INSTITUTE OF HIGH ENERGY PHYSICS, SERPUKHOV

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A STUDY OF A VACUUM SYSTEM INCORPORATING SPUTTER ION PUMPS AND A PULSED HYDROGEN FILLING

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Hydrogen is fed in pulses through an electrodynamic valve to the ion source of the pre-injector of the I-100 proton linear accelerator /1/. Paper /2/ describes the vacuum system of the pre-injector and gives some parameters of the NEM-IT sputter ion pumps for hydrogen.

By studying the time dependence of the hydrogen pressure, it is possible to determine some of the system's parameters (amount of hydrogen per pulse, hydrogen pressure in the source and the hydrogen pumping speed) and to define a procedure for designing similar vacuum systems.

Fig. 1 shows a schematic diagram of the vacuum system. The electrodynamic valve is open for less than 1 msec. A Q_1 amount of hydrogen enters the source's discharge chamber (volume Vp) whence it passes through a series of diaphragms with an overall hydrogen throughput u_p to the pre-injector's vacuum chamber (volume V_k) and is pumped out by two NEM-IT ion pumps with an overall hydrogen pumping speed S_k. The hydrogen pressures Pp and P_k in the discharge and vacuum chambers respectively are varied in time over a period t_u between hydrogen supply pulses. When the source is in operation, the discharge lasts 15-50 μsec. Since this time is short compared with t_u = 8.7-8.6 sec., the effect of the discharge on the time characteristics of the hydrogen pumping may be ignored and it may be assumed that all the Q_1 amount of hydrogen is pumped out.

The variations of the hydrogen pressure P_k in the pre-injector chamber, measured by means of a residual gas analyser (RGA), are plotted in fig. 2.

The chart speed of the EPP-09 recorder was increased to 29m/h in order to increase the scanning time. Readings were taken from the initial pressure P_{ok} settled just before the next pulse.

The variation of the hydrogen pressure in the source and in the pre-injector's chamber over the period t_u of any pulse may be described by the following system of equations:

$$V_p \frac{dP_p}{dt} = -u_p(P_p - P_k), \qquad (1)$$
$$V_k \frac{dP_k}{dt} = u_p(P_p - P_k) - S_k P_k.$$

It is assumed that within the limits of variation of P_k, S_k does not depend on time and pressure and u_p does not depend on pressure because of the molecular gas flow through the source's output channel. Since the pressure variation process is periodic, the following initial conditions may be specified for equation (1):

$$P_p = P_p' + P_{op}, \quad P_k = P_{ok}, \quad t = 0;$$
$$P_p = P_p', \quad P_k = P_{ok}, \quad t = t_u,$$

where P_p' is the pressure which would be in the source at instant $t = t_u$ if there was not another pulse, and P_{ok} is the pressure in the chamber at the beginning and end of the pulse. Having assumed that the time taken to establish maximum pressure in the source is short compared with t_m (fig. 2) and the amount of gas flowing into the chamber in that time is small compared with Q_1, then $P_{op} = \frac{Q_1}{V_p}$. In fact, when the source is in operation, the discharge occurs 2 msec after the valve is opened.

By using the initial conditions and by excluding P_p' and P_{ok} from equations (1), we obtain

$$P_p = \frac{Q_1}{V_p(\lambda_2 - \lambda_1)}[a(\beta_p + \lambda_2)e^{\lambda_1 t} - b(\beta_p + \lambda_1)e^{\lambda_2 t}], \qquad (2)$$

$$P_k = \frac{Q_1(\beta_p + \lambda_2)(\beta_p + \lambda_1)}{\beta_p V_p(\lambda_2 - \lambda_1)}(a e^{\lambda_1 t} - b e^{\lambda_2 t}), \qquad (3)$$

where $a = (1 - e^{\lambda_1 t_u})^{-1}$, $b = (1 - e^{\lambda_2 t_u})^{-1}$, λ_1, λ_2 – are the roots of the characteristic equation of system (1):

$$(\beta_p + \lambda)\left(\frac{u_p}{V_k} + \beta_k + \lambda\right) - \frac{u_p}{V_k}\beta_p = 0,$$
$$\beta_p = \frac{u_p}{V_p}, \quad \beta_k = \frac{S_k}{V_k}. \tag{4}$$

Since $\frac{u_p}{V_K} \ll \beta_K$ and $\frac{u_p}{V_K} \ll \beta_p$, then $\lambda_1 \simeq -\beta_K$ and $\lambda_2 \simeq -\beta_p$. By estimating u_p and S_k for the given system, it follows that $e^{\lambda_2 t_u} \ll 1$ and $e^{\lambda_1 t_u} \ll 1$. Taking into account the fact that $(\beta_p + \lambda_2)(\beta_p + \lambda_1) = -\beta_p \frac{u_p}{V_K}$ and by using the P_{ok} value from equation (3) at t = 0, we obtain an expression for the pressure in the chamber

$$P'_k = a\left(e^{-\beta_k t} - e^{-\beta_p t}\right), \tag{5}$$

where

$$a = \frac{Q_1 \beta_p}{V_k(\beta_p - \beta_k)},$$
$$\beta_p \neq \beta_k, \quad P'_k = P_k - P_{ok}. \tag{6}$$

We find the time required to reach maximum pressure in the pre-injector chamber from equation $\frac{dP_K}{dt} = 0$:

$$t_m = \frac{1}{(\beta_p - \beta_k)} \ln \frac{\beta_p}{\beta_k}. \tag{7}$$

By substituting equation (7) into equation (5), we obtain the maximum pressure

$$P'_{km} = \frac{Q_1}{V_k}\left(\frac{\beta_k}{\beta_p}\right)^{\frac{\beta_k}{\beta_p - \beta_k}}. \tag{8}$$

Taking into account equation (3), the average pressure in the pre-injector chamber over interval t_u is

$$\bar{P}_k = \frac{1}{t_u}\int_0^{t_u} P_k\,dt = \frac{Q_1}{t_u S_k}. \qquad (9)$$

By defining the average pressure, Q_1 and t_u, it is possible to define the system's required pumping rate from formula (9). By defining P'_{max} and knowing β_p and S_k, it is possible to determine the minimum chamber volume V_k required by means of expressions (8) and (9). Values $\bar{P}_k$ and $\bar{P}'_{max}$ are important for the vacuum system because the ion pumps may operate steadily at $\bar{P}_k \leqslant 5\cdot10^{-6}$ Torr and $P_{max} \leqslant (7\div8)\cdot10^{-5}$ Torr.

In order to determine Q_1, the hydrogen flow was measured using an LM-2 gauge after the pumps had been shut off. In this case $S_k = 0$, and the solution of the system for the first pulse, to the same approximation as for pumping, gives the following expression for the pressure in the chamber:

$$P_k' = \frac{Q_1}{V_k}(1 - e^{-\beta_p t}). \qquad (10)$$

The analysis of the experimental curves for P'_k was based on the assumptions of equation (5). The calculations show that β_p is several times bigger than β_k. Therefore, when $t > t_m$ the downward part of the experimental curve may be approximated by one exponential

$$P_k' = a e^{-\beta_k t}. \qquad (11)$$

By selecting two points on the curve at different moments in time and pressure values P'_{k1} and P'_{k2} at these points, we determine β_k from the relationship

$$\beta_k = \frac{1}{t_2 - t_1} \ln \frac{P'_{k1}}{P'_{k2}}. \qquad (12)$$

After calculating β_k for several pairs of points and making sure that from a certain t value β_k changes but slightly, an average β_k value can be selected for this curve.

It is rather difficult to determine the β_p value from the experimental curves because β_p may be calculated only from the initial part of the curve where the time constant of the RGA (residual gas analyser) and the recorder's chart speed are comparable to t_m. This may lead to errors in the determination of β_p. The distortions which the device makes in the experimental curves at close P'_{max} values depend only on the time. In that case the P'_k ratio for two curves with different β_k and identical Q_1 at the same time t will be equal to the ratio of the actual P'_k values.

Therefore, curves were plotted for a single pump and for two pumps. The β_p was determined according to the ratio of P'_{k1} and P'_{k2} values for the corresponding β_{k1} and β_{k2} at the same time according to the formula derived from equation (5):

$$\beta_p = \frac{\beta_{k2} - c\,\beta_{k1}}{1 - c} , \tag{13}$$

where

$$\frac{P'_{k1}}{P'_{k2}} e^{-(\beta_{k2} - \beta_{k1})t} .$$

By substituting the mean values of β_k and β_p into equation (5), the mean value "a" can be determined for each curve. Experimental curve 3 in figure 3 illustrates the variation of P'_k. Curve 4 is calculated according to the corresponding β_k, β_p and "a". It may be seen that curve 3 is satisfactorily described by equation (5). The slight time lag in the initial part of the experimental curve is due to the instrument time constant.

In order to determine the time delay caused by the RGA, the signal from the collector of a ionisation gauge was transmitted directly to an S1-37 oscilloscope. Since variations in the overall pressure during a pulse are due mainly to the hydrogen, the signal on the oscilloscope reflects qualitatively the variations in the hydrogen pressure. Curve 1 in figure 3 was plotted with the aid of the oscilloscope. The β_p value which is determined according to this curve by means of equation (5) is close to the β_k value determined from the ratio of the curves plotted by the RGA, which indicates the suitability of determining β_p by comparing the two curves in accordance with formulae (13). Fig. 3 shows that equation (5) describes curve 1 well without any time shift.

By using the β_k, β_p and "a" values, it is possible to calculate such parameters of the vacuum system and source as S_k, u_p, Q_1 and P_{ap}*.

The experimental curves for the hydrogen flow per pulse, plotted by the RGA with the pumps off, are satisfactorily described by equation (10). The Q_1 value derived from equation (10) is close to that obtained from equation (6).

In addition, Q_1 was measured by means of the ionisation gauge in the following way. The flow rate into the chamber was measured with no hydrogen being supplied to the source

$$\frac{V_k(P_{02}-P_{01})}{\Delta t} = Q_o + \sum_i Q_i, \tag{14}$$

and with n pulses of hydrogen supplied

$$\frac{V_k(P_2-P_1)}{\Delta t} = Q_o + \sum_i Q_i + Q', \tag{15}$$

where $\Delta t = nt_u$ is the pressure increase time, Q_o is the hydrogen flow with no pulsed supply, $\Sigma_i Q_i$ is the total flow of other gases and $Q' = \frac{nQ_1}{\Delta t}$ is the average hydrogen flow with pulsed supply. By subtracting expression (14) from (15), we obtain the expression for Q_1

$$Q_1 = \frac{V_k K t_u}{\Delta t}\left[(P_2-P_1)-(P_{02}-P_{01})\right], \tag{16}$$

* Not clear in original.

where K is the gauge's hydrogen sensitivity, and P_{o1}, P_1 and P_{o2}, P_2 are the pressures, nitrogen equivalent measured by the gauge. The Q_1 determined from formula (16) differs by $\pm$ 15% from the values found from (6) and (10).

Fig. 4 shows the dependence of "a" and P'_{max}, found using equation (5), on the Q_1 measured for these curves by the gauge. The P'_{max} value was determined from (5) at t = tm. As can be seen from the graphs in fig. 4, the linear dependences of "a" and P'_{max} confirm equations (6) and (8), thus indicating that the condition $P_{op} = \frac{Q_1}{V_p}$ and approximated equation (5) can be applied.

The experimental curves were used in conjunction with equation (5) to determine the mean values: $\beta_k = 0.9 \pm 0.1$ sec^{-1} for one NEM-IT pump, $\beta_p = 5.9 \pm 0.5$ sec^{-1} and $t_m = 0.38 \pm 0.05$ sec. The Q_1 for the different curves were varied over the range 0.5 - 15 μTorr.ℓ by regulating the valve's throughput. P_{op} was correspondingly varied over the range $1 \cdot 10^{-2} - 3 \cdot 10^{-1}$ Torr. The experimental values of t_m exceed those calculated from formula (7) by 0.1 sec on average; this is due to the effect of the RGA time constant. According to the β_k value at $V_k = 1.3 \cdot 10^3 \ell$, the average hydrogen pumping rate of the NEM-IT pump is $S_k = 1200 \pm 100\ \ell$/sec over the pressure range $6 \cdot 10^{-7}$ - $4 \cdot 10^{-6}$ Torr. According to the β_p value at $V_p = 5 \cdot 10^{-2}\ \ell$, the hydrogen throughput of the source's outlet valve is $u_p = 0.3\ \ell$/sec. With molecular gas flow through the two series-connected short cylindrical tubes of the source's outlet valve, the calculated value is $u_p = 0.35\ \ell$/sec which corresponds well with the experimental results.

The variation of the hydrogen pressure in the source's discharge chamber is described by a simplified version of equation (2),

$$P_p = P_{op}\left[\frac{u_p}{2\,V_k(\beta_p - \beta_k)}\ e^{-\beta_k t} + e^{-\beta_p t}\right]. \qquad (17)$$

Equation (17) can be used to determine the hydrogen flux from the source over the period t_p at the beginnning of a discharge.

Since $t_p \sim 2 \cdot 10^{-3}$ sec, then

$$Q \approx Q_1 \beta_p. \tag{18}$$

The hydrogen flux value at the instant of discharge serves to determine the source's gas consumption.

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2. K.G. Mirzoev, V.G. Rogozinskij, V.L. Ushkov. ZhTF, XL IV, v. 3 (1974).

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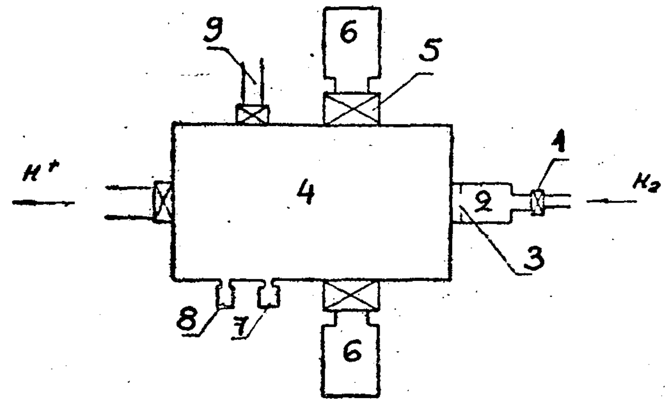

Fig. 1. Layout of vacuum system of pre-injector with pulsed hydrogen supply.
1 - pulsed valve,
2 - ion source's discharge chamber,
3 - ion source's outlet valve,
4 - vacuum chamber,
5 - vacuum valve,
6 - NEM-IT sputter ion pump,
7 - RMO-4S gauge,
8 - LM-2 ionization gauge,
9 - roughing line.

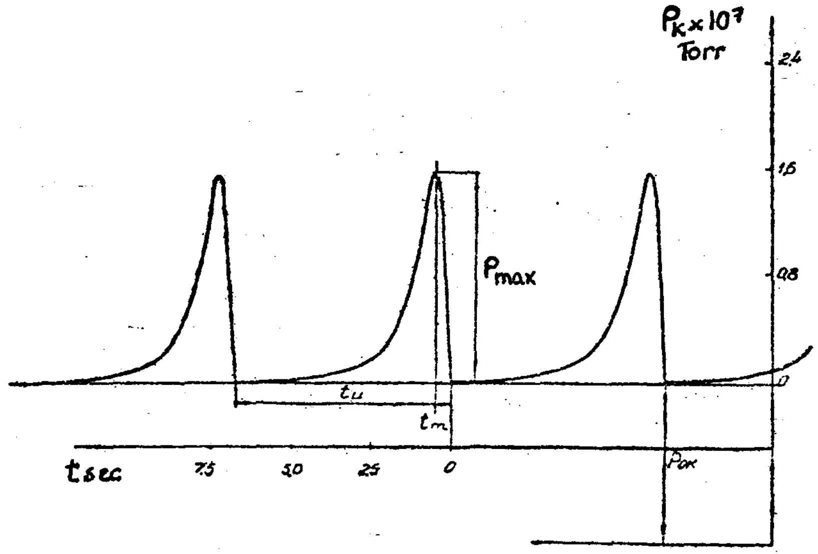

Fig. 2. Experimental curves for the variation of hydrogen pressure in the pre-injector chamber (copied from the recorder print-out).

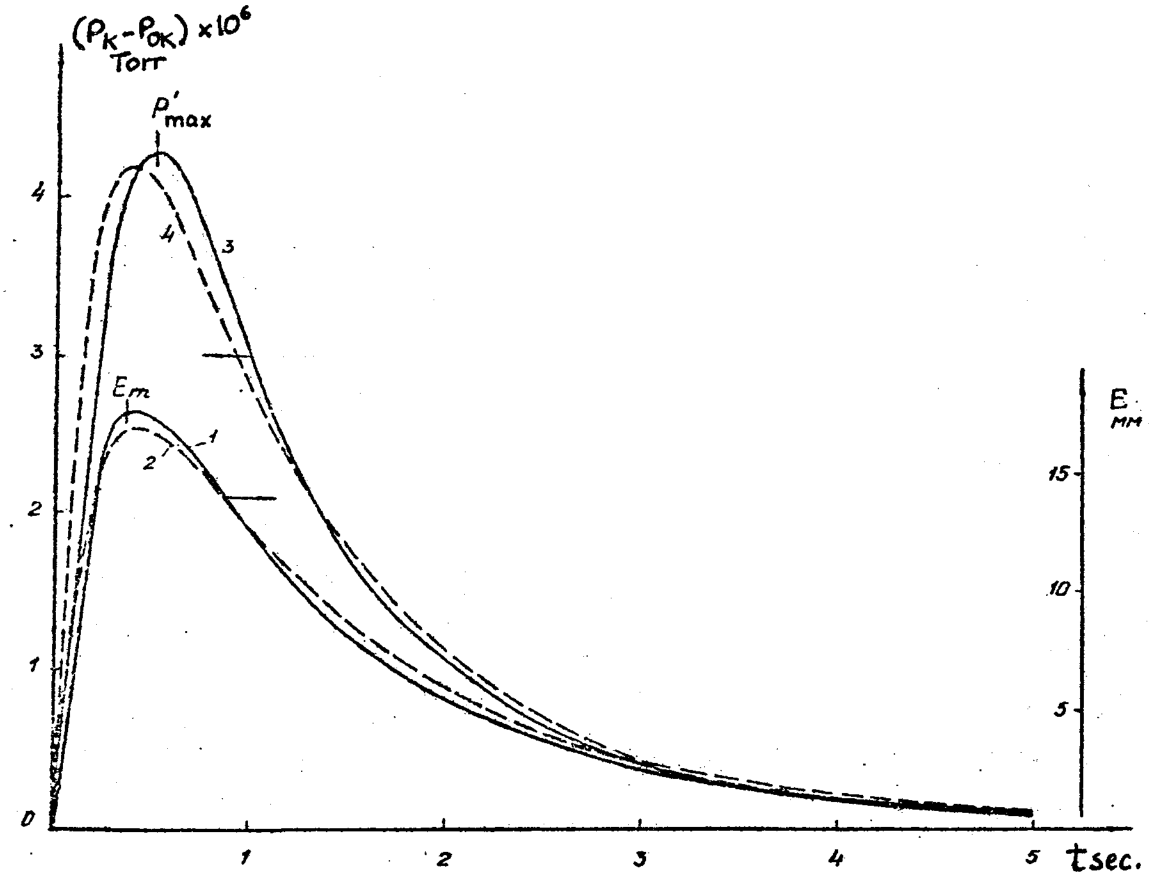

Fig. 3. Comparison of the experimental curves with the calculated time dependence of the hydrogen pressure.

1. - pressure variation curve plotted by means of an oscilloscope, in mm of the screen scale;
2. - calculated curve plotted using (5) at $\beta_k = 0.9$ sec^{-1}, $\beta_p = 5.9$ sec^{-1} and "a" = 27 mm determined from curve 1;
3. - experimental curve plotted by the residual gas analyser;
4. - calculated curve for P'_k according to (5) at $\beta_k = 0.9$ sec^{-1} and "a" = $6.9 \cdot 10^{-6}$ Torr determined from curve 3, and $\beta_p = 5.9$ sec^{-1}.

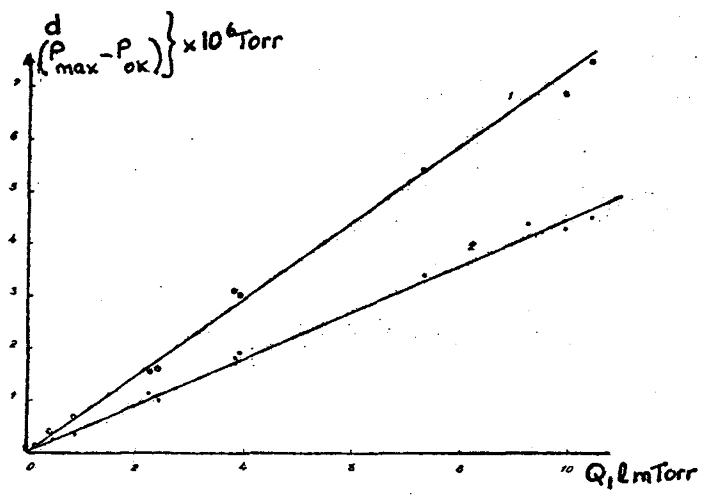

Fig. 4. Dependence of "a" (1) and P'_{max} (2), determined from RGA curves, on the Q_1 measured by gauge.