LOW PRESSURE LIMITATION OF THE ORBITRON IONIZATION GAUGE

by

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Abstract

It has often been supposed that the orbitron gauge is an instrument to measure pressures of less than $10^{-10}$ torr, since its theoretical low pressure limit is about $5 \times 10^{-13}$ torr. In order to check this suggestion, some orbitron gauges of optimal design parameters have been studied at pressures below $10^{-10}$ torr. It is found that a low pressure limit for orbitron gauges of less than $2 \times 10^{-11}$ torr is hardly achievable. This fact may be explained by space charges which are built up at very low pressures where the electron mean free path for electron-ion impact is in the order of some $10^9$ cm. Due to this space charge, which appears as a potential barrier in the vicinity of the cathode, the number of electrons injected onto stable orbitals is drastically reduced. Hence a major fraction of electrons fall onto the anode after only a few revolutions, thus giving rise to a higher X-ray limit than expected from theoretical predictions.

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1. **INTRODUCTION**

An orbitron ionization gauge is composed of a cylindrical grid with a very thin wire stretched out along its axis. Electrons which are usually injected by a hot filament cathode, orbit around this central wire which is at a high positive potential, and therefore referred to as the anode. Ions created by electron impact ionization of residual gas molecules are collected by the cylindrical grid which is at ground potential.

The collector current of a hot filament ionization gauge of sensitivity $S$ is given by

$$I_c = SpI_e,$$  \hspace{1cm} (1)

where $p$ is the pressure and $I_e$ the emission current. The sensitivity for nitrogen and an electron energy of about 75 eV may be obtained from $^1$

$$S = 10 \cdot \lambda \text{ torr}^{-1},$$ \hspace{1cm} (2)

$\lambda$ being the average distance that an electron travels within the ionization volume to the anode in cm.

Another important gauge parameter is the low pressure limit due to X-rays:

$$p_x = \frac{Y_{a} G Y_{c}}{S},$$ \hspace{1cm} (3)

where $Y_a$ is denoting the number of X-rays emitted from the anode per incident electron and $Y_c$ the number of electrons released from the collector per absorbed X-ray. $G$ is the fraction of the X-ray flux from the anode wire that is intercepted by the collector grid. In case of an orbitron, the geometrical factor, as $G$ is usually called, is equal to the ratio of the true to the geometrical surface area of the collector grid.
If the gauge is to be used in the ultrahigh vacuum range, the emission current $I_e$ has to be low in order to reduce heat production and thus degassing from surrounding surfaces. It is obvious from Eqn. (1) and (3) that for a high collector current and a low pressure limit, a maximum of sensitivity is an essential requirement at low pressures. The electron mean free path within the anode grid of a Bayard-Alpert gauge is in the order of the grid diameter (hence $S < 50 \text{ torr}^{-1}$), whereas extremely long path-lengths of several meters are typical for orbitrons, resulting in sensitivities of up to $10^5 \text{ torr}^{-1}$. For this reason, the orbitron has been considered to be a useful instrument for pressure measurements in the UHV range.

Orbitrons have so far been investigated down to pressures of $10^{-10} \text{ torr}$, however, a low pressure limitation has not yet been observed. An estimation from Eqn. (3) yields an X-ray limit of $P_x < 10^{-12} \text{ torr}$ using $Y_a Y_c = 2 \times 10^{-6}$, $S = 10^5 \text{ torr}^{-1}$ and $G = 0.05$. The purpose of this work lies in finding the low pressure limit of some orbitrons of optimal design and to decide whether one of them might be applied to the vacuum system of the CERN Intersecting Storage Rings, operated at about $10^{-11} \text{ torr}$, or even less.

2. EXPERIMENT

Although several orbitrons have been studied with various filament shapes, such as are used for previous investigations, the results did not differ essentially. Data presented in this work was obtained from an orbitron, the filament of which was made of 0.1 mm tungsten wire, stretched out parallel to the anode. Its collector had a radius of $r_c = 20 \text{ mm}$ and was 60 mm long, the geometry factor was about $8 \times 10^{-2}$. The anode was made of tungsten wire of $2r_a = 0.05 \text{ mm}$ diameter. The cathode's radial position was selected to yield the largest efficient injection domain at $r_f = 0.607 \cdot r_c = 12 \text{ mm}$. The optimal cathode bias is equal to the undisturbed logarithmic potential field at $r_f$:

$$U_{fo} = U_a / 2 \ln(r_c/r_a).$$ (4)
Since the highest sensitivity was found for an anode potential of $U_a = 1130$ V, we have biased the cathode at about $U_{fo} = 84$ V. The pressure in the UHV system was measured by a calibrated Helmer gauge, with an X-ray limit of below $2 \times 10^{-12}$ torr.

Sensitivity and low pressure limit of an ionization gauge are usually obtained from an injection of a test gas after the system has been pumped to its basic pressure, and plotting the collector current $I_c$ as a function of the pressure $p$. The result obtained from a hydrogen injection at emission current of $5 \times 10^{-7}$ amps is shown in Figure 1. The sensitivity of the orbitron at low pressure for $H_2$ is found to be $S(H_2) = 1.3 \times 10^4$ torr$^{-1}$ from this figure (corresponding to about $S(N_2) = 4 \times 10^4$ torr$^{-1}$) together with a residual current of $I_X = 8 \times 10^{-13}$ amps (corresponding to a low pressure limit of $4 \times 10^{-11}$ torr). The residual pressure is thus more than one order of magnitude greater than is expected from Eqn. (3).

3. SPACE CHARGE INFLUENCE

It has been reported in a recent paper$^2$ that at pressures below $10^{-8}$ torr, the orbitron's sensitivity decreases with the pressure due to the affection of the optimal injection conditions by space charges. The orbitron's operation conditions improved with decreasing emission current.

We have measured the filament power input as a function of the emission current at a pressure of $3 \times 10^{-11}$ torr in order to check whether a space charge builds up at low pressure; the result is plotted in Figure 2 together with the result from a calculation using Richardson's law $I_e \propto T^2 \exp(-\phi/kT)$ with $\phi = 4.53$ V and Stefan-Boltzmann's law $I \propto T^4$. The calculated curve was fitted to the experimental points at the low emission end. The filament consumes considerably more power for emission currents $I_e > 5 \times 10^{-7}$ amps than is to be expected from theory. This is due to a space charge arising in the orbitron, where higher filament temperatures are necessary to provide the required average electron energy that maintains the emission current at a prefixed value.
Another possibility to support the required emission current is to decrease the cathode potential $U_f$ while keeping the filament temperature constant in order to compensate the space charge effects. On the other hand, there must be a maximum cathode potential $U_f \leq U_m$, beyond which all emitted electrons return to the filament under the influence of the space charge potential; consequently the emission breaks down for $U_f > U_m$. This cut-off voltage $U_m$ must therefore be a function of the emission current in case of space charge:

$$U_m = U_f - U_s(I_e)$$  \hspace{1cm} (5)

The collector current $I_c$ is plotted in Figure 3 as a function of the cathode potential $U_f$ for different emission currents and for $p = 8 \times 10^{-11}$ torr. $I_c$ rises with increasing cathode potential and drops suddenly to zero at $U_f = U_m$. The maximum filament temperature was limited at about 1870°K (corresponding to 4.25 W, see Figure 2). This figure demonstrates that the space charge rises with increasing emission current and that it may be compensated by a lower filament potential.

The steep slope at $U_f = U_m$ allows a quantitative analysis of the function $U_s(I_e)$. We have plotted the cut-off potential $U_m$ as a function of the emission current $I_e$ in Figure 4. The experimental points fit a curve calculated from Eqn. (5) with

$$U_s = 1.2 \times 10^4 I_e^{2/3} \ V,$$  \hspace{1cm} (6)

as is to be expected for space charge limited emission\textsuperscript{6).}

4. **DISCUSSION**

In order to understand the influence of space charges on sensitivity and low pressure limitation, it is necessary to consider the injection conditions for the orbitron. Electrons are only placed at stable orbits, if their initial kinetic energy $E_i$ at the injection point $r_f$ is

$$E_i > E_{\min} = eU_f / \left\{ 1 - \left( \frac{r_c}{r_a} \sin \psi \right)^2 \right\}$$  \hspace{1cm} (7)
where $\psi$ is the injection angle with respect to a line through anode and cathode. Electrons, with energies of below $E_{\text{min}}$ fall directly onto the anode, their path-length is thus $\lambda = r_f$ only.

Eqn. (7) is drawn for our orbitron parameters in Figure 5: electrons with energies inferior to 0.05 eV are not placed onto stable orbits. Assuming isotropic emission from the filament at temperature $T$ and Boltzmann energy distribution of the emitted electrons, the probability $q$, that an electron is injected at a stable orbit is given by

$$q = \frac{2}{\pi} \int_{\psi_0}^{\pi/2} \exp(-E_{\text{min}}/kT)d\psi$$

(8)

where $\psi_0 = \arcsin \left( \frac{r_a F_0}{r_f} \left( \frac{\ln(r_C/r_a)}{r_C \ln(r_C^2/r_f^2) + r_f^2 \ln(r_f/r_a)} \right)^{1/2} \right)$.

The probability $q$, computed from Eqn. (8) is plotted in Figure 6 as a function of the average initial energy $E = 3kT/2$. At a filament temperature of about $T = 1650^\circ\text{K}$ for example, some 75% of the electrons are injected onto stable orbits, providing that there is no space charge barrier that reduces their average initial kinetic energy.

The mean free path of an electron of 75 eV kinetic energy in nitrogen is $\lambda_\infty = 1/10p$. This can be verified from Eqn. (1) and (2) for $I_c = I_e$. The probability that an electron at an orbit of maximum path-length $\lambda$ ionizes one residual gas molecule before arriving at the anode is thus for low pressures where $\lambda << \lambda_\infty$:

$$w(\lambda) = 10p\lambda$$

(9)

Hence for pressures of below $10^{-9}$ torr and for path-lengths $\lambda < 10^5$ cm, the fraction of electrons that leave their stable orbit due to an ionization impact is negligible. The average path-length of injected
electrons is then:

$$\bar{\lambda} = (1-q)r_f + q\lambda \approx q\lambda$$  (10)

provided that $q \gg r_f/\lambda > 10^{-5}$. The space charge, represented by $N$ electrons enclosed by the collector cylinder of volume $V$ is:

$$eN = I_e \bar{\lambda}/\bar{\nu}_e$$  (11)

where $\bar{\nu}_e$ is the average velocity of an orbiting electron. The space charge potential "seen" by an electron at its point of injection $r_f$ is

$$U_s = \frac{eNQ}{8\pi e_0 V}; \text{ where } Q = \int \frac{d^3r}{V}$$

being directly proportional to $\bar{\lambda}$ at low pressures.

However, since the average initial electron energy is reduced by the space charge potential to $E = 3kT/2 - eU_s$, the number of electrons injected onto stable orbits decreases according to Eqn. (8), (see Figure 6), whereas the number of those which return to the filament, or which directly fall to the anode, increases. If we neglect the space charge created by the latter ones, we find from Eqn. (10), (11) and (12):

$$q(E) = \frac{8\pi e_0 \bar{\nu}_e^2}{\lambda I_e Q_e} \left(\frac{3}{2} kT - E\right)$$

which, together with Eqn. (8) yields an estimation of $q$ at low pressure. For our gauge parameters, and with $I_e < 5 \times 10^{-7}$ amps one finds $q < 0.1$. Hence we get for the true X-ray limit

$$P_x = Y_a Y_c G/10q\lambda > 2 \times 10^{-11} \text{ G/q torr}$$

(14)

for $\lambda < 10^4$ cm. Using our orbitron parameters (i.e. $\lambda = 4 \times 10^3$ cm)
we obtain $p_x = 4 \times 10^{-11}$ torr, which is our experimental result (see Figure 1).

As it is rather difficult to measure collector currents of less than $10^{-13}$ amps accurately, $I_e$ cannot be reduced to below $10^{-7}$ amps for $p < 10^{-11}$ torr. Furthermore, since for reasons of mechanical ruggedness both $G > 0.05$, and $r_a > 10^{-3}$ cm, $G/q$ is greater than unity: the low pressure limit of the orbitron becomes therefore $p_x > 2 \cdot 10^{-11}$ torr.
References


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Figure Captions

Figure 1 The collector current $I_c$ as a function of the pressure $p$ ($N_2$-equiv.) of injected hydrogen.

Figure 2 The filament power input $I_f$ as a function of the emission current $I_e$ at $p = 3 \times 10^{-11}$ torr.

Figure 3 The collector current $I_c$ as a function of the cathode bias $U_f$ for different emission currents $I_e$.

Figure 4 The cut-off voltage $U_m$ as a function of the emission current.

Figure 5 Minimum injection energy $E_{min}$ for an electron to be placed at a stable orbit as a function of its injection angle $\psi$. Note that $E_{min}(90+\psi) = E_{min}(90-\psi)$, see Eqn. (7).

Figure 6 Injection probability onto a stable orbit $q$ as a function of the average initial electron energy $E$. With a filament temperature of $1650^\circ$K and a space charge potential of 0.19 eV for example, $q = 0.06$ for our gauge parameters.
$I_c/A$ vs. $P/Torr$

$P_{lim} = 4 \times 10^{11}$ Torr

$I_e = 5 \times 10^{-7}$ A

Fig. 1
Fig. 3