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Controlled cold helium spill test in the LHC tunnel at CERN

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Abstract

The helium cooled magnets of the LHC particle accelerator are installed in a confined space, formed by a 27 km circumference 3.8 m diameter underground tunnel. The vacuum enclosures of the superconducting LHC magnets are protected by a lift plate against excessive overpressure created by eventual leaks from the magnet helium bath, or from the helium supply headers. A three-meter long no stay zone has been defined centered to these plates, based on earlier scale model studies, to protect the personnel against the consequences of an eventual opening of such a lift plate. More recently several simulation studies have been carried out modelling the propagation of the resulting helium/air mixture along the tunnel in case of such a cold helium release at a rate in the range of 1 kg/s.
To validate the different scale models and simulation studies, real life mock-up tests have been performed in the LHC, releasing about 1000 liter of liquid helium under standard operational tunnel conditions. Data recorded during these tests include oxygen level, temperature and flow speed as well as video recordings, taken up- and downstream of the spill point (-100 m to +200 m) with respect to the ventilation direction in the LHC tunnel. The experimental set-up and measurement results are presented. Generic effects found during the tests will be discussed to allow the transposal to possible cold helium release cases in similar facilities.

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Keywords: Helium spill; LHC tunnel; Oxygen Deficiency Hazard

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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 by liquid helium at 4.5 K and superconducting magnets cooled with superfluid helium at 1.9 K. The total underground helium inventory reaches about 120 tons. This large amount of cryogenic liquid represents a risk for equipment and especially for personnel present in the confined space of the underground tunnel structure. An updated risk analysis of the LHC cryogenic and helium distribution system by Chorowski et al. [1] categorizes the risks of failures of the cryogenic system e.g. a release of cold helium vapor into the vacuum insulation of the magnet vessels. The maximum credible incident (MCI) with access of personnel that leads to a release of helium vapor into the LHC tunnel is identified resulting in a leak rate of 1 kg/s for a total helium amount of 1236 kg. The propagation of the vapor cloud through the tunnel is strongly influenced by the air ventilation speed and the conditions of the spilled cold helium vapor. Temperature profiles and oxygen levels vs. time were measured in a tunnel mock-up experiment [2] and calculated by Chorowski et al. [3]. Following the simulation results the temperature of the released helium flow would be in the range of 25 K to 40 K.

During Long Shutdown 1 (LS1) every magnet string of 107 m length has been equipped with a DN 200 mm lift plate device, depicted in Fig. 1(a). In case of a failure of the inner helium circuit causing an overpressure in the vacuum tank these resealing lift plates will open first, before other safety valves pop off.

Fig. 1 Pictures of the newly installed pressure relieve devices on the vacuum enclosure of a LHC dipole magnet. (a) resealing lift plate with an opening pressure of 0.107 MPa; (b) Exclusion zone – restricted working area 3 m long centered on the release point.

At the beginning of the operation of the LHC a restricted working zone (exclusion zone) was defined along the LHC tunnel where only passing of personnel is allowed while helium is present in the magnet string. This exclusion zone is marked at the floor and accounts for 3 m centered on the possible release point, see Fig. 1(b). Later on new overall arrangements of the exclusion zones were proposed based on the simulation results, shown in Fig. 2.

The new proposed restricted working zones are centered on the helium release points as well but are quite different in length. The deviation between the two models of the helium distribution after an incidental spill in the LHC tunnel caused the need of a full size test in the LHC tunnel itself. A real size mock-up test has been initiated to realize a controlled cold helium spill test in the LHC tunnel. The chosen parameters of the spill test are in

Table 1.

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

Parameter of the He spill	Value	Remarks

Air ventilation flow rate	18.000 m^3/h	Access of personnel condition
Duration of test	125 s	
Helium mass flow rate	1 kg/s	Using standard equipment like Dewars
Total amount of helium released in tunnel	125 kg	1000 liter in two Dewars

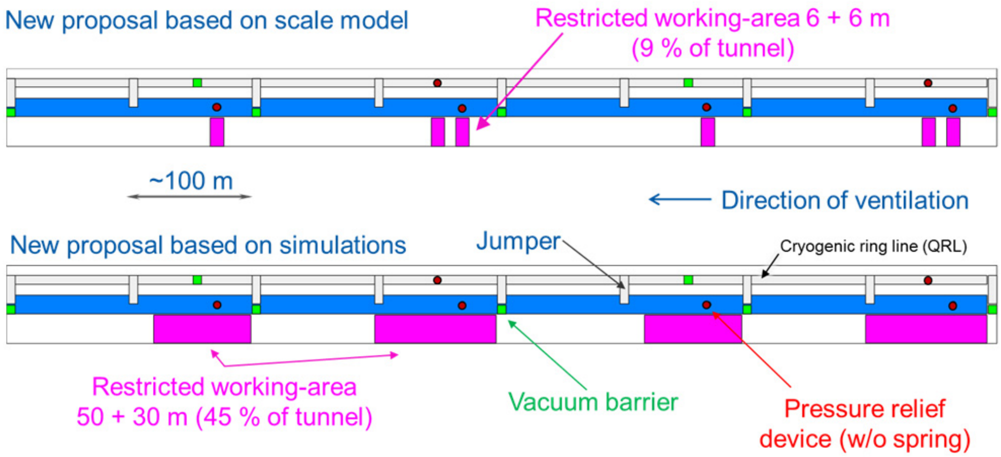

Fig. 2 Schematic view of the newly proposed restricted working areas in the LHC tunnel around the safety lift plates of the vacuum vessels of the main arc magnets. The upper schematic depicts the proposed exclusion zones based on the results of the mock-up test [2]. The lower schematic shows the increased exclusion zones as a restricted working area based on the results of the simulations.

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 diameter DN 200 mm as the real ones, compare Fig. 1. The helium release is placed on top of a magnet vacuum vessel with a special made support structure ensuring thermal insulation to the mechanical structure of the vacuum enclosure during the spill test. A schematic view of the tunnel cross section and a side view are shown in Fig. 3 depicting the arrangement of the two 500 liter liquid helium Dewars placed in the walkway symmetrically to the spill point. Both Dewars are simultaneously pressurized from a battery of 12 helium gas bottles to around 0.13 MPa to 0.14 MPa via a pressure reducer. The vacuum insulated extraction pipe guides the liquid helium out of the Dewars into the DN 125 mm interconnection towards the mock-up release device. The whole extraction chain is designed in a way to keep the necessary value of the pressurization in the Dewar well below the opening pressure of the primary safety valve of the Dewar 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 of the spill point (distributed over 100 m distance) and 8 downstream (distributed over 200 m). Those locations include a total of 25 temperature sensors Pt100 type and 25 special developed (fast reacting) Oxygen Deficiency Hazard (ODH) sensors. These acoustic sensors were custom-designed by the Wroclaw University. Each sensor contains an ultrasonic transmitter and receiver. An ultrasonic burst with a frequency of 40 kHz is produced by a transmitter and detected by a receiver after propagating through the space where the helium-air mix is present. From the time-of-flight of the ultrasonic pulse the sound velocity in the mixture is derived. The helium concentration is calculated with additional temperature correction. These temperature values are measured using separate Pt100 sensors. The sensor response time is below 1s. It is notably faster compared to the chemical O_2 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 is transmitted as standard 4-20 mA signal directly to the Data Acquisition (DAQ) system. Each ultrasonic sensor gives one analog signal proportional to helium content level in air (at the mounting location of this particular sensor). Additionally five ODH sensors of standard chemical type are installed in parallel to the new developed sensors to compare the measured values and the reaction time. Six video cameras are installed, four air velocity detectors and two scales, which measure the mass flow rate of the helium released out of 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 is located at 1.75 m height, probing the elevation of workers heads.

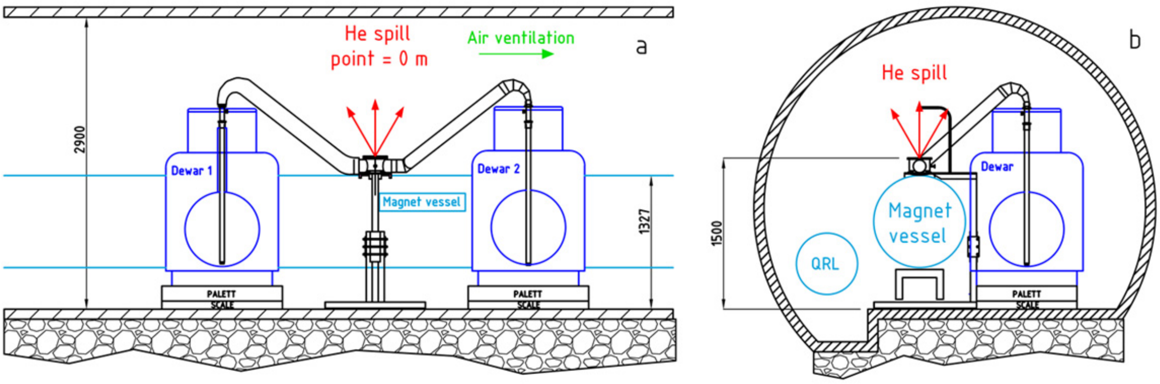

Fig. 3 Schematic view of the experimental set-up in the LHC tunnel; (a) Side view of the arrangement of the two Dewars centered on the spill point, which is set as reference s=0 m; (b) LHC tunnel cross section showing the placing of the 500 l Dewar in the walk-way and the mock-up helium spill on top of a dipole magnet. QRL stands for Cryogenic Ring Line.

3. Experimental results and observations

Two independent tests have been performed during night times, in which no personnel access was granted except for people related to the helium spill test. The spilled mass flow rate and its temperature are depicted in Fig. 4. There are two major flow rate regimes adjusted during the test, firstly a maximum flow of up to 1.3 kg/s followed by a reduced flow rate of around 0.4 kg/s. The flow change was caused by a non-proper function of one of the pressure reducers in the warm gas pressurization chain. Nevertheless, these different flow rates enable the measurement of different propagation behavior of the cold cloud along the tunnel. As a side note, the realized helium spill is qualitatively quite close to the measured flow evolution of helium evaporated from a cryostat by air ingress into the vacuum insulation of the vessel by Lehman and Zahn [4].

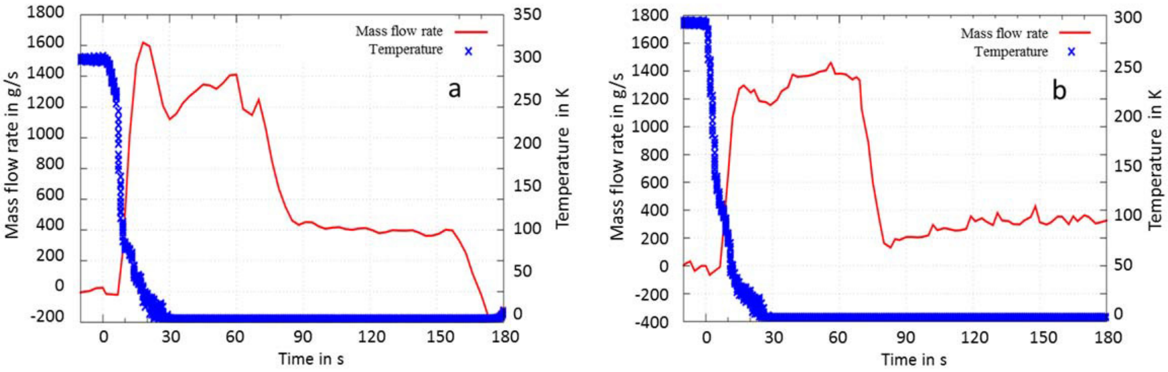

Fig. 4 Overview of the mass flow rate and respective temperature evolution of the released helium during the two independent test runs; a) 06th Feb and b) 07th Feb 2014. The temperature of the spilled helium flow is measured in the mock-up lift plate by a calibrated Cernox® sensor.

3.1. Observations during the tests

The recorded movies of the helium release into the LHC tunnel captured only little audible noise. An opaque cloud is visible that we associate with condensation from water and air-constituents due to the mixing of the air-ventilation flow with cold helium. This opaque cloud firstly dropped to the ground at the spill point location because of its temperature being well below 40 K. In the downstream direction, up to +60 m, the opaque cloud reached down to 50 cm height filling the whole tunnel cross section. Further downstream this opaque cloud occupied the upper third of the tunnel.

There was a minor vapor cloud very close to the ceiling (up to 0.3 m) that was propagating in upstream direction of the spill point.

3.2. Measured oxygen contents and temperatures

The measured temperature distribution along the tunnel for the first 270 seconds after initiating the helium spill is shown in Fig. 5 and Fig. 6 for workers head height of 1.75 m and kneeling height of 0.5 m, respectively. The time delay between the start of the helium spill and the onset of falling temperatures at the respective sensor position is clearly visible in Fig. 5. It takes 10 s to reach 10 m distance with temperature approaching 180 K after 30 s. Further away from the spill point the propagation speed keeps constant, while the lowest temperature reached during the test is increasing as further the sensor position is located e.g. 220 K for +30, +60 and +100 m, but only 270 K at +200 m. Obviously this is caused by the mixing of the cold helium cloud with the air flow in the tunnel and a slight heat exchange with the tunnel wall and the hosted equipment. At kneeling height an interesting effect of mixing/turbulent flow propagation seems to occur at the +20 m sensor location where temperatures are decreasing to lower values than the positions before and further downstream in the tunnel.

The measured oxygen concentration downstream of the spill point is shown in Fig. 7 and Fig. 8 for a height of 1.75 m and 0.5 m, respectively. At workers head height the oxygen level drops down to 9-12 % at all probed locations of 20 m to 150 m. The onset of reducing oxygen content shows the similar behavior as the temperature evolution but stays quite low for around 100 s to 120 s at each measurement point. Especially in Fig. 8 one can observe that the time span of low oxygen content can be linked to the duration and the mass flow rate of the helium spill itself.

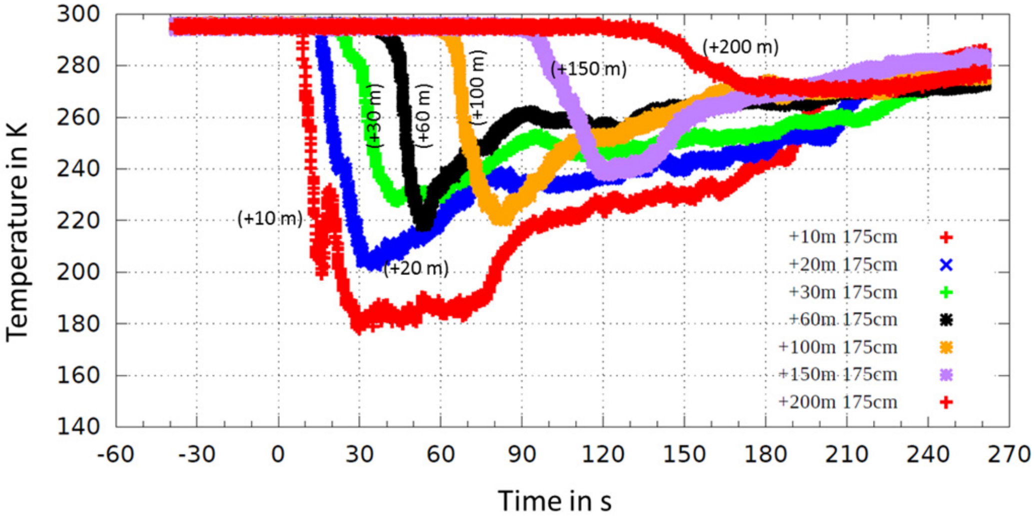

Fig. 5 Temperature evolution along the LHC tunnel with the start of the He spill at timestamp 0 s in the downstream direction up to 200 m. The height of the sensors is at 1.75 m considered to be workers head height.

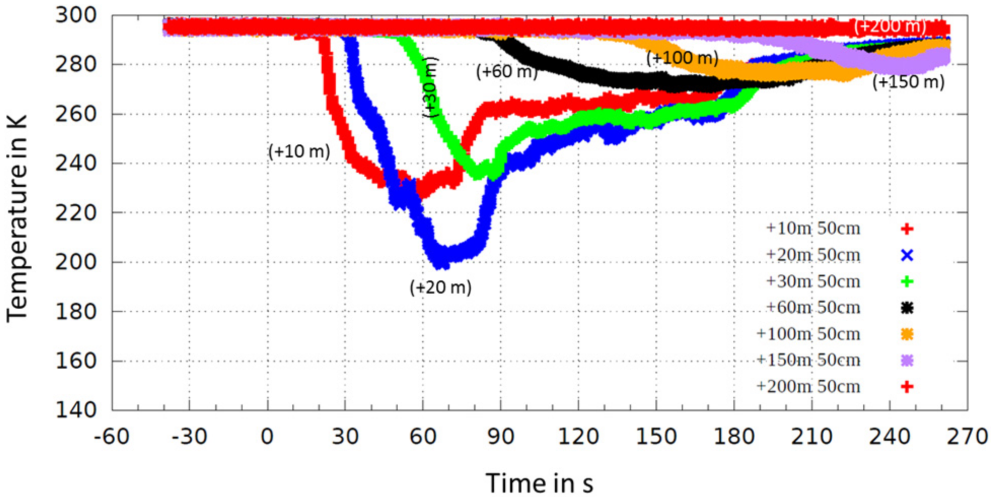

Fig. 6 Temperature evolution along the LHC tunnel with the start of the He spill at timestamp 0 s in the downstream direction up to 200 m. The height of the sensors is at 0.5 m kneeling height.

The different kinds of oxygen sensors show good agreement with a clear advantage in reaction time for the newly developed ultrasonic sensors. In contrast the chemical sensors show lower absolute values compared with the ultrasonic ones 9 % compared to 11 % e.g., measured at the same location of 20 m and 1.75 m height. At kneeling height of 0.5 m the oxygen concentration drops to around 12 % at all distances (except at the spill point where lower concentrations of oxygen down to 6 % are reached). The onset of reduced oxygen concentration shows varying influences at 0.5 m height, see Fig. 8. It happens at the spill point and at 10 m downstream almost at the same time caused by the temperature evolution of the released helium, because there is some time necessary to cooldown the extraction piping. At the start-up phase the density of the released helium is lower than air leading to a helium jet towards the ceiling. After 20 s the helium release temperature reaches T<40 K and the helium firstly drops down at the spill point, reaching in this way both sensor locations at roughly the same time.

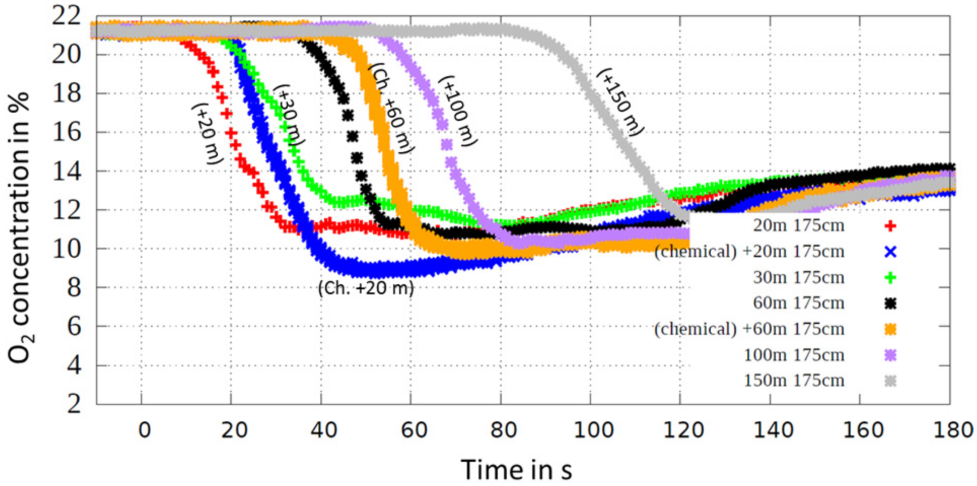

Fig. 7 Measured oxygen concentration during the helium spill test in the downstream direction at workers head height. At a distance of 20 m and 60 m an additional chemical oxygen detector was mounted, see label in the graph. Start of the pressurization of the Dewar at t=0 s.

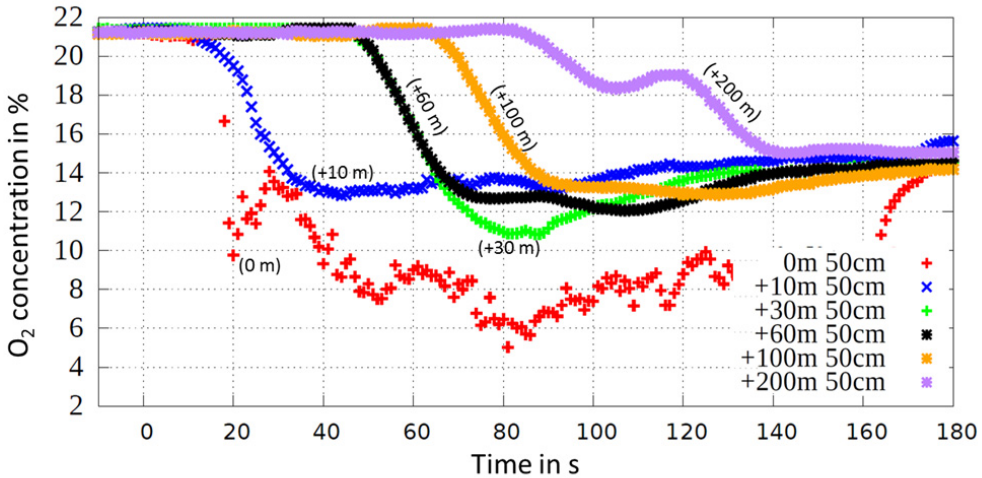

Fig. 8 Measured oxygen concentration downstream of the spill point at kneeling height (new developed ultrasonic sensors). Start of the pressurization of the Dewar is at t=0 s. The values for 30 m and 60 m distance are fairly close to each other before dropping below 14 % oxygen level (30 m value drops to 11 %).

Another phenomenon is visible for locations +30 m and +60 m in Fig. 8 with the same onset of oxygen reduction at around 50 s. This shows that the propagating helium-air mixture along the tunnel ceiling simultaneously reaches lower heights after a certain distance. For the locations at +100 m and + 200 m the mixing of the air flow and the cold helium vapor lifts the minimum oxygen concentration to around 14 %, but those values are low for longer time spans. The evolution of the oxygen levels in the upstream direction of the spill point at 50 cm height are summarized in Fig. 9. Only for -5 m distance upstream the oxygen content dropped below 20 %. All other sensors have measured values at or above a level of 20 %. A similar result holds for the oxygen level at the personnel height of 1.75 m upstream, where all sensors have shown an O_2 level dropping just to 20 %.

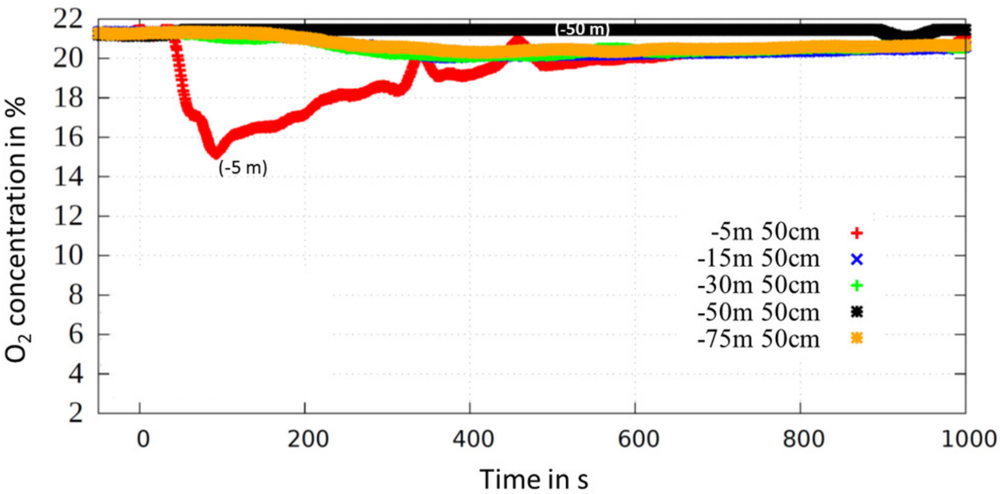

Fig. 9 Measurement results of the oxygen content in upstream direction at kneeling height. Start of the Dewar pressurization at t=0 s. The values for -15 m, -30 m and -75 m show almost the identical behavior.

Given the low temperature T ~ 4.2 K of the released helium after the initial cooldown of the extraction system, the strong influence to the -5 m location can be explained. The helium cloud is falling down to the floor before warming up sufficiently to rise to the ceiling, whereas further away from the spill point the dynamics is different with the helium density always lower than the air density.

The results of the second spill test, performed one night later, show similar results, expected for roughly the same mass flow rate spilled into the LHC tunnel, compare Fig. 4 (a) and (b). The observed averaged propagation velocity of the helium-air mixture through the tunnel (supported by the air ventilation velocity of 0.7 m/s) is 1.8 m/s to 2 m/s for all heights of 0.5 m, 1.75 m and ceiling height.

4. 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 new developed measurement equipment. The data constitutes a profound basis for further simulations. The repeatedly released mass flow of cold helium validated the up- and downstream propagation of the vapor cloud and the influence of the superposed air ventilation in the LHC tunnel. The helium-air mixture travels in downstream direction with a speed of about 1.8 m/s. The period in which the oxygen content drops below 18 % is stable for 450 s along the distance of 0 m to +150 m. The helium air mixture propagates further along the tunnel practically undisturbed towards the extraction point at the end of the sector. Comparing the measured O_2 content with the additionally recorded movies; including visual indication of portable oxygen detectors, the drop of oxygen content cannot be related to the visible formation of mist in the flow. Oxygen levels lower than 18 % are reached well below the visible interface from transparent gas to mist conditions towards the ceiling. All portable oxygen detectors triggered, including the one at +200 m at 0.3 m height. The evacuation alarm only becomes active after about 3 min (two independent ODH sensors need to pop off to trigger the alarm) while the helium travels around 320 m in the same time span. We conclude from the stated results that at the tested spill rates, corresponding to the original MCI of 1 kg/s, no safe zone is available to put on the self-rescue mask as personal protective equipment required in the LHC tunnel.

A CERN task force 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 sectors are cooled down or warmed up or powering tests are performed of helium cooled magnets.
- The access conditions for personnel need to be redefined such that they will never be exposed to an MCI of larger than 0.1 kg/s.
- New helium spill tests will be performed with mass flow rates of 0.25 kg/s and 0.1 kg/s to confirm safety levels of the proposed mitigation measures.

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