

Vacuum system

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Abstract

The vacuum system of a particle accelerator must provide the necessary conditions for the high energy beam to avoid loss of particles and deterioration of the beam quality. In this talk we will review basic design concepts, vacuum components and procedures required for an accelerator vacuum system.

1 Introduction

The residual gas in an accelerator plays an important part in the ultimate performance of the machine since it affects the particle lifetime as well as beam characteristics due to interactions by elastic and inelastic scattering, ionization of residual gas molecules, space charge neutralisation by trapped positive or negative charges in the beam. The cross sections of the different processes depend on the type of beam particles, their energy and on the particle velocity. Molecules with a high molecular mass are particularly harmful and must be avoided. The vacuum system design must provide not only low residual gas densities but the vacuum should contain light molecules, preferably H₂ only. This one hour lecture gives a brief introduction to some of the aspects relevant for the design of accelerator vacuum systems. For a more complete treatment of this subject, the interested reader is invited to consult the extensive literature, which is available [1–7].

1.1 Pressure and molecular density

The ideal gas law

$$P V = \frac{N}{N_0} R T$$

can be used in all practical cases, with pressure P , volume V , temperature T and the number of molecules N . R is the gas constant, 8.31 kJ kmol⁻¹ K⁻¹ and $N_0 = 6.02 \times 10^{26}$ molecules kmol⁻¹. As a reminder, the Boltzmann constant $k = 1.38 \times 10^{-23}$ J/K is related to the macroscopic gas constant $R = N_0 k$. It is important to point out that in (nearly) all cases, it is the gas density rather than the pressure, which matters for an accelerator vacuum system. Using the molecular density

$$n = \frac{N}{V}$$

the ideal gas law can be rewritten in the form

$$P = n k T \quad \text{and} \quad n = \frac{P}{k T} .$$

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It should be obvious from this equation that quoting only the pressure without also specifying the temperature is insufficient. In the past practically all of the vacuum systems were at room temperature. However, with the construction of more and more systems using cryopumps and machine components like superconducting RF cavities and magnets operating at temperatures down to liquid helium, such an implicit assumption is no longer admissible. For example the specification for the cold LHC vacuum system is not a pressure value but the equivalent H₂ density for a beam lifetime of 100 h [8].

1.2 Vacuum units

It may be useful to recall a few commonly used vacuum units.

- Pressure : Pa (N/m²), mbar = 100 Pa, Torr = 133 Pa .
- Gas load : Pa m³ = 7.5 Torr l, mbar l ~ 2.4 × 10¹⁹ molecules at 20°C.
- Specific outgassing rate : describes the release of gas molecules from the walls of the vacuum vessel in units of Pa m/s equivalent to 7.5 10⁻⁴ Torr l/s/cm².
- External leak rate or gas flow is measured in Pa m³/s, mbar l/s or Torr l/s.

1.3 Maxwell–Boltzmann distribution of molecular velocities

In thermal equilibrium molecules in a gas have velocities according to the Maxwell-Boltzmann distribution

$$\frac{1}{N} \frac{dN}{dv} = \frac{4}{\sqrt{\pi}} \left(\frac{m}{2kT} \right)^{\frac{3}{2}} v^2 e^{-\frac{mv^2}{2kT}} .$$

Here m is the product of the molecular weight M and of the unit mass $m_0 = 1.66 \times 10^{-27}$ kg. In calculations and for design purposes, it is common to use the average velocity given by

$$\bar{v} = \sqrt{\frac{8kT}{\pi M m_0}} .$$

Numerically this average velocity is $\sim 146 \sqrt{\frac{T}{M}}$ (m s⁻¹).

Typical average molecular speeds at 20°C range from about 1750 m/s for H₂ molecules ($M = 2$) to around 460 m/s for N₂ and CO ($M = 28$).

1.4 Total and partial pressures

For each gas component n_1, n_2, n_3, \dots the partial pressure is

$$P_i = n_i kT .$$

The total pressure is the sum of all partial pressures

$$P = \sum_i P_i = kT \sum_i n_i .$$

1.5 Wall collisions

The rate with which molecules strike the walls of a vacuum vessel is given by

$$\nu = \frac{1}{4} n \bar{v}. \quad (1)$$

The momentum transfer gives rise to the pressure exerted on the wall. This rate at which molecules strike a given area is relevant to calculate the gas transmission through a vacuum system and the intrinsic pumping speed of getter pumps.

1.6 Mean free path

An important quantity for the characterisation of a vacuum system is the relation of its characteristic dimensions and the molecular mean free path. In a gas the average distance traversed per second is given by the mean molecular speed \bar{v} . A molecule collides with all other molecules contained within a cylinder of radius D , which is the molecular diameter, approximately 3×10^{-8} m.

Number of collisions per second can be written as

$$Z \approx \pi D^2 \bar{v} n.$$

Mean free path is defined as

$$l = \frac{\bar{v}}{Z} = \frac{1}{\sqrt{2} \pi D^2 n}.$$

It follows that the product $n l \propto P l \approx \text{const}$. For air this value is $\sim 2 \times 10^{14} \text{ m}^{-2}$. For N_2 at 20°C and 1 Pa the mean free path $l \sim 9$ mm.

The ratio of the molecular mean free path and of the transverse dimensions of the vacuum system determines the characteristics of the vacuum. When this ratio is small, molecules collide mostly with other molecules and the gas behaves like a viscous medium. For a large ratio, the molecules collide predominantly with the walls of the vacuum vessel and the flow is determined by molecular diffusion. With the exception of the initial pump down phase from atmospheric pressure, all accelerator vacuum systems operate in the molecular flow regime.

1.7 Molecular flow

When the molecular mean free path is large compared to the transverse dimensions of the vacuum element the gas flow is proportional to the pressure gradient

$$Q = c \Delta P.$$

The molecular flow conductance

$$c = \frac{4}{3} \frac{\bar{v}}{\int_0^L \frac{H}{A^2} dl} \quad (\text{m}^3/\text{s})$$

does not depend on the pressure. It is a function of geometrical properties only: L the length of the element ($L \gg$ transverse dimensions), H its perimeter and A its cross section.

The conductance is proportional to the mean molecular velocity, i.e. to $\sqrt{T/M}$.

A useful expression for a straight, cylindrical duct with uniform section and radius r is

$$c = \frac{4}{3} \bar{v} \left(\frac{r^3}{L} \right) \sim 306 \left(\frac{r^3}{L} \right) \sqrt{\frac{T}{M}}.$$

The conductance of a circular orifice with $L \sim 0$

$$c = \frac{1}{4} \bar{v} A \sim 36.5 \cdot A \sqrt{\frac{T}{M}}.$$

The total conductance of elements connected in series or in parallel can be calculated in the same way as for electric circuits, namely

$$\frac{1}{c} = \frac{1}{c_1} + \frac{1}{c_2}$$

and for parallel elements

$$c = c_1 + c_2.$$

For practical, more complicated geometries it is generally necessary to use either analytic or Monte Carlo programs to calculate the molecular flow and to obtain correct pressure distributions.

1.8 Thermal conductivity

Thermal conductivity of a gas is independent of the pressure when the pressure is well above the molecular flow regime. In the transition regime, the heat transfer is proportional to the pressure and to the temperature difference. The Pirani vacuum gauge works according to this effect and covers the pressure range from about 10^4 Pa to 10 Pa.

At very low pressures, the heat transfer by conduction in the gas is negligible and this fact is used to achieve very effective thermal insulation. A good illustration of this effect is the thermal insulation vacuum of the LHC cryo-dipoles shown in Fig. 1. Since heat transfer by radiation from room temperature surfaces remains the dominant effect, a good thermal shield at an intermediate temperature must be provided to intercept the heat flow to the cold magnets.

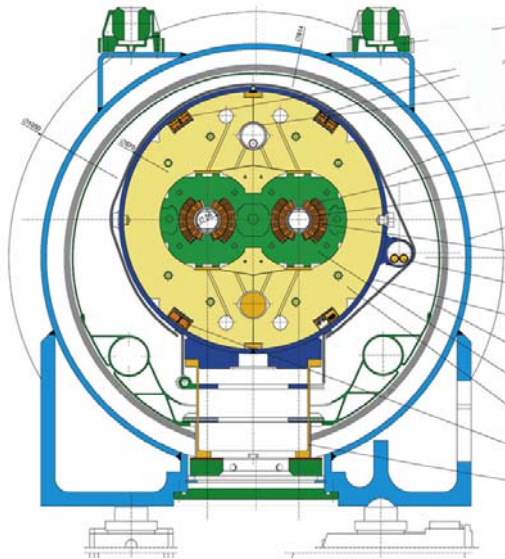


Fig. 1: LHC magnet with its cryostat

2 Simple vacuum system

A vacuum system with the basic elements is shown in Fig. 2. It consists of a volume V (m^3) surrounded by a total surface F (m^2). The pressure in the system, P (Pa) is obtained by an external pump with a pumping speed S (m^3/s). There is a continuous flow of gas from the surrounding walls, which is characterised by the specific outgassing rate q (Pa m/s). The equilibrium pressure results from the balance of the gas flowing into the volume and the gas removed by the pump.

$$qF = PS.$$

The equilibrium pressure is

$$P = \frac{qF}{S}.$$

Apart from the fact that a larger volume may require a larger surrounding surface, the equilibrium pressure is independent of the volume.

The dynamic pressure during the pump down of the system is obtained from

$$V \frac{\partial P}{\partial t} = qF - SP.$$

The solution is an exponential function with a time constant V/S . The integration constant K follows from the chosen initial conditions.

$$P(t) = Ke^{-\frac{S}{V}t} + \frac{qF}{S}.$$

Obviously, the pump down of a large vessel will take longer than that of a small one. To reach a low pressure, it is necessary to achieve a low outgassing rate, in particular to avoid any external leaks, and to provide a high pumping speed.

For the designer of a vacuum system, a large pumping speed generally implies a large capital cost. To achieve a low outgassing rate, implies clean surfaces and the use of appropriate preparation techniques.

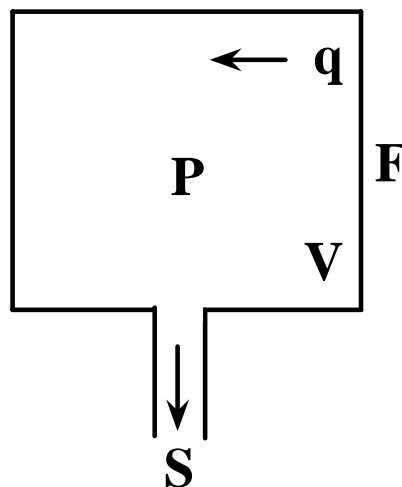


Fig. 2: Basic vacuum system

2.1 Pumping unit for LEP vacuum system

For most accelerator vacuum systems external pumps are required for the initial pump down only. During the operation stationary pumps can maintain the vacuum. Many accelerators use mobile groups, which are placed temporarily wherever they are required. The advantage is that expensive pumping units can be removed from the tunnel for maintenance and to avoid radiation damage. During operation of the accelerator, the manual separation valve on the beam line vacuum is closed. Figure 3 shows the schematic diagram of a mobile pumping unit, which has been used for the LEP vacuum system at CERN [9].

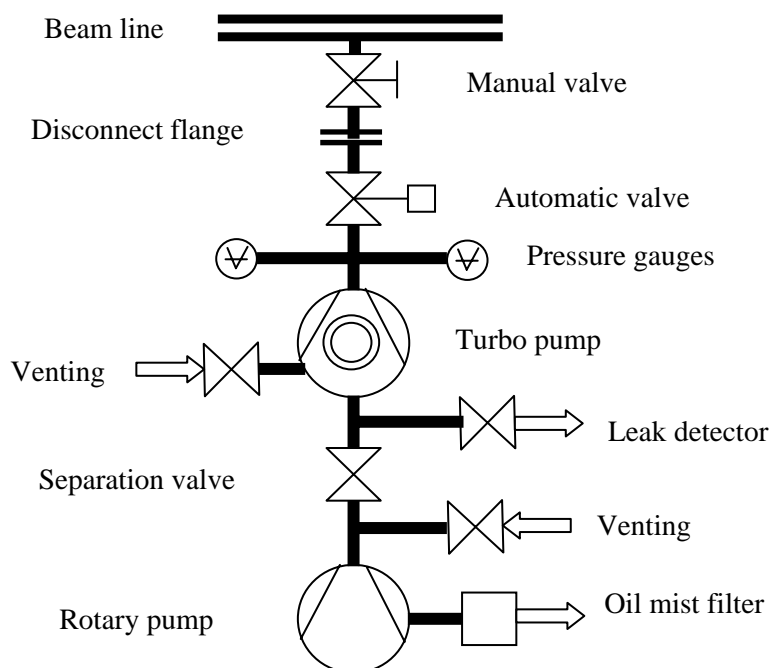


Fig. 3: Layout of a pumping station

2.1.1 Rotary pumps

The unit incorporates a rotary pump with oil sealed moving parts. The typical final pressure ranges from $\sim 10^{-2}$ to $\sim 10^{-3}$ mbar, typical pumping speeds are 4 to ~ 40 m³/h. Such a unit is adequate for long vacuum systems with relatively small volumes. For health reasons, in particular in a closed accelerator tunnel, it is imperative to include an oil mist filter. Dry pumps, without oil, have become available on the market but because of their cost, their use is so far limited to special applications.

2.1.2 Turbomolecular pumps

The principle of molecular pumps is that molecules collide with the fast moving surface and gain a velocity component in the direction of this movement. In this way the molecular movement is no longer entirely random but has a component in a preferential direction.

The pumping speed of a turbomolecular pump is

$$S \propto v A$$

where v is the rotational speed, typically $>40\,000$ rpm. A is the pump area, hence a large entrance flange is desirable. The pumping speed S of a turbomolecular pump is independent of pressure. An important quantity for the vacuum design is the compression ratio of the pump, defined as the ratio of outlet pressure to inlet pressure

$$K = \frac{P_{outlet}}{P_{inlet}} .$$

K is an exponential function of the molecular weight and of the rotational speed. Compression ratios of commercial pumps can vary from a few 10^3 for H_2 to 10^9 for N_2 . Hence the compression ratio is large for heavy molecules and this effect provides 'clean vacuum' without heavy hydrocarbon molecules. With proper handling of the pumps, oil contamination of the accelerator vacuum from rotary pump can be avoided.

2.1.3 Sputter ion pumps

Sputter ion pumps are the most common pumps to maintain the operating pressure in an accelerator vacuum system. Ion pumps use parallel electric and magnetic fields to achieve a self maintained discharge plasma, called a Penning discharge. The ion pumps require a high voltage supply of a few kV. The pump current is a function of the discharge and increases with increasing pressure. The pump current gives a convenient pressure measurement. Ionised residual gas molecules are accelerated towards a Ti cathode and 'trapped' and removed from the gas phase. The electrons of the discharge plasma oscillate in the combined electric and magnetic fields for a sufficiently long time to be able to ionise molecules even at a low pressure in the pump. The ion induced sputtering from the cathode produces a clean Ti getter film on the interior surfaces of the pump. To obtain large pumping speeds, arrays with large numbers of individual pumping cells are used.

The pumping action is composed of several effects:

- Gettering: chemisorption of active molecular species H_2 , CO, N_2 , O_2 , CO_2 .
- Diffusion: of H_2 into the Ti- cathode, but the inverse effect re-diffusion may also occur.
- Cracking: of chemically inert hydrocarbons into C, H, O which can be pumped and chemisorbed separately.
- Ion burial: energetic ions of noble gases He, Ne, Ar are implanted into the cathode.

To increase the pumping speed of chemically active molecular species it is beneficial to increase the sputtering rate of the titanium cathode, which can be done by providing a grazing incidence of ions at the cathode, e.g. in triode sputter-ion pumps. It should be remembered, that with an ion pump molecules are not removed from the vacuum system but remain trapped inside. Important memory effects of previously pumped gas may occur, e.g. the release of previously pumped gases. One such effect is the argon instability, which may occur after pumping of large quantities of air.

A particularly attractive feature of ions pumps in accelerators is the fact that they can profit from the fringe fields of magnets. Indeed, many particle accelerators use integrated ion pumps either in bending magnets (linear ion pumps), in quadrupoles and even in the solenoid field of detectors [10].

2.1.4 Titanium sublimation pumps

To start the pumping action of a sublimation pump a thin film of fresh Ti is deposited on a surface by heating a Ti wire to about 1300°C . Depending on the amount of gas pumped, the film has to be regenerated, typically after an exposure of 10^{-6} Pa h. The total pumping speed can be made very large by increasing the pump area, A

$$S = \frac{1}{4} \nu s A .$$

Here s is the probability that molecules stick on the pump surface, the sticking coefficient $0 < s < 1$ and ν is the rate at which molecules strike the pump surface given in Eq. (1). Since getters trap

only chemically active gases, the vacuum system design must include an appropriate number of ion pumps for inert gases. To increase the operational lifetime of a pump, multi filament holders (3–6 Ti filaments) can be provided.

2.1.5 *Non-evaporable getters (NEG)*

Non-evaporable getters use a suitable bulk material composed of Ti, Zr, V, which can be activated repeatedly by heating under vacuum without the need of depositing a fresh film by sublimation. The gas layer initially adsorbed on the surface diffuses into the bulk and a ‘clean’ getter surface can be obtained. Activation requires heating to 350°C up to 700°C for one hour depending on the specific getter. For the LEP vacuum system a metal ribbon coated with a thin layer of getter powder has been used [11].

A new development at CERN combining the advantages of evaporable getters and of bulk getters has been under development for many years [12]. With this new method a sputter deposited getter film of a few μm is coated directly onto the inner surface of vacuum chambers. The desired optimum composition and the surface roughness of the getter film is determined by the sputtering process. A very interesting result of this method is that the activated surface layer provides not only pumping but it has also a significantly reduced outgassing rate. In recent years sputter coating the inner surfaces of vacuum chambers with a thin getter film has become a standard method at many accelerators and storage rings [13].

As a final comment it should not be overlooked that getters have a limited total pumping capacity and they have a memory effect of the gas previously pumped.

2.1.6 *Cryopumps*

In contrast to getter pumps, where molecules are adsorbed with chemical binding energies, cryopumps use physical adsorption. The binding energies available are considerably smaller and hence the adsorption of molecules must occur on a substrate at low temperature. Commercial cryopumps operate, therefore, with a pumping surface at 20 K or even at liquid helium temperature. The pumping speed of a cryopump is proportional to the cold surface area and can be made as large as it is practical in the given application. The ultimate pressure, which can be achieved with cryopumps is limited by the saturated vapour pressure of the condensed gas species. Hence, in order to attain adequately low H_2 pressures in a commercial pump operating at 20 K it is necessary to stay well away from the saturated pressure. The adopted solution in most commercial cryopumps is to coat the cold surface with charcoal powder, and in this way to increase the effective surface area by many orders of magnitude.

In combination with superconducting magnets or superconducting accelerating cavities, at little, or no extra cost very effective integrated cryopumps can be obtained. A large freedom in the design of cryopumps is given since the cold walls of the respective elements will act as the pump. Nevertheless, an important limitation occurs in an accelerator system due to the exposure to room temperature radiation from surrounding components but also due to the bombardment by beam induced energetic particles like synchrotron radiation photons, electrons and ions. These effects impose, e.g. LN_2 cooled baffles to shield the pump surface against radiation and in the LHC vacuum system the He cooled beam screen [14].

2.2 *Vacuum gauges*

2.2.1 *Pirani gauge, thermal conductivity gauge*

Pirani gauges use the variation of the thermal conductivity of the gas with pressure. The pressure range covered by this gauge extends from near atmospheric pressure to ~ 0.1 Pa. A resistor with a large

temperature coefficient is mounted inside the vacuum and is heated to a constant temperature. The required heating current to maintain the resistance bridge balanced is a measure of the pressure. The electronic circuitry provides compensation for ambient temperature variations and linearization of the pressure reading. These gauges are inexpensive and reliable if the possibility of *in situ* calibration exists.

2.2.2 Cold-cathode ionization gauge

The cold-cathode ionization gauge or Penning gauge, works on the principle of an ion pump where the discharge current is proportional to pressure. The useful pressure range is from $\sim 10^{-2}$ to 10^{-7} Pa. At high pressure the discharge can be unstable due to arcing and at low pressure the discharge may extinguish since the ionization probability is too low. Leakage currents in the cables and in the gauge head may produce erroneous pressure readings. Contamination of the gauge electrodes may also change the calibration of the gauge. Since the gauge functions like a small pump, extended operation at high pressure may contaminate the gauge with mostly carbon deposits and may require demounting and cleaning of the gauge. An improved version of this system extending to lower pressures is available on the market as inverted magnetron gauge.

2.2.3 Hot-filament ionization gauge

In this gauge, gas molecules are ionized by the electrons, which are emitted from a hot filament, see Fig. 4. Ions produced in the residual gas are extracted by a central collector electrode. This ion current is proportional to the gas density and pressure. The ion collector current

$$I^+ = I_e P_i L P ,$$

where I_e is the emission current of the filament and L the path length of the electrons in the gauge. The ionization probability P_i , which gives the number of ion–electron pairs produced per Pa m depends on the type of molecule and on the kinetic energy of the electrons.

The gauge sensitivity S [Pa^{-1}]

$$S = P_i L$$

must be obtained by calibration with a known pressure. For calibration purposes nitrogen is used and gauge readings are displayed as nitrogen equivalent pressures. To measure the true pressure for another gas, the relative gauge sensitivity for this particular gas with respect to nitrogen, S_i/S_{N_2} , must be known. For H_2 , the value is typically $S_{\text{H}_2}/S_{\text{N}_2} \sim 0.38$.

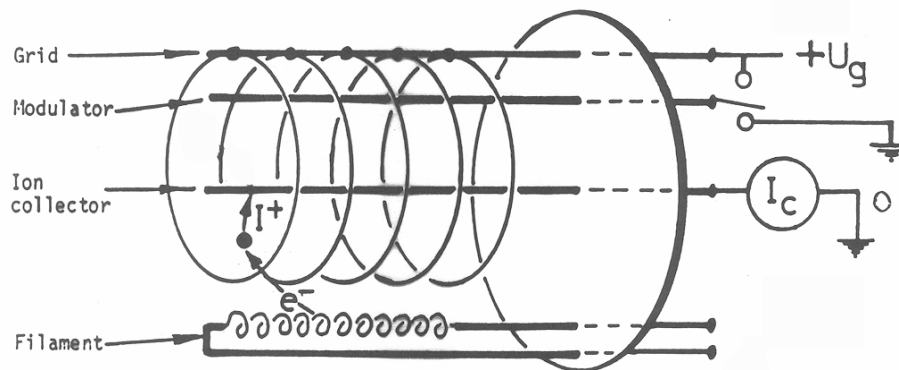


Fig. 4: Hot-filament ionization gauge

3 Thermal desorption

The specific desorption rate q [$\text{Pa m}^{-1} \text{s}^{-1}$] can be expressed as

$$q = \text{const } e^{-\frac{E}{kT}}.$$

Molecules, which are adsorbed on the surface, oscillate in the potential field and their mean residence time is given as

$$\tau = \frac{1}{\nu_0} e^{\frac{E}{kT}}.$$

Here E is the activation energy for desorption, $\nu_0 \sim 10^{13} \text{ s}^{-1}$ is the vibration frequency in the surface potential. As a function of temperature, the first-order desorption rate varies as

$$\log[q] = A - B \frac{1}{T}.$$

This relation can be used to measure the adsorption energy. For physisorbed molecules $E < 40 \text{ kJ/mole}$ (0.4 eV). Chemisorbed molecules have binding energies $E > 80 \text{ kJ/mole}$ (0.8 eV).

The exponential dependence of the desorption rate on temperature offers the possibility to remove the fraction of weakly bound molecules from the surface. A common method of reducing the outgassing rate is to bake the system at elevated temperature of 150°C to 300°C for many hours or days. At this high temperature the residence time is reduced and the molecules can be pumped out of the system in a relatively short time. After the bakeout, a reduction of H_2O , CO , CO_2 by several orders of magnitude can be achieved. Baking at even higher temperatures above 400 to 500°C will lead to cracking of hydrocarbon molecules into lighter constituents. A further consequence of the exponential temperature dependence of is the strongly reduced thermal desorption at cryogenic temperatures.

3.1.1 Outgassing rates

One observes a strong variation of outgassing rates from unbaked to baked materials and also from organic materials to metals. Baked metal surfaces are preferred since they provide the lowest specific outgassing rates. Outgassing rates of unbaked samples can vary considerably with time and temperature, it is therefore not very useful to quote precise values. For unbaked surfaces the outgassing species is dominated by H_2O . For baked samples, it is mostly H_2 . Table 1 gives typical values of specific outgassing rates of metal samples baked for 24 h at 150°C to 300°C followed by 50 h of pumping.

Table 1: Specific outgassing rates (Pa m s^{-1})

Gas	Al, Cu, stainless steel
H_2	1×10^{-9}
CH_4	5×10^{-12}
CO	1×10^{-11}
CO_2	1×10^{-11}

3.1.2 *Chemical pre-cleaning*

Prior to the assembly of any vacuum system it is required to pre-clean all parts in a cleaning facility with the appropriate solvents. The purpose of this step is to remove any gross contamination and machining oils using the appropriate solvents. To improve the cleaning efficiency, ultrasonic agitation can be used. The cleaning liquids should be selected according to the materials to be cleaned and may be chosen among a wide range of commercially available products. The cleaning procedure implies frequently the immersion of the whole piece into a bath of alkaline detergent or acid. This step must be followed by thorough rinsing in demineralised water. The final step should be drying in a hot air oven at $\sim 150^{\circ}\text{C}$. All subsequent handling must be done with clean gloves. Contamination by residues in the air must also be avoided. For intermediate storage, all parts should be wrapped in clean Al foil or paper.

3.1.3 *Vacuum firing at high temperature*

High temperature baking of stainless steel vacuum components in a vacuum oven at $\sim 950^{\circ}\text{C}$ has been used very successfully at CERN [15]. At this high temperature the surface oxide layer of stainless steel is reduced and any contaminating hydrocarbons and organic molecules are cracked and eliminated. During the subsequent cool down the surface is exposed to a clean nitrogen gas and by this means a new surface layer forms under controlled conditions.

3.1.4 *Criteria influencing the choice of materials*

The choice of materials for vacuum systems is conditioned by a large number of partially exclusive criteria. The following gives a list of aspects to be considered when making a choice. The individual weight of each point will depend on the specific requirements of the accelerator vacuum system.

3.1.4.1 *Requirements*

- Low outgassing rate and low vapour pressure.
- Temperature resistant and good thermal conductivity compatible with the bakeout temperature.
- Thermal and electrical conductivity to reduce beam induced power loss and beam-vacuum chamber interaction.
- Corrosion resistance to reduce the risk of leaks.
- Low induced radioactivity to facilitate the handling of vacuum components after prolonged operation in the accelerator.
- Good mechanical strength is required, also at the bakeout temperature, since the vacuum components must withstand the external atmospheric pressure.
- Established methods for fabrication for machining, welding, mounting and demounting.
- Cost of the raw material but also of the manufacturing process.

3.1.4.2 *Common choices for accelerator vacuum systems are:*

- Stainless steel, which is the material used for practically all commercial vacuum products.
- Aluminium, has been used extensively for beam pipes in many accelerators. This material can be extruded at low cost in practically any cross section and shape.
- Copper is preferred where good thermal and electrical conductivity is required. Serious drawback is the material cost and the required delicate and expensive welding technology.

- Ceramics are required for electric insulation, e.g., high-voltage feedthroughs. Ceramics for vacuum applications should have very low porosity to avoid the risk of leaks.

For particular applications it will be necessary to deviate from the ‘standard choices’. If this is absolutely required, then at least the amount of organic materials used should be as small as possible.

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