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SECOND SCHOOL ON THE USE OF SYNCHROTRON RADIATION IN SCIENCE AND TECHNOLOGY: *"JOHN FUGGLE MEMORIAL"*

25 October - 19 November 1993

Miramare - Trieste, Italy

VACUUM

O. Gröbner
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Molecular Concentration

$$n = \frac{N}{V}$$

V volume

N number of molecules

$$\rho = n\, M\, m_o$$

ρ specific mass

M molecular mass

$$m_o = 1.6604\ 10^{-27}\ \text{kg}$$

Pressure

p force per unit surface

Pascal, N/m^2 , Torr, bar

1 Torr = 133 Pa

1 mbar = 100 Pa

mean momentum of a molecule

$$\bar{q} = M\, m_o\, \bar{v}$$

$\bar{v}$ mean velocity follows from the Maxwell-Boltzmann distribution

VACUUM

1) Some basic facts

2) Building blocks of a vacuum system

3) How to get clean ultra high vacuum

4) Desorption phenomena

5) Practical examples from machines

Wall collisions

ν = const. n $\bar{v}$

ν frequency of wall collisions

const. = 1/ 4

ainsi

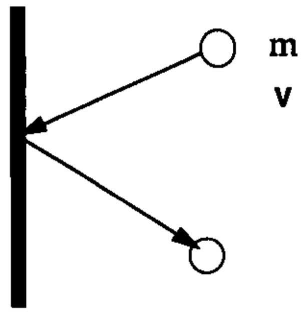
$$\nu = \frac{1}{4}\, n\, \bar{v}$$

substituting

$$\bar{v} = \sqrt{\frac{8\,k\,T}{\pi\, m}}$$

gives

$$\nu = n\sqrt{\frac{k\,T}{2\,\pi\, m}}$$

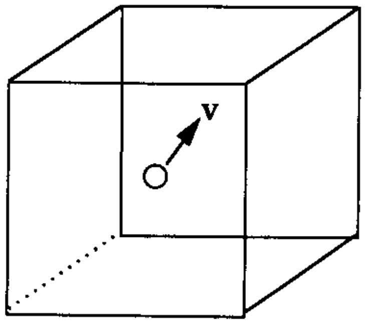


momentum transfer 2 m v

ν frequency of collisions

pressure : 2 m v ν

a cube with 1m :



n molecules / m^3

$\nu = n / 6\ v$

pressure = $1/3\, m\, n\, v^2$

with $\rho = m\, n$ -> pressure = $1/3\, \rho\, v^2$

Maxwell - Boltzmann Velocity distribution

velocity : $v^2 = \dot{x}^2 + \dot{y}^2 + \dot{z}^2$

$$\frac{1}{N}\frac{dN}{dv} = f_v = \frac{4}{\sqrt{\pi}}\left(\frac{m}{2\,kT}\right)^{\frac{3}{2}} v^2\, e^{-\frac{m v^2}{2kT}}$$

the maximum of the distribution gives the most probable velocity

$$v_m = \sqrt{\frac{2\,kT}{m}} = 1.29\;10^2\sqrt{\frac{T}{M}} \quad (m/s)$$

the mean velocity of the molecules is

$$\boxed{\bar{v} = \sqrt{\frac{8\,kT}{\pi\, m}} = 1.13\;\; v_m}$$

10 Kinetic Theory of Gases Ch. 1

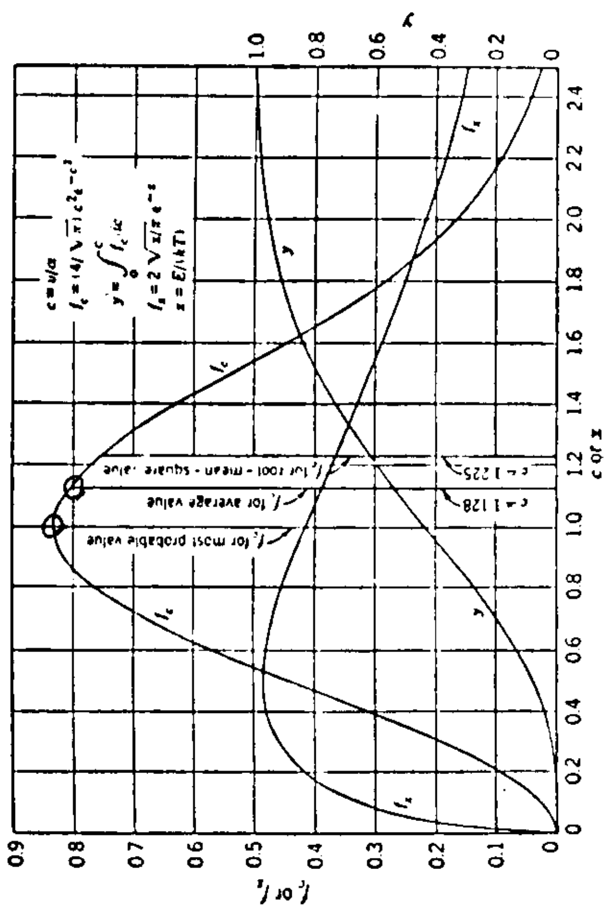


Fig. 1.1. Plots illustrating Maxwell-Boltzmann distribution laws. Plot f_c shows distribution function for random velocity, c expressed in terms of the most probable velocity x; plot f_x shows distribution function for energy, E, in terms of $x = E/(kT)$; y corresponds to the fraction of the total number of molecules for which the random velocity (expressed in terms of x) is less than or equal to a given value c.

Mean Velocity at 20 °C

Molecule	M	v (m/s)
Hydrogen	2.016	1754
Nitrogen	28.01	470
(Air)	28.98	464
Argon	39.95	393
Krypton	83.8	272

Pressure

$$p = \text{const.}\ \bar{q}\ \nu$$

Taking into account the random movement of the individual molecules **const.** $= \pi / 2$

Combining the previous results

$$p = \frac{\pi}{2} m \sqrt{\frac{8\,k\,T}{\pi\,m}}\ n \sqrt{\frac{k\,T}{2\,\pi\,m}}$$

and finally :

$$\boxed{p = n\ k\ T}$$

Expressed in units of Mole : $n = \frac{N_a}{V_o}$

$$\boxed{p\ V_o = N_a\ k\ T = R\ T}$$

R macroscopic gas constant

Total and partial pressures

each gas component $n_1, n_2, n_3,$
contributes a partial pressure

$$p_i = n_i\, k\, T$$

the total pressure becomes

$$p = \sum p_i = k\, T \sum n_i$$

-> total pressure measurement

-> partial pressure measurement

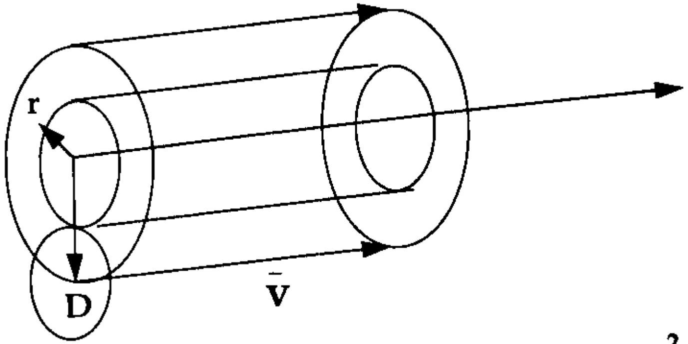
Partial Pressures for Air

	%	P_i (Pa)
N_2	78.1	$7.9\ 10^{4}$
O_2	20.95	$2.79\ 10^{3}$
Ar	0.93	$1.24\ 10^{2}$
CO_2	0.033	4.39
Ne	$1.8\ 10^{-3}$	$2.39\ 10^{-1}$
He	$5.2\ 10^{-4}$	$6.92\ 10^{-2}$
Kr	$1.0\ 10^{-4}$	$1.33\ 10^{-2}$
H_2	$5.0\ 10^{-5}$	$6.65\ 10^{-3}$
Xe	$8.7\ 10^{-6}$	$1.16\ 10^{-3}$
O_3	$1.1\ 10^{-6}$	$1.46\ 10^{-4}$

Mean free path, collisions

$D = 2\,r$ molecular diametre

$\bar{v}$ = mean velocity of a molecule



Volume of cylinder $\pi D^2 \bar{v}$

molecular density n

Per second a molecule traverses a distance given by its mean velocity. During this time, the molecule will collide with the molecules inside the cylinder of radius D

Number of collisions $Z = \pi D^2 \bar{v}\, n$

In reality, the other molecules also move and this leads to a correction factor $\sqrt{2}$

$$\boxed{l = \frac{\bar{v}}{Z} = \frac{1}{\sqrt{2}\,\pi\, n\, D^2}} \;\text{-->}\; \boxed{l\,n \propto l\,p = \text{constant}}$$

Conductance for molecular flow

molecular flow : mean free path >> distance or dimensions of the system

Knudsen :

$$Q = \text{const. } \bar{v}\,(p_1 - p_2)$$

$$Q = c\,(p_1 - p_2)$$

conductance $c\ (\text{m}^3\ \text{s}^{-1})$

$$\boxed{c = \frac{4}{3}\,\frac{\bar{v}}{\int_0^L \frac{H}{A^2}\,dL}}$$

A section
H perimeter
L length

Note :

c does not depend on the pressure

c proportional to molecular velocity, hence the conductance increases with temperature and decreases with molecular weight $\propto \sqrt{\frac{T}{M}}$

Example: circular hole :

$$c = \frac{1}{4}\,\bar{v}\,A \qquad \bar{v} = \sqrt{\frac{8\,k\,T}{\pi\, M\, m_0}} \qquad c = 36.4\ A\sqrt{\frac{T}{M}}$$

cylindrical tube :
length L
radius r

$$c = 305\left(\frac{r^3}{L}\right)\sqrt{\frac{T}{M}}$$

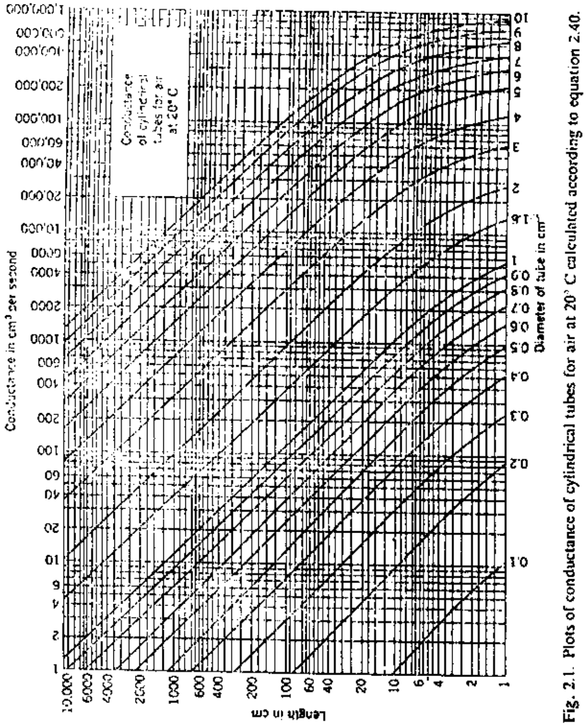


Fig. 2.1. Plots of conductance of cylindrical tubes for air at 20° C calculated according to equation 2.40.

Vacuum characteristics

gas : Nitrogen, N_2, 20°C, M = 28

	pressure Pa	n m^{-3}	ρ kg m^{-3}	ν m^{-2} s^{-1}	l m
atm	10^5	$2.5\ 10^{25}$	1.16	$2.9\ 10^{27}$	$9\ 10^{-8}$
primary vacuum	1	$2.5\ 10^{20}$	$1.16\ 10^{-5}$	$2.9\ 10^{22}$	$9\ 10^{-3}$
	10^{-1}	$2.5\ 10^{19}$	$1.16\ 10^{-6}$	$2.9\ 10^{21}$	$9\ 10^{-2}$
high vacuum	10^{-4}	$2.5\ 10^{16}$	$1.16\ 10^{-9}$	$2.9\ 10^{18}$	$9\ 10^{1}$
	10^{-7}	$2.5\ 10^{13}$	$1.16\ 10^{-12}$	$2.9\ 10^{15}$	$9\ 10^{4}$
uhv	10^{-10}	$2.5\ 10^{10}$	$1.16\ 10^{-15}$	$2.9\ 10^{12}$	$9\ 10^{7}$

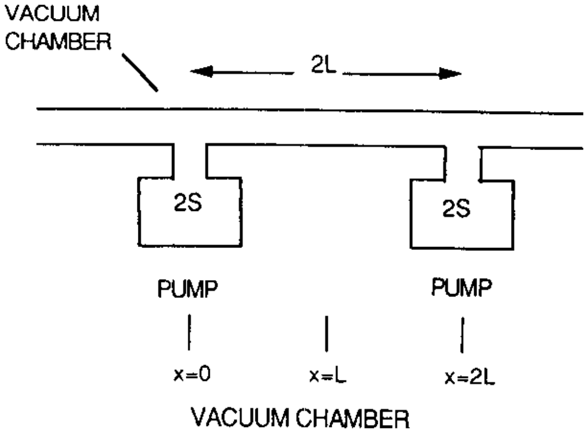
$$n = \frac{\rho}{kT} \qquad kT = 4.04\ 10^{-21}\ \text{Joule}$$

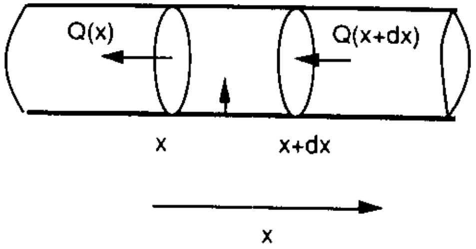
$$\rho = M\, m_o\, n \qquad M\, m_o = 4.65\ 10^{-26}\ \text{kg}\ , \quad m_o = 1.66\ 10^{-27}\ \text{kg}$$

$$\nu = \frac{1}{4}\, n\, v \qquad v = 1.45\ 10\ 2 \sqrt{\frac{T}{M}}$$

$$l = \frac{1}{\sqrt{2}\, \pi\, d^2\, n} \qquad d\,(N2) = 3.15\ 10^{-10}\ \text{m}$$

SIMPLE MACHINE





THE GAS FLOW **Q** THROUGH THE TUBE IS GIVEN BY THE EQUATION

$$Q = -c\ dP/dx$$

where P is the gas pressure (Torr)

V is the volume per unit length of tube (l m^{-1})

w is the perimeter of the tube (m)

c is the specific conductance of the tube (l s^{-1} m)

a is the gas desorption per unit length of tube (Torr l s^{-1} m^{-1})

q is the gas desorption per unit area of tube (Torr l s^{-1} m^{-2})

$a=q\ w$

THE CHANGE IN THE NUMBER DENSITY OF MOLECULES IN THE VOLUME ELEMENT **Vdx** BETWEEN **x** AND **x+dx** IS

$$V\ dx\ dP/dt = a\ dx + c\ [dP/dx]_{x+dx} - c\ [dP/dx]_x$$

$$V\ dP/dt = a + c\ (d^2P/dx^2)$$

IN THE STEADY STATE $dP/dt=0$

$$d^2P/dx^2 = -c/a$$

BOUNDARY CONDITIONS

BY SYMMETRY AT x=L $dP/dx = 0$

AT x=0 and x=2L $P=aL/S$

$cdP/dx=aL$

THE FINAL SOLUTION IS

$$P = aL/S + aLx/c - ax^2/2c$$

MAX. PRESSURE

$$P_{max} = aL/S + aL^2/2c$$

AVERAGE PRESSURE

$$P_{av} = aL/(1/S + L/3c)$$

5. VACUUM PUMPS AND VACUUM GAUGES USED IN LARGE ACCELERATOR VACUUM SYSTEMS

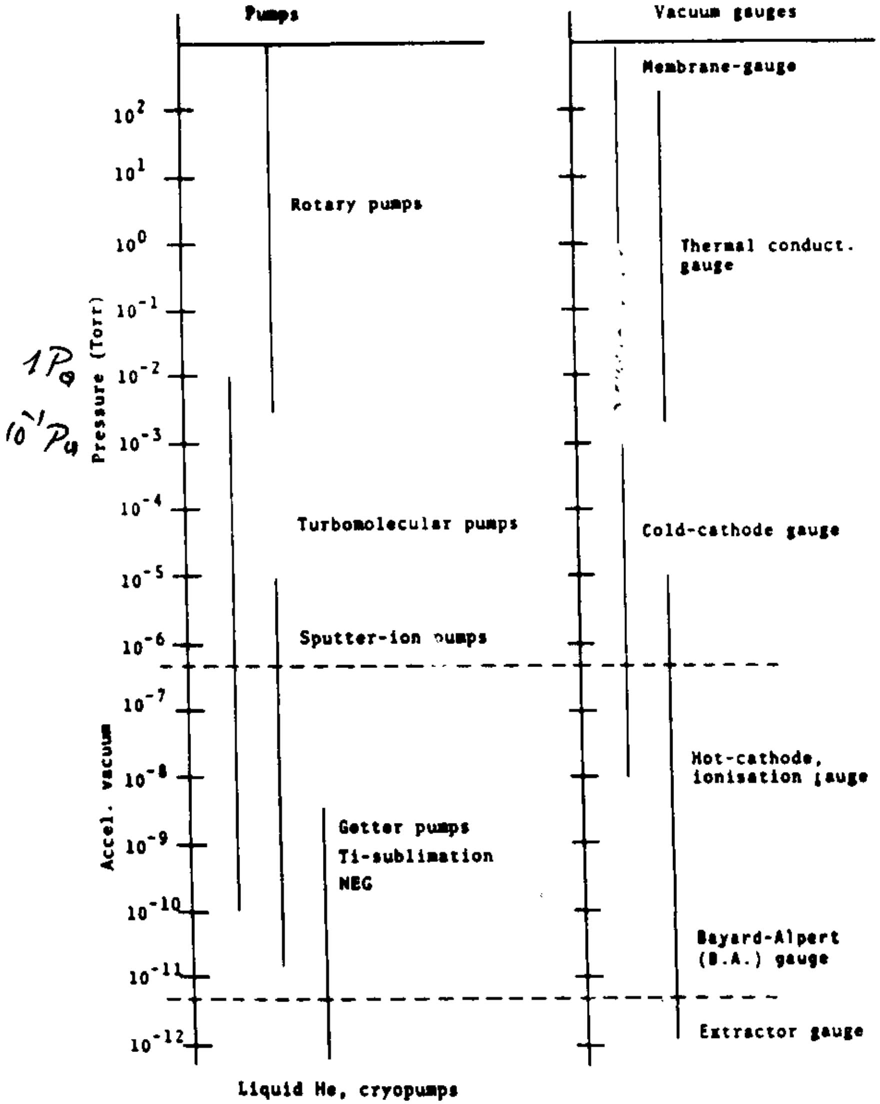
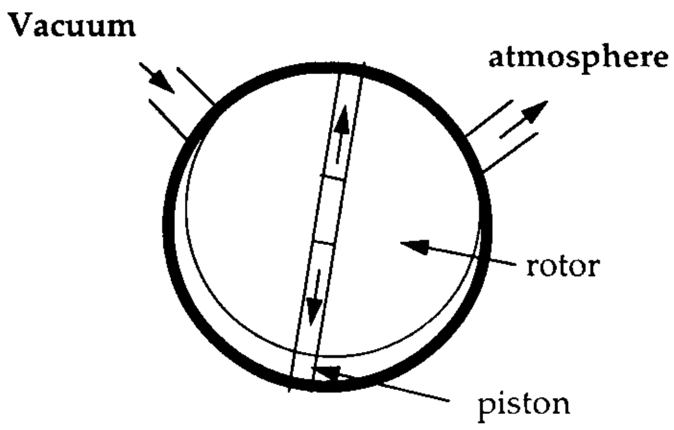


Fig. 4

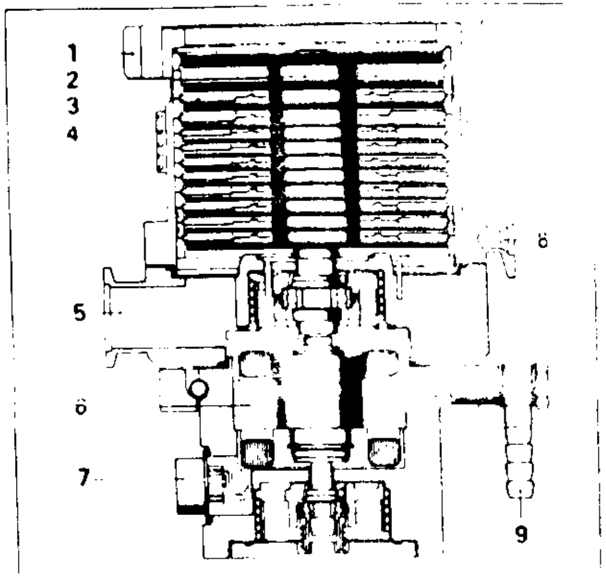
Rotary Pump



Lubrification: oil

limit pressure : 0.1 Pa

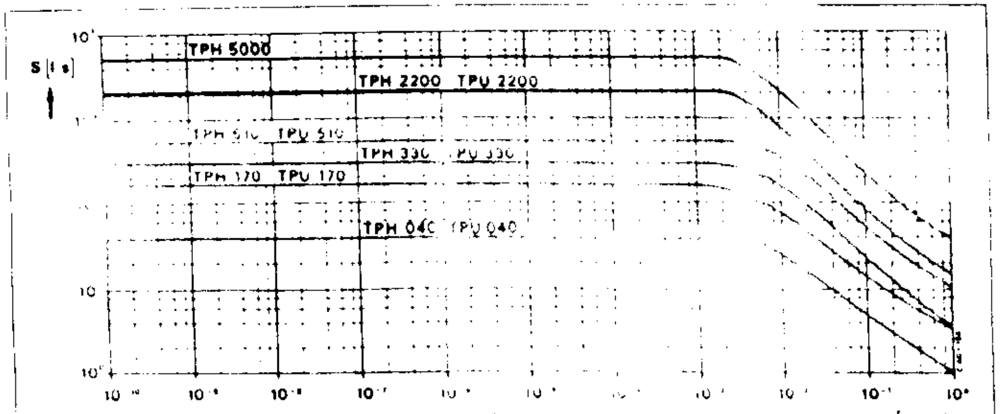
pumping speed ~ 4 - 30 m³ / h



Schnittdarstellung der PFEIFFER TURBO [illegible]

1 UHV-Anschluss 4 Heizung [illegible] Anschl.
2 Rotor 5 Vorvakuum [illegible]
3 Stator 6 Motor [illegible]

~ 40 [illegible]



Saugvermögen der PFEIFFER TURBO für N_2 in Abhängigkeit vom Druck

Pumping speed of a turbomolecular pump

$$S \cong u\ G$$

G pump geometry

u rotation speed

The compression factor is an exponential function of the molecular weight, hence large compression obtained for heavy molecules -> clean vacuum

The pumping speed is independent of the molecular mass

Ion Pump

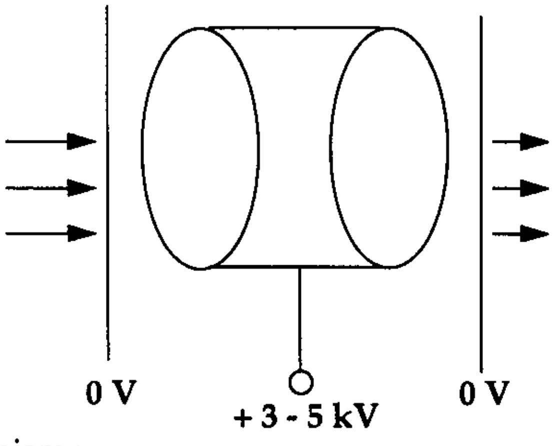
"Penning" configuration

electric field E

magnetic field B

E parallel to B

Penning cell



Pumping mechanism :

adsorption of molecules CO, CO_2, N_2

gettering

diffusion H_2

cracking of molecules C - H

" Ion burial " noble gases He, Ar

Sputtering of titanium at the cathode

A pump contains a large array of single

Penning cells in a common housing

Getter Pumps

The getter forms chemically stable compounds with the gas molecules:

H2, O2, N2, CO, CO2

noble gases : He, Ar, and CH4 ... are not pumped

Pumping speed: related to the molecular velocity

$F = 1/4\ v$ and $v = (8\,k\,T/\pi\,m)^{1/2}$

therefore $F = 36.38\,(T/M)^{1/2}$

molecules have a certain probability, α, to be adsorbed by the getter, hence the actual pumping speed depends on the coverage of the gettering surface -> saturated getter must be reactivated

Titanium sublimation pumps

NEG, Non Evaporable Getter pumps

Ti-Sublimation pump

An actice Ti-film is deposited on the internal surface of the vacuum system by heating a Ti-filament to about 1300°C

(duration a few minutes)

Practical pumps consist of a filament holder inserted in the vacuum system and an external power supply (12V, 50A)

Usually more than one filament is provided (filament burn-out)

The Ti film gradually saturates e.g. at 10^{-6} Pa it takes about 1 hour. Then a fresh film has to be deposited

The intrinsic pumping speed is very significant: at 20°C and unit sticking

H_2, N_2	24	m/s
CO	48	m/s
H_2O	32	m/s

Bulk Getter, Non Evaporable Getter, NEG

A bulk getter provides pumping without the need of sublimating a fresh, active film of e.g. Titanium.

The NEG requires instead an initial activation by heating to approx. 500-700°C during 1 hour. During this process, gas on the surface diffuses into the bulk of the getter drive by the gradient of concentration. Inside the getter the gas molecules form stable chemical compounds.

As in the case of surface getter, the bulk getter has to be regenerated when its surface has been saturated with an adsorbed layer of gas molecules.

For H_2, the diffusion rate is already significant at room temperature and the pumping of H_2 is reversible. During heating of the getter, H_2 rediffuses and can be released from the getter.

Total capacity is limited

Pumping speed is a strong function of the quantity already pumped. -> see pumping speed curves

application -> main pumping for the 27 km long LEP vacuum system

readily applied as a "distributed" pump since it is supplied in the from of a 'getter strip' by the firm SAES-Getters, Italy

Cryo pumps

Principle of operation

1) Cryo-sorption

adsorption of gas on the cold surface forming a mono-molecular layer.

When the surface is completely covered, the pressure is given by the saturated vapour pressure curves for the given gas. He, and H2 have very high vapour pressures even at 4.2 °K. Effective surface can increased by 'active charcoal 'coating.

2) Cryo-condensation

Pumping of thick layers of gas. The quantity of gas exceeds the monolayer coverage -> vapour pressure

3) Cryo-Trapping

A gas like H2, which is difficult to pump, is pumped in the presence of a readily condensable gas like Ar. H2 molecules are trapped by the Ar

Aspects of Cryo pumping

Large pumping speed

low base pressure (SVP must be avoided)

large pumping capacity -> Cryo-condensation

very 'clean' pump -> no pumping oils

atractive when combined with s.c magnets

Pirani Gauge

Reliable and simple

Fast time response, good precission

Large pressure range :

atmosphere -> < 0.1 Pa

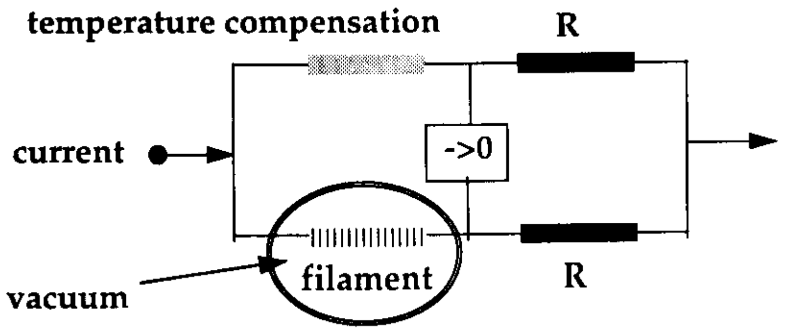
Principle

The thermal conductivity of a gas depends on the pressure within certain limits.

A resistor with a high temperature coefficient is mounted in the vacuum and heated by a constant current. (approx. 120°C),

The current required to maintain a constant temperature (resistance) is a direct measurement of the gas pressure.

Electronic circuitry provides a linearisation of the pressure indication (Wheatstone bridge)



Cold cathode gauge
Penning gauge

Basic principle : same as for ion pump

Intensity of the Penning discharge:

$$I / P = \text{const}$$

useful pressure range

$$10^{-2} > P > 10^{-7} \quad \textbf{Pa}$$

Limitation

at high pressure : discharge is unstable

at low pressure : discharge extinguishes

Problems : leakage current,
cable insulation

Contamination of the anode my affect the proportionality between discharge current and pressure

Hot cathode ionisation gauge

Residual gas is ionised by electrons emitted from a hot filament. The positive ion current on a collector electrode is proportional to the pressure.

-> Filament, grid and collector electrodes

P_i	ionisation probability for molecules
I_e	electron emission current
L	pathlength of the electrons

$$I^+ = I_e \, P_i \, L \, P$$

The product of $P_i L$ is called the sensitivity of the gauge and can be determined by calibration against a known pressure Si (Pa^{-1})

The gauge sensitivity depends on the type of molecules -> Nitrogen equivalent pressure

Limitations

high pressure : space charge affects sensitivity

low pressure : outgassing due to electron bombardment of the grid increases the pressure -> outgassing

x-ray limit due to photoelectrons from the collector electrode . Residual current is equivalent to approx. 10^{-8} Pa

improvements -> modulated Bayard Alpert gauge

-> extractor gauge

Bayard-Alpert gauge with modulator electrode

Extractor gauge

x-ray limit :

electrons produce Bremsstrahlung photons at the grid. Photons which arrive at the collector can produce photoelectrons which go to the positive grid. The photocurrent from the collector is equivalent to a positive ion current Ix, hence pressure reading is limited by this effect

Addition of a modulator electrode

modulator at gridpotential $I_c = I^+ + I_x$

modulator at ground $I_c = \alpha I^+ + I_x$

two measurements permit to eliminate I_x

the modulation factor, α, can be determined through a measurement at high pressure where I_x is negligible.

Alternative solution:

The collector is shielded optically from the grid. Ions are extracted from the ionisation volume to an external collector.

Partial pressure measurement:

Quadrupole mass filter

Ions produced from the residual gas traverse a mass filter. Only ions with the correct ratio e/m reach the collector.

To increase the sensitivity, a secondary electron multiplier can be used.

relative calibration for different gas species made by controlled gas inlet of a test gas.

Absolute calibration can be performed against a calibrated total pressure gauge.

Analysis of the residual gas spectrum is based on known kracking patterns for the different gas species since a given parent molecule can produce a series of ions with different e/m values.

Cleaning Procedures

Chemical solvent precleaning

Vacuum bakeout at 150°C to 300°C

Argon gas glow-discharge cleaning

High temperature vacuum firing (950°C)

Definition of cleanliness depends on the particular application!

Clean, dustfree handling without 'finger prints' after the precleaning

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CHEMICAL SOLVENT PRECLEANING PROCEDURE

(a) Removal of gross contamination and machining oils using the appropriate solvents

(b) Perchloroethylene (C_2Cl_4) vapour degreasing (121°C).

(c) Ultrasonic cleaning in alkaline detergent ($pH=11$).

(d) Rinsing in cold demineralised water (conductivity $< 5\,\mu$ S cm^{-1}).

(e) Drying in a hot air oven at 150°C

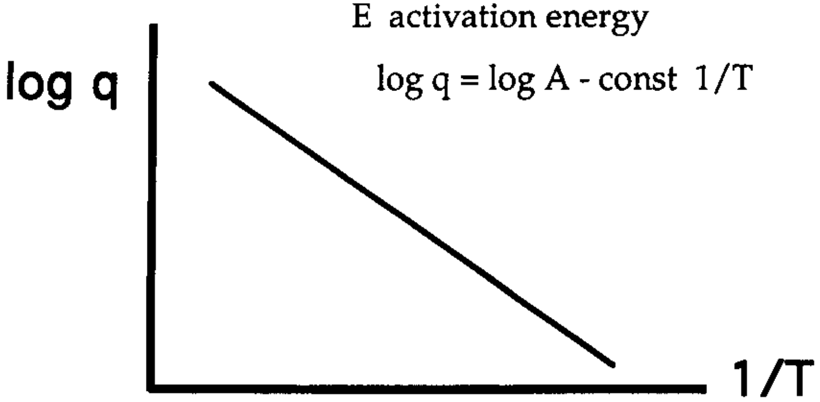
Thermal Desorption

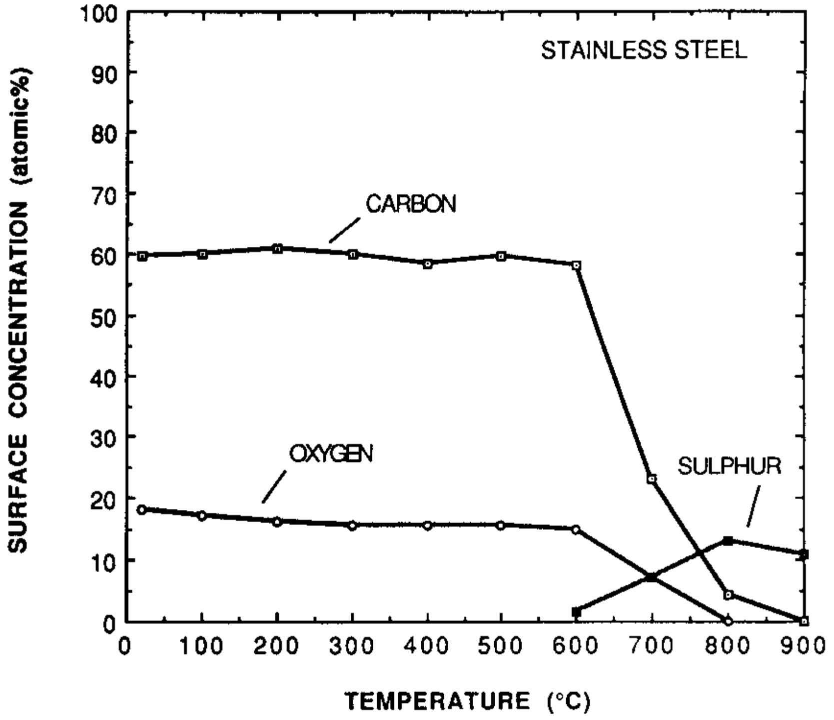
specific outgassing rate q (Pa $m^3/s/m^2$)

$$q = A \exp(-E/kT)$$

E activation energy

$$\log q = \log A - \text{const}\ 1/T$$





Bakeout at 150 - 300°C gives a significant reduction in outgassing rate. At high temperature, hydrocarbons are cracked and the indicidual components CO, CO2, H2 are pumped readily.

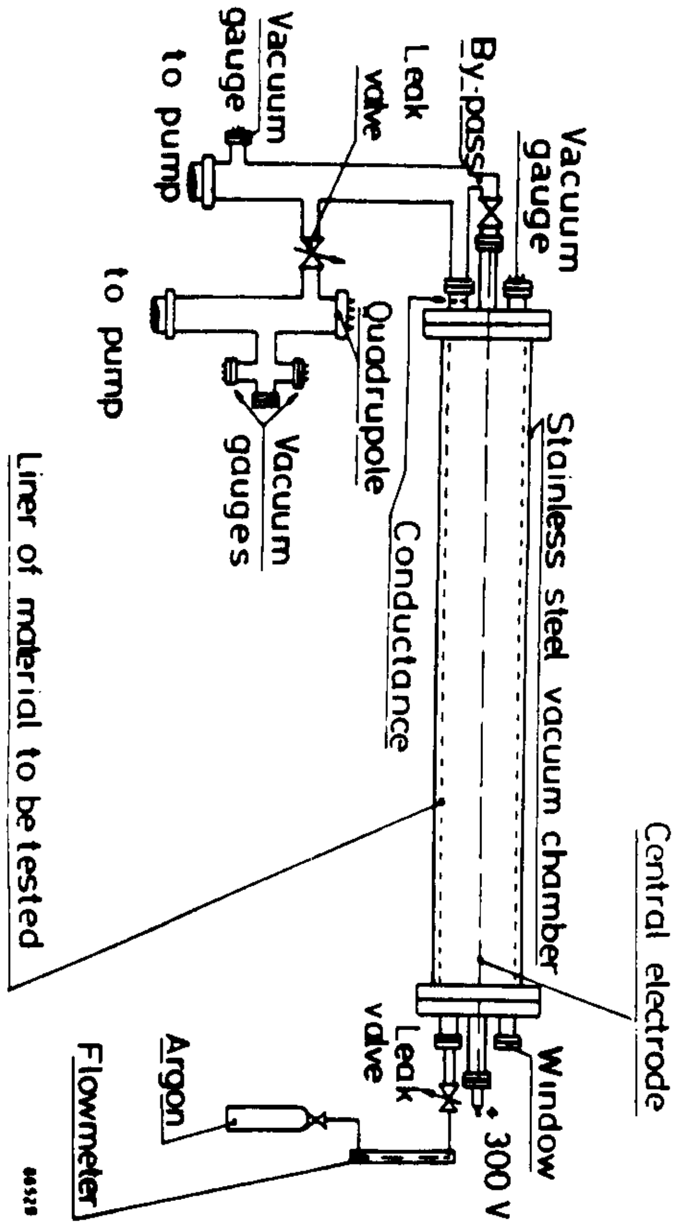


Figure 12

Desorption by synchrotron radiation

Critical photon energy $2.9\ 10^{7}\ \gamma^{3}\ /\ R$

Radiated power

$P\ (W) = 6\ 10^{-9}\ \gamma^{4}\ \ I\ /\ R$

I (A) beam current

R (m) magnetic bending radius

γ total energy/ rest energy

Photon flux

$N\ (s^{-1}) = 4\ 10^{17}\ \ \gamma\ I$

and per m

$N\ (s^{-1}\ m^{-1}) = 6.37\ 10^{16}\ \ \gamma\ I/R$

Dynamic pressure rise by photon induced desorption

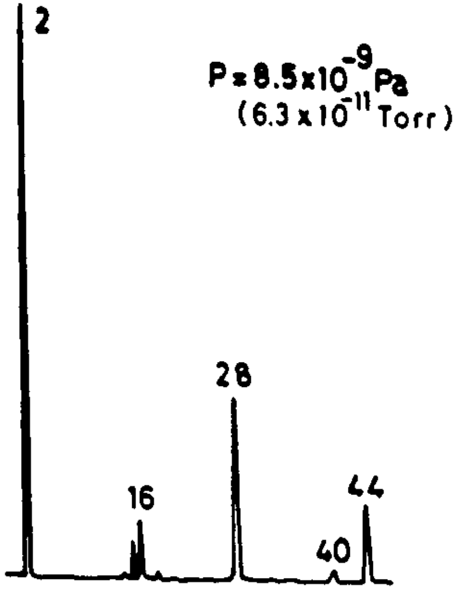
$$P = \eta\ N\ /(C\ S) + Po$$

η molecular desorption yield (molecules/photon)

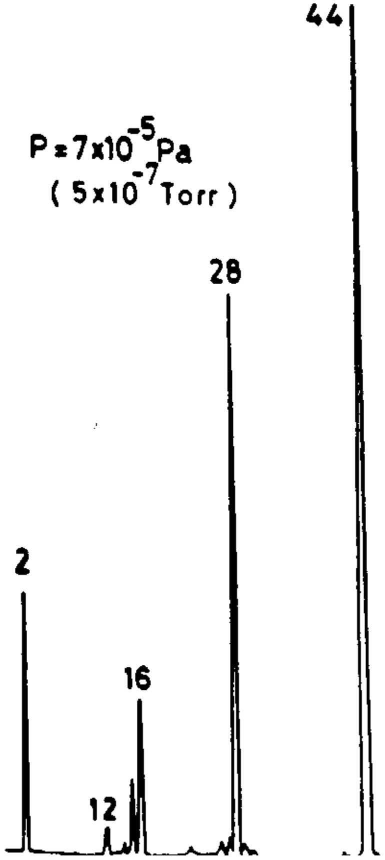
S linear effective pumping speed (l/s/m)

C $3.2\ 10^{19}$ (molecules/Torr l)

Po static base pressure, without beam



The residual gas spectrum before exposing the test chamber to synchrotron radiation.



The residual gas spectrum during exposure to synchrotron radiation.

Choice of materials

low outgassing rate
low vapor pressure
temperature resistant -> bakeout
thermal and electrical conductivity
corrosion resistance
low induced radioactivity
high mechanical strength
machining
welding
low cost

Examples:

Stainless steel
Aluminium
Copper

Ceramics
- low porosity
- electrically insulating
- brazing to metal

Polymers, Plastics only
for particular applications

Thermal induced stress ε (N/mm^2)

$\varepsilon = E \; \Delta l/L$

$\Delta l/L = \alpha \; \Delta T$

and therefore

α coeff. of linear expansion /°C

E Young's modulus (N/mm^2)

ΔT Temperature difference

$$\boxed{\varepsilon = E \alpha \; \Delta T}$$

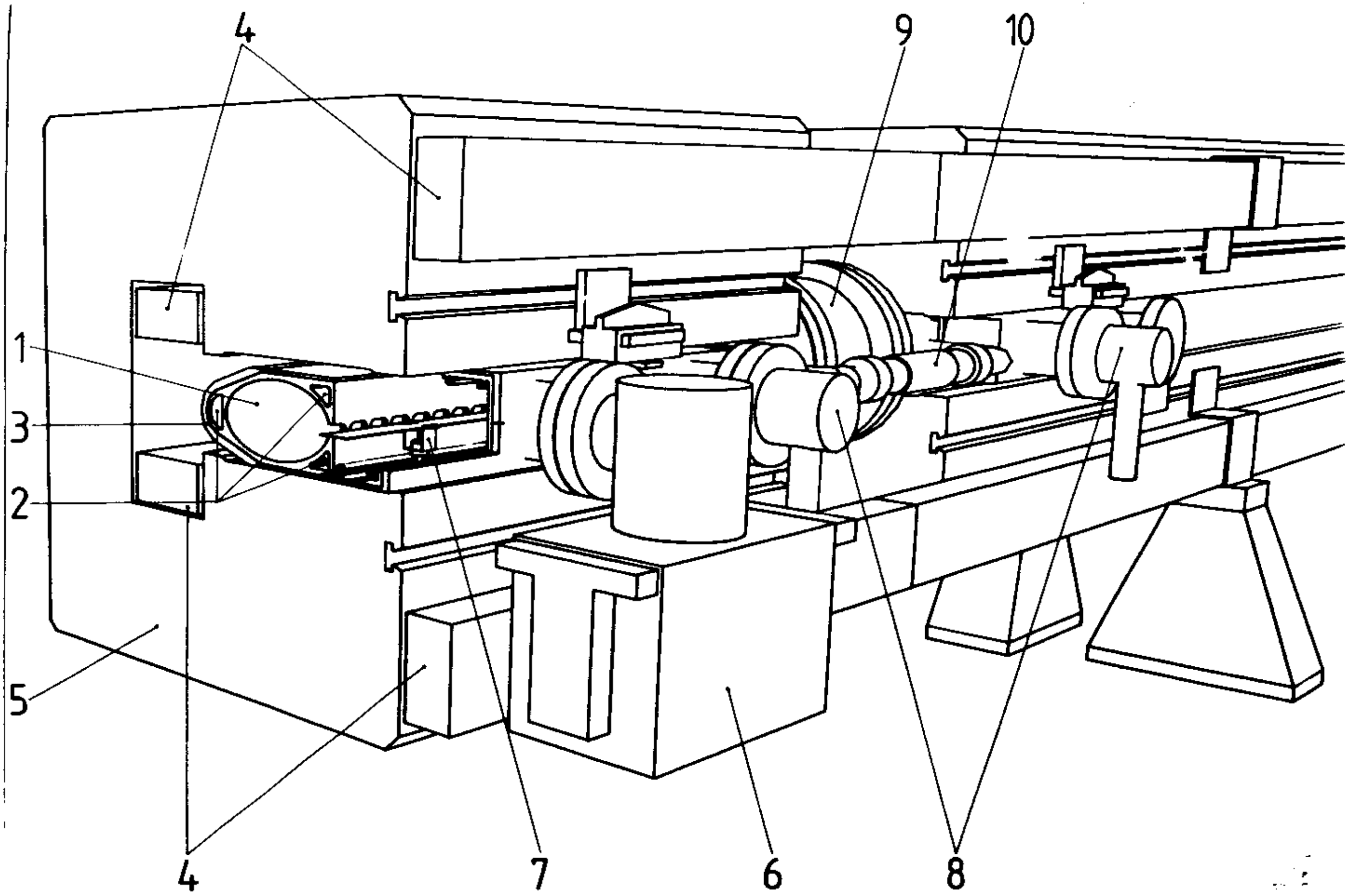
LEP vacuum chamber: the temperature in the region where the photons hit the wall increases by <u>17.8°C per kW/m</u> deposited S.R. power.

max. Power $= \varepsilon \; / \; (\alpha \; E \; 17.8)$ kW/m

This exceeds 5.5 kW/m (equivalent to > 11 kW/m power from the beam)

Stress-limits(Al, Cu)

	AlMgSi 0.5 (LEP)	OFHC (soft)	OFHC (hard)	"GlidCop"
Young's Modulus (N/mm2)	7.5E+4	1.2E+5	1.2E+5	1.2E+5
tensile strength (0.2) (N/mm2)	200.	60.	250.	338.
coef. linear expansion (1/°C)	2.7E-5	1.7E-5	1.7E-5	1.7E-5
thermal cond. (W/°C/cm)	2.37	3.85	3.85	3.8
Max. chamber temperature (°C)	98.77	29.41	122.55	165.69
Temperature rise (°C/W/mm)	17.80	11.60	11.60	11.60
Max. linear power (W/mm)	5.55	2.54	10.56	14.28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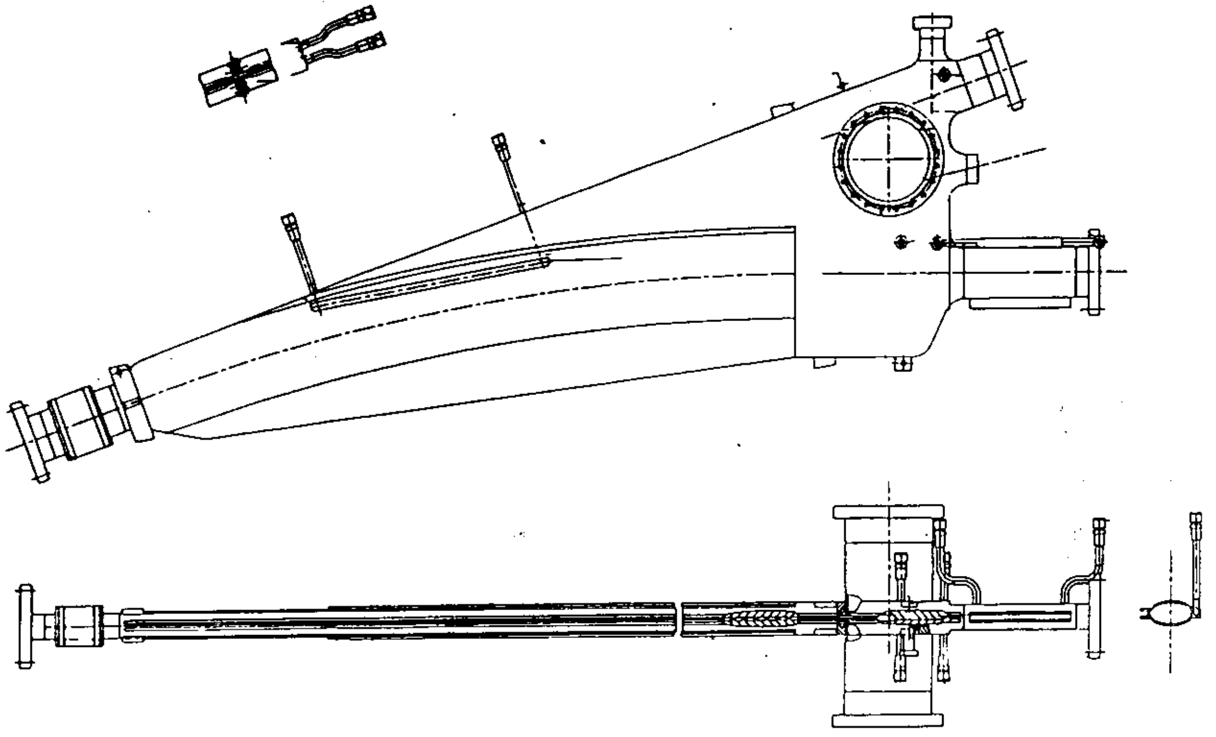
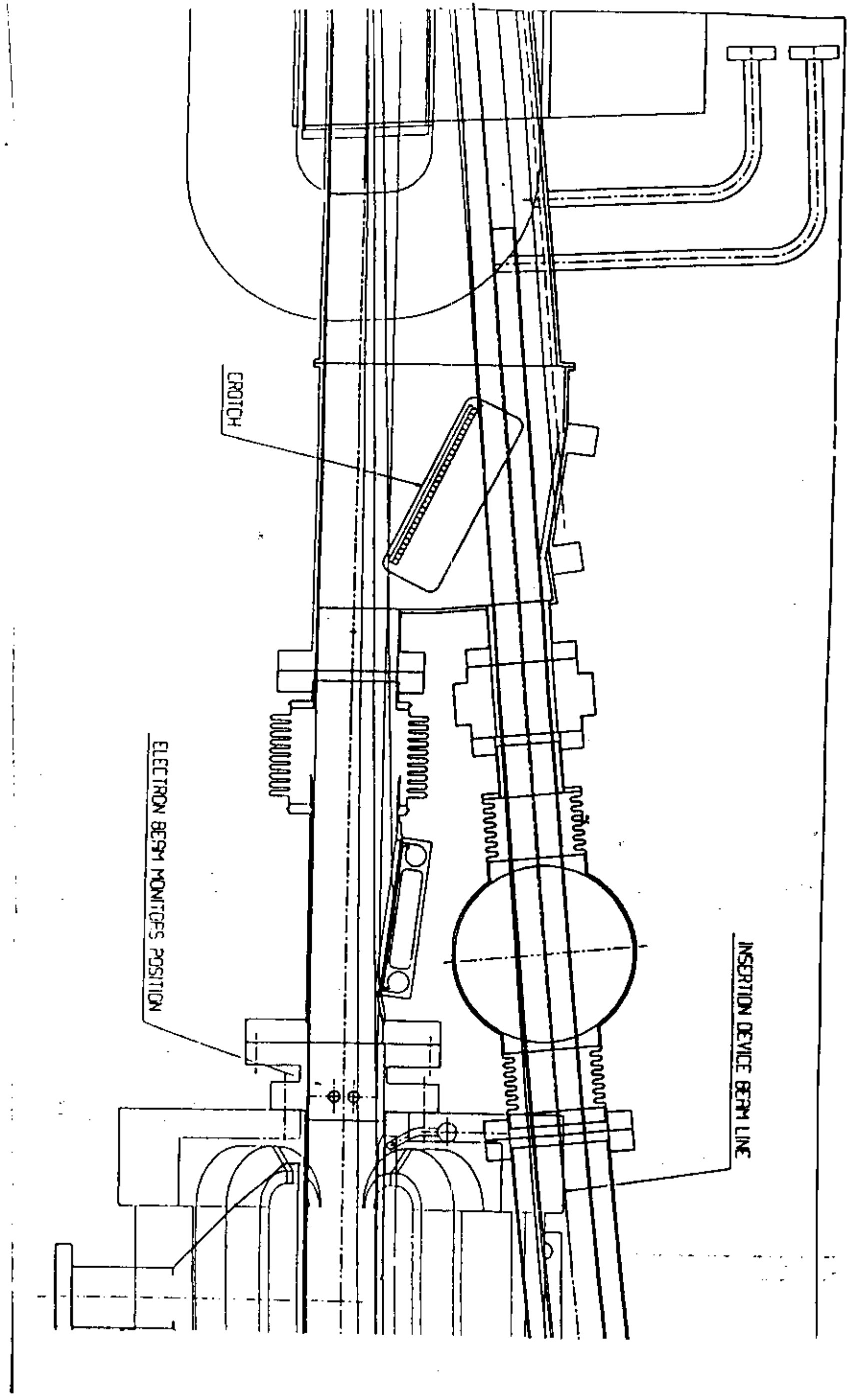
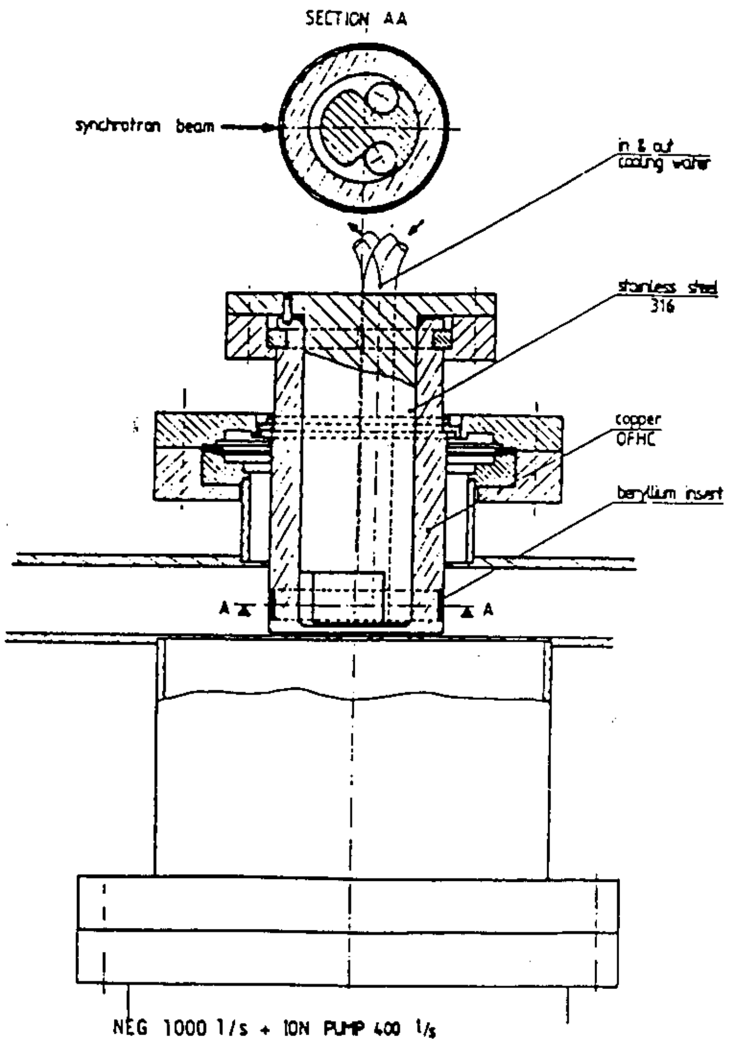






CROSS SECTION VACUUMCHAMBER AT CROTCH

Fig. 7.4.5.1

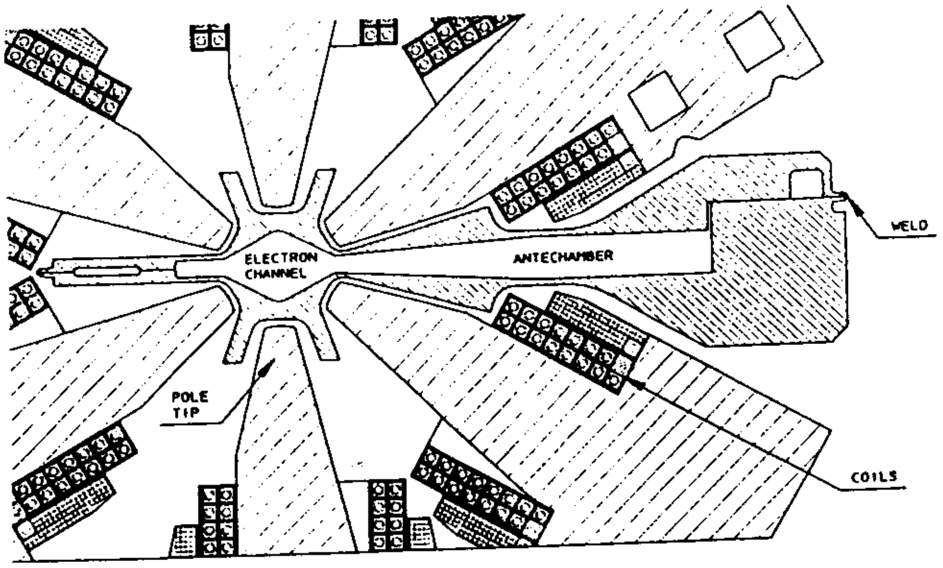
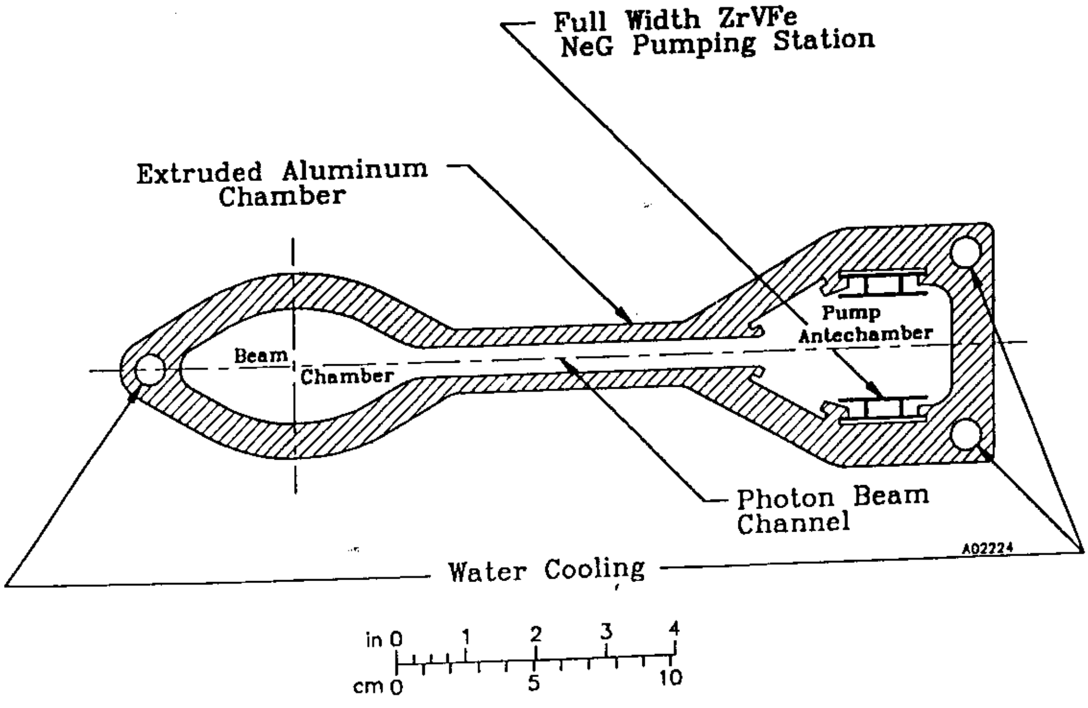


FIG. 1. CROSS SECTION AT SEXTUPOLE

ADVANCED PHOTON SOURCE



STORAGE RING VACUUM CHAMBER CROSS SECTION