Vacuum II

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CAS - Bilbao
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Creating Vacuum (continuation)

Measuring Vacuum

Partial Pressure Measurements
Diffusion Ejector pump

Schematic of the pump

operating pressure: $10^{-3} – 10^{-8}$ mbar
**Pump principle:**

The vacuum gas diffuses into the jet and gets kicked by the oil molecules imprinting a downward momentum.

The oil jets produce a skirt which separate the inlet from the outlet.
Inlet

Outlet

Diffusion
Problems

- Cold surface
- Inlet
- Back streaming
- Back-Migration
- Po
- Pi
Cures

Inlet

Baffle
(reduces the pumping speed of 0.3)

Cold surface

Pi

Cold Cap

Po

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with \( p_u \sim 10^{-6} \text{ mbar} \)

The pumping speed \( S_m \) is proportional to the area of the inlet port

100 mm diameter \( \Rightarrow S_m = \sim 250 \text{ l/s for } N_2 \)
Capture Vacuum Pumps

**Principle**

Capture vacuum pumps are based on the process of capture of vacuum molecules by surfaces.

- Getter Pumps
  - (evaporable, non-evaporable)
- Sputter ion Pumps
- Cryo Pumps
Getter Pumps

Gas

Surface

Solid Bulk
Getters are materials capable of chemically adsorbing gas molecules. To do so their surface must be clean. For Non-Evaporable Getters a clean surface is obtained by heating to a temperature high enough to dissolve the native oxide layer into the bulk.

\[ T = T_a \]

Native oxide layer -> no pumping

Heating in vacuum
Oxide dissolution -> activation

Pumping

NEGs pump most of the gas except rare gases and methane at room temperature
Sorption Speed and Sorption Capacity

C.Benvenuti, CAS 2007
Choice of the coating technique for thin film: **sputtering**

- **substrate to coat:** *vacuum chamber*
- **target material:** *NEG (cathode)*
- **driving force:** *electrostatic*
- **energy carrier:** *noble gas ions*

**NEG composition**

- The trend in vacuum technology consists in moving the pump progressively closer to the vacuum chamber wall.
- The ultimate step of this process consists of transforming the vacuum chamber from a gas source into a pump.
- One way to do this is by “ex-situ” coating the vacuum chamber with a NEG thin film that will be activated during the “in situ” bakeout of the vacuum system.
Sputter ion pumps

B - E

Anode +

Cathode -

P1

P2

Titanum

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The adsorbing material is sputtered around the pump.
A glimpse to the complexity

Adsorbed ions

Trapped electron

ion bombardment with sputtering

ionization process
Example of Pumping speed

Fig. 5.67. Volume throughput (VTP) of sputter ion pumps for nitrogen as a function of pressure. IZ270 is a pump with nominal VTP, $S=270$ liter·s$^{-1}$, diode and triode; IZ500 is a pump with nominal VTP, $S=500$ liter·s$^{-1}$, diode and triode.

Cryo Pumps

Dispersion forces between molecules and surface are stronger than forces between molecules.

Stick to the Wall!!
Schematic of a cryo pump

\[ P_w = \text{pressure warm} \]
\[ P_c = \text{pressure in the cold} \]
\[ I_w = \text{flux Vessel} \rightarrow \text{Pump} \]
\[ I_c = \text{flux Pump} \rightarrow \text{Vessel} \]

molecules stick to the cold wall
Now \( I_w = \frac{1}{4} \tilde{n}_w v_w A \) by using the state equation \( I_w = \frac{P_w A}{4k_B T_w} v_w \).

In the same way \( I_c = \frac{P_c A}{4k_B T_c} v_c \).

If \( I_c = I_w \) no pumping although \( P_c \neq P_w \).

Relation between pressures

**Thermal Transpiration**

\[
\frac{P_c}{\sqrt{T_c}} = \frac{P_w}{\sqrt{T_w}}
\]
When the two pressures breaks the thermal transpiration condition a particle flow starts

\[ I_{net} = I_w - I_c = \frac{A P_w v_w}{4k_B T_w} \left[ 1 - \frac{P_c v_c T_w}{P_w v_w T_c} \right] \]

We define \( I_{max} = \frac{A P_w v_w}{4k_B T_w} \) and \( P_w(ult) = P_c \sqrt{\frac{T_w}{T_c}} \)

We find \( I_{net} = I_{max} \left[ 1 - \frac{P_w(ult)}{P_w} \right] \)

\( P_c \) depends on the capture process

**Cryocondensation:** \( P_w \) is the vapor pressure of the gas at \( T_c \)
Gauges

Liquid Manometers

MacLeod Gauges

Viscosity Gauges

Thermal conductivity Gauges
  Hot Cathode Gauges
  Alpert-Bayard Gauges

Penning Gauges
Liquid Manometers

Relation between the two pressure

\[ P_1 - P_2 = h \rho g \]

issue: measure precisely “h” by eye +/- 0.1 mm
but with mercury surface tension depress liquid surface
High accuracy is reached by knowing the liquid density

Mercury should be handled with care: serious health hazard
McLeod Gauge

First mode of use:

The reservoir is raised till the mercury reaches the level of the second branch (which is closed)

\[ P_2 = \rho g \frac{\Delta h^2}{h_0 - \Delta h} \]

Quadratic response to \( P_2 \)

Second mode of use: keep the distance \( \Delta h \) constant and measure the distance of the two capillaries \( \rightarrow \) linear response in \( \Delta h \)
Viscosity Gauges

It is based on the principle that gas molecules hitting the sphere surface take away rotational momentum.

The angular velocity of the sphere decreases

\[ P = \frac{\pi}{10} \rho R v_a \left( \frac{1}{\omega} \frac{d\omega}{dt} + 2\alpha \frac{dT}{dt} \right) \]

\( \rho \) = sphere density
\( \alpha \) = coefficient of thermal dilatation
\( T \) = temperature
\( v_a \) = thermal velocity
Fig. 24: Schematic of a spinning rotor gauge. 1 rotor; 2 vacuum tube; 3 permanent magnets; 4 two coils for vertical stabilization; 5 four drive coils; 6 two detection coils; 8 four coils for horizontal stabilization. From *Wutz Handbuch Vakuumtechnik* by K. Jousten (ed.), Vieweg Verlag.

(K. Jousten, CAS 2007)

Thermal conductivity Gauges

A hot wire is cooled by the energy transport operated by the vacuum gas

\[ \dot{E} = \sqrt{\frac{2k}{\pi m T_g}} \alpha (T_w - T_g) P. \]

Accommodation factor

\[ \alpha = \frac{T_d - T_g}{T_w - T_g} \]

By measuring dE/dt we measure P
Energy Balance

- Energy loss by gas molecules
  \[ \dot{E} = \sqrt{\frac{2k}{\pi mT_g}} \alpha (T_w - T_g) P. \]
- Energy loss by Radiation
  \[ W_R = \varepsilon \sigma (T_w^4 - T_g^4) \]
  \[ \sigma = 5.673 \times 10^{-8} \text{ W m}^{-2} \text{K}^{-4} \]
  \[ \varepsilon = \text{emissivity} \]
- Energy loss by heat conduction

When the energy loss by gas molecule is dominant, \( P \) can be predicted with contained systematic error.
The Gauge tube is kept at constant temperature and the current is measured.

So that

\[ W = \frac{V^2}{4R} \]

Through this value \( \dot{E} \)

Example of power dissipated by a Pirani Gauge vs Vacuum pressure.
Ionization Gauges Principle

- Electrons are accelerated through the accelerating gap.
- The gap length is denoted by $L$.
- The voltage is denoted by $V$. 

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\[ V \]

\[ i_+ = \text{current proportional to the ionization rate} \]

**IONIZATION**

positive ions

new electrons
Electrons ionization rate

\[ \frac{i_+}{i_-} = \frac{\sigma_i L}{k_B T} P \]

Sensitivity
Hot Cathode Gauges

- Anode
- Grid
- Electric field
- Hot Cathode

Diagram shows a circuit with a grid between an anode and a hot cathode. The grid is connected to a 30 V power source, while the anode is connected to a 180 V power source.
Hot Cathode Gauges

In this region the electrons can ionize vacuum particles.

A current between grid and anode is proportional to the vacuum pressure.
Limit of use

Upper limit: it is roughly the limit of the linear response

Lower limit: X-ray limit

The new electron change the ionization current

\[ i_+ + i_r = KP_i - + i_r \]

\[ P_m \]

\[ 10^{-7} \text{ mbar} \]
Alpert-Bayard Gauge

The X-ray limit is easily suppressed by a factor ~100-1000

the probability that a new electron hits the anode is now very small
Schematic of the original design (K. Jousten, CAS 2007)

Fig. 11: The original design of the Bayard–Alpert gauge. From R.T. Bayard and D. Alpert, Rev. Sci. Instrum. 21 (1950) 571.
Penning Gauge (cold cathode gauges)

E = electric field
B = magnetic field

Electrons motion

\[ \frac{dm\gamma\vec{v}}{dt} = e\vec{E} + e\vec{v} \times \vec{B} \]
Under proper condition of \((E,B)\) electrons get trapped in the Penning Gauge.

One electron is trapped.
One electron is trapped

one vacuum neutral gas enters into the trap
Ionization process

Before Collision
Neutral vacuum atom
Electron at ionization speed

Collision $\rightarrow$ Ionization
Charged vacuum atom
Electron at ionization speed
New electron
this ion has a too large mass and relatively slow velocity, therefore its motion is dominated by the electric field and not by the magnetic field
Ionization

Charged vacuum atom

Motion of stripped ion

New electron
More electrons are formed through the ionization of the vacuum gas and remains inside the trap.
When the discharge gets saturated each new ionization produce a current
The time necessary for the discharge formation depends upon the level of the vacuum

lower pressure $\rightarrow$ longer time of formation

Sensitivity of a SIP (the same as for the Penning Gauge).

J.M. Lafferty, Vacuum Science, p. 322
Summary on Gauges

Pa $10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $10^{0}$ $10^{2}$ $10^{4}$

- **Vacuum Gauges**
  - U-tube
  - Bourdon gauge
  - Diaphragm gauge
  - Capacitance
  - Thermistor
  - Pirani gauge, Thermocouple
  - McLeod gauge
  - Spinning Rotor gauge
  - Penning gauge
  - Hot-Cathod Ionization gauge, Bayard-Alpert
  - Cold-Cathode Discharge gauge
  - Extractor-Ionization gauge, Modified Bayard-Alpert
Partial Pressure Measurements

These gauges allow the determination of the gas components.

Partial pressure gauges are composed of:

1. **Ion Source**
2. **Mass Analyzer**
3. **Ion current detection System**
4. **Data output**
Ion Sources

Vacuum gas is ionized via electron-impact

the rate of production of ions is proportional to each ion species

Electron-impact ionization process

Before Impact

After impact

inelastic scattering: kinetic energy transfer from the electron to the molecule
The minimum energy to ionize $M$ is called "appearance potential"

At the appearance potential the production rate is low

Ion source

Open source
Bayard-Alpert gauge

acceleration gap

ionization region

electrons

ions

E

V_f

V_g < V_c

V_c

V_g
A schematic

\[ i_+ = i_- \sigma_i F \frac{P}{T} \]

F = ion transmission factor
Ion Detection

- Faraday Cup
- Secondary electron Multiplier (SEM)

Idea: an ion enters into the tube, and due to the potential is accelerated to the walls. At each collision new electrons are produced in an avalanche process.

\[ G = \left( \frac{KV_0^2}{4V\alpha^2} \right) \left( \frac{4V\alpha^2}{V_0} \right) \]

\[ \alpha = \frac{L}{d} \]

\( V_0 = \) applied voltage

\( V = \) initial energy of the electron

\( K = \delta V_c \)

where

\( \delta = \) secondary emission coefficient

\( V_c = \) collision energy

Mass Analyzers

Quadrupolar mass spectrometer

Ion equation of motion

\[
\begin{align*}
\frac{d^2 x}{dt^2} &= + \frac{e}{m r_0^2} (U + V \cos \omega t) x \\
\frac{d^2 y}{dt^2} &= - \frac{e}{m r_0^2} (U + V \cos \omega t) y \\
\frac{d^2 z}{dt^2} &= 0
\end{align*}
\]

U, V constant

define:

\[
a = \frac{4eU}{Mr_0^2 \omega^2} \quad q = \frac{2eV}{Mr_0^2 \omega^2}
\]
By rescaling of the coordinates the equation of motion becomes

\[
\begin{align*}
\frac{d^2 x}{d\theta^2} &= (a + 2q \cos 2\theta)x \\
\frac{d^2 y}{d\theta^2} &= -(a + 2q \cos 2\theta)y \\
\frac{d^2 z}{d\theta^2} &= 0
\end{align*}
\]

Stability of motion

<table>
<thead>
<tr>
<th></th>
<th>horizontal</th>
<th>vertical</th>
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</thead>
<tbody>
<tr>
<td>(q=0, a&gt;0)</td>
<td>unstable</td>
<td>stable</td>
</tr>
<tr>
<td>(q=0, a&lt;0)</td>
<td>stable</td>
<td>unstable</td>
</tr>
</tbody>
</table>

The presence of the term \(q\), changes the stability condition

**Development of stable motion**

Stable or unstable motion is referred to a channel which is infinitely long, but typically a length correspondent to 100 linear oscillation is considered enough

Example:

For \(N_2\) at \(E_k = 10\) eV

\[\Rightarrow v_s = 8301\ \text{m/s}\]

For a length of \(L = 100\) mm

\(100\) rf oscillation

\[\Rightarrow f = 8.3\ \text{MHz}\]

Typically

\[f \sim 2\ \text{MHz}\]
Stability Chart of Mathieu equation

Stable in y

Stable in x
Stability region in both planes

$q_0 = 0.706$
$a_0 = 0.237$
Given a certain species of mass $M_1$ there are two values $U_1, V_1$ so that $q=q_0$ and $a=a_0$

By varying $V$ and keeping the ratio $V/U$ constant, the tip of the stability is crossed and a current is measured at $V=V_1$

\[
\frac{M_1}{e} = \frac{2V_1}{q_0 r_0^2 \omega^2}
\]

\[
\frac{M}{\Delta M} \propto \frac{M \omega^2 L^2}{2eV_z}
\]
Magnetic Sector Analyzer

Example: A 90° magnetic sector mass spectrometer

B is varied and when a current is detected then

\[ \frac{M}{q} = \frac{R^2 B^2}{2E_z/q} \]

\( E_z \) is the ions kinetic energy

Resolving power

\[ RP \approx \frac{R}{W_{source} + W_{collector}} \]

\( W_{source} \) = source slit width
\( W_{collector} \) = collector slit width

J.M. Lafferty, Vacuum Science, p. 462
Omegatron

FILAMENT

B

ION COLLECTOR

TO

ELECTROMETER

R.F. PLATES
The revolution time is independent from ion energy

\[
\tau = \frac{2\pi M}{B \frac{q}{q}}
\]

If the frequency of the RF is $1/\tau$ a resonant process takes place and particle spiral out

Resolving power

\[
\frac{M}{\Delta M} = 4.8 \times 10^{-5} \frac{R_0 B^2}{E_0} \frac{e}{M}
\]
Conclusion

Creating and controlling vacuum will always be a relevant part of any accelerator new development.

THANK YOU FOR YOUR ATTENTION

These two lectures provides an introduction to the topic, which is very extensive: further reading material is reported in the following bibliography
Kinetic theory and entropy, C.H. Collie, Longam Group, 1982
Vacuum in accelerators, CERN Accelerator School, CERN-2007-003 11 June 2007
Vacuum technology, CERN Accelerator School, CERN 99-05 1999

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