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Subject An analogue study of vacuum requirements on Beam Line IV		

1. Introduction

This report presents the results of a study of the vacuum requirements for the Proton Area Beam Lines. Results quoted here were obtained from an electrical network set up to simulate the vacuum system. A description of the analogue network is given.

An analogue roughly equivalent to Beam Line I was also studied. The results of the investigation are quoted in this report.

The concluding section of the report lists several recommendations for the standardization of vacuum components along Beam Line IV.

2. Electrical analogies to vacuum components

2.1 Ohm's law for a vacuum circuit

The existence of a pressure difference between two points in a vacuum system causes gas to flow from the high pressure region to the low pressure region. The rate of gas flow depends on the the impedance of the system between the points in question. Thus one has

$$\Delta p \;=\; Z\,\Delta q$$

where Δp is the pressure difference, Z is the impedance of the system and Δq is the amount of gas flow.

In vacuum work it is more usual to talk in terms of the *conductance* of a component. The conductance C is defined as the reciprocal of the impedance. Thus the usual form of Ohm's law for a vacuum system is

$$\Delta p \;=\; \frac{\Delta q}{C} \;=\; Z\,\Delta q \qquad (1)$$

where $C = Z^{-1}$ is the conductance.

2.2 Relationship of electrical parameters to vacuum parameters

Ohm's law for a (DC) circuit is well known as

$$\Delta V \;=\; R\,\Delta I \qquad (2)$$

where ΔV is the potential drop across a resistance R. This potential difference causes a current ΔI to flow through the resistor. From a comparison of equations (1) and (2) it is immediately seen that

1. a potential difference in an electrical system corresponds to a pressure difference in a vacuum system.
2. a current flow in an electrical system corresponds to a gas flow in a vacuum system.
3. a resistance in an electrical system corresponds to the impedance (or inverse conductance) in a vacuum system.

These correspondences, together with their appropriate units are listed in the following table.

Vacuum system		Electrical system	
Δp	Torr	ΔV	Volts
Δq	Torr-litres/sec	ΔI	Amperes = Coulombs/sec
$Z = 1/C$	litres/sec	R	Ohms

2.3 Electrical representation of vacuum components

In view of the sections above one can now define how various vacuum elements can be represented. Outgassing of the vacuum system is represented by the injection of current into the electrical analogue. Impedance of the vacuum system is represented by resistance in the electrical circuit. Pressures within a vacuum system are represented by voltages along the electrical network.

In addition, vacuum pumps must be represented. At high vacua the speeds of pumps are almost constant with pressure. Consequently, the pressure differential across a pump Δp determines its throughput ΔQ. If the pump speed is S then

$$\Delta p = \frac{\Delta Q}{S}$$

Hence in the electrical analogue the reciprocal of pump speed is represented by a resistor.

3. Design of an electrical analogue

3.1 General considerations fo vacuum design

This study considers gas loading due to vacuum system outgassing *only*. Implicit in the 'vacuum system' is gas loading presented by any magnet boxes along the line. Gas loads resulting from outgassing of the magnet box of the combination magnet are, however, *excluded*. It is assumed that such loading is carried by the main (cyclotron) vacuum system.

For this study the main concern has been to limit gas flow from the beam line into the vacuum system of the cyclotron. In the conceptual design for a vacuum system for Beam Line I [1)] this has been done using a differential pumping technique coupled with apertures within the beam line. On Beam Line IV, however, the size of the extracted beam does not allow the use of such apertures. Consequently, in the data presented in this report no apertures have been used.

In this study the following quantities were considered fundamental. These values are taken from ref [1)]. Item 4 is specifically added in this report.

1. Allowed gas flow into the cyclotron $\leq$ 8×10^{-7} Torr-litres/sec.
2. Cyclotron base pressure 5×10^{-8} Torr.
3. Outgassing rate per foot of 4 in. diameter stainless steel tubing 1×10^{-6} Torr-litres/sec.
4. No apertures allowed.

It should be noted that the outgassing rate of stainless steel tubing quoted above is conservative. This rate can be lowered by at least a factor of 100 by proper treatment of the steel [2)].

3.2 The basic electrical network

Figure 1(a) indicates a unit of the electrical system that represents a unit length of beam line.

The transistor is used to inject constant current at the midpoint of the unit. The magnitude of the injected current depends on the voltage across the emitter resistor of the constant current source and the values of the resistors representing the impedance of the vacuum circuit depend on its conductance.

By changing the value of the emitter resistor and holding the emitter-base voltage constant, a different current is injected into the system. Similarly, the impedance of the vacuum circuit can be changed. Figure 1(b) indicates the representation of a vacuum box in this study. The 'horn' marks a transition region from the beam line to the magnet box.

3.3 Choice of electrical parameters

The choice of parameters in the electrical analogue depends on the range over which one expects variation of the pressure in the vacuum system and on available components. In this case a pressure variation from 5×10^{-8} Torr to $\approx 10^{-5}$ Torr is anticipated. Thus a dynamic range $\geq 2 \times 10^{2}$ is required. Also, a 20 volt power supply was readily available.

Arbitrarily, it was decided to choose one foot as the unit of length and to set the

$$\begin{array}{lclcl} \text{outgas rate per foot of 4 in. diameter stainless steel tube} & = & 10^{-6}\ \text{Torr-litres/sec} & = & 14\ \mu\text{A} \\ \text{and} & & & & \\ \text{impedance of one foot of 4 in. diameter stainless steel tube} & = & 1/300\ \text{litres/sec} & = & 200\ \Omega. \end{array}$$

Thus the emitter resistors are 100 kΩ for 1 1.5 volt drop across them and the resistors representing the line impedance are each 100 Ω.

Using the allowable leak rate into the cyclotron the allowable pressure differential across the first foot of beam line is

$$\Delta p \;=\; \frac{\Delta Q}{c} \;=\; \frac{8 \times 10^{-7}}{300} \;=\; \frac{8}{3} \times 10^{-9}\ \text{Torr}.$$

Thus the allowable potential increment across the first unit of the electrical analogue is

$$\begin{aligned} \Delta V &= (\Delta I)\, R \\ &= \left[\frac{15 \times 10^{-6} A}{10^{-6}\ \text{Torr-litres/sec}} \times (8 \times 10^{-7}\ \text{Torr-litres/sec})\right] (200\ \Omega) \\ &= 2.4\ \text{mV}. \end{aligned}$$

The cyclotron pressure of 5×10^{-8} becomes

$$V_0 \;=\; (2.4\ \text{mV}) \times \left[\frac{3}{8 \times 10^{-9}\ \text{Torr}}\right] \times (5 \times 10^{-8}\ \text{Torr}) \;=\; 45\ \text{mV}.$$

For the sake of simplicity the magnet boxes for the 35° and 25° magnets have been taken as one large rectangular box 40 cm wide by 10 cm high by 305 cm long. The outgassing rate per foot of magnet box is then

$$q \;=\; 10^{-6}\, \frac{\text{Torr-litres}}{\text{sec-ft}} \times \frac{2(40+10)}{30.5} \approx 3(\text{outgassing rate per foot of beam line}).$$

Thus the outgassing load is represented by using a 33 kΩ resistor in the emitter lead of each transistor.

The conductance of the so-formed rectangular duct was calculated from the relation [3)]

$$C = \frac{60\,A^2}{U\,L}\,G_2$$

where A id the cross-sectional area, U is the perimeter and L is the length of the duct. G_2 is a factor that depends on the ratio of the short side of the duct to its long side and is tabulated in ref [3)]. Putting in the appropriate numbers one finds

$$C(\text{per foot of box}) \approx 4(\text{conductance per foot of beam line})$$

Thus the resistor corresponding to one foot of magnet box has a value of $(200\ \Omega)/4 = 50\ \Omega$ and, because two resistors per foot are used, each resistor has a value of $\approx 25\ \Omega$.

At the entrance and exit of the duct a one-foot long 'horn' was added to represent the transition from the beam line to the vacuum box. These horns were assumed to mate a 4 in. diameter tube to an 8 in. opening in the magnet box. The conductance value of a 6 in. diameter tube [$\approx$3(conductance of one foot of 4 in. diameter tube)] and an outgassing rate twice that of a unit length of 4 in. diameter tube were used. Thus emitter resistors become 47 kΩ and line resistors become $[(300/3)/2] \approx 47\ \Omega$.

When only a single bending magnet occurred in the system, a magnet box equivalent to 5 feet in length with a horn on each end was used.

3.4 Representation of the beam line

The entire beam line is built up of a series of units as indicated in figure 1(a). Magnet boxes of the appropriate length (as indicated in figure 1(b)) are inserted at the appropriate places.

Vacuum pumps are represented as resistors connected between beam line and ground. Such a configuration is shown in figure 2.

4. Procedure and results

4.1 General procedure

One realizes that the best procedure is to pump as close to the cyclotron exit as possible. Consequently, one pump was fixed approximately 4.5 feet from the exit of the combination magnet. Physically this places the pump midway between the first two quadrupoles of the beam line. Pump placement immediately downstream of the combination magnet exit would be ideal. However, it is planned to locate a manual valve at this point in order to be able to isolate completely the beam line from the cyclotron. The position chosen for the pump is the next best alternative.

All bias voltages are set appropriately and the voltage variation as a function of distance along the line is observed. Additional pumps ca be moved about on the line so as to optimize their positions. Optimum pump speeds can be determined by simply changing the values of the resistors.

4.2 Pressure distribution along Beam Lines IV-A and IV-B

The entire vacuum system up to the first target location on each of Beam Lines IV-A and IV-B was simulated in one-foot increments as described above. Beam Line IV-A was joined to the vault and Beam Line IV-B systems at the center of the magnet box of the 35° and 25° magnets.

Procedures outlined in § 4.1 above were followed for two variations of gas loading. The first approach was to 'blank off' each of the beam lines at their first target position. Electrically this is done by letting the 'target ends' of the beam line float free.

A second approach was an attempt to simulate a 'bad' condition. Her the entire gas load of an additional 100 feet of beam line was lumped and injected at each 'target' position on each line. The aim of this approach was to observe the effect on backstreaming into the cyclotron.

Results of these investigations along the vault and Beam Line IV-B vacuum systems are shown in figure 3. The results of the investigations along Beam Line IV-A to the first target position are shown in figure 4. Positions and speeds shown for the pumps have been optimized.

4.3 Pressure distribution along Beam Line IV-A from the first target position to the 10 μ beam dump

It is expected that Beam Line IV-A will be effectively blanked off on each side of the LD_2 target, that is, a window will exist on each side of the target. Consequently, the pressure distribution along this section of line was investigated assuming that pumping was done only by the pump attached to the scattering chamber. For this purpose the scattering chamber was assumed to inject a gas load of 10^{-3} T0rr-litres/sec at the position of a 240 ℓ/s pump. The gas load was calculated on the area of a 5 foot diameter by 2 feet high aluminum enclosure ($\approx$70 ft^2) and adding 30 ft^2) for additional internal equipment. An outgassing rate for aluminum ten times that for stainless steel was used to arrive at the figure quoted.

The results of this investigation are shown in figure 5.

4.4 Pressure distribution along Beam Line I

Because of the ease of modification of the electrical network and of the similarity between Beam Lines I and IV, a pressure distribution was taken along a line roughly equivalent to Beam Line I. In this analogue it was assumed that the lengths of Beam Line I and Beam Line IV are the same from the combination magnet to the entrance of the first bending magnet on either line. A 5 foot magnet box (with horns), constructed as noted above, was inserted and an additional 40 feet of beam line were added.

Various pump combinations were investigated. Two of these configurations—one using two 300 ℓ/s pumps and one using two 400 ℓ/s pumps—are shown in figure 6. In each case the pump locations on the line have been optimized.

5. Conclusions

5.1 Pumps required on Beam Line IV

This study has shown that three pumps are necessary to maintain gas flow into the cyclotron below the maximum allowed rate of 8×10^{-7} Torr-litres/sec. These pumps would be located as follows.

P–1	–	4.5 feet from the combination magnet exit with a minimum speed of 300 ℓ/s.
P–2	–	9 feet from the combination magnet exit with a minimum speed of 300 ℓ/s.
P–3	–	midway between the 35° and 25° magnets with a minimum speed of 150 ℓ/s.

It can also be concluded that no further pumping is necessary other than that which will exist at the target locations.

5.2 Pumps required on Beam Line I

The results of this study indicate that two 300 ℓ/s pumps, positioned as indicated in figure 6, could maintain acceptable flow rates into the cyclotron. However, as also indicated in that figure, two 400 ℓ/s pumps would provide a much better system.

5.3 General

The study has shown that conductance apertures are *not* required on either of Beam Lines I or IV if pumps of the capacities noted above are used.

This study has also indicated the usefulness of this model in determining pumping requirements. The analogue model is an inexpensive way to determine pressure profiles reasonably accurately. The cost of the entire model, assuming all components ($\approx$100 transistors and $\approx$50 resistors) had to be purchased, would be at most $35. A system could be set up and analyzed within 2 days.

6. Recommendations

On the basis of this work the following recommendations are made for the vacuum system for Beam Line IV.

1. Three noble-ion pumps be installed in the vault at the locations indicated in §5.1.

2. The above pumps have speeds of 400 ℓ/s, 400 ℓ/s and 200 ℓ/s respectively.

3. No pumping other than that available from target chambers be provided on the beam lines external to the vault. Should the scattering chamber on Beam Line IV-A be removed completely (that is, including its pump), the line would be kept under 'soft' vacuum by use of the roughing module suggested in ref[4].

   On Beam Line IV-B an estimate of the speed of the pumps located at target chambers was made by assuming a target chamber of the same size at that on Beam Line IV-A—5 feet in diameter by 2 feet in height. Its gas load, as calculated in §4.3, together with that of an extra 100 feet of beam line was injected at target location T1 on Beam Line IV-B. A pumping speed of 300 ℓ/s is then required at that target location to maintain a pressure of $\approx 5\times10^{-6}$ Torr. A 150 ℓ/s pump at the target does not prevent gas flow toward the cyclotron. The target chamber used for this test is, however, in all fairness, larger than that anticipated for use on Beam Line IV-B.

4. Except as noted above, the general philosophy of ref[4] be adapted. Specifically, this involves an all-metal system at least to the Proton Area side of the vault wall and, preferably, to the first target chamber on each line.

5. It is further recommended that areas of high radiation use an all-metal system. This latter remark is specifically aimed at the LD_2 target. The vacuum system should be all metal up to the entrance of the 35° clearing magnet.

6. Where an all-metal system is not used, it is recommended that all vacuum fittings be standardized to, or compatible with, the Dependex type flange.

7. All valves at experimental target locations must be mounted rigidly to the beam line. Should the target chamber be opened and/or removed, the valves must remain with the beam line.

References

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2. G. Lewin, *Fundamentals of Vacuum Science and Technology*, page 74, McGraw-Hill (1965).
3. L. Ward and J. Bunn, *Introduction to the Theory and Practice of High Vacuum Technology*, Butterworth (1967).
4. E. Cairns, J. Elliott, G. Roy and G. Stinson, *Vacuum System for Beam Line IV – Philosophy*, TRI-PNA-72-2.

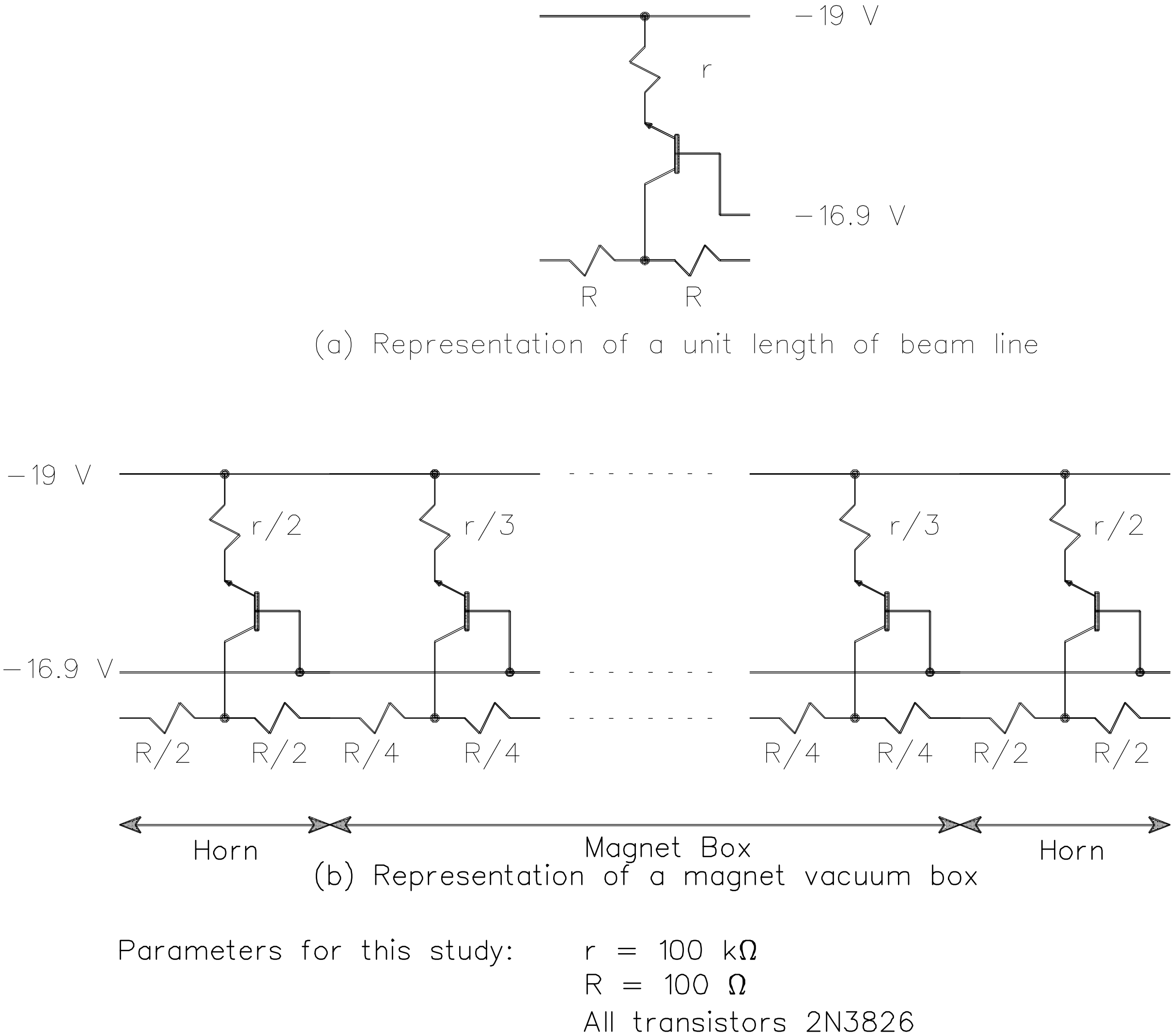
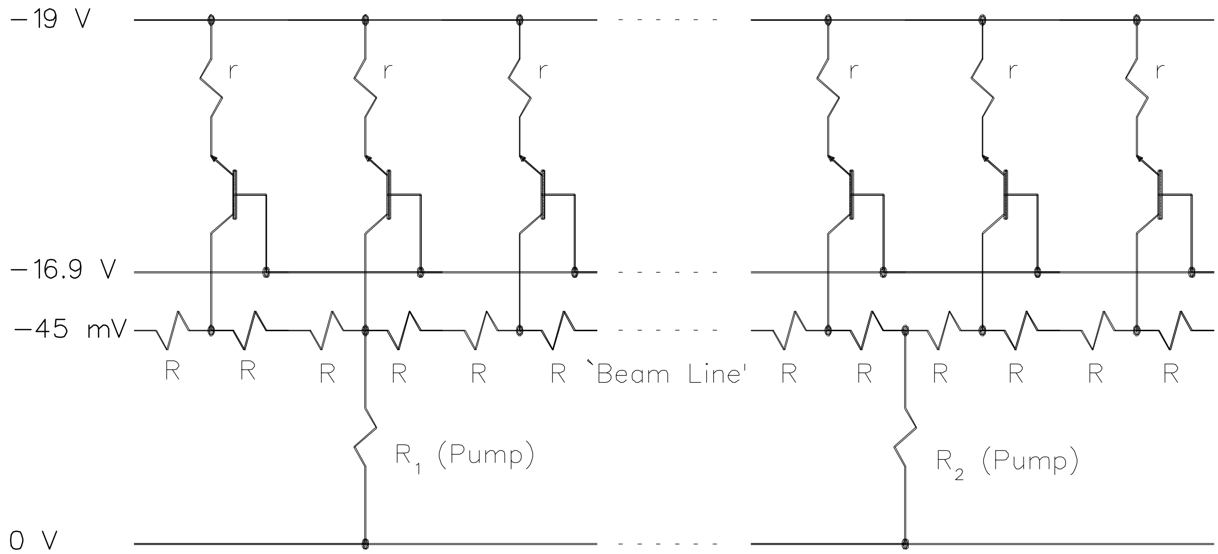


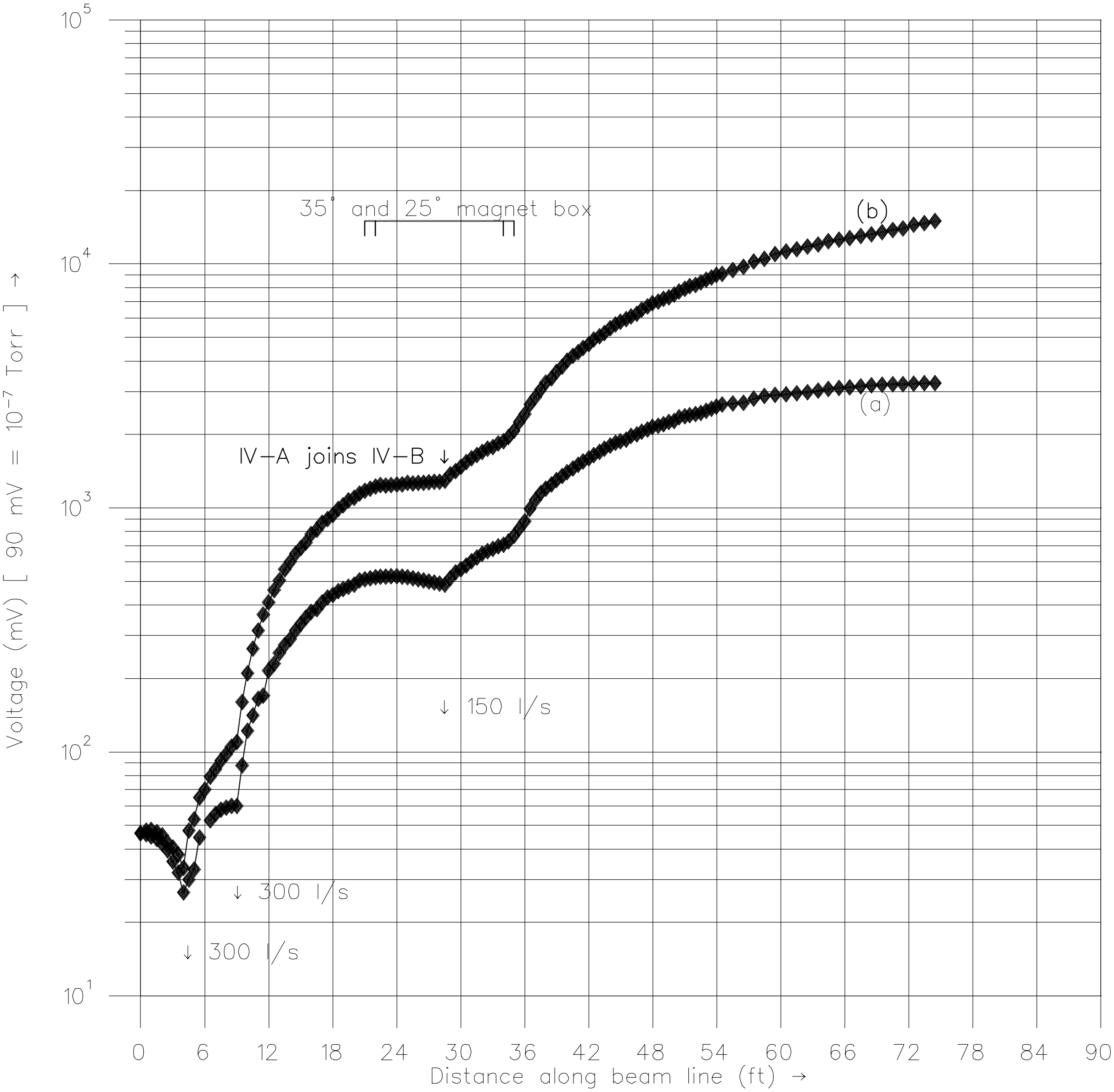
Fig. 1. Representations of the vacuum components.



The machine pressure is defined by holding the `Beam line' at 45 mV.

Parameters: r = 100 kΩ, R = 100 Ω for `Beam Line'
r = 33 kΩ, R = 22 Ω for `Horn'
r = 47 kΩ, R = 47 Ω for `Magnet Boxes'

Fig. 2. Build-up of the beam line.



Curve (a): Line blanked off at T1 on IV–B

Curve (b): Gas load of 100 extra feet injected at LD_2 on IV–A and at T1 on IV–B

Fig. 3. Pressure distribution on Beam Line IV–B.

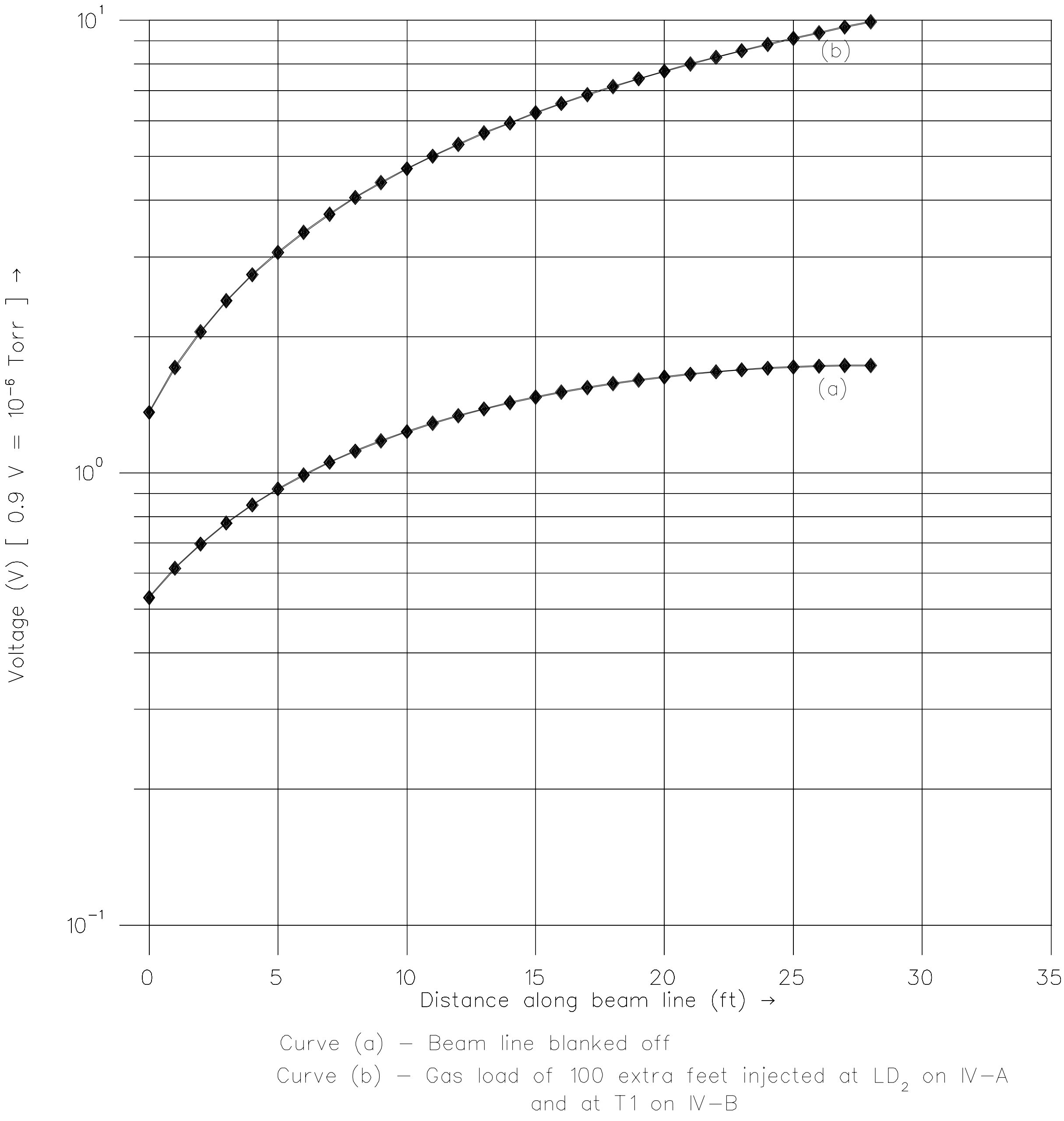


Fig. 4. Pressure distribution along Beam Line IV-A.

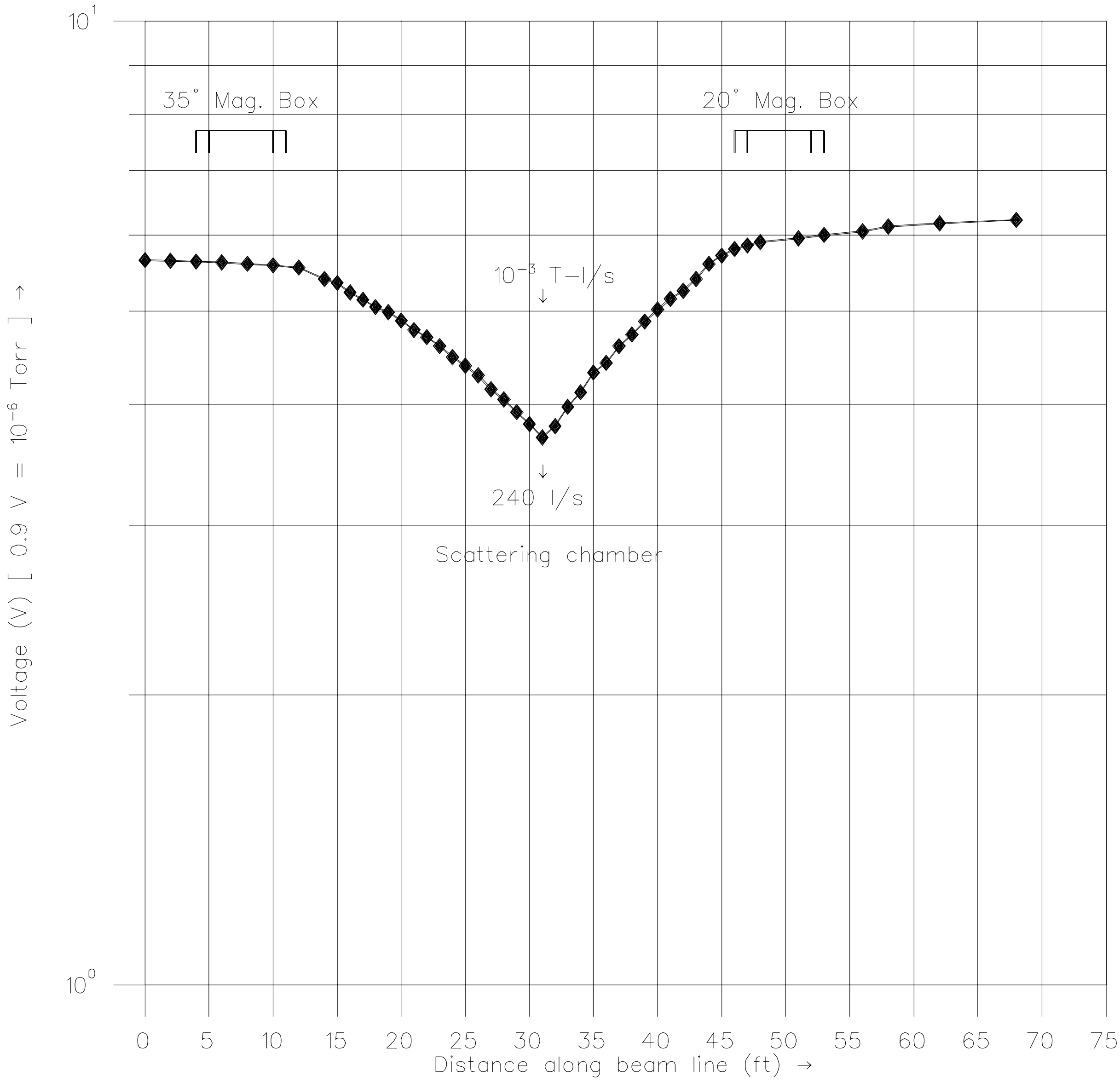


Fig. 5. Beam Line IV-A from LD_2 target to beam dump, pumping at the scattering chamber only.

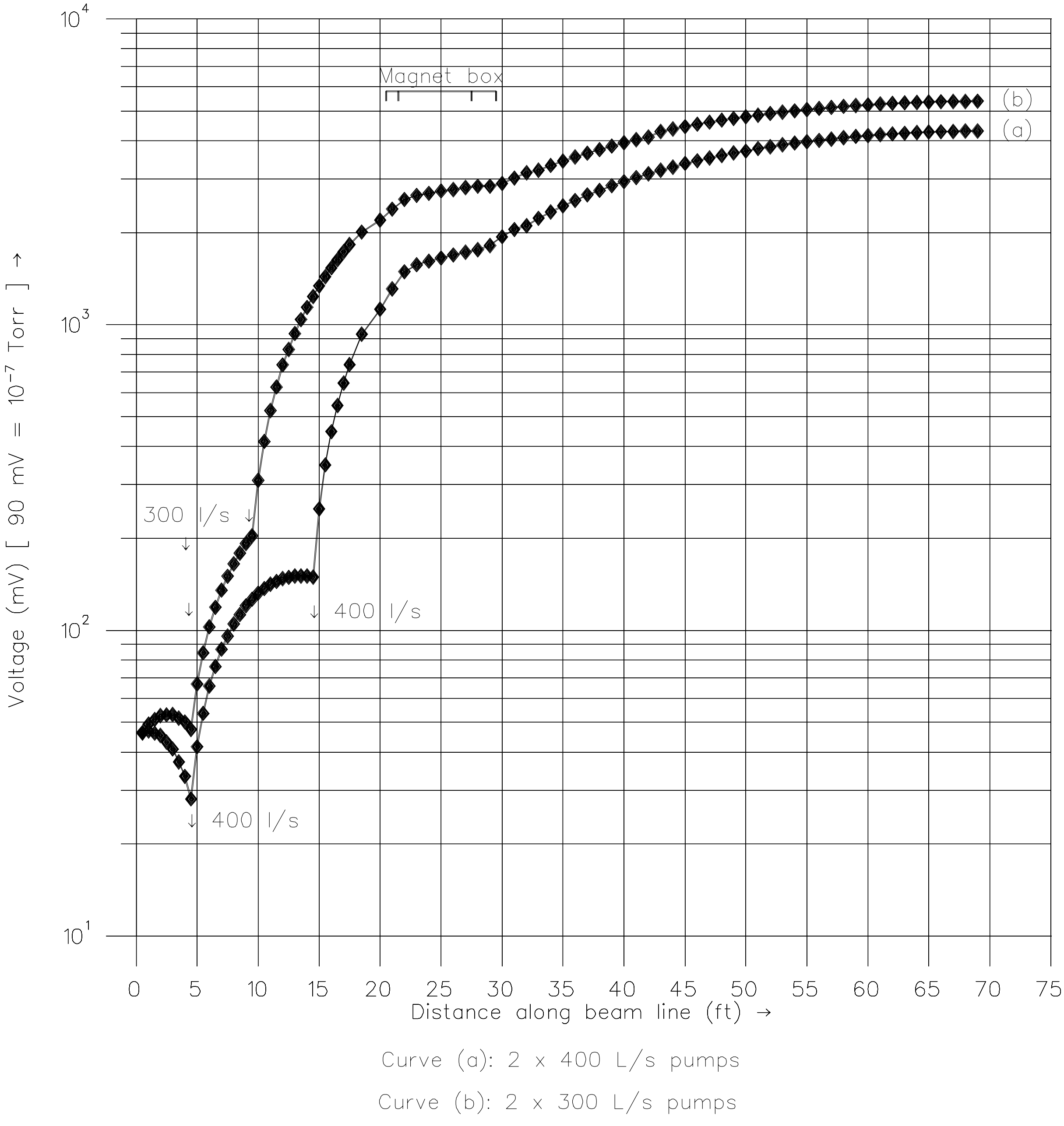


Fig. 6. Pressure distibution alng Beam Line I.