Conceptual design of the LHCb VELO vacuum system

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Abstract

We present the conceptual design of the LHCb vertex locator vacuum system. Servicing procedures such as venting (with ultrapure inert gas), pumping down, and baking out are described in detail.

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1 Introduction

To obtain the required performance of the LHCb vertex locator (VELO) the silicon strip detectors are operated in vacuum. This allows for positioning the sensitive area closer to the beam and reducing the amount of material traversed by particles, in particular the amount between the vertex and the first hit on a detector. To minimize the contamination of the primary vacuum by the large outgassing rates from some of the components of the detector modules, these are placed in a secondary vacuum which is separated from the primary (LHC) vacuum by a thin wall. This wall cannot withstand a pressure difference of 1 bar. As a consequence, the design must include a protection scheme against a possible increase of the pressure difference across the thin wall, in case of a failure. In addition, in order to preserve the NEG coating in the LHCb beam pipe, a method must be applied to vent both primary and secondary systems in parallel, while avoiding any flow of impurities into the primary vacuum (the primary vacuum must be vented with ultrapure inert gas to avoid saturation of the NEG material). In this way, access to the silicon detectors is decoupled from access to the primary vacuum.

The pressure difference between the two vacuum volumes must be kept at all times below the plastic deformation pressure (about 17 mbar) of the thin separation wall. This implies using a well calibrated procedure for pumping down and venting the system, which will be performed by a programmable logic controller unit (PLC). The PLC unit also monitors and controls the vacuum system during normal operation.

In this note, we describe in detail the layout of the vacuum system, the protection mechanisms, and the procedures to vent, pump down and bake out the system.

2 Overview of the LHCb vacuum system

In Ref. [1] a preliminary study for the design of the vacuum system for the LHCb VELO was presented and a first conceptual design proposed. There, it was suggested to use a differentially pumped system with primary and secondary vacua connected *at all times* via a fixed bypass conductance (pumped at its middle), which would limit the pressure difference across the thin wall. The base pressure of the secondary vacuum system was estimated to be about 10^{-4} mbar, consisting mostly of water vapour. The static primary vacuum pressure was expected to be in the 10^{-8} mbar range. A disadvantage of this design was that the primary vacuum vessel and LHCb beam pipe needed to be opened to air in order to access the silicon detectors, and a bake-out scheme for the VELO seemed not possible. As a consequence, after each access to the detectors a (time-consuming) re-activation of the NEG coating would have been necessary. Furthermore, the flux of gas from the VELO towards the LHCb beam pipe would result in a relatively quick saturation of the NEG coating, resulting in an increased static vacuum pressure in the LHCb beam pipe and, perhaps, an increased beam-induced desorption rate. Although these side effects were not shown to be unacceptable from the point of view of LHC operation (beam stability criteria [2, 3]) or LHCb performance (beam-gas background), they do constitute a potential obstacle and might result in complications of the design (such as the use of *in situ* getter coating of the primary vacuum surfaces in the vicinity of the beams). To overcome these potential difficulties, the design was improved by

1. decoupling access to the detectors from access to the primary vacuum, and
2. replacing the fixed bypass conductance by a dynamic valve with a conductance that increases as a response to an increasing differential pressure, but with a minimized (residual) conductance in normal operation.

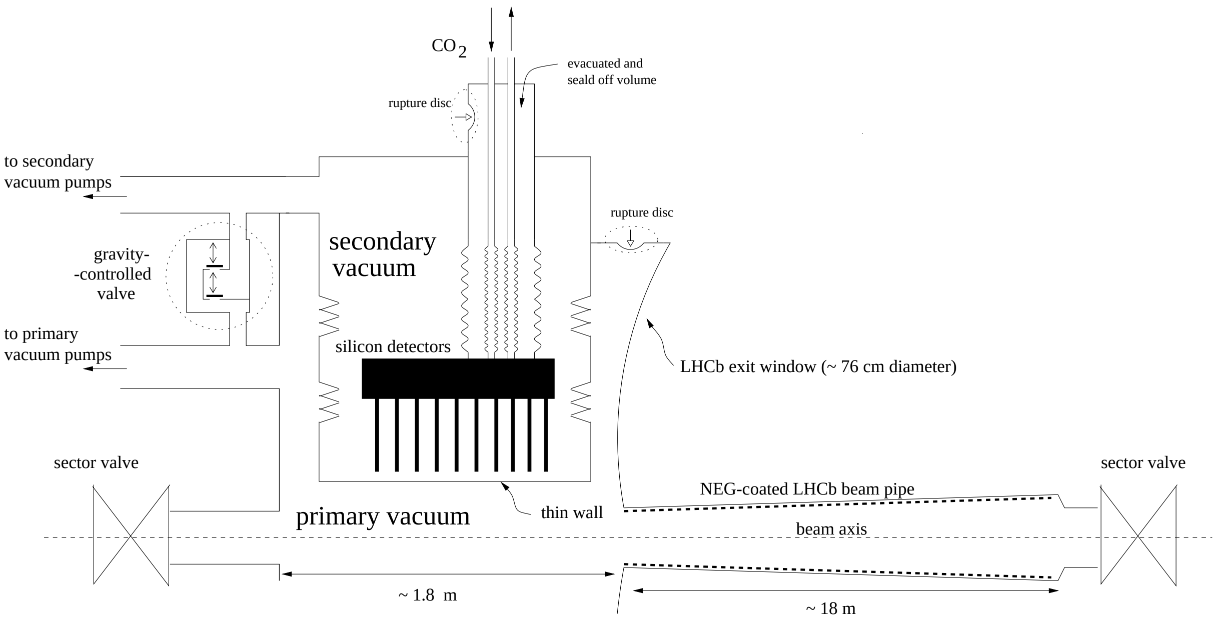

Figure 1: Sketch of the VELO and LHCb vacuum system. For clarity, only one half is shown.

The VELO vacuum system consists of three communicating sections, namely the VELO vacuum vessel, the LHCb beam pipe and the silicon detector housings, as schematically shown in Fig. 1. These three sections are not independent vacuum systems: one section cannot be brought to atmospheric pressure individually. The VELO primary vacuum vessel and LHCb beam pipe are part of the LHC primary vacuum system.

The LHCb beam pipe extends throughout the complete LHCb detector (length of about 18 m) and consists of three tapered, thin-walled metallic pipes (Al, Al-Be alloys and stainless steel are being considered). On the VELO side the pipe ends with a curved Ø76 cm and 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 is coated with low activation temperature NEG [9]. These will be activated *in situ* by baking the LHCb beam pipe to about 200 °C. The beam pipe can be vented in a controlled way (with clean air) and the NEG coating re-activated later (under high vacuum) without substantial loss of their pumping speed. However, because of the limited capacity of the NEG coating, it is expected that after several such cycles the NEG pumping speed will drop substantially. In the case of the LHCb beam pipe, it is not yet known whether the full pumping speed of the NEG coating will be needed to ensure acceptable (dynamic) vacuum conditions for the LHC. If not, the maximum number of venting cycles could be somewhat larger. Reactivation at higher temperature (about 250°C) and/or for longer times could be considered to increase the life time of NEG material [10]. To avoid relying on uncertain assumptions about properties of the NEG coating, we have adapted the design of the VELO vacuum system to extend the life time and preserve the efficiency of the NEG material. An established procedure using ultrapure inert gas (probably neon) will be applied, as is routinely done in e.g. the CERN EST/SM laboratories, to avoid bake-out after a venting/pump-down cycle.

The VELO primary vacuum vessel is a Ø1 m stainless steel chamber of about 1.8 m length, shown in Fig. 2, 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 (thin-walled detector housing). During bake-out, the silicon detectors are not in the secondary vacuum vessel. The nominal static pressure of the baked-out VELO primary

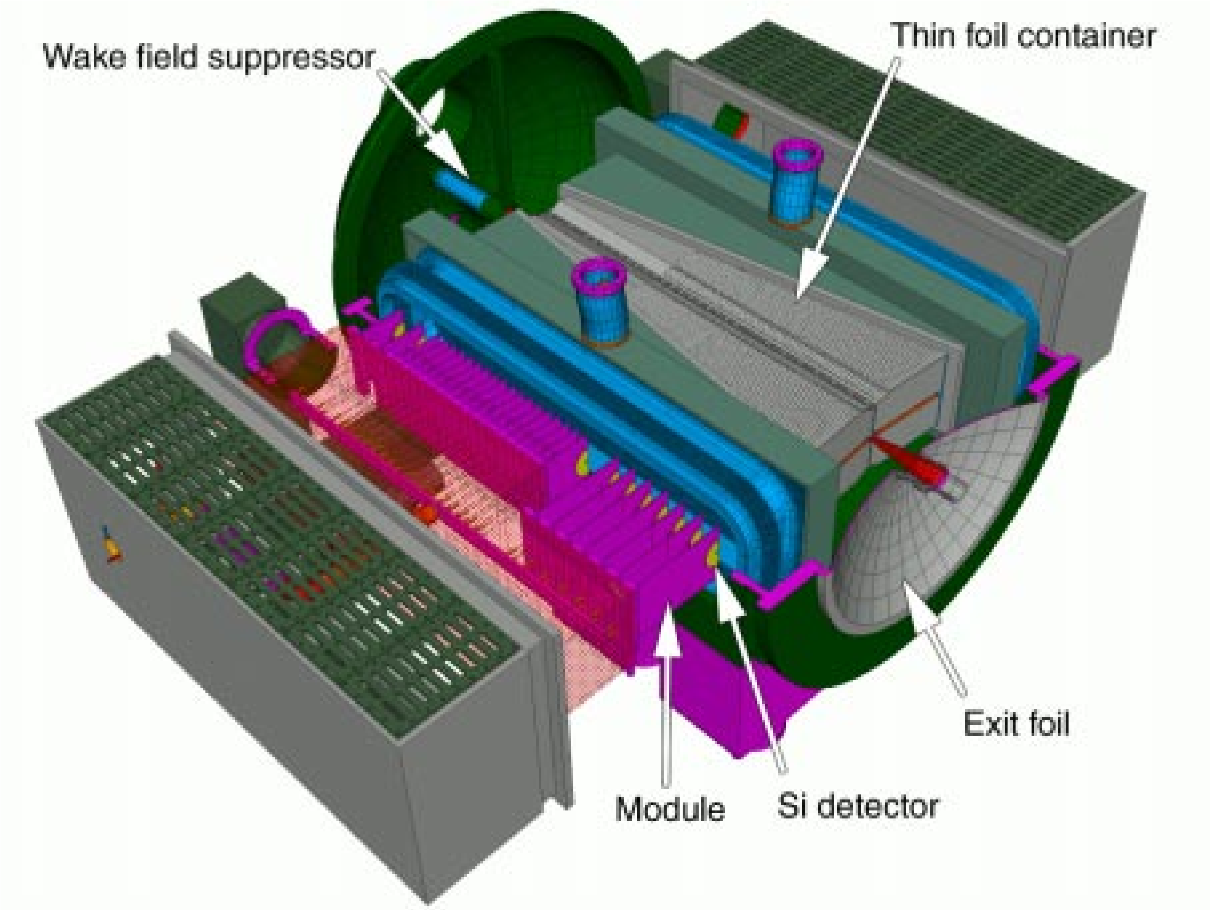

Figure 2: Three dimensional cut-out view of the VELO primary vacuum vessel, secondary vacuum containers and silicon detectors. One detector half is retracted from its vacuum container in order to show the silicon detector modules.

vacuum 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. 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 silicon detector modules. The detectors can be removed without exposing the primary vacuum to ambient air. 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 pumps. In normal operation these pumps have a common outlet duct. The housings are decoupled from the primary vacuum vessel by using large rectangular stainless steel membranes, which allow for moving the detector halves by the required amount in the two transverse directions [4]. 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 positioning system. All motors, gearboxes, chains 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, as described in Ref. [8]. The total amount of CO_2 in the system is relatively small, of the order of 5 kg which corresponds to approximately 2.5 m^3 at STP. Of this amount, only about 100 g is present in the tubing inside the secondary vacuum system. No tube fittings or flange connections for the

CO_2 cooling system are present in the detector vacuum. Only welds and vacuum-brazings are used. The first flange connection is situated just outside the secondary vacuum. The CO_2 supply and return lines arrive to these connections via bellows, to allow for positioning and retracting of the detector halves. These bellows are enclosed in a larger bellow, which is evacuated and sealed off to avoid condensation of ambient air moisture. A rupture disc, protects the outer bellow in case of a CO_2 leak in the supply and return lines.

Two kinds of valves are used to protect the thin separation foil (detector housing) from an irreversible deformation, or rupture, in case of a pressure increase on one side of the foil. A pressure switch is used to open an electrically activated protection valve whenever the pressure pressure between primary and secondary vacua rises above a first threshold value (about 1 mbar). If the pressure difference exceeds a second threshold value (about 5 mbar) a gravity-controlled valve opens under the direct effect of the pressure and independent of any electrical power or pressurized air supply. The purpose of these protection valves is to maintain the differential pressure below the value (about 17 mbar) above which the thin-walled Si detector housing is expected to deform irreversibly*. The dynamic response and reliability of the safety valves, as well as the mechanical properties of the detector housings, will be studied in detail by test measurements on prototypes, prior to final production. Note also that the residual conductance in molecular flow regime of the gravity-controlled valve is in the order of 10^{-5} ℓ/s (for air at room temperature).

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 separation valves between LHCb and its neighbouring LHC sections are yet to be studied. If used, such valves must be equipped with valve position sensors that trigger a beam dump when the valve crosses (toward the beam) a predefined boundary.

3 Vacuum control system

A detailed layout of the VELO vacuum system is depicted in Fig. 3. Redundancy is applied to minimize the consequences of a pump failure. Hence, two primary vacuum pumps (PS430 and PS440) are used, as well as two secondary vacuum pumps (PS110 and PS210) with two roughing pumps (RP101 and RP201). The auxiliary pump PS120 is solely used to reduce (by a factor 100) the residual gas flow from secondary to primary vacuum under normal operating conditions. Pump station PS301 is used during pump-down and vent procedures, as will become clear in section 4. Devices denoted with a label that starts with 'PI' and 'PE' indicate pressure gauges (most probably Pirani and Penning gauges) that have a range of sensitivity of about $10^{-3}...10^{+3}$ mbar and $10^{-10}...10^{-3}$ mbar, respectively. Pump-out valves on the various pump stations are not indicated.

The vacuum system will be controlled by a programmable logic controller (PLC), with an interface to the LHCb and LHC SCADA systems (probably via an ethernet connection) and a stand-alone operator console. The PLC is backed by an uninterruptable power supply (UPS) to ensure continuous operation even in the event of a power failure. The UPS can take over instantly after a power failure. However, their autonomy time is typically limited to about 10 minutes.

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*Note that, at 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 a few hundred mbar (for details, see in Ref. [7]).

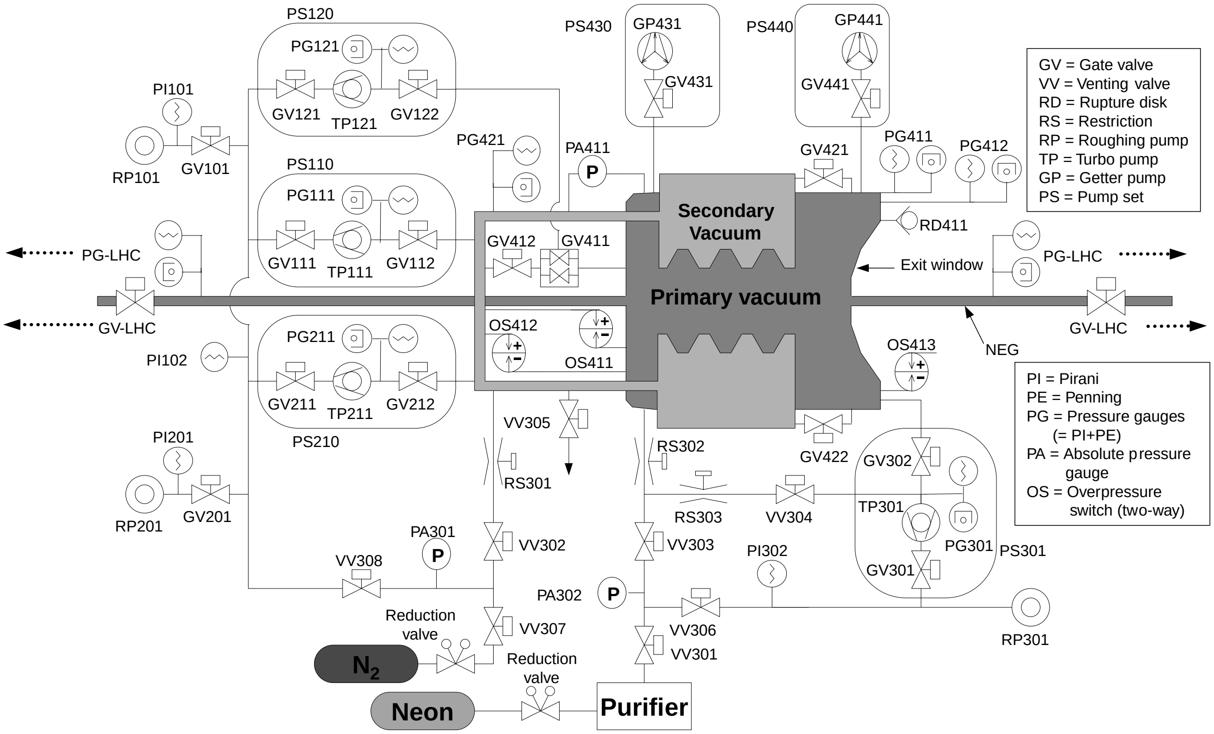

Figure 3: Layout of the VELO (LHCb) vacuum system.

To protect against long power failures, we assume here that LHCb will provide a high-power diesel generator. Since the take-over time of such a generator is expected to be of the order of minutes, the distributed UPS's are indispensable. In addition to the PLC unit, vacuum valves and monitoring devices (gauges, temperature sensors, etc.) will be backed by UPS. The vacuum pumps are not backed by UPS. Whether they should be powered up by the diesel generator is not yet decided.

The protection valves GV421 and GV422 are interlocked with the differential pressure switch OS412. This switch will trigger the valves to open if the *absolute* value of the pressure difference $\Delta p = p_2 - p_1$ between primary and secondary vacuum exceeds a predefined threshold value (about 1 mbar). Switch OS411 is used to control the venting valves VV302, VV303 and VV304 during the pump-down and vent procedures. The role of this switch is to signal whether Δp exceeds or not the threshold value, and *idem* for $-\Delta p$. The differential pressure switch OS413 signals whether the pressure difference between ambient air and primary vacuum exceeds a predefined threshold value and is used to protect the exit window during a vent procedure. Note that two gauge sets (PG411 and PG412) are mounted on the primary vacuum vessel to increase the availability of the pressure read-out: the second set is only turned on in case the first set fails. The gauges PG-LHC are monitors provided for and by the LHC vacuum control system. It is assumed that the two ion-getter pump currents (pump sets GP431 and GP441) can be used to some extent as a redundant read-out of the primary vacuum pressure. All gate valves are equipped with two status switches, for positions *open* and *closed*. It is further assumed that the LHC gate valves (GV-LHC) are closed (and not allowed to open) when the experimental zone is accessible.

The lower part of the vacuum scheme of Fig. 3 deals with the servicing procedures (venting and pumping down), which are described next.

4 Servicing procedures

Because the LHCb vacuum system combines the use of a thin separation between primary and secondary vacuum and of a NEG coating in the primary vacuum, complex procedures need to be applied for venting (with ultrapure inert gas), pumping down, or baking out the system. A first outline of these procedures is given in this section.

4.1 Procedure for pumping down

Start status:

1. We assume the ring sector valves are closed and the LHCb vacuum system is under atmospheric pressure.
2. The ion-getter pumps GP431 and GP441 are off, and their gate valves GV431 and GV441 are open.
3. The turbo-molecular pump TP121 for the gravity-controlled valve GV411 is off, its inlet gate valve GV122 is closed and its outlet gate valve GV121 is open.
4. The secondary vacuum turbo-molecular pumps TP111 and TP211 are off with their inlet gate valves GV112 and GV212 closed and their outlet gate valves GV111 and GV211 open.
5. The roughing pumps of the secondary volume RP101 and RP201 are off. One gate valve (e.g. GV101) is open, the other (GV201) is closed.
6. GV302, VV302, VV306 and VV307 are closed, VV308 is open.
7. We must distinguish between two cases: (a) the NEG coating has been preserved and need not be re-activated after pumping down (see subsection 4.2 below), and (b) the NEG coating must be re-activated after pumping down:
    - Case (a): the primary volume contains ultrapure inert gas, whereas the secondary vacuum system is open to ambient air (VV305 is open). The gravity-controlled valve GV411 is sealed off with GV412 to avoid contamination of the NEG coating. The pressure in the primary vacuum vessel is being regulated by the inert gas flow system. This system consists of a set of valves and restrictions which allows to both inject and pump out gas from the primary vacuum vessel. Gas is either injected via the valves VV301/VV303 and via restriction RS302 (valve VV304 is closed), or pumped out through restrictions RS302/RS303 and valve VV304 (VV303 closed) with a turbo-molecular pump (TP301). GV301 is open and the roughing pump RP301 is on. An overpressure switch (OS411), which reacts to the pressure difference between primary and secondary volumes, is used to control valves VV304 and VV304 (open/close), thereby ensuring that the differential pressure never exceeds a given threshold value. This inert gas flow system is fully baked and complies with the purity requirements for injection of ultrapure gas[†].

    - Case (b): both primary and secondary volumes are exposed to ambient air (VV305 and GV412 open). Gas injection and evacuation is off (VV301, VV303 and VV304 are closed). TP301 is off, GV301 is open and RP301 is on. We further assume that all

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[†] The required level of purity for LHCb is yet to be defined.

LHCb detector parts which cannot sustain bake-out have been retracted or protected (hence, the VELO silicon sensors are not installed), and all devices needed to bake out (such as heating jackets) have been installed prior to pumping down.

8. The protection valves GV421 and GV422 are closed, but active: they are interlocked with the differential pressure switch OS412 and will open as soon as the pressure difference between primary and secondary volumes exceeds a given threshold value (about 5 mbar). Optionally, for case (b) above, one might consider opening these two valves (the two volumes are filled with ambient air).

Pump down steps:

1. Close valve VV305.
2. In case (a), close valves VV303, VV304, VV301 and turn off TP301.
3. Start roughing pump RP101 and open pump-down valve VV306.
4. Start pumping down by opening valves VV302 and VV303. The flow restrictions RS301 and RS302 are designed to balance the gas flow to the pumps. Furthermore, the differential pressure switch OS411 is used to control (open/close) the valves VV302 and VV303, thereby ensuring that the pressure difference remains under a threshold value (about 1 mbar).
5. Wait approximately 3 to 4 hours until the pressure in both vacua falls below 5 mbar.
6. Start pumps TP111, TP211, TP121 and TP301.
7. Open GV302, GV112, GV212 and GV122.
8. Close valves VV302, VV303, VV308 and VV306.
9. Wait approximately 5 more hours until the pressure in the primary and secondary vacuum reaches about 10^{-4} mbar.
10. Open GV412 to enable protection by the gravity-controlled valve GV411.
11. In case (b), the system is now ready for the bake-out procedure, see section 4.3 below. In case (a), proceed with pumping down.
12. Turn on ion-getter pumps GP431 and GP441.
13. After approximately one day the pressure in the primary vacuum falls below 10^{-7} mbar.
14. Close gate valve GV302.
15. The system is now operational, in mode **Isolated**.

4.2 Procedure for venting the system

We describe a venting procedure which can be used in all cases, whether one wishes or not to avoid re-activating the NEG coating after the subsequent pump-down procedure. Ultrapure inert gas is injected into the primary vacuum chamber and dry air (or dry nitrogen) into the secondary vacuum container.

Start status:

1. We assume the ring sector valves are closed, the LHCb vacuum system is under vacuum and all pumps are on. The valve states are as in the last step of the procedure for pumping down, see section 4.1 above, or in the last step of the bake-out procedure, see section 4.3 below. In the second case, the ion-getter pumps GP431 and GP441 are off and GV302 needs to be closed.
2. If the detectors are in place and cooled, the cooling system is stopped.
3. The gas injection system is ready for use (lines injection lines have been flushed if necessary). VV306 and VV308 are closed.

Vent steps:

1. Seal off gravity-controlled valve GV411 with GV412.
2. Open valves VV301 and VV307.
3. Close valves GV112, GV212 and GV122 (and GV302, if open).
4. Switch off ion-getter pumps GP431 and GP441 (if on).
5. Switch off turbo-molecular pumps TP111, TP211 and TP121.
6. Switch off the roughing pump RP101.
7. Vent the two volumes in parallel by switching on the control (open/close) of valves VV302 and VV303 via the differential pressure switch (OS411). Note that valve VV304 is closed and decoupled from OS411.
8. Wait about 3 to 4 hours until the differential pressure switch OS413 between the primary volume and the surrounding air changes state. This signals that the pressure in the VELO exceeds the ambient pressure by a predefined amount, which stops gas injection (to protect the exit window).
9. The mode of operation of the gas flow system is changed: valve VV305 is opened to ambient air, valve VV307 is closed, valve VV302 is closed and decoupled from OS411, and pressure regulation is resumed by closing/opening the valves VV303 and VV304.
10. The secondary volume can now be accessed.

In case re-activating the NEG coating is needed, a somewhat simpler vent procedure could be used. Gas from the same bottle could be injected into both primary and secondary volumes, with open bypass protection valves (GV422 and GV421), thus reducing the risk of a failure. To allow for this procedure, some minor modifications of the gas injection system would be required.

4.3 Procedure for baking out the system

A bake-out procedure for systems including NEG-coated chambers, is currently being defined and tested by the CERN LHC vacuum group. This procedure will be adapted to the VELO vacuum system and tested at NIKHEF. We outline here the main steps of this (preliminary) bake-out procedure.

Start status:

We assume system is under vacuum, as left at step 11 of the pump-down procedure, see 4.1 above.

Bake out steps:

1. The VELO and LHCb beam pipe bake-out systems are turned on.
2. The temperatures are ramped up on both systems to about 80 °C. In this way, one tries to minimize the accumulation of desorbed molecules from the VELO onto the NEG-coated surfaces.
3. The VELO temperature is ramped up to and maintained at about 150 °C.
4. When the pressure in the primary vacuum has decreased below a given level, the VELO temperature is ramped down to about 80 °C, while the temperature of the LHCb beam pipe is raised to about 200 °C, and maintained to this value for about 24 hours. This activates the NEG coating.
5. Both bake-out systems are turned off.
6. The vacuum system is ready to proceed with the pump-down procedure (step 12 in section 4.1 above) or to undergo an ultrapure inert gas venting procedure (see section 4.2 above).

5 Summary

We have presented a conceptual design of the LHCb VELO vacuum system, with a first outline of various servicing procedures such as venting (with dry air and ultrapure inert gas), pumping down, and baking out.

The design builds on a previous version presented in Ref. [1] with the addition of two major improvements: (a) the ability to access the silicon sensors without exposing to ambient air the primary vacuum system, thereby avoiding a re-activation of the NEG coating, and (b) the use of a gravity-controlled valve which reduces the gas flow from secondary to primary vacuum, while keeping an intrinsic fault-tolerance to protect the thin foil separating the two volumes.

As a next step, a prototype setup will be constructed and the proper functioning of the presented scheme will be tested. Important features, such as the ability to preserve the necessary purity of the ultrapure inert gas and to maintain at all times a pressure difference below the required value, must be demonstrated.

References

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[3] *"Mechanical and Vacuum Stability Design Criteria for the LHC Experimental Vacuum Chambers"*, I.R. Collins, O. Gröbner, P. Lepeule, R. Veness, LHC Project Report 205.

[4] LHCb note describing the current mechanical design of the LHCb VELO, note number 2001-083 (to be published).

[5] *"Aperture requirements around interaction IP8"*, G. von Holtey, LHCb note LHCb-97-002.

[6] The minimum full aperture was tentatively estimated by B. Jeanneret to be 10.2 mm for $\beta^* = 36$ m, taking into account tolerances and 15 σ_{beam}.

[7] For further information on the thin-walled encapsulations (FEA results, prototypes, etc.), see http://www.nikhef.nl/pub/departments/mt/projects/lhcb-vertex.

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[10] C. Benvenuti *et al.*, CERN EST/99-008 (SM).