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CRYOPUMPING FOR CYCLOTRONS

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Summary

High pumping speeds and high pumping capacities are required for the vacuum systems of large cyclotrons. Only cryopumps and getter pumps safely provide these features. The best pumping system for a particular machine can be designed only upon fixing size, operating pressure, pumpdown time, mechanical design and materials of the latter. The criteria for the selection of the pumps are discussed here and the solutions adopted for a few existing machines reviewed. The vacuum design and performance of VICKSI, which makes use of condensation cryopumps developed at CERN, are described in detail.

1. Introduction

Interactions of charged particles with neutral gas molecules may result in an exchange of charge and consequent loss of the accelerated ions. To minimize this process, operating pressures in the range from 5×10^{-6} torr to 1×10^{-7} torr are usually specified for cyclotrons. Pressures as low as 2 to 5×10^{-8} torr are even required for operation with heavy ions. Since the cross-section for charge exchange increases with the atomic number of the residual gas species, not only the total pressure but also the composition of the residual gases is of importance. The figures above, which are valid for N_2 gas, can be raised by a factor 5 if the ions circulate in an atmosphere of H_2. Since the sensitivity of the ionization pressure gauges, which are commonly used for monitoring such pressures, also shows a similar dependence on the mass number of gases (being 2 to 3 times lower for H_2 than for N_2), in first approximation the specified pressures can be considered as direct gauge readings.

In a vacuum system, after the very initial pumpdown and in absence of leaks, the pressure is defined at any moment by the ratio of the rate of gas release from the walls of the system to the available pumping speed. The rate of wall degassing becomes very low and independent of time upon baking the system at temperatures above about 150°C. Typically, for metal surfaces after bakeout, it is lower than 10^{-11} torr $\ell\ s^{-1}\ cm^{-2}$. For unbaked surfaces, degassing is much higher and decreases with time. Cyclotrons of large dimensions cannot be baked, mainly for mechanical reasons. Therefore, the characteristics of their vacuum systems are defined not only by the chosen operating pressures, but also by the required pumpdown times. These times normally range from 10 to 50 hours. Upon fixing the value of the operating pressure and the pumpdown time, the vacuum engineer must take, basically, two decisions. First, he must compromise between quality of the building materials and/or surface treatments and size of the pumps. Second, he must select the type(s) of pump to be used for providing the required pumping speed.

2. Materials

The rates of degassing of the materials which are suitable for vacuum applications vary over many orders of magnitude. Since the gas molecules which are released at room temperatures from unbaked metals mainly come from the surfaces, where they are physisorbed, not only the chemical composition but also the surface conditions of materials affect the rate of degassing. Furthermore, the pressure evolution during the pumping cycle is strongly affected by the gas composition of the atmosphere to which the surfaces were exposed before pumping and by the duration of the exposure. Finally, pumping results in depleting the surfaces from physisorbed gases and consequently in a reduction of the degassing rate. The picture is still more complicated for organic materials, for which also sublimation, permeation and degassing from the bulk may play an important role.

Probably because of this complexity, the spread of the data available in the literature on this subject is large (for a good critical review, see ref. 1). In addition, the usefulness of these data is often strongly limited by the lack of definition of one or more of the parameters which play a role in the process. However, by combining published data, verbal information from different laboratories and direct experience obtained at CERN, the following statements can be made:

i) during the first 100 h of pumping, degreased metal surfaces mainly desorb water vapour, at a rate which decreases approximately proportionally to the reciprocal of time.[1] The rate of release of gases other than water does not exceed usually 10%.

ii) for stainless steel, the total degassing rate ranges from 3×10^{-9} to 3×10^{-10} torr $\ell\ s^{-1}\ cm^{-2}$ after 10 to 15 h pumping.[1] The lower figures are relative to samples which were degreased, pumped for many days and exposed for a short time (a few hours) to dry nitrogen atmosphere.

iii) between 100 and 1000 h of pumping an almost constant degassing rate is achieved, to which the contribution of H_2 is larger than initially (up to 50% in some cases).

iv) other metals, like Al and Cu, show a similar behaviour.[1] In contrast, mild steel may present a much larger degassing rate (10^{-8} torr $\ell\ s^{-1}$ at 10 h).[1] This point is of relevance for cyclotrons because the area of the magnet poles, which are mild steel, is 15 to 20% of the total area of the surface exposed to vacuum. However, mild steel can be improved to the level of stainless steel by proper treatments (nickel plating, glass bead blasting,[2] controlled oxydation).

v) organic materials may be 10^3 times worse than metals and their presence must be minimized. To avoid surprises, it is wise to measure the rate of degassing and its time dependence of all organics prior to final choice.

Unfortunately, fewer data are available on spectral composition of the degassing products. According to theoretical estimations,[3] gases which are physisorbed with binding energies below 5 kcal/mole, like N_2, H_2, O_2, CO, should disappear at the very beginning of pumping. However, microcrevices in the metal surfaces can fill up with gas when exposed to high pressure and subsequently release it with different time dependence. The case of H_2 is somewhat peculiar because it diffuses out from the bulk of metals and it remains the main degassing product after baking.[4] Extensive measurements carried out at CERN on stainless steels of different types and make showed that the rate of H_2 degassing after bakeout (300°C, 24 h) does not exceed

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5×10^{-12} torr ℓ s^{-1} cm^{-2}.[4,5] If a same sample is measured before bakeout, or after bakeout and exposure to air at atmospheric pressure, its H_2 degassing rate was found to be the same, and time independent during the pumping cycle, within a factor 5.[5] According to these results, a pumping speed of 10 ℓ s^{-1} per m^2 of surface area of the vacuum system would suffice to obtain a practically constant H_2 pressure lower than 10^{-8} torr (gauge reading). However, much higher H_2 rates are sometimes quoted for stainless steel, with a time dependence similar to that of water vapour.[6] In addition to desorbing from the walls of the vacuum system, H_2 is also produced in cyclotrons by the operation of the RF accelerating cavities. For TRIUMF the rate of H_2 degassing attributable to RF acceleration is 4×10^{-3} torr ℓ s^{-1} during the first day of operation.[7] This rate represents about 10% of the total degassing at 15 h for this machine, but it would equal the corresponding total degassing of VICKSI. The H_2 is presumably produced by water dissociation, and the degassing decreases with time (a factor 10 for TRIUMF in 2 weeks).[7] The physical mechanism of this effect is to our knowledge not understood sufficiently to enable one to make quantitative estimates at the stage of the vacuum design of a machine. In absence of better information, it would seem rash to install on a large cyclotron (total surface area under vacuum larger than 100 m^2) a pumping speed for H_2 smaller than 5 to 10% of the total, or in any case, lower than 10^4 ℓ s^{-1}. Since any pump able to pump H_2, independently of the type, provides a speed for N_2 and CO of the same order of magnitude, this choice will automatically insure a comparable speed for these latter gases.

3. Required pumping speed

Based on the discussion of section 2, plausible values of the rates of degassing of the most common gases from stainless steel surfaces are shown in Fig. 1.

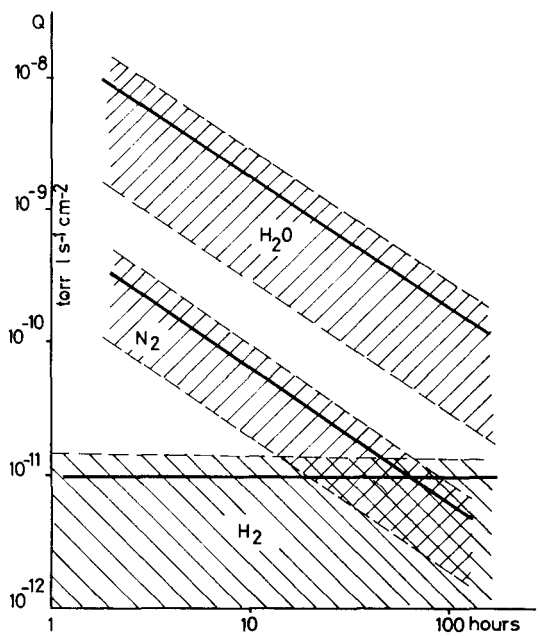

Fig. 1 : Variation of the rate of degassing of various gases from stainless steel as a function of the pumping time. The dashed areas represent the spread of the data and the full lines the plausible values on which one could base the estimates of the required pumping speeds.

They are plotted as a function of the time from the beginning of pumping. Stainless steels of worse quality certainly exist, but they should be disregarded for the construction of a cyclotron. Since copper or treated mild steel present similar values, these data may be taken as average figures for the components of a machine, with the exception of the organic materials, the amount of which may vary considerably from case to case. However, for machines of large size, it is not realistic to take degassing rates lower than 10^{-9} torr ℓ s^{-1} cm^{-2} at 10 h, because the cleanliness of the surfaces cannot be assured on a large scale. Furthermore, even if venting to atmospheric pressure is carried out with dry nitrogen, large ports are usually opened, and during the interventions water vapour enters along with the air. We will therefore take the average values represented by the full line in Fig. 1, which are 2×10^{-9}, 7×10^{-11} and 1×10^{-11} torr ℓ s^{-1} cm^{-2} at 10 h for water vapour, N_2 and H_2 respectively. At 100 h, both water vapour and N_2 desorptions are one order of magnitude lower, while the H_2 degassing remains constant. Table 1 depicts the vacuum behaviour of a hypothetical machine with a total surface area under vacuum of 1000 m^2 and a radio-frequency induced H_2 degassing of 4×10^{-3} torr ℓ s^{-1} during the first day of operation. We assume that the target pressures are 2×10^{-7} torr (proton acceleration) and 5×10^{-8} torr (for heavy ions operation) after 10 to 15 h of pumping. The choice of this time permits one to introduce in the estimates a safety factor of 2 for the reasonably short pumping time of 24 h.

TABLE 1

Case A : 2×10^{-7} torr after ≃ 10 h

gas	degassing rates at 10 h (torr ℓ s^{-1})	required pumping speeds (ℓ s^{-1})	partial pressures at 10 h (torr)	partial pressures at 100 h (torr)
H_2O	2×10^{-2}	2×10^5	10^{-7}	10^{-8}
N_2	7×10^{-4}	7×10^3	10^{-7}	10^{-8}
H_2	10^{-4}	2×10^4	5×10^{-9}	5×10^{-9}

H_2, RF induced, 2×10^{-7} torr the first day, 2×10^{-8} torr after two weeks.

Case B : 5×10^{-8} torr after ≃ 10 h

gas	degassing rates at 10 h (torr ℓ s^{-1})	required pumping speeds (ℓ s^{-1})	partial pressures at 10 h (torr)	partial pressures at 100 h (torr)
H_2O	2×10^{-2}	10^6	2×10^{-8}	2×10^{-9}
N_2	7×10^{-4}	2.5×10^4	3×10^{-8}	3×10^{-9}
H_2	10^{-4}	5×10^4	2×10^{-9}	2×10^{-9}

H_2, RF induced, 8×10^{-8} torr the first day, 8×10^{-9} torr after two weeks.

It is clear from the table that many different values of the pumping speeds for water vapour and N_2 can be selected to provide the same total pressure. The precise partition depends on the types of pump which are chosen and on price considerations. The pumping speed for H_2 may appear to be too large in this scheme. At 10 h, the pressure of H_2 would be 20 to 40 times smaller than the total pressure. However, it should be recalled

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that H_2 degassing will not change while those of all other gases will decrease even after 100 h, although at a rate lower than in the first period. After about 10 days, H_2 might become the dominant component of the residual pressure. Should a machine be designed to operate for two weeks with light ions and subsequently with heavy ions, the high pumping speed for H_2 would be necessary. Furthermore, the ill defined H_2^+ production by RF operation must not be forgotten. Even when assuming that it decreases to 10% of its initial value during the first two weeks as it does in TRIUMF,[7] H_2 would still be the main component of the residual pressure.

4. Pumps

Undoubtedly the best pump for water vapour is a metal surface cooled to 80-100 K. This pump acts as a non return aperture for water molecules and therefore presents the highest possible pumping speed, i.e. 15 $\ell\ s^{-1}\ cm^{-2}$. It is perfectly clean, easy to make and install, cheap and practically maintenance free. It can be put into operation at pressures as high as 10^{-2} torr and does not need activation by heating between pumping cycles nor special precautions when venting to atmospheric pressure. A square panel of 1 m side would provide $1.5 \times 10^5\ \ell\ s^{-1}$ pumping speed even if installed very close to the chamber wall, i.e. in a situation where the access to the back surface is restricted. The power losses would be about 90 W initially and increase to a maximum figure of 700 W due to the progressive rise of the thermal radiation absorptivity consequent to pumping of water. If liquid nitrogen is used as cooling agent, the consumption may be as low as 2 litres per hour initially and 15 litres per hour in the worst conditions.

To pump N_2 and H_2 other types of pump are needed. Oil diffusion pumps are presently not popular because of oil backstreaming and danger of catastrophic pollution. Sputter-ion and turbomolecular pumps are limited in size to the range of $10^3\ \ell\ s^{-1}$ and therefore not ideally suitable for providing the main pumping speed for machines of large dimensions. The choice is limited to getter pumps, either of two versions of Ti sublimation or non evaporable getters, and cryopumps, either at 20 K or at liquid helium temperature.

4.1 Getter pumps

Two main types of getter pump exist. The more widely used is the sublimation pump (SU) in which pumping is insured by a film of a chemically active metal deposited on the surrounding walls by heating a source which is usually titanium. In the other type, which is called non evaporable getter (NEG), pumping is provided by a gettering strip kept at a temperature high enough so that gases trapped on the surface diffuse continuously into the bulk. Both these pumps can provide very large speeds and throughputs. Particularly high speeds can be achieved by the use of NEG panels which can be combined inside a vacuum system to cover large fractions of its walls. The SU appears less favourable because of the need to avoid spreading of titanium and consequent peel-off problems in the main chamber. SU's are thus best installed as an appendix with a consequently reduced pumping speed. Connecting ports of 800 mm diameter provide speeds of about $10^4\ \ell\ s^{-1}$. The SU appears better than the NEG as far as the pumping capacity is concerned. Practically unlimited capacities can be made available by periodically replacing the inexpensive Ti filaments or rods. On the contrary, a NEG panel would only last a few thousand hours when operating in the 10^{-7} torr range.

In our opinion, although getter pumps may successfully be used for cyclotrons (as the SU's used at SIN show), they are less attractive than cryopumps for many reasons. Before activation, pressures in the low 10^{-5} torr range must be achieved. This implies the initial use of relatively large turbomolecular pumps and/or a longer preliminary pumping. Getter pumps are not selective for the main gases to be pumped and therefore they would offer excessively high speeds for N_2 and H_2 when dimensioned for water vapour. During operation at the pressures considered here, both getter pump types are important sources of heat. In the SU, Ti sublimates at temperatures above 1000°C and the NEG panels operate at 400°C. This heating, unless very effectively shielded, would raise the temperature, and therefore the rate of degassing, of a part of the vacuum chamber in a way which would be difficult to control. Heating also makes it difficult to combine getter pumping with N_2 cooled panels which could otherwise efficiently reduce the gas load to the getter by trapping the water vapour. However, these types of pump could be of some interest to remove H_2 whenever the other gases are previously pumped down to low pressure by other means.

4.2 20 K cryopump

A '20 K' cryopump consists of a metal panel cooled to about this temperature by a refrigerator. The cold surface is shielded from room temperature radiation by baffles at about 80 K. Cooling of the baffles can either be assured by liquid nitrogen circulation or by the higher temperature stage of the refrigerator. At 20 K the vapour pressures of all gases except Ne, H_2 and He are lower than the lowest pressures required for the operation of a cyclotron. Therefore, indefinite quantities of these condensable gases can be pumped. In contrast, no more than one monolayer of H_2 can be retained. To provide the necessary pumping capacity for H_2, materials like zeolites or activated charcoal providing very large specific surface areas are commonly glued onto the cryopanels. This type of pump presents the advantage that by proper design the speeds required for the various gases can be obtained in the right proportions. Furthermore, cryopanels can be shaped according to the available space inside the main vacuum chamber where they may provide very large pumping speeds. Among the inconveniences one might recall that the 20 K panels must be regenerated periodically by heating to 200°C to desorb water vapour which accumulates in the adsorbing material and reduces the pumping capacity for H_2. During thermal cycling, particles of the glued absorber may be lost. Furthermore, if the cryopanels are incorporated in the main vacuum chamber, the desorbed water will be readsorbed by the walls of the vacuum system, making the venting with dry gas ineffective. Finally, any power cut will be followed within a short delay by the warming up of the cold surfaces with consequent gas release and wall pollution by water vapour.

4.3 Condensation cryopump

At 3 K all the gases except helium have a vapour pressure lower than 10^{-9} torr. At these temperatures, which may be conveniently obtained by reducing the pressure over a liquid helium bath to about 200 torr, a bare metal surface offers a practically unlimited pumping capacity. This feature is the main advantage of the condensation cryopump. On the other hand, with respect to 20 K cryopumping, a condensation cryopump presents the disadvantages of a lower versatility, both from the geometrical and the operational points of view. The presence of a liquid helium bath usually results in bulky cylindrical structures which cannot be inserted easily inside a vacuum chamber. Furthermore, only vertical mounting is possible. Additional complications are the provisioning and the handling of liquid He.

An important improvement in this respect was rea-

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lised with the development of the low consumption condensation cryopump at CERN.[9] The latest version of this pump[10,11] is schematically shown in Fig. 2.

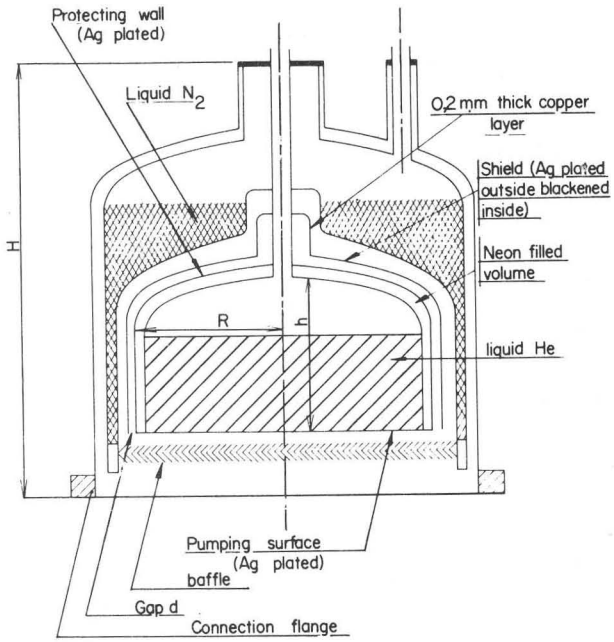

Fig. 2 : The CERN condensation cryopump

The liquid helium vessel is protected not only by walls at liquid N_2 temperature as in the previous model, but also by an additional shield which is welded to an appropriate point on the neck of the pump. It can be shown[11] that the temperature of this shield does not exceed 30 K if the height of the helium vessel is smaller than its diameter and the gap between shield and helium vessel is reasonably small. Under these circumstances, the thermal losses due to infrared radiation emitted by the shield are negligible with respect to those produced by radiation originating from the baffle and absorbed by the pumping surface. To minimize radiation absorption, all the surfaces of the He vessel are silver-plated (only 1.2% of the incident radiation is absorbed). Room temperature radiation filtering through the baffle is negligible. The liquid He consumption can then be expressed in the very simple form

$$Q = 0.1\ S\ cm^3\ day^{-1}$$

where S is the area of the pumping surface expressed in cm^2. So far, eight pumps of this type in two different sizes have been built. Both sizes provide an autonomy of about 200 days at 4.2 K. The two pumps of the larger size (about 500 mm diameter, 32 ℓ of liquid helium capacity), are presently installed on VICKSI. There, they are refilled with liquid He after 3 months of operation. At relatively high pressures, the liquid helium consumption is larger because of the heat released by the molecules which are pumped (heat of condensation and kinetic energy) and of the increase of radiation absorption due to the condensed gas layers. The latter effect may be particularly important if water vapour is absorbed on the pumping surface. Usually, water molecules are trapped by the optically opaque baffle at liquid N_2 temperature. However, when the pumps are warmed up, the well-insulated helium vessel remains initially much colder than the baffles and may trap the water vapour which is released by the latter. To avoid this inconvenience, the helium vessel must be heated up to room temperature before cooling again with liquid helium. As far as the losses due to the pumped molecules are concerned, they equal the radiation load (clean surface conditions) at a pressure of 5×10^{-6} torr for H_2 and 2×10^{-6} torr for N_2.

The good cryogenic performance of the CERN cryopumps eliminate the inconvenience of frequent handling of liquid He and make the running cost of the pump negligible. However, to fully exploit their endurance, the cryopumps must be connected to the main vacuum chamber via large gate valves which should be closed when the system is vented to atmospheric pressure. These valves are expensive and reduce considerably the pumping speed particularly for water vapour. For instance, in the case of the pumps of VICKSI, the presence of the valve reduces the speed for water vapour from 30'000 to 11'000 ℓ s^{-1}. The speeds provided by the cryopumps of this model per cm^2 of baffle area are 15 ℓ s^{-1} for water vapour, 9 ℓ s^{-1} for H_2 and 3 ℓ s^{-1} for N_2. Since for mechanical reasons it is difficult to build pumps of diameter larger than ≃ 1 m, this type of pump may be reasonably used only if the required speeds are lower than ≃ 10^5 ℓ s^{-1}.

5. VICKSI[12]

The vacuum specification for VICKSI was a pressure of 5×10^{-7} torr after 48 h pumping. The total area of the surfaces exposed to vacuum is 200 m^2, of which about 50 m^2 (magnet poles) are mild steel and the rest stainless steel or copper. Initially, no treatment was foreseen for the poles of the magnets. The amount of organic materials is negligible. The estimated total degassing rate at 10 - 15 h was 1.2×10^{-2} torr ℓ s^{-1}.

When the vacuum system of VICKSI was designed (May 1973), none of the large cyclotrons already under construction was yet operational. Very little was known on the behaviour of their pumping system in real operating conditions. Cryopumping with adsorbing materials at 20 K was at the laboratory prototype stage. The CERN cryopumps were chosen mainly to provide a large pumping speed for H_2.

An effective pumping speed for water vapour of about 20'000 ℓ s^{-1} was specified to obtain the required pressure after 15 h pumping. This speed was provided by the two cryopumps described in section 4, connected to the main vacuum chamber via a gate valve of 500 mm diameter. More precisely, the effective pumping speeds are 22'000 ℓ s^{-1} for water, 20'000 ℓ s^{-1} for H_2 and 6'000 ℓ s^{-1} for N_2.

In a typical pumping cycle, a roots pump and a rotary pump (total speed 270 m^3 h^{-1}) bring the pressure to the 10^{-1} torr range, when the two turbomolecular pumps of 1500 ℓ s^{-1} are switched on. The valves of the cryopumps are opened below 10^{-4} torr, and a total pressure of 5×10^{-7} torr is achieved 12 h after the beginning of pumping. This pressure is partly due to two leaks, one of which is on the water cooling circuit and the other on the chamber wall. These leaks contribute 1.5×10^{-7} torr, the value at which the pressure settles after about 1000 h pumping. By substracting this contribution, the pressure after 15 h is 2×10^{-7} torr, which corresponds to a total degassing rate of 4×10^{-3} torr ℓ s^{-1}, or an average rate of 2×10^{-9} torr ℓ s^{-1} cm^{-2}. This rate is about 3 times lower than estimated. The reason must certainly be found in the nickel plating of the poles of the magnets, which was decided later on during the construction of the cyclotron.

Estimating the partial pressures of the different

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gases during the pumping cycle is difficult. In a previous mounting, in the absence of leaks, the N_2 pressure was below 2×10^{-8} torr already after 15 h. In the present situation, and after more than 100 h, H_2 also does not exceed this pressure. It can be concluded that in the absence of leaks after 100 h the total pressure would be in the low 10^{-8} torr range and that the partial pressures of N_2 and H_2 would reach this value in 10-15 h. From the pressure increase when the RF system is put into operation, the H_2 degassing is estimated to be lower than 5×10^{-5} torr $\ell\ s^{-1}$.

6. Conclusions

It would seem that from the observed vacuum behaviour of VICKSI, the estimates of section 3 are reasonable. Thus, if the building materials of an unbaked vacuum system are properly selected and treated, the pumps may be dimensioned on an average degassing rate, after 10 to 15 h pumping, of 2×10^{-9} torr $\ell\ s^{-1}\ cm^{-2}$. During the first 100 h, more than 90% of the gas released is water vapour.

This gas composition makes cryopumping at 20 K or 3 K more attractive than getter pumping. Condensation cryopumps, with their isolation valves, are not adequate to provide pumping speeds larger than $10^5\ \ell\ s^{-1}$. If pumping speeds in this range are needed for H_2 or N_2, 20 K panels immersed in the main vacuum system appear to be the best solution. If the speeds required for gases other than water vapour are in the range $10^4\ \ell\ s^{-1}$, a combination of liquid N_2 cooled panels and low consumption condensation cryopumps with valves is, in our opinion, preferable. Condensation cryopumps are fail-safe in that they are insensitive to power cuts and have no moving parts. They do not need activation and do not risk producing dust during thermal cycling. They are cheap to run and need practically no maintenance. They can be protected by closing the valve when the system is vented to atmospheric pressure and therefore no time is needed for warm-up and cool-down. When they are warmed up, the valves prevent the desorbed water from being readsorbed by the walls of the main vacuum system.

In the case of large size cyclotrons, the pumping speeds required for N_2 and H_2 are within the possibilities of condensation cryopumping. A machine with a total surface area of 1'000 m under vacuum could be pumped down to 5×10^{-8} torr in 15 hours by using 5 N_2-cooled panels of 1 m side each and two condensation cryopumps of 800 mm diameter with gate valves of equal size. These cryopumps would provide a speed for H_2 of about 50'000 $\ell\ s^{-1}$, which would be enough to take care of the H_2 released when the RF cavities are put in operation, even if the rate of H_2 production is as high as it is in TRIUMF.

7. Acknowledgements

The author is indebted to the VICKSI team for providing the information on the behaviour of this machine. The usefulness of the many discussions with G. Rommel (GANIL) is gratefully acknowledged.

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** DISCUSSION **

H. BLOSSER: What is your opinion of a 4.6° liquid bath system with an Argon flash for pumping hydrogen?

C. BENVENUTI: This method works well, according to Air Liquide. However, argon is an undesirable gas to introduce in a cyclotron because of its high atomic number and consequent high cross-sections for coulomb scattering, charge exchange and ionization. Furthermore, relatively high argon fluxes are needed and the liquid helium consumption of a cryopump may increase noticeably.

Y. JONGEN: Concerning regeneration of cryopanels: isn't it possible to avoid recontamination of the walls by regenerating under quite good vacuum.

C. BENVENUTI: The desorbed water molecules have a high sticking probability when they interact with the vacuum system walls, which therefore are contaminated before the water vapor is pumped out. So, the auxilary pump cannot remove most of the water molecules from the system.

A. DAEL: In the VICKSI example what do you think of the case of poles without nickel plating?

C. BENVENUTI: Without Ni plating the estimated degassing rate at 10h was 1.2×10^{-2} torr ℓ/s. The rate resulting from pressure measurements is 4×10^{-3} torr ℓ/s at 10h. This difference is probably due to Ni plating which was decided upon during construction.

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