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UHV Technology

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Please note: These are preliminary notes intended for internal distribution only.

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UHV - Technology

Oswald Gröbner (ret.)

CERN LHC-VAC

- 1) Introduction and some basics
- 2) Building blocks of a vacuum system
- 3) How to get clean ultra high vacuum
- 4) Desorption phenomena
- 5) Practical examples

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Literature

Books

The Physical Basis of Ultrahigh Vacuum, P.A. Redhead, J.P. Hobson, E.V. Kornelsen, American Vacuum Society Classics, American Institute of Physics, 1993

Foundations of Vacuum Science and Technology, Edited J.M. Lafferty, John Wiley & Sons, 1998

Handbook of Accelerator Physics and Engineering, A. W. Chao, M. Tigner, World Scientific, 1998

CAS CERN Accelerator School : Vacuum Technology, Edited : S. Turner. CERN 99-05, 19 August 1999

Handbuch Vakuumtechnik, M. Wutz et. al, Vieweg, Braunschweig/Wiesbaden, 2000

Journals:

VACUUM

Journal of Vacuum Science and Technology (A)

Nuclear Instruments and Methods (Section A)

Accelerators at CERN

Historical map from 1996



Nearly all CERN accelerators require ultrahigh vacuum

Total length of vacuum systems over 60 km

LEP to be replaced by LHC (cryogenic vacuum system)

Pressure and Molecular Density

Ideal gas law: $P V = \frac{N}{No} R T$ with P pressure, V volume, T temperature N number of molecules R gas constant = 8.31 kJ kmol⁻¹ K⁻¹, $No = 6.02 \ 10^{26}$ molecules kmol⁻¹ Molecular density $n = \frac{N}{V}$ Pressure : $P = n \ k T$

Boltzmann constant $k = 1.38 \ 10^{-23}$ J/K Note : $R = No \ k$

In nearly all cases, it is the gas density rather than the pressure which matters.

<u>Units :</u>

<u>Pressure</u> :	Pa (N/m ²)
	mbar = 100 Pa
	Torr = 133 Pa
<u>Gas load</u> :	$Pa m^3 = 7.5 Torr 1$
	mbar l ~ $2.4 \ 10^{19}$ molecules at RT
Specific outgas	sing rate :
	Gas release from the walls
	Pa $m^3/s/m^2 \sim 7.5 \ 10^{-4} \ Torr \ l/s/cm^2$
Leak rate :	Pa m ³ /s or W
	mbar l/s or Torr l/s

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Wall collisions

Frequency of wall collisions

$$\mathbf{v} = \frac{1}{4} n \,\overline{v}$$

proportional to the number density n and to the average molecular velocity \overline{v} .



Momentum transfer to the walls is $2 m \overline{v}$, hence the pressure is proportional to $m v \overline{v}$

Distribution of Molecular Velocities

Maxwell-Boltzmann distribution of molecular velocities at the temperature T

$$\frac{1}{N}\frac{dN}{dv} = \frac{4}{\sqrt{\pi}} \left(\frac{m}{2kT}\right)^2 v^2 e^{\frac{mv^2}{2kT}}$$

The average velocity is given by $(m = M m_o)$

$$\overline{v} = \sqrt{\frac{8kT}{\pi M m_o}}$$
, numerically ~146 $\sqrt{\frac{T}{M}}$ (m s⁻¹)



Molecular velocities for N_2 at 50, 100, 300 and 500K.

Mean molecular velocities at 20°C (m/s)

H ₂	N ₂	Air	A	Kr
1754	470	464	393	272

Pressure

$$p = const m \bar{v} v$$

m mass of a molecule

 \overline{v} average molecular velocity

v rate of wall collisions

A complete calculation gives $const = \pi/2$

Thus one finds

$$p = \pi/2 m \sqrt{\frac{8kT}{\pi m}} n \sqrt{\frac{kT}{2\pi m}}$$

and the final result

p = n kT

Considering a molar quantity, $n = \frac{N_0}{V_0}$ One finds again the familiar result $pV_0 = N_0 kT = RT$ with the gas constant R

Mean Kinetic Energy

The kinetic energy :

$$E_{kin} = \frac{1}{2} m \bar{v}^2 = \frac{1}{2} M m_o \left(\frac{8kT}{\pi M m_o}\right) = \frac{4}{\pi} k T$$

M molecular weight

 $m_o = 1.66 \ 10^{-27} \ \text{kg}$

does not depend on the molecular mass, M, but only on temperature T.

In thermal equilibrium heavy molecules move

sufficiently slowly and light molecules move sufficiently fast to carry on average the same kinetic energy.

Total and Partial Pressures

For each gas component $n_1, n_2, n_3,...$ the individual contribution to the total pressure :

$$P_i = n_i kT$$

The total pressure is therefore the sum of the partial pressures:

$$P = \sum_{i} P_{i} = k T \sum_{i} n_{i}$$

Gas	%	Pi (Pa)
N ₂	78.1	7.9 10 ⁴
O ₂	20.5	$2.8 \ 10^3$
Ar	0.93	$1.2 \ 10^2$
CO ₂	0.0033	4.4
Ne	1.8 10-3	2.4 10-1
He	5.2 10-4	7 10 ⁻²

Partial pressures for atmospheric air

Mean Free Path

$$l = \frac{1}{\sqrt{2} \pi D^2 n}$$

D molecular diameter (~3 10⁻⁸ m)



Volume traversed by a molecule per second : $\pi D^2 \bar{v}$ Molecule collides with all other molecules contained within the cylinder of radius *D*.

Number of collisions: $Z \approx \pi D^2 \overline{v} n$. The mean free path is defined as

$$l = \frac{\bar{v}}{Z} = \frac{l}{\sqrt{2}\pi D^2 n}$$

It also follows that $n l \propto P l \approx const$.

Note: $\sqrt{2}$ accounts for the fact that molecules in the cylinder are not stationary.

For air the product $n l \approx const$ is ~ 2.5 10^{14} m^{-2} .

For N₂ at 20 deg. C and a pressure of 1 Pa $\rightarrow l \sim 0.9$ mm

Molecular Flow Conditions

Mean free path >> relevant dimensions of system

Knudsen relation: gas flow $Q \propto \Delta P$.

Knudsen relation. See Molecular flow conductance $c = \frac{4}{3} \frac{\overline{v}}{\int_{0}^{L} \frac{H}{A^{2}} dl}$ (m³/s)

L length of the element (L >> transverse dimensions). H perimeter, A cross section of the element.

The conductance is proportional to the mean molecular velocity, i.e. to $\sqrt{\frac{T}{M}}$.

A cylindrical duct with uniform section and radius r :

$$c = \frac{4}{3} \overline{v} \left(\frac{r^3}{L} \right) \sim 306 \cdot \left(\frac{r^3}{L} \right) \sqrt{\frac{T}{M}}.$$

An orifice (pumping orifice, L~0) :

$$c = \frac{1}{4} \,\overline{v} \, A \sim 36.5 \cdot A \sqrt{\frac{T}{M}} \,.$$

Conductance of elements in series or in parallel add the same as for electric circuits

$$\frac{1}{c} = \frac{1}{c_1} + \frac{1}{c_2}$$
 and $c = c_1 + c_2$

For complicated geometries it is often necessary to use Monte Carlo calculations for the molecular flow.



Molecular conductance of circular tubes

Fig. 2.1. Plots of conductance of cylindrical tubes for air at 20° C calculated according to equation 2.40.

Vacuum characteristics

Pressure	Р	n	ρ	v	l
	Pa	m ⁻³	kg m ⁻³	$m^{-2}s^{-1}$	m
atm	10 ⁵	$2.5 \ 10^{25}$	1.16	2.9 10 ²⁷	9 10 ⁻⁸
primary	1	$2.5 \ 10^{20}$	1.16 10 ⁻⁵	2.9 10 ²²	9 10-3
vacuum	10-1	2.5 10 ¹⁹	1.16 10-6	2.9 10 ²¹	9 10-2
high	10-4	2.5 1016	1.16 10-9	2.9 10 ¹⁸	9 10 ¹
vacuum	10-7	2.5 10 ¹³	1.16 10 ⁻¹²	2.9 10 ¹⁵	9 10 ⁴
uhv	10-10	2.5 1010	1.16 10 ⁻¹⁵	2.9 10 ¹²	9 10 ⁷
xhv	<10-11				

gas : Nitrogen, N₂, 20°C, M = 28

$$n = \frac{P}{kT}$$
 $kT = 4.04 \ 10^{-21}$ Joule

$$\rho = M m_0 n$$

$$M m_0 = 4.65 \ 10^{-26} \text{ kg}, \quad m_0 = 1.66 \ 10^{-27} \text{ kg}$$

$$\nu = \frac{l}{4} n \overline{\nu} \qquad \overline{\nu} = 146 \sqrt{\frac{T}{M}}$$

$$l = \frac{l}{\sqrt{2}\pi D^2 n} \qquad D(N_2) = 3.15 \ 10^{-10} \text{ m}$$

Thermal transpiration



At high pressure, the pressures on both sides are equal.

In molecular flow, the net number of molecules traversing the separating wall should be zero.



Thermal Conductivity

Thermal conductivity of a gas is independent of the pressure when the pressure is well above the molecular flow regime.

In the transition regime, the heat transfer is proportional to the pressure and to the

temperature difference.



100 **Residual Gas Pressure — TORR**

At very low pressures, the heat transfer by conduction is negligible -> vacuum for thermal

insulation in cryogenics.

LHC Cryodipole



Basic Vacuum System



Stationary conditions (independent of volume)

$$P = \frac{q F}{S}$$

Dynamic conditions

$$V \frac{\partial P}{\partial t} = q F - S P$$

Solution (constant K depends on initial conditions)

$$P(t) = K e^{-\frac{S}{V}t} + \frac{q F}{S}$$

The time constant of the system: $\frac{S}{V}$

To obtain a low pressure :

- 1) Low outgassing rate of the surface, No leaks !
- 2) Large pumping speed

Linear Vacuum System (Accelerators)





Gas flow:	Q(x)	$[Pa m^3 s^{-1}]$
Specific outgassing rate:	q(x))	[Pa m s ⁻¹]
Specific surface area per unit length:	А	[m]
Molecular conductance per unit length		

of the tube:

 $[m^4 s^{-1}]$

$$\frac{dQ}{dx} = A q \quad \text{et } Q(x) = -c \frac{dP}{dx}$$
$$c \frac{d^2 P}{dx^2} = -A q$$

с

Boundary conditions for this configuration :

By symmetry
$$\left[\frac{dP}{dx}\right]_{x=\pm L} = 0$$
 and the pressure at $x = 0$

$$P(x=0) = \frac{Q(x=0)}{2S}$$
$$Q(0) = 2AqL$$

One obtains a parabolic pressure distribution :

$$P(x) = A q \left(\frac{2 L x - x^2}{2 c} + \frac{L}{S} \right)$$

The average pressure, relevant for the beam :

$$P_{av} = \frac{1}{2L} \int_{0}^{2L} P(x)dx = A q \left(\frac{L^2}{3c} + \frac{L}{S}\right)$$

Note : the pressure is limited by the molecular conductance of the system.

Inspite of an increase of the pumping speed *S*, the average pressure is limited to the value :

$$P_{av\min} = \frac{A q L^2}{3 c}$$

Two important requirements :

Large diameter of the vacuum chamber

Close spacing of pumps



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$$t = \frac{\Theta}{\frac{1}{4}\,\overline{v}\,sn}$$

Mono layer coverage
Molecular velocity Θ (~ 3 10¹⁹ molecules m⁻²)Molecular velocity $\overline{\nu}$ (m s⁻¹)Gas densityn (molecules m⁻³)Sticking probabilitys = 1 (max. value)

UHV becomes indispensable for surface analysis and for thin film technology

-> Historically the main motivation to develop uhv techniques

Note: Area occupied per molecule ~ $A \sim 2\sqrt{3}r^2$

Beam Lifetime due to Vacuum

Beam loss by Bremsstrahlung :

$$-\frac{dE}{dx} = \frac{E}{X_o}$$

 X_o radiation length

Hence

$$\frac{l}{\tau} = -\frac{l}{N}\frac{dN}{dt} = \frac{c\rho}{X_o}W$$

c speed of particles and $\rho = \frac{m_0 M}{kT} P$ density of the residual gas at the pressure P. $W = \log(\frac{E}{\Lambda E})$

Represents the probability per radiation length to emit a photon with an energy larger than the energy acceptance of the machine so that the particle will be lost. The lifetime

$$\mathbf{r} = \frac{X_o}{c\rho W} \propto \frac{X_o}{P}$$

$$\tau P = 3.410^{-8} \text{ (Torr hours)}$$

Uhv is required for storage rings.

Heavy molecules must be avoided because of their short radiation length.

Vacuum pumps and vacuum gauges used in large accelerator systems



Rotary Pumps

Single stage and double stage pumps

Oil sealed

Typical end pressures : 10^{-2} to $\sim 10^{-3}$ mbar

Typical pumping speeds : 4 to ~ 40 m³/h (used for systems with small volume)

Filter for oil vapour is required.





Turbomolecular Pump



Molecules collide with the surface and gain a velocity

component in the direction of the movement.

Pumping speed of a turbomolecular pump

$$S \propto v A$$

S independent of pressure

v rotational speed, typically at least >40000 rpm

A pump geometry, large entrance flange



Hence the compression ratio is large for heavy molecules
-> 'clean vacuum' without heavy hydrocarbon molecules (no contamination by oil vapour from a primary pump) can be obtained

The Molecular Pump Principle



The molecular conductance of a rectangular duct, with the perimeter H = 2(w+h) and the section $A = w \cdot h$ is given by :

$$c = \frac{4}{3} \frac{\overline{v}}{\int\limits_{0}^{x} \frac{H}{A^2} dl} = \frac{2}{3} \overline{v} \frac{h^2 w^2}{x(h+w)}$$

In molecular flow : $\frac{dP}{dx} = \frac{Q}{c}$.

Assuming that one surface is moving with the speed u, the gas flow which traverses a given cross section corresponds

to :
$$Q = PV = P\frac{u}{2}A$$
.

Thus

$$\frac{dP}{dx} = \frac{u}{2c}AP$$

Integrating this equation over the length of the duct

 $\int_{P_1}^{P_2} \frac{dP}{P} = \frac{u}{2c} A \int_{0}^{L} dx \quad \text{one obtains the result :}$ $K = \frac{P_2}{P_1} = e^{\frac{u}{2c}AL}.$

K defines the compression ratio of a pump i.e. the ratio between input and output pressures.

K increases exponentially with the molecular weight, and with the rotational speed of the pump.

Typical values of commercial pumps :

for hydrogen ~2 10^3

for nitrogen ~ 10^8 !

A large compression ratio for heavy molecules results in a 'clean vacuum' without hydrocarbon (C-H) contamination.

The pumping speed S is proportional to the rotational speed and depends on the geometry of the pump.

S does not depend on the molecular weight M.

Turbomolecular pumps

Compression factor



Pumping speed curves



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Mobile pumping station for LEP



Basic configuration of a sputter-ion pump.

Configuration of a parallel electric and magnetic field produces a selfmaintained discharge plasma.

-> Penning configuration

Ionised residual gas molecules are accelerated towards the Ti cathode and 'trapped' and removed from the gas phase.



Sputtering of Ti from cathode produces a clean gettering film.

In a particle accelerator, the magnetic field can be provided by bending magnets. --> <u>integrated</u>, <u>linear ion-pumps</u>.

To increase the pumping speed arrays of cells are used

Pumping mechanisms :

Gettering -> chemisorption of active species H_2 , CO, N_2 , O_2 , CO₂

Diffusion of H_2 into the Ti- cathode (re-diffusion!) Cracking of inert hydrocarbons into C, H, O which can be pumped (chemisorbed) separately

Nobel gases: energetic ions of He, Ne, A by implantation into the cathode: "ion burial" of energetic ions.

To increase the discharge intensity and thus the pumping speed it is desirable to increase the sputtering rate of the titanium cathode

➔ Triode Sputter-Ion pump with grazing incidence of ions on a grid cathode

Note:

Molecules are not removed from the vacuum system. Therefore, memory effect of previously pumped gas.

Surface Pumping

Getters (chemisorption E~eV) Evaporable getter pumps (Ti sublimators) Non Evaporable Getters (NEG) Ti, Zr, V Surface pumping $\rightarrow S \propto \frac{1}{4} \overline{v} nF$



Gettering surface achieved by sublimation (Ti-filament) by surface activation (heating -> reduction of surface oxide layer and diffusion of O into the bulk) Cryo-pumps (physisorption E~ meV)

> Sorption (capacity ~ monolayer) Condensation (vapour pressure)

Monolayer Capacity

To illustrate the significance of a monolayer of gas, let us assume an evacuated sphere which has one monolayer molecules adsorbed on the inner surface.

$$N_{ads} = 4\pi r^2 \Theta$$

In case this gas is desorbed it would correspond to a volume density

$$n = \frac{N_{ads}}{V} = \frac{3\Theta}{r}$$

Taking, e.g. 1 m³ as the volume and $\Theta \approx 3 \cdot 10^{19} m^{-2}$ the pressure at room temperature would increase to typically

$$p = n kT \approx 0.4 Pa$$

Hence:

To reach uhv conditions, the 'surface gas' is extremely important.

Inversely, adsorbing molecules permanently on an 'active' surface (getters or cryo-pumps) is an extremely efficient pumping principle.

Getter Pumps

Evaporable getters: Titanium sublimation pump **Configuration**: **Control Unit** . Gettering Surface O (0) Titanium Active Gas Atoms Form Stable Compounds With Sublimes Titanium on Gettering Surface From Hot Filament

Deposition of a thin film of fresh Ti on the inner surface of the vacuum chamber Filament temperature ~ 1300 deg C To increase the lifetime of the pump one uses pump holders with several filaments (3-6)

Depending on the amount of gas pumped, the film has to be regenerated (e.g. typically at 10⁻⁶ Pa after one hour) The pumping speed increases with the surface of the pump and can be very substantial.

Note : only chemically active molecules can be pumped.

Non-Evaporable Getters or Bulk getters (NEG) :

Getter material (e.g. Ti, Zr, V) produced in the form of an alloy e.g. with Al and used as a bulk material. For LEP : metal ribbon coated with a thin layer of getter powder has been used.

Clean, active gettering surface is produced by heating under vacuum. Gas adsorbed on the surface diffuses into the bulk and a 'clean' surface can be obtained. Activation requires heating from 350 °C up to 700°C for one hour depending on the specific getter.

A combination of evaporable getters and of bulk getters is under development at CERN -> sputter deposited getter films (few μ m) coated directly onto the inner surface of vacuum chambers.

Note: Getters have a limited total pumping capacity and a memory effect of the gas previously pumped. Getters pump only chemically active gas i.e. nobel gases and hydrocarbons (methane, ...) are NOT pumped

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Reversible pumping of hydrogen by the NEG st101.



The equilibrium pressure of hydrogen is a function of the concentration of H_2 in the bulk, q (Pa m³g⁻¹) and of the temperature, T (K) :

$$\ln P_{equ} = 8.275 + \ln q^2 - \frac{7000}{T}$$

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Reduction of the pumping speed due to the gradual saturation of the surface by adsorbed molecules.

During re-activation, molecules diffuse into the bulk. A fresh surface is obtained for the next pumping cycle.



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LEP vacuum system with NEG pumping



Within less than 12 hours after the bakeout uhv conditions can be achieved.

Cryo-Pumpimg

Adsorption of molecules at low temperature -> e.g. at liquid helium temperature

A) Sorption _______

Adsorption of gas molecules with low surface coverage, to avoid the effect of the vapour pressure of the condensate. Increasing the effective surface area by a coating with a large specific surface area e.g. charcoal. -> Adsorption isotherms.



B) Condensation

adsorption in multi-layers -> limitation due to the vapour pressure of the condensed gas.



C) ' Cryo-trapping

Cryo-sorption of a gas e.g. H_2 or He with a high vapour pressure in the presence of an easily condensable carrier gas e.g. Ar.

Characteristics of cryo-pumping :

Large pumping speed

Low limit pressure : -> limitation occurs only by the vapour pressure of the condensed gas Large capacity -> Attention !! hazardous overpressure may build-up during warming up of a cryopumped system. ! -> a safety valve required !

- -> 'clean' vacuum -> absence of heavy hydro-carbon molecules.
- -> in combination with superconducting magnets or accelerating cavities, very effective integrated cryopumping can be obtained -> e.g. LHC vacuum system.

-> the walls of the vacuum system act as pumps (LHC).

The saturated vapour pressure limits the total quantity of gas which can be cryosorbed at low pressure.

Increase of the specific surface area of a cryo pump by using special cryo-sorbing materials with a large specific surface -> e.g. activated charcoal.

Design of a commercial cryp-pump

with a cryo-pannel :

Baffel to intercept thermal radiation.

Risk of overpressure during warm-up

when too large amount of gas has been condensed.

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Pressure (Torr)

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Solare (rinnovabili)

ma anche

Utilizzazione gas naturale evitando l'immissione di CO₂ nell'atmosfera, separandola prima e producendo idrogeno.

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- Rosei -

Richiede ricerca e sviluppo, (Scienza e Tecnologia)

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Pirani Gauge

Change of the thermal conductivity with pressure

Reliable and simple system.

Pressure range : atmospheric pressure to < 0.1 Pa

- A resistor with a large temperature coefficient is mounted inside the vacuum. This resistor is heated to a constant temperature and the required heating current is a measure of the pressure.
- The electronic circuitry (Wheatstone-bridge) provides temperature compensation and linearisation of the pressure reading.



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Cold Cathode Ionisation Gauge Penning Gauge

Based on the operating principle of an ion pump. Ratio of pressure and pump current ~ constant. Useful pressure range : 10^{-2} to 10^{-7} Pa

Limitations:

At high pressure the discharge is unstable (arcing)

At low pressure the discharge extinguishes -> zero pressure reading

Leakage current in the cables and in the gauge can simulate a higher pressure

Contamination of the gauge may change the calibration.

Extended operation at very high pressure can contaminate the gauge -> required demounting and cleaning.

Ionisation Gauge

Hot Filament Gauge



Operating principle :

Residual gas molecules are ionised by the electrons emitted from a hot filament.

Ions are collected by a "collector electrode". This ion current is proportional to the gas density, n, and hence the pressure, P.

The ionisation probability Pi (number of ion-electron pairs produced per m and per Pa) depends on the type of molecule and on the kinetic energy of the electrons. Ion collector current :

 $I^+ = Ie Pi L P$

Where :

- Ie emission current of the filament
- L path length of the electrons
- P pressure

Gauge Sensitivity

$$S = P_I L \quad [Pa^{-1}]$$

Obtained by calibration with a known pressure (N_2)

- -> Nitrogen equivalent pressure N₂.
- -> To measure a pressure for another gas, the relative gauge sensitivity for this particular gas with respect to nitrogen must be known.

 S_i/S_{N2} must be known for different gas species. For H₂, one finds typically $S_{H2}/S_{N2} \sim 0.38$





"Outgassing" of an Ionisation Gauge

Electrons emitted from the filament, reach the grid electrode with an energy of approximately ~ 150eV and may heat-up the grid and desorb gas molecules.

- -> pressure increase which disturbs the measurement.
- -> To suppress the effect, the grid and all other electrodes must be cleaned.
 - A common method to avoid this disturbance: the emission current is increased to heat the grid electrode temporarily to a very high temperature. -> Outgassing.

Pressure limitation : residual current -> limit pressure



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X-Ray Limit of an Ionisation Gauge

Electrons which hit the grid produce soft photons (x-rays) due to Bremsstrahlung.

A small fraction of these photons can reach the collector electrode and liberate photo-electrons which return to the grid -> this current is equivalent to a positive, "xray current" I_x , which is independent of the pressure. The correction of this effect can be done by the « modulation » method

'Modulated Bayard-Alpert' gauge

Modulator electrode	
measurement (1), $+ U_{grille}$,	$I_1 = I^+ + I_x$
measurement (2), 0 V,	$I_2 = \alpha I^+ + I_x$
Corrected collector current	$I^{+} = \frac{I_{\perp} - I_{\perp}}{1 - \alpha}$

The modulation factor : $1-\alpha$

can be determined easily by an independent measurement at high pressure where $I^+ >> I_x$.

Alternative design of an ionisation gauge:

Ions are 'extracted' from the grid volume to a collector which is optically screened from the photons of the grid.

-> Extractor gauge

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- R Reflector
- Uh Filament
- C Ion collector
- A Anode (grid)

Ions are extracted from the grid volume through a mask. The ion collector is optically shielded from the x-ray photons of the grid.

Partial Pressure Measurement



Combination of an ion source with a mass spectrometer.

- 1) Ion source
- 2) Quadrupole mass filter
- 3) Ion collector, Faraday-cup or secondary electron multiplier

Operating principle of a quadrupole mass filter :

- Ions with different mass to charge ratio are injected into the quadrupole structure. As they traverse the structure, ions are subjected to a periodically varying transverse electric field which excites transverse oscillations.
- Ions with an incorrect charge to mass ratio have unstable orbits, are lost and do not reach the collector.

The ion trajectories are described by the equations :

$$\ddot{x} + \left(\frac{e}{m}r_{o}^{2}\right)\Phi x = 0$$
$$\ddot{y} - \left(\frac{e}{m}r_{o}^{2}\right)\Phi y = 0 \quad and \quad \ddot{z} = 0$$

r_o is the radius of the structure and Φ the potential: $\Phi = U - V \cos(\omega t)$. With $a = 4 \frac{e}{m} \frac{U}{\varpi^2 r_o^2}$ and $q = 2 \frac{e}{m} \frac{V}{\varpi^2 r_o^2}$ -> Mathieu equation $\frac{d^2 u}{ds^2} + \{a - 2q\cos(2s)\}u = 0$

Solutions define regions with stable and unstable motion. Only the ions (e/m) with stable trajectories through the quadrupole mass filter are measured.

Stability Diagram



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Residual gas spectrum



Ion current (A) corresponding to a particular molecular species (e/m)

Total (N_2 -equivalent) pressure is obtained with a gauge.

Qualitative analysis relatively straightforward, e.g. : H_2 , H_2O , CO/N_2 , O_2 , CO_2

Distinction between CO/N_2 requires knowledge of the "cracking pattern" of the two molecular species.

Quantitative analysis requires a perfectly calibrated system for each residual gas component.

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peak	2	14	15	16	17	18	20	27	28	32	40	44
H ₂	100											
CH₄	2.4	10.7	85	100								
H ₂ O				1.8	27	100						
N ₂		6.2							100			
CO		0.9							100			
O ₂		_		18						100		
A							13				100	
CO ₂				7.5					18.5			100

Typical cracking patterns of common molecules

Principal peak is normalised to 100%.

Residual gas spectrum of a baked, 'clean' uhv system



Helium leak detector



Mass spectrometer tuned to Helium.

Leaks and leak detection

Leaks to atmospheric pressure : Gaskets Porosities Cracks in welds

Virtual leaks : Porosities, a volume enclosed inside the system

Helium leak detectors using He as tracer gas Based on the principle of a mass spectrometer

Example of a virtual leak :

The volume enclosed by a bolt in a threaded hole.

Solution : bolts have to be drilled with a central hole or a separate hole must be drilled to pump the dead volume.

In a large vacuum system, leak checks of all subcomponents are mandatory.

A global leak check after complete assembly should only concern those joints which have been done during the final installation phase.

Chemical solvent pre-cleaning procedure

- 1) Removal of gross contamination and machining oils using the appropriate solvents
- Perchloroethylene (C₂Cl₄) vapour degreasing at (121°C) to day no longer applicable
- 3) Ultrasonic cleaning in an alkaline detergent (pH =11)
- 4) Rinsing in cold demineralised water (conductivity $< 5 \ \mu S \ cm^{-1}$)
- 5) Drying in a hot air oven at 150° C
- 6) Wrapping in clean Al-foil or paper

Cleaning method will depend on the material (stainless steel, aluminium, copper)

Important:

Any subsequent handling must be done with clean gloves. Contamination by any residues in the air must be avoided.

No car exhaust gases, No smoking!!

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Chemical cleaning facility

- 1) Hot detergent with ultrasonic agitation
- 2) Hot vapour zone
- 3) Hot solvent bath
- 4) Cooling zone
- 5) Ultrasonic generators
- 6) Ultrasonic controls
- 7) Heaters
- 8) Drying zone
- 9) Covers
- 10) Cooling zone for solvent vapour



Cleaning of the surface by energetic ion bombardment (Usually Argon or some other inert gas)

Dose approx. 10^{18} - 10^{19} ions/cm²

Argon pressure between $10^{-1} - 10^{-2}$ Pa for optimum conditions

Desorption of chemisorbed, strongly bound molecules corresponding to a high activation enrgy.

Effective cleaning by removing the top layer of the surface by sputtering. -> Tokamak vacuum systems

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Vacuum firing

High temperature baking in a vacuum oven at 950 deg C

Cracking of hydrocarbons and organic compounds. Reduction of the surface oxide layer.



After the high temperature treatment, cool down in a clean gas to generate a controlled oxide layer

Thermal Desorption

Specific desorption rate : $q [Pa m^3 s^{-1} m^{-2}]$ $q = Const \cdot e^{-\frac{E}{kT}}$ Molecular residence time $\tau = \frac{1}{v_o} \cdot e^{\frac{E}{kT}}$ E activation energy for desorption, $v_o \sim 10^{13} \text{ s}^{-1}$ vibration frequency in the surface potential Log[q] $\log[q] = A - B \frac{1}{T}$ 1/T Physisorbed molecules E < 40 kJ/mole (0.4 eV)Chemisorbed molecules E > 80 kJ/mole (0.8 eV) Bakeout between $150 - 300^{\circ}$ C : reduced residence time. Reduction for H_2O , CO, CO_2 (by factors of 10^{-2} to 10^{-4})

At higher temperature > 400-500°C -> cracking of hydrocarbon molecules (C-H) Note: Reduced thermal desorption at cryogenic

temperatures

Thermal outgassing Rates

Comparison of organic materials and of metals

Unbaked samples (usually H₂O dominates)



Baked samples (24 hours at 150°C to 300 °C) Typical values after 50 hours of pumping : (units : Torr 1 s⁻¹ cm⁻²)

Gas	Al, Stainless steel
H ₂	5 10-13
CH ₄	5 10-15
СО	1 10 ⁻¹⁴
CO ₂	1 10-14

Bakeout of the LEP Vacuum System with NEG

Typical bakeout cycle with NEG



Within less than 12 hours after a bakeout uhv conditions can be achieved.

Criteria influencing the Choice of Materials

Low outgassing rate Low vapour pressure Temperature resistant -> bakeout Thermal and electrical conductivity -> beam interaction Corrosion resistance -> leaks Low induced radioactivity -> handling High mechanical strength -> 1dN/cm² external pressure! Machining, welding Low cost

Common choices :

Stainless steel Aluminium Copper

Ceramics for electric insulation Low porosity -> leaks Brazing to metal -> leaks

For particular applications

Organic materials (e.g. as composite materials (carbonfibers & epoxy), polymers to be used in small quantities

Synchrotron Radiation Induced Desorption

Radiated power (W): $P_{\gamma} = 88.6 \frac{E^4 I}{0}$ *E*, beam energy of electrons (GeV) *I*, beam current (mA) ρ , bending radius (m), Critical energy of the spectrum (eV) $\varepsilon_c = 2.2 \cdot 10^3 \frac{E^3}{2}$ Photon flux (s⁻¹) $\Gamma = 8.08 \cdot 10^{17} I E$ Linear photon flux (m⁻¹ s⁻¹) $\frac{d\Gamma}{ds} = 1.28 \cdot 10^{17} \frac{IE}{\rho}$ Gas desorption occurs in two steps : -> photons -> produce photo-electrons -> photo-electrons -> excite molecules which subsequently will desorb thermally Gas flow : $Q = \eta \Gamma$ $Q = K \eta I E + Q_{\alpha}$ with Q_{α} , the thermal desorption. η , molecular desorption yield (molecules per photon). The dynamic pressure : $P_{dyn} = \frac{Q}{S}$. The dynamic pressure increases proportionally with the beam intensity : $\frac{\Delta P}{I}$ (Pa/mA). 'Beam cleaning' (scrubbing) of the vacuum system.

Beam cleaning of the LEP vacuum system



Dose scale may be given in terms of accumulated photons/m or in Ah.

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Vacuum vessel of a synchrotron radiation light source

Bending magnet vessel with 'ante chamber' and light port.



Synchrotron radiation absorbers protect critical elements of the machine.



Water cooled absorber with integrated vacuum pumps

Fig. 5 Water cooled crotch absorber





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Comparison of successive vacuum treatments



Effect of various surface treatments including exposure to atmospheric air on the ion stimulated desorption yield.

Flanges and gaskets for primary vacuum and for uhv applications

Flange with clamp and elastomer seal





ConFlat flange





Clamped flanges with copper (gold) wire ring seals





