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Final report on the Controlled Cold Helium Spill Test in the LHC tunnel at CERN

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Abstract. The 27 km circumference LHC underground tunnel is a space in which the helium cooled LHC magnets are installed. The vacuum enclosures of the superconducting magnets are protected by over-pressure safety relief devices that open whenever cold helium escapes either from the magnet cold enclosure or from the helium supply headers, into this vacuum enclosure. A 3-m long no stay zone around these devices is defined based on scale model studies, protecting the personnel against cold burns or asphyxia caused by such a helium release event. Recently, several simulation studies have been carried out modelling the propagation of the helium/air mixture, resulting from the opening of such a safety device, along the tunnel. The released helium flows vary in the range between 1 kg/s and 0.1 kg/s. To validate these different simulation studies, real life mock-up tests have been performed inside the LHC tunnel, releasing helium flow rates of 1 kg/s, 0.3 kg/s and 0.1 kg/s. For each test, up to 1000 liters of liquid helium were released under standard operational tunnel conditions. The data recorded include oxygen concentration, temperature and flow speed measurements, and video footage used to assess qualitatively the visibility. These measurements have been made in the up- and downstream directions, with respect to the air ventilation flow, of the spill point.

This paper presents the experimental set-up under which these release tests were made, the effects of these releases on the atmospheric tunnel condition as a function of the release flow rate. We discuss the modification to the personnel access conditions to the LHC tunnel that are presently implemented as a result of these tests.

1. Introduction

The Large Hadron Collider (LHC) accelerator is located 100 m underground with several access shafts along the 27 km circumference. The tunnel contains the accelerating infrastructure of superconducting cavities cooled with liquid helium at 4.5 K and superconducting magnets cooled with superfluid helium at 1.9 K. The large amount of cryogenic liquid represents a risk for equipment and especially for personnel present in the underground tunnel structure. Several studies have been carried out focused on the effect of a helium spill on the oxygen content, on the temperature variations and on the visibility in the LHC tunnel area [1][2]. Benchmarking the simulations was considered a priority, so it was decided to perform a helium spill in the LHC tunnel, under standard operational conditions. The first test with a spilling rate of 1 kg/s corresponding to a mechanical damage caused by an electrical arc induced at an energy of 100 kJ has already been reported in the ICEC 25-ICMC 2014 conference [3].



After those tests the Helium Spill Working Group decided to perform several other experiments with two lower levels of helium spill rates. These tests represent conditions which could occur when the LHC is not in the “closed mode” for beam operation, and personnel could thus be present in the tunnel:

- 320 g/s: This failure mode is based on a local rupture induced by an electrical arc discharging an energy of 30 kJ, corresponding to the maximum energy authorized when the LHC is in “access mode” for experts. This spill rate can take place during the powering phase 1 with reduced power, 30 kJ maximum in each circuit with cables and bus bars operating in pressurized liquid helium at 1.9 K. This spill rate can also be reached during the copper stabilizer continuity measurement tests, with 300 kJ in each circuit with cables and bus bars operating in 20 K helium gas.
- <100 g/s: The failure mode is identified as a consequence of a possible human mistake of personnel accessing the tunnel when the magnet system is not energized.

2. Experimental set-up in the LHC tunnel

The aim of the test is to check the validity of the different models and calculations of the helium distribution dynamics along the LHC tunnel. To realize a representative helium spill test in the LHC tunnel a mock-up safety release device has been built with the same DN 200 mm diameter as the original. The helium release device is placed on top of a magnet vacuum vessel with a support structure ensuring the thermal insulation between the mock-up and the mechanical structure of the magnet vacuum enclosure during the spill test. A schematic view of the tunnel cross section and a side view are shown in Fig. 1 depicting the arrangement of the two 500 liter liquid helium dewars placed in the walkway symmetrically to the spill point. Both dewars can be simultaneously pressurized from a battery of 12 helium gas bottles to around 0.13 MPa to 0.14 MPa. A vacuum insulated extraction pipe guides the liquid helium out of the dewars into a DN 125 mm insulated interconnection pipe towards the mock-up release device. The whole extraction chain is designed to keep the dewars pressure during these tests well below the opening pressure of the primary safety valve of the dewars, which is set at 0.15 MPa.

The helium spill location acts as a reference for the distances of the measurement stands along the tunnel. There are 15 stands, 7 upstream in reference to the tunnel ventilation flow of the spill point (distributed over 100 m distance) and 8 downstream (distributed over 200 m). Those locations include a total of 25 Pt100 type temperature sensors and 25 special developed (fast reacting) Oxygen Deficiency Hazard (ODH) sensors [1]. These acoustic sensors were custom-designed by Wroclaw University of Technology. The sensors contain an ultrasonic transmitter and receiver. From the time-of-flight of the ultrasonic pulse the sound velocity in the mixture can be derived. The helium concentration is then calculated including a correction for local temperature. These temperature values are measured using independent Pt100 sensors. The acoustic sensor response time is below 1s, which is notably faster than the reaction time of chemical O₂ sensors, which have a time constant of about 10 - 20 s. The ultrasonic sensor can provide up to 5 readings per second. The output signal of this sensor is transmitted as a standard 4-20 mA signal to the Data Acquisition (DAQ) system. Additionally, five ODH sensors of the standard chemical type are installed in parallel to the newly developed sensors to compare the measured values and their reaction times. Also installed are six video cameras, four air velocity measurement devices, and two scales used to calculate the mass flow rate of the helium released from the dewars. The height of the ODH sensors varies at the different measurement stands between 0.5 m and 1.75 m. Additionally, there are temperature sensors placed close to the ceiling of the tunnel. The majority of the sensors are located at 1.75 m height, probing the elevation of worker’s heads.

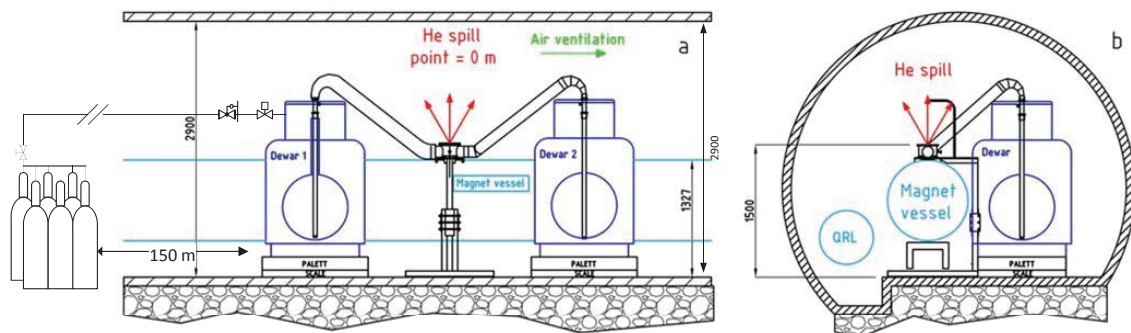


Figure 1. Schematic view of the experimental set-up in the LHC tunnel; (a) Side view of the arrangement of the two dewars centered around the spill point, which is set as reference $s=0$ m; (b) LHC tunnel cross section showing the placement of the 500 l dewars in the walk-way, the mock-up helium spill on top of a dipole magnet and the cryogenic distribution line (QRL).

3. Experimental results and observations

All tests have been performed at night times, while no personnel access was granted except for people related to the helium spill test. In the second run (340 g/s and 100 g/s), the released helium from the dewars was mixed with helium gas at room temperature from a battery, providing a control of the helium spill temperature. A higher spill temperature was desired to make the test more representative of an eventual incident in the tunnel. We compare the tests with three spill rates performed under the same operational ventilation conditions. The chosen parameters of the spill test are summarized in table 1.

Table 1. Summary of the chosen parameters of the helium spill test in the LHC tunnel.

Parameter of the He spill	Test1	Test2	Test3
Air ventilation flow rate	18.000 m ³ /h	18.000 m ³ /h	18.000 m ³ /h
Duration of test	125 s	275 s	600 s
Helium mass flow rate	1 kg/s	340 g/s	100 g/s
Total amount of helium released in tunnel	125 kg	60 kg	60 kg
Temperature of spill helium	5 K	15 K	34 K

3.1. Measured oxygen contents and temperatures

To illustrate the measurements two locations will be considered:

- One at 30 m from the spill point at kneeling height (0.5 m from floor level) to represent a person near the incident putting on his self-rescue mask.
- The other one at 100 m from the spill point at 1.75 m from floor level to illustrate workers head height.

The measured temperatures for the first minutes after initiating the helium spill are shown in figure 2. The measured oxygen concentrations downstream of the spill point are shown in Fig. 3 for equivalent location as the temperatures given before.

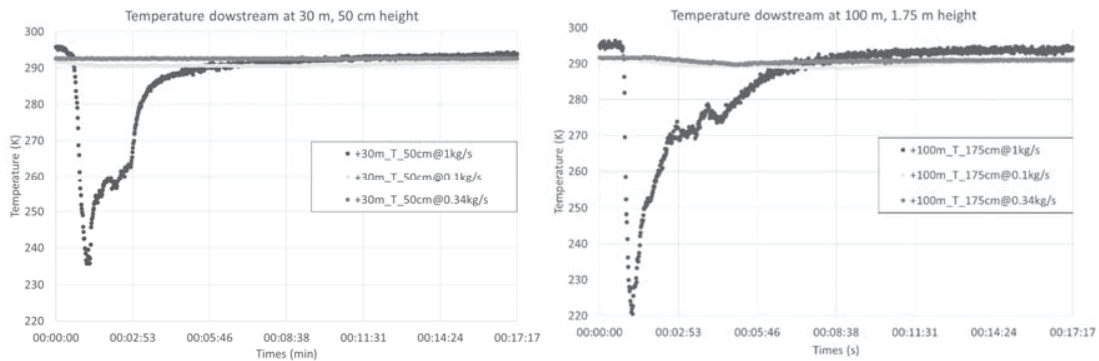


Figure 2. Temperature evolution along the LHC tunnel in the downstream direction with the start of the He spill at timestamp 0 s.

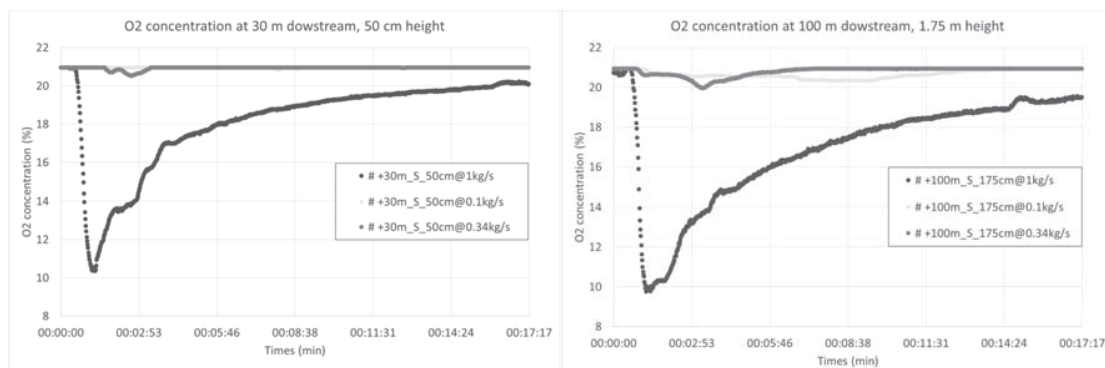


Figure 3. Measured oxygen concentration during the helium spill test in the downstream direction. Start of the pressurization of the dewars at $t=0$ s.

3.2. Helium Spill @ 1 kg/s

The main results from the helium spill at 1 kg/s carried out under possible access conditions (ventilation at 18,000 m³/h corresponding to airspeed in the tunnel of about 1.1 m/s) are:

Direct observations:

- Close to the release point: cloud, homogeneous and noise.
- The fixed tunnel installation ODH sensors, placed every 200 m at the ceiling, triggered only after several minutes the evacuation alarm. Alarms triggering strongly depends on where fixed ODH sensors are localized with respect to the spill zone.
- Cloud (water condensation due to presence of cold helium) disappears quickly (>20 m) nevertheless the ODH remains <18 % oxygen, due to the presence of warm helium.

Measured observations:

- Cloud travels at 1.1 m/s, similar to temperature wave propagation.
- Oxygen deficiency propagates on entire tunnel cross-section, both in the horizontal and vertical planes.
- All additionally placed mobile ODH detectors triggered, including farthest one at 200 m and 0.3 m height.
- Recovery from the oxygen deficiency improves faster close to the ground.

- The measurements upstream of the ventilation show a fast attenuation of the impact of the helium spill.

With a larger helium inventory, case of the maximum credible incident (MCI) of 1 kg/s, the cloud is expected to continue propagating. The experimental data taken showed a divergence with respect to the simulation data available: The oxygen content in the tunnel lowers over a large area down to 16%. Also the general visibility in the tunnel was lowered drastically except for heights below 1 m, caused by a visible cloud resulting from the condensation of the water present in the air flow by the lowering of the temperature.

3.3. Helium Spill @ 320 g/s

- Near the spill point the temperature decreased to 150 K. Nevertheless 40 m away from the spill point the ambient temperature in the tunnel lowers nowhere more than 15 K.
- The oxygen content in the tunnel lowers nowhere more than 2 % except for the area directly next to the spill point (lowering of about 10 %). The oxygen concentration close to the floor is higher than 18 %. The presence of a “safe” volume close to the floor is therefore granted. The temperatures and the oxygen contents in upstream direction were not impacted by the helium spill.
- The general visibility in the tunnel was lowered near to the spill point only, caused by a visible cloud. At around 40 m from the spill point the visible cloud is only present at the top of the tunnel.

3.4 Helium Spill @ 100 g/s

- The ambient temperature in the tunnel lowers nowhere more than 10 K, except for the volume directly against the tunnel ceiling (height from tunnel floor of more than 2 m) close to the release point, where a lowering of the temperature of about 40 K is measured.
- The oxygen content in the tunnel lowers nowhere more than 1 % except for the area directly next to the spill point (lowering of about 9 %). At a distance of 10 m from the spill point the lowering of the oxygen content at 50 cm above floor level is already less than 1 %, while this value is also reached at the 1.75 m above floor level at a distance of 20 m from the spill point. The given values are valid for the direction downstream of the spill point (with reference to the ventilation flow), while the oxygen content in the upstream direction stays at values within 1 % of the original value at already a distance of 10 m from the spill point.
- The visible cloud (water present in the air flow condensed by the lowering of the temperature) is only present at the top of the tunnel, above 1.75 m above the floor level. This cloud reduces partially the visibility in the tunnel since it covers the ceiling lights.

4. Simulation

Comparison of various 2D and 3D simulation models with experimental results on the atmospheric consequences of a controlled helium spill in the LHC tunnel are still carried out.

Up to now, a zero dimensional model has been used, based on the following considerations:

- Only downstream flow, upstream flow is not taken into account.
- Full adiabatic mixing of air and helium.
- Incompressible flow.
- No heat exchange with tunnel surface or magnet string.

Its validity extends from ten tunnel diameters onwards. Since no stratification is considered, the simulated values are conservative for the lower half of the tunnel.

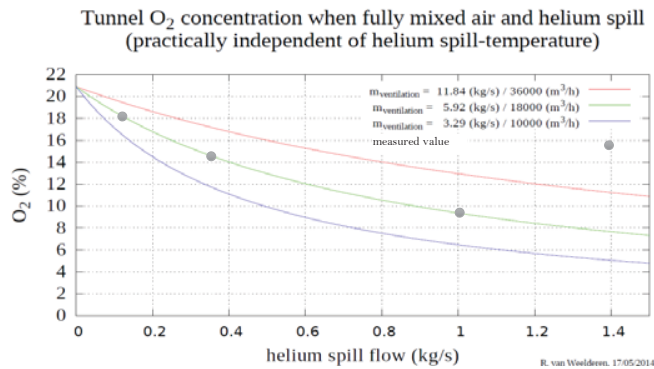


Figure 4. Zero dimensional model and minimum value measured during the spill tests measurement. LHC tunnel O₂ concentration for fully mixed air and spilled helium is considered (practically independent of helium spill temperature in this model). The three tested helium spill rates are marked on the medium air flow rate of 18000 m³/h.

5. Discussion and safety implication for personnel access in the LHC tunnel

A successful helium spill has been realized in the LHC tunnel under controlled conditions using newly developed measurement equipment. The data constitutes a profound basis for further simulations. The repeatedly released mass flow of cold helium, the propagation of the helium cloud and the influence of the superposed air ventilation in the LHC tunnel let us validate the access conditions. The Helium Spill Working Group has concluded that in order to mitigate the ODH the following safety measures and access rules for personnel need to be implemented:

- No personnel access to the tunnel while cooldown and warm-up procedure as well as during powering tests of the helium cooled magnets are performed.
- The access conditions for personnel are redefined so that they will never be exposed to an MCI of larger than 0.1 kg/s.
- Extensive personal training to prevent human mistake.
- The access is restricted to expert with authorization.
- Use remote controlled instrumentation whenever possible.

References

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- [3] Controlled Cold Helium Spill Test in the LHC Tunnel at CERN; ICEC 25-ICMC 2014 conference