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Vacuum Technology Practice Course

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Contents

Chapters 1-4 were primarily adapted from the textbooks *'Vacuum Technology'* [1] and the *'Handbook of Vacuum Technology'* [2].

1 Rarefied gas theory for vacuum technology

1.1 Pressure and mean free path

Due to the bond between its molecular particles, a solid or liquid substance occupies a certain volume hardly influenced by ambient conditions (temperature, pressure, etc.). Therefore, this volume is an inherent property of the substance. A gas behaves differently: when a container holds a certain amount of gas, the gas spreads across the complete inner volume of the container and fills it homogeneously. The larger the container, the thinner the gas. The container's volume V determines volume as well as state of the gas. The gas in the container exerts a force on the walls of the container. A larger wall area is subject to a larger force than a smaller wall area. Therefore, it is convenient to introduce the term pressure p. The quantity pressure is defined as the ratio of the force F, exerted perpendicularly to a surface element of the container's wall, to the area of this surface element A:

$$p = \frac{F}{A} \tag{1}$$

The word vacuum typically means a dilute gas or the corresponding state at which the pressure or density is lower than that in the surrounding atmosphere. The defining equation (1) shows that pressure is a derived quantity. The unit of pressure in the International System of Units (SI) is given by:

$$[p] = \frac{[F]}{[A]} = \frac{\text{newton}}{\text{meter}^2} = \text{pascal} \tag{2}$$

One pascal (unit symbol Pa), therefore, is the pressure at which a force of 1 N ($= 1\,\text{kg}\cdot\text{m/s}^2$) is exerted perpendicularly to a flat surface of $1\,\text{m}^2$. A number of additional pressure units are in use; the most important are listed in Table 1. According to SI, the only additional unit accepted besides Pa is bar (and

Table 1: Pressure units according to ISO 3529/1

Unit Symbol	Unit, definition	Conversion
bar	Bar	1 bar = 10^5 Pa
mbar	millibar	1 mbar = 100 Pa
Torr	Torr 1/760 of standard pressure p_0	1 Torr $= \frac{101325}{760}\,Pa \approx$ 133.32 Pa
mmHg	Millimeters of mercury = the pressure exerted at the bottom of a vertical column of mercury, 1 mm deep, at standard acceleration due to gravity and at 0 °C	1 mmHg ≈ 133.32 Pa
psi	Pound-force per square inch = pressure due to weight (at standard acceleration due to gravity) of one American pound to an area of one square inch	1 psi ≈ 6894.76 Pa

mbar). The unit mmHg is often used in medicine (for blood pressure, internal eye pressure). In the United States, the units torr and, for higher pressures, psi are common in vacuum technology.
During their motion the molecules suffer collisions between themselves. The distance traversed by a molecule between successive collisions is its free path. Since the magnitude of this distance is a function of the velocities of the molecules, the conception of mean free path λ is used. This is defined as the average distance traversed by all the molecules between successive collisions with each other, or as the average of the distances traversed between successive collisions by the same molecule, in a given time. It can be shown [1], that for a molecule having a diameter ξ at absolute temperature T and pressure p:

$$\lambda = \frac{kT}{\sqrt{2}\pi\xi^2 p} \tag{3}$$

We distinguish four different vacuum ranges, depending on the lower pressure limit of the achievable vacuum:

- low vacuum: $1\,\text{hPa} < p < 1000\,\text{hPa}$
- medium vacuum: $10^{-3}\,\text{hPa} < p < 1\,\text{hPa}$
- high vacuum: $10^{-7}\,\text{hPa} < p < 10^{-3}\,\text{hPa}$
- ultra high vacuum: $p < 10^{-7}\,\text{hPa}$

Table 2: Values of molecular density n and mean free path λ as a function of pressure p for air at 25 °C

p [Pa]	p [mbar]	$n\left[cm^{-3}\right]$	λ [cm]
101325	1013.25	$2.46{\cdot}10^{19}$	$6.7{\cdot}10^{-6}$
133.32	1.33	$3.25{\cdot}10^{16}$	$5.1{\cdot}10^{-3}$
0.13	$1.33{\cdot}10^{-3}$	$3.25{\cdot}10^{13}$	5.1
$1.33{\cdot}10^{-4}$	$1.33{\cdot}10^{-6}$	$3.25{\cdot}10^{10}$	$5.1{\cdot}10^{3}$
$1.33{\cdot}10^{-7}$	$1.33{\cdot}10^{-9}$	$3.25{\cdot}10^{7}$	$5.1{\cdot}10^{6}$
$1.33{\cdot}10^{-10}$	$1.33{\cdot}10^{-12}$	$3.25{\cdot}10^{4}$	$5.1{\cdot}10^{9}$
$1.33{\cdot}10^{-13}$	$1.33{\cdot}10^{-15}$	32.5	$5.1{\cdot}10^{12}$

Table 2 lists values of λ and molecular density n at different pressures for air at 25 °C [1].

1.2 Flow regimes, conductance, and throughput

1.2.1 Flow regimes

The gas in a vacuum system can be in a *viscous* state, in a *molecular* state or in a state which is *intermediate* between these two. When a system is brought from the atmospheric pressure to "high vacuum", the gas in the system goes through all these states. The mean free path of the gas molecules is very small at

atmospheric pressure (see table 2) so that the flow of the gas is limited by its *viscosity*. At low pressures where the mean free path of the molecules is similar to the dimensions of the vacuum enclosure, the flow of the gas is governed by viscosity as well as by molecular phenomena; this is the *intermediate flow*. At very low pressures where the mean free path is much larger than the dimensions of the vacuum enclosure, the flow is *molecular*. In the range where the state of the gas is *viscous*, the flow can be *turbulent* or *laminar*. When the velocity of the gas exceeds certain values, the flow is turbulent, the flowing gas layers are not parallel, their direction is influenced by any obstacle in the way. In the cavities formed between layers, spaces of lower pressures appear. At lower velocities the viscous flow is laminar, i.e. the layers are parallel, their velocity increasing from the walls toward the axis of the pipe. Thus the flow can be *turbulent, laminar, intermediate* and *molecular*. The limit between the turbulent and laminar flow is defined by the value of *Reynold's number* while those between *laminar, intermediate* and *molecular* flow are described by the value of the *Knudsen number*. The *Reynold's number* is a dimensionless quantity expressed by

$$R_e = \frac{\rho v D}{\eta} \tag{4}$$

where ρ is the density of the gas, v the velocity, η the viscosity, and D the diameter of the tube. It was established that for *Reynold's numbers*, larger than 2100, the flow is entirely turbulent, while for $R_e < 1100$ it is entirely laminar. The exact value of R_e for which the flow changes from turbulent to laminar depends upon the roughness of the surface of the tube and other experimental factors, but for most cases the mentioned range is valid.

The Knudsen number K_n is the ratio λ/D between the mean free path λ and the diameter of the pipe (vessel) D. In terms of K_n the flow ranges can be defined as

$$K_n < \frac{1}{110} \qquad \rightarrow \text{viscous flow} \tag{5}$$

$$1 \geq K_n \geq \frac{1}{110} \qquad \rightarrow \text{intermediate flow} \tag{6}$$

$$K_n > 1 \qquad \rightarrow \text{molecular flow} \tag{7}$$

1.2.2 Conductance

The flow of a gas can be interpreted as the number of molecules N, passing per unit time through a cross section of the pipe. Considering two subsequent cross sections 1 and 2 of the same pipe, the number of molecules crossing them will be

$$N_1 = A_1 v_1 n_1 = S_1 n_1 \tag{8}$$

and

$$N_2 = A_2 v_2 n_2 = S_2 n_2 \tag{9}$$

where A is the area of the cross sections, v is the flow velocity of the gas, n is the number of molecules per unit volume, while $S = Av$ is the rate of flow, or the *pumping speed*. In a permanent flow, the number of molecules crossing the various cross sections is the same. Thus $N_1 = N_2 = N$, and

$$N = S_1 n_1 = S_2 n_2 \tag{10}$$

By writing that the drop in molecular density (or the pressure drop since $p \propto n$) is proportional to the number of molecules, it results that

$$N = C(n_1 - n_2) \tag{11}$$

where the factor C can be a constant or a function of the molecular density (pressure). The factor C is called the *conductance* of the pipe. From eqs.(11) and (10) we have

$$\frac{1}{C} = \frac{n_1 - n_2}{N} = \frac{1}{S_1} - \frac{1}{S_2} \tag{12}$$

Since S_1 and S_2 have volume/time dimensions, the *conductance* is also expressed in [$\mathrm{m^3\,s^{-1}}$] units.
When pipes 1, 2, ... are connected in *parallel* then the total conductance C_p is given by

$$C_p = C_1 + C_2 + ... \tag{13}$$

When conductances are connected in *series* the total conductance C_s is given by

$$\frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_2} + ... \tag{14}$$

1.2.3 Throughput and pumping speed

The pumps used in a vacuum system remove (evacuate) gas from the system. The rate at which the gas is removed is measured by the pumping speed S_p. The pumping speed is defined as the volume of gas per unit of time dV/dt which the pumping device removes from the system at the pressure existing at the inlet to the pump. The pumping speed is expressed in liter/sec, $\mathrm{m^3}$/hr, etc. The throughput Q is defined as the product of the pumping speed and the inlet pressure, i.e.

$$Q = p \cdot S_p = p\frac{dV}{dt} \tag{15}$$

The throughput is also defined as the quantity of gas, in *pressure* $\times$ *volume* units, at a specified temperature, flowing per unit time across a specified cross section. The throughput is expressed in [$\mathrm{Pa \cdot m^3/s}$] or [$\mathrm{mbar \cdot L/s}$] at a specified temperature (usually 0°C or 25°C). By multiplying Eq.11 by kT, it results

$$NkT = C(n_1 kT - n_2 kT) \tag{16}$$

and with eqs.10,15

$$NkT = Np/n = S \cdot p = Q = C(p_1 - p_2) \tag{17}$$

According to Eq.17, Q is the quantity of gas entering per unit of time the pipe with conductance C, at pressure p_1. If no additional gas leaks into or is removed from the pipe this same quantity of gas Q comes out of the pipe at pressure p_2. Thus *if the system is isothermic* (Eq.17), *Q is the same all over the system.* By analogy with the expression (15), the pumping speed at any point of the vacuum system is

$$S = \frac{Q}{p} \tag{18}$$

where Q is the throughput in the system and p is the pressure at the point at which the pumping speed is defined. Substituting the values of $p_1 = Q/S_1$ and $p_2 = Q/S_2$ into Eq.17 we have

$$\frac{1}{S_1} = \frac{1}{S_2} + \frac{1}{C} \tag{19}$$

which is identical to Eq.12. This equation shows that the pumping speed at any point in the system can be obtained from the known pumping speed at some other point and the conductance of the portion of the system (pipes, holes, valves etc.) in between. The pumping speed S obtained in a chamber, connected by a conductance C, to a pump having a pumping speed S_p, is given by

$$\frac{1}{S} = \frac{1}{S_p} + \frac{1}{C} \tag{20}$$

If Eq. 20 is expressed in the form

$$\frac{S}{S_p} = \frac{\frac{C}{S_p}}{1 + \frac{C}{S_p}} \tag{21}$$

the decrease of the pumping speed $\frac{S}{S_p}$ results as a function of the ratio $\frac{C}{S_p}$ between the conductance of the system and pumping speed (of the pump). This relationship is represented in Fig. 1. It can be seen that when the value of the conductance is equal to that of the pumping speed of the pump, 50% of the pumping speed is used at the vacuum vessel. In order to use 80% of the pumping speed the ratio $\frac{C}{S_p}$ must be 4, while for a ratio $\frac{C}{S_p}$=0.1, only 10% of the pumping speed of the pump is felt in the vacuum enclosure. From this it results that it ***is no use increasing the pump, if the conductance of the pipe is the factor which limits the pumping speed.***

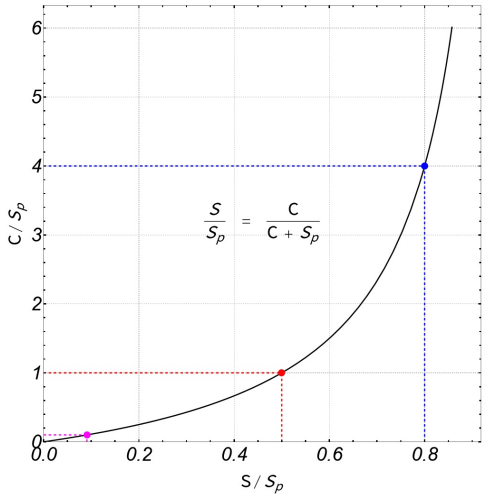


Figure 1: $\frac{S}{S_p}$ as a function of $\frac{C}{S_p}$.

1.3 Molecular flow - conductance of an aperture and a pipe

A volume where the pressure is p_1 is connected through an aperture (area A) to a second volume where the pressure is $p_2 < p_1$. If the pressure p_1 is low enough for molecular flow (see Table 2 and Eq.7), the

rate at which the gas passes through the aperture from p_1 to p_2 is (Eq.15)

$$Q_1 = p_1 \frac{dV}{dt} \tag{22}$$

while the gas passing from p_2 to p_1 is

$$Q_2 = p_2 \frac{dV}{dt} \tag{23}$$

In molecular flow, where there is no collision between molecules, they *pass through the aperture in both directions without any influence on each other*. The throughput is the difference:

$$Q = Q_1 - Q_2 \tag{24}$$

which is directed from p_1 toward p_2, since $p_1 > p_2$. It can be shown [1] that

$$Q = Q_1 - Q_2 = \left(\frac{R}{2\pi}\frac{T}{M}\right)^{1/2} A(p_1 - p_2) \tag{25}$$

where R is the universal gas constant, T is the absolute temperature and M the molar mass of the gas. Thus, from Eq.17, *the conductance of an aperture of area A (in molecular flow)* is :

$$C = \frac{Q}{p_1 - p_2} = \left(\frac{R}{2\pi}\frac{T}{M}\right)^{1/2} A \tag{26}$$

For air with $M = 0.029\,\mathrm{kg\,mol^{-1}}$ at 20 °C Eq.26 yields (in SI units)

$$C\,[\mathrm{m^3\,s^{-1}}] = 115.7 \cdot A\,[\mathrm{m^2}] \tag{27}$$

or :

$$\boxed{C\,[\mathrm{L\,s^{-1}}] = 11.6 \cdot A\,[\mathrm{cm^2}]} \tag{28}$$

Similarly, it can be shown that the conductance of a long pipe with a uniform circular cross section and a diameter of D and a length of L is given by

$$C_p = \frac{1}{6}\left(\frac{2\pi RT}{M}\right)^{1/2} \frac{D^3}{L} \tag{29}$$

For air at 20 °C Eq.29 yields (in SI units)

$$C_p\,[\mathrm{m^3\,s^{-1}}] = 121.1 \cdot \frac{D^3\,[\mathrm{m^3}]}{L\,[\mathrm{m}]} \tag{30}$$

or:

$$\boxed{C_p\,[\mathrm{L\,s^{-1}}] = 12.1 \cdot \frac{D^3\,[\mathrm{cm^3}]}{L\,[\mathrm{cm}]}} \tag{31}$$

2 Calculation of vacuum systems

2.1 Sources of gas in vacuum systems

A vacuum system is the assembly of the components used to obtain, to measure and to maintain the vacuum in a chamber, or device. Any vacuum system is made up of a pump (or pumps), gauges and pipes connecting them together. The system contains also valves, traps, motion seals, electric lead-throughs In order to express the behavior of a vacuum system, the various sources of gas existing in it must be considered as being at any moment in equilibrium with the pumping action of the pumps on the system. It can be considered that the sources of gas in a vacuum system are:

a) The gas molecules of the initial atmosphere enclosed in the system (Q),

b) The gas which penetrates into the system as a result of leakage (Q_L),

c) The gas provening from the outgassing of the materials in the system (Q_D),

d) The gas (or vapours) resulting from the vapour pressure of the materials (Q_V),

e) The gas entering the system by permeation through walls, windows (Q_P).

The quantities of gas resulting from sources (b) to (e) are functions of the construction of the system. For the present discussion the totality of the gas resulting from these sources (Q_G) is considered

$$Q_G = Q_L + Q_D + Q_V + Q_P \tag{32}$$

as *being constant* (for the time interval considered).

2.2 Pumpdown in the viscous range

One consideres the pumpdown of a vessel of volume V, which is connected directly to a vacuum pump. It is assumed that the pumping speed S_p is a constant. The throughput (see Eq.15) can be written in the form

$$Q = p \cdot S_p = -V\frac{dp}{dt} \tag{33}$$

where $p\left(\frac{dV}{dt}\right) = -V\left(\frac{dp}{dt}\right)$, when $pV = Const$ is used, because in the viscous regime $Q_G \ll Q$. With the initial condition $p(0) = p_0$ the solution of equation (33) reads

$$\boxed{p(t) = p_0 e^{-\frac{S_p \cdot t}{V}}} \tag{34}$$

which describes the time dependence of the gas pressure in the vessel in the viscous range - from *1* bar *to about 0.1* mbar i.e. the pressure range in which usually the flow is viscous.
When the pump is connected to the vessel via a pipe with a diameter of D and a length of L, the conductance of the pipe and the viscosity η of the gas must be considered. The time-dependent pressure $p(t)$ in

the vessel is the solution to the differential equation:

$$\boxed{\frac{dp}{dt} = \frac{A - \sqrt{A^2 + 4B \cdot p^2}}{2B}} \tag{35}$$

where $B = (V/S_p)^2$ and $A = \frac{256\eta LV}{\pi D^4}$.

2.3 Pumpdown in the molecular range

The pumpdown in the molecular range is limited by the equilibrium between the gas load and pumping speed in the pump itself, as well as by this equilibrium in the vacuum chamber. The gas load Q_o of the pump itself is constituted by the leakage into the pump, and the backstreaming of the pumping fluid. If the theoretical pumping speed of the pump is S_t, the throughput will be

$$Q = S_t P_p - Q_o = S_t p_p \left(1 - \frac{Q_o}{S_t p_p}\right) \tag{36}$$

where p_p is the pressure at the inlet of the pump. The lowest pressure of the pump p_0 will be obtained when $Q = 0$, thus

$$Q_o = S_t p_0 \tag{37}$$

The real pumping speed of the pump S_p is given by

$$S_p = \frac{Q}{p_p} = S_t \left(1 - \frac{Q_o}{S_t p_p}\right) = S_t \left(1 - \frac{p_0}{p_p}\right) \tag{38}$$

At the vacuum chamber, connected to the pump through the conductance C, the pumping speed is

$$S = \frac{S_p C}{S_p + C} \tag{39}$$

and the ultimate pressure p_u in the chamber due to the gas load is

$$p_u = \frac{Q_G}{S} = \frac{Q_G (S_p + C)}{S_p C} \tag{40}$$

It can be shown, that for a constant, independent of the pressure pumping speed S_p, the time required for lowering the pressure in the chamber from initial p_i to p is

$$t(p) = \frac{V}{S_p} \left(1 + \frac{S_p}{C}\right) \ln\left(\frac{p_i - p_u}{p - p_u}\right) \tag{41}$$

and

$$\boxed{p(t) = (p_i - p_u) e^{\left(-t \cdot \frac{S}{V}\right)} + p_u} \tag{42}$$

where S ig given by Eq.39. Furthermore, equation (42) shows that after a very long pumping time, the pressure tends toward the ultimate pressure p_u, determined by the gas load. Thus eq. (42) describes both the *transient* pumpdown

$$p(t) = p_i e^{-\frac{S \cdot t}{V}} \tag{43}$$

as well as the *steady state*

$$p(t) = p_u = \frac{Q_G}{S} = Const \tag{44}$$

3 Production of low pressures

3.1 Principles of pumping

Since vacuum technology extends on so many ranges of pressure, no single pump has yet been developed, which is able to pump down a vessel from atmospheric pressure to the high vacuum or ultra-high vacuum range. Although all the vacuum pumps are concerned with lowering the number of molecules present in the gas phase, several different principles are involved in the various pumps which are used to attain low pressures. Vacuum pumping is based on one or more of the following principles:

- *Compression-expansion* of the gas, in piston pumps, liquid column or liquid,ring pumps, rotary pumps, Root's pumps,
- *Drag by viscosity effects*, in vapour ejector pumps,
- *Drag by diffusion effects*, in vapour diffusion pumps,
- *Molecular drag*, in molecular pumps,
- *Ionization effects*, in ion pumps,
- *Physical or chemical sorption* in sorption pumps, cryopumps and gettering processes.

3.2 Parameters and classifications

The selection of the pumping principle or of the pump to be used is defined by its specific parameters. The main parameters are: the *lowest pressure*, the *pressure range*, the *pumping speed*, the *exhaust pressure*. In the ultra-high vacuum range two other parameters are added: the *selectivity* of the pump and the composition of the *residual* gas.

The lowest pressure which can be achieved by a pump at its inlet, is determined either by the leakage in the pump itself, or by the vapour pressure of the fluid utilized in the pump. This pressure determines the low pressure end of the pressure range in which the various pumping types are effective (see Fig.2). The pressure range of a single pump is that range in which the pumping speed of that pump can be considered useful. Pumps of the same type but of different sizes or constructions may have adjacent pressure ranges, so that the pressure range of a specific pumping method can be larger (Fig.2) than that of an individual pump.

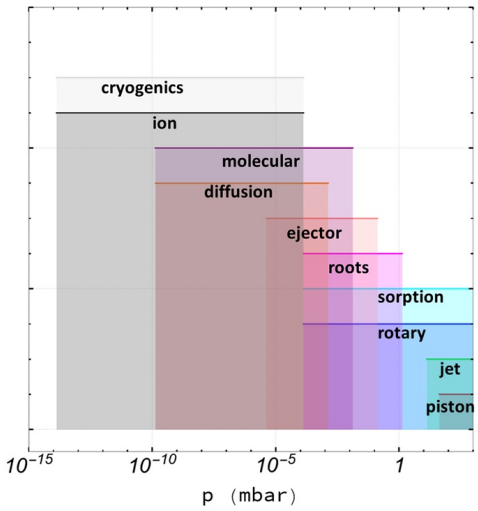


Figure 2: Pressure ranges of vacuum pumps.

The pumping speed of the pumps is not constant, but is a function of the pressure. The pumping speed vs. pressure curve of pumps has either a shape of a curve decreasing as the pressure decreases (e.g. rotary pumps), or of a curve increasing first with decreasing pressure, reaching a maximum and then decreasing as the pressure decreases (e.g. diffusion pumps, Root's pump). The classification of the pumps, according to the pressure range, is summarized in Fig.2, while the typical variation of the pumping speed is shown in Fig.3, expressed as percents of the maximum pumping speed of each type of pump.

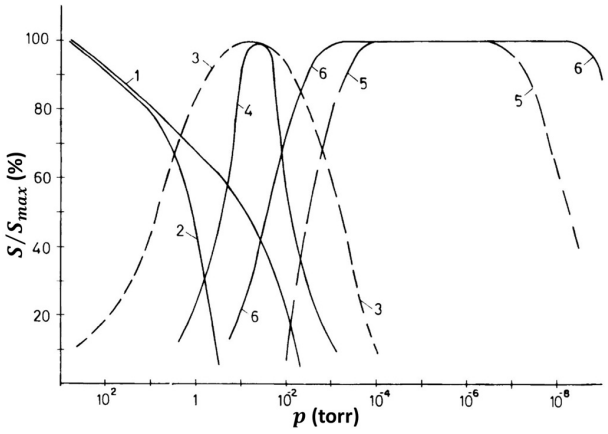


Figure 3: The pumping speed range of several pumps, in terms of their maximum pumping speed. 1- Single stage rotating-vane pump; 2. Single stage gas ballast pump; 3. Root's pump; 4. Ejector pump; 5. Diffusion pump; 6. Molecular pump

The *exhaust pressure* is the pressure against which the pump may be operated. From this point of view the vacuum pumps, which exhaust to atmosphere are usually known as roughing or *backing* pumps. The removal of the atmospheric air from the system to some acceptable operating pressure is referred to as roughing out the system. The maintenance of a required low pressure at the outlet of another pump, is referred to as backing. The ratio of the exhaust ressure to the inlet pressure is termed the pump *compression ratio*.

There are two types of pumps relevant to the experiment: scroll pumps and turbo-molecular pumps. These two types will be discussed briefly here.

3.3 Scroll pumps

A scroll pump features two nested Archimedean screws. Each screw contains an equidistant spiral wall, built onto a circular base plate. If the screws, arranged at a 180° offset, are joined, the walls sectionally enclose sickle-shaped volumes. Centrally-symmetric oscillation (orbiting) of one hull against the other

Figure 4: Working principle of the scroll pump. *source:* [3]

causes the volume to move along the spirals (Figure 4). Thus, positive displacement occurs. The inlet can be arranged at the outside; an axial borehole provides the outlet. Usually a scroll pump can pump down to pressures in the order of 0.1-0.01 mbar.

3.4 Turbomolecular pumps

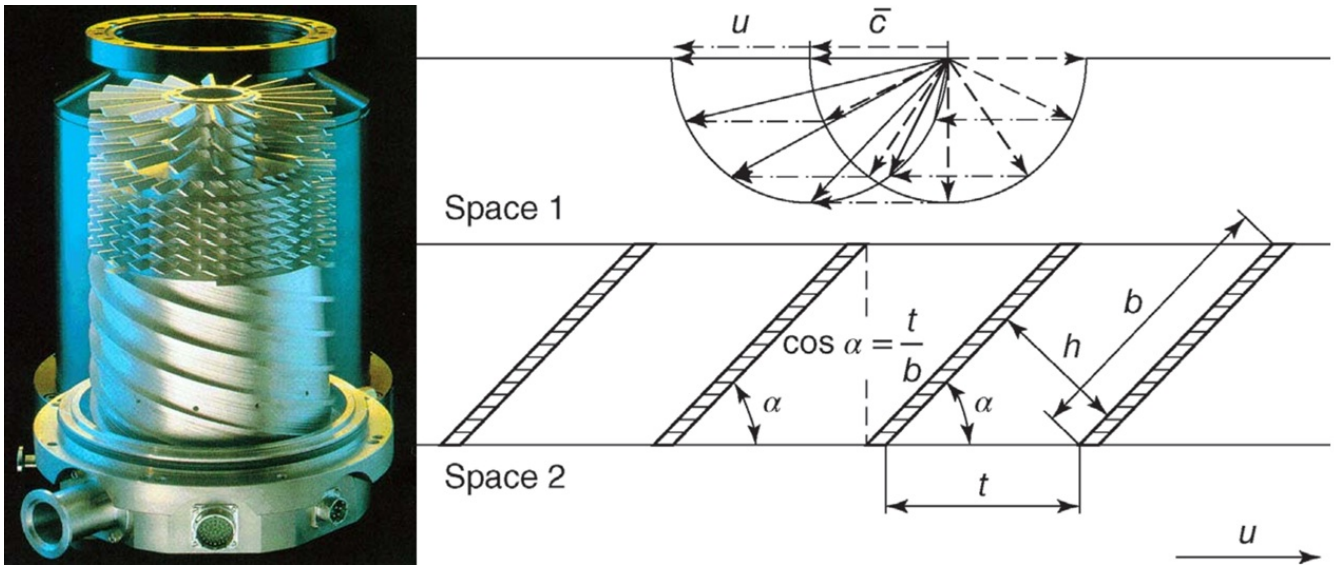


Figure 5: Working principle of turbomolecular pumps: A row of blades with distances t between the blades, blade angle α, blade width b, and channel height h moves toward the right at velocity u. For an observer moving with the blades, blade velocity u is added to the thermal velocity $\bar{c}$. For $u \approx \bar{c}$ nearly all molecules move in the direction of the channel or to the bottom side of the blades from where backflow into chamber 1 is improbable. $\cos\alpha = t/b$ is valid for an optically tight blade design.

The pumping mechanism of a turbomolecular pump stage can be understood by by investigating Fig. 5. A row of blades moving from left to right at a velocity u separates the spaces 1 and 2. Looking at the incoming particles as an observer moving with the blades, the blade velocity u will be added to the particle velocity c vectorially. In the case of approximately equal velocities u and $\bar{c}$, many particles pass through the blade channel from space 1 without touching the blades. Particles that do touch the blades 'condense' there for a given time (called the *dwell time*) and desorb according to the cosine law. For high velocities u, many particles touch the bottom surface of the blades and desorb mainly into space 2. If the same concept is applied to space 2, obviously only few particles will move in the direction of the channel and, therefore, only a small fraction enters space 1. These considerations lead to the conclusion that the transmission probability P_{12} for particles passing from 1 to 2 must be higher than P_{21} in the

opposite direction. Thus, a pumping effect is produced. The rotation speed of the rotor can be as high as 90 000 rpm. Usually a turbomolecular pump can evacuate to pressures down to 10^{-8} mbar.

3.5 Ion-pumps

If a gas is ionized and the resulting positive ions are accelerated to a negatively charged plate, atoms of the gas are effectively removed from the system, and thus a pumping action is produced. The general term ion-pump includes those vacuum pumps in which gas molecules are pumped by being ionized and transported in the desired direction by an electric field. The ionization may be produced by collisions of the gas molecules with electrons emitted either from a hot filament or from a cold cathode discharge. The first type of pump is referred to as hot cathode ion-pump, while those belonging to the second type are known as cold cathode ion-pumps. Sorption in ion getter pumps relies on (cathodic) sputtering of a getter material inside a gas discharge, and additionally, on bombardment (implantation) of ions from the gas discharge. Gas discharge in an ion getter pump is of the *Penning* type (see Section 4.3.2). Figure 6 illustrates an electrode arrangement, two parallel cathode plates $K1$ and $K2$, and an anode cylinder A with the z-axis arranged perpendicularly to the cathode planes. A magnetic field of flux density B is aapplied in the z-direction. In detail, the pumping effects are as follows:

a) *Ion implantation*. The applied electrical potential (6 kV) accelerates the ions produced in the discharge to several kV, depending on their point of origin. Acceleration occurs nearly along a straight path toward the cathode because the ions, due to their large mass compared to electrons, are hardly influenced by the magnetic field. The ions penetrate the crystal structure of the cathode by approximately 10 atomic layers (ion implantation). This corresponds to a gas depletion that affects any species of gas ion including atomic and molecular ions of noble gases and other gas species. However, very large molecular ions, such as hydrocarbons, do not penetrate the lattice structure.

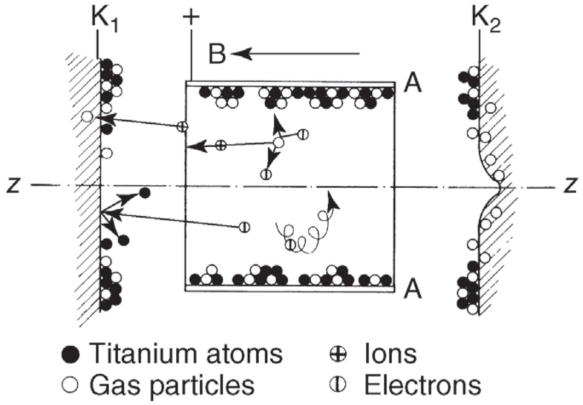


Figure 6: Diagram of the pumping action in a Penning cell (diode). $K1, K2$ cathode plates made of getter material (titanium), A anode cylinder with the z-axis, B magnetic field. The getter film with buried gas particles is visible on A and toward the ends of $K1$ and $K2$. Implanted gas particles in the center of $K2$ (and $K1$ as well, not drawn).

b) *Cathode sputtering*. The ions hitting the cathode are implanted in part and sputter individual or larger numbers of lattice atoms. These atoms are released and deposit on surrounding surfaces where they form the getter film when the cathode is made from getter material (e.g., titanium). The mass of the sputtered material is roughly proportional to the pressure in the pump so that the pumping speed adjusts to this pressure. Depending on the field configuration caused by the electrons and the volume charge in the discharge, the ions accelerated toward the cathode can become focused

to the z-coordinate. This produces a sputter crater in the center of the cathode (Figure 6, cathode $K2$). In any case, getter action takes place mainly at the edges of the cathodes and at the anode; implantation occurs mostly in the center of the crater because the getter film here is resputtered.

c) *Neutral particle implantation*. When ions, particularly noble-gas ions, impinge the surface, they can be reflected if they become neutralized in the metal. Indeed, this occurs often in an ion getter pump. Neutralized gas particles then become implanted at other spots because they still carry high kinetic energy.

4 Measurement of low pressures

4.1 Overview

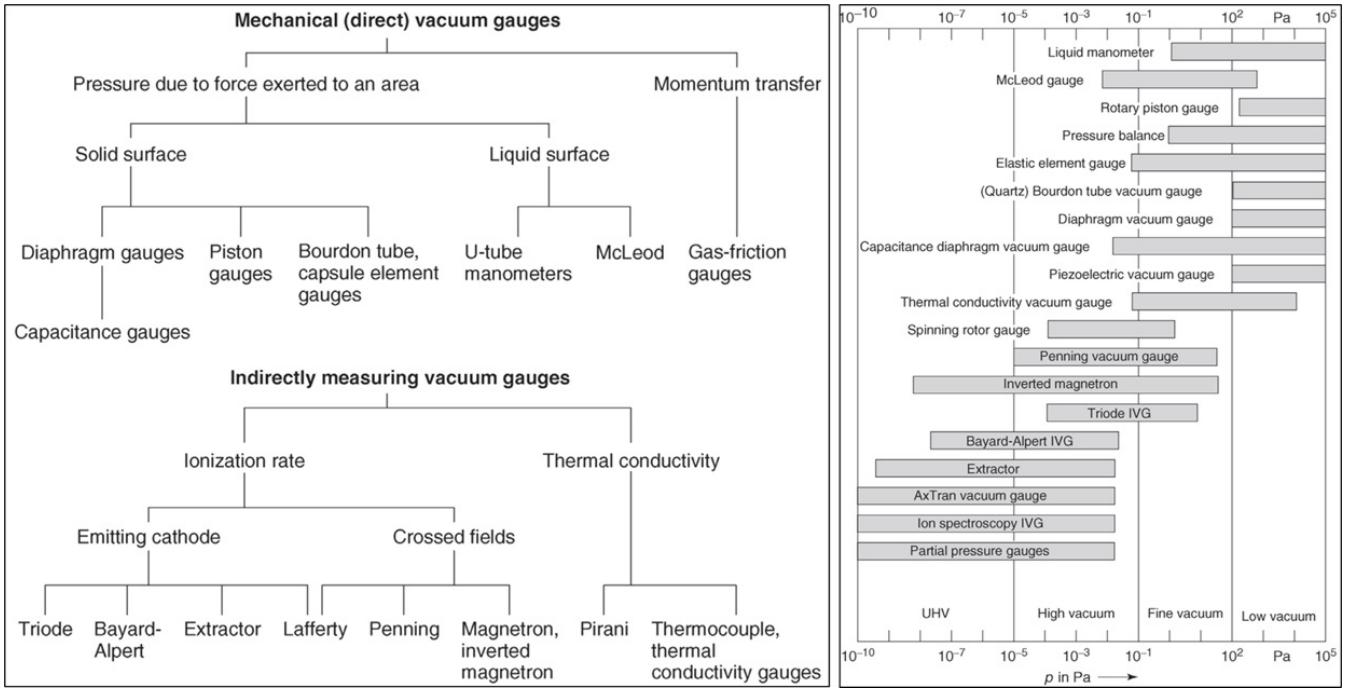


Figure 7: *left:* Classification of common vacuum gauges according to their physical principles. Crossed fields mean crossed electric and magnetic fields, *right:* Overview of measuring ranges of commercial vacuum gauges. In the ranges indicated, the specified measuring principles provide acceptable accuracy. IVG: ionization vacuum gauge.

Vacuum technology measures pressure p either directly according to its defining equation, by measuring the force $F = p \cdot A$ exerted to an area A or indirectly by measuring a physical quantity proportional to the pressure, for example, particle number density n, particle impingement rate n_c, and thermal conductivity, among others. Measuring pressure directly by assessing the effect of a force is limited to pressures greater than approximately 1 mPa. At this pressure, the force exerted to 1 cm^2 amounts to only about 10^{-7} N. Measuring such low forces requires an electrically amplified signal. The pressure range measured in vacuum technology spans across 15 powers of magnitude. No single gauge type covers the whole range. Figure 7 (*left*) classifies common vacuum gauges according to their physical measuring

principles. Figure 7 (*right*) provides an overview of the gauges common to individual pressure ranges. The operation principle of some relevant vacuum gauge types will be briefly discussed below.

4.2 Thermal Conductivity Vacuum Gauges

Thermal conductivity vacuum gauges are pressure measuring instruments for medium and low vacuum that measure the pressure-dependent thermal loss (loss of energy) of a heated element, usually a wire, through the gas. The measuring principle is based on a heated wire and electronics that measure its resistance or dissipated power. Thermal conductivity vacuum gauges are often referred to as Pirani gauges. These gauges offer several different modes of operation: gauges that maintain constant wire temperature and measure the required heating power, which depends on the pressure, represent the most precise setup and show the largest linear measuring range (0.1 Pa to 10 kPa). However, measuring technology here is the most complex and thus expensive. Alternatively, the heating power or current can be kept constant and the resistance variation can be used as a measure of pressure. Also, circuits that keep heating power constant and measure the temperature, which depends on the gas pressure, are possible. Usually, a thermocouple is used for this temperature measurement. Here, however, the measuring range is only approximately 0.1 Pa to 1 kPa. Less sophisticated and cheaper versions use a simple thermocouple for measuring the current that follows the contact voltage in the thermoelement if the heated wire receives constant current. Their measuring range is 0.1-100 Pa.

The principal design of a thermal conductivity vacuum gauge (Figure 8) usually includes a wire W with a diameter of 5-20 µm and length of 50-100 mm suspended axially in a cylindrical tube of 10–30 mm diameter. When the wire is heated electrically, it approaches an equilibrium temperature T_1 at which the supplied electrical power $\dot{Q} = U \cdot I$ equals the dissipated thermal power. The latter is made up of four components (Figure 9):

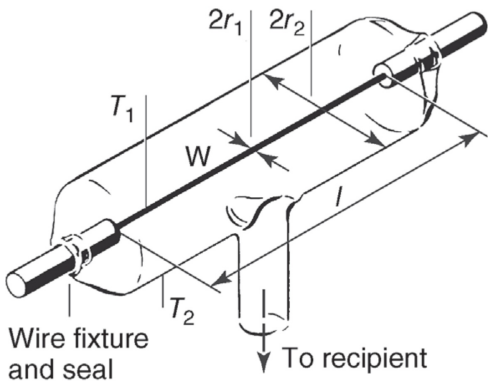


Figure 8: Basic setup of a thermal conductivity vacuum gauge.

1. Thermal conduction $\dot{Q}_{gas}$ via the gas between the warm wire and the wall at room temperature. The energy flux rate or dissipated thermal power is proportional to the pressure p.

2. Thermal conduction $\dot{Q}_{end}$ at the wire ends via the wire fixing.

3. Thermal radiation $\dot{Q}_{rad}$ emitted by the hot wire (hot with respect to its surrounding).

4. Thermal conduction due to convection at pressures $\dot{Q}_{conv} > 1\,\mathrm{kPa}$

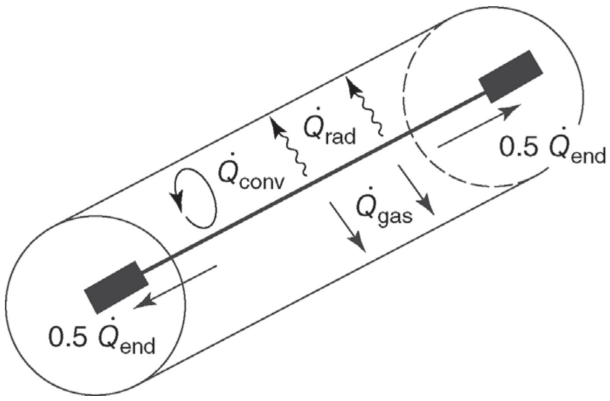


Figure 9: Heat fluxes from a heating wire in a thermal conductivity vacuum gauge: $\dot{Q}_{gas}$ via the gas, $\dot{Q}_{rad}$ due to radiation, $\dot{Q}_{conv}$ due to convection, and $\dot{Q}_{end}$ due to thermal conduction.

$\dot{Q}_{rad}$ and $\dot{Q}_{end}$ are are disturbing effects that create the false impression of a gas pressure in the measuring cell even if the cell does not contain any gas. The heat dissipation due to convection dominates at high pressures, where $\dot{Q}_{gas}$ is pressure independent. At low pressures, thermal radiation, which is also pressure independent, dominates so that the measured signal merges into a constant offset Thus, only for pressures at which $\dot{Q}_{gas} \propto p$, measuring the electrical heating power supplied to the wire in a measuring cell, or a related quantity, with respect to pressure p, yields a linear proportional signal.

4.3 Ionization Gauges

Ionization gauges measure pressures indirectly by determining an electrical quantity proportional to the particle number density n. In order to make this quantity available, the gas whose pressure is to be measured is partially ionized in the measuring head of the ionization gauge. Depending on the method of ionization, the measured electrical quantity is either a pure ion flow (hot- or emitting-cathode ionization gauge) or a gas discharge flow (crossed-field ionization gauge). In the hot-cathode gauge, the electrons used for ionizing the gas are emitted from an emissive cathode, usually a glow cathode, and accelerated toward a surrounding anode screen. The electrons emitted by cathode C with a current I^- collide with gas particles that subsequently become ionized with a certain probability. The resulting positive ions reach the ion collector (IC) and are measured as an ion current I^+. The gas discharge current is pressure dependent and is used as a measure of gas density, that is, gas pressure p.

4.3.1 Hot-cathode ionization gauges, Bayard–Alpert Gauges

In any ionization gauge, the residual gas existing in the gauge head is subjected to ionizing radiation and some of the gas molecules become ionized. Hot cathode ionization gauges use the thermionic emission of a cathode, the emitted electrons being accelerated by the electrostatic field through the grid of radius r_g (Fig. 10) set at a positive potential $V_g \approx 200\,\mathrm{V}$ relative to the cathode. The anode of radius r_a is set at a

negative potential $V_a \approx -20\,\mathrm{V}$ relative to the cathode. The grid is made of fine wire, thus most of the electrons coming from the cathode miss the grid wires and continue toward the anode until they reach a point at which the electrical potential is the same as that of the cathode. From this point (shaded area, Fig. 10) the electrons are turned back to oscillate radially, through the grid until they finally strike a grid wire and are captured. The oscillating electrons will eventually collide with gas molecules, and ionization of the gas molecules may occur. The positive ions which are created in the annulus between grid and anode are driven to the anode, and produce an ion current.

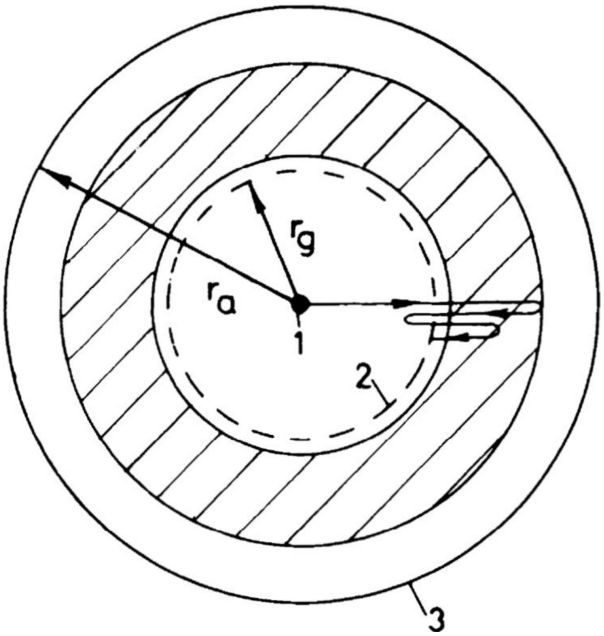


Figure 10: Typical electron trajectory in a hot-cathode ionization gauge. 1. Cathode; 2- Grid; 3. Anode.

The above operation principle is that of the oldest type of hot-wire ionization gauge system - the concentric triode. The problem with this system is that when electrons impinge on matter, they release photons (X-rays). The number of photons released is proportional to the electron current. When these photons hit metal surfaces, they release photoelectrons that leave the surface if an appropriate electrical field is present. In an ionization gauge, such a field exists at the ion collector. The pressure-dependent photoelectron current leaving the collector is proportional to the electron current and adds a constant value to the positive ion current toward the collector.

Thus, pressure readings are too high. For reducing the X-ray effect, *Bayard and Alpert* suggested building an ionization gauge (see Fig.11) in which the surface of the ion collector was particularly small. The fundamental step in this direction is interchanging the positions of the hot-cathode and the ion collector and using a wire as the ion collector. This reduced the X-ray limit to about 10^{-10} mbar.

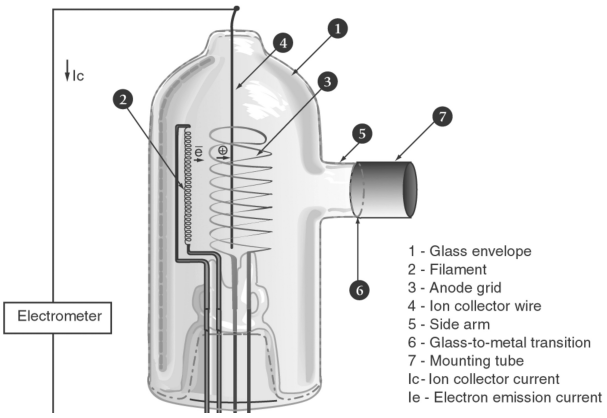


Figure 11: Typical Bayard-Alpert ionisation gauge.

4.3.2 Crossed-Field Ionization Gauges, inverted magnetron gauge

The operation principle of these gauges for low pressures uses a gas discharge ignited between two metal electrodes (anode, cathode) by applying sufficiently high DC voltage (in the kilovolt range). The gas discharge current is pressure dependent and thus used as measured quantity. However, if no additional

measures are taken, the lower measuring limit is only about 1 Pa. At lower pressures, the number of carriers produced is insufficient for sustaining the gas discharge. The so-called *Penning* discharge maintains gas discharge even down to very low pressures. For this, it uses a sufficiently powerful magnetic field arranged so that the electron paths from the cathode to the anode are stretched considerably by forcing the electrons onto spiral paths. This leads to higher ion yield. Due to their higher mass, ions are hardly distracted by the magnetic field and travel directly to the cathode. Secondary electrons, produced when the ions impinge on the cathode, nourish the discharge.

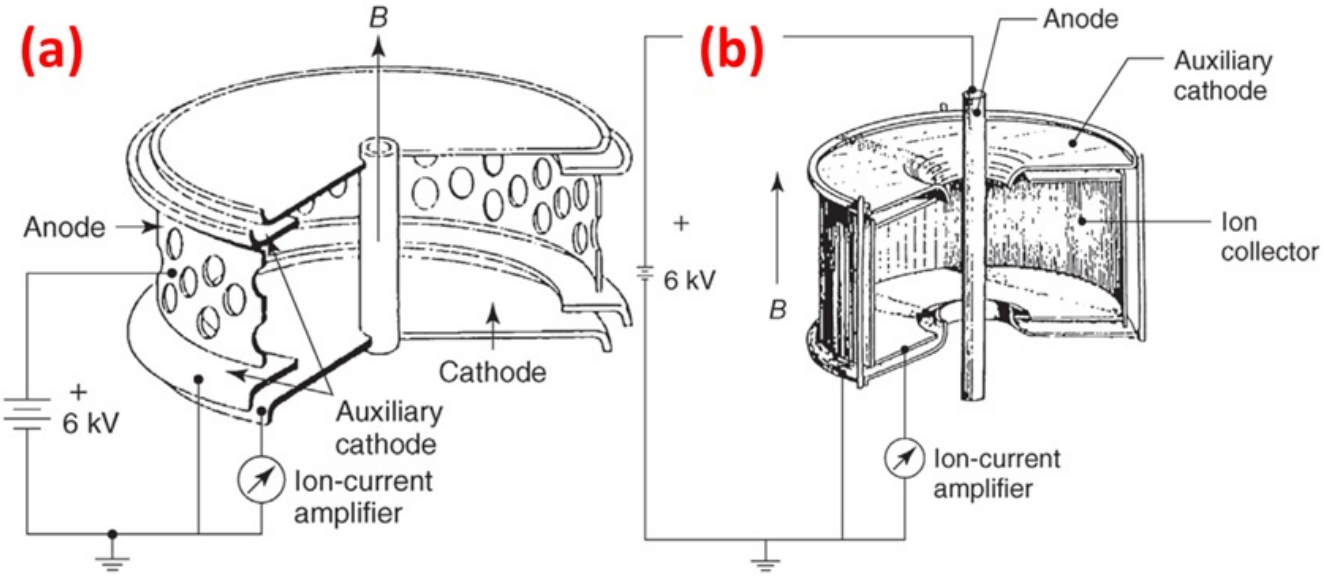


Figure 12: Diagram of a magnetron (a), and inverted magnetron (b).

In order to stabilize the discharge and improve starting behavior, *Redhead* developed the magnetron and *Hobson and Redhead* designed the inverted magnetron (see Fig. 12(a)). In a magnetron, the anode is an open cylinder. The cathode forms axis and both end plates of the cylinder. In the inverted magnetron (see Fig. 12(b)), the anode is a rod on the axis of a nearly closed cylinder serving as cathode. In the magnetron, two annular rings at cathode potential shield the end disks of the cathode from the high electrical fields. In inverted magnetrons, guard rings prevent field emission currents between the cathode and the anode. The magnetic field is parallel to the anode. Both types of gauges with crossed electromagnetic fields trap electrons more efficiently than the Penning type. This improves starting conditions and the discharge is stable down to much lower pressures. The usable pressure range goes down to 10^{-13} mbar.

5 Experimental setup- and procedures

Practice course will be held in the Vacuum technology laboratory of CANDLE synchrotron research institute. The practice course has 2 main tasks:

1. Determination the pumping speed in the end volume for different pumps and gauges.
2. Measurement of the vacuum conductance of aperture.

5.1 TASK 1

The first task of the practical course consists of the following stages:

- Preparation of vacuum components

for the Assembly of the vacuum chamber, including a vacuum chamber, measuring sensors (full pressure sensor, inverted magnetron sensor, ionization sensor), gate elements (valves and valves), vacuum pumps, adapters for vacuum pumps, sealing elements, controllers and power supplies.

Preparation of vacuum components is a special cleaning procedure to remove dirt from the internal surfaces formed as a result of being in the open state, storage, etc. All the main elements of the vacuum chamber and adapters are made of 304 stainless steel. Thus, the cleaning procedure of the components should be carried out according to the technology given below.

The procedure described below for cleaning stainless steel is a very high specification process for the very demanding requirements of an electron storage ring where cleanliness is of paramount importance. For less demanding applications, the procedure could stop at the appropriate point in the procedure where requirements had been met.

1. Remove all debris such as swarf by physical means such as blowing out with a high pressure air line, observing normal safety precautions. Remove gross contamination by washing out, swabbing or rinsing with any general purpose solvent. Scrubbing, wire brushing, grinding, filing or other mechanically abrasive methods may not be used.

2. Wash in a high pressure hot water (approx. 80^{o}C) jet, using a simple mild alkaline detergent. Switch off detergent and continue to rinse thoroughly with water until all visible traces of detergent have been eliminated.
3. If necessary, remove any scaling or deposited surface films by stripping with alumina or glass beads in a water jet in a slurry blaster.
4. Wash down with a high pressure hot (approx. 80^{o}C) water jet, with no detergent, ensuring that any residual beads are washed away. Pay particular attention to any trapped areas or crevices.
5. Dry using an air blower with clean dry air, hot if possible.
6. Immerse completely in an ultrasonically agitated bath of clean hot stabilised trichloroethylene for at least 15 minutes, or until the item has reached the temperature of the bath, whichever is longer.
7. Vapour wash in trichloroethylene vapour for at least 15 minutes, or until the item has reached the temperature of the hot vapour, whichever is longer.
8. Ensure that all solvent residues have been drained off, paying particular attention to any trapped areas, blind holes etc.
9. Wash down with a high pressure hot (approx. 80^{o}C) water jet, using clean demineralised water. Detergent must not be used at this stage.
10. Immerse in a bath of hot (60^{o}C) alkaline degreaser (P3 Almeco P36) with ultrasonic agitation for 5 min. After removal from the bath carry out the next step of the procedure immediately.
11. Wash down with a high pressure hot (approx. 80^{o}C) water jet, using clean demineralized water. Detergent must not be used at this stage. Ensure that any particulate deposits from the alkaline bath are washed away.
12. Dry using an air blower with clean dry air, hot if possible.
13. Allow to cool in a dry, dust free area. Inspect the item for signs of contamination, faulty cleaning or damage.
14. Vacuum bake to 250^{o}C for 24 hours using an oil free pumping system.
15. Reduce the temperature to 200^{o}C and carry out an internal glow discharge using a helium 10% oxygen gas mix.
16. Raise the temperature to 250^{o}C for a further 24 hours then cool to room temperature.

For other components, the cleaning procedure is carried out according to the requirements of the technical documentation from the manufacturer. It should be noted for vacuum pumps cleaning procedure is not carried out due to the peculiarities of their operation and storage. In the practical course, the complete cleaning procedure of the vacuum components will be carried out in advance by the laboratory staff and pre-Assembly of the components to the vacuum chamber will be carried out. Participation in the procedure of cleaning components before installation is provided in the second task of the practical course.

After pre-installation of vacuum components, measuring equipment and vacuum pumps, the vacuum system is sealed and can be left in the open air without additional insulation procedures.

- Pre-installation of the vacuum system.

Installation of the vacuum system is carried out according to the scheme shown in Figure 5.1.

Installation of the vacuum system is carried out in the following sequence:

- Mounting the blank flange to the vacuum chamber.
- Installation of measuring equipment to the vacuum chamber.
- Mounting the shutter 8 to the vacuum chamber
- Mounting the gate 9 to the vacuum chamber.
- Closing gates 8 and 9.
- Installation of flexible connection 10 to the chamber and turbomolecular pump.
- Installation of the ion pump.

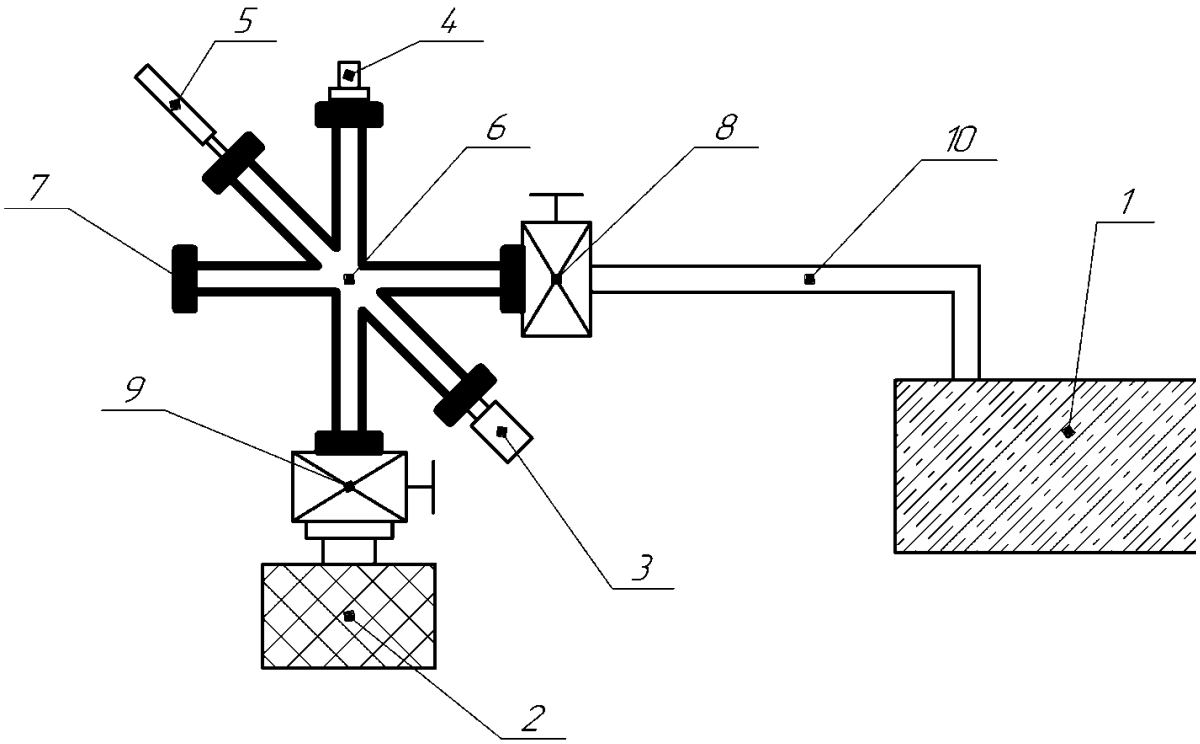


Figure 5.1 – Principal scheme of vacuum system. 1 – TPS-compact Turbo vacuum pump, 2 – Ion Pump, 3 – Pirani, Bayard-Alpert gauge, 4 – IMG 300 gauge, 5 - Hot filament ionization gauge 270 (HFIG 270), 6 – vacuum chamber, 7 – Blank flange CF35, 8 – Turbo pump valve, 9 – Ion pump gate valve, 10 – Flexible connecting bellow.

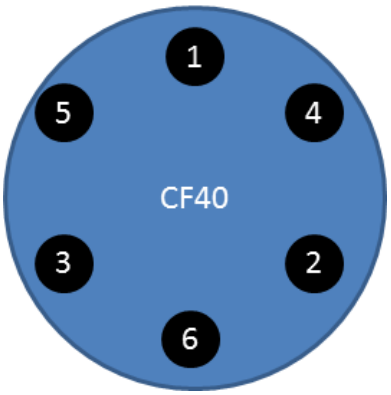


Figure 5.2 CF-40 flange nut tightening sequence

Installation of the ion pump is carried out in the last place to prevent long-term contact with open air. Most of the elements of the vacuum chamber is equipped with vacuum flanges CF 35, which is designed for use as a copper gasket seal (Fig. 3.6). Technology to tighten the flanges to obtain a uniform compression and a minimum clearance between the flanges is presented below [8].

The implied but unvoiced condition is to ensure that the Cu gasket is evenly clamped and creating a leak-free seal. In regard to the order to tighten the nuts the general rule is

“Do one miss one, until you land back where you started and when you do, do not do that one but instead the next one, then do one miss one in the opposite direction and try to ensure even loading by only increasing the tightness by ¼ a turn on each nut” Needless to say this is expressed more simply in a diagram, and pay attention to figure 5.2. Once you reach nut 6, restart again from nut 1 and continue until the copper of the gasket is just visible between the flanges (~1.5 mm) or if using a torque wrench set it to 20 Nm.

Once the vacuum system is installed, all flange connections are insulated with Teflon tape to prevent contamination from entering the gaps between the flanges through the leak check holes. Otherwise, accumulated contamination in the gaps between the flanges may enter the vacuum system during scheduled operations or equipment replacement.

- Bakeout

In order to obtain UHV, a system needs to be “baked”, i.e. heated to high temperatures (100 - 300 degrees °C or so). The reason is that rest gas (mostly water) is adsorbed to the chamber walls and the vapour pressure from the water is so high that the system does not go into the UHV range. This also means that the water slowly desorbs and is thus pumped away but this takes a very, very long time at room temperature [7].

The bakeout is performed in order to accelerate this process. Baking the system can take a long time because everything inside has to reach the high temperature at which the water (or other contamination) is desorbed. Especially for complicated chambers with a many thermally well-insulated components inside, getting everything to high temperatures (and down again) is necessarily slow.


Figure 5.3 View of the Bakeout setup.

There are different possibilities for heating the chamber, some are shown below. Electrical heating tapes can be used which are wrapped around the different parts of the chamber (shown in the picture below). Then everything is covered with aluminum foil for insulation and heat distribution. An easier solution is to put the whole chamber in an insulated box with some heaters inside. The drawback of this is the lack of flexibility. If you decide to attach something later to your chamber, the boxes might be too small. A good possibility is to use heating tents around the chamber, again with a heater (and sometimes a fan) in the tent.

Even if you use boxes or a tent, it is necessary to cover viewports and electrical feedthroughs with aluminum foil before bakeout to avoid thermal stress across these.

- The procedure of work

The procedure is presented in table 5.1.

Action	Description
1. Connection of power cables to vacuum pumps Connect the high voltage cable to the ion pump. Use the supplied cable or a cable with the appropriate mating connector for your feedthrough. Connect the high voltage cable to an Ion pump controller with the correct polarity. Connect the SAFECONN SMB connector, if included. Enable high voltage on the ion pump controller. The Ion pump should start immediately and follow the time, pressure, and current specifications recorded on the included certificate of conformance.	 +    +
2. Connecting cables to vacuum sensors.	 ,  ,  + 
3. Connecting cables to control devices. As a controller will be used Agilent XGS 600 controller.	 
4. Connecting cables for data collection with the monitoring instruments. For data collection we will use interfaces RS 485 an RS 232.	
5. Check the valves: Valve 9 must be opened; Valve 8 must be open (see scheme, Figure 5.1).	
6. Switch on the FRG720 gauge Gauge must show the atmospheric pressure of approximately 760 Torr.	 

7. Switch on the turbomolecular TPS compact station. Start data registration from the FRG720 gauge. On first stage starts work the fore pump IDP 3. When the pressure on FRG 720 rich the level of $8x10^{-3}$ Torr switch on another two gauges – IMG 100 and ionization gauge transducer. Start registration data from all gauges. According to the technical parameters of backing pump to identify the time of starting the turbomolecular pump.	
8. Switch on the Ion pump. Starting time of Ion pump depends on the residual pressure in vacuum system. The highest pressure when pump can be started is $7x10^{-4}$ Torr. But, for increasing life time of pump and relief starting, the pressure in vacuum system better be as lowest as possible for respective condition before starting of pump. For existing vacuum system, starting of Ion pump can be possible after reaching of pressure in $5x10^{-5}$ Torr. Switch on the Ion Pump and keep turbomolecular pump switch on before High Voltage in Ion pump controller reach 6000 V. After that close the valve 8 and switch off the turbomolecular pump. Switching on of Ion pump procedure must be fix in the data collection. This will be transitional period.	2. Switch on the High voltage (press and hold 3 s)  1. Switch on the Power 
9. Pump down the system up to the 10^{-8} Torr.	
10. Close the gate valve 9, Switch off the Ion pump and collect data during pressure increasing up to 10^{-5} Torr. On the pressure curves it will be system outgassing process. In the data analysis process to give asses to gas load rate in the chamber.	
11 Switch off all gauges and finish data collection	

Procedure of data processing is listed in Section 6.

5.2 TASK 2

The main purpose of the second task of the practical course is to determine the conductance of the vacuum pipeline depending on the aperture relative to the initial value for the corresponding type of flange connection. In the course of the work, three similar vacuum pipeline structures with different aperture ratios will be used. The standard value of the channel for the CF35 flange is accepted as 100% in the experiment. This channel is a tube Ø38,1 mm and a wall thickness of 1,65 mm. and inner diameter $38{,}1 - 2 \cdot 1{,}65 = 34{,}8$ mm. In the course of the experiment it is supposed to use apertures of 50% and 10% of the initial to determine the effect of the vacuum channel reduction on its capacity.

Define the values of the pipe diameters for the specified space of the aperture. It should be noted that the aperture values will be considered relative to the inner diameter of the initial channel.

Thus, for 50% of the aperture, the diameter value is determined by the cross-sectional area:

$$F_{50\%} = 0.5 \cdot F_{100\%}$$

$$F_{100\%} = \frac{\pi D_{100\%}^2}{4} = \frac{3.14 \cdot 34.8^2}{4} = 950.67\ mm^2$$

$$F_{50\%} = 0.5 \cdot 950.67 = 475.335\ mm^2$$

The diameter value is determined on the basis of the conversion of the area value.

$$D_{50\%} = \sqrt{\frac{4F_{50\%}}{\pi}} = \sqrt{\frac{4 \cdot 475.335}{3.14}} = 24.6\ mm$$

Based on the standard sizes of pipes according to ASTM A312 for Stainless steel gauge pipes, the nearest value corresponds to the pipe size Ø25,4 and wall thickness 1,2 mm. The inner diameter of the pipe will be $25{,}4 - 2 \cdot 1{,}2 = 23$ mm, what makes 43,7%.

For 10% of the aperture value of the pipe size is determined by a similar method:

$$F_{10\%} = 0.1 \cdot F_{100\%} = 0.1 \cdot 950.67 = 95{,}067\ mm^2$$

$$D_{10\%} = \sqrt{\frac{4F_{10\%}}{\pi}} = \sqrt{\frac{4 \cdot 95{,}067}{3.14}} = 11\ mm$$

Similarly, the nearest standard pipe size for ASMT A312 correspond to the pipe Ø12,7 mm with a wall thickness of 1.0 mm. the internal diameter of the pipe will be $12{,}7 - 2 \cdot 1{,}0 = 10{,}7$ mm, what makes 9,45%.

The pipe length for all diameters is 200 mm and the relative dimensions and parameters of the vacuum elements to be used in the experiment are shown in Fig. 5.4.

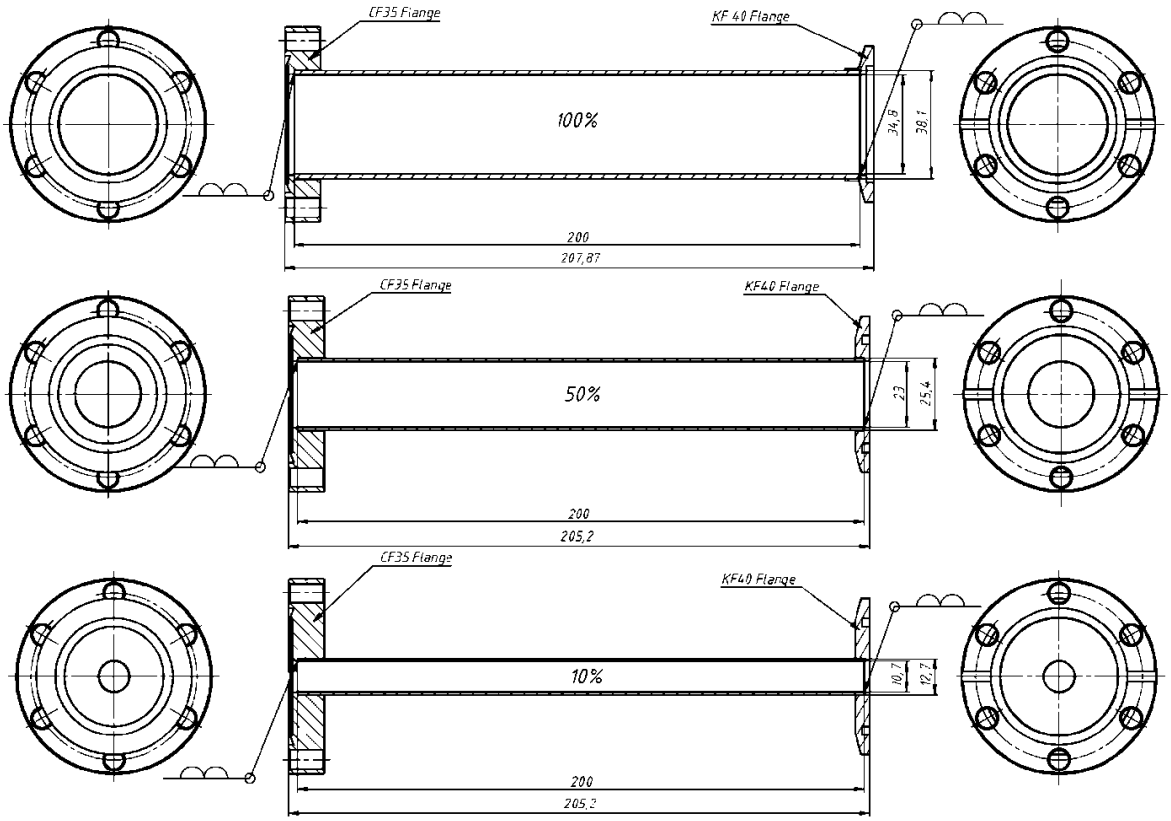


Figure 5.4 Vacuum components for experiment

- Preparation of elements.

All elements of the experiment on the capacity of the components of vacuum systems will be made at the Institute of synchrotron research CANDLE. After manufacturing, the elements will be subjected to cleaning procedures according to the procedure described above. Also, all elements will be pre-tested for vacuum density Packed and prepared for the experiment.

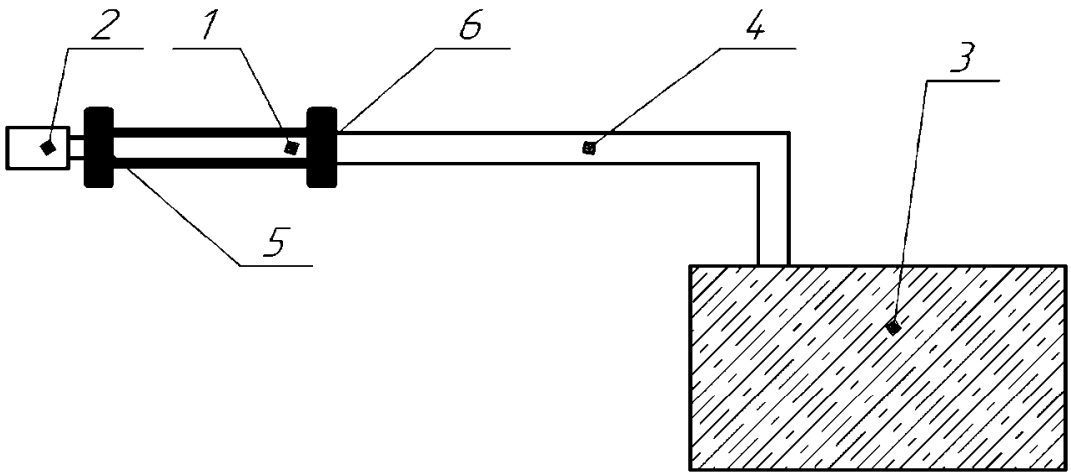


Figure 5.5 Principal scheme of conductivity test stand. 1 – test aperture, 2 – Pirani, Bayard-Alpert gauge, turbomolecular pump, 4 – flexible vacuum bellow, 5 – CF flanges connection, 6 – KF flanges connection.

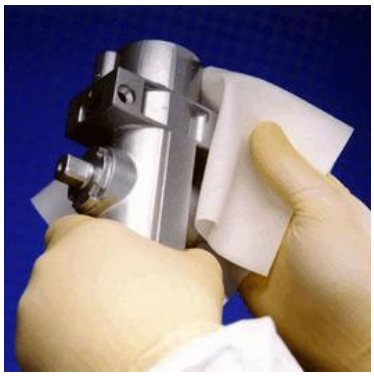
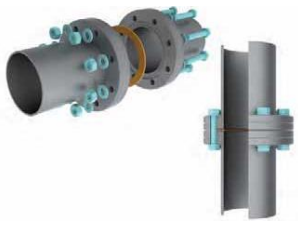
Each of the elements (Fig. 5.4) before installation must be subjected to final cleaning using alcohol and clean wipes. Wiping the elements before installation will allow you to partially familiarize yourself with the requirements and procedure for cleaning vacuum components.

- Installation of the vacuum system.

For each of the vacuum ducts, the vacuum system will be mounted separately by replacing element (1) in the common vacuum duct. The General scheme of the vacuum system for the experiment is shown in Fig. 5.5

- Procedure of work

The procedure is given in table 5.2

1.Final cleaning of vacuum components. Before cleaning the vacuum components (mounted pipe, rubber gasket, copper gasket, vacuum parts of the connecting flanges), you must wear clean gloves. Contact with non-hermetic vacuum elements should be carried out only in clean gloves corresponding to the class of clean rooms (not lower than ISO 7 by ISO-14644-1). Cleaning is carried out using pure alcohol and clean room wipes (not lower than ISO 7 by ISO-14644-1).	
2.Installation of vacuum components Mounting the vacuum sensor (2) Fig. 5.5 for test pipe (1) using copper Gazette for CF 35 flange. Mounting the test aperture to the KF connection flange (6) of the flexible bellow (4).	 (CF flanges)

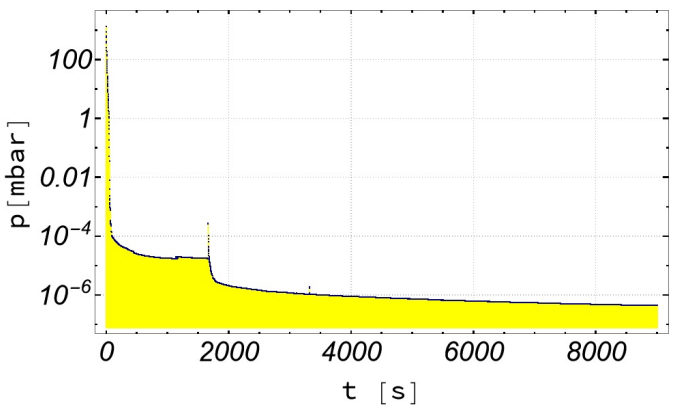
Once the system is sealed, the protective gloves can be removed.	 (KF flanges)
3.Connection of power cables to vacuum pumps	 + 
Connecting cables to vacuum sensors.	
4.Connecting cables to control devices. As a controller will be used Agilent XGS 600 controller	 
5.Connecting cables for data collection with the monitoring instruments. For data collection we will use interfaces RS 485 an RS 232.	
6.Switch on the FRG720 gauge Gauge must show the atmospheric pressure of approximately 760 Torr.	 
7.Switch on the turbomolecular TPS compact station. Start data registration from the FRG720 gauge. On first stage starts work the fore pump IDP 3. Pump down the system before reaching saturation in pumping speed (approximately level $6x10^{-5}$ Torr). Saturation depends on conductivity of the aperture and will be different for each one.	
8.Finish the data collection	
9.Switch off the FRG 720 gauge	 

10.Switch off the turbomolecular pump After switching off turbomolecular pump, wait for stopping of the pump's main rotor.	
11.Vent the system For venting use the venting valve of the turbomolecular pump.	
12.Disconnect cable from the FRG720 vacuum gauge	
13.Disassembling the vacuum system Conduct procedure in the reverse order: 1. 1.Disassemble the KF flange connection (6) 2. 2.Dismount the FRG 720 from CF flange connection (5)	
14.Change the type of aperture and start from the paragraph 1 of this procedure.	
15.After finishing of all experiments last procedure will be paragraph 11.	

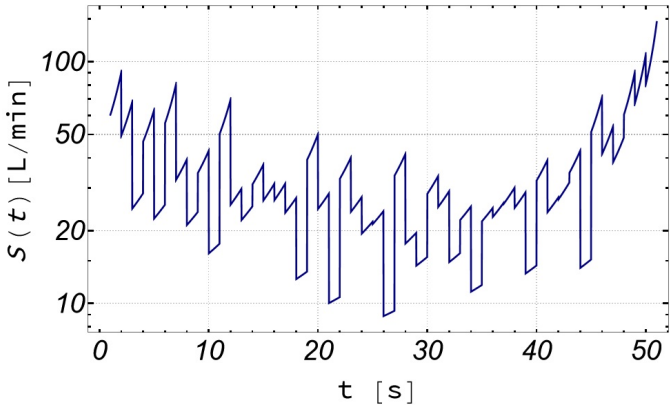
6 Data analysis

6.1 Pumpdown in viscous range

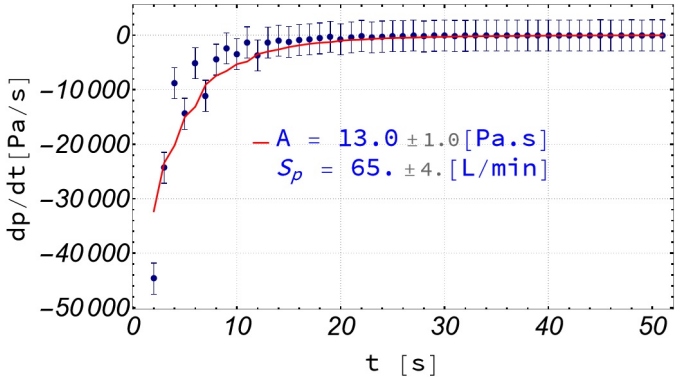
6.1.1 Direct pumping speed calculation



(a) typical raw data format.



(b) direct S_p calculation.



(c) fitting viscosity parameter A and S_p.

Figure 13: Examples - data analysis in viscous range

The measured data are presented in the form of pressure as a function of time, as illustrated in Figure 13a. The pressure range may encompass a broad spectrum, spanning multiple orders of magnitude and potentially including points at which various pumps are engaged. Choose the points where the pressure is above 0.1 mbar. That means one should choose the points where the flow is viscous, crosscheck using Eqs.3, 5 and Table 2. In the example in Figure 13a, these are the points corresponding to $t \leq 50\,\mathrm{s}$. Consider Eq.34 and rewrite it in the form

$$\frac{d}{dt}p(t) = -\frac{S_p}{V}p(t) \tag{45}$$

In terms of finite differences $dp \to \Delta p = p_2 - p_1$ and $dt \to \Delta t = t_2 - t_1$ the equation above can be used to estimate dp/dt from the experimental data.

$$p'(t) = \frac{\Delta p}{\Delta t} = -\frac{S_p}{V}p(t) \tag{46}$$

and finally to calculate the pumping speed S_p

$$S_p = -\frac{V p'(t)}{p(t)} \tag{47}$$

Such a direct calculation of pump speed is shown in Fig.13b.
Estimate S_p from your measured data and compare the results with the specification of the scroll pump. Please ask your supervisor for the value of V.
Alternatively, assuming $S_p = Const$, one can fit S_p using the measured $p(t)$ and Eq.34.

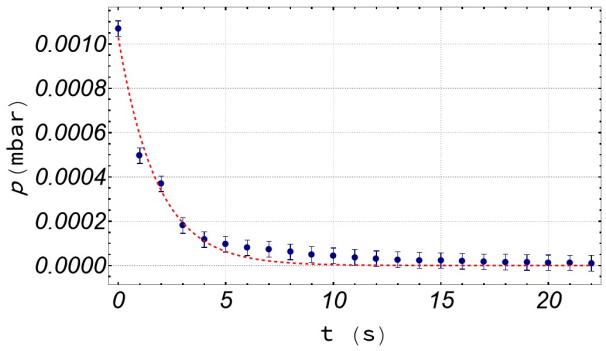
6.1.2 Determination of viscosity parameter

In the analysis above the impact of the pipe conductance and the viscosity of the air was fully neglected, i.e. the viscosity parameter A in Eq. 35 was set to zero. This can be corrected by fitting the unknown viscosity parameter A and pumping speed S_p in Eq. 35 to the measured data as defined with Eq.46.

- fit A and S_p as illustrated in Fig.13c,
- compare the value of the fitted Sp to the mean value of the directly calculated and discuss the difference,
- assuming that the volume V and the viscosity $\eta = 1.85 \cdot 10^{-5}$ Pa$\cdot$s are known, estimate the ratio D^4/L of the pipe connection, compare with the actual experimental set-up.

6.2 Pumpdown in molecular range

6.2.1 Measurement of effective pumping speed



(a) fitting of effective pumping speed S.

Figure 14: Examples - data analysis in molecular range

The measurement is based on the transient pumpdown condition Eq. 43 and consists of recording the pressures $p(t)$ for a given time interval τ i.e. $0 \le t \le \tau$. The vacuum system should operate within the molecular flow range. In other words, the pressure should be less than 10^{-3} mbar, or one should filter the

data beforehand to select data points within the appropriate range. The (*effective*, Eq. 39) pumping speed can be either fitted (see Fig14a) to the measured data using Eq. 43 or alternatively calculated with

$$S = \frac{V}{\tau} \ln \frac{p_1}{p_2} \tag{48}$$

where p_1 and p_2 are the presures at the beginning and end of given time interval τ.

6.2.2 The influence of pipe diameter on the effective pumping speed

During the experimental portion of the course, three sets of data, $p_i(t)$, were measured. Each set corresponds to a different pipe diameter, $D_i = \{3.48, 2.30, 10.70\}$ cm. The goal is to estimate the nominal speed S_p of the pump and the unknown, but constant, conductance C_x of the vacuum elements and appertures connected to the pump. Note that the pipe conductance C_p is known and given by Eq. 31 and according to Eq. 14 the total conductance C of the pipe and the rest of the vacuum elements is given by:

$$\frac{1}{C} = \frac{1}{C_p} + \frac{1}{C_x} \tag{49}$$

The data analysis consists of the following steps:

- Determine effective pumping speeds S_i for each data set p_i, as discussed in Ch.6.2.1,
- The set of S_i together with Eq. 49 and Eq. 39 forms an overdetermined system for the unknowns C_x and S_p. Solve the system numerically to find values of C_x and S_p that fit best to measured S_i.
- Compare the obtained value of S_p with the manufacturer's specifications. Use Eq. 28 to estimate the size of the apperture limiting the pumping speed.

References

[1] A. Roth, *Vacuum Technology (third edition)*. Elsevier, 1990.

[2] K. Jousten, *Handbook of Vacuum Technology*. Wiley-VCH, 2016.

[3] Agilent-Technologies, "Quiet, oil-free, worry-free: Vacuum made better." `https://www.agilent.com/cs/library/brochures/IDP_Dry_Scroll_Vacuum_Pumps_5991-7583EN_Brochure_LR.pdf`, Jan 2025.