Contents

1. Introduction

The demands on the performance of the Main Injector will require sufficient beamtube vacuum in order to achieve expected beam intensities and lifetimes. This analysis of the vacuum system will show that we are on course to achieve this goal. We present the results from a test half-cell vacuum system, and apply those results to the design geometry in order to predict the performance of the ring. The goals outlined in MI-0067 [2] have been achieved in the test half-cell, but with different methods and not with the rebuilt Main Ring ion pumps, in accordance with the design at the time this paper was authored.

We begin by defining the variables used in the analysis and then we calculate pumping speeds, tube conductances, and the pressure distributions for the majority of the lattice elements. We then average the pressure over all of these elements to estimate the ring's pressure. These calculations will use the specific outgassing rate that is measured in the appendix.

The measured values are compared to those called for in MI-0067 [1] and are shown to be equal or better. This leads us to believe that our current design will meet the future demands that the Fermilab HEP program will present.

2. Assignments of variables:

a=5.9817 cm (major radius)
b=2.4956 cm (minor radius)
A=cross-sectional area of the tube
B=perimeter of the tube cross-section
v=mean thermal velocity (Maxwell distribution)
W=transmission probability for the tube
C=molecular flow conductance
P=pressure
s=effective pumping speed at the beamtube
L=length of a device
q=specific outgassing rate
Averaged quantities are italicised

3. Effective pumping speed, s:

Let S=30 l/s be the pumping speed of the design ion pumps. Then the effective pumping speed s is related to S through the conductance C of the pump arm assembly. This yields:

$$s=\frac{S\ C}{S + C}\ ,\text{ where } C=48.07\text{ l/s (for the arm assembly).}$$

So, s=18.5 l/s at the beamtube.

4. Beamtube conductance, C:

Because of the unique cross-section of the beamtube, the molecular flow conductance can be approximated for a long elliptical cylinder. The circle or rectangle approximations will not work. For a derivation of this conductance, refer to Holland [1]. The conductance is given as:

$$C=\frac{1}{4}\ vAW,\text{ where } A=\pi ab,\ W=\frac{\frac{8\,b}{L}}{\frac{3}{2}}=\frac{16b}{3L}\ ,\text{ and } v=4\sqrt{\frac{kT}{2\pi M}}\ .$$

For air (M=29 g/mol) at 298°K, v=46641.5 cm/s., and A=46.897 cm^2. And since b=2.4956 cm, a convenient formula for the elliptical beam tube is obtained. For a lattice element of length L, the conductance needed in the pressure calculation is given by:

$$C=\frac{2426}{L} \text{ in l/s if L is in cm.}$$

It is important to note that this is actually the conductance for a tube of length $\frac{L}{2}$, which will be used for averaging the pressure over the ring.

5. Beam tube cross-sectional perimeter, B:

An approximation for the perimeter of an ellipse is:

$$B=\pi\sqrt{2(a^2+b^2)-\frac{1}{2.2}(a-b)^2}\ .$$

For this beam tube, B=27.83 cm.

6. Specific outgassing rate, q:

A test half-cell vacuum chamber was set up to study the performance of the designed system. The results of the study are given in Appendix I. With two ionization gauges to measure with, the specific outgassing rates were 5.0×10^{-12} and 4.52×10^{-12} . To be conservative, the value used in this analysis is:

$$q=5.0\times10^{-12}\,\frac{\text{torr-l}}{\text{cm}^2\text{-s}}\ .$$

It is interesting to note that this is the value called for in MI-0067 [2].

7. Pressure, P(x):

For a derivation of the following formula for the pressure distribution along the beam tube, refer to Roth [3].

$$P(x)=qB\{\frac{l}{s}+\frac{x}{c}-\frac{x^2}{2lc}\}\ ,\text{ where } l=\frac{L}{2}\ .$$

The $-x^2$ term drives the function to be inverted parabolic, with the maximum found at the midpoint between any two pumps. This is the origin of the $l=\frac{L}{2}$ term. A more useful form of the pressure equation is:

$$P(x)=\alpha x^2+\beta x+\gamma\ ,\text{ where x is in cm and:}$$

$$\alpha = -\frac{qB}{LC} = -5.74\times10^{-14},$$
$$\beta = \frac{qB}{C} = L(5.74\times10^{-14}), \text{ and}$$
$$\gamma = \frac{qBL}{2s} = L(1.50\times10^{-11}).$$

Let P denote the average pressure for a lattice element. This value is found by:

$$P = \frac{2}{L}\int_{x=0}^{L/2} P(x)dx \text{ , which reduces to:}$$

$$P = \frac{1}{12}\alpha L^2 + \frac{1}{4}\beta L + \gamma .$$

The average pressure in a half-cell is just :

$$P = \frac{1}{L}\,[2L_D P_D + L_Q P_Q] \text{ , where D means dipole and Q means quad.}$$

For a normal half-cell, $P_N = 5.70\times10^{-9}$ torr. For a Dispersion-Suppressing (D-S) half-cell, the quadrupoles have no pumps on their tubes so their lengths are added to the adjacent "C" dipoles for the pressure calculations. The average pressures are tabulated below.

Lengths of the devices in cm		Quantity	Average
Quadrupole	Quad with C Dipole	of Devices	Pressure
404.3	850.3	48	1.02E-08
328.9	774.9	8	8.67E-09
366	812	16	9.34E-09
417.2	863.2	8	1.04E-08

The average pressure for a "D" dipole is 5.74×10^{-9} torr. Denoting the pressures for "C" dipole-quad combinations and "D" dipoles as P_C and P_D respectively, the average pressure for a D-S half-cell is:

$$P = \frac{1}{L}\,[L_C P_C + L_D P_D].$$

The average pressures for each type of D-S half-cell are tabulated below:

Quad Beamtube Length inches	cm	Pressure torr
159	404.3	8.67E-09
129	328.9	7.60E-09
144	366	8.06E-09
164	417.2	8.81E-09

The D-S half-cells with 122" quadrupoles were not calculated because the drawings were not available at the time. This prevented the author from having the length dimensions on each side of the quad.

An estimate for the average ring pressure is obtained from the sum of the normal and D-S half-cells. This method does not account for many devices, but does give a rough indication of the vacuum system performance. The ring will require 100 normal half-cells. The average pressure will be:

$$P = \frac{\sum P_i L_i}{\sum L_i} \text{ for each lattice element i.}$$

The sums are taken using individual magnet tubes for a ring-average pressure of $P = 6.73 \times 10^{-9}$ torr.

8. Ultimate Pressure

Pressure data was saved from the two ion gauges and the three ion pumps on the test half-cell. These numbers were plotted for each individual device, beginning with the fifth day of ion pumping to examine the pumpdown below 10^{-6} torr where molecular flow is by far the dominant vacuum regime. By leaving out the viscous and transition flow regimes, the extrapolation of the curve is simpler. Exponential curve fits were obtained as Figures 2 through 6 and are of the form:

$$P(t)=A \times 10^{-Bt}.$$

A linear correlation coefficient R is also given on each graph. For times of six months and one year, the extrapolated pressures for each instrument become:

Pressure Predictions (torr)

Device	One Year	Six Months
IP 1	9.13E-10	3.96E-09
IP 2	1.57E-09	4.47E-09
IP 3	1.39E-09	3.34E-09
IG 1	9.36E-09	1.83E-08
IG 2	2.51E-09	1.46E-08

As mentioned before, this study was done using 20 l/s pumps, so the actual ring should perform better with its 30 l/s pumps. Since IP 2 is in the middle of the test system (see Figure 1), it should be considered the most representative of what to expect. Also note that the IG 1 is mounted on a 1.5" O.D. vacuum cross, which will heat up and outgas more than the Main Injector system (without ion gauges) will. IG 2 is mounted on the end of the quadrupole tube, where the adjacent half-cell will be, so that this point will be at a pump arm location.

Figure 1:
Main Injector
Test Half-Cell
Schematic

system specifications:

tube type:	*ovular/race track electropolished stainless steel 304 (unbaked)*
pump compliment:	*(3) Varian 20 l/s Diode Ion Pumps*
gauge compliment:	*(2) ion gauges*
system location:	*ER tunnel (experimental research facility)*

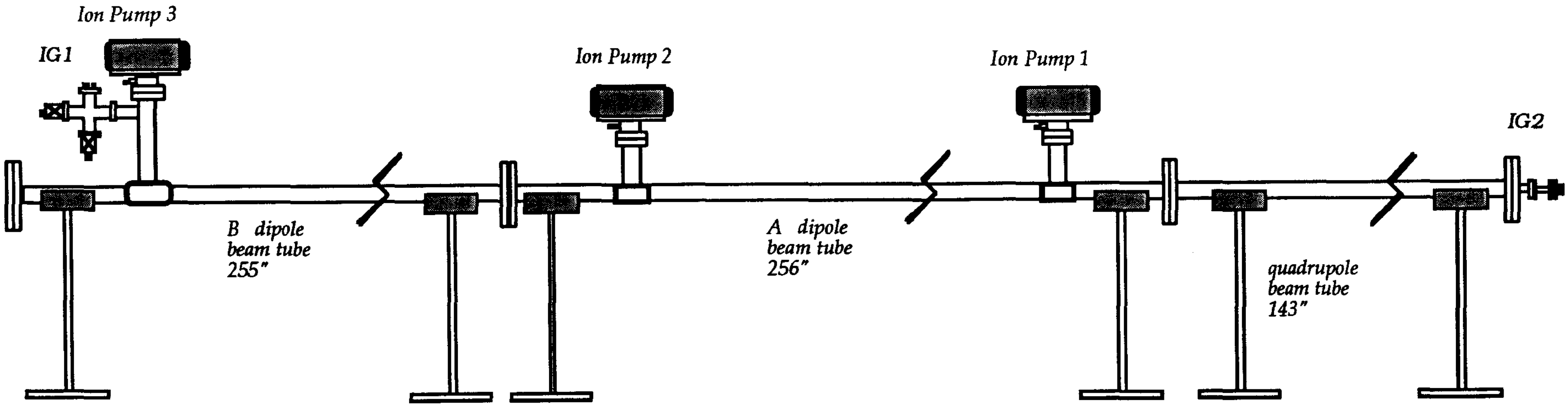


Figure 2: IG 1 Curve Fit

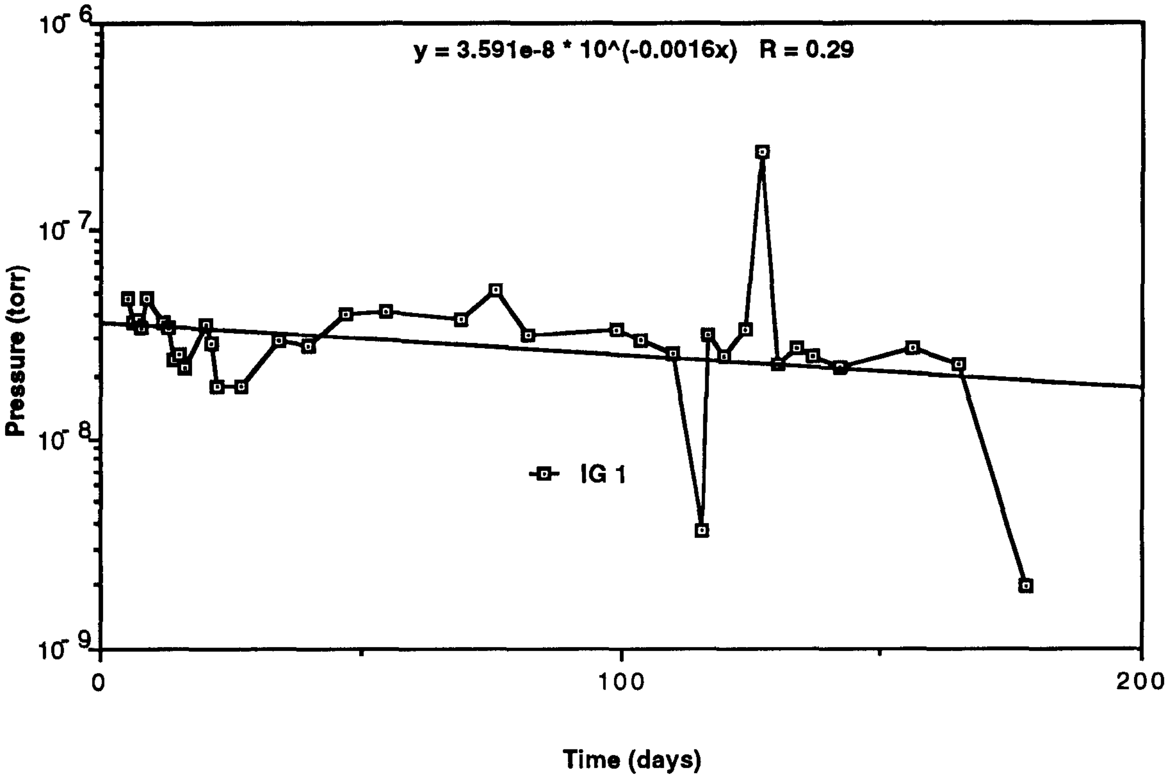


Figure 3: IG 2 Curve Fit

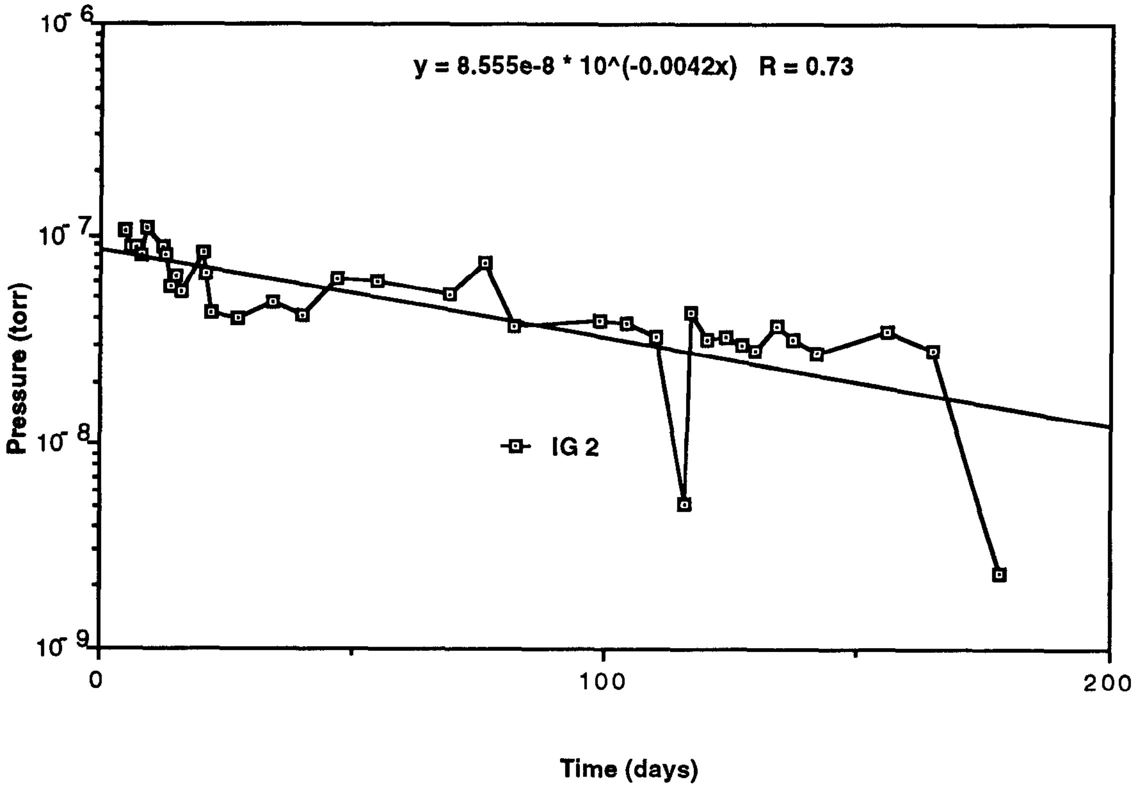


Figure 4: IP 1 Curve Fit

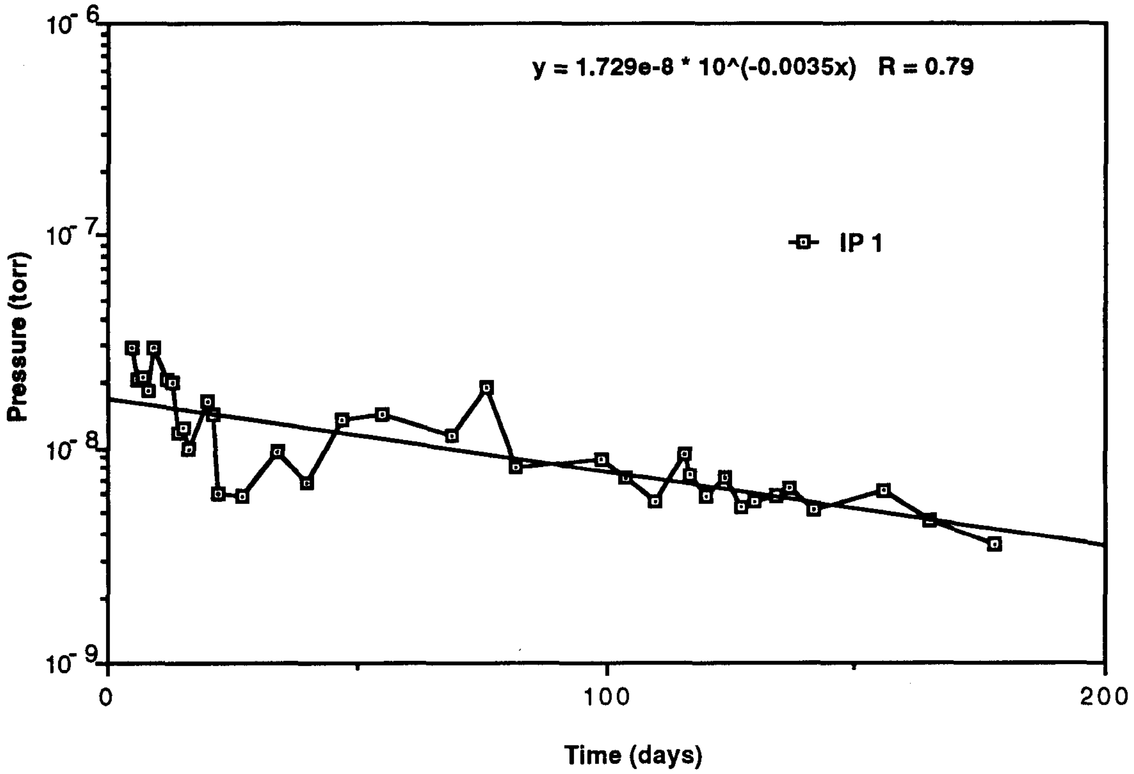


Figure 5: IP 2 Curve Fit

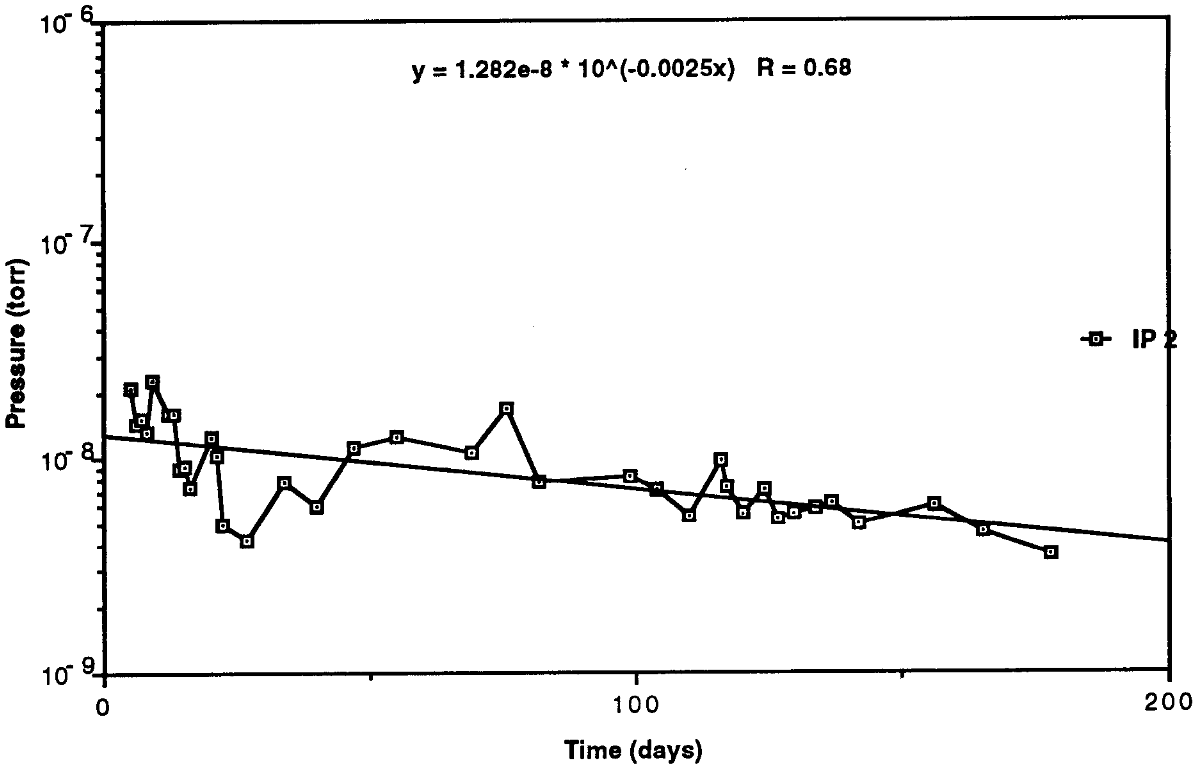
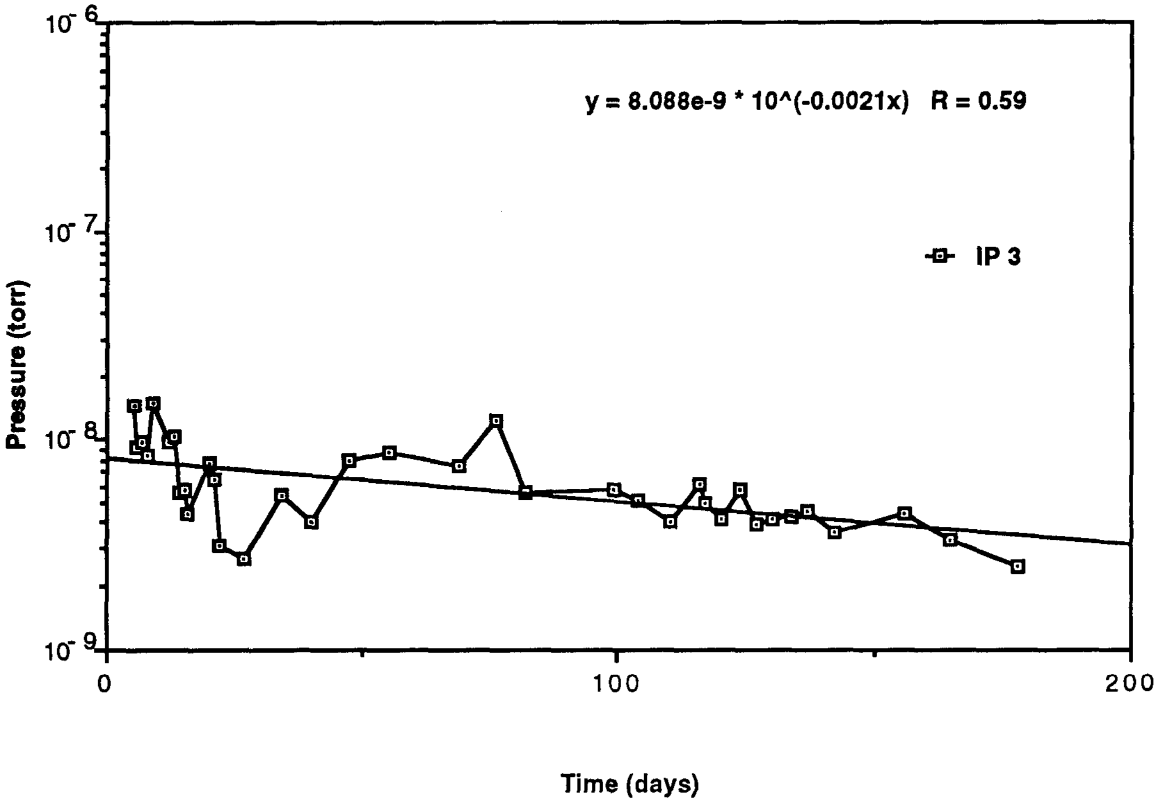


Figure 6: IP 3 Curve Fit



Appendix I

Outgassing Study of a Test Half-Cell

A vacuum system with dimensions similar to a normal half-cell was assembled and pumped on with three 20 l/s diodes. The MI ring will use 30 l/s diodes, but the test should still be reasonable as a conservative sample. The actual ring should perform better. The layout of the system is shown in Figure 1.

The beamtube cross-section was approximated to be elliptical with the area given as A=46.9 cm^2 and the perimeter B=27.83 cm. The arm assemblies were approximated in components of circular and nearly-rectangular cross-section. The near-rectangle cross-sectional area was modelled as a rectangle with quarter-circle cutouts of diameter 2.5 cm. The orifice between the arm assembly and the beamtube was neglected due to its large area (and very short length.) The volume and surface areas of the basic arm assembly were calculated as V=2.55 l and S=3552.246 cm^2 (with the ion pump). The arm assembly with the extra pumpout port, cross, valve, and ion gauge came out to V=2.9445 l and S=4046.870 cm^2..

The quadrupole tube had a length of 363.22 cm so, with it terminated off at the one end with the short $1\frac{3}{8}$ " I.D. tubes for the ion gauge, it had V=17.190 l and S=10333.22cm^2. The "B" dipole was 647.7 cm long so, with an arm assembly with the extra port, it had V=33.319 l and S=22074.502 cm^2.

The "A" dipole tube had two bellows with the following radii:

Bellows Dimensions (cm)

	Major	Minor
Outer	7.4817	3.9956
Inner	5.9817	2.4956

Since the inner and outer perimeters are elliptical, and accounting for both sides of each convolution, S=1222.440 cm^2. The volume is accounted for in the length of the tube, with the volume between each convolution negligible. The "A" dipole tube had two bellows, two basic arm assemblies, and a length of 650.24 cm. This adds up to V=35.594 l and S=27647.7 cm^2.

The volume and surface area parameters for the overall system come to V=86.103 l and S=60055.4 cm^2.

In order to perform a rate-of-rise type outgassing measurement, the main control room vacuum page was used to power off IP1,2, and 3 almost simultaneously for a measured time interval. The pressures of IG1 and 2 were recorded before and after. The specific outgassing rate R is given as:

$$R=\frac{V\Delta P}{S\Delta t} \text{ in units of } \frac{\text{torr-l}}{\text{cm}^2\text{-sec}}.$$

The calculations and data are given below:

Specific Outgassing of the Main Injector

t=60.46 sec	IG 1	IG 2
Final	2.26E-07	2.09E-07
Initial	1.51E-08	1.82E-08
Change	2.11E-07	1.91E-07
R	5.00E-12	4.52E-12

The average rate was $R = 4.76\times10^{-12}\,\frac{\text{torr-l}}{\text{cm}^2\text{-sec}}$. Out of caution, the highest rate was used in the calculation of the average pressure over the ring. It should also be reiterated that this test was done with 20 l/s diodes pumping on the system while the Main Injector design call for 30 l/s diodes. The result of this should be an even better vacuum performance than predicted here.

References

[1]. Vacuum Manual, edited by L. Holland, 1974, E.& F. N. Spon Ltd. Chapter 1, Section 4.

[2]. Conceptual Design Report of Vacuum Pumping System for Main Injector, by Shuxiu Zhang, Fermilab MI-0067.

[3]. Vacuum Technology, A. Roth, 2nd Edition, 1982, North-Holland Physics Publishing. Reprinted 1986, Chapter 3, Section 7.4.