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THE PRESSURE PROFILE IN A LONG OUTGASSING VACUUM TUBE*

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ABSTRACT

As a simple extension of the long tube formula, an analysis is given whereby the pressure profile may be determined along a uniformly outgassing pipe pumped at both ends. The theoretical analysis is extended to include nonuniform outgassing situations such as occur in particle storage rings. These findings are used to determine the optimum vacuum system configuration for various vacuum system parameters, while affording minimum vacuum system cost. Calculations were checked experimentally using a stainless steel tubing with a 5.7 centimeter inside diameter, and a length of ~50 meters.

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Introduction

The cost of vacuum systems for particle accelerators and storage rings is appreciable ($\sim$10 to 20% of the total system cost). High vacuum is required in storage rings and accelerators to afford electrical insulation for high peak rf electric fields. Ultrahigh vacuum is required in particle storage rings to minimize beam scattering due to collisions with gas molecules, and thus extend beam storage lifetime. Vacuum problems are complicated in electron-positron storage rings by outgassing which occurs as a consequence of synchrotron radiation. A knowledge of the pressure profiles for various possible outgassing situations will permit the design of a minimum cost system for predetermined vacuum performance requirements.

A recirculating linear accelerator has been proposed for construction at the Stanford Linear Accelerator Center.[1] The recirculating system will almost double the beam energy of the present two-mile accelerator. This is accomplished by storing the beam after initial acceleration so that it can be reinjected and accelerated a second time the full two-mile length of the accelerator. Figure 1 illustrates the principle of operation.

There are two regions of vacuum system in the recirculator scheme with distinctly different vacuum problems. One is in the region where the electron beam is bent by alternating gradient magnets. In this region vacuum problems are similar in many respects to those problems encountered in storage rings.[2,3] The second region is the long, essentially field free, beam drift tubes which interconnect the beam bending magnet sections at each end of the accelerator. The following analysis and tests relating to uniform outgassing situations would apply to this second region. The analysis for the nonuniform outgassing case applies to the region of the bending magnets.

Uniform Outgassing

In this section the pressure profile and average pressure of a long uniformly outgassing tube are calculated. Assume no vacuum leaks exist and that several pumps are spaced equidistant along a tubing. If each pump has the same speed S_p, the pressure profile between any two pumps in the system (neglecting end pumps) will be symmetrical. The pressure will be a maximum at the halfway point between any two pumps. The net gas flow past this maximum pressure point will be zero. Therefore, the analysis simplifies to one of finding the pressure profile in a long uniformly outgassing tube pumped at one end.

At the pump end of the manifold the following relation may be written:

$$Q = q\pi D\ell = q\pi D\Delta\ell + \Delta C\Delta P \tag{1}$$

where

Q = total outgassing rate from long tube

q = outgassing rate per unit area

D = tube diameter

ℓ = total length of tube

$\Delta\ell$ = increment of tube length

ΔC = vacuum conductance of tube of length $\Delta\ell$

ΔP = pressure difference across increment $\Delta\ell$

Given that the vacuum conductance $C = kD^3/\ell$, where k is a function of temperature and molecular weight of the gas,[4] then

$$q\pi D\ell = q\pi D\Delta\ell + \frac{kD^3\,\Delta P}{\Delta\ell} \quad ,$$

or

$$q\pi D\ell\Delta\ell \approx kD^3\,\Delta P$$

and in the limit

$$\int_0^{\ell} q\pi D\ell \, d\ell = \int_{P_p}^{P_e} kD^3 \, dP$$

$$q\pi \ell^2/2 = kD^2 (P_e - P_p)$$

where P_e = pressure at the end of the manifold and P_p = pressure at the pump (or effective pump); then

$$P_e = P_p + \frac{q\pi\ell^2}{2kD^2} = P_p + \frac{Q}{2C} \tag{2}$$

The average pressure may then be calculated as follows. In the molecular flow region one may use the principle of pressure superposition. Pressure at some point x along a manifold (such as shown in Fig. 2) results from two sources. The first, P_{1x}, is due to outgassing of the manifold between the pump and point x and the second, P_{2x}, is due to outgassing of the manifold from point x to the end farthest from the pump. Then, $P(x) = P_{1x} + P_{2x}$ is the total pressure at point x. Also the pump pressure is $P_p = P_{1p} + P_{2p}$, where subscripts 1 and 2 denote variables associated with the above two sources of gas. Using Eq. (2)

$$P_{1x} = P_{1p} + Q_{1x}/2C_{1x} \tag{3}$$

Also, from elementary vacuum equations

$$Q_{2x} = (P_{2x} - P_{2p})\, C_{2x}$$

then,

$$P_{2x} = P_{2p} + Q_{2x}/C_{2x} \tag{4}$$

But $C_{2x} = C_{1x} = kD^3/x = C(x)$. Therefore,

$$P(x) = P_{1x} + P_{2x} = P_{1p} + P_{2p} + (Q_{1x}/2 + Q_{2x})/C(x),$$

and

$$P(x) = P_p + \frac{\pi q}{2kD^2} (2x\ell - x^2) \qquad (5)$$

Note that Eq. (5) may be used to express pressure over the total interval $(0, 2\ell)$.

The average pressure, P_{av}, may now be calculated:

$$P_{av} = \frac{1}{\ell} \int_0^{\ell} P(x)\, dx$$

or

$$P_{av} = P_p + \frac{2}{3} \left[\frac{\pi q \ell^2}{2kD^2} \right] \qquad (6)$$

Note that if $P_p \ll P_e$, $P_e \approx (\pi q \ell^2/2kD^2)$ and therefore $P_{av} \approx 2/3P_e$. This result is important in that it emphasizes the problem of "conductance limitation".

In the above calculations it has been assumed that "q" is independent of pressure. For a baked system this is a very good approximation. For an unbaked system, Eqs. (5) and (6) will be conservative estimates from the standpoint of yielding results higher than will be experimentally observed.

Nonuniform Outgassing

One may extend the use of the "long tube" formula and the principle of pressure superposition to include situations of nonuniform outgassing. The mathematics becomes formidable for a general analytic q(x) (the outgassing rate per unit length). For this reason two specific cases will be discussed —

a q(x) corresponding to (1) a "squarewave" function, and (2) a "delta function", each at some arbitrary location in the long tube. Through superposition of solutions of P(x) for either of these functions a solution for any analytic q(x) may be represented to the accuracy required.

Again it is assumed that pumps are spaced at intervals of 2ℓ, and that each pump has a speed S_p. This assumption with regard to pump speed is done to simplify the analysis, but is done without loss of generality. The simplification made possible by this assumption is that each pump operates at the same pressure as long as q(x) is periodic in 2ℓ. Only such periodic cases will be treated.

The Delta Function

A delta function may be used to represent some concentrated gas source such as a leak. The location and size of respective leaks (the word leak is hereafter used in the figurative sense) is defined by the function $Q_\delta\, \delta(b-x)$, where Q_δ is the leak amplitude and "b" the location within $(0,2\ell)$. The function $\delta(b-x)$ has the usual interpretation of

$$\lim_{\Delta x \to 0} \int_{b-\Delta x}^{b+\Delta x} \delta(b-x) = 1 \ . \qquad \text{Therefore} \int_0^{2\ell} Q_\delta\, \delta(b-x)dx = Q_\delta \ .$$

Assume that aperiodic q(x) exists in (0, L) such as shown in Fig. 3. The average pressure for interval $(0, 2\ell)$ will be calculated using delta functions distributed along the length (e-a), shown in this figure. Using the long tube formula it can be shown that pressure along the tubing with a single "leak" at "b" and of magnitude Q_δ is given by:

$$P(x) = P_p + \frac{Q_\delta(2\ell-b)}{2k\,D^3\ell}\, x \qquad 0 \le x \le b \qquad (7a)$$

$$P(x) = P_p + \frac{Q_\delta(2\ell-x)}{2k\,D^3\ell}\, b \qquad b \le x \le 2\ell \qquad (7b)$$

Assume that the length (e-a) is divided into integer n equal sections. Subtending each section let there be an outgassing function of magnitude Q_δ, where $Q_\delta = \left(\int_a^e q(x)\,dx\right)/(n+1)$. Define the following functions:

$$u(x) = u = 1 \;, \qquad 0 < x \leq 2\ell \tag{8a}$$

$$u(x-b_i) = u_i = 0 \;, \qquad 0 \leq x < b_i \tag{8b}$$

$$= 1 \;, \qquad x \geq b_i$$

$$b_i = a + \frac{(i-1)(e-a)}{n} \tag{8c}$$

Equation (8c) gives the location of one of the (n+1) delta functions. Note also that for some analytic f(x) in the interval $(0, 2\ell)$, Eq. (8) implies that $\int_0^{2\ell} u_i f(x)\,dx = \int_{b_i}^{2\ell} f(x)\,dx$. Using Eqs. (7) and (8), $P_i(x)$, the pressure as a function of x as a consequence of the delta function located at b_i, is:

$$P_i = P_{p_i} + \frac{Q_\delta}{2k D^3 \ell}\left[(2\ell-b_i)x\,(u-u_i) + (2\ell-x)b_i u_i\right] \tag{9}$$

Using linear superposition of each pressure component, the total pressure, $P_t(x)$, is given by $P_t(x) \approx \sum_{i=1}^{n+1} P_i(x)$, or

$$P_t(x) \approx P_p + \frac{Q_p}{2k D^3 \ell\,(n+1)}\Big[\Big(2\ell(n+1) - (b_1+b_2+\ldots+b_{n+1})\Big)\,x u +$$

$$2\ell\,\Big((b_1u_1+b_2u_2+\ldots+b_{n+1}u_{n+1}) - x(u_1+u_2+\ldots+u_{n+1})\Big)\Big] \tag{10}$$

The exact expression for average pressure is then:

$$P_{av} = \lim_{n\to\infty} \frac{1}{2\ell}\int_0^{2\ell} \sum_{i=1}^{n+1} P_i(x)\,dx \tag{11}$$

which is:

$$P_{av} = P_p + \frac{Q_p}{4k D^3 \ell}\left[\ell(e+a) - \frac{1}{3}(e^2+a^2+ea)\right] \tag{12}$$

Analytic Expression for Pressures

Where on the one hand particle beam physicists may be primarily interested in average pressure values, on the other hand there may be those interested in pressure values at specific locations. For example, should an rf cavity exist somewhere in interval $(0, 2\ell)$, would there be problems of electrical breakdown? For this reason analytic expressions of P(x) for a "square wave" outgassing function similar to that shown in Fig. 3 were developed. These expressions were derived using the long tube formula and equations similar to Eq. (5) for appropriate intervals. Due to the lengthy development only the results will be given, which are:

$$P(x) = P_p \left[1 + \frac{S_p}{kD^3(e-a)} (c-a)x \right] , \qquad 0 \le x \le a \qquad (13a)$$

$$P(x) = P_p \left[1 + \frac{S_p}{2kD^3(e-a)} (2cx - x^2 - a^2) \right] , \qquad a \le x \le c \qquad (13b)$$

$$P(x) = P_p \left[1 + \frac{S_p}{2kD^3(e-a)} \left((2c-x)\,x - e^2 + 4\ell(e-c) \right) \right] , \qquad c \le x \le e \qquad (13c)$$

$$P(x) = P_p \left[1 + \frac{S_p}{kD^3(e-a)} (e-c)\,(2\ell-x) \right] , \qquad e \le x \le 2\ell \qquad (13d)$$

The value "c" is that point at which dP(x)/dx vanishes and is given by:

$$c = \frac{(a+e)(a-e)}{4\ell} + e \qquad (14)$$

On solving for average pressure using Eq. (13), and substituting the value of "c" given by Eq. (14), one obtains the exact expression for average pressure given by Eq. (12). But Eq. (12) was derived using only the conventional long tube formula and linear superposition, both principles valid in the molecular flow region. Therefore, though obtaining Eq. (12) on integrating Eq. (13) does not constitute a rigorous proof of Eq. (13), it does provide more confidence in its validity and in the validity of Eq. (5) used in deriving Eq. (13).

Remember that Eq. (13) does not take into account a uniform outgassing component which may exist over the entire interval $(0, 2\ell)$. Should there be such a component, Eqs. (5) and (13) must be used to find the pressure profile. Equivalents of Eqs. (6) and (12) would be added to find the average pressure in this case.

Minimizing Vacuum System Costs

Let the constant L represent the total length of one interconnecting beam drift tubing between the recirculator bending magnet loops. The problem is to determine the optimum diameter of this tubing and the distribution and size of vacuum pumps which will minimize cost while satisfying performance requirements. Assume that integer n sections of tubing are used so that $2n\ell = L$. Suppose pumps of speed $S_p/2$ are placed at the ends of the assembled tubing of length L, and pumps of speed S_p distributed at spacings of 2ℓ along the tubing. Given that $S_p P_p = Q$, then S_p in terms of ℓ is:

$$S_p = \frac{2\pi\ell q D}{P_p} \qquad (15)$$

Using Eq. (6), D is expressed in terms of ℓ as:

$$D = \ell \left(\frac{q\pi}{3k\delta P}\right)^{1/2} \qquad (16)$$

where $\delta P = (P_{av} - P_p)$. Incorporating this expression in Eq. (15) gives:

$$S_p = \left(\frac{4(\pi q)^3}{3kP_p^2\,\delta P}\right)^{1/2} \ell^2 \qquad (17)$$

Assume that sputter-ion pumps and welded stainless steel pipe are used in the above application. The cost of sputter-ion pumps is given to a close approximation by the expression $K_p \approx a_1 S_p^{5/8}$, where a_1 is a constant; tubing cost per unit length is given by $K_t \approx a_2 D$, where a_2 is a constant. Total cost of tubing and sputter ion pumps is then:

$$K_{total} = (n-1+2^{3/8})\, a_1\, S_p^{5/8} + (2n\ell)\, a_2 D \tag{18}$$

Substituting Eqs. (16) and (17) into Eq. (18), and making the approximation $n \approx (n-1+2^{3/8})$ for large n, Eq. (18) reduces to:

$$K_{total} \approx c_1\, L \left[\frac{q^{3/2}}{(k\delta P)^{1/2}\, P_p}\right]^{5/8} \ell^{1/4} + c_2\, L \left(\frac{q}{k\delta P}\right)^{1/2} \ell \tag{19}$$

where c_1 and c_2 are constants determined by market situations. Equation (19) suggests that the greatest economy is achieved by the smallest spacing possible between pumps. However, D must be large enough to permit unobstructed passage of the particle beam. And in that $\ell \propto D$, the value of D imposes the lower limit on system cost.

Meeting Vacuum System Performance Requirements

Vacuum "system constants" including P_{av}, P_p, and "q" must be established. A value of $q \approx 5 \times 10^{-12}$ Torr liters/sec-cm^2 (at 40° C) is well within the state-of-the-art for properly cleaned and baked stainless steel.[5,6] Due to a number of considerations, P_{av} was set at 5×10^{-7} Torr. To assure extended life and ease of restarting, $P_p = 1 \times 10^{-7}$ Torr was chosen. Using these vacuum system constants or others as may be appropriate, one may then select one of the three variables S_p, D, or ℓ, and using Eqs. (8) and (9) solve for the required values of the other two variables. For example, suppose accelerator beam phase space considerations dictate the use of a beam drift tubing with D = 1 cm. Using Eq. (16) one may solve for ℓ, and with Eq. (17) find the value of S_p.

Table I shows how tubing diameter and spacing between pumps varies as a function of pump speed for given system constants. Results, in terms of the large spacing between pumps, is somewhat surprising.

Experimental Procedure and Results

The design of the recirculating accelerator required the use of a beam drift tube with an inside diameter of 5 - 6 cm. Using Table 1, for D = 5.79 cm, and the given values of P_p, P_{av}, and "q", it is seen that 10 L/sec pumps will be required at intervals of 111 meters. Each sector of the present SLAC accelerator is 100 meters in length.[7] This length was therefore considered a more logical interval between pumps.

The objective then became one of determining the pressure profile in a stainless steel tubing ~ 5.7 cm inside diameter, 50 m in length, and pumped on one end with a small ion pump of known speed. A test apparatus was assembled similar to that shown schematically in Fig. 4. Such a configuration was chosen to minimize problems of gauge pumping, and relative gauge calibration.

The roughing system consists of a reciprocating welded bellows pump used in conjunction with a small sorption pump.[8] A 100 L/sec ion pump was used for final roughing and during bakeout. A schematic representation of the throughput measuring instrumentation and calibrated quadrupole gas analyzer[9] is shown in Fig. 5. Photographs of the assembled system are shown in Figs. 6 and 7. The system was "all metal" in the accepted sense of the word. The test manifold, steamed cleaned[10] prior to final assembly welding, is 304 stainless steel welded pipe. Excluding the 50 m of tubing, the entire high vacuum system was baked at 300° C for an extended period. The 50 m of tubing was baked at ~ 200° C for 100 hours.

Both "rate-of-pressure-rise" and "known conductance" methods were used to determine outgassing rates. With the 50 m of tubing unbaked, discrepancies of as much as 2 orders of magnitude existed between outgassing rates indicated by the two methods; the "rate-of-rise" method in this case always gave results lower than indicated by the known conductance method. Subsequent to baking there was close agreement between the two methods. The "known conductance" method was used as the more reliable of the two methods for finding "q". Linearity of the system configuration (including 18 elbows) was verified by introducing both hydrogen and nitrogen through the variable leak V_6 shown in Fig. 4.

Table II lists the theoretical normalized partial pressure profiles to be expected for the gases H_2, H_2O, CO, and CO_2 at a temperature of 20° C. These values are based on the small ion pump having speeds for hydrogen as measured at SLAC,[11] and roughly comparable speeds for the other gases.

Table III is a composite of pressure profiles observed at various times throughout the experiment. The numbers in parenthesis under each entry represent the theoretical values which should be indicated using Eq. (5) while taking into account the conductances for the various species, and temperature of the tubing, but not allowing for possible error in assumed values of pump speed. The first entry in Table 3 is data taken after ~ 500 hours of pumping at room temperature. The outgassing rate was asymptotic with time at this point for constant temperature. However a 5° C change in room temperature would result in a change of a factor of 2 in outgassing at this time. At ~ 27° C, partial pressures of the mass species 2, 18, 28, and 44 appeared in the approximate proportions 1.0 : 1.5 : 0.5 : 0.3 respectively. The total outgassing rate at this time was $q \sim 2.5\ 10^{-11}$ Torr L/sec-cm^2.

The temperature of the system was increased to $\sim 35^{\circ}$ C and held there for ~ 160 hours at which time outgassing became asymptotic in time and $q \sim 8.3 \times 10^{-11}$ Torr L/sec-cm^2. The temperature was gradually increased to 100° C over a period of 5 days and the next data taken at this temperature. The system was then cooled to room temperature and data were taken. The system was then baked at $\sim 200^{\circ}$ C for 100 hours. After cooling data were then taken at room temperature and subsequently higher temperatures as listed in Table III.

Normalized theoretical pressure profiles for the various gases in Table II are based on assumed pump speeds for these gases. On manipulating Eq. (5), the ratio $P(x)/P_p$ is found to be:

$$\frac{P(x)}{P_p} = \left[1 + \frac{S_p}{2k\,D^3 \ell}\,(2x\ell - x^2)\right] \qquad (20)$$

where S_p is the effective pump speed at the end of the 50 meters of tubing. From Eq. (20) it is seen that errors resulting from the value chosen for S_p are amplified parabolically, and may become appreciable for large x.

A second area of possible discrepancy is the effect of pressure on outgassing rate. This effect was determined by first measuring outgassing rate with only valves V_1 and V_{10} open, and subsequently with valves V_2 through V_5 also open. The increase in outgassing as a consequence of also opening valves V_2 through V_5 was always on the order of 10 - 20% of the initial outgassing rate. If one were to use Eq. (6) for both of the above experimental configurations, assume $S_p \sim 6$L/sec and constant, a change in average pressure of 4X is required to result in a 20% change in outgassing rate.

Conclusion

An equation has been derived for pressure in a long uniformly outgassing tubing pumped at each end (Eq. (5)). This equation was found to be in good agreement with experimental evidence. It was shown, using Eq. (5), that minimum cost of periodically pumped systems is achieved by use of the smallest possible pumps spaced at the smallest possible interval. Uniform outgassing equations were then extended to include cases of nonuniform outgassing in a long tube (Eqs. (12) and (13)).

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TABLE I

Accelerator beam drift tube inside diameter and length between vacuum pumps as a function of pump speed assuming $P_{av} = 5 \times 10^{-7}$ Torr, $P_p = 1 \times 10^{-7}$ Torr and $q = 5 \times 10^{-12}$ Torr liters/sec-cm^2.

Pump Speed (liters per second)	Tubing Inside Diameter (centimeters)	Length of Tubing Between Pumps (meters)
0.5 (S_p)	1.29 (D)	24.7 (2ℓ)
5	4.09	78.3
10	5.79	111
50	13.0	247
100	18.3	350

TABLE II

Theoretical normalized pressure profile along tubing for various gas species at 20° C.

Mass Number	Normalized Pressure as a Function of Distance Along Tubing				
	$x = 0$	$x = 0.2\ell$	$x = 0.4\ell$	$x = 0.6\ell$	$x = \ell$
2	1.00	1.80	2.40	2.85	3.20
18	1.00	2.10	2.95	3.6	4.05
28	1.00	2.20	3.10	3.80	4.25
44	1.00	2.30	3.35	4.05	4.55

TABLE III

Indicated total pressure profile along a uniformly outgassing tubing fifty meters long and pumped on one end.

Elapsed Time of Experiment hours	System Temperature ^{o}C	Indicated Total Pressure — Torr (Bayard-Alpert Gauge)					Gas Species Proportion				q - Total
		x = 0	x = 0.2 ℓ	x = 0.4 ℓ	x = 0.6 ℓ	x = ℓ	Mass 2	Mass 18	Mass 28	Mass 44	Torr L/sec-cm^2
500	27	4.3×10^{-7}	9.68×10^{-7} (9.0×10^{-7})*	1.55×10^{-6} (1.3×10^{-6})	1.95×10^{-6} (1.5×10^{-6})	2.35×10^{-6} (2.0×10^{-6})	1	1.5	0.5	0.3	2.5×10^{-11}
600	35	4.52×10^{-6}	9.41×10^{-6}	1.58×10^{-5}	1.81×10^{-5}	2.05×10^{-5}	No Data				
760	35	1.17×10^{-6}	2.44×10^{-6} (2.5×10^{-6})	3.60×10^{-6} (3.4×10^{-6})	4.49×10^{-6} (4.2×10^{-6})	5.39×10^{-6} (4.7×10^{-6})	1	5.0	0.4	0.3	8.3×10^{-11}
910	100	3.85×10^{-5}	7.0×10^{-5}	8.8×10^{-5}	1.05×10^{-4}	1.15×10^{-4}	No Data				
1100	23	5.18×10^{-8}	9.55×10^{-8} (9.4×10^{-8})	1.48×10^{-7} (1.2×10^{-7})	1.81×10^{-7} (1.5×10^{-7})	2.0×10^{-7} (1.7×10^{-7})	1	0.041	0.045	0.008	8.2×10^{-12}
System Baked at 200^{o} C for 100 Hours											
1410	23	3.5×10^{-8}	5.64×10^{-8} (6.3×10^{-8})	7.35×10^{-8} (8.4×10^{-8})	8.4×10^{-8} (1.0×10^{-7})	8.9×10^{-8} (1.2×10^{-7})	1	0.03	0.07	0.02	5.5×10^{-12}
1450	42	1.5×10^{-7}	2.58×10^{-7} (2.7×10^{-7})	3.38×10^{-7} (3.5×10^{-7})	3.85×10^{-7} (4.2×10^{-7})	4.15×10^{-7} (4.7×10^{-7})	1	0.02	0.02	0.01	2.3×10^{-11}
1480	90	7.3×10^{-7}	1.32×10^{-6} (1.3×10^{-6})	1.72×10^{-6} (1.7×10^{-6})	2.0×10^{-6} (1.9×10^{-6})	2.15×10^{-6} (2.1×10^{-6})	1	0.01	0.01	0.005	1.15×10^{-10}
1500	120	2.98×10^{-6}	5.62×10^{-6} (5.1×10^{-6})	7.6×10^{-6} (6.6×10^{-6})	8.92×10^{-6} (7.8×10^{-6})	9.7×10^{-6} (8.7×10^{-6})	1	0.007	0.004	0.001	4.6×10^{-10}

*Values in parenthesis theoretically predicted.

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1. Schematic layout of the recirculating linear accelerator.

2. Pressure distribution in a long uniformly outgassing manifold pumped on one end.

3. Pressure and nonuniform outgassing functions appearing between pumps separated a distance 2ℓ.

4. Schematic representation of vacuum system configuration used in evaluating outgassing calculations.

5. Schematic representation of throughput measuring instrumentation.

6. Vacuum test apparatus.

7. Vacuum test apparatus.

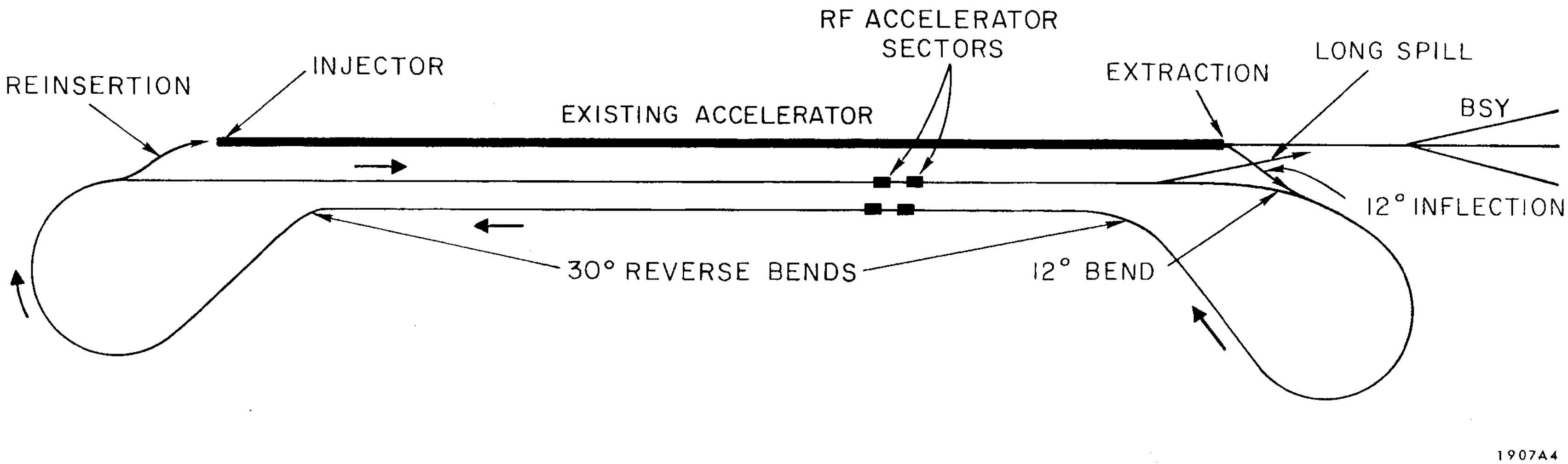
RF ACCELERATOR
SECTORS
INJECTOR
REINSERTION
EXTRACTION
LONG SPILL
BSY
EXISTING ACCELERATOR
12° INFLECTION
30° REVERSE BENDS
12° BEND
1907A4

Fig. 1

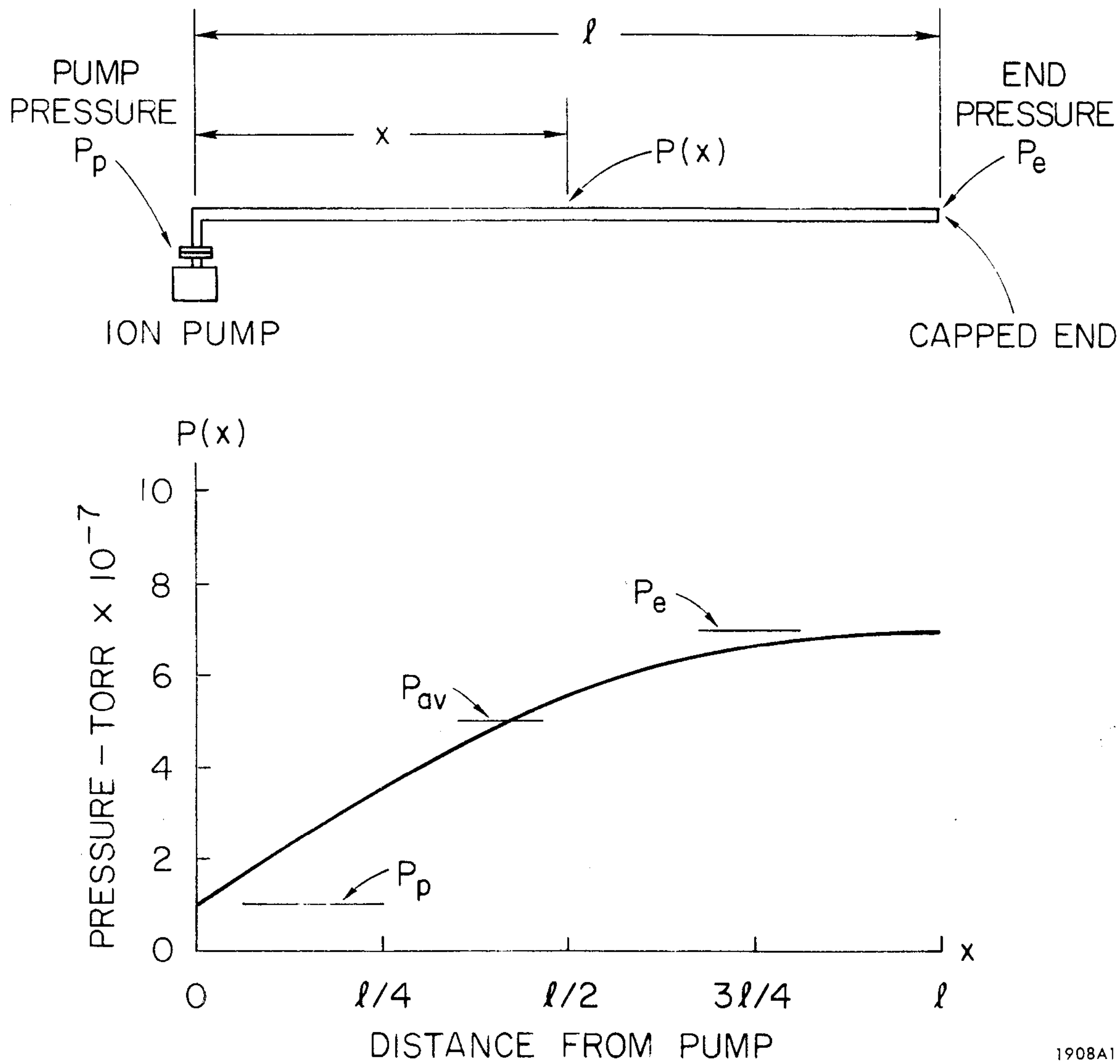
ℓ
PUMP PRESSURE P_p
x
P(x)
END PRESSURE P_e
ION PUMP
CAPPED END
P(x)
PRESSURE - TORR × 10^{-7}
10
8
6
4
2
0
P_e
P_{av}
P_p
x
0
ℓ/4
ℓ/2
3ℓ/4
ℓ
DISTANCE FROM PUMP
1908A1

Fig. 2

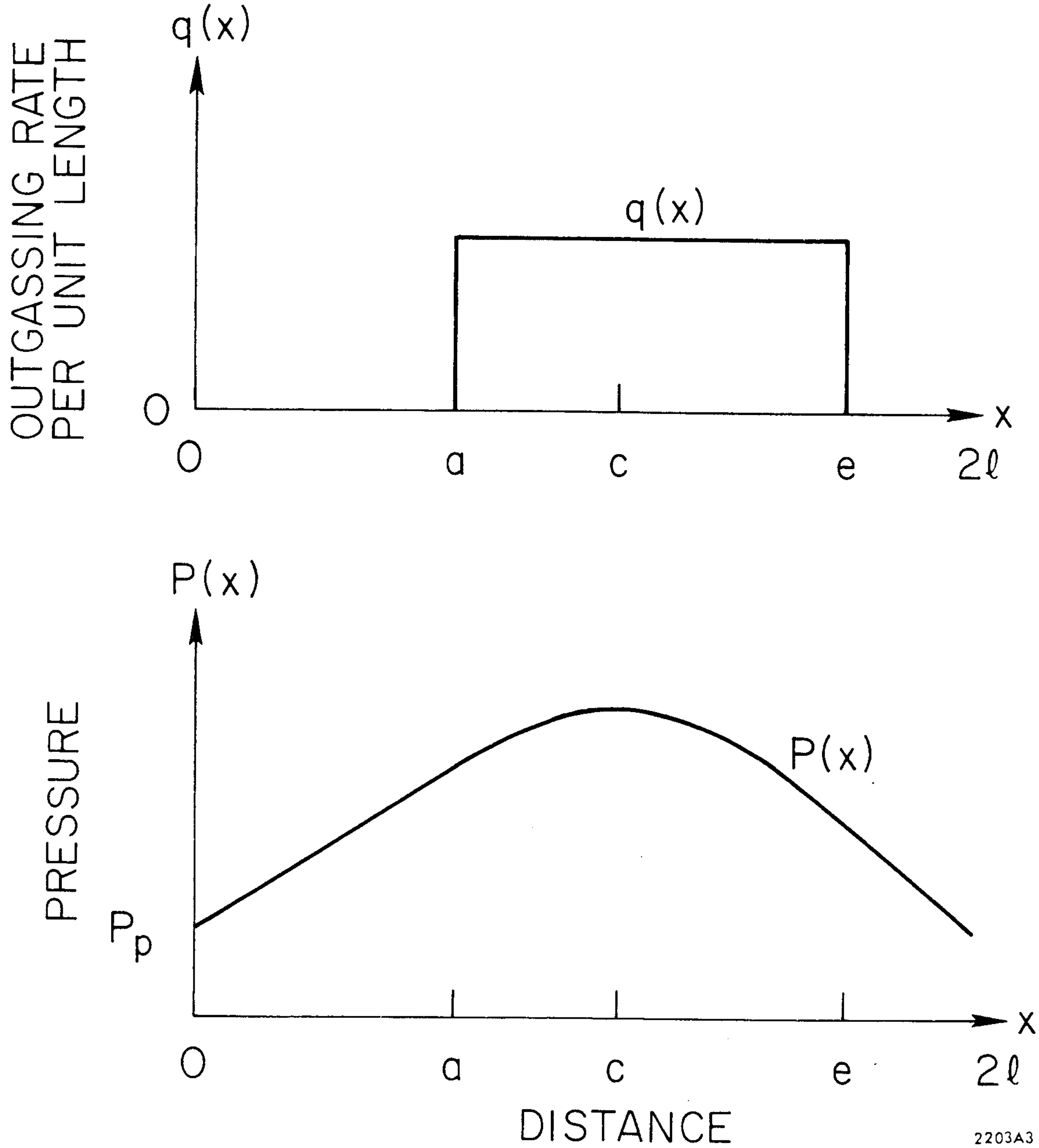
q(x)
OUTGASSING RATE
PER UNIT LENGTH
q(x)
0
x
0
a
c
e
2ℓ
P(x)
PRESSURE
P(x)
P_p
x
0
a
c
e
2ℓ
DISTANCE
2203A3

Fig. 3

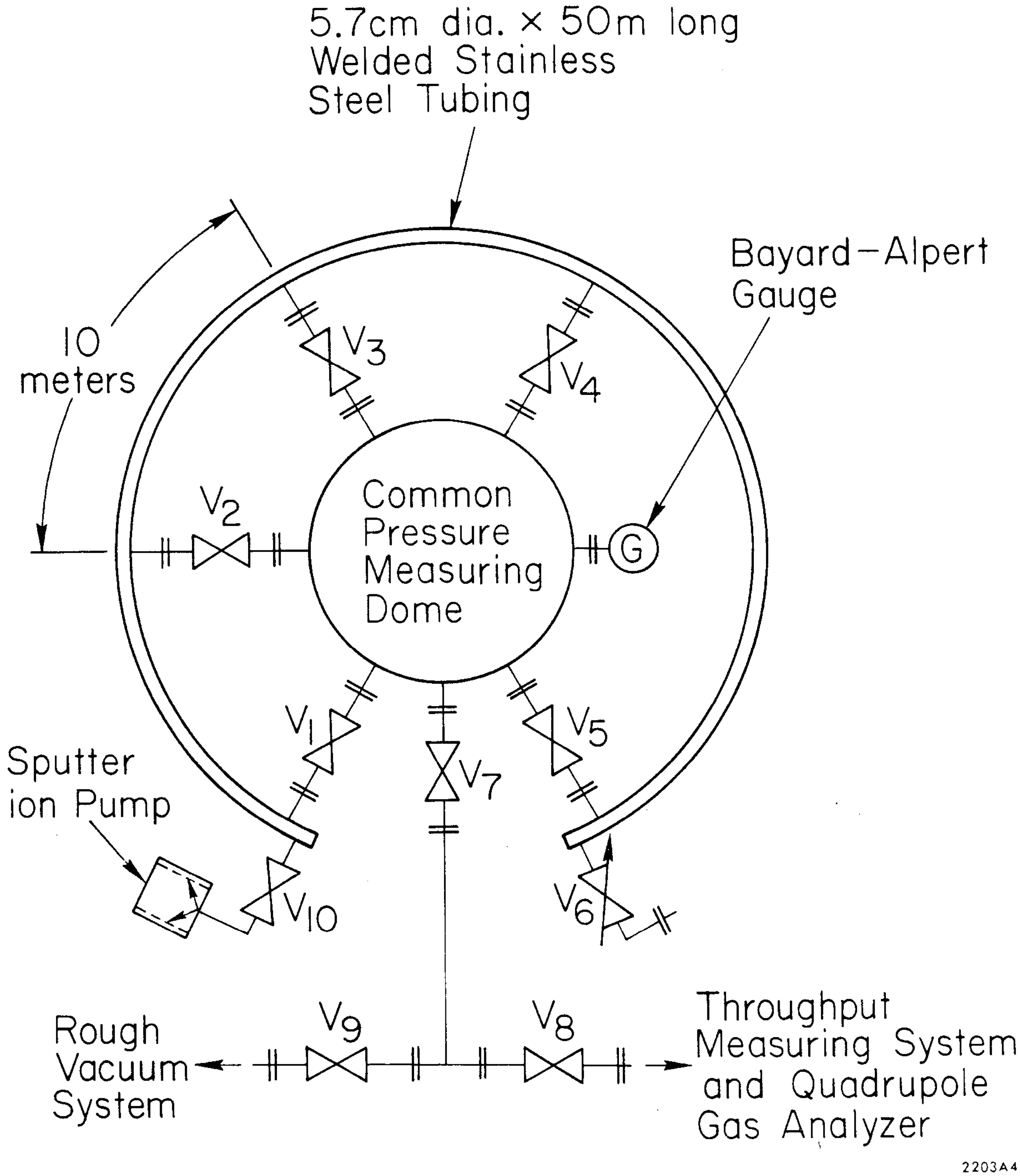
5.7cm dia. × 50m long
Welded Stainless
Steel Tubing
Bayard–Alpert
Gauge
10
meters
V3
V4
V2
Common
Pressure
Measuring
Dome
G
V1
V7
V5
Sputter
ion Pump
V10
V6
Rough
Vacuum
System
V9
V8
Throughput
Measuring System
and Quadrupole
Gas Analyzer
2203A4

Fig. 4

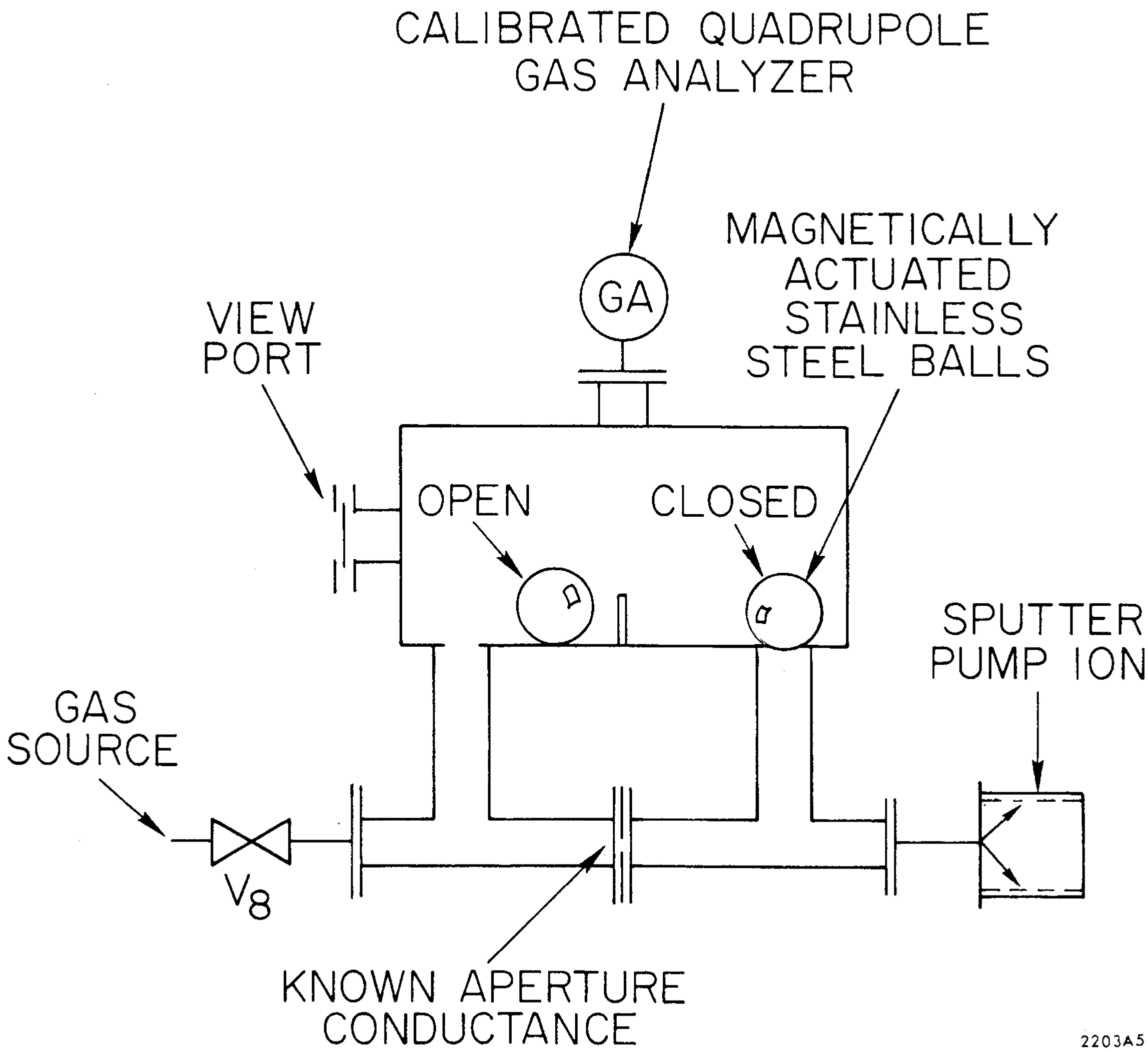
CALIBRATED QUADRUPOLE
GAS ANALYZER
GA
MAGNETICALLY
ACTUATED
STAINLESS
STEEL BALLS
VIEW
PORT
OPEN
CLOSED
SPUTTER
PUMP ION
GAS
SOURCE
V8
KNOWN APERTURE
CONDUCTANCE
2203A5

Fig. 5