Preliminary Risk Analysis for the LHCb Vertex Detector

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June 8, 2001

Abstract

We present a preliminary risk analysis for the LHCb vertex locator (VELO). The scope of this risk analysis is to identify possible failure scenarios at the LHCb VELO and estimate the ensuing damage to equipment and downtime for LHC. Further, on the basis of a (preliminary) risk level for acceptability, we formulate requirements and suggest a number of precautions for the design of the VELO system.

LHCb note 2001-079 / VELO

1 Introduction

The LHCb vertex locator (VELO) [1] represents a major challenge in that it must provide identification and reconstruction of primary and secondary vertices with micrometer precision, at distances of a few millimeters from the interaction point (IP). The choice was made to use a microstrip silicon tracker positioned at a distance of 8 mm from the beam axis, which corresponds to a full aperture (16 mm) smaller than that required by LHC during injection (minimum full aperture of 54 mm [2]). As a consequence, the tracker must be retractable to leave a full aperture of at least 54 mm when required. The results of extensive physics Monte-Carlo simulations have shown the need for keeping to a minimum the material mass between the IP and the silicon sensors [3]. This is best accomplished by placing the sensors in vacuum. A thin-walled box encapsulating the sensor modules must be used to protect the LHC vacuum from excessive outgas rates and reduce RF interference effects. The design of this encapsulation is optimized to minimize multiple scattering, while taking into account RF coupling to the beams [3, 4]. This results in a complex shape with corrugations of varying depth [5]. The design must further consider the effects of ion-bombardment and electron multipacting in the vicinity of the beams [6, 7].

The above constraints and requirements make of the VELO a complex system which must be integrated to the LHC machine vacuum without adding excessive risk. The purpose of this note is to perform a preliminary risk analysis (PRA) to address failure scenarios and, importantly, to provide a basis for further discussions and improvements on the LHCb vertex detector system. In the future, when all implementation details are known (PLC safety logic, hardware choices for the materials used and vacuum devices, etc.), this risk analysis will be refined and complemented with a reliability analysis.

The note is organized as follows. In section 2 we describe the framework of our PRA. We present the risk analysis for the VELO system in section 3, and draw some conclusions in section 4.

2 Risk analysis framework

We base our PRA on the model used for the CERN Safety Alarms Monitoring System (CSAMS) [8]. In this model, definitions for the classification of risk events are given in terms of frequency (see Table 1) and gravity (Table 2). The latter is associated with two classes of criteria, namely "Injury to personnel" and "Damage to equipment". In this work we are concerned with the impact on LHC operation of a possible failure at LHCb. We only consider the criterion "Damage to equipment" and do not treat potential risk for personnel. However, for the failure scenarios described in this work we believe this risk to be low and the requirements set by the criterion "Injury to personnel" to be less stringent than those set by "Damage to equipment" (*i.e.* equipment losses and/or downtime).

The two parameters, frequency and gravity, are merged in a "risk matrix" to classify events in four levels of acceptability, as shown in Table 3. The interpretation of these levels is explained in Table 4. We use these definitions to classify any given undesired event (UE) for the VELO system.

For each identified UE, we apply the following procedure (taken from Ref. [8]) to define a number of requirements which will render the system *acceptable*.

Procedure:

- Step 1: Identify undesired event (UE).
- Step 2: Determine the *consequence category* of this UE by means of Table 2.
- Step 3: Fix the *maximum allowable frequency* by using the risk matrix given in Table 3 and requiring the UE to be of risk class II.
- Step 4: The effective *required frequency* is then determined by reducing the *maximum allowable frequency* by two orders of magnitude.

In some cases the estimated gravity might fall just above the lower boundary of a given consequence category. For these cases the required frequency is artificially more stringent than for the average case. It should therefore be kept in mind that the risk classification contains a certain degree of arbitrariness in

Category	**Description**	**Indicative frequency level (per year)**	**Probability to never occur in 10 years (indicative)**
Frequent	Events which are very likely to occur in the facility during its life time	> 1	$\simeq 0$ %
Probable	Events which are likely to occur in the facility during its life time	$10^{-1} - 1$	< 35 %
Occasional	Events which are possible and expected to occur in the facility during its life time	$10^{-2} - 10^{-1}$	90 - 35 %
Remote	Events which are possible but not expected to occur in the facility during its life time	$10^{-3} - 10^{-2}$	99 - 90 %
Improbable	Events which are unlikely to occur in the facility during its life time	$10^{-4} - 10^{-3}$	99.9 - 99 %
Negligible	Events which are extremely unlikely to occur in the facility during its life time	$< 10^{-4}$	> 99.9 %

Table 1: Definition of frequency categories for risk events.

Category	**Injury to personnel**		**Damage to equipment**	
	Criteria	**# of fatalities (indicative for the process)**	**Loss in CHF (indicative for the process)**	**Downtime (indicative for the process)**
Catastrophic	Events capable of resulting in multiple fatalities	> 1	$> 10^8$	$>$ 3 months
Major	Events capable of resulting in a fatality	1	$10^6 - 10^8$	1 week to 3 months
Severe	Events which may lead to serious, but not fatal, injury	0.1	$10^4 - 10^6$	4 hours to 1 week
Minor	Events which may lead to minor injuries	0.01	$0 - 10^4$	$<$ 4 hours

Table 2: Definition of consequence categories for risk events. The section "Injury to personnel" is not used in this work.

the discretization. An alternative way of determining the required frequency is thus to use the criterion that the product $frequency \times gravity$ remain below a given level.

To our knowledge, a risk level of acceptability, regarding the impact of LHC experiments on LHC operation, has not yet been officially agreed upon. Hence, for steps 3 and 4 above, we presently use the same level of acceptability as proposed in Ref. [8].

As will become clear after section 3.6, the LHC downtime caused by the undesired events is, in our case, always at least as severe as the loss in CHF. In other words, the induced LHC downtime is the dominant criterion for determining the consequence category. When expressed as $risk = frequency \times downtime$, the risk level of acceptability used here amounts effectively to about 10^{-2} days/year (for individual scenarios).

In section 3.6 we analyse a list of undesired events using the above procedure and suggest, where needed,

Frequency	**Consequence**			
	Catastrophic	**Major**	**Severe**	**Minor**
Frequent	I	I	I	II
Probable	I	I	II	III
Occasional	I	II	III	III
Remote	II	III	III	IV
Improbable	III	III	IV	IV
Negligible	IV	IV	IV	IV

Table 3: Risk classification of accidents.

Risk class	**Interpretation**
I	Intolerable risk
II	Undesirable risk, and tolerable only if risk reduction is impracticable or if the costs are grossly disproportionate to the improvement gained
III	Tolerable risk if the cost of risk reduction would exceed the improvement gained
IV	Negligible risk

Table 4: Interpretation of risk classes. Classes II and III fall into the so-called ALARP region (As Low As Reasonably Practicable).

a number of tests, measurements and/or precautions that should be considered in the development of the VELO system. We stress again that, in step 2 above, the consequence category is always defined with respect to the LHC downtime and equipment losses (in CHF), and *not* with respect to the damage for LHCb. However, for the sake of completeness, we will also mention the estimated downtime and equipment loss for LHCb.

3 Risk analysis

Before discussing risk scenarios, their gravity and occurrence probability, we give in section 3.1 a brief description of the current design of the VELO system and outline some important protection features of the design in section 3.2 (for details see Ref. [1, 5, 9]). We discuss the relevant modes of operation and servicing procedures of the VELO system in section 3.3 and 3.4. We estimate the time needed to carry out maintenance and repair operations on the VELO or LHCb beam pipe in section 3.5. Subsequently, we attempt to identify possible failures and evaluate their gravity in section 3.6.

3.1 Description of the LHCb vertex locator system

A detailed description of the vacuum system under study can be found in Ref. [9]. This vacuum system consists of three communicating sections, namely the VELO primary vacuum vessel, the LHCb beam pipe and the Si detector housings, as schematically shown in Fig. 1. Note that these three sections are not independent vacuum systems: one section cannot be brought to atmospheric pressure individually. However, it is useful to consider them as three distinct sections in view of their different characteristics and functions. The VELO vacuum vessel and LHCb beam pipe are part of the LHC primary vacuum system.

The VELO primary vacuum vessel is a Ø1 m SS vessel of about 1.8 m length which will be evacuated by two powerful ion-getter pumps. It contains the Si detector housings and the supporting frames. The VELO primary vacuum vessel can be baked out in-situ to a temperature limited to about 150°C by the mechanical properties of the secondary vacuum vessel (detector housing). During bake-out, the silicon

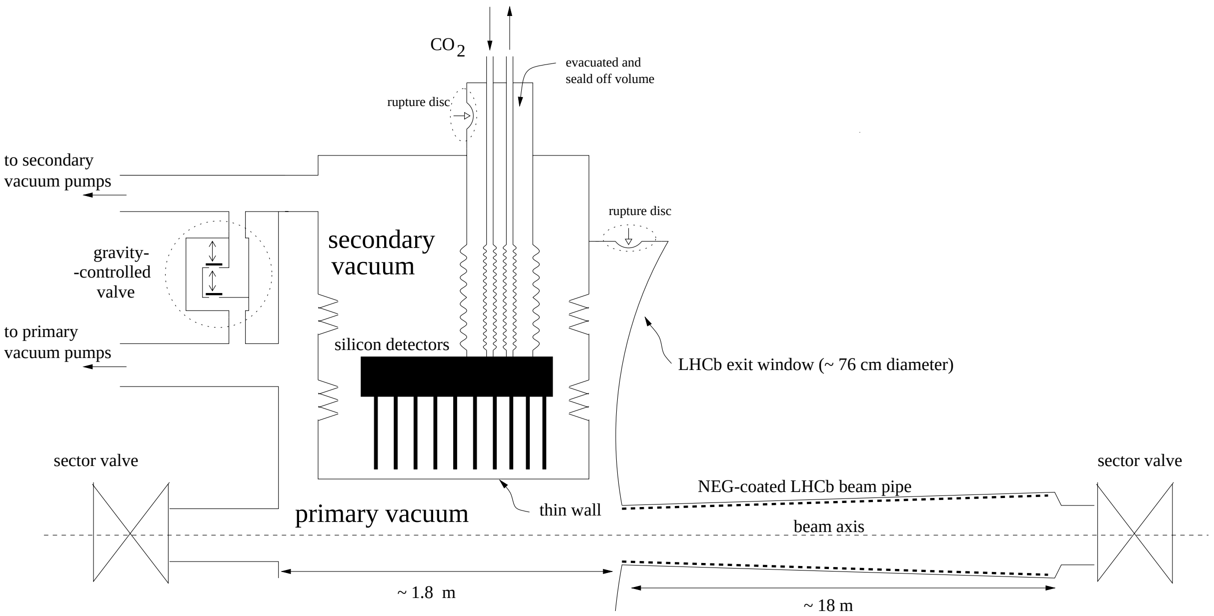

Figure 1: Sketch of the vertex locator and LHCb vacuum system. For clarity, only one half is shown.

detectors are not in the secondary vacuum vessel. The residual static pressure of the baked-out VELO vessel is expected to be in the 10^{-9} mbar range (mostly H_2 and CO).

The main function of the Si detector housings is to protect the primary vacuum from excessive outgas rates and to reduce RF coupling between the LHC beams and the VELO system. About 22'000 feedthroughs interface the Si modules to the outside world. Thus, the primary vacuum is not directly exposed to outgassing from the large number of wires. Each housing contains 27 Si detector modules. The detectors can be removed from the vacuum chamber without exposing the primary vacuum to ambient air by venting with ultrapure inert gas. The detector housings protrude inside the primary vacuum vessel. In the current design option, the sides of the housing which fall within the LHCb acceptance are made of 0.5 mm Al. The side facing the beams is made of 0.25 mm Al. The two detector housings are evacuated by two turbo-molecular pump stations. In normal operation the two pump stations are communicating. The housings are decoupled from the primary vacuum vessel by using large rectangular stainless steel bellows, which allow for moving the detector halves by the required amount in the two transverse directions [1]. The detectors are supported by a frame which, during installation, mounts on the secondary vacuum feedthrough flange. After installation, the detector support frame is decoupled from the flange and attached to the movable system. All motors, gearboxes, belts and bearings are located outside the vacuum and coupled to the parts in vacuum via bellows.

The cooling of the detector modules is achieved by using a mixed-phase CO_2 cooling system. Fig. 2 shows a schematic layout of the cooling circuit. From the main supply line the liquid is expanded into a number of stainless steel capillaries (inner/outer diameter of 0.9/1.1 mm, one line per Si module) via flow restrictions. The temperature of the coolant in these capillaries is set by controlling the pressure on the return line (typically 15 bar). The capillaries and flow restrictions are vacuum-brazed to a manifold. The CO_2 system is filled with the coolant at room temperature up to about 40 bar. Note also that the pump and compressor units will be located in the accessible area (behind the shielding wall).

The LHCb beam pipe extends throughout the complete LHCb detector (length of about 18 m) and consists of three tapered, thin-walled Al pipes connected to each other. On the VELO side the pipe ends with a curved Ø76 cm and about 2 mm thick Al window, the LHCb 'exit' window. The window is welded to the LHCb beam pipe. The interior of the LHCb beam pipe will be coated with low activation temperature NEGs [10]. These will be activated in-situ by baking the LHCb beam pipe to about 200 °C. The NEGs can be vented in a controlled way (with clean air) and re-activated later (under high vacuum). However, because of the limited capacity of the NEG coating, the NEG pumping speed is expected to drop substantially after several such vent/pump-down cycles [11]. In the case of the LHCb beam pipe, it is not yet clear whether the full pumping speed of the NEGs will be needed to ensure acceptable (static

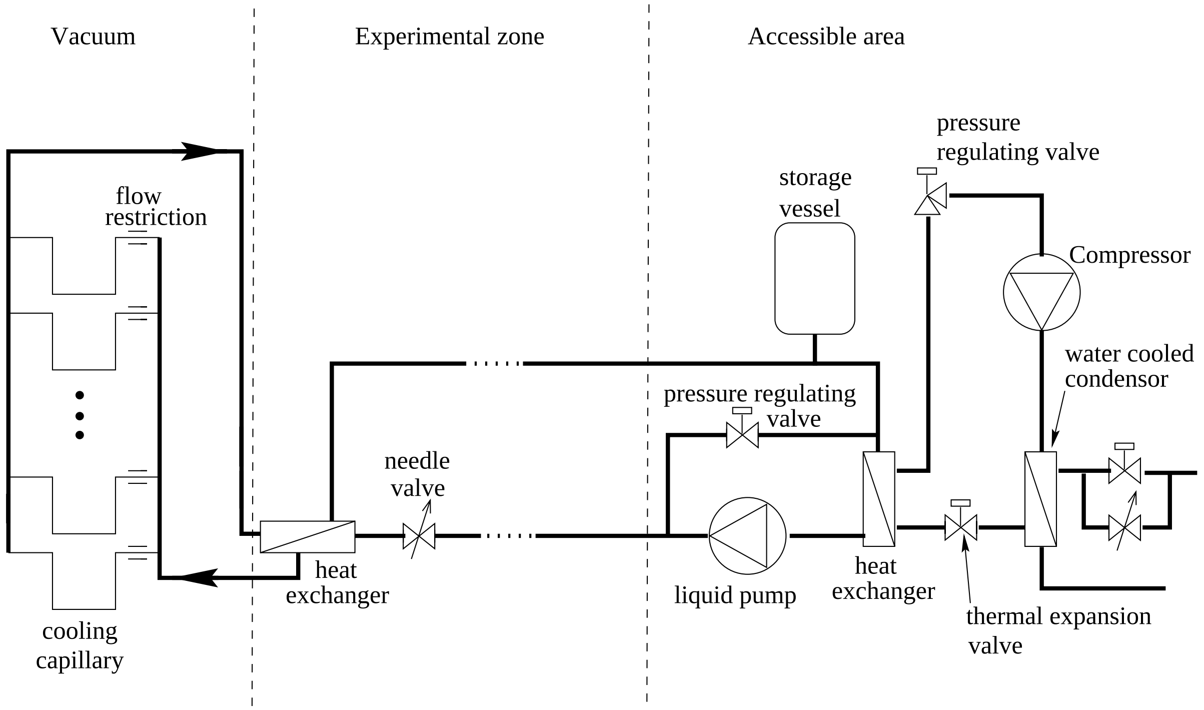

Figure 2: Schematic layout of the LHCb vertex locator CO_2 cooling system.

and dynamic) vacuum conditions for the LHC. If not, the maximum number of venting cycles could be somewhat larger. For the purpose of this work, to avoid relying on uncertain assumptions concerning NEG properties, we consider that if the primary vacuum is exposed to air (even if according to an established procedure), then the NEGs must be re-activated after the subsequent pump-down in order to reach stable vacuum conditions in the presence of the beams.

The LHCb beam pipe (including the exit window) is a critical and fragile component of the experiment. Various options are being studied to ensure that the vacuum system will be minimally exposed to ambient air when accessing components that are located in the vacuum. When access to the primary vacuum is not required, a well-established procedure using ultrapure inert gas (probably neon) will be applied, in order to avoid bake-out after a venting/pump-down cycle. To minimize exposure to humidity and dust of the primary vacuum surfaces (in particular the interior of the LHCb beam pipe) when access to the primary vacuum is inevitable, we are considering to enclose the LHCb VELO and RICH1 sub-systems in a clean area with a controlled atmosphere (low humidity, dust-free). In any case, the VELO setup should be located in an area with restricted access for reducing risk due to human action. Furthermore, all servicing and maintenance operation on the VELO setup will be performed by qualified personnel exclusively, in conformance with CERN rules.

3.2 Safety interlocks of the LHCb vertex locator system

The complete control logic and interlock system of the VELO will be described in another note. We briefly mention here the main precautions which will be taken for protection against failure.

3.2.1 Foil protection against differential pressure rise

As described in Ref. [9], two kinds of safety valves are used to protect the thin separation foil (detector housing) from an irreversible deformation ($\Delta p_{\mathrm{crit}} \simeq 17$ mbar), or rupture, in case of a pressure increase on either side of the foil. Above a pressure difference Δp_{max1} ($\simeq 1$ mbar) between primary and secondary vacua, an electrically activated valve is triggered to open. If the pressure difference exceeds the value Δp_{max2} ($\simeq 5$ mbar) a gravity-controlled valve opens under the direct effect of the pressure and independent of any electrical power or pressurized air supply. Note that, under the above mentioned pressure difference of approximately 17 mbar, the largest (permanent) displacement on the encapsulation is about 0.3 mm. The actual rupture pressure of the encapsulation is expected to be several hundred mbar (for details see Ref. [5]). The vacuum system is equipped with two electrically activated protection valves and one (two-way) gravity-controlled valve.

The dynamic response and reliability of the protection valves, as well as the mechanical properties of the detector housings, will be studied in detail by test measurements on prototypes, prior to installation at IP8. Note also that the residual conductance in molecular flow regime of the gravity-controlled valve is of the order of 10^{-5} ℓ/s (for air at room temperature).

3.2.2 Precautions against CO_2 leak into secondary vacuum

The amount of CO_2 in the cooling system will be kept to a minimum (about 5 kg, which corresponds to approximately 2.5 m^3 at STP). The complete cooling circuit is designed (and will be tested according to the CERN D2 safety code [12]) to sustain a pressure of at least 200 bar, well above the equilibrium pressure of CO_2 (72 bar at 30 °C). The quality and reliability of the cooling tubes, welds and brazings will be inspected by NIKHEF and CERN, and tests will be performed to investigate how the VELO vacuum system reacts under a sudden leak of CO_2 into the secondary vacuum system. The safety valves mentioned in section 3.2.1 are expected to efficiently protect the foil in such a scenario. If necessary, more safety can be added to protect the detector housing against a possible CO_2 burst into the secondary vacuum. Shutter valves can be inserted in the supply and return lines of the cooling system, just outside the vacuum chamber. These valves can be configured e.g. to close in response to a detected pressure rise in the secondary vacuum. In this case, the total amount of CO_2 that could ever be evaporated into the vacuum would amount to less than 100 g, *i.e.* less than 90 mbar at room temperature in about 0.6 m^3 (which corresponds to the volume of the secondary vacuum containers). However, this pressure level is not expected to be reached, as most of the CO_2 has to flow through a number of restrictions before reaching the secondary vacuum.

3.2.3 VELO protection against beam displacement

In case of a large beam displacement in the vicinity of the LHCb VELO, the first detectable effect should be an increased radiation due to the larger fraction of the beam-originating particles hitting the materials closest to the beams. Fast[*] radiation detectors can be placed upstream and downstream of the IP to detect such sudden increases of radiation. If the measured rates exceed a predefined threshold, the radiation detector sends a beam veto signal to the beam dump interface. This interface is designed to empty the rings within 0.1 to 0.2 ms after receiving the dump signal.

Such a protection scheme for LHCb based on particle detectors is yet to be studied and designed.

3.2.4 Section protection against vacuum leak in neighbouring section

The effect of a leak in the LHCb vacuum section on its neighbouring sections should be minimized, and vice versa. Sector valves will be positioned on both sides of the LHCb vacuum system. The exact locations are yet to be defined. Sensitive devices, such as the inner triplets, should be separated from the LHCb vacuum section by these sector valves. Furthermore, to protect the LHC ring vacuum against possible human-induced mishaps, the sector valves around LHCb should be automatically closed whenever access to the experimental area is granted.

The implementation and impact of fast-acting separation valves between LHCb and its neighbouring LHC sections are yet to be studied. If used, such valves can be equipped with valve position sensors that trigger a beam dump when the valve crosses (toward the beam) a predefined boundary. The valves should be located such as to protect the IR8 inner triplets from a vacuum failure in the LHCb section. The fast-acting valves should be placed at a distance d from the point of collapse which fulfills $d \gtrsim t \cdot v_{\mathrm{gas}}$,

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[*] To take full advantage of the speed of the dump control system, the time needed to detect a 'beam failure' and to send a beam dump request should not exceed the LHC revolution time, about 80 μs.

where $v_{\mathrm{gas}} \simeq 1000$ m/s is here the wave-front speed and t is the closing time of the valve, typically $10-20$ ms. Fast-acting valves are not leak tight, and thus must be supplemented with sector valves[†].

3.2.5 Protection against power failure

The LHCb equipment will be divided in subsystems, each having its own uninterruptable power supply (UPS). These UPS's can take over instantly after a power failure. However, their autonomy time is typically of about 10 minutes. To protect against long power failures, LHCb will rely on a high-power diesel generator. Since the take-over time of such a generator is of the order of minutes, the distributed UPS's are indispensable. The autonomy time of the diesel generator can be assumed to be infinite.

In the case of the VELO, all PLC units, vacuum valves and monitoring devices (gauges, temperature sensors, etc.) will be backed by UPS. The vacuum pumps are not backed by UPS, but could be powered up by the diesel generator.

To reduce the risk of malfunctioning in the event of a power failure, all UPS's used for the VELO vacuum system should be serviced regularly.

3.3 Functional analysis

Both the gravity and frequency of an undesired event can strongly depend on the status (or mode of operation) of the system under study. We foresee three modes of operation, as described below.

As will become clear in section 3.6, for the present system the gravity and frequency of the identified undesired events will in most cases strongly depend on

(a) *the status of the sector valves*

which, when closed, isolate the LHCb vacuum system from the LHC vacuum system, and

(b) *the full aperture between the two VELO halves.*

Therefore, for the purpose of this work, we consider three main modes of operation for the VELO system for which we specify the status of the two items given above:

- **LHCb Physics** mode: the sector valves are open and the full aperture is smaller than the minimum IP8 aperture required for injection [2], but larger than the minimum aperture required for stable beam conditions [13]. This implies that the machine interface has declared the beams ready for the experiments, which guarantees that all operations which could result in a large beam displacement are inhibited. This is the normal running mode for data acquisition in the LHCb experiment.
- **Standby** mode: the sector valves are open but the full aperture is larger than the minimum IP8 aperture required for injection. This mode will be used e.g. during injection, ramping, machine development periods, or when the machine interface transmitted the warning of a scheduled beam dump[‡]. In some cases, LHCb will acquire data with the detectors retracted, e.g. when trying to determine the beam position before inserting the two detector halves.
- **Isolated** mode: the sector valves are closed. There is no constraints on the full aperture. This mode will be activated when e.g. an access to the experimental area is granted, or some maintenance operations (with or without access) must be carried out on the LHCb setup.

3.4 Servicing procedures

We foresee a number of additional (transient) states of the LHCb vacuum system encountered e.g. during the pump-down or vent procedures. Such servicing actions are only taken during long shutdown periods of LHC or as a response to some undesired event occurring during a static operation mode. By definition, the time spent in a transient state is expected to represent only a small fraction of the total running

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[†] Standard sector valves have typically closing times of a couple of seconds.

[‡] Full retraction of the two detector halves requires a time of the order of one minute.

time. Hence, the occurrence probability (per year) of an UE in such a state (outside a long shutdown period) is suppressed by a large factor compared to the probability that the same UE occurs during a static operation mode. For this reason, we will not treat here risk scenarios for these states. A detailed description of the various servicing procedures and their associated safety features can be found in Ref. [9].

3.5 Estimation of downtime for repair operations

In Table 5 a number of tasks are listed which might have to be performed in the occurrence of an undesired event. The estimated LHC downtime for the various tasks is also given. We use the convention that one day equals three consecutive shifts of 8 hours. The estimations are indicative and preliminary but accurate enough to assess the LHC downtime caused by any given UE and classify it accordingly. One can assume, on the basis of a first calculation [14], that radioactivity of the relevant parts is low enough that radiation protection measures will not increase the downtime estimated here. Note also that some of the tasks can be carried out in parallel. In particular, installation (or removal) of a VELO component can be simultaneous to work around the LHCb beam pipe.

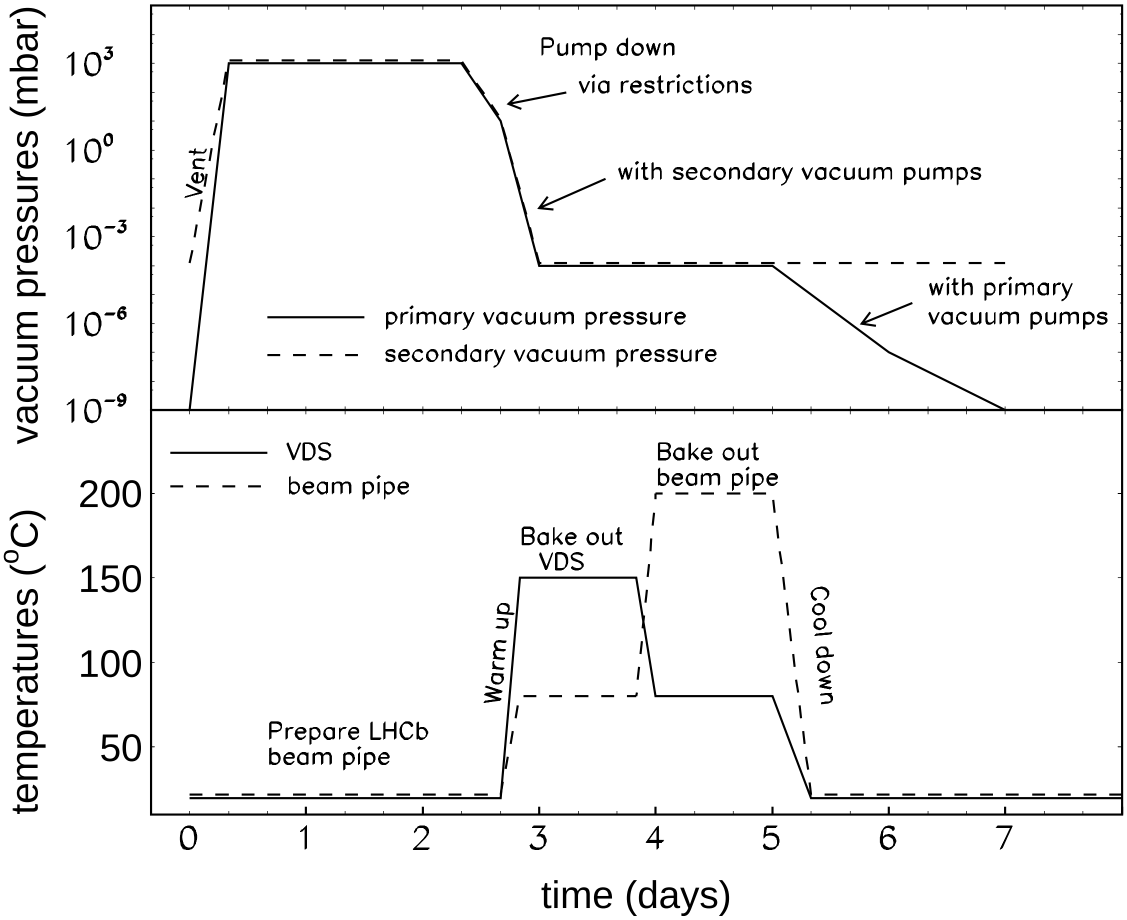

Figure 3: Qualitative evolution of the VELO vacuum pressures and temperatures of the LHCb beam pipe and vacuum vessel during a vent/pump-down cycle with bake-out of the system (described in the text).

For illustration, we outline the steps of a vent/pump-down cycle with bake-out of the LHCb beam pipe and VELO. The procedure[§] is qualitatively illustrated in Fig. 3. The system is slowly vented with clean gas, while controlling the pressure difference $|p_1 - p_2|$ (duration = 1 shift). Here, p_1 and p_2 indicate the

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[§] The procedure described is not final and might need some refinements to take into account actions such as baking out the ion-getter pumps, leak chasing, etc. However, we expect that these tasks can be accomodated in such a way that the overall duration of the procedure is not increased much. Further, the procedure will be tested on a realistic setup.

Actions	**LHC downtime**
Access to VELO:	
Overhead time for setting up LHC in standby mode and for granting access to the VELO area	1/2 shift
Overhead time for closing the experimental zone and setting up LHC for injection	1/2 shift
Vacuum system:	
Bring VELO to atmospheric pressure	1 shift
Pump down VELO from atmospheric pressure to about 5 mbar	1 shift
Pump down from about 5 mbar to below about 10^{-4} mbar (pressure at which the ion-getter pumps can be turned on and the NEGs activated)	1 shift
Pump down from about 10^{-4} mbar to about 10^{-7} mbar (pressure at which beam injection can start)	1 day
Bake out:	
Retraction of all sensitive devices around the LHCb beam pipe for a NEG activation	2 days
Ramping up or down of VELO temperature	1/2 shift
Ramping up or down of LHCb beam pipe temperature	1/2 shift
Bake out VELO (with LHCb beam pipe at elevated temperature)	1 day
Bake out LHCb beam pipe (VELO at elevated temperature)	1 day
Repositioning of all detectors moved away for baking out the NEGs (LHCb beam pipe at atmospheric pressure)	2 days
Installation *or* removal of	
One (or both) detector half (halves)	1/2 shift
Feedthrough flange	1/4 shift
Upstream spherical flange and beam pipe section	1/2 shift
Emergency wake field suppressor in the primary vacuum vessel	1/2 shift
Secondary vacuum vessels	1/2 shift
LHCb beam pipe	1 week

Table 5: Major repair operations and associated LHC downtime (1 day = 3 consecutive shifts of 8 hours).

primary vacuum and secondary vacuum pressures. The LHCb beam pipe is prepared for bake-out, *i.e* all sensitive devices are retracted from the beam pipe and heat jackets are mounted (2 days). At the same time, if required, some repair operations can be performed on the VELO. The system is slowly pumped down via restrictions and with regulation of the pressure difference $|p_1 - p_2|$, until $p_{1,2} \lesssim 5$ mbar (1 shift). Below this value, evacuation is taken over by the turbo-molecular pumps and the vacuum system temperature is ramped up. This proceeds until the VELO is ready for bake out (0.5 shift). The LHCb beam pipe is kept at an elevated temperature (about 80 °C) to avoid that desorbed gases from the VELO accumulate on the NEG-coated surface. After approximately 3 shifts, the LHCb beam pipe temperature is ramped to the nominal bake-out value of about 200 °C (0.5 shift), while the VELO temperature is set to approximately 80 °C. Bake-out of the complete system continues for approximately 1 day. Subsequently, the heaters are turned off and the system is further pumped down (with the ion-getter pumps turned on) while the system is cooling down. Vacuum conditions sufficiently good for LHC beam injection are reached after about 1 day. The total LHC downtime for such a cycle is about 6 days. Note however that, in this scenario, LHCb is not in a position to take physics data at the end of the procedure. If exposure to air of the primary vacuum can be avoided (venting with ultrapure inert gas and no bake-out needed), the LHC downtime caused by a vent/pump-down cycle amounts to less than 3 days, and LHCb is *a-priori* in position to take physics data.

The general strategy to minimize downtime for LHC, in case of an UE near IP8, will be to have available a set of emergency elements which can rapidly be inserted in place of the normal elements, so that LHC can readily recover. The use of such emergency elements is allowed to hinder LHCb operation, if unavoidable, the priority being to bring back LHC beam conditions. For instance, in case the VELO halves must be taken out for repair, the feedthrough flanges interfacing the VELO detectors to the outside world could be replaced by dummy flanges, leaving the secondary vacuum without detectors, while these are being repaired. Vacuum conditions appropriate for injection can be rapidly restored. In case of a failure which requires removal of the secondary vacuum containers, an emergency wake field suppressor can be installed in the vacuum vessel to provide a conductive (cylindrical) connection between its two ends. This pipe will be provided with holes for vacuum pumping and, if necessary, coated with adequate materials. Of course, in both of these emergency scenarios, LHCb would suffer from the unavailability of the VELO for a certain amount of time. For the more severe scenario where one must remove the exit foil and LHCb beam pipe, an emergency pipe will be available which can be installed *throughout* the VELO vacuum vessel (leaving the latter at atmospheric pressure). In this way, re-positioning of the primary vacuum vessel and detector support frames can be avoided. The design of this emergency pipe will be taken over from the design of a standard LHC warm straight section. The replacement of the LHCb beam pipe represents by far the time-costliest of all repair operations. However, even in the improbable case that such an operation would be required, the total downtime for LHC would not exceed 2 weeks.

In the following description of undesired events, it is assumed that spare parts are always available, and the fastest path toward restoration of LHC beam conditions is chosen.

3.6 Identification of undesired events and estimation of their gravity

We attribute an identifier name to each undesired event. The base name UE will be used, followed by a number referring to a given originating event. In case we want to distinguish between events which have the same originating event but differ in their level of gravity (e.g. because of the coincidental occurrence of another event or failure), we append a letter to the number, for example UE-1a, UE-1b, etc.

The required frequency depends on the chosen risk level of acceptability. We give both the class of the required frequency determined according to Table 3 and, in brackets, the required frequency according to the criterion $risk = frequency \times downtime \leq 10^{-2}$ days/year.

UE-1a: Leak from ambient air to secondary vacuum

A leak from ambient air to the secondary vacuum is most likely due to either a slow degradation of a feedthrough by e.g. corrosion, or to a human-induced damage of a feedthrough (mishap, pulling/mounting of a connector, etc.). Other scenarios with similar consequences can be thought of, but seems more unlikely. Human-induced damage can only occur when the systen is in mode **Isolated**. The system might be in **Physics** mode if the leak was due to a slow degradation of a feedthrough. However, in this case the leak would appear slowly and action would be taken to close the sector valves well before the NEGs are affected. The only relevant difference would be the possible overhead time needed to access (and later close off) the experimental area (in total, about 1 shift). We assume for this UE that the leak rate following the breaking of a feedthrough pin is low enough that the pumps continue running and keep the pressure below Δp_{max1} (and if not, then see UE-1b and UE-1c below). The residual vacuum conductance of the gravity-controlled valves (between primary and secondary vacua) is of the order of 10^{-5} ℓ/s for air, in the molecular flow regime. Therefore, even if p_2 comes close to the trigger pressure Δp_{max1} of about 1 mbar, the leak rate to the primary vacuum is expected to be no more than 10^{-5} mbar ℓ/s. The time between the occurrence of the damage and the actions taken to isolate the two vacua (for venting the VELO) is of the order of a few minutes. In this time, the amount of gas that has flown into the primary vacuum vessel is less than 10^{-2} mbar ℓ. Since only about 1 % of this gas reaches the NEGs in the LHCb beam pipe, one can safely assume that those are negligibly affected[¶] by this undesired event.

Estimated damage: The leaking connector feedthrough is localized (1/2 shift). The VELO and LHCb beam pipe are vented using ultrapure inert gas. The secondary vacuum only is exposed to ambient air during repair of the connector feedthrough. Baking after the subsequent pump-down is not necessary. We estimate the downtime to be about 2.5 days. The spare feedthrough connector (or feedthrough flange) represents the only relevant CHF loss (for LHCb). The gravity of this undesired event is estimated to be **Severe**.

Category: **Severe** *CHF Loss*: ≈ 0 *Downtime*: ≈ 2.5 days

Required frequency: **Remote** (or 4×10^{-3} year^{-1})

Requirements/remarks: A realistic frequency estimate can be extracted from the CERN SPS and LEP experience. Crash tests will be performed at NIKHEF to evaluate the consequences of breaking a connector by human action. Sufficient precautions must be taken to ensure that the probability for such an event is indeed **Remote**. For instance, the female (cable-side) connectors should be bolted to the flange. The male (flange-side) connectors should be countersunk into the flange. Cables coming from the connectors should be tightened to a cable holder. A protective cage should cover the feedthrough flange whenever possible. The setup could be located in an area with restricted access, which reduces risk due to human action. Servicing operations on the setup will be performed by qualified personnel exclusively. The choice of connector feedthroughs should take into account aging effects.

UE-1b: 1a and pressure difference does not stay below Δp_{max1}

As in UE-1a, but the leak is such that the pressure difference overshoots the value Δp_{max1} which triggers the electrically activated bypass valves to open. If the pressure difference reaches Δp_{max2} the gravity-controlled protection valves also open and increase the vacuum conductance between the primary and secondary vacuum. Therefore, the primary vacuum is also exposed to the air leak.

Estimated damage: The VELO is brought to atmospheric pressure using a clean gas. The VELO and LHCb beam pipe have been exposed to ambient air via the leak. The ion-getter pumps and thin foils need to be inspected. In this case the NEGs are probably affected (substantial reduction of the number of pumping sites). During replacement of the feedthrough flange, some LHCb sub-detectors are retracted from the beam pipe. The system is pumped down. The VELO is baked out, then the NEGs are activated. Following the discussion of Fig. 3, we estimate the LHC downtime to be about 6 days. Equipment losses are similar to those estimated for UE-1a. Thus, the gravity of this undesired event falls into the category **Severe**. For LHCb, the damage is more important, since some detectors are left in the retracted position, until an access of about 4 consecutive days is granted.

Category: **Severe** *CHF Loss*: ≈ 0 *Downtime*: ≈ 6 days

Required frequency: **Remote** (or 1.7×10^{-3} year^{-1})

Requirements/remarks: Although the consequence category is as for UE-1a, it is useful to estimate by test measurements the frequency of UE-1b relative to UE-1a. This would imply measuring the behaviour of the secondary and primary vacuum pressures as a function of time in the event of a sudden leak due to e.g. a broken feedthrough.

UE-1c: 1a and pressure difference exceeds Δp_{max2} and protection valves fail

As in UE-1b, but the pressure difference exceeds Δp_{max2} and all protection valves (electrically activated and gravity-controlled) fail to keep the pressure difference below Δp_{crit}. The primary vacuum is assumed to be exposed to the leak. The Si detector housing might irreversibly deform or rupture, in which case the gravity of the damage will depend on the material used and its thickness. The higher the rupture pressure, the larger the probability that a number of Si modules shatter.

[¶] Indeed, 10^{-4} mbar $\ell \simeq 3 \times 10^{15}$ molecules: the LHCb beam pipe NEGs have, at start-up, more than 10^{19} pumping sites on the surface.

Estimated damage: The VELO is brought to atmospheric pressure. The damage is at least as important as in the case of UE-1b. If it is estimated that the NEGs on the LHCb beam pipe are still usable, the downtime is only about 2 days longer than in the case of UE-1b: the extra downtime arises from the replacement of the (damaged) thin foil encapsulations by the emergency wake field suppressor, which also implies removing the Si detector halves. In the worst case, the LHCb beam pipe must be replaced, which would represent an equipment loss of about 10^5 CHF. Even in this case, the LHC downtime is not expected to exceed 2 weeks. Therefore, we estimate that the gravity will make this UE fall into the category **Major**. Estimated equipment losses for LHCb are between 10^4 and a few 10^5 CHF (depending on the damage to the Si modules), with an additional 10^6 CHF if using a beryllium encapsulation. LHCb operation might be stopped for several months.

Category: **Major** *CHF Loss*: 10^5 *Downtime*: ≈ 2 weeks

Required frequency: **Improbable** (or 7×10^{-4} year^{-1})

Requirements/remarks: The mechanical properties of the foil (deformation, rupture) should be studied by test measurements. The probability that, in case of an event UE-1b, the pressure difference exceeds $\Delta p_{\rm max2}$ and both kinds of protection valves (electrically activated and gravity-controlled) fail to keep the pressure difference below $\Delta p_{\rm crit}$ should be such that the resulting frequency falls into the class **Improbable**, *f.i.* if the frequency of UE-1b is **Remote**, then the above probability should be at most 1 in 10. This can be demonstrated in the laboratory, prior to installation at IP8.

UE-2: Rupture of LHCb exit window or beam pipe

Both the LHCb exit window and beam pipe are critical parts of the LHCb setup. Rupturing of these components cannot be excluded. However, their design and fabrication are carried out according to strict rules (see below). Hence, such a scenario can reasonably be assumed to be highly improbable when the system is in **Physics** or **Standby** mode (no personnel in the experimental zone).

Estimated damage: Rupture of the LHCb exit window or beam pipe results in a large inflow of ambient air into the primary and secondary vacuum systems. If the vacuum system is in **Isolated** mode, the consequences for LHC can be expected to be as in UE-1c. The LHCb beam pipe must be replaced, inducing a downtime for LHC of less than 2 weeks. In the highly improbable case that this UE occurs when the system is not in **Isolated** mode, the gravity of the event would depend on the presence and position of fast-acting valves (see also section 3.2.4). If fast-acting valves are used and located such as to protect the IR8 inner triplets, the gravity is unchanged. In case fast-acting valves are not used or are to close to the point of collapse, the inner triplets may be affected by the burst of air, which could result in a downtime for LHC of more than 2 months.

Category: **Major** *CHF Loss*: 10^5 *Downtime*: ≈ 2 weeks

Required frequency: **Improbable** (or 7×10^{-4} year^{-1})

Requirements/remarks: The design of the exit window and beam pipe must comply with the CODAP rules for pressure vessels [15]. A safety factor of 4 in the loaded scenario during the activation and vertex baking procedure is considered in the calculations. This safety factor of 4 means having an external pressure of 4 bars that the window and beam pipe must withstand without buckling. Destructive pressure tests must be performed with window prototypes as well as vacuum tests to validate the design. If no human operation is allowed in the neighbourhood of the exit window and beam pipe when the system is under vacuum, the occurrence probability of an implosion of these critical components due to a human mishap is largely reduced. The added value of fast-acting valves is yet to be studied.

UE-3: Loss of electrical power during normal operation

In the worst case, a loss of electrical power occurs while the VELO is in **Physics** operation. Immediately after the power loss, an alarm will be transmitted to the LHC interface, requesting a beam dump. After the dump the ring sector valves are closed. The vacuum system is brought into a safe mode (for details, see Ref. [9]). Basically, the vacuum system is isolated from the mechanical pumps. The electrical power and high voltages of the detector modules are turned off. The cooling compressor and pump units are off (not backed by UPS). In this state the primary and secondary vacua are expected to rise slowly. After about one minute, electrical power from the central diesel generator should be available. If necessary, normal vacuum conditions can be restored by powering up the vacuum pumps.

Estimated damage: No material damage is expected. The downtime introduced in addition to the duration of the electrical power loss and time needed to prepare beam injection is negligible (fraction of an hour). Strictly speaking, the gravity of this UE falls into the category **Minor**.

Category: **Minor** *CHF Loss*: 0 *Downtime*: < 4 hours

Required frequency: **Occasional** (or 3×10^{-1} year^{-1})

Requirements/remarks: The probability for such an event to occur is known from LEP experience to be at least **Probable** (a few occurrences per year). In view of the fact that power failures are uncorrelated with the design of the LHCb detector, requiring the frequency to be **Occasional** is unrealistic. However, LHCb should indeed make use of an appropriate back-up system, based e.g. on distributed UPS's and a central high-power generator, thereby trying to minimize any possible downtime caused by a power failure (an added downtime of one hour seems acceptable). For example, if, during a power failure, outgassing from the detectors can trigger the protection valves to open (which would introduce a considerable amount of water into the primary vacuum system), uninterrupted pumping on the primary and secondary vacuum during the power failure should be implemented in the design of the back-up system. Such issues should be addressed in a test setup.

UE-4: Failure of a compressor/pump unit in the CO_2 cooling system

Due to a failure of a compressor or pump unit, the CO_2 cooling system goes down and cannot be brought up again within minutes. The CO_2 pressure equalizes in the whole cooling circuit to about 40 bar (filling pressure). All electrical power and voltages to the Si modules are turned off. The Si detectors slowly warm up and the secondary vacuum pressure p_2 might rise somewhat. The nominal pressure p_2^{nom} of the secondary vacuum (before cooling the detectors) is 10^{-4} mbar, whereas the vapour pressure of water at the lowest temperature envisaged for the Si detectors (-25 C°) is about 10^{-1} mbar. In consequence, surface coverage by water molecules should be of the order of one monolayer or less. Therefore, one does not expect p_2 to rise much above p_2^{nom} during warm-up of the detectors.

Estimated damage: Repair of the compressor or pump unit can be carried out without interrupting LHC operation. This causes no LHC downtime.

Category: irrelevant *CHF Loss*: 0 *Downtime*: 0

Required frequency: any

Requirements/remarks: One should determine experimentally the secondary vacuum pressure rise during warm-up of the detectors (after several weeks of operation at the lowest temperature). If the pressure p_2 exceeds Δp_{max1}, the gravity of this event should be reconsidered.

UE-5: Leak into the vacuum from the CO_2 cooling circuit

A leak occurs in the CO_2 cooling circuit inside the secondary vacuum. The most significant scenario is a small crack near a vacuum-brazed connection. In the worst case the VELO is in **Physics** mode. The secondary vacuum pressure rise is immediately detected by pressure gauges. The pressure in the secondary vacuum might reach the value which triggers the foil protection valves to open. In any case, a beam dump is requested and the sector valves are closed. The Si detectors must be taken out to avoid deterioration due to long exposure to room temperature after irradiation.

Estimated damage: The VELO is vented (with ultrapure inert gas, if appropriate). The defective detector half is taken out for repair of the cooling circuit. LHC operation can be resumed after the subsequent pump-down, with (without) bake-out if the pressure rise in the secondary vacuum reached (did not reach) the value which triggers the foil protection valves to open. The LHC downtime amounts to about 6 days (2.5 days), essentially as in UE-1b (UE-1a). The gravity of this undesired event is **Severe**. Again, LHCb downtime might extend to several weeks.

Category: **Severe** *CHF Loss*: 0 *Downtime*: 2.5 to 6 days

Required frequency: **Remote** (or 4 to 1.7×10^{-3} year^{-1})

Requirements/remarks: The behaviour of the system in the occurrence of a small crack in one of the brazed connection should be studied in a test setup. This would imply measuring the behaviour of the secondary and primary vacuum pressures as a function of time in the event of such a sudden CO_2 leak.

UE-6: Damage by sudden beam displacement

The VELO is in **Physics** mode. Downtime for LHC is only expected if the thin-walled secondary vacuum containers were seriously damaged (pierced) by the beam. This scenario presupposes that either the radiation detector mentioned in section 3.2.3 or the beam dump system fails to protect the VELO. A sudden increase in the VELO primary vacuum pressure will be observed for a short time (seconds), due to an increased desorption from the thin-walled containers. The pressure should then quickly stabilize to a value between the nominal secondary (10^{-4} mbar) and primary (10^{-9} mbar) vacuum pressures. An alarm is sent by the VELO control system to the LHC dump interface and the LHCb vacuum system is isolated.

Estimated damage: The VELO must be vented in order to remove the thin-walled encapsulations and detector halves. An emergency wake field suppressor pipe can be inserted in place of the thin encapsulations, thereby exposing to ambient air the VELO and LHCb beam pipe. During this operation, some LHCb sub-detectors are retracted from the beam pipe. The system is pumped down. The VELO is baked out, then the NEGs are activated. The loss in CHF for LHCb is between 10^4 and few 10^5 CHF (depending on the damage to the Si modules), or more if using a Be box. The LHC downtime is estimated to be about 6 days (compare with UE-1b). Therefore, we classify this UE in the consequence category **Severe**. For LHCb, the damage is more important: some detectors are left in the retracted position, and the Si detector halves and new thin foil encapsulations must be installed. LHCb is down until an access of about 1 week is granted.

Category: **Severe** *CHF Loss*: 0 *Downtime*: $\approx$ 6 days

Required frequency: **Remote** (or 1.7×10^{-3} year^{-1})

Requirements/remarks: It must be ensured that the probability for such an event is **Remote**. Possible scenarios of beam oscillations and their consequences are being simulated and analysed by the LHC group. The required reliability of the radiation detector and beam dump request system should be specified on the basis of the results of these studies.

UE-7: Both ion-getter pumps break down

In the worst case, the VELO is in **Physics** mode. We do not expect any downtime for LHC if only one of the two ion-getter pumps breaks down, irrespective of whether the failure came from the power supply or the pump itself. In the former case, the power supply can be exchanged without interrupting LHC operation. In the latter, case the ion-getter pump must be vented and replaced at the next access (the main vacuum system does not need to be vented). The gate valve to the defective ion-getter pump can be shut, if necessary, in which case the pressure in the VELO primary vacuum vessel will raise by about a factor two. The primary vacuum conditions are still acceptable for **Physics** operation. If both pumps fail simultaneously, the VELO must be isolated from LHC, until at least one pump is repaired.

Estimated damage: The repair of the two pumps (or their power supplies) is straightforward and does not require venting either primary or secondary vacua (see above). The primary vacuum can be pumped temporarily by the (baked out) turbo-molecuar pump station (see Ref. [9]). LHC downtime is estimated to be less than 4 hours if the failure was in the power supplies and less than 2 days if the pumps have to be replaced, *i.e.* the consequence category for this UE is of type **Minor** or **Severe**, respectively. LHCb losses will range from 10^3 to a few 10^4 CHF, depending on the nature of the damage.

Category: **Minor (or Severe)** *CHF Loss*: 0 *Downtime*: < 4 hours (or 1 day)

Required frequency: **Occasional (or Remote)**

Requirements/remarks: The use of redundancy (two pumps) is expected to be sufficient to keep the risk at an acceptable level, provided the pumps a regularly serviced.

UE-8: Both secondary vacuum pump stations break down

In the worst case, the VELO is in **Physics** mode. This UE is similar to the previous one. If only one of the two turbo-molecular pump stations on the secondary vacuum breaks down, we do not expect any LHC downtime. The pump station is isolated and repaired at the next access[‖]. The pressure in the Si detector housing will raise by about a factor two, as well as the leak to the primary vacuum through the gravity-controlled valves. However, the primary vacuum conditions are still acceptable for **Physics** operation. If both pumps fail simultaneously, the VELO must be isolated from LHC, until at least one pump is repaired.

Estimated damage: The VELO is vented with ultrapure inert gas. Before this procedure is started, the secondary vacuum might have been pumped for a short time (minutes) via the small residual conductance of the gravity-controlled valve, through the primary vacuum. The effect on the NEGs is still expected to be negligible. The two pumps (or their power supplies) are repaired or replaced. LHC downtime is estimated to be less than 3 days. The consequence category for this UE is of type **Severe**. LHCb losses will range from 10^3 to a few 10^4 CHF, depending on the nature of the damage.

Category: **Severe** *CHF Loss*: 0 *Downtime*: < 3 days

Required frequency: **Remote**

Requirements/remarks: The argumentation here is similar to the case of UE-7. No special requirements need to be specified, provided the pumps a regularly serviced. If the risk is nonetheless estimated to be too high, a third pump could be used, as in UE-7, to evacuate temporarily the secondary vacuum and avoid venting the system. This would reduce the LHC downtime to zero, since normal beam conditions could be maintained until the next access.

UE-9: Bellow in vacuum breaks

In the worst case, the VELO is in **Physics** mode. Due to repetitive mechanical motion, one of the bellows interfacing the Si detector housing to the primary vacuum vessel might break. The leak rate from the secondary vacuum to the primary vacuum would then increase, and the VELO would be immediately **Isolated**. The aperture of the crack can be reasonably expected to give leak rates below a few times 10^{-3} mbar ℓ/s. Under this assumption, the primary vacuum pressure should remain below a few times 10^{-7} mbar.

Estimated damage: The bellow needs to be replaced. The system is vented and the NEGs are baked out after the subsequent pump-down. The complete secondary vacuum containers are taken out and replaced by an emergency wake field suppressor. The LHC downtime is essentially as in UE-6. category **Minor**, in the second case it will be **Severe**. Therefore, the UE falls into the consequence category **Severe**. Equipment losses for LHCb will amount to about 10^5 CHF.

Category: **Severe** *CHF Loss*: 0 *Downtime*: ≈ 6 days

Required frequency: **Remote** (or 1.7×10^{-3} year^{-1})

Requirements/remarks: The occurrence probability for such an event can be approximately determined in the laboratory by repeated mechanical motion or estimated from manufacturer specifications (if available).

UE-10: Two detector halves are jammed in the closed position

In the worst case, the VELO is in **Physics** mode. The two detector halves are in the closed position and cannot be moved due to jamming of the positioning system.

Estimated damage: No beam can be injected when the detectors are in the closed position. An access to the experimental zone is required to identify the cause of the failure and repair. All moving parts (gearboxes, belts, motors and bearings) are located outside the vacuum. The VELO can be moved manually in the outer position and repaired during a later access. LHC downtime is estimated to be at most 1 day. Strictly speaking, the gravity is **Severe** (but the downtime is dominated by the overhead time needed to enter and later close the experimental zone).

[‖] It is not yet known whether the turbomolecular pump model used will allow placing the power supplies in the accessible area, because of a possible limitation on the cable length.

Category: **Severe** *CHF Loss*: 0 *Downtime*: < 1 day

Required frequency: **Remote** (or 10^{-2} year^{-1})

Requirements/remarks: The expected usage of the detector retraction system is less than 1000 open/close cycles per year. A reliability test can be performed prior to installation by repeating the open/close cycle a few 1000 times.

4 Conclusions

We have presented a preliminary risk analysis of the LHCb VELO system. Critical items in the design were identified and their possible failure scenarios discussed. An estimation of the consequences of these failure scenarios was presented and several recommendations were given which should minimize the risk for LHC. The most critical parameter in the quantification of the damage to the LHC results to be the induced downtime. However, it was argued that even in the improbable case of the most catastrophic of these scenarios (which would require replacing the LHCb beam pipe with an emergency pipe), the downtime for LHC would not exceed 2 weeks, provided the damage does not extend to the neighbouring inner triplets.

When detailed technical descriptions of the VELO system and components become available, this risk analysis will be refined and complemented with a reliability analysis.

Acknowledgements

We are grateful to A. Desirelli, O. Gröbner, K. Potter, R. Schmidt, B. Skoczen, P. Strubin, and L. Vos for their help and constructive criticism.

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