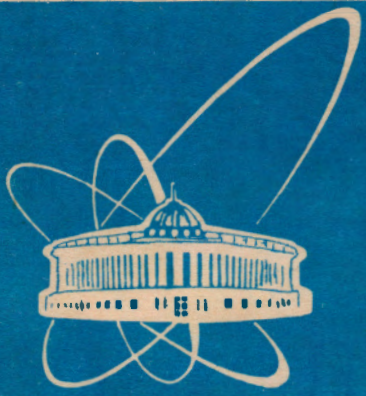

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VACUUM AND BEAM TRANSPORT LINES: MAIN PRINCIPLES

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1. Introduction

The vacuum system of the beam transport line is one of the main components of the transport line. Whereas, operating pressure ranges for vacuum systems of the ECR ion sources are 5 x 10^{-2} - 10^{-5} Pa [1], the required operating pressure range for the vacuum system of the beam transport line is 10^{-4} - 10^{-9} Pa, respectively. Basically, it consists of stainless steel and copper. The beam tubes are pumped with turbomolecular, cryosorption, getter - Ti - sublimation, NEG pumps combined with sorption and rotary pumps. Other suitable combinations of the vacuum pumps as well as the pressure measuring gauges are shown in Fig. 1.

This paper is giving a view on the gas desorption processes especially ion - induced pressure instability influencing on the operating vacuum inside the beam pipe of the transport system. Scaling relationships are also pointed out as a bases for understanding the vacuum configurations of beam transport lines as well as molecular conductances and beam pipe outgassing. The outgassing rates at room temperature are also presented for materials as viton (Russia and Roumania versions), 'O' rings (RUBBER 7889 and TU MCHP 9024), molybdenum VNII NP-257 and Apiezon 'L' greases, Ramsay fet, rotary pump oil VM-4 and glassfibre samples, currently used at our laboratory.

2. Desorption of Gases

The pressure from 10^{-4} - 10^{-9} Pa must be maintained inside the transport beam lines and its beam pipe in despite of:

- The thermal outgassing of surfaces;
- Outgassing due to the desorption of weakly bound molecules on the walls of the vacuum system;
- The ions induced by extracted and accelerated ions;

- The diffusion of hydrogen from the walls of the vacuum system;
- The neutral gas produced inside the transport beam lines;
- The desorption of molecules generated by hard X - ray bremstrahlung.

To establish the required pressure for a given pumping speed the average thermal outgassing rate and the total average desorption rate must be below certain definite values.

2.1 Ion - induced pressure instability

The ions induced by extracted and accelerated beam can produce desorption of strongly bound molecules. The desorption flow rate n_i, Q_i can be expressed by [1]

$$n_i = \eta\sigma L(I/e)n \qquad Q_i = \eta\sigma L(I/e)p \tag{1}$$

where η is the molecular desorption yield (molecules ion^{-1}), σ is the ionization cross section of extracted and accelerated ions (m^2) (for example for high energy protons $\sigma = 1.2 \times 10^{-22}$ m^2 [2] and for CO, L is the length of beam section (m), I is the beam intensity (A), e is the electron charge (A s), n is the number of molecules in unit volume (m^{-3}) and p is the pressure (Pa). Note, if ions are taken from the restgas, then η will represent a net desorption yield. For $\eta < 0$ 'a beam pumping' can be observed, i.e. the system acts like an ion pump. In the presence of the ion induced desorption $\eta > 0$ and the equilibrium pressure can be expressed as

$$p = Q/S_{eff} = \frac{\eta\sigma(I/e)p + qA}{S_{eff}} \tag{2}$$

which gives

$$p(I) = \frac{p_o}{1 - \frac{\sigma}{e}\frac{\eta I}{S_{eff}}} \tag{3}$$

where $p_o = q\ A/S_{eff}$.
By introducing

$$(\eta I)_{crit.} = \frac{e}{\sigma} S_{eff} \tag{4}$$

we obtain

$$p = \frac{p_o}{1 - \frac{\eta I}{(\eta I)_{crit.}}}. \tag{5}$$

Hence, the "critical current" product for $S \longrightarrow \infty$ cannot exceed

$$(\eta I)_{crit.} = \frac{e}{\sigma}\frac{12w}{L^2}. \tag{6}$$

Therefore, the pressure p is a function of the beam current I. The higher the current I, the higher is the equilibrium pressure p. The ratio C/L is also important parameter. The higher the ratio C/L, the higher is the 'critical current' $I_{crit.}$.

The pressure instability caused for example by the pressure bumps in the vacuum system of the beam line can be reduced by adding cryogenic, getter - Ti sublimation, or NEG pumps, respectively. With a 300 °C bakeout and Ar glow discharge cleaning of the source stages and beam pipes the molecular desorption yield η can be reduced.

The required ion dose on the beam pipe is typically 10^{22} m^{-2} and results in that $\eta \leq 0$. The Ar glow discharge gives efficient sputtering and desorption of strongly adsorbed gas molecules. On the other hand, the addition of O_2 produces CO and CO_2 compounds from carbon contaminants on the surface which can easily be pumped out.

However, the ion - induced pressure instability desorption rate dQ^i/dt is given by

$$\frac{dQ^i}{dt} = Q_i \cong 7\text{x}10^{-11}\ \text{Pa m}^3\ \text{s}^{-1} \tag{7}$$

if the molecular desorption rate $\eta = 1$ molecules ion^{-1}, the length L = 1 m. the beam current $I = 10^{-3}$ A, and the pressure $p = 10^{-4}$ Pa, respectively.

3. Main Principles

The highest obtainable average pumping speed of the beam transport line vacuum system strongly depends on the beam pump conductance. To illustrate this important limitation caused by the finite conductance, let us consider the system shown in Fig. 2. In the molecular flow regime the flow of molecules along the vacuum pipe to the nearest pump is expressed by the equation

$$Q(x) = -w\frac{dp}{dx} \qquad \frac{dQ}{dx} = Aq \tag{8}$$

where Q is the gas flow (Pa m^3 s^{-1}), w is the specific molecular conductance (m^4 s^{-1}) (w = LC), C is the conductivity (m^3 s^{-1}), p is the pressure inside the pipe (Pa), A is the specific surface area (m) (A = F/L), F is the surface area (m^2) and q is the specific outgassing rate (uniform) (Pa m s^{-1}). These equations can be combined to give

$$w\frac{d^2p}{dx^2} = -Aq \tag{9}$$

together with the boundary conditions of this simple problem

$$\left.\frac{dp}{dx}\right|_{x=L/2} = 0 \quad \text{and} \quad p|_{x=0} = \frac{AqL}{S} \tag{10}$$

which follow from the evident symmetry considerations. As the solution we can find a well known parabolic pressure profile along the beam pipe

$$p(x) = Aq\Big(\frac{Lx - x^2}{2w} + \frac{L}{S}\Big). \tag{11}$$

The maximum pressure occurs at the midpoint between pumps

$$p_{max} = Aq\Big(\frac{L^2}{8w} + \frac{L}{S}\Big). \tag{12}$$

For the beam pipe the average pressure is more relevant

$$p_{av} = \frac{1}{L}\int_0^L p(x)dx = Aq\Big(\frac{L^2}{12w} + \frac{L}{S}\Big). \tag{13}$$

It is convenient to define an 'effective linear pumping speed'

$$S_{eff} = \Big(\frac{L^2}{12w} + \frac{L}{S}\Big)^{-1} \tag{14}$$

so that $p_{av} = Aq/S_{eff}$. It is evident that S_{eff} cannot exceed $12w/L^2$ irrespective of how large pumps are used.

Equally, the lowest achievable average pressure is limited to $AqL^2/12w$. Since the conductance is generally determined by the apertures in electrodes and screens (screening of high frequency), the only parameter is the interpump distance L. Obviously, many small pumps at short distance are preferable to a few and large pumps. Fig. 3 illustrates this effect for a vacuum beam pipe conductance of 0.07 m^4 s^{-1} and different pumping speeds S (0.02, 0.04, 0.06, 0.12, 0.24, 0.5, ∞ m^3 s^{-1}), respectively. It is shown that the effective pumping speed is practically the 'linear function' of the pump distance for various

sizes of pumps. Such a pumping structure may be installed along the vacuum system and hence the analysis provides a 'linear pumping speed' inside the beam pipe.

The real pressure distribution and therefore the average pressure also follow from the equation similar to the previous one

$$-w\frac{d^2p}{dx^2} = Aq - sp \tag{15}$$

where s is the specific pumping speed defined as $s = S/L$ (m^2 s^{-1}). By the solution of differential equation (15) using the boundary conditions (10) we find other pressure profiles along the beam pipe. It holds that

$$p(x) = C_1e^{rx} + C_2e^{-rx} + \frac{Aq}{s} \tag{16}$$

where

$$C_1 = \frac{AqL}{S}e^{-rL}(1 + e^{-rL})^{-1}, \quad r = (s/w)^{0.5}$$

and

$$C_2 = \frac{AqL}{S}(1 + e^{-rL})^{-1}.$$

Usually, the vacuum system is designed with respect to s≪w. In this configuration one can obtain

$$C_1 \cong C_2 \cong C_o = \frac{Aq}{2}\frac{L}{S}. \tag{17}$$

The equation (16) is reduced to

$$p(x) = C_o(e^{rx} + e^{-rx}) + \frac{Aq}{s} \tag{18}$$

and the average pressure is determined by

$$p_{av} = \frac{C_o}{rL}(e^{rL} - e^{-rL}) + \frac{Aq}{s} \cong \frac{2AqL}{S}. \tag{19}$$

It is evident that the lowest achievable pressure depends only on the ratio of 2AqL/S. The average pressure versus the distance between pumps L for different pumping speeds S (0.02, 0.04, 0.06, 0.12, 0.24, 0.5 and ∞ m^3 s^{-1}) is shown in Fig. 4.

4. Molecular Conductance

In high vacuum the flow of molecules is limited by wall collisions, i.e. the mean free path λ of the gas molecules is greater than the characteristic dimensions of the vacuum system ($D/\lambda < 1$; D is the diameter of the beam pipe). In this molecular flow regime, the conductance C ($m^3\ s^{-1}$) is independent of the pressure, therefore the flux of gas is proportional to the pressure gradient Δp. It holds that

$$Q = C\,\Delta\, p. \tag{20}$$

Some useful expressions for conductance are [3]:

a) Orifice of area F (m^2);

$$C = 36.4F\sqrt{\frac{T}{M}} \quad m^3\ s^{-1}, \tag{21}$$

b) long cylindrical tube, radius r (m), length L (m);

$$C = 305\frac{r^3}{L}\sqrt{\frac{T}{M}} \quad m^3\ s^{-1} \tag{22}$$

c) long tube with elliptic section (semi-axes a, b), a (m), b (m);

$$C = 431\frac{a^2b^2}{L(a^2+b^2)^{1/2}}\sqrt{\frac{T}{M}} \quad m^3\ s^{-1} \tag{23}$$

where T is the absolute temperature (K) and M is the molecular weight.

The molecular flow through complex systems can be computed with Monte Carlo programs adapted to the specific geometry [2].

5. Outgassing of the Beam Pipe

For every vacuum system the size of the required pumps is directly related to the outgassing. The first important source is the static and thermal outgassing of weakly adsorbed molecules and diffusion of H_2 from the bulk of the material. The standard procedure to reduce the thermal outgassing is the well known bakeout of the beam pipe.

The pressure inside an unbaked system is mainly determined by water vapours. In a clean and well baked system H_2 will be the dominant residual gas constituent. Typically, total specific outgassing rate q for unbaked and baked beam pipe made of stainless steel is given in Table 1. Therefore, the thermal outgassing rate dQ_T/dt of the surface area F = 0.1 m^2 is given by

$$\frac{dQ_T}{dt} = Fq = 10^{-7}\ \text{Pa m}^3\ \text{s}^{-1}. \tag{24}$$

The second important source of gas in the beam line is the so - called 'dynamic' outgassing [4] in the presence of the beam. Here, strongly bound molecules can be desorbed which do not otherwise contribute to the thermal desorption.

The outgassing characteristics of several materials used in vacuum technology are shown in Fig. 5 [5]. The quantity of the outgassing rate very strongly depends on the finished treatment with materials (untreated; degreased: solvent, vapour; polished: mechanical, chemical, blast, electro; baked: non - metals at 80 - 100 °C up to 24 h, metals at 300 - 400 °C up to 100 h). It is also shown that the best metals used in the vacuum technology are Al, Cu and stainless steel. Then, in order to obtain the specific outgassing rate less than 10^{-7} Pa m s^{-1} the vacuum systems are not using RUBBER, POLYAMIDS, EPOXY and PTFE - TEFLON materials, respectively.

The outgassing characteristics of materials exposed to vacuum are also published in papers [6-8].

6. Residual Gas Species Results

Outgassing characteristics of several materials were studied in vacuum at room temperature for periods as long as 24 h. Samples were placed in a stainless steel vacuum chamber which was evacuated by a 0.5 $m^3\ s^{-1}$ turbomolecular pump. The vacuum chamber volume and surface area were approximately 0.0025 m^3 and 0.12 m^2, respectively. Pressures were measured from 0.1 MPa to 10^{-6} Pa by using a combination of thermocouple, Pirani, Bayard -Alpert and Penning gauges.

Typically, the test chamber and connecting lines were conditioned between test runs using a vacuum bakeout at about 150 °C at a base pressure of about 10^{-4} Pa. Concurrently, the RGA (Residual Gas Analyser) probe was baked out at 150 °C. A minimum of 10 h was allowed for the chamber to cool to room temperature prior to loading the next test samples.

The residual gases which were evolved from the samples under test were determined using the zero order method of peak height summation and by subtracting the spectra measured of the empty test chamber from the spectra measured with the samples.

6.1 Vacuum stand

Scheme of the stand is shown in Fig. 6. It is designed to pump the vacuum chamber with diagnostic elements and gauges to the pressure of 10^{-6} Pa. The entire system including the holder of the samples is constructed of stainless steel, combined with copper and steel materials, respectively. One rotary pump is used in order to produce the vorvacuum (BL 90) [9].

The rotary and turbomolecular pumps continuously pump the whole system. The rotary pump is also used for slow - acting evacuation of the tested chamber before connection of the turbomolecular pump.

Proceeding from the dimensions of the vacuum system an effective speed S_{eff} is calculated for the center of the stand chamber. There was found to be: $S^{ch}_{eff} = 0.1$ m^3 s^{-1} for air at 10^{-5} Pa. The reduced pumping speed of the turbomolecular pump is mainly due to the small diameter of the used pipes and trap, respectively.

6.2 Results

Outgassing rates are summarized in Table 2. It is seen that the VITON 'O' ring is better than RUBBER 7889 by a factor of 15 times and RAMSAY fet is worse than APIEZON 'L' grease by a factor of 100 times. The worst material is the RUBBER 7889 and the worst grease is the Ramsay fet.

The outgassing rates presented for the VITON are the same than those reported in [10]. Similarly, our results again indicate not to recommend the use of the RUBBER 7889 and RAMSAY fet for clean interior surfaces of the beam transport line vacuum systems.

The RGA spectra are shown in Fig. 7 - 13. The spectra are measured by the RGA spectrometers MX 7304 (monopole) [11] and IPDO - 2A (omegatron) [12], respectively. The spectrometer gauges are placed directly on the measuring chamber of the stand (Fig. 6). By spectra analysis one can see the peak sets as 27, 29; 39, 41, 43; 55, 57, 58; 69; 77, 78; 85, 87; 101, 103, 105; 130, 132, 134, 136; 149, 151, 153, 155; 198; corresponding to the characteristic clusters of the n - C_x H_y hydrocarbons, or m - C_r Cl_w F_z freons. These fragments arise also during the ionization processes from oils used in the backing pumps, some diffusion pumps and turbomolecular pumps.

In addition to the spectra the expressive water vapor contamination is illustrated but there are also the peaks as 135, 137, 138, 140, 148, 155, 157 and 160 which can give rise to some difficulties in interpretation, mainly if the vacuum chamber is made of the stainless steel and if it is devided from the vacuum pumps by two liquid nitrogen traps. Nevertheless, by means of the spectral catalogs, where the spectra of the pure substances are standardized, it is possible to find the appropriate substances in the majority of cases.

Table 1. Total specific outgassing rate q for unbaked and baked beam pipe made of stainless steel [2].

Process	Temperature [K]	q [Pa m s^{-1}]
unbaked 100 h **pumpdown**	293	10^{-6}
baked 30 - 150 h at 300 °C	573	10^{-9}

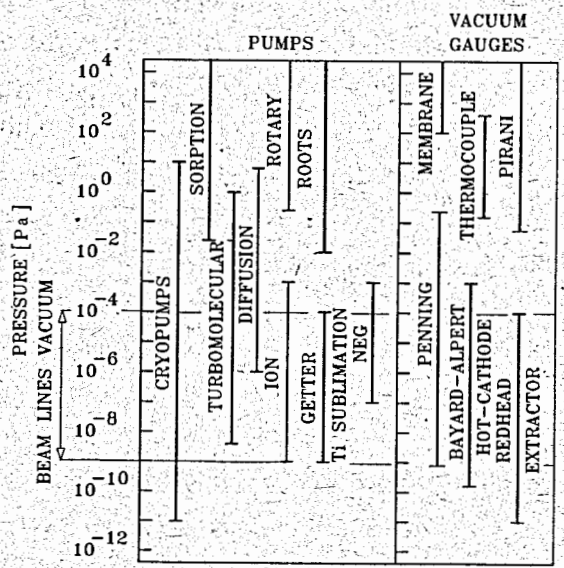

Fig. 1. Vacuum pumps and gauges used for pumping and pressure measurement in beam transport lines.

Table 2. Specific outgassing rates q for some materials used in the beam transport line vacuum technology.

Sample	Exposure [h]	Pressure [Pa]	q [Pa m s^{-1}]
'O' ring - VITON Russia	24	7×10^{-6}	6.5×10^{-5}
'O' ring - VITON Roumania	24	4×10^{-5}	2×10^{-6}
'O' ring - RUBBER -7889	24	10^{-4}	10^{-3}
'O' ring - TU MCHP -9024	20	2×10^{-5}	8×10^{-4}
Mo grease	20	4×10^{-6}	9×10^{-5}
APIEZON 'L'	20	5×10^{-7}	2×10^{-5}
RAMSAY	20	10^{-4}	2×10^{-3}
Rotary pump oil - VM-4	20	7×10^{-5}	7×10^{-3}
Glass - fibre	20	5×10^{-5}	10^{-4}

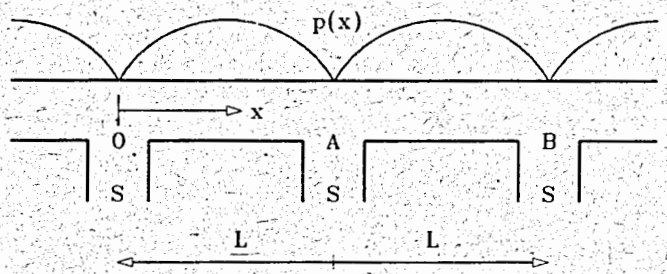

Fig. 2. Outline of the beam transport line pumping system. S is the pumping speed of the pump in points "O", "A", "B" [$m^3\ s^{-1}$], L is the distance between pumps [m] and x is the distance measured from the reference point "O" [m].

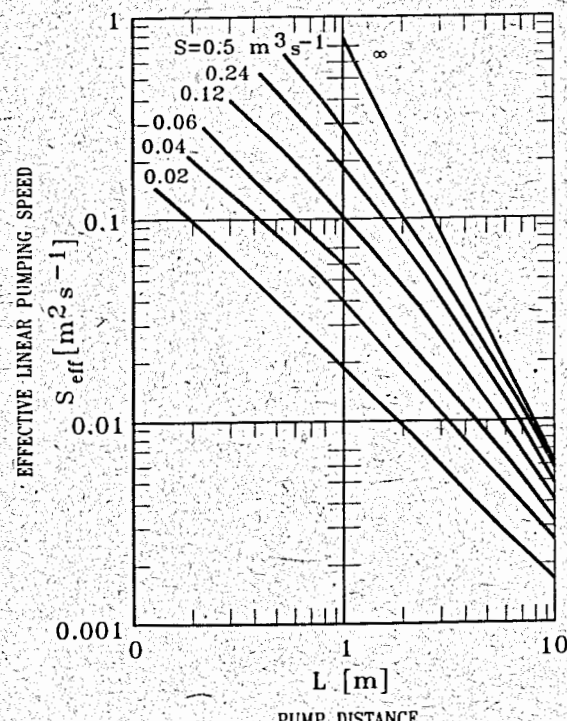

Fig. 3. Effective linear pumping speed S_{eff} as a function of pump distance L for various sizes of pumps, a vacuum beam pipe conductance w = 0.07 $m^4\ s^{-1}$ and different pumping speeds S = 0.02, 0.04, 0.06, 0.12, 0.24, 0.5 and ∞ $m^3\ s^{-1}$, respectively.

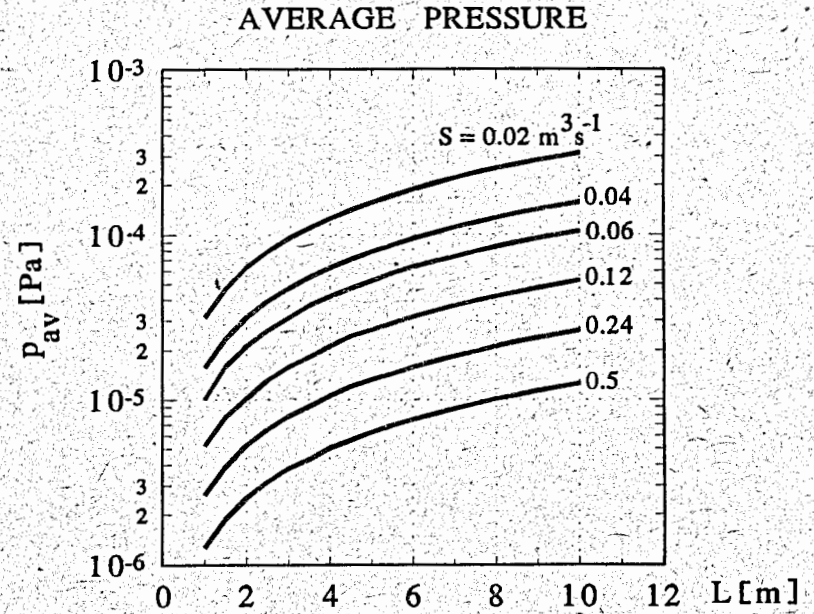

Fig. 4. Plot of the average pressure p_{av} versus distance L between pumps for different pumping speeds S = 0.02, 0.04, 0.06, 0.12, 0.24, 0.5 and ∞ $m^3\ s^{-1}$, respectively.

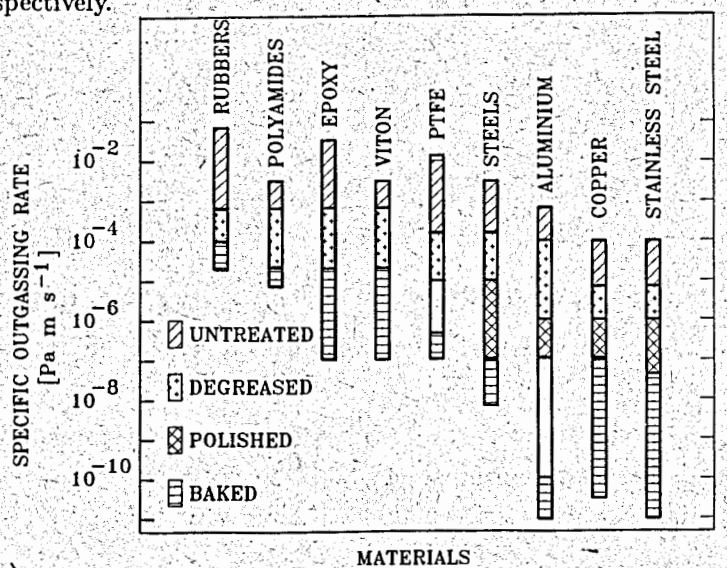

Fig. 5. Outgassing characteristics of several materials used in vacuum technology [5].

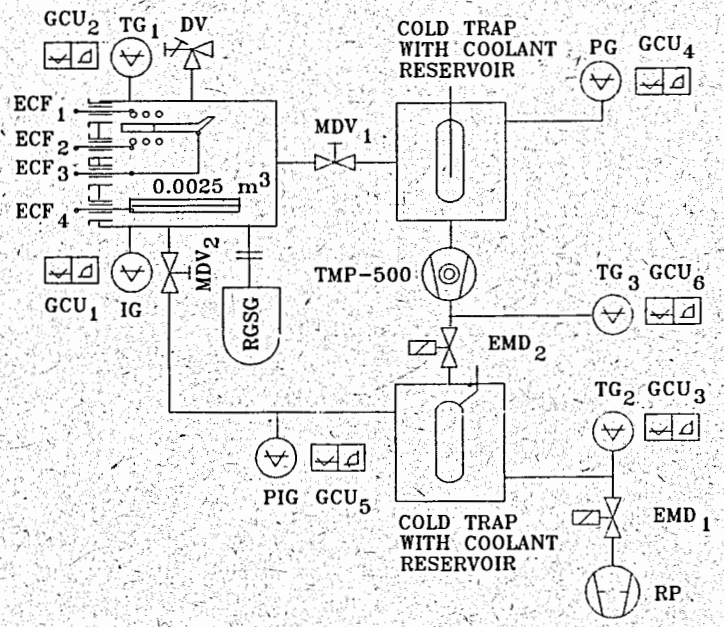

Fig. 6. Scheme of the stand used for measuring of the RGA spectra. RP is rotary pump, TMP is turbomolecular pump, ECF is electrical current feedthrough, DV is dosing valve, RGSG is residual gas spectrometer gauge, MDV is manual drive valve, EMD is electro - magnetic drive valve, PG is Penning gauge, IG is ionization gauge, TG is thermocouple gauge, PIG is Pirani gauge, and GCU is gauge control unit.

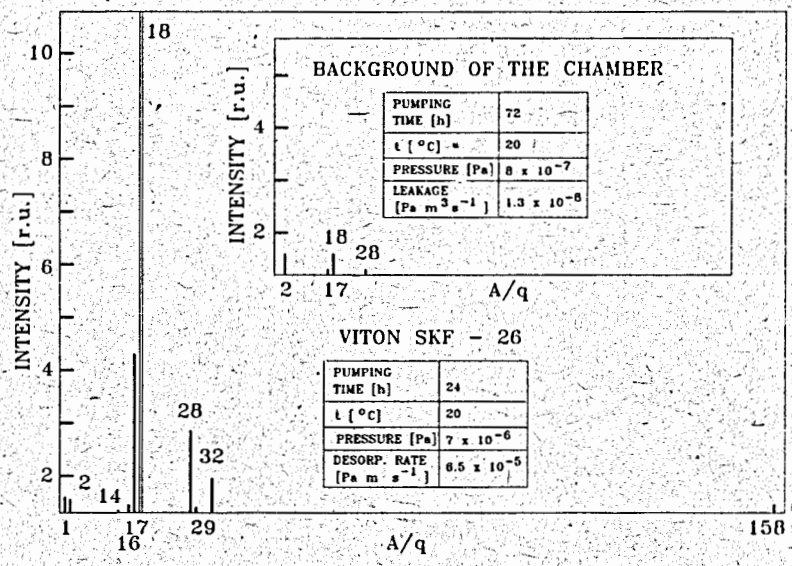

Fig. 7. Spectrum of 'O' RING VITON SKF - 26 and background of the chamber from the plasma of the RGA spectrometer MX 7304 (monopole). Measuring conditions were: 'O' RING VITON - pumping time - 24 h; temperature - 20 °C; pressure - 7×10^{-6} Pa and desorption rate - 6.5×10^{-5} Pa m s^{-1}. BACKGROUND of the chamber - pumping time - 72 h; temperature - 20 °C; pressure - 8×10^{-7} Pa and leakage - 1.3×10^{-8} Pa·m^3 s^{-1}.

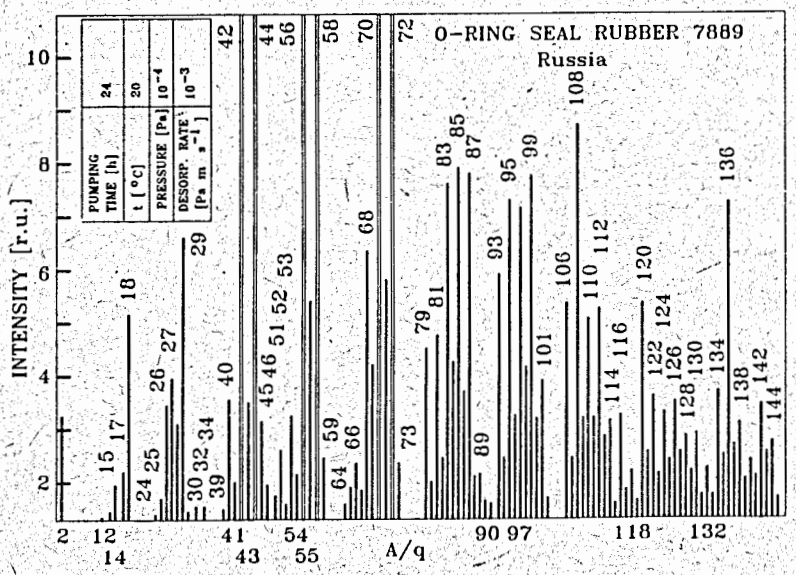

Fig. 8. Spectrum of O-ring seal RUBBER 7889 - to A/q = 145 (Russia) sample from the plasma of the RGA spectrometer MX 7304 (monopole). Measuring conditions were: Pumping time - 24 h; temperature - 20 °C; pressure - 10^{-4} Pa and desorption rate - 10^{-3} Pa m s^{-1}.

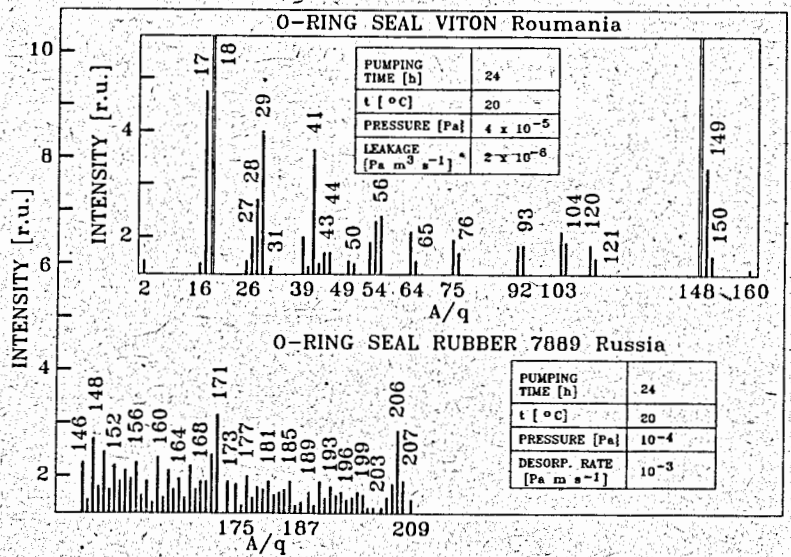

Fig. 9. Spectrum of O-ring seal RUBBER 7889 - from A/q = 145 (Russia) and O-ring seal VITON (Roumania) samples from the plasma of the RGA spectrometer MX 7304 (monopole). Measuring conditions were: O-ring seal RUBBER - pumping time - 24 h; temperature - 20 °C; pressure - 10^{-4} Pa and desorption rate - 10^{-3} Pa m s^{-1} and O-ring seal VITON - pumping time - 24 h; temperature - 20 °C; pressure - $4x10^{-5}$ Pa and desorption rate - $2x10^{-6}$ Pa m s^{-1}.

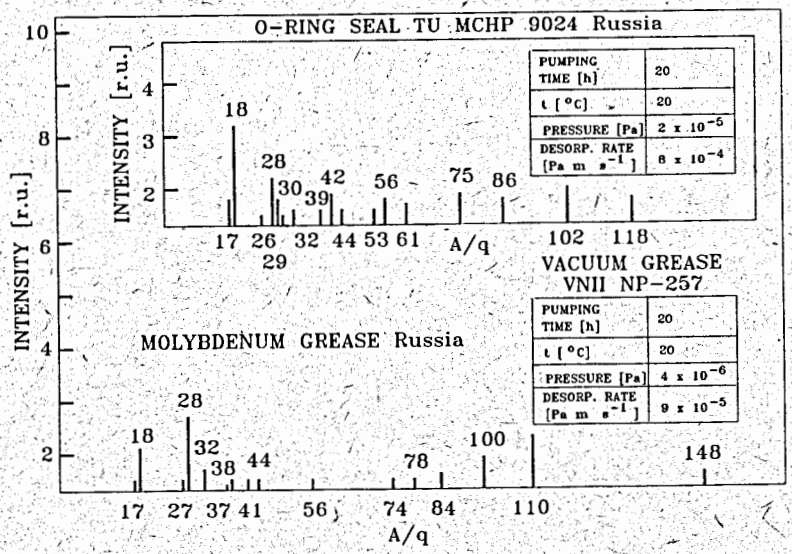

Fig. 10. Spectrum of O-ring seal TU MCHP 9024 (Russia) and MOLYBDENUM grease VNII NP-257 (Russia) from the plasma of the RGA spectrometer IPDO - 2A (omegatron). Measuring conditions were: O-ring seal TU MCHP 9024 - pumping time - 20 h; temperature - 20 °C; pressure - $2x10^{-5}$ Pa and desorption rate - $8x10^{-4}$ Pa m s^{-1} and MOLYBDENUM grease - pumping time - 20 h; temperature - 20 °C; pressure - $4x10^{-6}$ Pa and desorption rate - $9x10^{-5}$ Pa m s^{-1}.

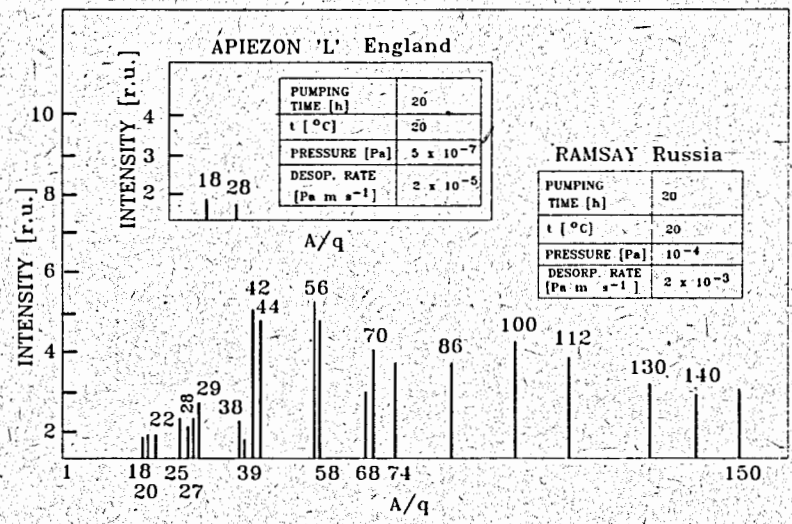

Fig. 11. Spectrum of APIEZON 'L' (England) and RAMSAY (Russia) greases from the plasma of the RGA spectrometer IPDO - 2A (omegatron). Measuring conditions were: APIEZON 'L' - pumping time - 20 h; temperature - 20 °C; pressure - $5x10^{-7}$ Pa and desorption rate - $2x10^{-5}$ Pa m s^{-1} and RAMSAY - pumping time - 20 h; temperature - 20 °C; pressure - 10^{-4} Pa and desorption rate - $2x10^{-3}$ Pa m s^{-1}.

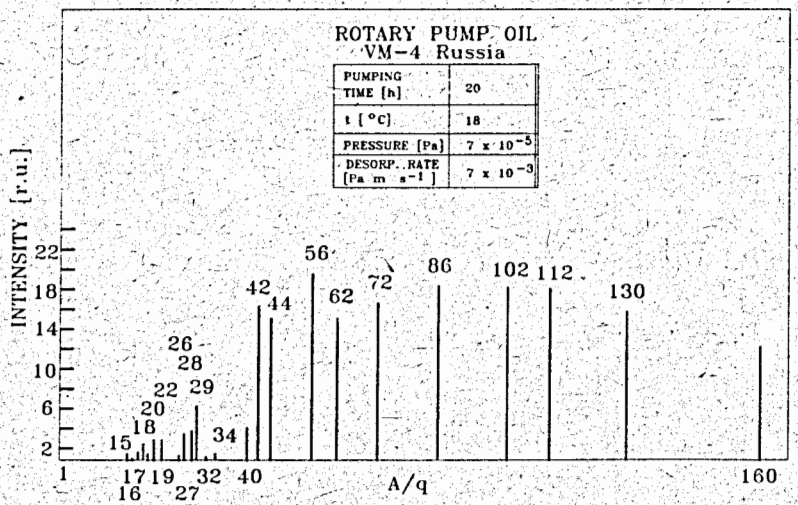

Fig. 12. Spectrum of rotary pump oil VM-4 (Russia) samples from the plasma of the RGA spectrometer IPDO - 2A (omegatron). Measuring conditions were: Pumping time - 20 h; temperature - 20 °C; pressure - $7x10^{-5}$ Pa and desorption rate - $7x10^{-3}$ Pa m s^{-1}.

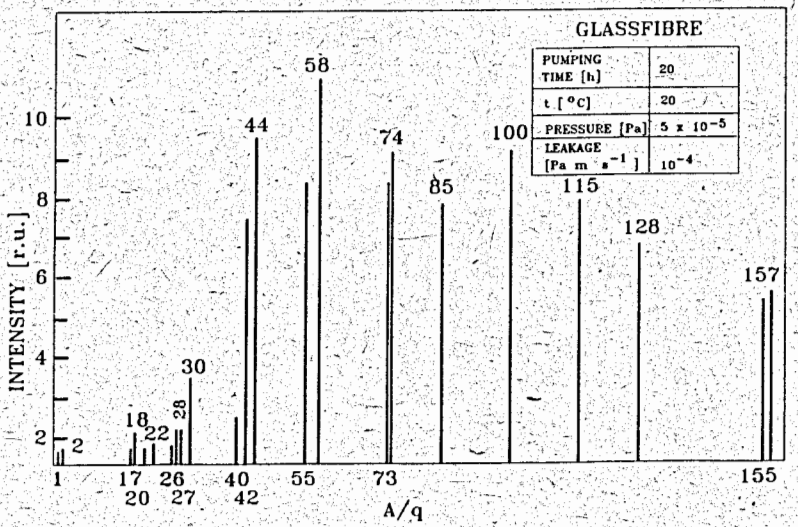

Fig. 13. Spectrum of glassfibre samples from the plasma of the RGA spectrometer IPDO - 2A (omegatron). Measuring conditions were: Pumping time - 20 h; temperature - 20 °C; pressure - $5x10^{-5}$ Pa and desorption rate - 10^{-4} Pa m s^{-1}.

7. Conclusion

The present work describes not only the scaling relationships used at the construction of the beam transport line vacuum systems but also provides the new data in the region of the outgassing rates and the RGA spectra for the different solid, grease and liquid materials. Taken together, all these data show that it may be impossible to obtain the suitable operation vacuum (10^{-5} Pa) and the necessary cleanliness of the beam lines if the vacuum exposed surfaces have higher specific outgassing rates than 10^{-4} Pa m s^{-1}.

We recommend to make the beam tubes of the transport beam lines with stainless steel, steel with stable structure and with a low relative magnetic permeability. The aluminium and copper can also be successfully used because of good mechanical properties, availability and very low desorption rates. It is practically impossible to separate the effects of outgassing, diffusion, and permeation which are manifold higher in polymers than in metals [13].

We don't recommend to use polymers for clean interior surfaces of the transport beam line vacuum systems.

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