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Lafferty Gauge for Pressure Measurement of Extremely High Vacuum

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Abstract

The electron motion, the upper limit of the electron density, the electron density balance and the ion collection current of the Lafferty gauge with negative wall potential were analyzed for the pressure measurement of extremely high vacuum, XHV. The electron emitted from the cathode takes $\vec{E}\times\vec{B}$ drift along the azimuthal direction within a time scale determined by the Bohm diffusion. The upper density of the electron may be determined by the condition that the negative self potential be smaller than the negative wall potential. For the ion to be collected without collision with the residual gas or the wall, the negative potential of the ion collector has to be larger than some critical value. The ion output of the gauge with a reasonable size becomes ~0.1A/Torr, so that the ratio of secondary emission due to photons produced in the wall has to be below 10^{-9} for the measurement pressures less than 10^{-14} Torr.

1. Introduction

Extremely high vacuum, XHV, has been obtained by using the vacuum chamber made by aluminium alloy[1)] or specially pretreated stainless steel[2)]. In the R&Ds of the XHV, one of the major concerns is how to effectively apply the XHV into the ingustrial fields. In addition, the method to measure the pressure less than 10^{-12} Torr (10^{-10} Pa) has to be established sine the prssure measurement due to the gauge of a EG type is limited to such the low pressure by the photoelectron emission caused by soft X-rays[3)]. In order to expand the measurable pressure into the low range, several schemes such as the multiple electron emitters[4)] and the flash desorption spectroscopy[5)] have been proposed, and then some of these methods showed the possibility to measure the pressure less than 10^{-12} Torr.

The principle for the measurement of such the low pressure without the electron emission from the ion collector is to lengthen the electron flight path, e.g. ionization number per an electron be enhanced. To lengthen the flight path of the electron emitted from the cathode, the electrons have to be well confined by the electrostaic potential well or the magnetic well. It is also desirable to spacially fix the electron orbit for the electron not to collide with the gauge elements such as the shield wall. One of the gauges which satisfy

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these requirements is the Lafferty magnetron gauge[6], if the walls including the ion collector are negatively biased. However, there seems to be little detailed analysis of this gauge with respect to the electron orbit, the electro confinement time and the requirements such for the electrostatic potential of the wall. In this note, analytically examined are the electron orbit, the electron density balance, the electrostatic potential for the ion to be effectively collected and the ion collection current. The effect of the secondary electron emissions due to the ion and the photons caused by the electron bombardment with the wall is also discussed.

2. Electron Drift in Lafferty Gauge

The Lafferty magnetron gauge or the Lafferty gauge shown in Fig.1 is discussed. The permanent magnets placed at upper and bottom yield the axial magnetic field, $\vec{B}$. The electrons emitted from the cathode have the $\vec{E}\times\vec{B}$ drift motion along the azimuthal direction, in addition to the Lamor motion along the magnetic field. Since both the shield wall and the ion collector are negatively biased compared with the cathode (Fig.2), the electrons emitted from the cathode take the orbit shown in Fig.3.

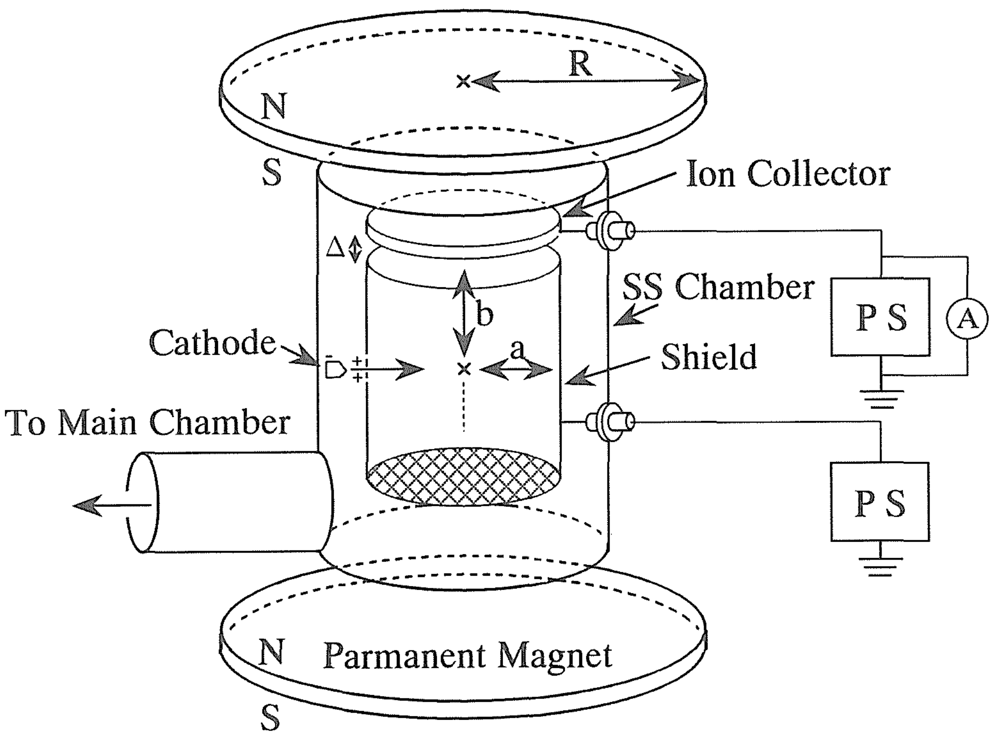

Fig. 1 Lafferty magnetron gauge.

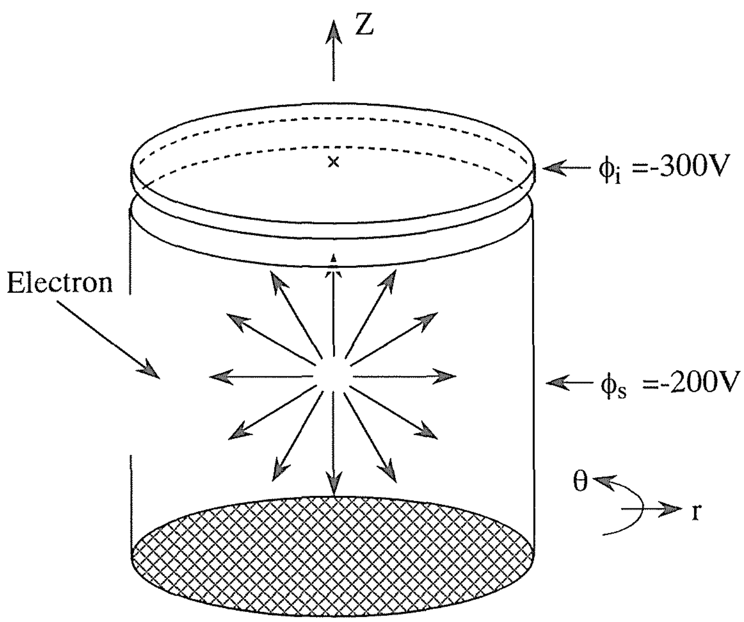

Fig. 2 Sketch of electric field.

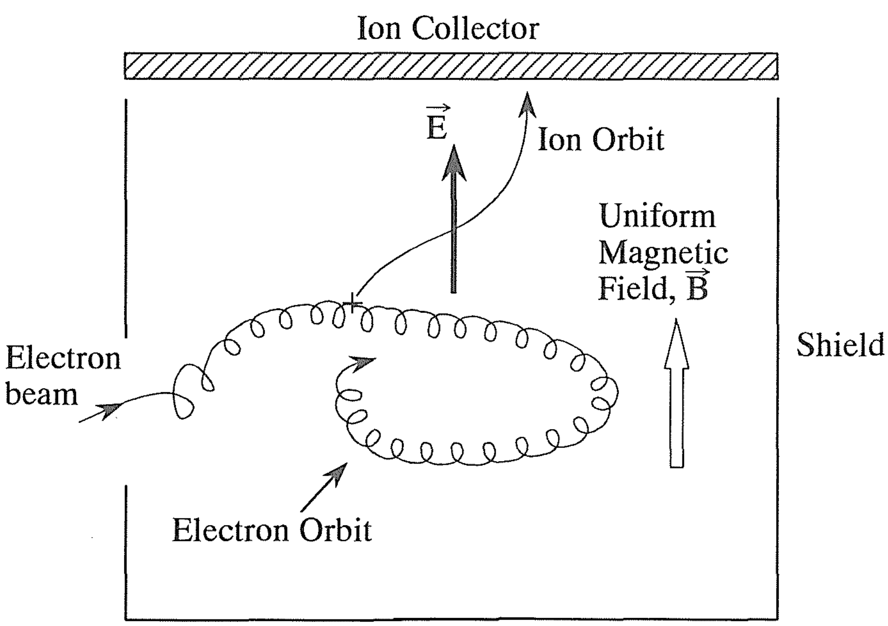

Fig. 3 Orbits of ion produced by ionization and electron emitted from filament.

The guiding center of the charged particle is described by the following equation[7],

$$v_{d\perp}=(1+\frac{\rho^2}{4}\nabla^2)\frac{\vec{E}\times\vec{B}}{B^2}+\frac{m(2v_{\parallel}^2+v_{\perp}^2)}{2qB^3}(\vec{B}\times\vec{\nabla}B), \quad (1)$$

$$v_{d\parallel}=v_{\parallel}+\frac{q}{m}E_{\parallel}t \quad (2)$$

where $v_{d\perp}$ and $v_{d\parallel}$ are the drift velocities perpendicular and parallel to the magnetic field, respectively, $E_{\parallel}$ the electric field parallel to the magnetic field, $v_{\parallel}$ the velocity parallel to the magnetic field, $\rho=v_{\perp}/\Omega$ the Lamor radius, $v_{\perp}$ the velocity perpendicular to the magnetic field, $\Omega=qB/m$ the Lamor frequency, q the charge and m the mass. The Lamor radii and frequencies of electron and hydrogen ion are expressed as

$$\rho_e=3.4\times10^{-6}\frac{\sqrt{T_{\perp,e}(eV)}}{B(T)}\ (m),$$

$$\rho_i=1.5\times10^{-4}\frac{\sqrt{T_{\perp,i}(eV)}}{B(T)}\ (m),$$

$$\Omega_e=1.8\times10^{11}B(T)\,(1/s),$$

$$\Omega_i=1.0\times10^{8}B(T)\,(1/s).$$

Here, the temperatures parallel and perpendicular to the magnetic field are related to the velocities as $v_{\parallel}=\sqrt{kT_{\parallel}/m}$ and $v_{\perp}=\sqrt{2kT_{\perp}/m}$, respectively. The Boltzmann constant is defined as $k=1.602\times10^{-19}$(J/eV).

In Eq.(1), the gradient of the electric field is of order of 1/a or 1/b, so that the term of $(\rho^2/4)\nabla^2$ becomes roughly ρ^2/a^2 and ρ^2/b^2. Here, a and b are the radius of the shield wall and a half of the axial length of the shield wall, respectively. When B=0.08T and $T_{\parallel,e}\sim T_{\perp e}\sim$20eV, ρ_e and ρ_i are 0.2×10^{-3}m and 8×10^{-3}m, respectively. If a and b are taken several centimeters, the term of $(\rho^2/4)\nabla^2$ can be ignored because of ρ^2/a^2 or $\rho^2/b^2 \ll 1$. The term of the radial gradient of the axial magnetic field, $\vec{\nabla}B/B$, also can be ignored when the magnet radius, R, is much larger than the size of the shield wall, i.e. a or b. Then the electron drift velocity perpendicular to the magnetic field is simplified as $v_{d\perp}^e\sim E_r/B$, where $E_r=-(\nabla\phi)_r\sim|\phi_s|/a$ is the radial electric field. Then, the electron drift velocity is roughly given by

$$v_{d\perp}^e\sim\frac{|\phi_s|}{aB}, \quad (3)$$

where ϕ_s is the relative electrostatic potential of the shield wall. The electron drift velocity parallel to the magnetic field is approximated as $v_{d\parallel}^e\sim v_{\parallel}^e-(e/m_e)(|\phi_i|/b)t$ since$E_{\parallel}=-(\nabla\phi_i)\sim|\phi_i|/b$. Here, ϕ_i is the relative electrostatic potential of the ion collector. The electrons which go towards the ion collector and the shield wall are pushed back by the negative electrostatic potential. For example, the electron drift velocity in the azimuthal direction becomes 5×10^4 m/s or 2.5×10^5m/s when B=0.08T and a=0.05 m or 0.01 m, respectively.

The electrons emitted from the cathode have to be accelated to the energy higher than the ionization energy of hydrogen, 14 eV. If the temperatures of the electron, $T_{\perp}^e\sim T_{\parallel}^e$

$\sim 20eV$, the electron velocity becomes $\sim 2\times10^6$ m/s which is much higher than the drift velocity. Thus, the electrons have many gyromotions during a transit along the azimuthal direction as shown in Fig.3.

During the electron motion, the ionization takes place and then the produced ion has to be collected to the ion collector. The ion drift velocities are expressed as

$$v^i_{d\parallel} \sim v^i_{\parallel} + \frac{e}{m_i}\frac{|\phi_i|}{b}t, \tag{4}$$

$$v^i_{d\perp} \sim \frac{|\phi_s|}{aB}, \tag{5}$$

The initial velocity of the ion may be much smaller than that of the electron. For the ions to be effectively collected to the ion collector without the collision with the gas species, it is adequate that the flight time of the ion, $b/v^i_{d\parallel} \sim \sqrt{m_i/e|\phi_i|}\cdot b$, is comparable with or shorter than the transit time in the azimuthal direction, $2\pi a/v^i_{d\perp} \sim 2\pi a^2 B/|\phi_s|$. In addition, the ion should not be collected to the shield wall, e.g. $|\phi_I| \geq |\phi_s|$. When a=b and B=0.08T, the former condition becomes $|\phi_I| \geq 2\times10^{-4}|\phi_s|^2/a$. If $\Delta\phi_s = -200\,V$ and a=0.05 m, $|\phi_I|$ has to be larger than 160 V. From the later condition, the value of $|\phi_I|$ should be larger than 200 V. In the case that a is taken short, e.g. a=0.01 m, the value of $|\phi_i|$ has to be very large, $|\phi_I| \geq 800\,V$. Thus, the small radius of the shield cylinder requires a large negative potential for the ion collector. We then take the parameters of the Lafferty gauge as follows.

$a = 0.05m$
$b = 0.05m$
$R = 0.10m$
$\phi_I = -300\,V$
$\phi_s = -200\,V$
$B = 0.08\,T$

The above parameters are employed in the later sections.

3. Density Balance of Electrons

The electrons emitted from the cathode form the electrostatic potential inside of the shield cylinder. The potential of the electrons is obtained by the Poisson equation, $\nabla^2\phi_{el} = -en_e/\varepsilon_0$, as,

$$\phi_{el} \sim -\frac{ea^2}{\varepsilon_0}n_e \tag{6}$$

where $\varepsilon_0 = 8.855\times10^{-12}$ (F/m) is the permeability in vacuum, and n_e the electron density. For the electrons to be confined by the electrostatic potential, the following condition has to be satisfied,

$$-\phi_{el} \geq -\phi_{i,s}. \tag{7}$$

Thus, there is the upper limit of the electron density. When a=0.05 m, $-\phi_i \sim 300$ V and $-\phi_s \sim 200$ V, the maximum electron density becomes $\sim 4.5 \times 10^{12} m^{-3}$.

In the electron plasma with the fluctuations of the electrostatic potential, the electron diffusion perpendicular to the magnetic field may be determined by the Bohm diffusion,

$$D_{el} \sim \frac{kT_e}{16eB}. \tag{8}$$

Then, the diffusion loss time, τ_e, is roughly given by

$$\tau_e \sim \frac{a^2}{D_{el}}. \tag{9}$$

Using the diffusion loss time, we have the electron density balance equation

$$V_e \frac{dn_e}{dt} = -\frac{n_e}{\tau_e} V_e + \frac{S_e}{e}, \tag{10}$$

where $V_e \sim \pi a^2 b$ is the volume of the electron plasma and S_e the electron emission current of the cathode. In the steady state, the electron density is expressed as $n_e = (\tau_e S_e / e V_e)$. When a=b=0.05 m, $T_e \sim 20$eV, B=0.08 T and $S_e = 10^{-6}$ A, n_e and τ_e become 2.5×10^{12} m^{-3} and 1.6×10^{-4} s, respectively. The obtained value for the electron density is close to the maximum electron density derived from Eq.(7), when the value of ϕ_i or ϕ_s is several hundreds eV.

4. Ion Collection Current

The ion collection current is determined by the number of the electron ionization rate. The electron collision frequency for the ionization, ν_e, may be expressed as

$$\nu_e \sim \frac{v_{\perp e}}{\lambda_e}. \tag{11}$$

where $\lambda_e = 1/\sigma n_0$ is the mean free path, σ the cross section and n_0 the residual gas density, $n_0 = 3.5 \times 10^{22}$ P(Torr)m^{-3} and P the pressure. The ion collection current, I_i, becomes

$$I_i = e n_e v_e V_e \tag{12}$$

when a=b=0.05 m, $n_e = 2.5 \times 10^{12}$ m^{-3}, $T_{\perp e} \sim 20$eV and $\sigma = 10^{-20}$ m^2, we have

$$I_i = 0.11 P\,(\text{Torr})\ (A).$$

The ion current output in this case is approximately 0.1A/Torr.

In order to measure the pressure as low as 10^{-14} Torr, the ion current of order of 10^{-15} A has to be detected without the noise or the background. The noise or the background may come from the emission of secondary electrons due to the ion impact on the collector and the bombardment of the photon caused by the electron diffusion to the shield wall. If the energy of the electrons lost to the shield wall is of order of eV, the electron photoemission seems not be a serious background source. In the case that the cathode current is 10^{-6} A, the electron diffusion current is also 10^{-6} A. For the measurement of the pressure less than 10^{-14} Torr, the probability of secondary electron emission due to the photons has to be less than 10^{-9}. On the other hand, the ions which are accelerated to the energy level of order of several hundreds eV may produce the secondary electrons with a high probability. For example, the ratio of secondary electron emission due to H^+ ion with energy of 100 eV on copper is about $10^{-3} \sim ^{-2}$. Since the ratio of secondary electron emission is much less than unity, this background may not limit the ion collection current.

5. Summary

The electron motion, the upper limit of the electron density and the ion collection current of the Lafferty gauge with negatively biased walls were analytically examined. The results obtained are as follows,

(1) For the ion to be collected to the ion collector without the collision, the collection time roughly has to be shorter than the transit time in the azimuthal direction. In addition, the negative potential of the ion collector has to be larger than that of the shield wall to avoid the ion flow to the shield wall.

(2) The electron density has to be limited by the self potential, e.g. the negative wall potential be larger than that of the self potential.

(3) The electron density may be determined by the Bohm like difusion, since the fluctuation of the electric potential is the major mechanism for the diffusion.

(4) The ion collection current is estimated as ~0.1 A/Torr in the Lafferty gauge with a radius of 0.05 m and an axial lenghth of 0.1 m.

(5) The ratio of secondary emission due to the photons produced by the electron diffusion has to be less than 10^{-9} for the measurement of the pressure less than 10^{-14} Torr.

In summary, the principle of the Lafferty gauge with negatively biased walls for the pressure measurement of XHV was analyzed and several requirements were suggested.

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