Agilent 4UHV Ion Pump Controller Design to Optimize Pump Performance

Vacuum Solutions

Technical Overview

Introduction

Ion pump controllers are often considered just accessories needed to power ion pumps. Only basic parameters such as the maximum power and the communication interface are considered relevant, with the power usually being overspecified, resulting in needlessly expensive controllers. However, a properly designed controller can substantially improve the ion pump performance. A controller with variable voltage as a function of the pump operating pressure maximizes the pumping speed in the entire operating range. This is because the energy with which the ions inside the pump bombard the cathodes is the nominal applied high voltage (multiplied by the electrical charge), reduced by the space charge effect due to the electron cloud present in the ion pump cell[1]. Since the space charge effect is pressure-related, a variable high voltage should be applied to maintain optimum bombardment energy, resulting in the best possible pumping performance at any pressure. Additionally, reducing the applied voltage at low pressure enables use of the ion pump as a reliable pressure gauge down to the 1×10^{-10} mbar range[2]. Furthermore, a properly designed voltage-versus-current controller curve can start even a large ion pump at relatively high pressure (1×10^{-4} mbar) with limited power, and with negligible aging of the pump.

State-of-the-art ion pump controllers allow up to four large ion pumps in limited rack space to be started, controlled, and monitored independently, thereby providing optimum pumping speed and accurate pressure readings for the entire operating range, as well as limited power consumption.

The reason a low-power controller can drive big sputter ion pumps (SIPs) even at high pressure is analyzed theoretically in this Technical Overview. In addition, extensive experimental data are reported, and the difference between diode and StarCell ion pump element configurations is also described.

Agilent Technologies

Theoretical Background

Current-pressure relationship

It is well known that in a sputter ion pump, the current is proportional to the pressure[3]. This is due to the structure and working principle of the Penning cell, which is not described this document. In general, the relation between current and pressure in an SIP can be expressed as follows:

$P = a \times I + b$ Equation 1.

Where (if the pressure P is expressed in mbar, and the current I is in A):

a is usually in the range of 1–5
b is in the range of 0.5 –1.5

The a and b parameters depend upon the geometrical dimensions and distances of the Penning cell, the number of cells, the magnetic field, and the voltage[4]. Another way to express this concept is to give what is called sensitivity (k) of the SIP:

$k = I/P$ (A/mbar) Equation 2.

The same parameter is used to characterize ionization gauges, thus reflecting the use of the ion pump as a gauge, in which the current drawn by the pump is converted to obtain a measurement of the pressure. Therefore, all geometrical and magnetic parameters are fixed, following the SIP selection. The only parameter that can change is the voltage applied. If the voltage changes, the parameters a and b (and, therefore, the sensitivity, k) change.

Power supply maximum current and SIP minimum starting current

The sensitivity k is sometimes used to determine the current needed by an ion pump to start at a certain pressure. This use of k is not correct, and is discussed in the following sections.

For example, a 300 L/s pump absorbs a current of 4 mA at a pressure of 1×10^{-6} mbar. Therefore, for a 300 L/s pump, k is 4,000 A/mbar. This value is valid only with an applied voltage equal to 7 kV (if the voltage is lower, then k will be lower, too). Now, assume that we want to start the SIP at 1×10^{-4} mbar. Using the k value calculated above, the obtained current value is 400 mA. This is valid with voltage at 7 kV, meaning that the total power delivered to the ion pump would be 2,800 W. This amount of power would cause overheating of the ion pump and increased outgassing, leading to pump downtime, and presenting a serious risk of damaging the pump. In addition, starting an SIP in the 1×10^{-4} mbar range will shorten the life of the pump. It is better to start in the 1×10^{-6} mbar range, which is easily reached by a turbomolecular pump. Therefore, the k is a sensitivity factor that is useful to calculate the pressure, but not to decide the maximum power to be provided to the pump. More precisely, there is no formula that can describe the minimum current needed by an SIP to start at a certain pressure. Therefore, specifying the short circuit current is of no value because normally the short circuit current is intended at 0 V output, and under this condition the SIP does not pump at all.

Agilent 4UHV Ion Pump Controller output curve and ion pump high-pressure behavior

To have some minimal pumping effect, the voltage must be at least greater than 200 V. In the range of 0–200 V, the current/power provided to the SIP is completely transformed into heat, and generates outgassing. Therefore, it is better to provide lower power in this region. Beyond the 200 V yield, if the pressure is very high, more precisely in the 1×10^{-1} to 1×10^{-3} mbar range, the SIP itself will limit the voltage in the range of 500–800 V (Zener region), whatever current is provided to the ion pump. In this condition, only a part of the current/power provided will pump the gas (only by ion implantation, since no sputtering effect occurs in this range). The remaining part of the current/power provided will only increase the temperature and outgassing. It is desirable to limit the current provided to the SIP. A real sputtering process starts in an SIP above 1 kV, and the discharge is well confined (and efficient from the pumping speed standpoint) around 2 kV.

Summarizing, from 0 V to 2 kV the current should be limited because only part of it will contribute to the gas pumping. As shown in the output curve in Figure 1, in the 80 W channel of the Agilent 4UHV Ion Pump Controller, the current is limited to 40 mA up to 2 kV.

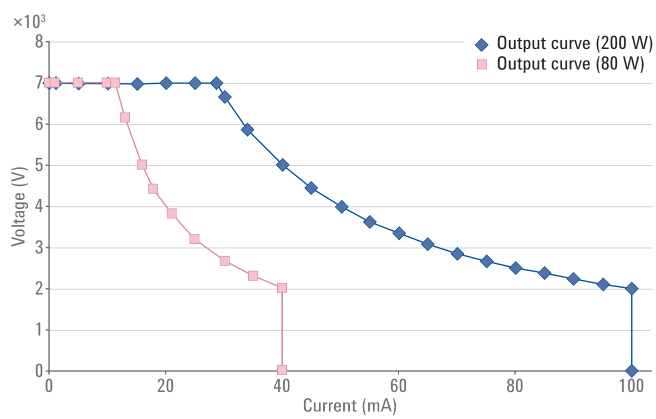

Figure 1. Output voltage versus output current for the Agilent 4UHV Ion Pump Controller (200 and 80 W).

While the pressure improves, the current delivered to the ion pump stays constant, and the power increases from 0 W (at 0 V) to the maximum power of 80 W (at 2 kV). Consequently, the pumping efficiency increases, and the outgassing generated by the power is compensated.

At 2 kV, with the pressure decreasing (thanks to the SIP pumping action), the current absorbed by the ion pump will decrease. Then, there is room for the 4UHV controller to increase the voltage and the pumping/sputtering effect, keeping the power constant. In a positive loop, keeping the power constant keeps the heating and outgassing constant, while the voltage and the pumping efficiency increase. Once the maximum voltage of 7 kV is reached, the voltage is kept constant. Eventually, it can be decreased step by step (the Step Mode function of the 4UHV controller) if the pressure is low enough. This is to optimize the pumping speed, reduce the leakage current, and have a more precise current reading (and a more accurate pressure indication). In this region, it makes sense and is correct to use the *k* value to determine the pressure from the current read by the power supply.

The values of power and maximum current available in the 4UHV controller (80 W–40 mA and 200 W–100 mA) have been defined as the best values to limit outgassing and improve pump downtime for medium and large-size ion pumps. First, the behavior of the discharge in the SIP at high pressure, until the moment when the discharge is well confined, has been studied, and the value of 2 kV has been determined. Therefore, after several startup tests with pumps in different cleaning conditions, the maximum power value has been determined. The best compromise between the output curve and the power/current parameters implemented in the 4UHV controller has been validated by carrying out the startup tests described in the next paragraphs.

Experimental setup

Figure 2 shows a schematic of the experimental setup used for high-pressure startup tests.

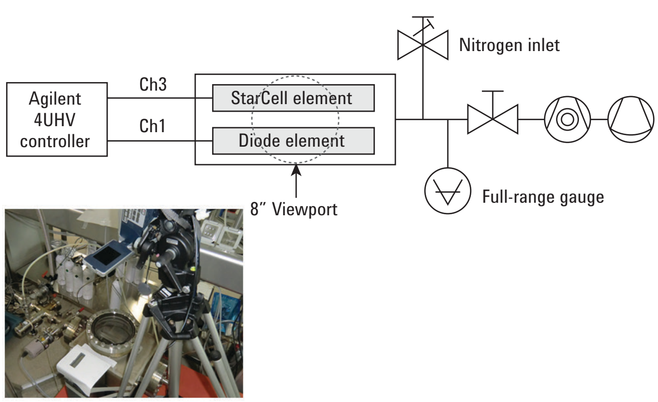

Figure 2. Experimental setup used for startup tests.

The vacuum chamber is constituted by a special large ion pump body (approximate volume 12 L, double-ended), inside which two different elements are installed:

- A Diode
- A Triode (StarCell type)

Each element is electrically connected to a feedthrough, and can be powered independently. The control unit used to operate the elements is an Agilent 4UHV Ion Pump Controller, equipped with four independent channels with 80 W maximum power per channel. From the front panel of the controller, it is possible to limit the maximum power of each channel down to a minimum of 20 W.

We carried out measurements at 20 and 50 W applied to the single element. These measurements simulate starting a 300 L/s pump (inside which four elements are mounted) with a channel 80 or 200 W.

The chamber is equipped with a CFF 8 inch viewport through which it is possible to see both the elements. This window allows observation of the behavior of the plasma created inside the ion pump at startup, and when the confinement of the discharge inside the pump elements occurs. Some videos were recorded during the startup phase.

A dry nitrogen injection line, connected to a variable leak valve, was used to raise the pressure inside the chamber at the desired value before starting the ion pump, allowing simulation of startup at high pressure. The pressure was measured using an Agilent FRG700 full-range gauge.

Two different measurement campaigns were performed, referred to in this and the next sections as Test A and Test B. During Test A, with the ion pump off, the turbomolecular pump was isolated from the chamber, then the pressure was set to the desired value by the variable leak valve. The leak valve was then closed, and the ion pump was switched on. For the measurements of Test B, with the ion pump still off, the valve between the turbo and the chamber was not closed completely, and a very small conductance was kept open. Then, the variable leak valve was opened to the desired pressure until a steady stream was obtained. At this moment, the ion pump was switched on, with the leak valve still open. This procedure was followed to reproduce the harsh conditions of the startup of an ion pump in the presence of a continuous gas flow. These conditions can occur, for example, due to the outgassing of a large experimental chamber.

Results and Discussion

Test A

For the measurements carried out within the Test A campaign, the pressure in the chamber was varied between 2.0×10^{-4} mbar and 2.2×10^{-2} mbar.

For every test, the pressure, voltage, and ion current were recorded as a function of time. In all cases, both elements started successfully with 20 or 50 W applied. The following are the results obtained with the power limited to 20 W, which was the most challenging condition. The time elapsed between the pump startup and the achievement of the maximum applied voltage is in direct ratio with the chamber initial pressure. Figure 3 shows the data obtained starting the diode element at 2×10^{-4} mbar (20 W).

As shown in Figure 3, the pressure inside the chamber starts to decrease abruptly just after the pump is switched on, and the maximum voltage (7,000 V) is achieved immediately. The StarCell element has a similar behavior when started at the same pressure.

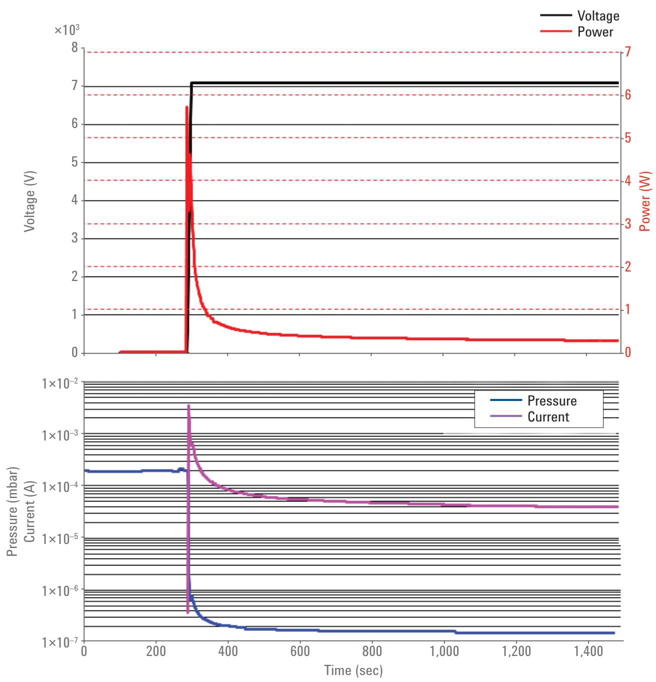

Figure 3. Diode element, no gas flux, starting pressure 2×10^{-4} mbar, 20 W maximum power.

When a higher starting pressure (2×10^{-2} mbar) is set, the diode voltage starts to increase slowly just after switching on the pump, and the pump current is at its maximum value (1×10^{-2} A). This is shown in the graph in Figure 4.

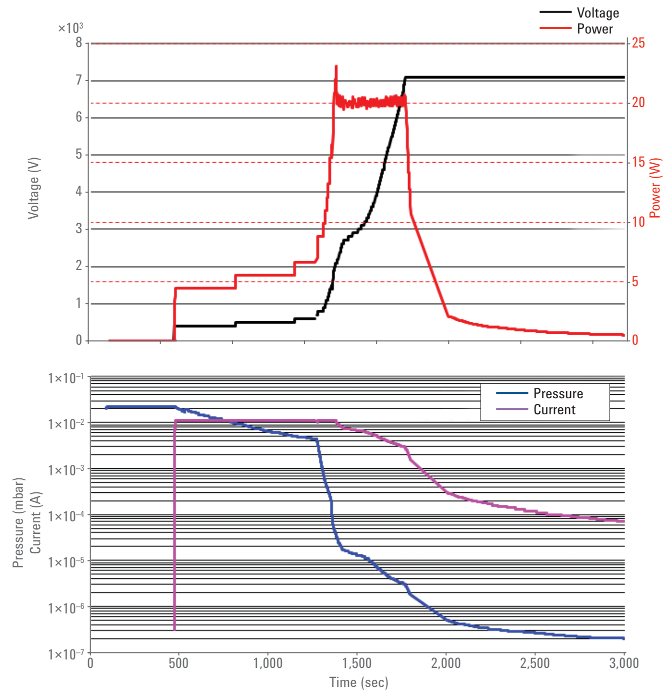

Figure 4. Diode element, no gas flux, starting pressure 2×10^{-2} mbar, 20 W maximum power. After approximately 10 minutes around 500 V, where the pumping is poor since only ions implanted in the cathode are pumped, the pumping efficiency increases as V increases, since gas is also pumped at the anode due to cathode sputtering. Maximum voltage is achieved in about 20 minutes from the moment the voltage is switched on.

For approximately 10 minutes, the diode pump stays constant at 500 V. At this voltage, the pumping efficiency is poor since the only pumping mechanism occurring is the ion implantation into the cathodes, and the plasma discharge is not contained but extended to the entire pump volume, as shown in Figure 5.

Figure 5. Diode element. For voltages below approximately 1 kV, the discharge is not confined, but it is extended to the entire pump volume.

After another 5 minutes, an applied voltage of 900–1,000 V is achieved. Immediately, the pumping efficiency improves, since titanium sputtered from the cathodes onto the anode cells starts to contribute to the pumping of getterable gases and hydrogen. For the diode element, the maximum voltage (7,000 V), corresponding to the full pumping speed, is achieved approximately 20 minutes from the beginning of the test. As the voltage increases above approximately 1 kV, the plasma discharge first becomes confined inside the element pocket, and then is not visible when the voltage reaches the maximum value and the pressure drops into the 1×10^{-6} mbar range.

The same test was performed for the StarCell element, also started at 2×10^{-2} mbar.

As shown in the graph in Figure 6, a voltage of approximately 900 V is achieved after approximately 8 minutes. Up to that moment, the pumping efficiency is very low (as already stated for the diode). However, the pump-down for the StarCell is faster than the diode, and the plasma discharge does not extend to the pump volume, but is confined inside the ion pump element pocket, as shown in Figure 7.

When the voltage reaches 900–1,000 V, the contribution of the pumping at the anode allows the pump to reach the maximum voltage (7 kV) and full speed in approximately 16 minutes. This time is significantly shorter than that observed for the diode. For the StarCell, the plasma discharge is no longer visible as the voltage increases towards its maximum value and the pressure decreases into the 1×10^{-6} mbar range.

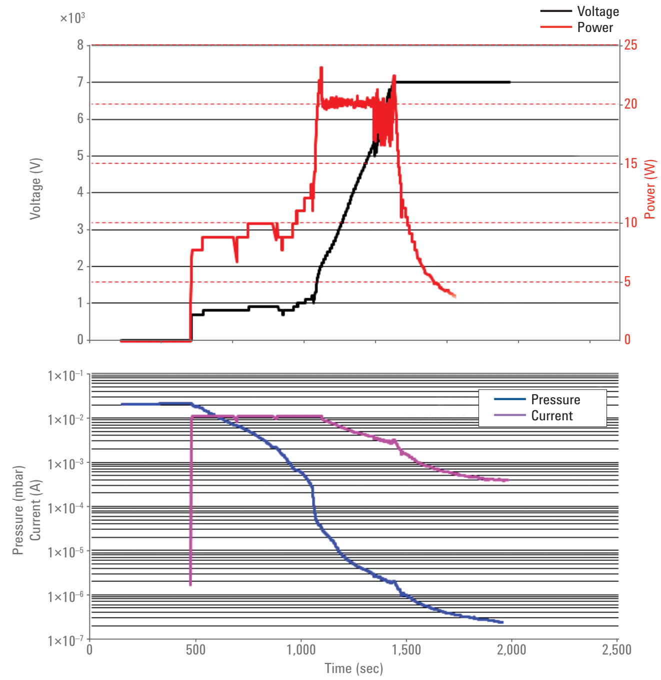

Figure 6. StarCell element, no gas flux, starting pressure 2×10^{-2} mbar, 20 W maximum power. After approximately 8 minutes at 900 V, where the pumping is poor since only ions implanted in the cathode are pumped, the pumping efficiency increases as V increases, since gas is also pumped at the anode due to cathode sputtering. Maximum voltage was achieved approximately 16 minutes after the voltage was switched on.

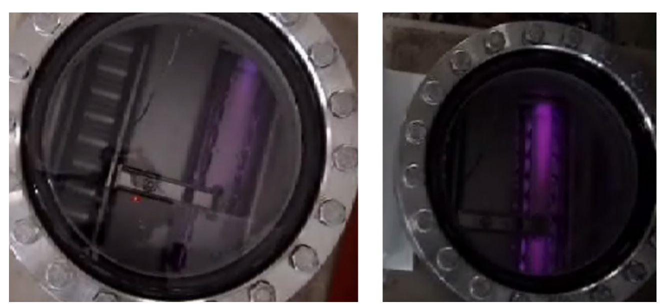

Figure 7. StarCell element. For voltages below approximately 1 kV, the discharge is contained within the ion pump element pocket.

Test B

Results obtained for Test B, with the power limited to 20 W, represent the most challenging condition. For the test carried out on the diode element, a gas flux was introduced into the chamber by a leak valve to achieve a steady pressure of 2×10^{-3} mbar. The corresponding gas load was approximately 3×10^{-4} mbar L/s, which is equivalent to the outgassing load of a 3 m^2 stainless steel unbaked surface (for example, a 10-m long tube, with a 10-cm diameter). The leak valve was kept open, and the ion pump was turned on. For the test of the StarCell element, the steady pressure before applying the voltage was 3×10^{-3} mbar, corresponding to a gas load of approximately 4×10^{-4} mbar L/s. This is equivalent to the outgassing load of a 4 m^2 stainless steel unbaked surface (for example, a 13-m long tube, with a 10-cm diameter). In the case of the StarCell, the leak valve was kept open.

The graph in Figure 8 shows that the diode displayed a two-step starting mode. The achievement of a voltage >1,000 V was almost immediate, while the full speed at 7 kV was reached approximately 8–9 minutes after the high voltage was switched on.

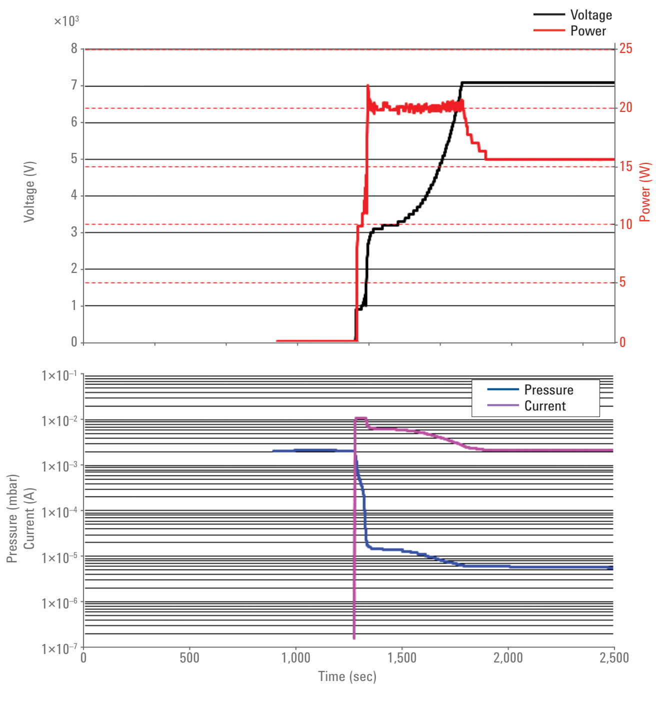

Figure 8. Diode element with gas flux, 20 W maximum power, starting pressure 2×10^{-3} mbar, with a gas load of about 3×10^{-4} mbar L/s, which is comparable to the outgassing load of a 3 m^2 stainless steel unbaked chamber (for example, 10-m long tube, 10-cm diameter) or a stainless steel baked chamber of 300 m^2.

For the StarCell, the voltage reaches 5 kV in a couple of minutes, and the maximum voltage is reached in approximately 10 minutes (Figure 9).

In both cases, the recorded pressure stabilizes in the high 1×10^{-6} mbar range, since in the test conditions the ion pump works against a continuous gas flux. In addition, note that the starting pressures used for the test are well above the value at which ion pumps are commonly started in almost all their application fields. In the past, ion pumps needed to be started at high pressure because they were directly connected to a primary pump. However, the invention of turbomolecular pumps made this no longer necessary, and not recommended if the pump lifetime is to be preserved.

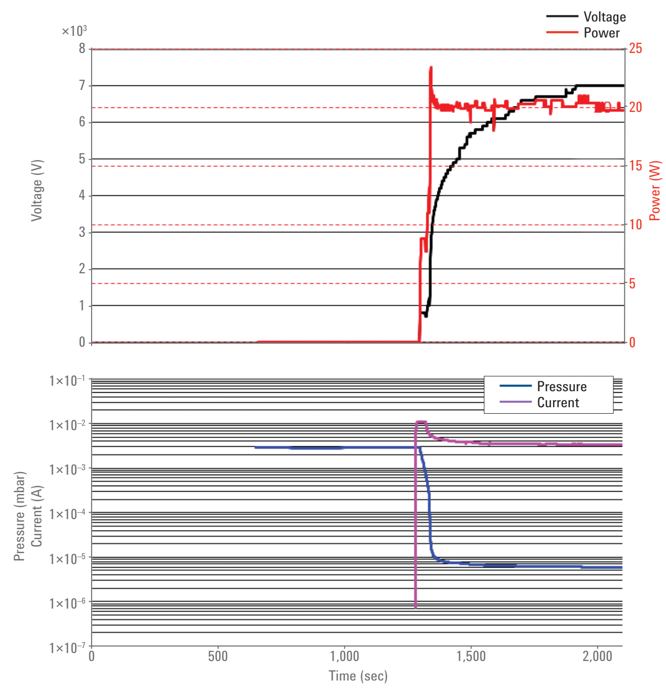

Figure 9. StarCell element with gas flux, 20 W maximum power, starting pressure 3×10^{-3} mbar with a gas load of about 4×10^{-4} mbar L/s. This gas load is comparable to the outgassing load of a 4 m^2 stainless steel unbaked chamber (for example, a 13-m long tube, 10-cm diameter) or a 400 m^2 stainless steel baked chamber.

Conclusions

As discussed previously, applying the sensitivity value/formula used to calculate the current-pressure curve to evaluate the maximum current needed for the ion pump to start at certain pressure is of no value. There is no real formula to calculate this value, just estimations. A simple request of a current rating or short circuit current of 400 mA, for example, makes no sense either, since the SIP pumping effect, at high pressure, is voltage, not current, driven.

What is reasonable, is to find the best compromise between the pumping effect, the voltage, and the power (and the outgassing related to this). We determined the best compromise with the output curve and power/current parameters implemented into the Agilent 4UHV Ion Pump Controller, accounting for the considerations explained in this document and the experimental tests performed.

In addition, we would like to focus on the requirements that the state-of-the-art power control units must be tailored to satisfy.

To maximize ion pump performance, control units must be able to feed the pump at different voltages, depending on the operating pressure. This means that when switching on the power supply the voltage is kept as high as possible to guarantee discharge ignition at any pressure; in the high-pressure range, the voltage is maintained at the highest value to achieve the highest pumping speed values. When the pressure decreases, the voltage decreases too (in one or two steps to avoid instabilities), to get the highest pumping speed values at any pressure. As a consequence of the lower applied voltage, the leakage current is dramatically reduced. Therefore, the total current is closer to the actual ion current, allowing a reliable pressure reading on a wider ultra-high-vacuum (UHV) range.

The experimental tests described in this work clearly demonstrate that there is no real need to oversize the power provided by the control unit to start a large ion pump at high pressure.

To summarize, the 4UHV Ion Pump Controller was used to reproduce the startup conditions of a 300 L/s ion pump ignited at high pressure or in the presence of a gas load (simulating the long tube of a beam line) with 80 W maximum power. We can conclude that:

- The 4UHV Ion Pump Controller showed excellent starting characteristics in all the tested conditions.
- Ion pump performance is maximized at low pressure due to optimization of the operating voltage.
- This resulted in a reliable pressure reading in the UHV range from the ion pump.

A further advantage of the 4UHV Ion Pump Controller is the ability to power and control up to four large ion pumps, simultaneously and independently, in a half-rack size.

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Published in the USA, May 24, 2017
5991-8141EN

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