Vacuum System Design and Performance Calculations for Phase 1 of the 5 MeV Electron Cooling Test Beam Facility

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Phase 1 of the 5 MeV Electron Cooling Test Beam Facility calls for the use of a 12.351 keV kinetic energy proton beam. Within phase 1 there are 3 sub-phases which are envisioned. The final vacuum system envisioned used during sub-phase 1.3 is sketched in figure 1. During sub-phase 1.1 only the proton gun and the first 20' of 6" O.D. vacuum pipe is installed. During sub-phase 1.2 the pipe is extended by an additional 20'.

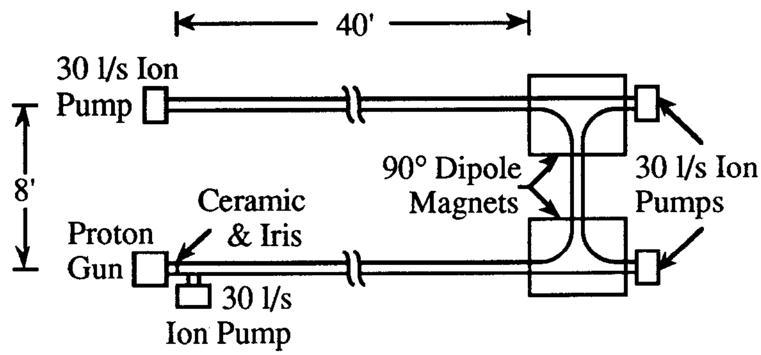

Figure 1: Sketch of the final vacuum system envisioned in phase 1 of the 5 MeV Eletron Cooling Test Beam Facility.

At the proton gun an iris is required after the ceramic holding off the 12 keV potential. This iris is used to set the emittance and to turn down the intensity from the gun to a current of less than 1 μA. In order to assure sufficient conductance across this iris, it has a diameter of 4" in the 6" O.D. vacuum pipe. Figures 2 and 3 contain sketches of the proposed vacuum chamber and iris geometry at the interface with the ceramic tube. The iris is moveable so as to tune the emittance of the beam it passes. The 2-1/2" side tube connected to the ion pump is 12" downstream of the vacuum chamber interface with the ceramic tube.

In sub-phases 1.1 and 1.2, the dipoles shown in figure 1 are not yet installed. During these phases a 6" diameter blank is used to terminate the beam chamber. Into this blank a 2-1/2" round section of tubing is used for pumping, roughing, and instrumentation signal feedthrougths. A sketch of this construct is shown in figure 4.

During operations there will be a crawling wire diagnostic cart which will move up and down inside the vacuum chamber. Because of the fact that it will represent a fairly low conductance obstruction from the point of view of vacuum, it will be necessary to calculate the pressure as a function of the cart. For the sake of ascertaining a worst-case result, it will be assumed that the cart is a complete vacuum restriction.

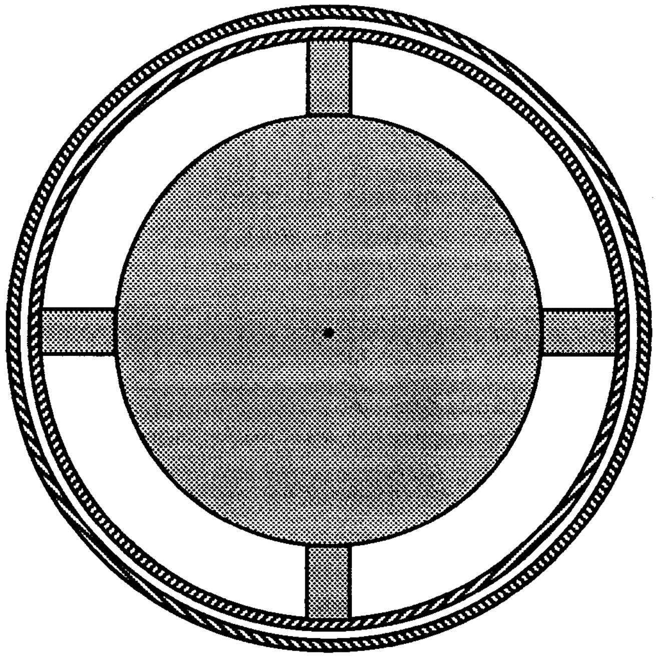

Figure 2: Beam eye view of the proton gun iris which is at ground potential with respect to the gun. Calculations of the iris diameter indicate a radius of approximately 1 mil.

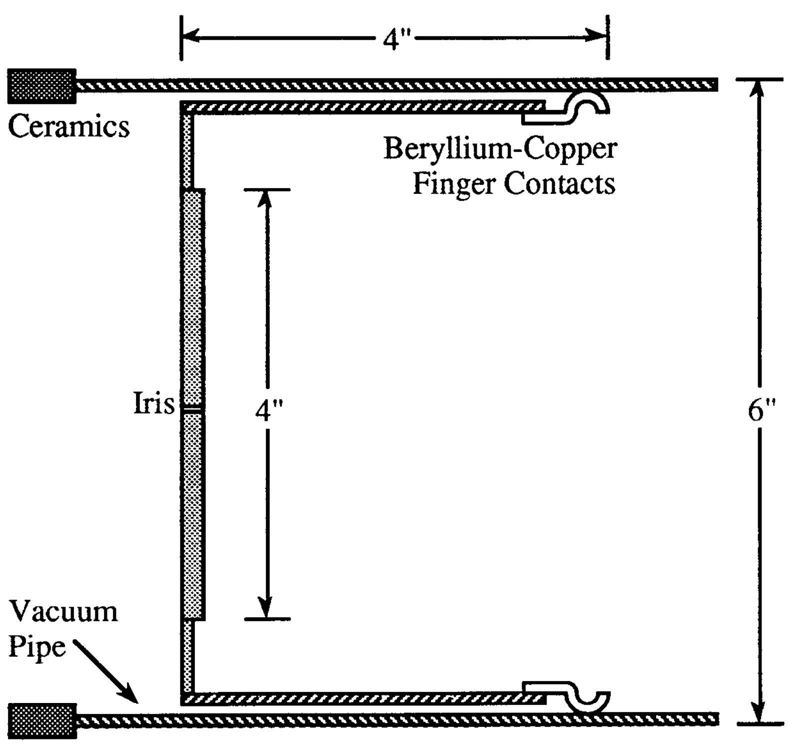

Figure 3: Side view of the proton gun iris which is at ground potential with respect to the gun.

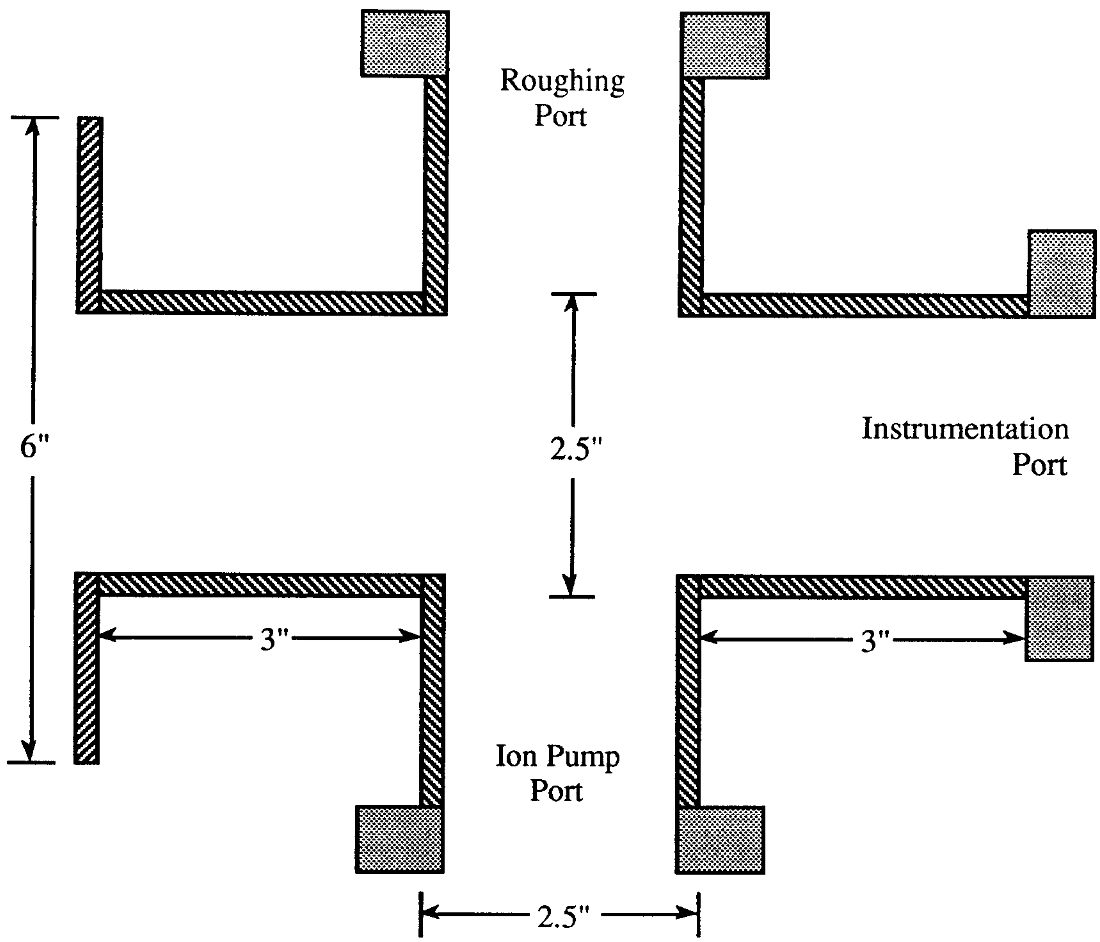

Figure 4: Side view of the 6" vacuum pipe termination showing the tree through which roughing pumps, ion pumps, and an instrumented 2-1/2" vacuum pipe cap are attached.

The pressure at some point in a vacuum chamber and gas flow past that same point form a conjugate variable pair which can be calculated using transfer matrices, very similar to the case of the dispersion function and its derivative. In a section of beamline without any pumping, the pressure P and gas flow rate Q at a point 2 are related to the values of these quantities at another point 1 by the vector multiplication

$$\begin{pmatrix} P \\ Q \\ 1 \end{pmatrix}_2 = \begin{pmatrix} 1 & -L/c & -qL^2/2c \\ 0 & 1 & qL \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} P \\ Q \\ 1 \end{pmatrix}_1 \quad . \tag{1}$$

The distance between beamline positions 1 and 2 is designated by the variable L. The specific conductance c quantifies the resistance to gas flow in the beam pipe. For a round beam pipe of radius R it has the value

$$c[m-l/s]=0.928(R[cm])^3\sqrt{\left(\frac{T[^\circ K]}{300}\right)\left(\frac{28}{M}\right)} \quad . \qquad (2)$$

The surface outgassing rate depends on the surface cleanliness and temperature treatment of the chamber wall. The surface outgassing rate σ_q for a a clean metallic surface such as aluminum, copper, or aluminum is approximately $1x10^{-12}$ T-l/(s-cm^2). The outgassing rate for a non-baked but ultrasonically cleaned stainless steel pipe has been measured to be 5 times that minimum value. To convert from the surface outgassing rate σ_q to the specific outgassing rate q it is necessary to multiply σ_q by the surface area per unit length. For a round pipe

$$q[T-l/s-m]=200\pi\, R[cm]\, \sigma_q[T-l/s-cm^2] \quad . \qquad (3)$$

In a short section of vacuum chamber in which there is a lumped pump, the transfer matrix across that locations can be written as

$$\begin{pmatrix} P \\ Q \\ 1 \end{pmatrix}_2 = \begin{pmatrix} 1 & 0 & 0 \\ -S & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} P \\ Q \\ 1 \end{pmatrix}_1 \quad . \qquad (4)$$

The pumping speed S of the lumped ion pumps used at Fermilab are roughly 30 l/s.

In sub-phase 1.1 equal capacity pumps at either end will create a pressure profile along the beampipe in which the pressure is equal at both ends. Figure 5 shows the geomentry of this situation. In addition, since the ends are sealed the gas flow Q equals zero at both ends. Propagating these boundary conditions across the vacuum system, one finds that the pressure at the ends is

$$P_{end}=\frac{q\,L}{2\,S} \quad . \qquad (5)$$

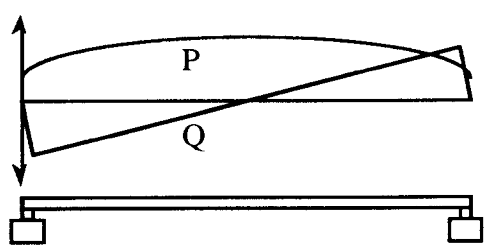

Figure 5: Pressure and gas flow as a function of position within the sub-phase 1.1 vacuum system.

The pressure in the middle, specifically where Q=0 by symmetry, is solved similarly. The result of this calculation is

$$P_{mid}=P_{end}+\frac{q\,L^2}{8\,c} \quad . \qquad (6)$$

The pressure at any point within the beampipe a distance s away from the Q=0 midpoint is described by the equation

$$P(s) = P_{mid} - \frac{q\,s^2}{2\,c} \quad . \qquad (7)$$

The average pressure is found by integrating P(s) along the entire beam pipe divided by the length of the beam pipe. Performing this integration yeilds the result

$$P_{ave} = P_{mid} - \frac{q\,L^2}{24\,c} \quad . \qquad (8)$$

For a 20' length of the beampipe which has not been baked, the expected pressure performance can now be calculated. The values for the above parameters are listed in table 1. Since sub-phase 1.2 is basically the same vacuum system except for the extended length of 40', it is also listed in table 1.

Table 1: Values for pressure performance of the vacuum system for sub-phase 1.1 and 1.2 of the 5 MeV Electron Cooling Test Beam Facility.

Parameter	Phase 1.1	Phase 1.2
Lumped Pump Pumping Speed (l/s)	30	30
Surface Outgassing Rate (T-l/s-cm2)	5.00E-11	5.00E-11
Length of Vacuum System (ft)	20	40
Diameter of the Vacuum Pipe (in)	5.87	5.87
Length of Vacuum System (m)	6.096	12.192
Radius of the Vacuum Pipe (cm)	7.455	7.455
Specific Conductance (m-l/s)	384.480	384.480
Specific Outgassing Rate (T-l/s-m)	2.34E-07	2.34E-07
Pressure at Lumped Pumps (T)	2.38E-08	4.76E-08
Pressure at Q=0 Point (T)	2.66E-08	5.89E-08
Average Pressure (T)	2.57E-08	5.51E-08

The above calculations assume that if the cart does exist, that it is parked at the Q=0 point in the middle of the beampipe. In general the cart will be parked anywhere along the length of the pipe. On the assumption that the flow of gas through the cart is completely restriced, the pump pressure, the cart pressure, and the average pressure are calculated using the equations

$$P_{pump} = \frac{q\,L}{S} \quad , \qquad (9)$$

$$P_{cart} = P_{pump} + \frac{q\,L^2}{2\,c} \quad , \qquad (10)$$

$$P_{ave} = P_{cart} - \frac{q\,L^2}{6\,c} \quad , \qquad (11)$$

where L is the distance of the cart from the pump at the proton gun. Performing this calculation as a function of L, the graph in figure 5 was generated.

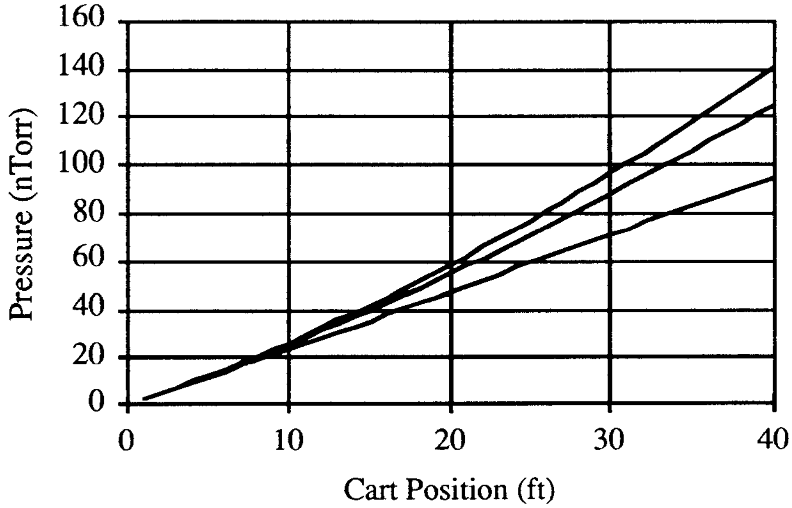

Figure 5: Cart pressure (top curve), average pressure (middle curve), and pump pressure (lower curve) as a function of cart distance from the proton gun.

In sub-phase 1.3 the entire vacuum system shown in figure 1, including the two 90° bend magents, is installed. The instrumentation cart will be place in the 2nd 40' straight section. Because of the symmetry of the situation, the gas flow through the vacuum pipe linking the dipole magnets is essentially zero. Therefore, the pressure on the beam side of the instrumentation cart is very similar to the values displayed in figure 5, where the x-axis now represents the distance of the cart from the 90° bend magnet.