Calculation of the vacuum system for the new RFQ cooler and buncher at ISOLDE

Ivan Podadera, CERN AB-OP-ISO

March 31, 2003

Abstract

This document contains the calculations for a first attempt to design the suitable vacuum system for the RFQ cooler and buncher due to install at ISOLDE facility at CERN. This system is chosen to take the pressure from the medium vacuum (0,1 mbar) inside the RFQ cooler cavity up to the high vacuum (10^{-7} mbar) for the beam line using three turbomolecular pumps.

Contents

1 First considerations

Firstable, it could be interesting to describe a bit how the RFQ cooler works. To run this kind of facilities we must use a gas inside a RFQ cavity that helps to cool the ion beam. The theoretical calculations show the ideal work pressure for this gas is around 0,1 mbar. So, if one thinks that the high vacuum pressure inside the main beam line has to be around 10^{-7} mbar, one needs some system to pump the gas and avoid that the gas leaking from the RFQ cavity through the entry and out holes come into the high vacuum section.

The system here considered is composed of three turbomolecular pumps. The first of that is placed at the section between the injection and ejection electrodes, and pump the most part of the gas from the RFQ cavity. The pressure calculated in this cavity is around 10^{-3} mbar. The second and third pump are placed between the ground and injection electrodes and between the ejection and ground electrodes, respectively. These are the pumps that take the pressure up to the high vacuum (10^{-7} mbar), and normally have a less pumping speed that the main pump. In the next sections, the results for the vacuum system calculated will be presented.

For safety reasons, it should be mentioned that the number of pumps has been doubled even though this option is more expensive. For the first simplified calculations this item doesn't affect very much.

2 Theoretical pumps calculations

The first consideration that has to be made when we construct a gas pumping system is the type of flow what one is working with (viscous, molecular or Knudsen flow). This implies to calculate the Knudsen number in every section of our system and to do it one needs to calculate first the mean free path of the gas (helium in this case).

The mean free path of the gas is calculated in the first sheet (Geometry and other parameters) of the Excel's file "Vacuum system.xls". The worst case (mean free path lower) will be inside the RFQ cavity where the gas pressure is greater. It has been calculated for a inner diameter between electrodes of 40 mm and it turns out to be around 2 mm. The data used to calculate it is found in [2]. First, a table with the mean free path of some gases at 25 C and 10^{-3} Torr is used. This value has to be extrapolated now to our enviromental conditions (20 C and 0,1 mbar inside the RFQ cavity) using:

$$\lambda(T_2, p_2) = \lambda(T_1, p_1)(T_2/T_1)(p_1/p_2)$$

that relate the mean free path in a two different conditions of temperature and pressure, (T_1, p_1) and (T_2, p_2). In this case $T_1 = 298K$, $p_1 = 10^{-3}Torr$, $T_2 = 298K$ and $p_2 = 0,1mbar$. The formula results from relating two conditions in [2] formula:

$$\lambda = 2,33x10^{-20}T/(\xi^2 P)(cm)$$

where ξ is the diameter of the gas molecule in cm.

It's possible to find out some similar results using the figures in [3]. In this case, the mean free path is already given at 20 C, and one only has to change the pressure. Once one has calculated the mean free path it can be seen that one works with intermediate or Knudsen flow. According to [2] it has to be applied some different equations for this flow but one will approximate the flow to a molecular flow and will apply the equations for this kind of flow. To calculate the parameters of the RFQ vacuum system the equations in [1] have been used. There, the throughput for the RFQ cooler cavity is approximated by:

$$Q \approx 4\frac{r_0^3}{L}P$$

where r_0 is the radius between electrodes, L is the half of the length of the cavity and P is the pressure in the middle of the cavity.

The conductance of the RFQ cavity will be the throughput divided by the pressure:

$$C_{RFQ} = 4\frac{r_0^3}{L}$$

The conductances in the holes can be calculated with:

$$C_{hole} = 0,3d^2$$

where d is the diameter of the hole.

For our system we can imagine that we have two conductances in parallel (entry and out of the RFQ cavity). Every one of this conductances are in series with the RFQ cavity conductance. So, the final conductance is:

$$C_1 = C_{entry} + C_{out}$$

where

$$C_{entry} = ((1/C_{RFQ}) + (1/C_{entryhole}))^{-1}$$

and

$$C_{out} = ((1/C_{RFQ}) + (1/C_{outhole}))^{-1}$$

The throughput will be the conductance multiplied by the pressure inside the cavity. This would give us the throughput for the pump 1 if the cavity were closed, but there is another two conductances for the holes towards the pumps 2 and 3.

For Pump 1, this conductances will be as leaks of the system so:

$$C_{pump1} = C_1 - C_{injection} - C_{ejection}$$

where $C_{injection}$ and $C_{ejection}$ are the conductances of the injection and ejection electrodes respectively.

This would be if the pressure inside the cavity and the intake pressure of Pump 1 were the same. How it's different, the throughput of Pump 1 will be:

$$Q_1 = C_1 P_{RFQ} - (C_{injection} + C_{ejection}) P_2$$

where P_{RFQ} is the pressure inside the RFQ cavity and P_2 the intake pressure of Pump 1. So, the intake pressure of Pump 1 will be:

$$P_1 = \frac{C_1 P_{RFQ}}{C_{injection} + C_{ejection} + S_{p1}}$$

where S_{p1} is the pumping speed of the pump chosen as Pump 1. Once one has obtained the value of this pressure have to check in the catalog if with this pressure one has really this pumping speed (for low values of pressure the pumping speed decreases a lot).

The throughput for Pump 2 and 3 are calculated multiplying the conductance $C_{injection}$ and $C_{ejection}$ by the intake pressure of Pump 1. Then, the intakes pressures of pumps 2 and 3 are:

$$P_{2,3} = \frac{C_{injection,ejection} P_1}{S_{p2,p3}}$$

where $S_{p2,p3}$ are the pumping speeds of the pumps chosen.

Finally, it has been calculated the time that one would spend in consuming one bottle of 200 l of helium at a pressure of 200 bar. To make this calculation the problem is to chose the proper throughput. I'm not sure if we should consider the conductance of all the RFQ cavity or only that a half of it.

Intake pressure for Pump 1	$1,5 \cdot 10^{-3}$ mbar
Intake pressure for Pump 2	$5,93 \cdot 10^{-6}$ mbar
Intake pressure for Pump 3	$4,17 \cdot 10^{-6}$ mbar

Table 1: Final pressures

3 Calculations

For our entreaties of pressure and pumping speed, it seems that the most proper kind of pumps are the turbomolecular pumps. CERN works with two types of pumps Alcatel and Pfeiffer that are the only that guarantee the support for radioactive environments. Besides, Pfeiffer is the only that provides turbomolecular pumps with the enough pumping speed for our entreaties (see [4]).

Once we have chosen the vendor, we must choose the pump. In the case of Pfeiffer we can choose among a lot of differents turbomolecular pumps, joined in two main groups: with magnetic bearing, and classical. The magnetic pump provide us less vibration problems but their cost is two times greater. In the sheet Pfeiffer Magnetic Pumps we have done the calculations for these kind of pumps but in principle we center ourselves in the use of the classical turbomolecular pumps. Among the Compact Pumps, we can also choose a lot of models. For a first aproximation, it's been decided to take the highest pumping speeds pumps that Pfeiffer provide us. The calculations with these pumps can read in the sheet Pfeiffer Compact Pumps. The main problem is, besides the greater cost, the huge dimensions of this pump and its horizontal placement. A order of these dimensions is done in the sheet.
For the first attempt, 2 Pfeiffer pumps with 900 l/s helium pumping speed for the main pump, and 4 Pfeiffer pumps (2 before and 2 after) wuth 500 l/s helium pumping speed will be used.
The results applying the geommetry included in the file "Vacuum system.xls" and the formulas of the last section are:
For the calculation of the helium consumption, a standard bottle of 200 l of helium stored at 200 mbar has been used. Taking into account that the throughput inside the cavity is 321,6 Pal/s, then the time to consume all the bottle is 144 days. Or, from another point of view, we use 3 bottles every 2 years.

3.1 Breakdown of pumps

When all the pumps are working fine, the pressures that one gets are as mentioned above. But usually in daily work, there can be problems and breakdowns of the pumps. That affects obviously the vacuum system and the pressures reached, since one or more pumps failed the pumping speed

Intake pressure for Pump 1	$1,5 \cdot 10^{-3}$ mbar
Intake pressure for Pump 2	$1,18 \cdot 10^{-5}$ mbar
Intake pressure for Pump 3	$4,17 \cdot 10^{-6}$ mbar

Table 2: Final pressures with breakdown of one of the two injection pumps

Intake pressure for Pump 1	$3 \cdot 10^{-3}$ mbar
Intake pressure for Pump 2	$1,18 \cdot 10^{-5}$ mbar
Intake pressure for Pump 3	$8,3 \cdot 10^{-6}$ mbar

Table 3: Final pressures with breakdown of one of the two main pumps

is decreased. Hence, the pressures obtained in the vacuum system will be higher. This is the reason that one thinks about doubling the number of pumps in all the sections of the system, to keep the pressure at least to end the experiment.
Here one is going to concentrate only in the case that the breakdown occurs in one of pumps since the probability that two pumps failed at the same time is very slow. To study the effect of doubling the number of pumps, one is going to calculate the pressures with the breakdown of one pump for every one 3 sections (injection, main section and extraction) is produced with 3 or 6 pumps.

3.1.1 6 pumps

Injection For the breakdown of one pump at the injection side, the pumping speed (with the same Pfeiffer pumps used in the normal vacuum system calculation above) will change from 1000 l/s to 500 l/s. The final pressures are showed in the table below.

Main pumping section For the breakdown of one pump at the main pumping section side, the pumping speed (with the same Pfeiffer pumps used in the normal vacuum system calculation above) will change from 1800 l/s to 900 l/s. The final pressures are showed in the table below.

Extraction For the breakdown of one pump at the extraction side, the pumping speed (with the same Pfeiffer pumps used in the normal vacuum system calculation above) will change from 1000 l/s to 500 l/s. The final pressures are showed in the table below.

Intake pressure for Pump 1	$1,5 \cdot 10^{-3}$ mbar
Intake pressure for Pump 2	$5,93 \cdot 10^{-6}$ mbar
Intake pressure for Pump 3	$8,34 \cdot 10^{-6}$ mbar

Table 4: Final pressures with breakdown of one of the two main pumps

Intake pressure for Pump 1	$0,42$ mbar
Intake pressure for Pump 2	$1,82 \cdot 10^{-3}$ mbar
Intake pressure for Pump 3	$1,2 \cdot 10^{-3}$ mbar

Table 5: Final pressures with breakdown of the main pump

Conclusions When one works with 6 pumps, the worst result (highest pressures) is obtained if one of the main pumps is broken down.
The results for injection and extraction pumps breakdown are very similar and they depend on the geommetry of the holes (injection and extraction electrodes).

3.1.2 3 pumps

For this case, one will only consider the case of the breakdown of the main pumps because the breakdown of the pumps at injection or extraction side would need a most careful study and the knowledge of the vacuum system in the whole beam line.

Main pumping section For the breakdown of one pump at the extraction side, the pumping speed (with the same Pfeiffer pumps used in the normal vacuum system calculation above) will change from 1100 l/s to no pumping. The final pressures are showed in the table below.

3.1.3 Conclusions

For safety reasons, they can be seen that is better to work with 6 pumps because in case one of the pumps breaks down, the experiment could keep on up to the end even though the pressures are higher.
In case one uses only 3 pumps the most probably is that one should stop suddenly the experiment and change the pump before restarting.

References

[1] Moore, R.B. (1998) "Buffer gas cooling of ion beams." Unpublished notes.

[2] Roth, A. (1990) *Vacuum technology*, North-Holland, Amsterdam.

[3] Leybold Vacuum (2001). *Products and reference book*,Cologne.

[4] Pfeiffer(2002). *Catalog 2002-2004, Vacuum technology.*