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 \( V_p \)) 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 \( P_p \) 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 \( \mu \)sec. 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:

\[
\begin{align*}
V_p \frac{dP_p}{dt} & = -u_p (P_p - P_k), \\
V_k \frac{dP_k}{dt} & = u_p (P_p - P_k) - S_k P_k.
\end{align*}
\]  

(1)

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):

\[
\begin{align*}
P_p(t=0) & = P'_p + P_{op}, \\
P_k(t=0) & = P_{ok}, \\
P_p(t=t_u) & = P'_p, \\
P_k(t=t_u) & = P_{ok},
\end{align*}
\]

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 \( P_{op} \) from equations (1), we obtain

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

(2)

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

(3)
where \( a = (1 - e^{\lambda_1tu})^{-1}, \ b = (1 - e^{\lambda_2tu})^{-1}, \lambda_1, \lambda_2 \)

are the roots of the characteristic equation of system (1):

\[
(\beta_p + \lambda)(\frac{u_p}{V_k} + \beta_k + \lambda) - \frac{u_p}{V_k} = 0,
\]

\[
\beta_p = \frac{u_p}{V_p}, \quad \beta_k = \frac{S_k}{V_k},
\]

Since \( \frac{u_p}{V_k} \ll \beta_k \) and \( \frac{u_p}{V_k} \ll \beta_p \), then \( \lambda_1 \approx -\beta_k \) and \( \lambda_2 \approx -\beta_p \).

By estimating \( u_p \) and \( S_k \) for the given system, it follows that \( e^{\lambda_1tu} \ll 1 \) and \( e^{\lambda_2tu} \ll 1 \). 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

\[
P'_k = a(e^{-\beta_p t} - e^{-\beta_k t}),
\]

where

\[
a = \frac{Q_1 \beta_p}{V_k (\beta_p - \beta_k)},
\]

\[
\beta_p \neq \beta_k; \quad P' = P_k - P_{ok}.
\]

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

\[
\cdot t_m = \frac{1}{(\beta_p - \beta_k)} \ln \frac{\beta_p}{\beta_k}.
\]

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

\[
P'_{km} = \frac{Q_1}{V_k} \frac{\beta_k}{(\beta_p - \beta_k)}.
\]
Taking into account equation (3), the average pressure in the pre-injector chamber over interval $t_u$ is

$$\bar{P}_k = \frac{1}{t_u} \int_0^{t_u} P_k \, dt = \frac{Q_1}{t_u S_k}.$$  \hspace{1cm} (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 $P_{\text{max}}$ and knowing $\beta_p$ and $S_k$, it is possible to determine the minimum chamber volume $V_k$ required by means of expressions (8) and (9).

Values $P_{k}$ and $P_{\text{max}}$ are important for the vacuum system because the ion pumps may operate steadily at $P_k \leq 5 \cdot 10^{-6}$ Torr and $P_{\text{max}} \leq (7 \cdot 8) \cdot 10^{-5}$ 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:

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

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

$$P_k' = e^{-\beta_k t}.$$  \hspace{1cm} (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 $\beta_k$ from the relationship

$$\beta_k = \frac{1}{t_2 - t_1} \ln \frac{P_{k1}'}{P_{k2}'}.$$  \hspace{1cm} (12)
After calculating $\beta_k$ for several pairs of points and making sure that from a certain $t$ value $\beta_k$ changes but slightly, an average $\beta_k$ value can be selected for this curve.

It is rather difficult to determine the $\beta_p$ value from the experimental curves because $\beta_p$ 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 $\beta_p$. The distortions which the device makes in the experimental curves at close $P'_{\text{max}}$ values depend only on the time. In that case the $P'_k$ ratio for two curves with different $\beta_k$ 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 $\beta_p$ was determined according to the ratio of $P'_{k1}$ and $P'_{k2}$ values for the corresponding $\beta_{k1}$ and $\beta_{k2}$ at the same time according to the formula derived from equation (5):

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

(13)

where

$$P'_{k1} = (\beta_{k2} - \beta_{k1})t_{1}.$$  

By substituting the mean values of $\beta_k$ and $\beta_p$ 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 $\beta_k$, $\beta_p$ 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 \( \beta_p \) value which is determined according to this curve by means of equation (5) is close to the \( \beta_k \) value determined from the ratio of the curves plotted by the RGA, which indicates the suitability of determining \( \beta_p \) 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 \( \beta_k, \beta_p \) 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

\[
\frac{V_k(P_{o2}-P_{o1})}{\Delta t} = Q_o + \Sigma_i Q_i, \quad (14)
\]

and with \( n \) pulses of hydrogen supplied

\[
\frac{V_k(P_2-P_1)}{\Delta t} = Q_o + \Sigma_i Q_i + Q', \quad (15)
\]

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 \( Q' = \frac{n Q_1}{\Delta t} \) is the average hydrogen flow with pulsed supply.

By subtracting expression (14) from (15), we obtain the expression for \( Q_1 \)

\[
Q_1 = \frac{V_k K t_a}{\Delta t} [(P_2-P_1)-(P_{o2}-P_{o1})]. \quad (16)
\]

* Not clear in original.
where \( K \) is the gauge's hydrogen sensitivity, and \( P_{01}, P_1 \) and \( P_{02}, P_2 \) 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 \( P_{\text{max}}' \), found using equation (5), on the \( Q_1 \) measured for these curves by the gauge. The \( P_{\text{max}}' \) value was determined from (5) at \( t = t_m \). As can be seen from the graphs in fig. 4, the linear dependences of "a" and \( P_{\text{max}}' \) confirm equations (6) and (8), thus indicating that the condition \( P_\text{op} = \frac{Q_1}{V_p} \) and approximated equation (5) can be applied.

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

\[
P_P = P_\text{op} \left[ \frac{u_p}{2 V_k (\beta_p - \beta_k)} \right] e^{-\beta_k t} + e^{-\beta_p t}. \tag{17}
\]

Equation (17) can be used to determine the hydrogen flux from the source over the period \( t_p \) at the beginning of a discharge.
Since $t_p \sim 2 \cdot 10^{-3}$ sec, then

$$Q \approx Q_1 \beta_p.$$  \hspace{1cm} (18)

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

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Bibliography


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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 $\beta_p = 0.9 \text{ sec}^{-1}$, $\beta_p = 5.9 \text{ sec}^{-1}$ and "$a" = 27 \text{ mm} determined from curve 1;
3. - experimental curve plotted by the residual gas analyser;
4. - calculated curve for $P'$ according to (5) at $\beta = 0.9 \text{ sec}^{-1}$ and "$a" = 6.9 \cdot 10^{-6} \text{ Torr} determined from curve 3, and $\beta_p = 5.9 \text{ sec}^{-1}$.
Fig. 4. Dependence of "a" (1) and $P_{\text{max}}'$ (2), determined from RGA curves, on the $Q_1$ measured by gauge.