Technical Overview

How to Optimize Ion Pump Performance by Selecting the Correct Operating Voltage

Introduction

Ion pumps are devices able to create and maintain ultra-high vacuum, reaching pressures as low as $10^{-11}$ mbar when combined with a suitable ultra-high vacuum system. Lower pressures are in principle achievable, but their measurement is particularly challenging and strongly depends on the outgassing of the system on which the ion pump is mounted.

With respect to other vacuum pumps, such as turbomolecular pumps or primary pumps, ion pumps have some characteristics that make them unique:

1. Ion pumps are closed capture pumps: they do not have a backing line and as a consequence do not need a backing pump. In fact, whatever is pumped by an ion pump will remain trapped inside the pump. This eliminates the risk of contaminating the vacuum system when venting. Also, because ion pumps do not need a backing pump there will not be any contamination from a backing pump except at start-up. Since the ion pumps cannot be started at atmospheric pressure, they will need to be roughed out with a turbo pump and roughing pump.

2. Ion pumps are static devices. They have no moving parts, so are vibration free and they don’t need any lubricant making them contamination free, because lubricant is a potential source of contamination.
Over the years, several ion pump configurations have been developed to cope with different gases, such as reactive gases, hydrogen, or noble gases.

The first configuration developed was the diode pump, in which the pumping element is made of one anode and two cathodes (Figure 1a): the anode comprises an array of cylindrical cells, the cathodes are two titanium plates placed at both sides of the anode, lining the pump body inner surfaces.

![Figure 1a. The diode element.](image)

As described in more detail in the next section, by feeding the anode with positive voltage the positive ionized gas molecules are accelerated towards the cathodes, causing the titanium sputtering, which is responsible for the pumping effect. The diode element is optimized to pump reactive gases, such as nitrogen and oxygen, which are chemically trapped in the sputtered titanium film. It also has high performance for pumping hydrogen. The diode element however, is not the best solution for pumping noble gases, since noble gases are not chemisorbed by the sputtered titanium film.

To provide improved pressure reading capabilities, an improved diode element was developed more recently, in this improved diode element, interstitial cavities between contiguous anode cells were eliminated. This optimized element is named the "SEM element", since it is often used in Scanning Electron Microscope applications (Figure 1b) as an alternative to the conventional pressure reading devices.[6]

![Figure 1b. The anode of the SEM element.](image)

The second configuration developed was the triode pump: in the triode pumping element, the anode is the same used in the diode pump’s element, while the cathodes are made of strips separated from the pump body (Figure 1c). By feeding the cathodes with a negative voltage, the anode and the pump body’s surfaces become the positive poles of the triode structure.

![Figure 1c. The triode element.](image)

More recently Varian developed an improved version of the triode element, named the StarCell element. The shape of the cathode in this element, which is made of stars with small formed wings, is optimized to ensure a longer lifetime. This is because titanium erosion due to the pumping mechanism is not centered in a few points, but it is distributed more evenly (Figure 1d).

The StarCell element is optimized to pump noble gases, however it provides good performance for active gases and a high hydrogen pumping capacity.

![Figure 1d. The StarCell element.](image)

In this technical overview, the use of ion pumps in high and ultra-high vacuum pressure ranges is discussed, focusing in particular on the influence of the applied voltage on the pump performance. We discuss the use of high voltage in the ion pumps’ pumping mechanism and how pumping speed depends on the applied voltage. Then we consider two common issues, the leakage current effect and the issue of restarting ion pumps in the ultra-high vacuum pressure range.
Why ion pumps need high voltage?
Ion pumps require a high voltage to trigger their pumping mechanism. In fact, when an ion pump is powered on, the ignition process is as follows:

1. By applying a high voltage, free electrons are produced.
2. An intense electric field is generated between the anode tube and cathode plates and together with the magnetic field created by the permanent magnets is responsible for the confinement of free electrons within the pumping element structure.
3. This confinement or ‘trapping’ increases the path of the electrons from cathode to anode by many orders of magnitude and hence increases the probability of a collision between the electrons and gas molecules.
4. Because of these collisions, the trapped electrons ionize the background gas, thus creating positive ions and ejected electrons.
5. Ions, which are positively charged, are attracted towards the cathodes (as represented in Figure 2), while ejected electrons are trapped and ionize even more gas molecules.
6. Ions which hit the cathodes cause the sputtering of titanium from the cathodes.

Pump performances vs applied voltage
The typical voltage used to feed ion pumps is in the range of 3 to 7 kV. The choice of the applied voltage can lead to enhanced or decreased pump performance, especially in terms of pumping speed and pressure reading.

Therefore, the applied voltage must be carefully chosen according to the conditions of the vacuum system and the intended application.

The pumping speed of an ion pump depends on many “fixed” parameters that are set by the design, such as the pumping element type and dimensions, the number of elements inside the pump, and the magnetic field intensity. The most important parameter is the applied voltage which can be set by the user.

Figure 3 shows pumping speed (S) as a function of pressure, when an ion pump is fed with different voltages (3, 5, or 7 kV).

The resulting curves show that at high pressures (10^{-7} mbar or above), S is optimized when the applied voltage is 7 kV (green curve). However, in the range of 5x10^{-9} to 1x10^{-7} mbar, the best value of S is achieved using 5 kV (red curve). Finally, at low pressures (10^{-9} mbar or below) the optimum is reached with 3 kV (blue curve).

It is worth noting that this graph represents the typical behavior of an ion pump, but the exact pressure limits for each range depend on the pump size.

Figure 2. A representation of the elementary cell of a pumping element in an ion pump.

Figure 3. Typical trends of the ion pump pumping speed (expressed as a percentage of its nominal pumping speed) over pressure. The nominal value is intended as the maximum of the curve obtained for a saturated pump with 7 kV of applied voltage.
The explanation of this behavior is related to the space charge effect: when the pressure is relatively high, in the range of $10^{-6}$ to $10^{-7}$ mbar, the concentration of ions on the cathodes reduces the effective potential available for the ion's acceleration. Whereas, at low pressure, the space charge due to the ions is almost negligible and hence 3 kV is enough to optimize the sputtering yield. At the same time, a higher potential results in a cloud of electrons that generates an electric field in unwanted directions, which interferes with the electric field responsible for trapping electrons and driving ions to the cathode, thus limiting the pumping speed in this pressure range.\[2\]

The effect of the applied voltage on the pumping speed is an important characteristic that affects how the ion pump and its control unit are used.

The "STEP" mode function, implemented in the Agilent 4UHV and IPCMini ion pump controllers, is designed to automatically adjust the applied voltage when the pressure in the pump increases or decreases, to optimize the pumping speed as discussed.

A typical use of "STEP" mode in ultra-high-vacuum application is:

- When the ion pump is powered on in the $10^{-5}$ to $10^{-7}$ mbar range, after an initial pumpdown using a turbomolecular pump, the applied voltage is set at 7 kV.
- For about 1 minute, the controller maintains 7 kV voltage independently of the pressure to help the pump starting. Then, because of the ion pump action, the pressure decreases towards the high-vacuum region and at around $10^{-8}$ mbar the voltage automatically switches to 5 kV.
- After some time, the ultra-high-vacuum region is reached, and the voltage is finally set at 3 kV.

**Low-pressure issues: leakage current and pump restart**

Ion pumps are often used as pressure indicators, thanks to the well-known, almost linear correlation between pressure and ion current. Unfortunately, some spurious currents (typically called leakage currents), independent of pressure, can arise in the ion pump; at low pressures, such currents can be comparable to or much higher than the pressure related ion current, as shown in *Figure 4*. It is important to note that the leakage current does not actually affect the pumping efficiency at all, but when this phenomenon occurs the ion pump becomes useless in accurately reading pressures in low-pressure applications (typically lower than $10^{-9}$ mbar).

With some types of pumping elements, even pressures below $10^{-7}$ mbar cannot be reliably read with any accuracy.

![Figure 4. Schematic trend of total current, ion current and leakage current over pressure: at low pressure, the total current is strongly affected by leakage current's contribution.](image-url)

The leakage currents can arise from both external sources, such as the power supply, the connecting cable, or the high-voltage feedthrough, and internal sources.

Among the internal sources, the main cause of leakage current is the field electron emission (FEE), by which free electrons are emitted from the titanium surface when a strong electric field is applied.\[3\]
As shown in Figure 5a, the FEE phenomenon strongly depends on the applied voltage and it has been experimentally verified that decreasing the applied voltage is the most effective way to reduce FEE and, as a consequence, the total leakage current value (Figure 5b).

Therefore, to mitigate the leakage current effect and achieve an accurate current to pressure conversion, the best practice would be to use the pump at the lowest possible applied voltage.

Nevertheless, the current to pressure conversion is not the only effect to consider when choosing the applied voltage. When using an ion pump at low pressure, another possible issue is what we call the pump restart issue. If the voltage is set at the minimum possible (usually 3 kV), and the pressure is \(10^{-6}\) mbar or lower, when the ion pump is powered off and then on, the pumping mechanism might not start immediately.

Also, if the pressure is extremely low (\(10^{-10}\) mbar range or below) the ion pump can also automatically interrupt its pumping effect even when still powered on. This is because the probability of ionizing gas atoms is very low and the discharge mechanism can no longer be fed by new free electrons.

In general, the lower the pressure, the lower the probability that the ion pump can be restarted without external help, such as a gentle knock or heating. This is especially so when the applied voltage is 3 kV.

A way to resolve this issue is to apply a higher voltage, usually 5 or 7 kV. This increases the FEE effect and increases the probability that electrons are trapped in the pumping element structure and therefore increases the probability of starting the pumping process.

So, when operating in the low pressure range, the choice of the applied voltage is not obvious: on one hand, the lower the applied voltage, the better the current to pressure conversion; on the other hand, the higher the applied voltage, the higher the probability of starting or keeping the ion pump active at very low pressures.

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**Figure 5a.** FEE current as a function of applied voltage. The current is expressed in arbitrary units because the real values depend on other factors not discussed in this paper.

**Figure 5b.** Experimental current versus pressure curves at different applied voltages (3, 5, and 7 kV), showing, especially at low pressure, the higher influence of leakage current when applying higher voltage.
From a practical perspective, it is worth mentioning two good practices when using the ion pumps at low pressure, in $10^{-9}$ mbar range or below:

1. Start the ion pump using the maximum possible voltage, typically 7 kV, to increase the probability of starting the pumping process.

2. When the stable low-pressure value is achieved, 5 kV of applied voltage is a good compromise to obtain an accurate pressure reading and, at the same time, mitigate the pump restart issue.

The first of these two practices is handled automatically when the “iSTEP” mode is selected on the Agilent IPC-Mini controller. When using this feature, which is an improved version of the “STEP” function, the controller provides 7 kV until a current threshold is reached, then the voltage is adjusted to optimize the pumping speed.

When the current decreases below a certain value depending on the pump size, with both “STEP” and “iSTEP” functions the controller automatically sets to 5 kV or 3 kV of applied voltage to optimize the pumping speed in that pressure range (as discussed previously).

For the second of these practices, the “FIXED” mode of operation on the controller should be used to maintain 5 kV in the ultra-high vacuum pressure range.
Conclusions:

An ion pump’s pumping speed is defined by fixed parameters such as anode geometry, cathode geometry, and magnet strength; and variable parameters such as the applied voltage, which can be determined by the user.

On one hand, operating at the lower applied voltage will produce a more accurate pressure reading because resultant lower leakage current will have a much smaller contribution to the overall current reading.

On the other hand, operating at the lower applied voltage when the pump is in the lower the pressure region can lower the probability that the ion pump can restart at that pressure.

For these reasons the STEP (available on the Agilent 4UHV and IPCMini ion pump controllers) and iSTEP (available on IPCMini) modes are offered to optimize the applied voltage and obtain the best pumping speed achievable in the pressure range of interest.

To summarize, the choice of the best voltage to use at low pressure should be driven by a balance between four needs:

- Achieving the best performance in terms of pumping speed.
- Mitigating the leakage current effect to achieve an accurate pressure reading.
- Mitigating the pump restart issue.
- Maintaining the ionization process if the pressure is extremely low.

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