VACUUM PERFORMANCES ESTIMATION OF THE CRYOSORBERS TO BE INSTALLED IN THE LHC LSS

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The installation of cryosorbers is foreseen in the LHC cryogenic elements operating at 4.5 K. Several cryosorbers have been studied since a few years; however, the vacuum design performances were not clearly stated. In this note, the design criteria and the derivation of the required vacuum performances of such cryosorbers are given. Finally, the minimum sticking probability and the required capacity of these cryosorbers are evaluated.
1- Introduction

In the LHC Long Straight Section (LSS), some elements operate at 4.5 K. The cryosorbers are installed in these 4.5 K cryogenic components to ensure the required capacity and pumping speed. It is assumed that the cryosorbers are expected to operate in the 5 to 20 K range (however, unexpected temperature increase up to 25 K is possible). The cryosorbers are installed onto supports which are thermalised onto the beam screen. A preliminary estimation indicated that 4 ribbons of 5 mm each could be installed onto the beam screen. So, the cryosorber specific surface is \( \sim 200 \text{ cm}^2/\text{m} \) [1, 2, 3].

Since a few years, several studies with different cryosorbers materials have been performed [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Cryosorbers based on metallic or active charcoal technology in pellets or woven fibres forms have been studied. Some cryosorbers, such as the activated charcoal exhibit large vacuum performances, others, such as porous copper exhibit poor vacuum performances. Over the years, the evolution of the understanding of the LHC behaviour need to re-actualise the vacuum inputs. The purpose of this note is to define the required capacity for the design pressure and the required pumping speed of the cryosorber to be installed in the LHC LSS.

2- Pumping speed

As a design principle, the minimum pumping speed of the cryosorber should be at most as large as the slot pumping speed of the arcs. In this case, the pressure in the LSS would be twice the arc pressure for equal gas load in the arcs and in the LSS.

2.1 Slots pumping speed

The beam screen specific surface, \( A_{BS} \), and pumping speed, \( S_{BS} \), is given by equation (1) where \( \sigma \) is the sticking probability of the beam screen. The beam screen diameter \( d \) is expressed in [cm].

\[
A_{BS} = 100 \pi d; \quad \left[ \text{cm}^2/\text{m} \right] \\
S_{BS} = 3.63 \sigma A_{BS} \sqrt{\frac{T}{M}}; \quad \left[ \ell \text{s}^{-1}.\text{m}^3 \right]
\]

The beam screen is perforated with slots, its transparency, including capture factor, is \( h \). The holes specific pumping speed, \( S_h \), is given by equation (2) where \( S \) denotes the maximum pumping speed.

\[
S_h = h S; \quad \left[ \ell \text{s}^{-1}.\text{m}^3 \right]
\]

2.2 Cryosorber pumping speed

The cryosorber specific surface, \( A_{Cryo} \), and its pumping speed, \( S_{Cryo} \), are given by equation (3) where \( \sigma_{Cryo} \) is the sticking probability of the cryosorber. For a cryosorber of cylindrical type, its diameter is \( d_{Cryo} \) (in [cm]). If the cryosorber is flat, its width is \( w_{Cryo} \) (in [cm]).

\[
A_{Cryo} = 100 \pi d_{Cryo} \quad \text{or} \quad 100 w_{Cryo}; \quad \left[ \text{cm}^2/\text{m} \right] \\
S_{Cryo} = 3.63 \sigma_{Cryo} A_{Cryo} \sqrt{\frac{T}{M}}; \quad \left[ \ell \text{s}^{-1}.\text{m}^3 \right]
\]

To satisfy the design principle, the cryosorber pumping speed should be a factor, \( f \), larger than the holes pumping speed. From the above equations, the required area of the cryosorber could be computed.

\[
S_{Cryo} = f S_h \\
\Rightarrow A_{Cryo} = f \frac{h A_{BS}}{\sigma_{Cryo}}; \quad \left[ \text{cm}^2/\text{m} \right]
\]
In the simplest case of 4 rows of cryosorbers installed onto the beam screens, the required cryosorber diameter and width of each row are:

\[
d_{\text{Cryo}} = \frac{1}{4} \frac{f h d}{\sigma_{\text{Cryo}}}; \text{[cm]}
\]

\[
w_{\text{Cryo}} = \pi d_{\text{Cryo}}; \text{[cm]}
\]

(5)

### 2.3 Application

For a beam screen with a transparency, \( h \), of 2%, a diameter, \( d \), roughly approximated to 5 cm and a safety factor, \( f \), of 1, the following table gives the minimum diameter and width for a cryosorber as a function of the \( \text{H}_2 \) sticking probability. Due to space limitation, values in italic are unrealistic.

**Table 1** Minimum diameter and width of a cryosorber, as a function of the \( \text{H}_2 \) sticking probability, to satisfy the design principle.

<table>
<thead>
<tr>
<th>( \sigma_{\text{Cryo}} )</th>
<th>0.01</th>
<th>0.05</th>
<th>0.08</th>
<th>0.1</th>
<th>0.15</th>
<th>0.5</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_{\text{Cryo}} ) [cm]</td>
<td>2.50</td>
<td>0.50</td>
<td>0.31</td>
<td>0.25</td>
<td>0.25</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>( W_{\text{Cryo}} ) [cm]</td>
<td>7.85</td>
<td>1.57</td>
<td>0.98</td>
<td>0.78</td>
<td>0.52</td>
<td>0.16</td>
<td>0.08</td>
</tr>
</tbody>
</table>

For the practical cases the minimum required sticking probability is given below:

1) In the four rows installation case, a cylindrical (flat) type of cryosorber of 3 mm diameter (5 mm width) having a hydrogen sticking probability of at least 8% (15%) should be used.

2) In the two rows installation case, a cylindrical (flat) type of cryosorber of 3 mm diameter (5 mm width) having a hydrogen sticking probability of at least 16% (30%) should be used. This statement assumes that the conductance limitation between the beam screen and the cold bore is negligible with respect to the slots pumping speed.

### 3- Cryosorber capacity

As a design principle, the cryosorbers are regenerated during the shutdown period. The required capacity of the cryosorbers is estimated following a first operational period in LHC without electron cloud and a second operational period in LHC with electron cloud. Each year of operation is defined as 200 days with 100% operation efficiency. The capacity is defined as the surface coverage where the vapour pressure equals \( 10^{-8} \) Torr i.e. when the 100 h life time due to nuclear scattering is reached.

#### 3.1 Operation under synchrotron radiation

Below the electron cloud threshold, the beam current is about 1/3 of nominal current, therefore the average photon flux in the LSS is \( 1.7 \times 10^{15} \) ph/m/s [11]. After one year, the accumulated dose is \( 3 \times 10^{22} \) ph/m. To compare with the gas load in the LHC arcs, the calculation is performed with 45 eV critical energy. However, an average estimation of the critical energy in the LSS is about 18 eV, thus, if the photon stimulated desorption (PSD) behaviour at cryogenic temperature is similar to room temperature, the estimated gas load below could be overestimated by a factor three [12].

At a critical energy of 45 eV, the variation of the primary desorption yield of \( \text{H}_2 \) measured at 10 K is given by equation (6) where \( \eta_0 = 5 \times 10^{-5} \) H\(_2\)/photon, \( D_0 = 2 \times 10^{22} \) photons/m and \( a = 0.6 \) [13].
\[ \eta(D) = \eta_0 \left( \frac{D}{D_0} \right)^{-a} \]  \hspace{1cm} (6)

The gas load, \( Q \), is the integral of equation (6):
\[ Q(D) = \frac{\eta_0 D_0}{1-a} \left[ \frac{D}{D_0} \right]^{1-a} - 1 + \eta_0 D_0 \]  \hspace{1cm} (7)

As an example for the first year of LHC operation, Table 2 shows the primary desorption yield, the accumulated dose, the \( \text{H}_2 \) molecular flux and the gas load after 2, 20 and 200 days of operation.

Table 2  Primary desorption yield, photon gas, gas flux and gas load after 2, 20 and 200 days with synchrotron radiation the first year of LHC operation.

<table>
<thead>
<tr>
<th></th>
<th>( \eta ) ( \text{(H}_2/\text{ph}) )</th>
<th>( D ) ( \text{(ph/m)} )</th>
<th>( \eta \Gamma ) ( \text{H}_2/\text{m/s} )</th>
<th>( Q ) ( \text{H}_2/\text{cm}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 days</td>
<td>( 5 \times 10^{-5} )</td>
<td>( 3 \times 10^{20} )</td>
<td>( 9 \times 10^{10} )</td>
<td>( 9 \times 10^{12} )</td>
</tr>
<tr>
<td>20 days</td>
<td>( 5 \times 10^{-5} )</td>
<td>( 3 \times 10^{21} )</td>
<td>( 9 \times 10^{10} )</td>
<td>( 9 \times 10^{13} )</td>
</tr>
<tr>
<td>200 days</td>
<td>( 3 \times 10^{-5} )</td>
<td>( 3 \times 10^{22} )</td>
<td>( 5 \times 10^{10} )</td>
<td>( 8 \times 10^{14} )</td>
</tr>
</tbody>
</table>

After the first year of operation, in the LSS, the primary desorption yield equals \( 3.0 \times 10^{-5} \) \( \text{H}_2/\text{ph} \), the accumulated dose equals \( 3 \times 10^{22} \) \( \text{ph/m} \) and \( 8 \times 10^{14} \) \( \text{H}_2/\text{cm}^2 \) are desorbed from the beam screen. Assuming a beam screen diameter of 5 cm, the corresponding specific gas load is \( 1 \times 10^{18} \) \( \text{H}_2/\text{m} \). During the shut down, this gas load will be pumped out while the cryosorber will be regenerated.

The following years, at nominal parameters i.e. \( 5 \times 10^{15} \) \( \text{ph/m/s} \), the accumulated dose will be \( 9 \times 10^{22} \) \( \text{ph/m} \), taking into account cleaning during the first year exposure, the primary desorption yield equals \( 1.2 \times 10^{-5} \) \( \text{H}_2/\text{ph} \) and \( 1 \times 10^{18} \) \( \text{H}_2/\text{m} \) (\( 9 \times 10^{14} \) \( \text{H}_2/\text{cm}^2 \)) are desorbed during the second year. This amount of gas load will decrease during the following year thanks to the vacuum cleaning.

So, if ~ 200 cm\(^2\)/m of cryosorbers are installed in the LSS, a cryosorber capacity of \( 10^{16} \) \( \text{H}_2/\text{cm}^2 \) would be sufficient to pump \( 2 \times 10^{18} \) \( \text{H}_2/\text{m} \) (\( 1.3 \times 10^{15} \) \( \text{H}_2/\text{cm}^2 \)) desorbed from the beam screen which is a factor two larger than the predicted gas load.

### 3.2 Operation under electron cloud

We assume that 2 W/m could be dissipated onto the LSS beam screens i.e. a flux of \( 4 \times 10^{16} \) e/m/s for a mean energy of the cloud of 300 eV. The mean energy of the electron cloud observed in the SPS is measured to be 300 eV in dipole field and 180 eV in field free regions [14]. For the LHC, with a maximum of the secondary electron yield of 1.1, the simulated mean energies of the electron cloud are 249 eV, 65 eV and 48 eV in quadrupole field, dipole field and field free respectively [15]. Since the PSD yield is smaller than the electron stimulated desorption (ESD) yield, the gas load due to PSD is negligible compared to the gas load due the to electron cloud.

In the LSS, the electron cloud is developed in dipole or quadrupoles fields, thus, only a part of the chamber could desorb the \( \text{H}_2 \) under the electron impact. For simplicity, we assume that 50\% of the vacuum chamber will be subjected to the ESD. So, for a beam screen diameter of 5 cm, the electron flux is \( 5 \times 10^{13} \) e/cm\(^2\)/s. Since the time to perform the conditioning is not known, ESD is assumed for a year (200 days), during this period the accumulated dose is \( 9 \times 10^{20} \) e/cm\(^2\) i.e. 1.5 C/mm\(^2\).

The behaviour of the ESD at cryogenic temperature is not known. We will base our estimation assuming an exponential dependence similar to equation (6) for 3 cases. The first case is based on measurements performed at room temperature (RT) with 300 eV electrons [16]. The second case simulates the decrease of the primary desorption yield observed at cryogenic temperature with PSD.
Finally, the third case simulates a lower cleaning rate as observed again in PSD experiments at cryogenic temperature [19]. Table 3 shows the parameters used for the simulation of the three cases.

**Table 3** Parameters used in the calculations to describe the behaviour of the ESD at cryogenic temperatures for three different cases. The first case is based on RT experimental data, the second and third cases are extrapolated data at cryogenic temperature.

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_0$</td>
<td>2 $10^{-1}$</td>
<td>2 $10^{-2}$</td>
<td>2 $10^{-2}$</td>
</tr>
<tr>
<td>$D_0$</td>
<td>3 $10^{14}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>0.47</td>
<td>0.47</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Using the above parameters and the equation (7), the primary ESD yield and the number of desorbed H$_2$ after an accumulated dose corresponding to a year of operation could be computed. Table 4 shows the results of the computation and demonstrate that the number of desorbed H$_2$ is in the range $0.3 - 2 \times 10^{20}$ H$_2$/m thereby underlining the necessity to know in details the behaviour of ESD at cryogenic temperature. From RT measurements, it is known that the ESD yield decrease with decreasing the electron energy [16]. So, for a mean energy of the cloud of 100 eV, the expected gas load could be increased by a factor two.

**Table 4** Calculated primary ESD yield and number of desorbed H$_2$ after a dose corresponding to one year of operation with an electron cloud dissipating 2 W/m in the LSS beam screens. The first case is based on RT experimental data, the second and third cases are extrapolated data at cryogenic temperature.

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$ (H$_2$/e)</td>
<td>2 $10^{-4}$</td>
<td>2 $10^{-5}$</td>
<td>1 $10^{-4}$</td>
</tr>
<tr>
<td>Desorbed (H$_2$/m)</td>
<td>2 $10^{20}$</td>
<td>3 $10^{19}$</td>
<td>2 $10^{20}$</td>
</tr>
</tbody>
</table>

When about 200 cm$^2$/m of cryosorbers are installed in the LSS, the required capacity of a cryosorber is the range $10^{17} - 10^{18}$ H$_2$/cm$^2$. This gas load is several orders of magnitude larger than the gas load due to synchrotron radiation. Therefore, the required cryosorber capacity is dominated by the ESD of the beam screen whose long term behaviour with electron dose is known neither during LHC operation nor in the laboratory. It should be stressed that $2 \times 10^{20}$ H$_2$/m is equivalent to the removal of 160 monolayers of H$_2$ ($2 \times 10^{17}$ H$_2$/cm$^2$) from the beam screen. This number is only a factor two larger than experimentally observed in RT experiments where the exposed dose was limited to 350 (W/m).h i.e. 7 days of operation with 2 W/m dissipated onto the beam screen [16]. Assuming that the ESD behaviour is similar at RT and cryogenic temperature, a pumping capacity of $10^{18}$ H$_2$/cm$^2$ is required.

For the purpose of the experimental simulations in the laboratory, it is interesting to derive the molecular flux expected in the LHC as a function of the number of days of operation. Table 5 shows the H$_2$ flux expected after 2, 20 and 200 days of LHC operation for the three studied cases.

**Table 5** Molecular flux H$_2$/m/s expected in the LSS under ESD as a function of the days of operation for three different cases. The first case is based on RT experimental data, the second and third cases are extrapolated data at cryogenic temperature.

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 days</td>
<td>7 $10^{13}$</td>
<td>7 $10^{12}$</td>
<td>3 $10^{13}$</td>
</tr>
<tr>
<td>20 days</td>
<td>2 $10^{13}$</td>
<td>2 $10^{12}$</td>
<td>1 $10^{13}$</td>
</tr>
<tr>
<td>200 days</td>
<td>7 $10^{12}$</td>
<td>7 $10^{11}$</td>
<td>6 $10^{12}$</td>
</tr>
</tbody>
</table>
4- Conclusions

The vacuum requirements for the cryosorbers to be installed in the LHC LSS have been derived according to the current knowledge of the vacuum behaviour in the LHC. These requirements shall be met in the temperature range of cryosorber operation.

As a design principle, the minimum sticking probability of the cryosorber provides a pumping speed at least equal to the arc slot pumping speed. Thus, for a similar gas load in the LSS and in the arcs, the pressure in the 4.5 K elements of the LSS will be twice the pressure of the arcs. The minimum sticking probability is defined for two practical cases:

1) Assuming the installation in four rows, a cylindrical (flat) type of cryosorber of 3 mm diameter (5 mm width) having a hydrogen sticking probability of at least 8 % (15 %) should be used.

2) Assuming the installation in two rows, a cylindrical (flat) type of cryosorber of 3 mm diameter (5 mm width) having a hydrogen sticking probability of at least 16 % (30 %) should be used.

As a design principle, the regeneration of the cryosorbers is foreseen during the shutdown. Thus, the required cryosorber capacity is defined by the yearly gas load. The cryosorber capacity is defined as the surface coverage where the vapour pressure equals $10^{-8}$ Torr. In the practical cases derived below, it is assumed that four rows of 5 mm width i.e. 200 cm$^2$/m of cryosorbers are installed in the LSS.

A cryosorber capacity of $10^{16}$ H$_2$/cm$^2$ would be sufficient to pump twice the yearly gas load due to PSD. In this case, the pumped quantity is $2 \times 10^{18}$ H$_2$/m i.e. an equivalent of $1.3 \times 10^{15}$ H$_2$/cm$^2$ desorbed from the beam screen.

A cryosorber capacity between $10^{17}$– $10^{18}$ H$_2$/cm$^2$ is required to pump the yearly gas load due to ESD. During electron activity, when the electron cloud dissipates 2 W/m onto the beam screen, the gas load is dominated by ESD. But, due to uncertainties in the conditioning mechanism in the LHC and uncertainties of the ESD yield at cryogenic temperature, an accurate prediction of the required cryosorber capacity cannot be made.

It is expected that the above defined quantities would help to define the best suitable cryosorber for the LHC LSS. Assuming the installation of 200 cm$^2$/m of cryosorber, a sticking probability of ~ 15 % will ensure that the pressure in the 4.5 K elements on the LSS will be less than twice the pressure in the arcs. Based on a dissipated power by the electron cloud of 2 W/m and a mean electron energy of 300 eV, a pumping capacity of $10^{17}$– $10^{18}$ H$_2$/cm$^2$ will ensure the pumping of the gas load produced during a year (200 days) of operation with 100 % efficiency. The price to pay to install a cryosorber with a smaller sticking coefficient than the one defined above is to increase the specific surface of cryosorber. Similarly, when installing a cryosorber with a capacity smaller than the one defined above a solution is to increase the specific surface of the cryosorber and / or allow for the regeneration of the cryosorbers during the operational year.
5- References


