SPUTTER-ION PUMPS

L. Schulz
Paul Scherrer Institut, Villigen, Switzerland

Abstract
The following paper outlines the working principles of sputter-ion pumps. The pumping mechanisms for reactive and inert gas species, as well as argon instability are explained. The operating pressure range, special designs for integrated linear pumps in accelerators and operational aspects are discussed.

1. INTRODUCTION

In the ultrahigh vacuum technique applied for accelerator vacuum systems special pumping methods are required. Capture pumps, which trap the pumped gas molecules in the pump body, are the dominating pumps in the ultrahigh- and high-vacuum (UHV and HV) region of accelerator systems. Capture pumps have many advantages: they form a closed vacuum system with the vacuum chamber of the accelerator; no additional valves with complicated valve interlocks are necessary; there are no moving parts in the pump and no vibrations are transmitted to the magnet lattice.

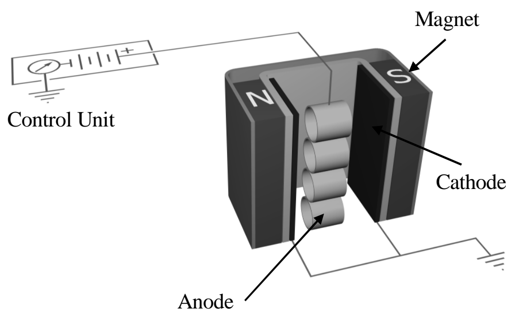
The principal pumping mechanism employed is chemical transformation whereby gases are chemically combined into solid compounds with very low vapour pressure. At UHV and HV conditions a surface can hold large quantities of gases compared to the amount of gas present in space. A pumping action can be produced by physisorption or gettering, which refers to a chemical combination between the surface and the pumped gas.

Many chemically active materials can be used for gettering. In vacuum systems titanium is commonly used because it is chemically reactive with most gases when it is deposited on a surface as a pure metallic film, but it is rather inert in bulk form because of the tenacious oxide film covering its surface. Pumps using chemical and ionisation pumping effects can generally be called sputter-ion pumps. Early designs (after 1955) had a variety of arrangements for electron sources and for titanium evaporation. Today the most common designs are based on a Penning cell [1, 2] and are called sputter ion pumps because the supply of a fresh titanium film is produced by a process called sputtering.

2. PUMPING MECHANISM

The pumping effect of sputter-ion pumps is produced by sorption processes, which are released by ionised gas particles. The pumping speed is achieved by parallel connection of many individual Penning cells.

A sputter-ion pump consists basically of two electrodes, anode and cathode, and a magnet (Fig. 1). The anode is usually cylindrical and made of stainless steel. The cathode plates positioned on both sides of the anode tube are made of titanium, which serves as the gettering material. The magnetic field is orientated along the axis of the anode. Electrons are emitted from the cathode due to the action of an electric field and, due to the presence of the magnetic field, they move in long helical trajectories which improves the chances of collision with the gas molecules inside the Penning cell (Fig. 2). The usual result of a collision with the electron is the creation of a positive ion that is accelerated to some kV by the anode voltage and moves almost directly to the cathode. The influence of the magnetic field is small because of the ion's relatively large atomic mass compared to the electron mass.



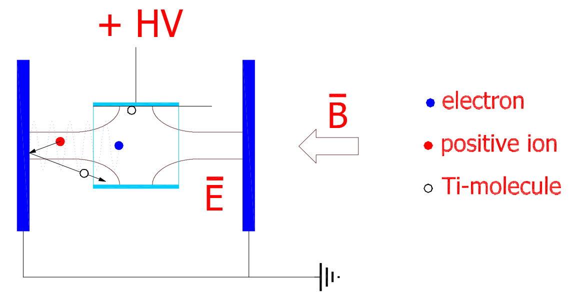


Fig. 1 Configuration of a sputter-ion pump.

Fig. 2 Penning cell.

Ions impacting on the titanium cathode surface sputter titanium away from the cathode forming a getter film on the neighbouring surfaces and stable chemical compounds with the reactive or "getterable" gas particles (e.g. CO, CO_2, H_2, N_2, O_2). This pumping effect is very selective for the different types of gas and is the dominating effect with sputter ion pumps. The number of sputtered titanium molecules is proportional to the pressure inside the pump. The sputtering rate depends on the ratio of the mass of the bombarding molecules and the mass of the cathode material. The higher this ratio, the higher is the sputtering rate. For hydrogen, the lightest gas molecule, the sputtering rate of titanium is negligible.

In addition to the sputtering process a second important effect can be observed. The energy of the ionised gas particles allows some of the impacting ions to penetrate deeply (order of magnitude 10 atomic layers) into the cathode material. This sorption process pumps all kinds of ions, in particular ions of noble gases which do not react chemically with the titanium layer formed by sputtering. However, this pumping effect is not permanent since due to the erosion of the cathode material previously implanted molecules are released.

The cathode sorption process also works for hydrogen. Large amounts of hydrogen ions can diffuse deep into the bulk material beyond the range of the implanting ions and are permanently buried there.

3. OPERATING PRINCIPLES

3.1 Standard diode

The configuration described above is typically referred to as a standard diode pump. The anode cells are electrically isolated from the pump body and work with a positive voltage while the two cathode plates, made of titanium, are at ground potential. The electrodes are contained in the pump body, and the magnetic field is induced by external permanent magnets (Fig. 1).

A cell's pumping speed depends on several parameters i.e. its diameter, length, electrical and magnetic field and these parameters have been optimised in several theoretical studies and experimental tests [3–7]. Common designs for sputter-ion pumps use anode cell diameters between 15 and 25 mm, magnetic fields between 1 and 1.5 kGauss, and electrical fields between 3 and 7 kV. The ratio I/P (pump current/pressure) which is the main parameter of a Penning cell reaches values between 3 and 25 Ampere/mbar in such a configuration while the typical pumping speed for one cell is between 0.3 and 2 liters/second.

The diode pump has the highest pumping speed for all getterable gases but only low pumping speed for noble gases. For argon, the most common noble gas (1% in air) the pumping speed in a standard diode is only 2–5 % of the nominal pumping speed.

3.2 Noble gas pumping mechanism, argon instability

When pumping noble gases the following mechanism can be observed. Some of the noble gas ions that bombard the cathode surfaces become neutralised and rebound maintaining a part of their energy. They can then reach, unaffected by magnetic or electrical fields, the anode or the pump walls or other zones of the cathode. Energetic neutrals have far greater penetrating depth than ions that are quickly decelerated in the bulk materials by coulomb forces.

Argon instability occurs when the standard diode pump is pumping on an “air leak”. The high rate of ion bombardment in the centre of the standard Penning cell erodes away cathode material. Previously buried molecules are released after the pump has removed a relatively large amount of argon. The pump dramatically and suddenly releases part of the buried molecules in sharp and repeated bursts of pressure.

3.3 Noble gas stabilised diode

A solution to argon instability is to increase the number of gas ions that “bounce back” as neutrals and sink into the anode or the pump body, where they are permanently buried. The reflection probability is a function of the mass ratio of the ion species and the cathode material and depends also on the incidence angle of the impinging ions on the cathode surface.

When an ion bombards the surface of a titanium cathode and is neutralised much of the kinetic energy of the ion is absorbed in the lattice structure of the bulk material. The penetrating power of the rebounded neutrals can be increased when for example a titanium cathode is replaced by a tantalum cathode. Tantalum is also a chemically active material but with a very heavy atomic mass (Ta = 181 amu, Ti = 48 amu). The number of elastic collisions is increased when an ion hits on a tantalum surface. The neutralised and rebounded ion now maintains much of its original kinetic energy and can be buried deeply in the anode or pump wall. For this type of pump, commercially referred to as a “noble diode” or “differential ion (D-I) pump”, higher pumping speeds for noble gases have been observed, characteristically 20% of the pumping speed for air under stable conditions. However, with the same configuration of Penning cells the overall sputter rate for titanium and tantalum is reduced which leads to a reduction of the total pumping speed for getterable gases (typically by 15%) compared to the standard diode.

A different approach to increase the number of “rebounded” ions is the design of a diode pump with “slotted cathodes”. In a standard diode the ions bombard the cathode more or less under normal incidence. With the slotted cathode (Fig. 3) more favourable incidence angles can be obtained. The reflection probability and the sputter yield of cathode material is much higher for glancing incidence than for normal incidence angles. A pumping speed for argon of 5–10% of the pumping speed for air can be achieved and is quite stable and leads to a higher pump capacity for getterable gases.

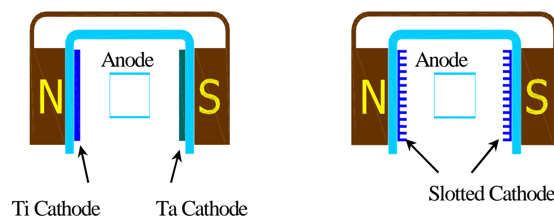


Fig. 3 Diode cell with tantalum and slotted cathode

3.4 Triode

In the triode configuration the effect of reflected neutrals due to glancing incidence on the cathode surface is increased. The cathode plates are replaced with a grid made of several titanium and is powered with negative high voltage (Fig. 4). The same relative voltage potentials as in the diode configuration are obtained when the anode and the auxiliary electrode are connected to ground potential.

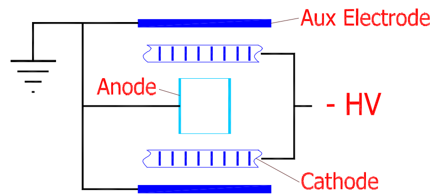


Fig. 4 Triode cell configuration.

In the triode the energetic ions bombard the cathode grid under glancing incidence with a high sputter yield of titanium. The energetic neutrals created by ion impingement on the cathode grids hit the auxiliary electrode or are reflected back and buried in the anode.

For energetic ions it is impossible to reach the pump body or anode. There is no sputtering of the body or anode and sorbed noble gases can remain buried on these surfaces. This leads to a very stable pumping of noble gases even after long-term pumping. The pumping speed for noble gases is increased up to 20–25% of the air pumping speed. Here, with the same number of anode cells of the same magnetic gap, the length of the anode cells is reduced and leads to a reduction of the total pumping speed for getterable gases (typically by 20%) compared to the standard diode. At high pressure (>10^{-6} mbar) the triode reaches a higher pumping speed compared to a diode pump.

4. PRESSURE RANGE

The pumping speed of ion sputter pumps varies with pressure. The operating pressure is in the range of less than 10^{-4} mbar since at higher pressures the space charge in the Penning cells changes into a glow discharge and the sputtering process stops. The maximum pumping speed, also called the nominal pumping speed (S_N) is reached at about 10^{-6} mbar (Fig. 5).

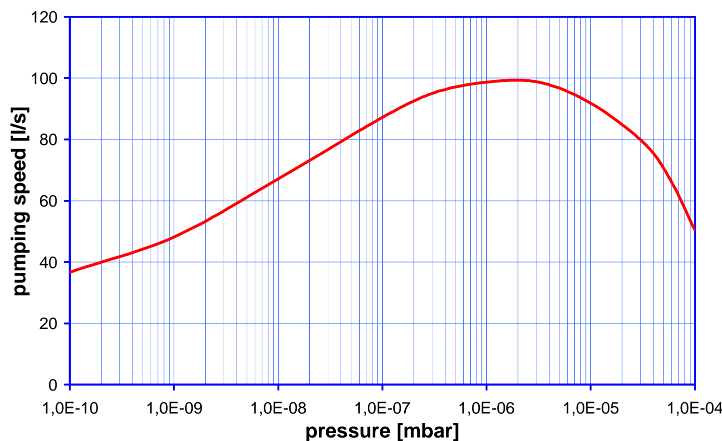


Fig. 5 Pumping speed vs pressure for a standard diode with S_N = 100 l/s (for air after saturation).

Down to the base pressure the pumping speed decreases. The base pressure is limited by the equilibrium between pumped and desorbed molecules and not by the absence of discharge. The ultimate lowest pressure range of 10^{-11} and 10^{-10} mbar can only be reached after a bakeout of the ion sputter pump [8, 9].

5. SPECIAL DESIGN FOR INTEGRATED LINEAR PUMPS

For pumping systems in particle accelerators, especially in storage rings, distributed sputter-ion pumps (Fig. 6) can be used [5–7, 10]. The pump elements typically are integrated in the vacuum chamber of the bending magnets that provide the required magnetic field. In electron storage rings the beam induced gas desorption is proportional to the electron energy which is also proportional to the field of

the bending magnets with ranges typically between 0.5 and 15 kGauss. The resulting pumping speed of the distributed sputter-ion pumps is proportional to the magnetic field.

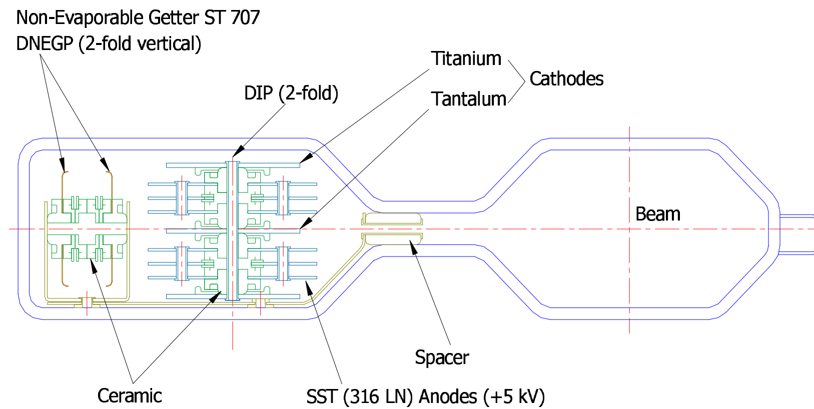


Fig. 6 Distributed sputter-ion pump in the DELTA storage ring.

Use of distributed sputter-ion pumps is ideal when long pump elements are installed in the vacuum chambers and when the desorption rate has a homogenous distribution in the longitudinal direction. The resulting pumping speed depends on the magnetic field in the bending magnets. When the accelerator is operated over a wide range of the magnetic field the design of the pump elements has to be optimised to take this into account.

Common designs for distributed sputter-ion pumps often use laminar anodes instead of anode tubes. The cylindrical anode cells are formed by stacked stainless-steel plates with coaxial holes [11, 12]. The anodes are stacked with a gap between the stainless-steel plates which leads to a higher conductance in the transverse direction.

6. OPERATIONAL ASPECTS

As mentioned above the cathode of a sputter-ion pump is sputtered away due to the impacting ions. This leads to a limited lifetime of the pumps when they are operated at high pressure. For example at a pressure of 10^{-4} mbar the cathode is eroded in 400 hours, but has a lifetime of over 40000 hours at a pressure of 10^{-6} mbar. To achieve high pump lifetimes it is recommended to start the sputter-ion pumps at pressures less than 10^{-6} mbar.

The lower pressure limit of sputter-ion pumps is in the range of 10^{-11} to 10^{-10} mbar. Lower pressures in the range of 10^{-12} mbar can only be achieved when the sputter-ion pump works in a combination with other pumping methods. Well established are the combinations of a sputter-ion pump with a titanium sublimation pump (TSP) or a non-evaporable getter module (NEG) [13].

The current measured in a sputter-ion pump is in the typical operation range, proportional to the pressure (Fig. 7). This gives additional pressure information concerning the vacuum system that results in a good overview of the pressure distribution in accelerators where usually a huge number of pumps are installed.

By connecting several sputter-ion pumps to only one power supply the number of power supplies can be reduced. Individual pump currents can be measured by using shunt resistors that are installed in a high voltage splitter between the pumps and power supply [14].

7. CONCLUSIONS

For most accelerators excellent vacuum conditions are required. Therefore the highest possible pumping rates are necessary. For most applications the standard diode pump meets these requirements and is optimal from a financial point of view.

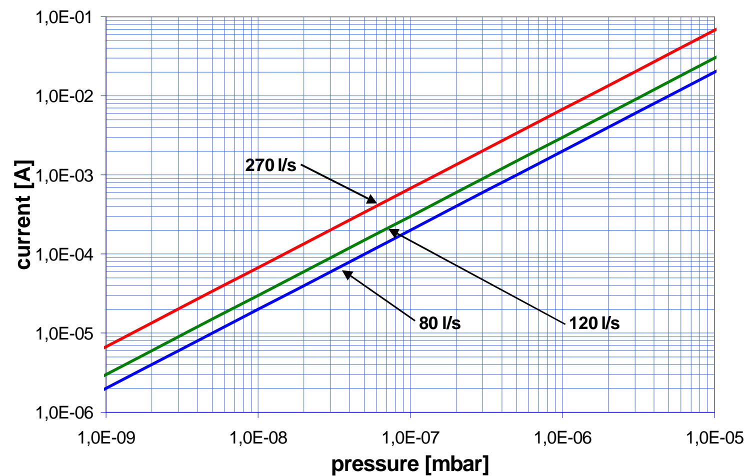


Fig. 7 Pump current vs pressure for different sputter-ion pumps.

However, to achieve the ultimate pressure regime of 10^{-12} and 10^{-11} mbar a sputter-ion pump combination with TSP or NEG-modules is needed. At high pressure ranges (>10^{-7} mbar) combination pumps become less effective. These high pressure ranges are the field of the triode pump.

The diode pump with tantalum cathode or the triode pump is optimal for vacuum systems which need high pumping speed for noble gases

REFERENCES

[1] F.M. Penning, Philips Technical Review, 2 (1937) 201.

[2] W. Schuurman, Investigation of a low pressure Penning discharge, Physica, **36** (1967) 136.

[3] L. Rutherford, Trans 10th Nat Vac Symp, AVS (1963).

[4] K.M. Welch, Capture Pumping Technology, Pergamon Press Ltd., Oxford, 1991.

[5] M.D. Malev, and E.M. Trachtenberg, Built-in getter-ion-pumps, *Vacuum*, **23** (11) 1973 pp. 403.

[6] H. Hartwig and J. Kouptsidis, A new approach for computing diode sputter-ion pump characteristics (for particle accelerators), J. Vac. Sci. Technol., **11** (6) (1974).

[7] W. Ho, R.K. Wang, and T.P. Keng, Calculation of sputter ion pump speed, J. Vac. Sci. Technol., **20** (4) (1982).

[8] M. Audi, Ion pumps, *Vacuum* **37** (8-9), (1987) pp. 629.

[9] M. Audi, Pumping speed of sputter ion pumps, *Vacuum* **38** (8-10), (1988) pp. 669.

[10] J.M. Laurent, and O. Gröbner, Distributed Sputter-Ion Pumps for use in Low Magnetic Fields, Particle Accelerator Conference, San Francisco (1979).

[11] B. Hippert and N. Marquardt, The DELTA vacuum system, European Particle Accelerator Conference, Sitges (1996).

[12] H. Pingel, and L. Schulz, Proc. 8th Intern. Vac. Congress, Cannes, 1980.

[13] M. Audi, A new ultrahigh vacuum combination pump, J. Vac. Sci. Technol., **A5** (4) (1987).

[14] F. Giacuzzo, and J. Miertusova, Total pressure measurements in the ELETTRA storage ring according to the performance of the sputter-ion pumps, European Particle Accelerator Conference, Sitges (1996).