Shielding Charged Particle Emission from Ion Pumps

Introduction

This Technical Overview describes our study of the emission of charged particles from ion getter pumps (IGP) and the design and testing of particle shielding. The first aim was to understand the degree to which particles are emitted from an IGP. Subsequently, an optimized optical shield was designed and tested. The goals were to maximize the charged particle shielding effect while minimizing as much as possible the impact on pumping speed. Comparative testing was done with a standard Agilent IGP (without shields) as well as with a competitor’s pump of equivalent size, equipped with dedicated particle shielding.

At the heart of an ion getter pump (IGP) is the Penning cell, made up of a cylindrical anode and planar cathode surfaces, which uses electric and magnetic fields to trap electrons. These trapped electrons ionize gas molecules that are then accelerated towards a titanium cathode. Due to ion impacts on the cathode, titanium atoms are sputtered onto the inner surfaces of the IGP. This constantly refreshed film of titanium acts as an active getter material and can pump getterable gas molecules by chemisorption.
Typically, IGPs have an array of multiple Penning cells. The ion current in each cell, and therefore the total current of the IGP, is directly proportional to the gas pressure; the intensity of the discharge is defined as the current divided by the pressure (I/P). Gaps exist between the cylindrical anode array and the planar cathodes on each end. Particles can escape the Penning cells through this gap and strike surfaces within the IGP or pass into the vacuum facility to which the IGP is connected. The image in Figure 1 shows plasma formation in a Penning cell array with the anode-cathode gaps indicated. From these gaps, particles can escape, such as photons, neutral molecules (for example, sputtered titanium), and charged particles.

Such interactions affect the beam quality (focus, energy, and so forth) and hence reduce the performance of the system. While they provide the required vacuum, IGPs can emit particles that interfere with device operation. To prevent negative effects, such as titanium sputtering onto sensitive elements of the system, it is common practice to introduce so-called "optical shielding" that interrupts the line of sight between the IGP and the system. These shields reduce the gas conductance between the system and the Penning cells, and can therefore reduce the effective pumping speed. Consequently, their shape and relative position with respect to the flange must be carefully evaluated.

Experimental

Agilent Vacuum (previously Varian Vacuum) has been selling ion pumps equipped with shields for many years\textsuperscript{2,3}. The shield described in this paper, shown in Figure 2A, represents the latest proposed version, whose position and design have been improved recently with respect to previous implementations. The shielding comprises a horizontal flat surface and a vertical baffle (Figure 2A) that work in conjunction to prevent particles emitted by the ion pump from escaping into the vacuum chamber, as well as blocking the emission of secondary particles (for example, electrons) from the internal surfaces of the pump. The shield is placed under the flange (Figures 2B and 2C) and is connected to the anode, so that it is polarized at the same voltage at which the pump is operated (typically 3, 5, or 7 kV).

Ion getter pumps are typically used in the range from $1 \times 10^{-7}$ mbar down to $1 \times 10^{-11}$ mbar or lower. Two typical applications, among many others, are high-energy physics (HEP) particle accelerators and scanning electron microscopes (SEM). In these applications, the required vacuum level is in the range of at least $1 \times 10^{-8}$ mbar and down to $1 \times 10^{-10}$ mbar. These vacuum levels are required to reduce beam losses and improve image resolution, due to the fact that the lower the pressure, the lower the probability of collisional scattering of beam particles (protons, ions, or electrons) by the residual gas.
Experimental measurements were carried out to study the physical phenomenon of particle emission and to analyze the efficiency of shielding in blocking these particles. To achieve these goals, we decided to compare two ion pumps of the same size, which differ only in the presence or absence of a shield. Specifically, we tested a standard Agilent diode VacIon Plus 40 ion pump (indicated as VIP40, Figure 3) and a special diode VIP40 with a shield (indicated as VIP40S). These pumps were tested using the experimental setup shown in Figure 4.

In all tests, a conical copper Faraday cup was positioned in a vacuum chamber above the flange of the ion pump, as shown in Figure 5.

A Faraday cup (Figure 6) is a conductive metal electrode designed to measure the current induced by particles incident on the cup. This current can be measured by an ammeter and used to estimate the flux of particles hitting the cup. A bias voltage applied either to the cup itself or a repelling grid preceding the cup, or a magnetic field, are often used to control the polarity of particles incident on the cup or to prevent secondary electron emission from distorting the reading. The design can be significantly more complicated when it is necessary to make measurements of very short pulses or very high energy beams that may not be fully stopped by the thickness of the detector. This device is a nearly universal detector because of its ability to detect particles largely independent of the energy, mass, or species of the analyte. When using a Faraday cup to count the number of charged particles collected per unit time, there can be several sources of error, including: (1) the emission of low-energy secondary electrons from the surface struck by any incident particle with sufficient energy (ions, electrons, photons, high-energy neutral atoms/molecules) and (2) field emission of electrons directly from the Faraday cup itself.
It is fundamentally impossible to distinguish between one or more incident ions and secondary electrons emitted from the cup due to high-energy particle impacts, or field-emitted electrons. Even if the Faraday cup does not clearly allow us to distinguish between particles, due to these complications, from an end user’s perspective the particular species of particle(s) is likely not important; only the fact that charged particles or energetic particles in general are being emitted is relevant. Despite these limitations, we operated under the assumption the Faraday cup is sufficient to estimate the relative rate of particle emission for different pumps and configurations, to assess the efficacy of shielding.

The cup was polarized with a voltage in the range –500 to +500 V to measure the current-versus-voltage (I/V) curve. As stated above, positive (or negative) bias of the cup does not strictly mean selective detection of exclusively negative (or positive) charged particles. For example, when the Faraday cup is biased at a negative voltage, a positive current is measured, mostly due to the ions emitted by the pump, but increased by the escape of secondary electrons from the cup itself.

A Keithley 6487 picoammeter/voltage source was used for reading the current generated by the particle emission from the ion pump and for polarizing the Faraday cup. The pressure in the vacuum chamber was measured with an Agilent UHV24 ionization gauge, with the possibility of increasing it by introducing dry nitrogen into the dome through a variable leak valve. After verifying that the current collected by the Faraday cup increased linearly with the pressure, the amount of nitrogen in the vacuum chamber was maintained constant in the mid 1 × 10⁻⁷ mbar range for all measurements.

Using the same setup, we also characterized an ion pump produced by a competitor, having the same inlet flange size as the VIP40S and VIP40 (2 3/4") and internally equipped with tilted baffles. This pump is advertised as specifically designed to block primary and secondary particles with a small loss of pumping speed. The nominal pumping speed of this competitor pump (referred to as Comp45S) is 45 L/s. (The nitrogen pumping speed indicated in the specification sheet for the 4 1/2” flanged version is 36 L/s). The nitrogen pumping speed for the 2 3/4”-flanged version is not clearly stated by the manufacturer in the publicly available documentation, but it is obviously lower due to the reduced gas conductance of the smaller flange.
Results and discussion

VIP40S versus VIP40

All ion pumps were tested by measuring the current collected by the Faraday cup as a function of the bias applied to the cup in the range –500 to +500 V. As discussed previously, the current collected by the Faraday cup is proportional to the amount of the detected particles, but it does not allow determination of the absolute number of particles or their energy, due to secondary electrons. Figures 7, 8, and 9 show the current (\(I_{\text{cup}}\)) as a function of the voltage (\(V_{\text{cup}}\)) for the VIP40, the VIP40S, and the overlaid curves, respectively.

The shape of the curve is similar for both pumps, but the magnitude of the current detected for the VIP40 is approximately 30 nA, while that detected for the VIP40S is only ~10 pA, so a factor of 3000 lower. This significant difference indicates that the shield with which the VIP40S is equipped works very efficiently in reducing the emission of particles from the ion pump.

Figure 7. Plot showing the current \(I_{\text{cup}}\) as a function of the voltage \(V_{\text{cup}}\) for the VIP40 ion pump.

Figure 8. Plot showing the current \(I_{\text{cup}}\) as a function of the voltage \(V_{\text{cup}}\) for the VIP40S ion pump.

Figure 9. Overlaid curves of the absolute value of collected current for the VIP40S and VIP40 ion pumps (logarithmic scale).
VIP40S versus Comp45S

In this case, the test was aimed at comparing the efficiency of two different shielding geometries. We measured the current collected by the Faraday cup for the same range of bias voltage for the Comp45S (Figure 10).

It is worth pointing out that the detected current increases with the absolute voltage for both positive and negative bias, but to a different degree. For negative voltages the maximum absolute value of the current saturates to approximately 21 pA, while for positive voltages it reaches 260 pA at +500 V, nearly 12 times higher.

If we compare the data taken on Comp45S and VIP40S pumps (Figure 11), we notice that for positive voltages, the detected current for the Comp45S pump is about 15 times higher than for the VIP40S. Referring to negative cup voltages, the current measured for Comp45S ion pump is only somewhat higher than VIP40S. These data confirm that the best shielding effectiveness is obtained with the baffle geometry implemented in the VIP40S (patent pending).

Figure 10. Plot showing the current $I_{cup}$ as a function of the voltage $V_{cup}$ for the Comp45S ion pump.

Figure 11. Absolute value of $I_{cup}$ for VIP40S and Comp45S ion pumps (logarithmic scale).
Pumping speed measurements

As a consequence of the implementation of shields inside the ion pumps with the goal of reducing particle emission, the gas conductance is reduced and, unavoidably, the effective pumping speed of the pump is lowered as well.

To determine the effect of the shield on the VIP40 pump and to assess the pumping performance of the competitor pump, we measured pumping using a Fischer-Mommsen dome. The results reported in Figure 12 refer to the pumps fed at 7 kV; each curve represents the average of at least three measurements carried out on the same pump. The pumping speed curve of the VIP40 is also shown for reference.

We want to point out that the measured curves in Figure 12 start in the low 1 × 10⁻⁹ mbar range since for all the pumps the achieved base pressure, after a mild bakeout (about 12 hours at 180 °C) and after saturation with nitrogen, was in the mid 1 × 10⁻¹⁰ mbar range. As expected, the VIP40 exhibits the best pumping speed performance, since there are no shields mounted inside it. If we then compare the two pumps with shields of different geometry, we see that the Agilent VIP40S has a higher pumping speed than the competitor’s ion pump (Comp45S) for every pressure in the considered range.

Considering the maximum value of each curve (which corresponds to a pressure of about 4 × 10⁻⁹ mbar), we measured 31 L/s for the VIP40S (23 % lower than for the VIP40, close to forecast) and 27 L/s for the Comp45S. As stated above, we cannot calculate the percentage of reduction for the pumping speed of this last pump, since we have no reference data about the performance of the analogous pump without the shield.

Simulations were also performed to assess the conductance of the ion pumps under investigation. The Molecular Flow Module of COMSOL Multiphysics was used, which uses the angular coefficient method (an alternative to particle trajectory modeling using the Direct Simulation Monte Carlo method, which is more computationally demanding). In these simulations, a cylindrical vacuum chamber with a gas inlet is attached to the vacuum flange of each pump geometry. The inlet nitrogen mass flow (gas throughput) is held constant for all cases (1.0 × 10⁻¹⁰ kg/s or 8.7 × 10⁻⁶ Pa·m³/s), and diffuse scattering is assumed on all surfaces. To simulate pumping, loss surfaces are introduced at the anode-cathode gap and a pumping speed is imposed that represents the approximate intrinsic pumping speed of the Penning cell array (80 L/s is assumed in all cases). The simulation calculates the pressure at all surfaces in the model. Conductance (C, in m³/s) of a gas flow path is defined as the gas throughput (Q, in Pa·m³/s) divided by the pressure differential (ΔP, in Pa) across the path:

\[ C = \frac{Q}{\Delta P} \]

To measure the conductance of each configuration, the imposed gas throughput was divided by the difference between the surface-averaged backpressure in the vacuum chamber and the pressure at the anode-cathode pumping surface. The results are shown in Table 1.

The relative difference in the simulated conductance between the cases can be used to estimate the expected pumping speed change in the presence of a shield because the speed is directly proportional to conductance. Comparing the normalized simulated conductance and the measured pumping speed, the simulation somewhat underestimated the speed reduction due to the shield in the VIP40S, and overestimated the relative speed of the shield-equipped Comp45S compared to the shieldless Agilent VIP40. However, the error in the expected relative speed was less than 10 % in each case.
Conclusions

The experimental tests carried out on VIP40 and VIP40S ion pumps have demonstrated that the new shield design in the Agilent ion pump leads to a decrease in the amount of emitted charged particles by a factor of ~1,000, observed as a reduction of the measured current collected by a Faraday cup. Moreover, it exhibits a higher efficiency in comparison to the competitor Comp45S ion pump; in particular, for positive voltages applied to the Faraday cup, the measured current for the VIP40S is approximately a factor of 15 lower than for the Comp45S. Also in terms of pumping speed, despite the conductance reduction with respect to the shieldless VIP40, the Agilent VIP40S still provides higher performance than the competitor’s pump (Comp45S).

As a final consideration, it is worth mentioning that the analysis reported in this paper does not address the type of particles being emitted by the ion pumps. The Faraday cup is in fact sensitive to any particles that can induce current, which include not only ions and electrons but also neutral particles (photons and neutral atoms/molecules) that can induce secondary electron emission. A more detailed investigation of particle species will be the subject of further experiments with a modified setup that we plan to build in the near future.

References

4. DIN28429.