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Large Hadron Collider Project

LHC Project Report 523

OXYGEN DEFICIENCY HAZARD (ODH) MONITORING SYSTEM IN THE LHC TUNNEL

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Abstract

The Large Hadron Collider (LHC) presently under construction at CERN, will contain about 100 tons of helium mostly located in equipment in the underground tunnel and in caverns. Potential failure modes of the accelerator, which may be followed by helium discharge to the tunnel, have been identified and the corresponding helium flows calculated [1, 2, 3]. In case of helium discharge in the tunnel causing oxygen deficiency, personnel working in the tunnel shall be warned and evacuate safely. This paper describes oxygen deficiency monitoring system based on the parameter of limited visibility due to the LHC tunnel curvature and acceptable delay time between the failure and the system activation.

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1. Introduction

The philosophy of the proposed oxygen deficiency monitoring system is to warn personnel present in the tunnel in case of a helium discharge causing oxygen deficiency. It must be a “fool-proof” system indicating in an easy, comprehensive way all actions to be taken to escape safely from the LHC tunnel sector concerned.

Persons may not enter the underground without being equipped with personal survival kits containing self-rescue supplied atmosphere oxygen masks. They shall be warned (alarm level 3) [4] sufficiently in advance to protect themselves by help of atmosphere respirators [5].

Personnel shall have sufficient education and training. Furthermore, when working in the LHC underground, people shall never work alone [6].

2. Definitions and assumptions

2.1. Assumptions

For this study, the following assumptions have been taken into consideration:

1. Some of the analysed failure modes of the LHC cryogenic system can be followed by a helium discharge into the tunnel and consequently an oxygen deficiency could occur [1]. According to the TIS Safety Instruction [8], a minimal allowable percentage of oxygen in the atmosphere is 19%.
2. Important cold helium release will cause visible humidity condensation in the vicinity of the relief point.
3. Helium release in large quantities will generate noise.
4. The concept of the ventilation system for underground tunnels has been specified according to reference 7.
5. The discharged helium will propagate together with the ventilation airflow along the tunnel. The tunnel slope does not enable helium-enriched mixtures to flow against the ventilation air.
6. The air-helium mixture propagation velocity will be similar to that of the ventilation air. Due to the increase in the total volumetric flow in the tunnel after the warm-up of the discharged helium, an average air-helium propagation velocity may exceed the initial ventilation velocity by a factor of about two.
7. An oxygen deficiency will be detected by the system as soon as the oxygen deficient atmosphere reaches the closest ODH monitor.
8. Persons present in the tunnel could be warned either by an alarm signal activated by an ODH monitor, a visible cloud of moisture, noise of exhausting helium or by other persons leaving the discharge zone.
9. Each ODH monitor must trigger alarm indicators (e.g. flashing lights or signals) and must also inform the safety control room (e.g. fire brigade) which has to take actions adequate to a level 3 alarm.

2.2. Access to the tunnel

As a general rule only people authorised may have access to the tunnel.

The LHC areas from the surface site to the tunnel have been classified [8] in the following way:

1. Access sites and surface buildings (e.g. SD, SZ, SX): no radiation risk is present in these zones.
2. Underground zones accessible when beam on (e.g. some PM, PX, PZ shafts, some US caverns, part of UX halls): low residual radiation and people holding a film badge have access to them during LHC operation.
3. Underground zones not accessible when beam on (e.g. some PM, PX, PZ shafts, the klystrons galleries UA, the technical service zones US, UW and UL, part of the UX halls, portions of the UJ tunnels): no access is allowed during LHC operation.
4. Experimental caverns and tunnel (e.g. main ring, part of the UX halls, injection tunnel TI1 and TI8): the beam is circulating in these zones and no access is allowed during LHC operation.

For each zone a dedicated type of control system is associated. Depending on the zones, a CERN card, a film badge, the access key or a dosimeter may be required. For example, to enter the LHC sites and the surface building the CERN card with the ID number is required, while to enter the underground tunnel and caverns, a film badge and access key are needed in addition. Details are given in reference [9].

2.3. Warning signals

Personnel in the tunnel can be notified about ODH by the following signals:

- signals generated by activated ODH monitors located in the tunnel,
- signals generated by activated personal ODH monitors,
- visible mist caused by condensed humidity in the vicinity of a helium relief point,
- noise generated by an important amount of helium vented to the tunnel.

2.4. Signals indicating the direction of escape

The system must provide clear and simple indications to assure safe escape of personnel in the right direction.

Persons present within the visibility distance from the helium discharge shall always evacuate away from the discharge point.

Persons warned by the activated oxygen deficiency system shall evacuate in the direction of the nearest exit. If the helium discharge point is between them and the exit, they shall change the escape direction as soon as they notice the point of incident (e.g. cloud, noise).

3. Concept of the LHC ventilation system

The ventilation concept for the LHC is based on a nominal air velocity of 0.55 m/s (nominal volumetric-flow of 6.25 m^3/s) and an emergency air velocity of 0.88 m/s (emergency volumetric-flow of 10 m^3/s). The air is supplied at the even points 2, 4, 6, 8 by ventilators located at surface and extracted at the odd points 1, 3, 5, 7. The operational principle of the ventilation system is shown in Figure 1.

Details concerning the conditioning of the supplied air are given under reference 10. The elevation of the LHC tunnel and the direction of the ventilation air for the different sectors are shown in Figure 2. Calculations of relative air/helium velocity have confirmed that the tunnel slope is too small to enable helium-enriched mixtures to flow against the ventilation air flow.

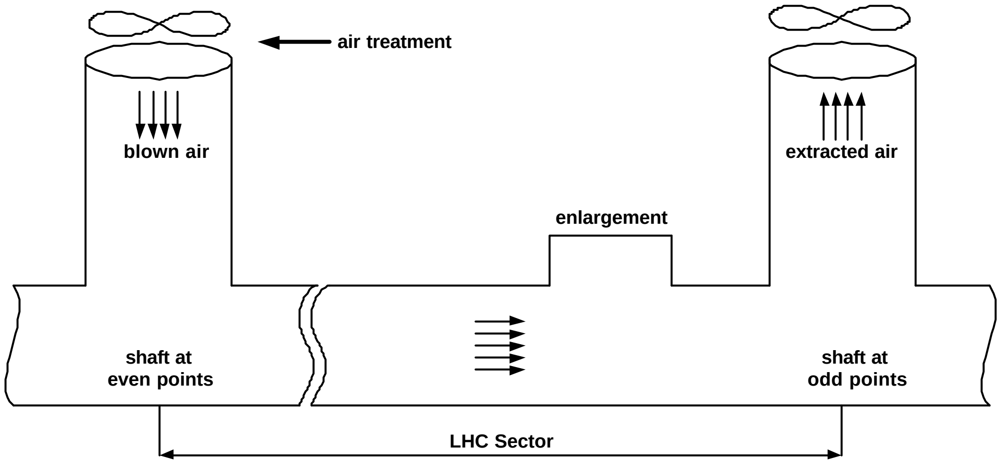


Figure 1: Operating principle of the LHC ventilation system

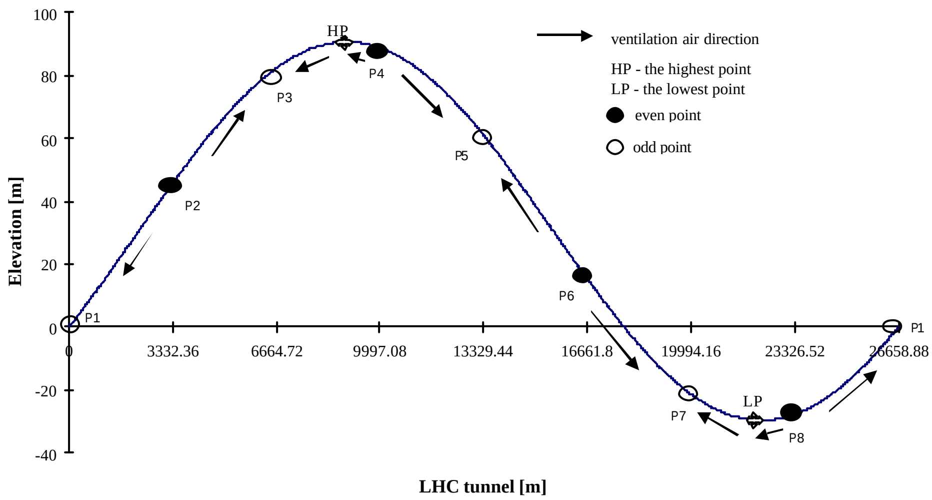


Figure 2: Tunnel elevation and ventilation air direction

4. Helium discharge and propagation in the LHC accelerator tunnel under worst case scenario cryogenic failure conditions

Three failure modes of the LHC cryogenic system leading to the worst case scenario with respect to the helium discharge into the tunnel have been identified [1]. They are listed in Table 1, where the corresponding helium mass flow (q_{m_He}), the initial helium temperature (T_{He}) [2], the minimum and maximum oxygen concentration in the stratified helium-enriched layer ($O_{2,min}$ and $O_{2,max}$) [3] are also given.

The minimum oxygen concentration ($O_{2,min}$) corresponds to the helium-air mixture with the same density as air (see also Figure 3a). The maximum oxygen concentration ($O_{2,max}$) corresponds to the helium-air mixture with the minimum density (see also Figure 3a). The columns q_{mcr_mix} for nominal (w = 0.55 m/s) and emergency (w = 0.88 m/s) air flow give the minimum mass flows of the helium-air mixture that ensure a stratification of oxygen concentration in the LHC tunnel [3].

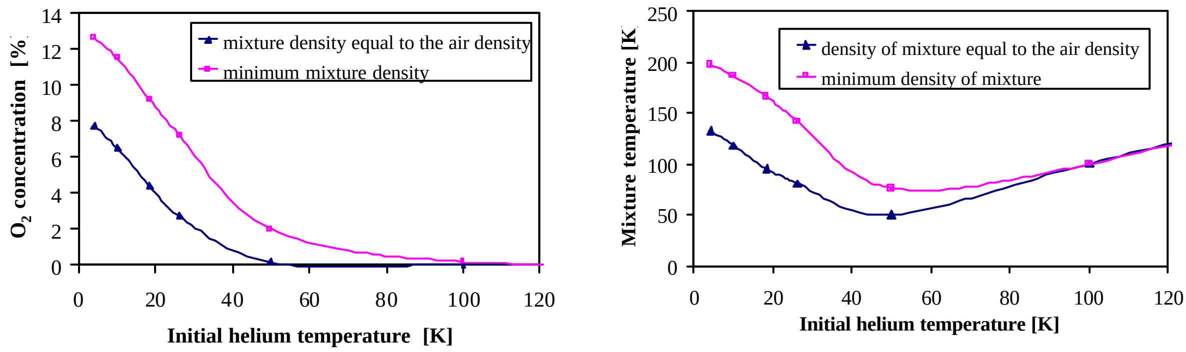
As the estimated helium mass discharge q_{m_He} is higher by at least an order of magnitude, the stratified flow of helium-air mixture along the LHC tunnel is to be taken into account in any case of an important helium relief to the tunnel.

Table 1. Worst case scenario of helium discharge into the LHC tunnel

Failure	Description	q_{m_He} [kg/s]		T_{He} [K]	$O_{2,min}$ [%]	$O_{2,max}$ [%]	q_{mcr_mix} (w=0.55 m/s) [kg/s]	q_{mcr_mix} (w=0.88 m/s) [kg/s]
1	Break of header C	average*	1	10	6.5	11.5	0.0145	0.0597
		peak	3	25	2.8	8.0	0.0074	0.0307
2	Break of jumper connection	average*	2	19	4.0	9.5	0.0096	0.0396
		peak	20	4	7.7	12.5	0.0196	0.0805
3	Break of ring line	average*	1	290	---	13**	0.0723	0.2965
		peak	14	290	---	13**	0.0723	0.2965

* average mass-flow rate over 15 min following the peak, ** obtained experimentally

The oxygen concentrations and the corresponding mixture temperature in the stratified layer are calculated with respect to the buoyancy condition (see Figure 3). If the discharge helium temperature is lower than 50 K (failures 1 and 2), air must be added to reach air density of the mixture and even more to obtain a minimum density (see also Table 1).



a) oxygen concentration
b) mixture temperature

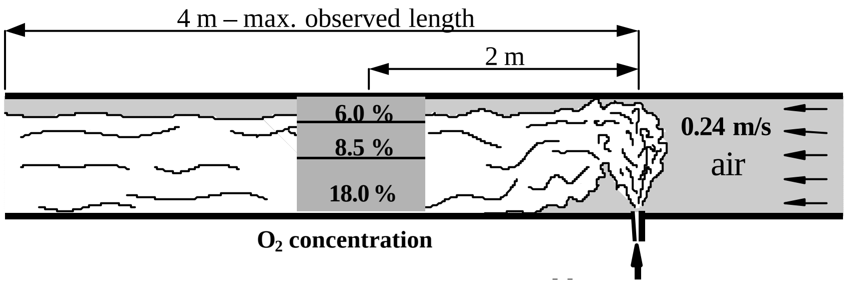
Figure 3. Properties of helium-air mixture versus initial helium temperature

As a result of an extensive mass and heat exchange with atmosphere in the lower part of the tunnel, the temperature of the stratified layer will be high enough to avoid air condensation. The temperature in the lower part of the tunnel will remain relatively high, not creating a hazard of tissue freezing (refer to Figure 6).

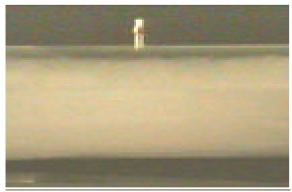
If the helium is discharged at ambient temperature (failure 3), the mixing with air is the result of a turbulent jet only and the oxygen concentration corresponding to the helium-air mixture with the minimum density has been determined experimentally (see Table 1) [3].

4.1. Experimental study of helium dispersion in air

A dedicated test set-up representing a section of the LHC tunnel at a scale 1:13 has been built and different scenarios of the LHC cryogenic system failures have been experimentally simulated. The hydrodynamic scaling from the test set-up to the full-scale tunnel is described in [3]. The flow pattern to be expected in case of an important cold helium discharge (failures 1 and 2) to the LHC tunnel is shown in Figure 4. Figure 5 gives the oxygen concentration to be expected in case of warm helium discharge. In this case there is no mist, but oxygen stratification is still observed. Stratification of an oxygen-deficient layer in the upper part of the tunnel means that oxygen deficiency will occur, especially in tunnel enlargements.



a) test boundary conditions and measured oxygen concentration



b) flow visualisation

Figure 4. Schematic representation of cold helium discharge to the test tunnel

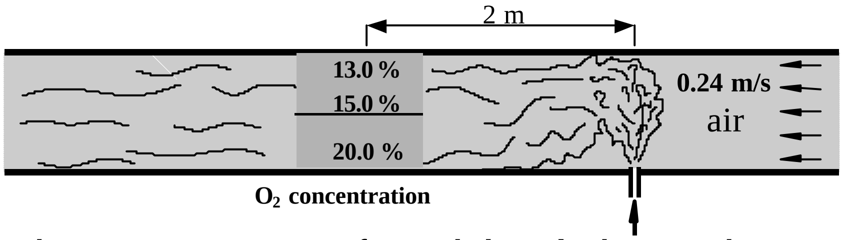
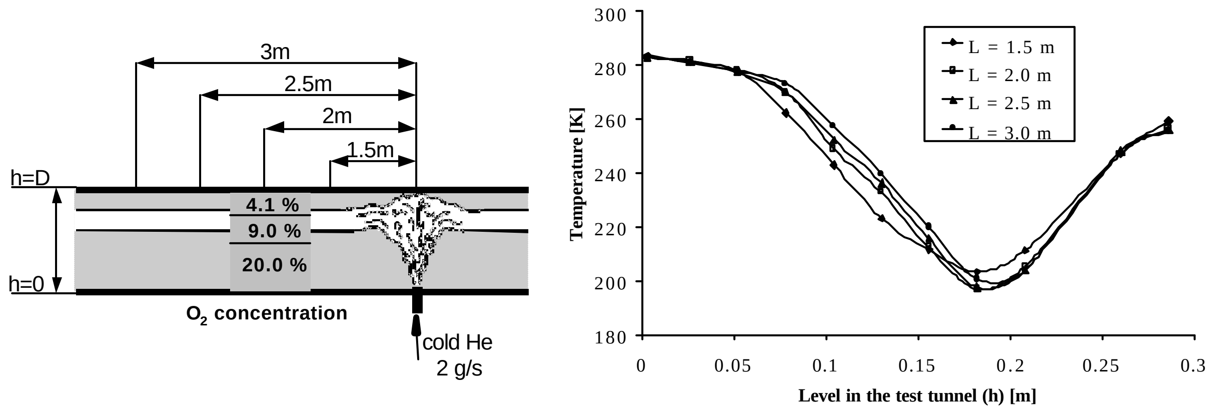
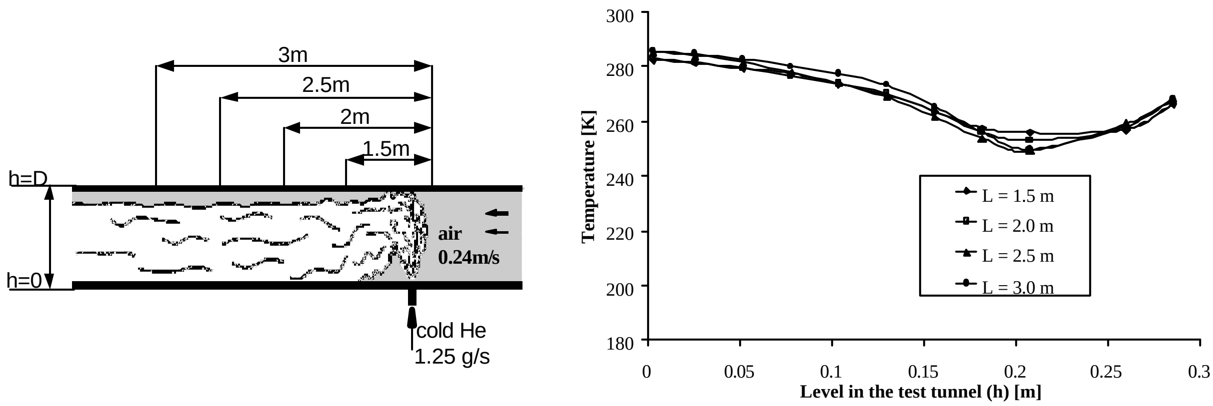


Figure 5. Schematic representation of warm helium discharge to the test tunnel

The temperature distribution across the test tunnel during an important cold helium release is shown in Figure 6. A temperature of about 200 K was observed at 0.18 m tunnel height when helium was discharged to the tunnel without any forced airflow (Figure 6a). The temperature increases rapidly towards the lower part of the tunnel. Higher temperatures were observed in the flowing mixture with initial air velocity of 0.24 m/s (Figure 6b). In both cases the temperatures were higher than those calculated (Figure 3b). The temperature profile does not significantly change with the distance (L) from the helium discharge point.



a) no forced airflow



b) forced air flow

Figure 6. Temperature distribution across the test tunnel

4.2. Humidity condensation and its visibility

Figure 7 shows the calculated variation of the average temperature in the tunnel cross section where the helium discharge occurs as a function of the discharge mass flow rate. Two cases of initial helium temperature (failure 1 and 2) have been considered with respect to the nominal and emergency air ventilation flow. The mixture temperature significantly drops below the dew point even for helium flows as low as 0.2 kg/s, what means that condensed humidity will be clearly visible in the vicinity of an important cold helium discharge point.

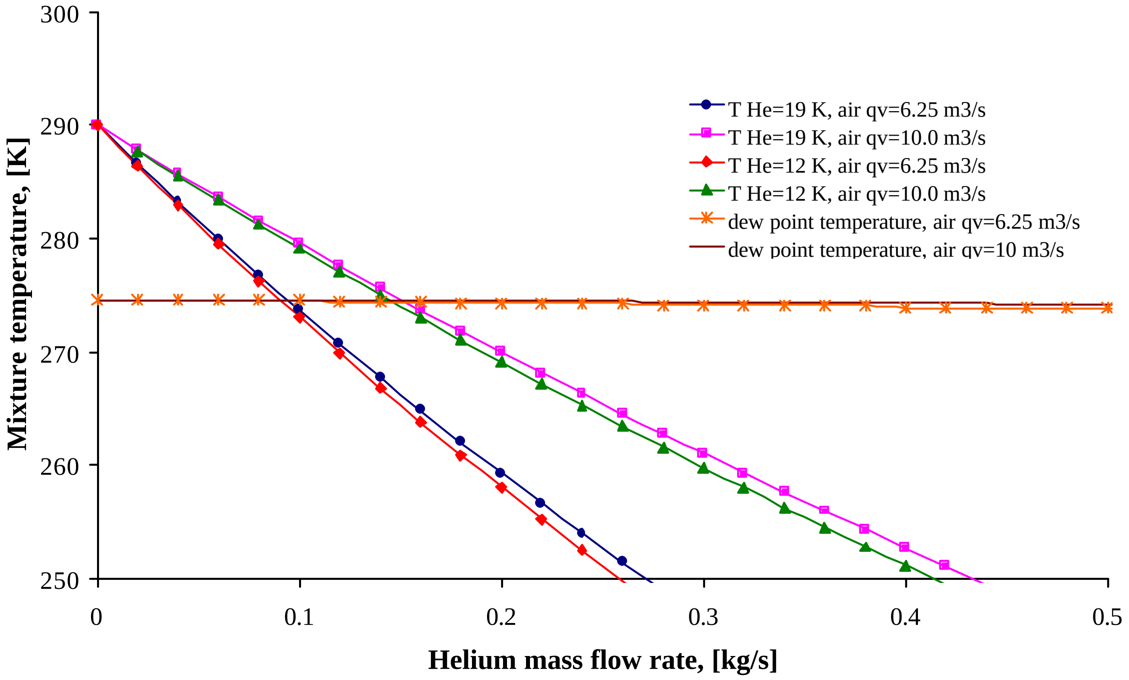


Figure 7. Helium-air mixture temperature versus helium discharge mass flow rate

Taking into account the heat exchange process between the gas mixture and the tunnel wall as well as the machine equipment, the mixture temperature will remain lower than the dew point temperature over a distance of at least 20 m.

In case of failure, the helium discharge point will be visible to persons present in the LHC tunnel but the visibility distance will be limited by the tunnel curvature as shown in Figure 8. In this analysis the distance is 284 m.

Taking into account a nominal velocity of 0.55 m/s, maximum delay time between the first visual observation of a discharge and the time the helium-air front reaches the observer is 516 s.

5. ODH monitor distribution in the LHC tunnel

The ODH monitors must be distributed in such a way as to ensure efficient warning of all persons in the tunnel sector concerned during a possible helium discharge. According to the position of persons in the tunnel, two cases must be analysed as shown in Figure 9.

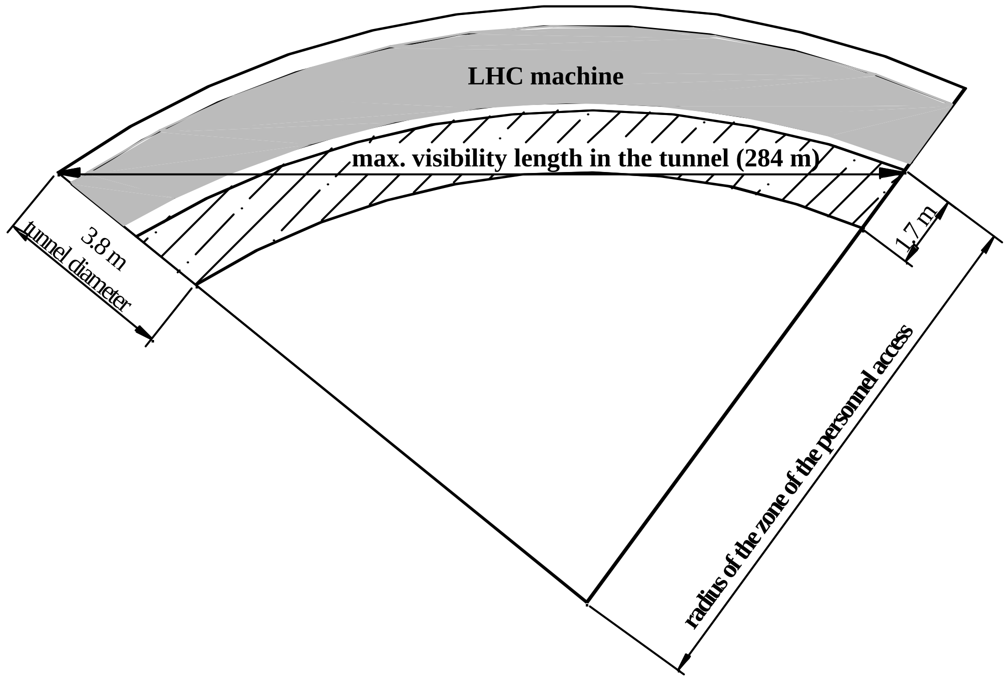


Figure 8. Maximum visibility distance in the LHC tunnel

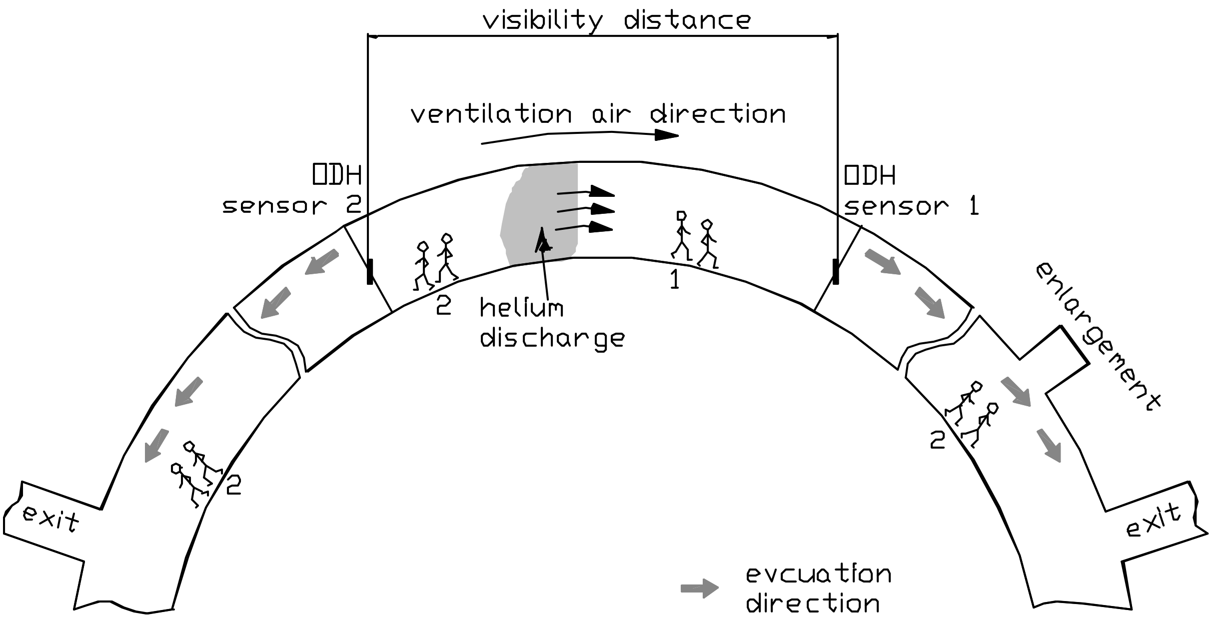


Figure 9. ODH evacuation conditions for personnel

Case 1: tunnel section between the discharge point and the adjacent ODH sensor following the ventilation direction.

The persons to be warned and evacuated are located between the discharge point and the ODH sensor that will be activated first (sensor 1 in Figure 9), and will thus not be warned by the lattice ODH sensors before they may find themselves in an oxygen deficient atmosphere. The way to be informed about the event is to hear the noise from the exhausting helium or to notice the formation of mist in case of cold helium discharge. To warn the persons in case they cannot see the mist formation, the distance between two adjacent ODH sensors should not exceed the visibility distance in the LHC tunnel, namely 284 m (see Figure 9).

Case 2: rest of the tunnel.

The persons located within the visibility distance from the discharge point should evacuate away from it as soon as they notice the event. The persons located outside the visibility distance from the discharge point will be warned by the activated ODH system and should start walking towards the nearest exit from the tunnel. In case they approach the discharge point they should change direction.

The ODH monitors should be located (see Figure 10):

- at the upper parts of the tunnel enlargements and junctions,
- in the alcoves,
- along the regular tunnel at the maximum distance of 284 m between two adjacent sensors.

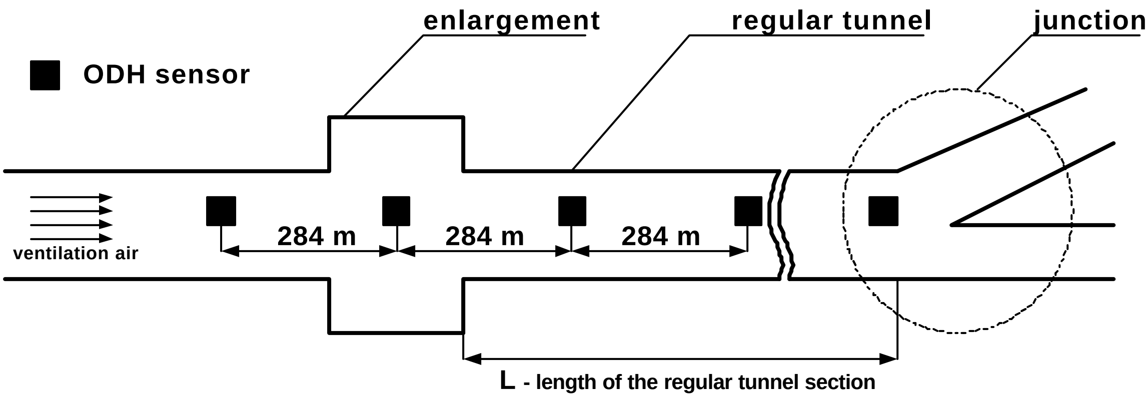


Figure. 10. Location of the ODH monitors in the LHC tunnel

Table 2 summarises the inventory of the ODH monitors in the tunnel. The LHC sectors are named according to the LHC sectorization as shown in the Appendix A. The detailed inventory of the sensors is also given in the Appendix A.

Table 2. Number of ODH sensors in the LHC tunnel

Sectors	Enlargements and junctions [11]	Alcoves	Regular tunnel	Total
2-1	8	2	8	18
2-3	5	2	7	14
4-3	7	2	11	20
4-5	5	2	9	16
6-5	11	2	9	22
6-7	5	2	9	16
8-7	8	2	9	19
8-1	8	2	8	18
Total	**57**	**16**	**70**	**143**

6. Training

As the access to the LHC zones, experimental caverns and the tunnel will be extensively controlled (compare point 2.2), only well-trained personnel should be allowed to access underground areas. Dedicated safety training shall be implemented for personnel to work in the tunnel. These courses shall have the aim:

- to give information on the underground areas and type of cryogenic system failure related hazards (asphyxiation, tissue freezing),
- to explain the procedures to be applied in case of helium discharge to the tunnel,
- to define the conditions under which individual protection equipment must be used,
- to train how to use the individual protecting equipment.

The instructions to be followed shall always be clear, simple and easy to apply. Personnel must be trained such that they always move away from the discharge point.

7. Conclusions

The personnel should be trained before being given access to underground areas.

Important helium venting to the tunnel causing an oxygen deficiency hazard will generate noise and in case of cold helium release it will be followed by a visible humidity condensation in the vicinity of the discharge point.

Persons present between the discharge point and the first ODH sensor to be activated will hear the noise of exhausting helium and may see the cloud caused by humidity condensation.

The visibility distance of 284 m in the LHC tunnel should be the parameter, which limits the maximum distance between two adjacent ODH sensors.

When hearing the noise of exhausting helium, persons must always move away from the discharge point. Persons being outside the visibility distance from the relief point will be warned as soon as the oxygen deficient cloud reaches the closest ODH monitor. They shall move towards the closest exit. In case they approach the discharge point they should change direction. The longest distance one may have to walk is the length of one and a half sector.

Due to the stratification of the oxygen deficient layer at the upper part of the tunnel, ODH sensors should be located at the top in the regular part of the tunnel, in the enlargements, in the junctions and in the alcoves.

Table 3 summarises the number of ODH sensors in the different locations and gives the main parameters linked to the location of the ODH sensors.

Table 3. Location of ODH sensors

Element	Quantity of ODH monitors	Radiation resistant equipment	Helium accumulation
Enlargements/jonctions	57	Yes/No	Yes
Alcoves	12	No	No
Tunnel	70	Yes	No

8. References

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[2] Helium Discharge and Dispersion In the LHC Accelerator Tunnel in Case of Cryogenic Failure, Chorowski, M.; Konopka, G.; Riddone, G.; CERN-LHC-Project-Report-381; In: 18th International Cryogenic Engineering Conference, Mumbai, India, 21 - 25 Feb 2000 / Ed. by Narayankhedkar, K G - ICEC Office, Mumbai, 2000. - pp.231-234

[3] An experimental study of cold helium dispersion in air, Chorowski, M., Konopka, G.; Riddone, G.; Paper presented at the CEC-ICMC'01 - July 16-20, 2001 – Madison, Visconsin, USA

[4] TIS Safety Instruction IS37: Alarms and Alarms systems

[5] TIS Safety Instruction IS7: Individual protection

[6] Safety code A6, The two-person rule of working, Issued by CERN HS Department, 1982

[7] Cooling and Ventilation for LHC, Principe R., Wilhelmsson M., Chamonix XI

[8] TIS Safety Instruction IS47: The use of cryogenic fluids

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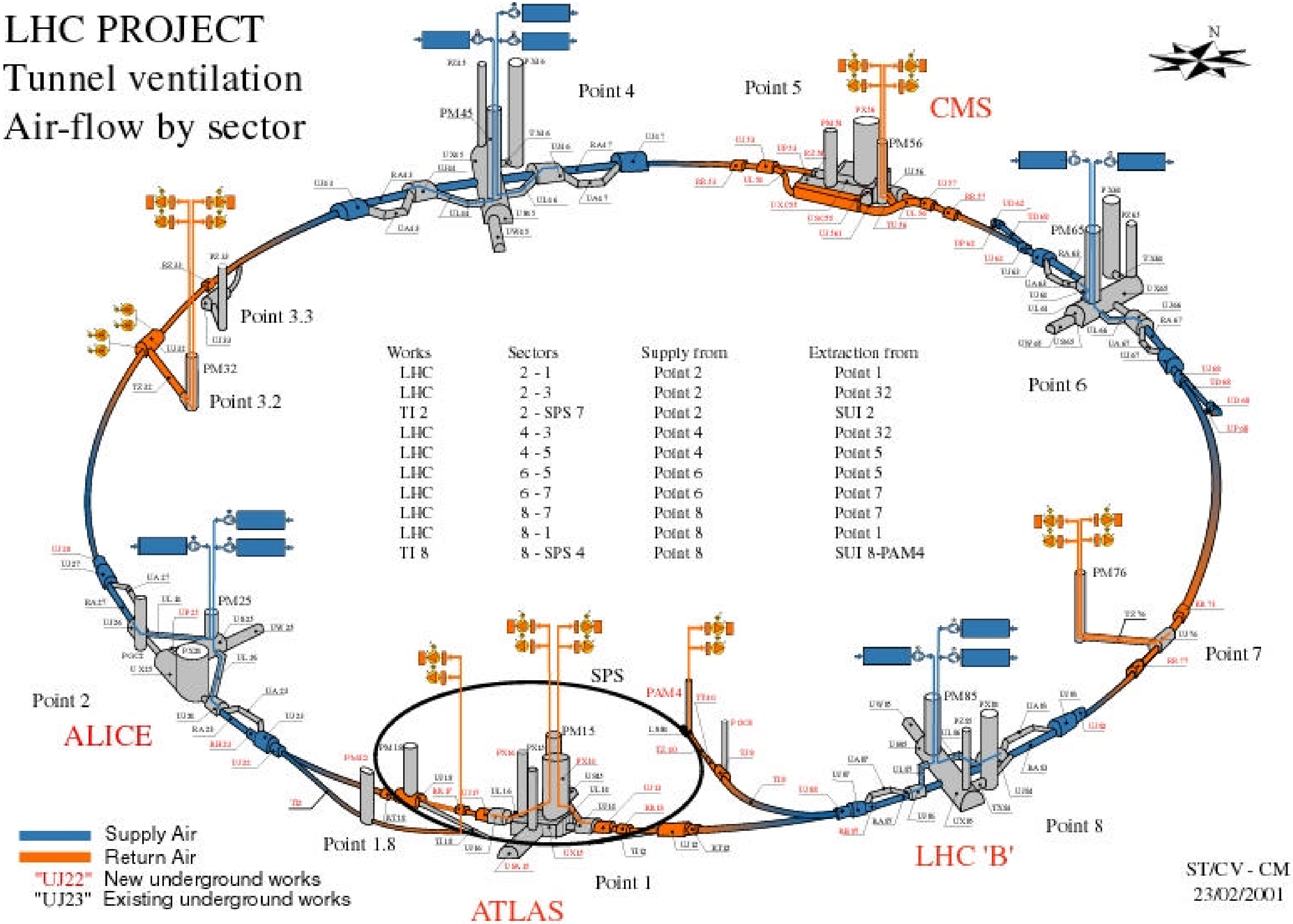
[10] Traitement d’air du tunnel LHC, Martel, C., CERN-ST-2001-026, 31 Janvier 2001-05-23

[11] P. Proudlock, Memorandum 17.08.01

Appendix A: Location of ODH sensors in the LHC tunnel

LHC PROJECT
Tunnel ventilation
Air-flow by sector



Works	Sectors	Supply from	Extraction from
LHC	2 - 1	Point 2	Point 1
LHC	2 - 3	Point 2	Point 32
TI 2	2 - SPS 7	Point 2	SUI 2
LHC	4 - 3	Point 4	Point 32
LHC	4 - 5	Point 4	Point 5
LHC	6 - 5	Point 6	Point 5
LHC	6 - 7	Point 6	Point 7
LHC	8 - 7	Point 8	Point 7
LHC	8 - 1	Point 8	Point 1
TI 8	8 - SPS 4	Point 8	SUI 8-PAM4

Table 1. Sector 2–1

Location		Number
Enlargements/junctions	PM25 (top of pit)	1
	UJ24	1
	UJ23	1
	PM18	1
	RR17	1
	UJ16	1
	PM12 (top of pit)	1
	TI2	1
Alcoves		2
Regular tunnel	from UJ23 to PM18	8
	Total	18

Table 2. Sector 2–3

Location		Number
Enlargements/junctions	UJ26	1
	UJ27	1
	UJ32	1
	UJ33	1
	PM32 (top of pit)	1
Alcoves		2
Regular tunnel	from UJ27 to UJ32	7
	Total	14

Table 3. Sector 4–3

Location		Number
Enlargements/junctions	PM45 (top of pit)	1
	PZ45 (top of pit)	1
	UX45	1
	UJ44	1
	UJ43	1
	PZ33 (top of pit)	1
	RZ33	1
Alcoves		2
Regular tunnel	from UJ43 to RZ33	11
	Total	20

Table 4. Sector 4–5

Location		Number
Enlargements/junctions	UJ46	1
	UJ47	1
	RR53	1
	UJ53	1
	RZ54	1
Alcoves		2
Regular tunnel	from UJ47 to RR53	9
	Total	16

Table 5. Sector 6–5

Location		Number
Enlargements/junctions	PM65	1
	PZ65	1
	UX65	1
	UJ64	1
	UJ63	1
	UJ62	1
	UD62	1
	RR57	1
	UJ57	1
	UJ56	1
	PM56 (top of pit)	1
Alcoves		2
Regular tunnel	from UJ62 to RR57	9
	Total	22

Table 6. Sector 6–7

Location		Number
Enlargements/junctions	UJ66	1
	UJ67	1
	UJ68	1
	UD68	1
	RR73	1
Alcoves		2
Regular tunnel	from UJ68 to RR73	9
	Total	16

Table 7. Sector 8-7

Location		Number
Enlargements/junctions	PM85 (top of pit)	1
	PZ85 (top of pit)	1
	UX85	1
	UJ84	1
	UJ83	1
	RR77	1
	UJ76	1
	PM76 (top of pit)	1
Alcoves		2
Regular tunnel	from UJ83 to RR77	9
	Total	19

Table 8. Sector 8–1

Location		Number
Enlargements/junctions	UJ86	1
	UJ87	1
	UJ12	1
	RR13	1
	UJ14	1
	PM15 (top of pit)	1
	TJ8	1
	TT40	1
Alcoves		2
Regular tunnel	from UJ87 to UJ12	8
	Total	18