A vacuum system for the thermal insulation of
the SciFi distribution lines and manifolds

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Abstract
This note describes some calculations and estimates for
the layout, technology choice and performance of
a vacuum system which shall ensure thermal insulation
of the distribution lines and manifolds of
the SiPM cooling system of the LHCb SciFi detector.
We estimate the heat losses in
concentric corrugated stainless steel pipes
which leads to the conclusion that the pipes need
be evacuated to a pressure of about $1 \times 10^{-4}$ mbar.
We then estimate the pumping conductance of the
pipes and find that it will dominate over the effective
pumping speed of any pump. We therefore conclude
that a turbo molecular pump of small nominal
pumping speed, which can easily achieve end
pressures below $10^{-5}$ mbar is adequate for
this purpose. A preliminary layout of the vacuum system
is being discussed at the end of the document.
**Introduction**

The mechanical structure of the LHCb SciFi tracker is based on 2 x 6 C-frames which close up around the central beam pipe. In total 12 layers of scintillating fibre modules are mounted on the front and back side of the C-frames. Altogether, there are 128 fibre modules, which are read out by arrays of SiPM detectors at the top and bottom end of the modules.

![Diagram of 2 x 6 C-frames with scintillating fibre modules](image)

*Figure 1: Left: Arrangement of the 2 x 6 C-frames. Two C-frames on the right side have been opened up. Right: A C-frame with the upper and lower Novec manifold. Every manifold supplies 2 x 6 cold boxes (not shown).*

The SiPM photodetectors will be operated at a temperature of -40°C in order to mitigate radiation-related dark noise. The SiPM arrays are mounted on 3D printed Titanium cold bars which are placed in insulated shells, the so-called cold boxes, which are attached to the module ends.

**SiPM cooling**

The coolant Novec-649 will be cooled and circulated by a dedicated plant located remotely from the experiment. Glass foam insulated transfer lines ensure the supply of the cold Novec over a distance of about 60 m to the detector, more precisely to the bunker area under the SciFi, as well as its return to the cooling plant. In the bunker area the transfer lines are split in two and connected to the two distribution boxes (side A and side C).

All cold boxes which are mounted on the top or bottom of a C-frame are fed via a manifold which runs along the top and bottom beam of a C-frame. Coolant-wise, a C-frame corresponds therefore to 2 circuits.

On both sides, the 12 distribution lines and their returns, between the distribution box and the manifold need to be flexible to allow for the opening and closing of the detector halves. Furthermore, as the available space on the C-frames is very limited, it was decided to equip these lines, as well as the manifolds and the connections between the manifolds and the cold boxes with vacuum insulation.

The distribution lines will be made from concentric corrugated steel tubes (bellows) of DN32/DN16 diameter. The cold Novec will flow in the inner tube, while the outer tube will be evacuated for thermal insulation. The distribution lines are about 20 m long. Vacuum wise, the feed and return lines are connected via the vacuum volume of the manifold.
This note evaluates the required vacuum level and sketches a system to generate and measure the vacuum.

Thermal insulation by vacuum

Thermal insulation by vacuum is a well-established technology. Prominent examples are the vacuum insulated coffee pot and the cryogenic transfer lines. More recently, vacuum insulation has been used for insulating cooling lines in detectors: ATLAS IBL and CMS pixel.

The transport of heat between two surfaces separated by a gas is driven by three effects:

- In the **convective** regime, when the mean free path of the gas molecules is much smaller than the gap between the surfaces, heat is transferred predominantly by collisions between gas molecules.
- At lower pressure, in the **molecular** regime, when the mean free path is much larger than the gap, the collisions of the gas with the walls dominates.
- At very low pressure, heat transfer by **radiation** becomes the dominant source.

In the following we estimate the magnitude of these effects and conclude on the required vacuum level in the distribution lines and manifolds of the SciFi detector.

We follow the argumentation and formulae given by H. Frey and R.A. Haefer in the textbook ‘Tieftemperaturtechnologie’, VDI-Verlag.

**Convective heat transfer**

At sufficiently high pressure and for large systems, collisions between gas molecules are much more frequent than collisions with the walls of the system. The heat transport \( \dot{Q} \) is proportional to the area \( A \) and the temperature difference \( \Delta T \) and reciprocal to the distance \( d \) between the two walls.

\[
\dot{Q} = \lambda \cdot A \cdot \Delta T / d \tag{1}
\]

\( \lambda \) is the heat conductivity, which depends on the gas type and also on gas temperature. The heat transfer is in first order independent of the pressure.

For a system of two concentric cylindrical walls, like it is foreseen for the SciFi distribution lines, the expression becomes

\[
\dot{Q} = \lambda \cdot A_1 \cdot \Delta T / (r_1 \cdot \ln(r_2/r_1)) \tag{2}
\]
Evaluating this expression, setting $A_1 = 1.3 \text{ m}^2$, $\lambda_{\text{air}} = 0.026 \text{ W/m/K}$, the tube radii $r_1 = 1.05 \text{ cm}$ and $r_2 = 1.7 \text{ cm}$, and $\Delta T = 293 - 223 = 70 \text{ K}$, we obtain a heat transfer of 9.4 W distributed over the length of the 20 m long tube. We have ignored the enlargement of $A_1$ (by about a factor 2) due to the shape of the corrugated pipe geometry. A more realistic value is expected to be around 20 W.

**Heat transfer in the regime of molecular flow**

For air, the product of mean free path and pressure is constant

\[ l \cdot p = 4 \cdot 10^{-5} \text{ mbar m.} \quad [3] \]

In order for the mean free path to exceed 10.5 mm - which is about the minimal distance between inner and outer walls of the concentric tubes - the pressure $p$ must be below $4 \cdot 10^{-3} \text{ mbar}$. Below this pressure, the collision with the walls dominate and the heat transfer is proportional to the pressure.

\[ \dot{Q} = A_1 \cdot a \cdot K \cdot p \cdot \Delta T \quad [4] \]

The factor $K$, which depends on the isentropen exponent $\kappa (=1.405$ for $N_2$) and on the temperature at which the pressure is measured, is found to be 1.7 W m$^{-2}$ Pa$^{-1}$ K$^{-1}$. The accommodation coefficient (a) is calculated to be 0.21. By reducing the pressure, the molecular heat transfer can in principle be fully eliminated. It follows

\[ \dot{Q}/p = 2810 \text{ W/mbar (with } A_1 = 1.3 \text{ m}^2) \quad [5] \]

At a pressure of $4 \cdot 10^{-3} \text{ mbar}$ the molecular heat transfer $\dot{Q}$ is about 11 W. Again increasing $A_1$ by a factor 2 leads to $\dot{Q} = 22$ W, lining up at $p = 4 \cdot 10^{-3} \text{ mbar}$ with the convective contribution.

**Heat transfer by radiation**

Independent of pressure and distance, heat is transferred from the warm to the cold surface in form of electromagnetic radiation (infrared light).

\[ \dot{Q} = e_r \cdot A_1 \cdot \sigma \cdot (T_2^4 - T_1^4) \quad [6] \]

with $\sigma$ being the Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4$ and $e_r$ describing the emissivity of the surfaces. Assuming both surfaces to be made from polished stainless steel, $e_r = 0.027$.

For $\Delta T = 70 \text{ K}$ and $A_1 = 1.3 \text{ m}^2$, we find $\dot{Q} = 8.4 \text{ W}$.

We don’t increase the surface by the usual factor 2, assuming that only the projected surface counts.

The high $\Delta T$ of 70 K leads to the situation where the radiative heat transfer is of the same order of magnitude as the molecular contribution in the $10^{-3} - 10^{-4} \text{ mbar}$ range. Only eliminating the molecular contribution by a pressure reduction is therefore not effective. To reach a low heat transfer the radiative contribution needs to reduced, too. This can be achieved by inserting between the metallic walls heat screens in form of one or several metallized mylar foils, as shown in Figure 3. This is also called Multi-Layer Insulation (MLI). After a short time these foils will assume intermediate temperatures and the overall radiated heat decreases. For $n$ foils (with identical emissivity as stainless steel) one obtains

\[ \dot{Q} = e_r \cdot A_1 \cdot \sigma \cdot (T_2^4 - T_1^4)/(2(n + 1)) \quad [7] \]
In practical terms it may be an advantage to increase the number of MLI layers, e.g. to 10, and to attach it to the inner tube by means of a thin adhesive aluminium tape. This technique allows to suppress the spacer, which simplifies the process and improves pumping conductance.

Figure 4 illustrates the dependence of the heat transfer on the pressure for a SciFi distribution line of 20 m length. The dashed lines show from right to left how the heat transfer is driven by the different effects. The grey horizontal line shows the radiative heat transfer without any screens while the yellow line shows a reduction by a factor 10 by inserting 4 aluminized mylar foils.
The combination of low vacuum pressure \(10^{-4}\) mbar or lower) and a couple of MLI layers allow to reach a heat transfer of about 1 W, while without these radiation screens the heat losses would be about a factor 10 higher. The reduction of the pressure from 10^{-3} to 10^{-4} mbar would then have no impact on the heat loss.

We estimate the total heat losses to 1 W for every 20 m long line distribution line, fully dominated by radiative heat transfer. The total loss of the system should be of the order 50 – 100 W, which is negligible given that the available cooling power is in the O(10 kW) range.

**Evacuating a long tube with small diameter**

In the following we use formulae from ‘Fundamentals of vacuum technology’.

The layout of the SciFi distribution lines and manifolds requires to pump through long corrugated tubes with small diameters. The nominal pumping speed of the vacuum pump \(S\) (in l/s or m\(^3\)/h) will be reduced to an effective value

\[
\frac{1}{S_{\text{eff}}} = \frac{1}{S} + \frac{1}{C}
\]

with the conductance \(C\) calculated from the conductances of all sub-elements (orifices, bows, valves) of the system as

\[
\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_n}
\]

In the molecular regime, i.e. for vacuum pressures below about 10^{-3} mbar, the conductance of an element is pressure independent.

The conductance of a straight pipe of length \(l\) and diameter \(d\) (\(l \gg d\); \(l\) and \(d\) are given in cm), the conductance in the molecular regime is

\[
C = 12.1 \cdot \frac{d^3}{l} \quad \text{[l/s]}
\]

A SciFi distribution line consists of two concentric corrugated lines with free diameter of 35 and 21 mm, respectively. The free section is therefore \(F = \pi/4 (35^2 - 21^2) = 615\) mm\(^2\). The corresponding free diameter of a simple round pipe would be 28 mm. A 20 m long piece of this line has a conductance of \(C = 0.13\) l/s.

We consider now a system where 24 such lines are connected in parallel to a pump. The effective conductance is \(C_{24} = 24 \cdot C_{\text{single}} = 3.1\) l/s.

The so-called gas evolution

\[
Q = \Delta p \cdot V / t
\]

is the gas quantity which arises in the steady state due to outgassing of surfaces and leaks. A typical value for a non-baked system is \(3 \cdot 10^{-6}\) mbar l/s per m\(^2\) surface.

The SciFi vacuum system is estimated to have for each of the sides a total surface of 24 \(\times\) 7.5 m\(^2\) = 180 m\(^2\), corresponding to a gas evolution of \(Q = 5 \cdot 10^{-4}\) mbar l/s (per side)

The minimum required effective pumping speed to cope with the gas evolution is

\[
S_{\text{eff}} = Q/p_{\text{end}}
\]
Where \( p_{\text{end}} \) is the desired end pressure to be reached – in our case \( 1 \cdot 10^{-4} \text{ mbar} \).

The required effective pump speed is therefore \( S_{\text{eff}} = 5 \text{ l/s} \).

The required pumping speed of the pump can be calculated from

\[
\frac{1}{S} = \frac{1}{S_{\text{eff}}} - \frac{1}{C_{24}} \quad \text{[13]}
\]

However, as the total conductance \( C_{24} \) is (just a bit) smaller than \( S_{\text{eff}} \), the equation has no meaningful (positive) solution.

Instead, we assume that the system shall be evacuated by a (turbo molecular) pump with nominal pumping speed \( S = 50 \text{ (500)} \text{ l/s} \). Taking into account the conductance \( C_{24} \) leads in both cases to an effective pumping speed of \( S_{\text{eff}} \approx 3 \text{ l/s} \). The system is largely conductance constrained and the use of a pump with a larger pumping speed brings no advantage.

The expected achievable end pressure of the system is \( p_{\text{end}} = Q / S_{\text{eff}} = 1.6 \cdot 10^{-4} \text{ mbar} \), essentially independent of the chosen pumping speed.

**Choice of the pump technology and layout of the system**

The system shall achieve an end pressure in the range of \( 10^{-4} \text{ mbar} \). We therefore require a high vacuum pump with small pumping speed and sufficiently low end pressure. A turbo molecular pump appears as most suitable candidate. A pumping speed of 50 l/s is sufficient. An adequate roughing pump, e.g. a scroll pump with a pumping speed of 10 m3/h, shall provide the fore vacuum at the exit of the turbo pump.

A preliminary layout of the system is shown in Figure 5. We assume, that for reasons of redundancy the two detector sides (side A and C) will be equipped with two independent pumping systems which are connected only to the distribution lines and Novec manifolds on their respective sides.

Each subsystem takes care of 12 cooling loops, i.e. of 24 vacuum lines. It has its own vacuum pumping group; made of a scroll type primary pump (CP1, AP1) connected to a turbo pump (CP2, AP2), both groups have can be shut off by a valve (APV1, CPV1). A Pirani vacuum sensor (CPT0001, APT0001) is placed between the valve and the turbo pump and according the pressure value will define the valve operation.

The subsystem will be interconnected by a large diameter line with minimal effect on the overall conductance but separated by a valve (PV1) in order to use one vacuum pumping group as a backup of the other, in case of a pump failure or during maintenance of one of the subsystems.

The valves (CPV1, APV1) connect vacuum the pumping group to the main DN63 vacuum lines (A side and C side) and also to all cooling loop vacuum lines by means of DN25 ports and small flexibles. It remains to be decided whether every DN25 line shall have a manual isolation valve.

At the end of each cooling loop, at the detector side, a Pirani gauge is installed to observe the vacuum pressure at the end of the line. Also a Pirani pressure gauge will be place in the main DN63 vacuum line to survey the pressure at the beginning of the vacuum lines. The total number of vacuum gauges is 27.

Ideally, to cover the full vacuum range, dual Pirani/Penning probes would be preferred. The radiation environment, which is characterised by a total accumulated dose of 50 Gy, poses problems to the vacuum probes. Probes with integrated readout electronics will most likely not stand the radiation
over the full lifetime of the experiment. In addition cost arguments lead us to the use of simple Pirani probes, which below some $10^{-4}$ mbar may run in saturation (underrange), however would be fully suitable to indicate the presence of leaks in any of the lines.

The option to detach the electronic head of the compact Pirani probe and to install it in the bunker area, where the radiation levels are about 5 times lower has been considered (see Annex 2). It was demonstrated that the probe can be operated when the displaced head is electrically connected by a 3-wire cable.
Figure 5: Layout of the LHCb SciFi vacuum insulation system.
**Control System**

The Vacuum Control System will be based on PLC (Programmable Logic Controller) technology commonly used and supported at CERN. The different layers of the control system are shown in the Figure 6.

All the components included in the Field Layer: sensors (vacuum pressure gauges, switches...) and actuators (pumps, valves) will be connected to the PLC (Control Layer) containing the logic control program; executing the proper actions and generating the interlocks according to the defined and programmed conditions.

The PLC control program will follow the CERN BE-ICS control system standards called UNICOS framework (1) which allows the connection of the PLC program to the WinCC scada software used in the Supervisor Layer that in that case is the SciFi Detector Control System or DCS. The DCS operator will monitor and operate, according to defined rights, the vacuum control system from the LHCb control room. Alarms can be defined and programmed in the control system (PLC-WinCC) taking the proper actions; in addition SMS and e-mail alerts can be setup at the WinCC level. The WinCC software will also archive all the relevant data in the ORACLE data base. Furthermore there is the possibility to connect by remote desktop from outside CERN network to the WinCC scada application by means of terminal server connection.

![Figure 6 – LHCb SciFi Vacuum Control System layout](1)

(1) [http://unicos.web.cern.ch](http://unicos.web.cern.ch)
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Annex 1

Test evacuation of a 15 m long corrugated stainless steel pipe of diameter DN16

A test set-up has been prepared as shown in the figure below.

Figure 7: Test set-up.

A 15 m long corrugated stainless steel pipe of a free section DN16 was evacuated by a turbo molecular pump \( S = 50 \text{ l/s} \) behind a scroll pump \( (30 \text{ m}^3/\text{h}) \). The surface of the pipe, taking account of the corrugated shape, is about \( 1.5 \sim 2 \text{ m}^2 \).

The pressures were measured at the beginning and end of the 15 m long section. The pressure evolution is shown in the figure below.

Figure 8: Pressure versus time.

The pressure at the end of the line drops within 1 day to about \( 3 \cdot 10^{-4} \text{ mbar} \) and tends towards an ultimate pressure of about \( 2 \cdot 10^{-5} \text{ mbar} \).

The conductance of the pipe is \( 0.0027 \text{ l/s} \). The effective pumping speed of the turbo pump \( S_{\text{eff}} \) assumes the same value as the pipe conductance.

The gas evolution \( Q = S_{\text{eff}} \cdot p_{\text{end}} \) of the system is calculated as \( 5.5 \cdot 10^{-8} \text{ mbar l/s} \) or \( 3 \cdot 10^{-8} \text{ mbar l/s per m}^2 \).
The company Leybold GmbH\textsuperscript{1}, with which we entered in discussions about the required vacuum systems, offered to perform a simulation of the pump down time for the above set-up. As shown in Fig. 9, the set-up consists of ten 1.5m long segments of straight (non-corrugated) DN16 pipes. In order to simulate the degassing of the surface, small vacuum chambers are placed between any 2 segments. Every chamber represents a surface of 0.07 m\textsuperscript{2} and a desorption rate of 1·10\textsuperscript{-7} mbar·l/s.

In the simulation the characteristics of the pumps were very close to the real ones, i.e. a 50 l/s turbo molecular pump and a 30 m\textsuperscript{3}/h scroll pump.

\textbf{Figure 9:} Set-up for the simulation by Leybold GmbH, Germany.

After a pump time of 120 h, the simulated system reaches in the first chamber (close to the pumps) a pressure of 3.7·10\textsuperscript{-6} mbar and in the last chamber a pressure 2·10\textsuperscript{-5} mbar, both values in good agreement with the measured data. It should be stressed that the result depends crucially on the assumed desorption rate.

The simulation was also used to verify a conclusion which we had drawn from the analytical calculations, namely that the pump down time is fully governed by the conductance of the system and little affected by the nominal pumping speed.

\textsuperscript{1} F. Hall and O. Wasser, Leybold GmbH, Cologne, Germany.
Annex 2

Considerations related to radiation and magnetic field environments

1.) Use of Leybold compact Pirani sensors (or equivalent models) in ionising radiation

When mounted on the Novec manifold the Pirani sensor will accumulate an ionising dose of 50 Gy over the lifetime of the experiment. As the electronics of this sensor is made from conventional components, it will fail well before the lifetime of the experiment. Even though not foreseen by the supplier, the electronic head of the sensor can be removed and operated at a remote location, if sensor part and electronics are connected by a 3-wire cable. This would allow to operate the electronics in the bunker, where the radiation levels are about 5 times lower. A test has been performed with a 10 m long cable which showed that the pressure reading was only very little affected by the resistance of the additional cable. We believe that this scheme can be implemented for the SciFi detector.

2.) Use of turbo molecular pumps in a magnetic field

Turbo molecular pumps with rotors spinning at high frequencies should not be operated in magnetic fields exceeding certain thresholds, which depend on the relative orientation of field and rotor axis. The Leybold TMP050 pump can operate in a field of up to 10 mT if field and rotor are perfectly aligned. For other orientations the field should not exceed 5 mT.

The field values in the LHCb bunker, where the pumps are to be installed, are in the range of 5-10 mT (according to simulations, not yet confirmed by measurements).

It is therefore required to shield the turbo pumps from the magnetic field by simple iron cylinders (not steel). The iron should have a thickness of about 3 mm and the length of the tube should be three times its diameter.

In case the turbo pump is being used with an air cooler, the fan must be included in the cooling shield, which increases the diameter and length unpractically. In general, for operation in magnetic field, the water cooled option is recommended.