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# Failure mechanism and consolidation of the compensation bellows of the LHC cryogenic distribution line

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## Abstract

In the beginning of the year 2013, after the first three years of operation, the Large Hadron Collider (LHC) was progressively emptied from helium and warmed up to ambient temperature in order to perform, during its first long shutdown, all necessary consolidation and maintenance of the different technical systems. During the warm-up, six helium leaks were declared on the cryogenic distribution line (QRL). All the leaks were detected on the main header supplying supercritical helium at 4.5 K during normal LHC operation. Following a complex investigation based on combination of time-of-flight leak detection over 400-m long vacuum sub-sectors and X-rays, the leaks have been localized on the compensation bellows required for longitudinal thermal contraction. During the investigation, some compensation bellows were found damaged but not leaky yet, amounting to 16 the total number of bellows to be repaired. This paper will present the investigation method for the localization of damaged bellows, the failure mechanism and the applied improvements in the bellows design. The QRL repair procedures and the final leak-tightness validation campaign will be also described.

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*Keywords:* LHC; bellows; failures; transfer line

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## 1. Introduction

The Cryogenic Distribution Line (QRL) is part of the LHC cryogenic cooling system [Brüning et al. (2004)]. It contains five helium pipelines so-called headers. Two supply and three recovery headers allow for helium distribution to the local magnet cooling loops. The pressures and temperatures of the helium distributed in the headers are summarized in Table 1 [Erdt et al. (2000)].

Table 1. The main dimensions, working pressure and temperature of the QRL headers.

| Header | DN | Pressure (bar) | Temperature (K) |
|---|---|---|---|
| Header B (return) | | 0.016 | 3.8 – 4.2 |
| Header C (supply) | 100 | 3.6 | 4.6 |
| Header D (return) | 150 | 1.3 | 20 |
| Header E (supply) | 80 | 19.5 | 50 – 65 |
| Header F (return) | 80 | 19 | 65 – 75 |

The first sign of a tightness problem occurred already during the 2010/2011 end of the year technical shut down when one leak on the QRL header C was declared during partial warm up of the system to about 80 K. Helium leak detection by means of time-of-flight over 400 m vacuum subsector identified the leak zone where the bellows, to compensate thermal contractions of the line at each ~53.5 m, are installed. The QRL standard cell design layout is presented in Fig. 1 [Brodzinski et al. (2006)].

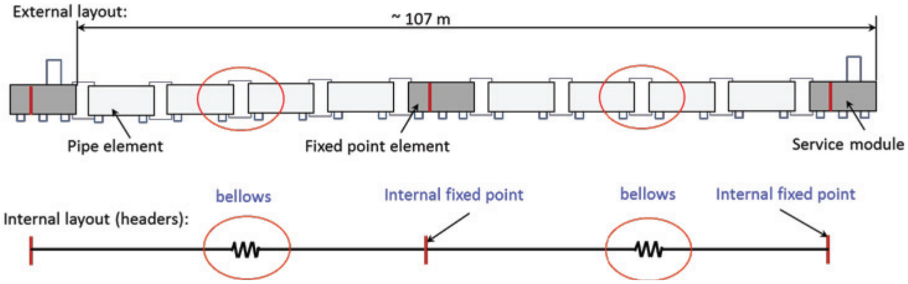

Fig. 1. The QRL standard cell layout.

The X-rays of the suspected interconnection confirmed visually deformations on the header C. The X-ray and photo of later removed bellow are presented in Figs. 2a and 2b. Because of tight LHC run schedule the interconnection was not repaired and additional pumping capacity has been put in place to compensate the leak. The damage mechanism for this singular case was not understood at that time.

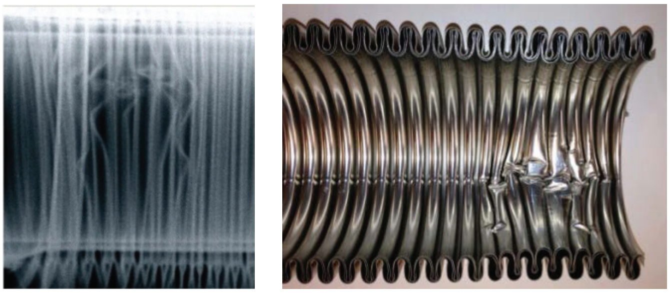

Fig. 2. (a) X-ray of first leaky bellow; (b) photo of the first leaky extracted bellow.

After 3 years of accelerator operation, the first complete warm up started in spring 2013. All magnets were progressively emptied from helium and warmed up to ambient temperature according to the planned long shut down period dedicated to maintenance and consolidations of the machine technical systems. During the warm up, six additional helium leaks were declared on different QRL vacuum subsectors.

## 2. Compensation bellows design

The bellows chosen for the QRL installation are working with external helium pressure. Because of mechanical requirements the intermediate bellow part was fabricated as multiply assembly welded to the flanges on both extremities to provide lower stiffness and helium tightness , see Fig. 3.

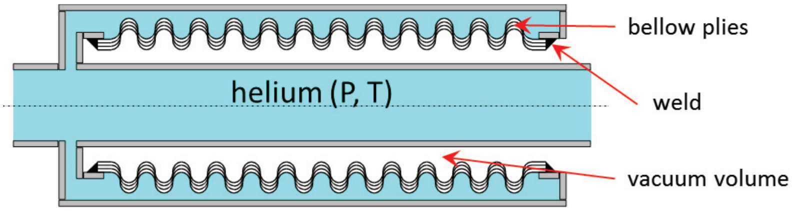

Fig. 3. The simplified bellow design.

## 3. Investigation and failure mechanism

After the long shut-down warm-up the situation required full investigation and understanding of the origin of the problem. The first step of methodology was the same as in the case of the first leak – helium time-of-flight calculation combined with X-rays of all interconnections within the affected vacuum subsectors. In all seven cases X-ray showed bellow deformation on the header C. The detailed analysis of the X-rays confirmed clear damage of the bellow plies, see Fig. 4.

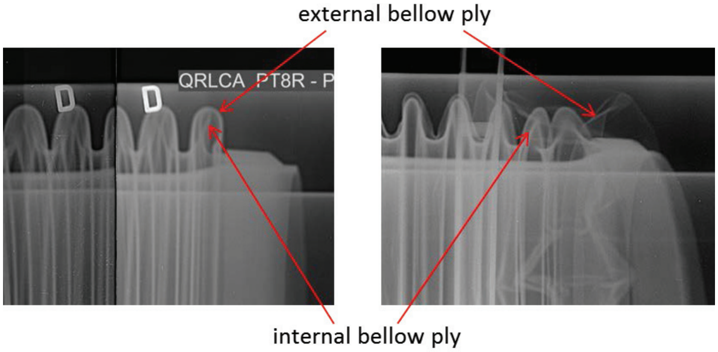

Fig. 4. X-rays of damaged compensator plies.

This finding lead to presume that during three years of operation some bellows faced a helium tightness problem into the inter-ply volumes. These leaks were not visible in the monitored vacuum space since the leaks were not traversing from the helium volume to the vacuum. As additional investigation, one of the first bellows was submitted to the metallurgical analysis. This analysis confirmed the existence of a crack on the double weld between the plies extremity and the flange, see Fig. 5.

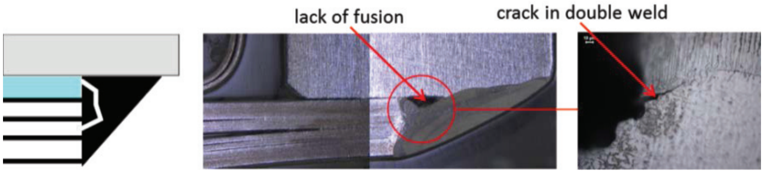

Fig. 5. Crack in double weld allowing helium passing in between the plies.

During warm up the supercritical helium trapped in-between the plies did not have enough time to escape via the micro leaks. The increasing inter-ply pressure lead first to bellow deformation and secondly to the creation of a traversing leak from the helium to the vacuum volume. Visual representation of the damage sequence is presented in Fig. 6. The effect of the helium discharge from the inter-plies volume to the vacuum was visible on vacuum pressure monitoring and is shown on the graph in Fig. 6.

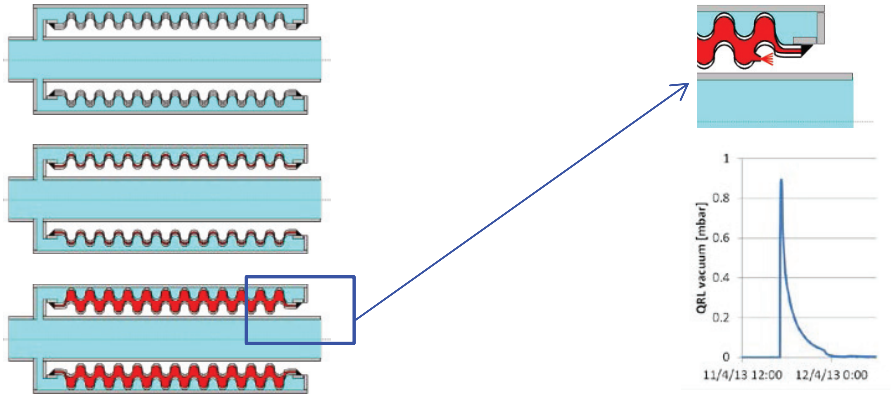

Fig. 6. The bellows damage sequence with the insulation vacuum pressure evolution .

In order to not to miss any deformed compensator which could stay in the intermediate damage state (deformed but not leaky to the vacuum) the decision was taken to make an X-rays campaign on entire machine length. This investigation confirmed intermediate damage of two additional compensators on header C and seven compensators on header D (constituted of 5 plies), rising up the total number of damaged compensators to sixteen. Fig. 7 shows the repartition of the damaged compensators in the different LHC sectors and Table 2 presents summary on helium leak rates. No correlation was identified with respect to compensator production batches. Given the total number of compensators on these headers, a failure rate of 1.4% has been reached (taking into consideration the total number of installed bellows).

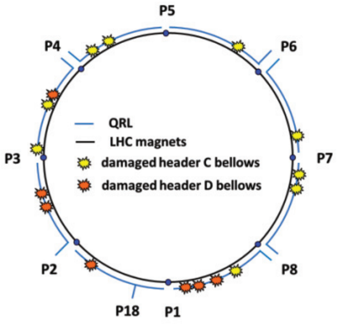

Fig. 7. Repartition of damaged compensators.

Table 2. Helium leak rate from damaged bellows (pressurized at 1 bara) to insulation vacuum.

| Cell number (bellow identification) | DN | Leak rate measured in related vacuum volume (mbar l/s) | Remarks |
|---|---|---|---|
| 14L2 (SSB) | DN150 | 4.30E-08 | deformed but not leaky |
| 32R2 (SSD) | DN150 | 3.40E-10 | deformed but not leaky |
| 23L3 (SSG) | DN150 | 2.50E-09 | deformed but not leaky |
| 6R3 (SSI) | DN100 | 2.80E-03 | leaky |
| 32L4 (SSD) | DN100 | 9.00E-10 | deformed but not leaky |
| 31L4 (SSD) | DN150 | 9.00E-10 | deformed but not leaky |
| 14R4 (SSB) | DN100 | 1.30E-05 | leaky |
| 22R4 (SSC) | DN100 | 1.10E-09 | deformed but not leaky |
| 24L6 (SSC) | DN100 | 4.80E-04 | leaky |
| 12L7 (SSH) | DN100 | 2.70E-06 | leaky |
| 10R7 (SSH) | DN100 | 2.60E-03 | leaky |
| 19R7 (SSG) | DN100 | 5.00E-03 | leaky |
| 29R8 (SSD) | DN100 | 4.40E-04 | leaky |
| 24L1 (SSG) | DN150 | 2.10E-08 | deformed but not leaky |
| 14L1 (SSH) | DN150 | 1.90E-09 | deformed but not leaky |
| 13L1 (SSH) | DN150 | 1.90E-09 | deformed but not leaky |

## 4. Repairs

### *4.1. Existing spares validation*

All existing spare compensators which were tested after fabrication by means of standard tightness test between helium and vacuum volumes could not be used without a complete validation against potentially existing leaks into the inter-ply volume. Before installation in the LHC machine the bellow validation was completed by CERN for each spare compensator applying the so-called “boombing test”. This test consists of first accumulating helium in the inter-ply volume via a possible leak by pressurization of the compensator at 10 bar during 1 week and secondly performing a global helium leak of the compensator. In case of a conform compensator, the background signal of the leak detector recovers quickly. In case of a leak, the inter-ply volume will degas the accumulated helium which will be detected.

### *4.2. New spares design*

The repairs required the order of additional spares. In parallel with existing old spares validation, CERN, together with the original bellows supplier, applied improvements in the compensator design. The new spares have a modified flange shape and weld between the plies extremity and the flange, see Fig. 8. The new design allows welding of the 4 plies in one passage. A similar design was successfully applied to the 5000 thermal compensators produced for the LHC cryo-magnets and based on DN80 non-perforated multiply bellows operated with superfluid helium. The other modification is to keep only one ply tight (on the helium side) and all other plies are perforated to create ventilation holes.

The old design required two superposed welds to separate mechanical withstanding (the rings reduces the stress on the bellows weld) and tightness. The cause of the crack is not clearly identified. The micrographic of welds shows an important lack of fusion of the second weld. This defect generates a notch effect which could explain the start-up of a crack. Further investigation would be necessary to identify the root causes of this defect.

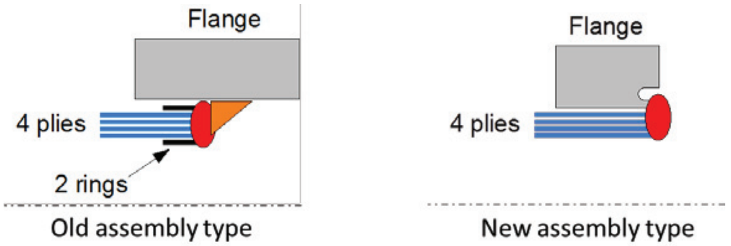

Fig. 8. The modified assembly procedure for new type of spare bellows.

### *4.3. Repair schedule*

The repair of the sixteen interconnections was performed between September 2013 and April 2014 and consisted in the following steps for each interconnection:

- Opening of the external envelope bellow using orbital cutting machine (tight operation because of space limitation around the QRL)
- Removal of multilayer insulation and thermal screens
- Replacement of faulty expansion joint (with manual welding)
- Local helium tightness testing at 1 bar
- Installation of thermal screen and multilayer insulation
- Closing of the interconnection
- Vacuum pumping and helium tightness test under vacuum

The total repair, including new spares, did cost about 1 MCHF. Although the guarantee period of the QRL distribution line was over, Air Liquide – the QRL supplier, has recognized the problem (insufficient evaluation of the risk with dead volume and weld defects of their supplier) and contributed substantially to this repair cost.

## 5. Conclusion

After the first LHC operation run, eight year after installation completion of the QRL distribution line, sixteen thermal compensators were found damaged following the LHC warm-up and had to be repaired during the first long shut-down.

The failure mode has been identified and is due to the over-pressurization of the non-controlled inter-ply volumes in case of link of these volumes with the process fluid via leaks. The encountered failures were linked directly with fabrication problems.

As basic rule, the design of non-controlled volumes is not recommended for cryogenic applications. Consequently, the use of vented-plies is advised for cryogenic compensators. However, if for specific applications several plies need to be tight (e.g. if the compensator need to withstand individually high internal and external pressure), the bellow should be validated for tightness by means of the boombing test.

## References

Brüning, O., Collier, P., Lebrun, P., Myers, S., Ostojic, R., Poole, J., Proudlock, P. (editors), 2004, LHC Design Report, Volume I The LHC Main Ring, CERN-2004-003, Geneva.
Erdt, W. Riddone, G., Trant, R., 2000, The cryogenic distribution line for the LHC: functional specification and conceptual design, Advances in Cryogenic Engineering, 45 1387-1393.
Brodzinski, K., et al., 2006, Reception test of the Cryogenic Distribution Line for the Large Hadron Collider. ICEC21 Proceedings, Prague, Czech Republic.