BNL-101816-2014-TECH

AD/RHIC/RD/34;BNL-101816-2013-IR

Engineering Analysis of Vacuum Pump Requirements of AGS/RHIC Beam Transfer Line

J. Guilmette

January 1992

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

AD/RHIC/RD–34

RHIC PROJECT

Brookhaven National Laboratory

Engineering Analysis of Vacuum Pump Requirements of AGS/RHIC Beam Transfer Line

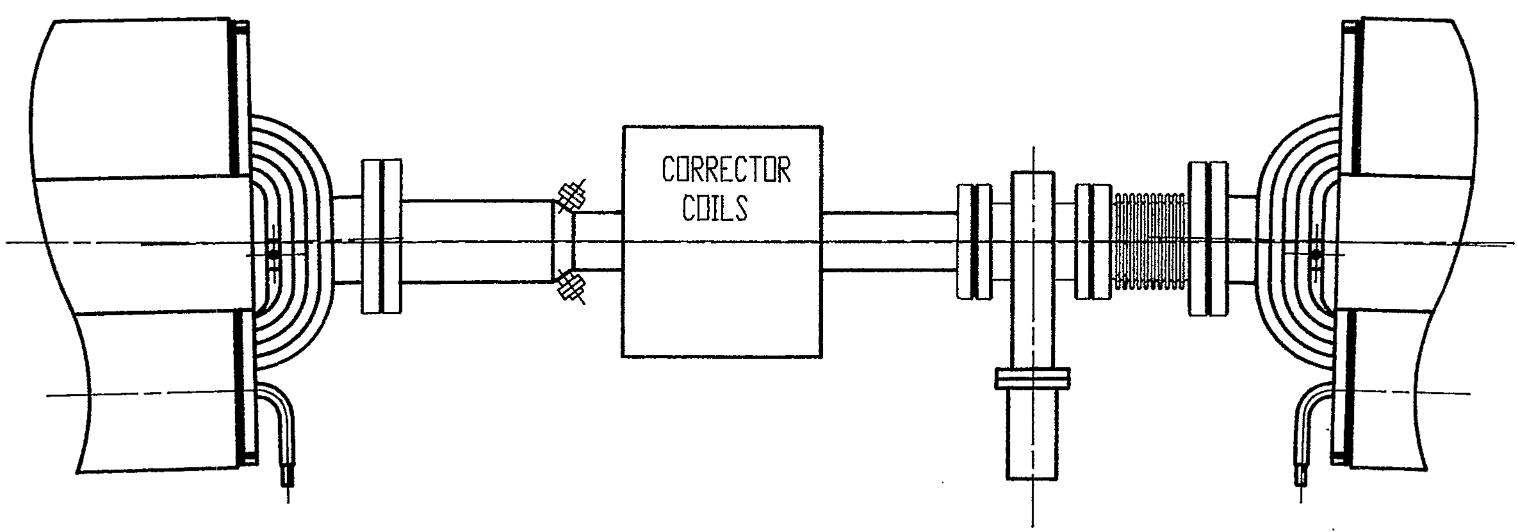
Joseph Guilmette

January 1992

1. <u>Introduction</u>

The AGS/RHIC transfer line consists of three interconnected lines to connect the AGS FEB line to the RHIC Rings. A single feeder line from the AGS called the W line consists of six quad magnets, eight gradient magnets, two pitching magnets and straight pipe sections between the magnets. Total length of this line is approximately 240 meters. Drift spaces between the magnets average approximately 14 meters except for one close area between the second pitching magnet and third quad. From this observation, it may be concluded that the placement of vacuum pumping apparatus is not a problem in this W line since most of the line is straight pipe.

Located at the downstream end of the W line is a switching magnet which selects the direction of the beam for injection into either of the two RHIC rings. These two lines are identified as the X and Y lines and are mirror-symmetric thus only the Y line will be discussed. This line consists of twenty six alternating gradient magnets located just downstream of the switching magnet. This comprises the "big bend" section of the injector line. In terms of discussing the vacuum chambers, this is the most difficult line to analyze due to the limited amount of space available for the vacuum components. For purposes of this analysis, it may suffice to describe the vacuum system centerline on an arc with a nominal 96.96 meter radius and an angular displacement of 1.043 radians. This translates into an arc length of approximately 101 meters. The twenty six magnets are placed such that the drift space pattern between the magnets alternates between .45 meters and 1.43 meters. Since a bellows and possibly a conflat flange connection are necessary between each magnet and a significant portion of the space is occupied by the magnet coil, the .45 meter drift space is considered unavailable for other vacuum system components. Figure 1 below shows a typical 1.43 meter drift space vacuum system component layout.



1.43 M BIG BEND DRIFT SPACE WITH SECTOR VALVE

FIGURE 1

Downstream from the "big bend" is a shorter matching section used to condition the beam for RHIC injection. This space consists of six quadrupoles, five horizontally deflecting dipoles, two septums and one kicker completing the injection process. Here the vacuum system will be dictated by differential pumping requirements and space availability rather than pumping characteristics due to this section's relatively short length as compared to the other two areas previously discussed. This section is not analyzed in this report but will be addressed at a later date.

2. Objectives

The objective of the roughing system analysis is to determine the effect of vacuum sector length versus pumpdown time to obtain a maximum pressure in the system of 1×10^{-5} Torr. This value has been chosen because it is the maximum desirable pressure for sputter ion pump startup and it is a safe margin for beam operation.

Once it has been determined that the roughing system can maintain pressures below 1×10^{-5} Torr throughout the system, it then may be concluded that a sputter ion pump for the high vacuum system can be placed anywhere in the system and started with no difficulty. The high vacuum analysis follows using the same analytical tools to determine the system's ultimate performance which is useful in determining system operating pressures and corresponding pump useful lifetimes.

3. Roughing System

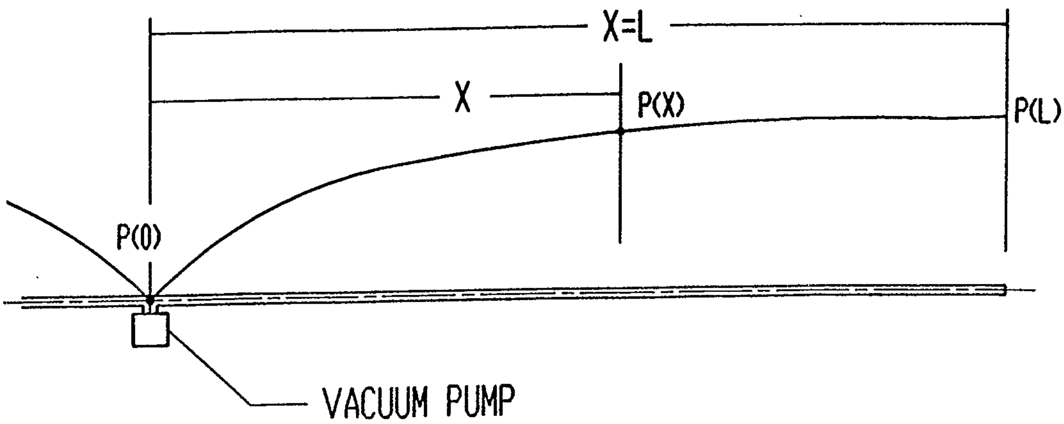
Conceptually, the roughing system will consist of one portable roughing cart equipped with an oilless mechanical pump or sorption pump, turbo molecular pump and required controls for normal operation. An important component of the roughing cart will be a dry nitrogen bottle for venting. Since the entire transfer line has a volume of approximately 50 cubic feet, a 240 ft^3 cylinder is capable of backfilling the entire system four times. Dry nitrogen backfilling significantly reduces subsequent roughing cycle times since water vapor is a major component of the pump load. The cart will be disconnected from the line once the roughing process is completed.

Figure 2 shows the pressure relationship in a half vacuum sector which is assumed to be symmetrical around the vacuum pump. The pressure profile is a result of the outgassing from the chamber walls along its length and the conductance losses between point x and the pump inlet. This relationship may be described by Eg. (1)[1] below:

$$P_{(x)} = P_p + \frac{\pi q}{2KD^2}(2xL - x^2) \qquad (1)$$

where

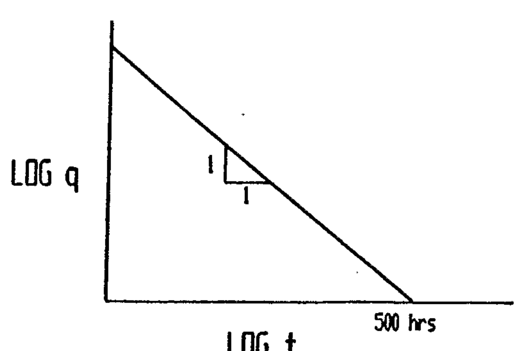
$P_{(x)}$	=	Pressure at distance from x from pump, torr $(0 \le x < L)$
P_p	=	Pump pressure, Torr
q	=	chamber outgassing rate, Torr -l/sec•cm^2
L	=	chamber length from pump to extreme end, cm
D	=	Equivalent chamber cross-section diameter = 6.98 cm.
K	=	constant relating to the molecular weight and temperature of the gas media. K = 12.1 for an AMU of 28 and temperature of 293° K



PRESSURE PROFILE IN A LONG VACUUM CHAMBER

FIGURE 2

It has been shown[2] that the outgassing constant for a clean stainless steel vessel is a time dependent variable according to the Figure 3 below:



OUTGASSING CONSTANT AS A FUNCTION OF TIME

FIGURE 3

From initial pumpdown, the relationship may be approximated from eq. (2).

$$q_t = q_{500}\left[\frac{t}{500}\right]^m \tag{2}$$

where q_{500} is assumed to be value after 500 hrs of pumping[(2)] and equal to 3.0×10^{-11} Torr-liters/sec-cm^2. The value of m will be assumed as equal to -1[(2)]. Thus eq. (1) may be modified to account for these time dependent variables at x = L as follows:

$$P(t) = P_p + \frac{\pi q(t) L^2}{2KD^2} \tag{3}$$

P_p may be expressed in terms of the gas load and the pump speed, S_p.

$$P_p = \frac{C_1 L q(t)}{S_p} \tag{4}$$

where

C_1 = surface area per unit length of chamber = 27.94 cm^2/cm of chamber length (assuming a 1.32" x 4.5" rectangular cross section).

Combining eqs. (2), (3) and (4) and solving for t results in the following expression.

$$t = \frac{500 q_{500}}{P(t)}\left[\frac{C_1}{S_p}L + \frac{\pi}{2KD^2}L^2\right] \tag{5}$$

Pumpdown times required to attain the 1×10^{-5} Torr ion pump starting pressures at the furthest point from the roughing pump for various chamber lengths may now be evaluated using eq (5). Table I below shows pumpdown times in terms of number of magnets in an entire vacuum sector of length 2L for $P(t) = 1.0 \times 10^{-5}$ torr. Two pumps were used in the calculations; an 80 l/s and a 200 l/s. The pumping speeds used in Table 1 account for conductance losses to the pump entrance, hence the lower values.

Table I

No. of Magnets (2L)	t (Sp = 65 l/s)	t(Sp = 160 l/s)
4	3.58 hours	3.25 hours
8	13.23	12.58
12	28.95	27.98
24	112.53	110.57

Table I indicates that increasing the turbomolecular roughing pump size from 80 l/s to 200 l/s does not significantly reduce pumping time for roughing the sector. We may therefore conclude that the vacuum system is conductance limited thus larger roughing pumps are not necessary for this system. The results shown on Table 1 are for a water vapor contaminated system as may be expected on initial pumpdown. After venting with clear, dry nitrogen, the outgassing constant will follow a different characteristic than that described by eq (2). Since the exact pumpdown characteristics are dependent on many variables, (minute amount of oil, water molecules, absorbed gasses in the walls etc.) it will be assumed that the chambers are relatively clean and were previously vented using clean, dry nitrogen. It will be further assumed that the system was exposed to the atmosphere for a relatively short period of time. In this case, the pump down characteristics would approach a theoretical limit described by eq (6) below for an ideal gas pumping cycle with no outgassing or leakage[3].

$$t=\frac{V}{S_p}\ln\frac{Po}{P(t)} \qquad (6)$$

t = time, seconds
V = chamber volume, liters
S_p = pumping speed, liters/second

In terms of the number of magnets and a pumping speed of 100 liters/second eq (6) reduces to

$$t=16.28\ n\ \ln\frac{Po}{P(t)} \qquad (7)$$

n = Total number of chambers in a vacuum sector 2L long

Table II below illustrates the results from eq (7) using a pressure ratio Po/P(t) = 10^3

Table II

No. of Magnets (2L)	t (hours)
4	.12
8	.25
12	.38
24	.50

Comparing Table II to Table I shows the dramatic improvement in pumpdown time by keeping a system clean and free from water vapor contamination. Again, it must be emphasized that the results in Table II are theoretical limits that will not be fully attained, but may be approached with reasonable care.

4. <u>High Vacuum System</u>

The high vacuum system analysis will be based upon a 20 l/s sputter ion (SI)pump replacing the turbo roughing pump in an otherwise identical vacuum sector to that analyzed in the roughing analysis. The analytical procedures are similar to the preceding sections and the SI pump location will be assumed to be at the roughing pump location. It will be also assumed that the system is roughed to 1 x 10^{-5} Torr or lower as an initial condition. The high vacuum analysis will determine the pressure gradient in the vacuum chambers after a long time interval to assure that outgassing from chamber walls does not result in excess pressure bumps. Outgassing from chamber walls will result in a pressure gradient along the chamber assembly according to eq. (3).

$$P(t)=P_p+\frac{\pi q(t)L^2}{2KD^2} \tag{3}$$

We may consider the second term of the above to determine the pressure gradient in the tube

$$\Delta P=\frac{\pi q(t)}{2KD^2}L^2 \tag{8}$$

if we assume that after 100 hours for roughing time to 1 x 10^{-5} Torr, then, after 100 hrs,

$$q_{100} = 3.0\ x\ 10^{-11}\left(\frac{500}{100}\right) = 1.5\ x\ 10^{-10} torr.l/\text{sec}/cm^2$$

$$\Delta P = \frac{\pi(1.5x10^{-10})}{2(12.1)(48.8)}L^2 = 4.025x10^{-13}L^2 torr \tag{9}$$

Then shortly after startup of the SI pumps, the pressure at the furthest point from the S/I pump can be expressed as

$$P_0 = P_1 + \Delta P = 1x10^{-5} + \Delta P \tag{10}$$

However, after a very long time the value of the P_1 at the SI pump would approach the system base pressure which may be determined as follows:

$$P_B = \frac{A\ q_{00}}{S_s} = \frac{C_2\ n\ q_{00}}{S_s} \tag{11}$$

where,

A = Surface area of total vacuum system, cm^2
S_s = Sputter ion pump speed (assume 10 l/s due to conductance losses).
C_2 = Surface area of a single magnet beam chamber = $1.187 \times 10^2\ cm^2$.
n = Number of chambers in one vacuum sector.

The base pressure may be computed from eq. 11

$$P_B = 3.56\ x\ 10^{-8} n\ torr \tag{12}$$

P_∞ is the pressure at the farthest point after pumping at a time approaching infinity, (> 500 hours) and is obtained by combining eq. (9) modified for 500 hours and eq. (12).

$$P_\infty = P_B + \Delta P = 3.56\ x\ 10^{-8} n + .80\ x\ 10^{-13}\ L^2\ torr \tag{13}$$

Table III below illustrates the system pressure gradients existing in a pump sector while being pumped with a sputter ion pump located at the center of the sector.

Table III

No. of Magnets (2L)	Po (eq 10)	P_B (eq 11)	P_{00} (eq 13)
4	1.11×10^{-5}	1.42×10^{-7}	2.00×10^{-7}
8	1.46×10^{-5}	2.84×10^{-7}	5.15×10^{-7}
12	2.10×10^{-5}	5.70×10^{-7}	1.09×10^{-6}
24	5.15×10^{-5}	1.14×10^{-6}	3.22×10^{-6}

5. Conclusions

Table I illustrates the effects of the number of magnets in a vacuum sector on pumpdown times from an initial "contaminated" system. Although there is no clear best solution, a reasonable pumpdown time versus the amount of equipment tradeoff must be approached. With only four magnets/sector, the pumpdown time is 3.58 hours indicating that the sector would be available the first day. With a sector twice as large, the system would be ready the second day, while a 12 magnet sector would be available the second or third day. A 24 magnet sector would take 4 days and is obviously out of the question. Table II suggests that the difference between 4, 8 or 12 magnets becomes small once the system is clean and vented with dry nitrogen. This however, is a theoretical limit that may be approached, thus the pumping times will be greater than these values however it is uncertain to what degree at this time.

If we observe Table III, we may conclude that after turning on the SI pumps, the pressure at the far point from the pumps varies approximately 1 1/2 orders of magnitude depending on the length of the vacuum system. If our objective is to remain below 1×10^{-5} Torr throughout the system, then a maximum of eight magnets/sector would be our criteria. Furthermore since a sector length of eight magnets appears acceptable for both the roughing and high vacuum applications, the design will include both pumps at one location midway between sector valves resulting in a sector length of approximately 37 meters.

6. <u>Vacuum System Configuration</u>

A vacuum sector 8 magnets long would have the configuration shown below:

1. Approximate sector length = 36.0 meters
2. Roughing pump locations:

a)	x and y line	between qmi2 and bmi2
b)	x and y line	between g20d and g21d
c)	y and y line	between g12d and g13d
d)	x and y line	between g4d and g5d
e)	w line	upsteam of vq6t
f)	w line	between vq5d and vq4f
g)	w line	between vp2a and vq2f
h)	w line	between w7d and w8f
i)	w line	between w5d and w6f
j)	w line	between w4f and w3d
k)	w line	between w1d and w2f

Total = 15 roughing pump ports

7. Sector valve locations

a) x and y line, upstream qmi5
b) x and y line, between g24d and g25d
c) x and y line, between g16d and g17d
d) x and y line, between g8d and 2gd
e) x and y line, between SWM and g1d
f) w line, between vq5d and vq6t
g) w line, between vq3d and vq4t
h) w line, between vq1d and v2qt
i) w line, between w6f and w7d
j) w line, between w4f and w5d
k) w line, between wp1 and w3d
l) w line, upstream of w1d

Total = 17 sector valves

References

(1) Welch, K. M. "Captive Pumping Technology, and Introduction, (Pergamon Press, Inc. NY, NY, 1991) P. 34.

(2) Conversations with K. Welch, Sept. 1991.

(3) Tompkins, Harland G., "An Introduction to the Fundamentals of Vacuum Technology", American Vacuum Society Monograph series, American Institute of Physics Inc., NY, NY, (1984) P. 19.