohm carbon resistors) are placed in the end volumes and midlength in the collar and yoke. Silicon-based pressure sensors are placed in the end volumes (Siemens KPY16), and at three locations along the length in the collar noses (Siemens KPY47), see figures 1 and 2. The pressure sensors in the end volumes give information about the bulk cryostat pressure rise. The pressure sensors at the collar noses were put because we expect the highest pressures to occur near the coils, where the helium trapped inside absorbs the heat.

Data was recorded with a sampling rate of 1 ms for a time period of 3 s and with a sampling rate of 10 ms for a time period of 40 s, using a commercial based transient recorder (Visual Designer) running on a personal computer.

RESULTS

Pressure Distribution

The rate of pressure increase is determined by a combination of the way the dissipated power in the coil changes when the current is being discharged, the transfer of this power to the helium trapped inside and in close contact with the coils, and of the hydraulics of the cold mass. The differences between the magnets are thus reflected in their respective pressure versus time curves.

Figures 3 and 4 show a typical measurement of pressure development after a quench as function of time and at different measurement locations. Figure 3 also shows the current and the QRV opening (normalized on a scale of 1 to 10). The quench is detected at $t = 0$ s. The magnet is then discharged within 600 ms. The QRV starts to open 120-

Fig. 1. Cross section of a 10 m long LHC dipole prototype magnet, showing the placement of sensors at midlength: $P_{nose,m}$ in the collar nose, T_{collar} and T_{yoke} in collar and yoke respectively. 1:yoke, 2:coils, 3:beam screen, 4:collars, 5:beam tube, 6:shrinking cylinder.

Fig. 2. Simplified longitudinal cut of a 10 m long LHC dipole prototype magnet inside its cryostat, showing the placement of sensors: $T_{end,a}$, $P_{end,a}$, $T_{end,b}$ and $P_{end,b}$ in the end volumes, $P_{nose,a}$, $P_{nose,m}$ and $P_{nose,b}$ in the collar noses, T_{collar} and T_{yoke} in collar and yoke respectively. The helium discharge is at the MFB connection side.

Fig. 3. Pressure, Current and QRV opening versus time for A3.

Fig. 4. Collar nose pressure compared with end pressures versus time for A3.

Table 1. Characteristics of quench pressure rise

magnet	t_{rise} [ms]	$(dP/dt)_{max}$ [bar/s]	$t_{changeover}$ [ms]	$(dP/dt)_{medium}$ [bar/s]	$t_{discharge}$ [ms]	$t_{collar\ rise}$ [ms]
A1	80 ± 10	39 ± 5			210 ± 10	210 ± 10
A2	60 ± 10	96 ± 5	150 ± 10	35 ± 5	210 ± 10	120 ± 10
A3	60 ± 10	99 ± 5	160 ± 10	45 ± 5	210 ± 10	130 ± 10
N1	80 ± 10	100 ± 5	150 ± 10	0	210 ± 10	150 ± 10

130 ms after the quench detection signal and reaches 90 % opening within 210-250 ms.

For the four dipoles tested we grouped together some characteristics of the pressure development curves in table 1. The meaning of the table becomes clear as one follows the pressure versus time curve of figure 3.

We observe that after quench detection and with the QRV still closed all pressures start to rise gently at t_{rise} . This time corresponds to the transition from superconducting to normal of all the conductors in the outer layer². We measure for A2 and A3 a 20 ms faster t_{rise} time than for A1 and N1.

Afterwards, with the QRV still closed, all pressures start to increase sharply. This rate of increase of pressure with time, $(dP/dt)_{max}$, is significantly lower for A1 (39 bar/s), than for all other magnets (96-100 bar/s). There is a change in slope of pressure increase from $(dP/dt)_{max}$ to $(dP/dt)_{medium}$ at $t_{changeover} = 150$ and 160 ms for A2 and A3 respectively. There is no change in slope for A1, and the slope becomes zero at $t_{changeover} = 150$ ms for N1.

Next the pressure nearest to the QRV starts to go down, indicating that the helium begins to discharge from the cold mass. This is confirmed by the mass flow measurement using a cryogenic Pitot tube located just after the QRV. It corresponds to the times indicated with $t_{discharge}$, and to a QRV-opening of 90 ± 5 %. All magnets show the same behaviour and start to discharge at $t_{discharge} = 210$ ms.

The pressures at locations further away from the QRV continue to increase until there is a maximum pressure difference over the magnet length, $(P_{end,a} - P_{end,b})$, of about 1 to 1.5 bar. After 2 seconds the pressure peak has passed and the pressures are down again to practically 1 bar.

We know from earlier measurements⁵ and from numerical simulations⁶ that if the helium which is trapped inside the coils is forced to flow through the annular space between beam tube and coil in order to reach the end volumes, the collar nose pressures will be very high with respect to the end volume pressures. Our measurements (figure 4)

Fig. 5. P_{max} versus dissipated energy for A3.

show that all pressures, in the ends and in the collar noses, rise simultaneously and that no extreme pressure differences develop. Therefore we conclude that for these LHC prototype magnets the principal escape path for the helium trapped inside the coils is radially through the collar noses, the collaring and the yoke and then longitudinally towards the end volumes.

Maximum Pressure versus Stored Energy

Figure 5 shows for the A3 magnet the maximum pressures, P_{max} , after a quench as function of dissipated magnetic energy and at different measurement locations. The maximum pressures depend about linearly on dissipated energy. Our measurements show that similar linear relationships hold for the other three magnets. Furthermore they show that for all magnets all pressures remain below the 2 MPa (20 bar) cryostat design limit. In conformity with the observations from the pressure versus time curves, table 1, the pressures are highest in A2 and A3 (12 and 12 bar at 4000 kJ) and lowest in A1 and N1, (8 and 7 bar at 4000 kJ).

Influence of Valve Opening Time on Maximum Pressure

On A3 and N1 we measured P_{max} when the quench relief valve was already open before the quench, see figure 6. This was easily achieved during current ramps by opening the valve a few minutes before the current would reach quench values. Opening the valve caused only a very slight rise in bath temperature, of the order of tens of mK. Since quenches in these magnets have a structural cause these measurements are representative of maximum pressures one could get with a very fast valve. They give the lower bound for P_{max} . Furthermore these measurements provide an opportunity to observe the time at which the helium would start to discharge when there is no obstruction in the discharge line. It gives the time below which a faster opening QRV would no longer result in a decrease in P_{max} . For the A3 magnet we observed that all pressure peaks are reduced by approximately 2.5 - 3 bar. The maximum pressure is reached after 180 ($P_{end,a}$) ms. $P_{end,b}$ and $P_{end,a}$ join each other after 250 ms. The mass starts to discharge after 130 ± 10 ms. At the same time of the mass discharge we see that the temperature in the collar starts to increase, see t_{rise}^{collar} in table 1. For the N1

Fig. 6. Pressure versus time for A3, QRV open.

Fig. 7. Pmax versus valve opening time for A3. Dissipated energy 4732 kJ, corresponding to a 13 kA quench current.

magnet we observed no change in P_{max} , except near the QRV where $P_{end,b}$ went down by approximately 1.5 bar. The maximum pressure is reached after 160 ($P_{end,a}$) ms. Again $P_{end,b}$ and $P_{end,a}$ join each other after 250 ms. The mass starts to discharge after 150 ± 10 ms, while the collar temperature starts to increase after $t_{rise}^{collar} = 150 \pm 10$ ms. Both measurements show that the increase in collar temperature is correlated with the onset of the mass discharge.

On A3 we have also done some measurements with longer QRV opening times. The opening time being defined as the total time from quench detection until the valve reaches a given aperture. Because of the QRV-characteristic we choose the time at which it has opened by 95 % as reference. Figure 7 shows the effect of opening time on maximum quench pressure for A3. Using the measured linear relationship between maximum pressure and dissipated energy for A3 (see figure 5), all pressures are rescaled to an energy dissipation of 4732 kJ corresponding to a 13 kA quench current. The rate of increase, 48 bar/s for $P_{end,a}$, and 42 bar/s for $P_{end,b}$ agree with the expected rate of $(dP/dt)_{medium}$ from table 1

Based upon the mass discharge measurements with the QRV open we would choose an opening time for A3 not lower than 130 ms. and for N1 not lower than 150 ms. However extrapolation of the measurements shown in figure 7 indicate that for A3 we could probably use an QRV-opening time of about 180 ± 20 ms, without significantly increasing the P_{max} . This is close to the measured discharge time with QRV opening

Fig. 8. Mass discharge. A3, dissipated energy 4222 kJ, 13.804 kA quench current

Fig. 9. Temperatures. A3, dissipated energy 4222 kJ, 13.804 kA quench current

on the quench trigger, $t_{discharge} = 210 \pm 10$ of table 1.

Mass Discharge

The mass discharge was measured using a cryogenic Pitot tube. Figure 8 shows a typical mass discharge curve. The onset is at 210 ± 10 ms. It reaches a maximum of 11.5 kg/s 240 ms after the quench. At 350 ms this initial burst goes down and it reaches a steady 3 kg/s after 2 s, where it remains until practically the whole cryostat (84 %) is emptied.

Temperatures

Figure 9 shows typical temperature development curves. The end plate and helium temperatures rise to 3-4 K. The yoke follows until after 17.5 s (8.5 s after all the helium is discharged) it starts to rise, reaching 16 K after 40 s. The collar temperature increases 120 ± 10 ms after the quench and reaches 30 K after 40 s. This onset of collar temperature corresponds to the onset of mass discharge and collar temperature as measured with the QRV open before the quench. As a consequence we can take the onset of collar temperature t_{rise}^{collar} measured with the QRV closed as the time below which a faster opening QRV would no longer result in a decrease in P_{max} , see table 1. t_{rise}^{collar} for A1 is significantly higher than for the other magnets.

CONCLUSIONS

Our measurements show that all quench pressures remain below the 2 MPa (20 bar) cryostat design limit.

The maximum pressures reached depend about linearly on dissipated energy.

The pressures in the ends and in the collar noses, rise simultaneously and no extreme pressure differences develop. This is in sharp contrast with a scenario in which the helium escapes longitudinally along the annular space between beam tube and coils. Therefore in these LHC prototype magnets the principal escape path for the helium trapped inside the coils must be radially through the collar noses, the collaring and the yoke and then longitudinally towards the end volumes.

The onset in collar temperature, t_{rise}^{collar} , is correlated with the onset of the mass discharge in case the QRV is open before the quench. The t_{rise}^{collar} time is therefore the lower limit, below which a faster QRV opening time will no longer be an effective means to reduce maximum quench pressures. For opening times exceeding $t_{discharge}$ the pressure increase can be estimated using the dP/dt values deduced from the pressure versus time measurements.

There are differences between the different magnets. The low rate of bulk pressure increase for A1 and its significantly higher t_{rise}^{collar} remain unexplained as well as the leveling off of P_{max} after 150 ms for N1.

ACKNOWLEDGMENT

The authors would like to thank the crew of the LHC test bench for all their effort in getting the measurements taken. Thanks are also due to W. Cameron for providing the schematics.

REFERENCES

1. Ph. Lebrun, Superfluid Helium Cryogenics for the Large Hadron Collider Project at CERN, *Cryogenics* **34** ICEC Supplement (1994), pp. 1-8.
2. F. Rodriguez-Mateos, G. Gerin and A. Marquis, Quench Protection Test Results and Comparative Simulations on the First 10 Metre Prototype Dipoles for the Large Hadron Collider, *Fourteenth International Magnet Technology Conference (MT-14)*, Tampere, (1995).
3. R. Perin, Status of LHC Program and Magnet development, *Applied Superconductivity Conference (ASC)*, Boston, (1994).
4. V. Benda, M. Granier, Ph. Lebrun, G. Novellini, V. Sergo, L. Taviani and B. Vullierme, Cryogenic Benches for Superfluid Helium Testing of Full-Scale Prototype Superconducting Magnets for the CERN LHC Project, *Cryogenics* **34** ICEC Supplement (1994), pp. 733-736.
5. M. Granier, D. Hagedorn, K.N. Henriksen, Ph. Lebrun, D. Leroy, R. Perin, J. Vlogaert, J. Deregél, P. Genevey, J.P. Jacquemin, F. Kircher, J. Le Bars, Performance of the Twin Aperture Dipole for the CERN LHC, *European Particle Accelerator Conference (EPAC)*, Berlin, (1992) and CERN Internal Note AT-MA/9204 (1992).
6. Ph. Lebrun, Th. Wahlström, R. van Weelden and L. Williams, Investigation of Quench Pressure Transients in the LHC Superconducting Magnets, *Cryogenics* **34** ICEC Supplement (1994), pp. 705-708. Genova, (1994).