Vacuum Performance Requirements

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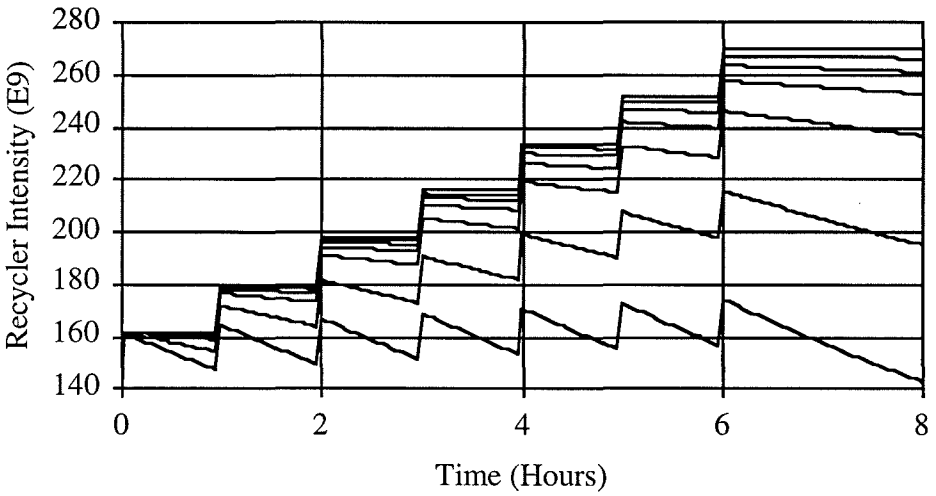
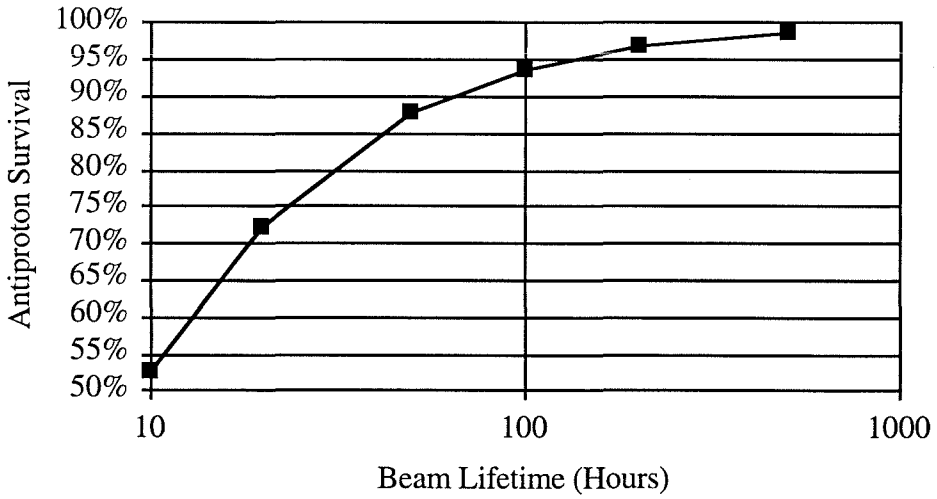
Beam Intensity Lifetime Requirement

The required beam intensity lifetime is determined by modeling the evolution of antiproton intensity in the Recycler assuming injections from the Tevatron and Accumulator. At the beginning of each collider cycle the Recycler contains the antiprotons recycled from the Tevatron. Every hour after the start of a collider store antiprotons stacked in the Accumulator are injected into the Recycler. The stacking rate is **20×10^{10}** antiprotons/hour.



Assuming beam intensity lifetimes of infinity (top), 500, 200, 100, 50, 20, and 10 hours (bottom), evolution of the antiprotons injected from the Tevatron (recycled) and the Accumulator (stacked).



Fraction of the injected antiprotons (both recycled and stacked) which survive to the start of the next Tevatron Collider store.

Ion Trapping Requirement

The rate at which the ion density increases R_i is determined by the equation [M. Reiser, "Theory and Design of Charged Particle Beams", pg. 273]

$$R_i = n_g \, n_b \, \sigma_i \, v$$

where n_g is the gas density, n_b is the beam density, σ_i is the ionization cross-section, and v is the beam velocity. The standard relationship between the gas density and the partial pressure P of the gas in question is

$$n_g[m^{-3}] = 3.54 \times 10^{22} \, P[Torr]$$

The ionization cross-section depends on the velocity of the beam and the atomic properties of the gas in question. In the case of the Recycler the equation used to calculate the cross-section can be written in the approximate form

$$\sigma_i[m^2] = 1.9 \times 10^{-24} \, A_1 \left\{ Ln\left(7.5 \times 10^4 \, A_2 \, \gamma^2\right) - 1 \right\}$$

The parameters A_1 and A_2 are molecule specific. The value of γ is 9.45 at a kinetic energy of 8.000 GeV. The results of calculations of ionization cross-section are listed in table below.

Values of the parameters A_1 and A_2 [M. Rudd, et. al., Rev. Mod. Phys. **57**, 965 (1985)] and the cross-sections themselves of relevant gasses in the Recycler vacuum system.

Gas	A_1	A_2	σ_i [m^2]
H_2	0.71	2.5	2.1×10^{-23}
N_2	3.8	0.52	1.0×10^{-22}
CO	3.7	0.54	1.0×10^{-22}

Assuming a peak Recycler antiproton intensity of **4×10^{12}** in a circumference of 3.3 km, the peak longitudinal beam density λ_b is 1.2×10^9 antiprotons/m. Therefore, given assumptions justified later in this section for the vacuum partial pressures, the rate at which the longitudinal ion densities are growing can be calculated. The results of these calculations, and the estimation of the time it takes for the ion density to equal the beam density, are listed in the next table.

Ion production rate calculations based on partial pressure predictions and an antiproton beam intensity of **$4x10^{12}$**. The neutralization time of the beam for each gas does not assume the existence of the other gas.

Gas	Pressure [nTorr]	Gas Density [m^{-3}]	Ionization Rate [m^{-1} s^{-1}]	Neutralization Time [s]
H_2	0.1	$3.5x10^{12}$	$2.6x10^{7}$	46
$CO+N_2$	0.002	$7.1x10^{10}$	$2.6x10^{6}$	460

The average transverse rms beam size σ_r in the Recycler is **2.3** mm. Given a Gaussian transverse beam distribution and longitudinal density λ_b the beam density is described by the equation

$$n_b(r) = \frac{\lambda_b}{2\pi\sigma_r^2}\exp\left[-\frac{r^2}{2\sigma_r^2}\right]$$

Therefore, the peak density at the beam center is **$3.5x10^{13}$ antiprotons/m^3**. If the beam has been neutralized to an ion density equal to the beam density, then the effective peak pressure seen by the beam due to the trapped ion cloud is $3.5x10^{13}$ molecules/m^3, or a pressure of **1 nTorr**. This calculation is an over estimate, since it ignores the fact that trapped ions can become multiply ionized, thereby neutralizing the space charge of the beam with fewer ions.

The pressure implication of the neutralized ion cloud around the antiproton beam will become evident later in the section. There are two other effects from these ions. First, a coherent instability can develop due to the electromagnetic coupling between the transverse oscillations of the antiprotons and those of the ions. Second, the ions will induce an incoherent tune spread due to the static transverse electrostatic field generated by the ion cloud.

The ion cloud has the same transverse dimensions as the beam, since the probability density of ionization has the same profile as the transverse beam density distribution. The radial electric field E_r generated by this distribution is

$$E_r(r) = \frac{e\lambda_b}{2\pi\varepsilon_o r}\left\{1 - \exp\left[-\frac{r^2}{2\sigma_r^2}\right]\right\}$$

The radial space charge force F_r is

$$F_r(r) = \frac{e^2\lambda_b}{2\pi\varepsilon_o r}\left\{1 - \exp\left[-\frac{r^2}{2\sigma_r^2}\right]\right\}$$

At a radius small compared to the rms cloud radius this equation reduces to

$$F_r(r) = \frac{e^2\lambda_b}{4\pi\varepsilon_o\sigma_r^2} r$$

But this is the same force equation as found in either the horizontal or vertical plane of a quadrupole magnet. Converting this result into the form of a quadrupole gradient error ΔK yields the result

$$\Delta K = \frac{e^2\lambda_b}{4\pi\varepsilon_o\sigma_r^2}\frac{1}{P_o v} = \frac{r_o\lambda_b}{\left(\gamma\beta^2\right)\sigma_r^2}$$

Plugging in all of the number expressed so far for the factors in the rhs form of this equation yields a space charge gradient of **$3.7\text{x}10^{-5}$ m^{-2}**.

The tune shift $\Delta\nu$ due to this gradient error is expressed as

$$\Delta\nu = \frac{1}{4\pi}\oint \beta(s)\Delta K\, ds$$

where the integral is evaluated around the circumference of the ring. Assuming a constant average beta function β_{ave} around the ring of 30 m,

$$\Delta\nu = \frac{r_o\lambda_b}{\left(\gamma\beta^2\right)\sigma_r^2}\frac{\beta_{ave}C}{4\pi} = \frac{3r_o\lambda_b C}{2\pi\beta\varepsilon_N}$$

the value of the peak tune shift at the antiproton beam intensity of $4\text{x}10^{12}$ and full neutralization is **0.29**, a value which is approximately two orders of

magnitude too large for a stored beam. Therefore, it is imperative to employ methods for eliminating ions from the beam.

Three methods are planned for the Recycler.

1) Use a coherent transverse beam closed orbit oscillation at the resonant frequency of the ion oscillation about the beam centroid. The transverse dampers installed in the Recycler to combat coherent instabilities are planned to have electronics capable of exciting this closed orbit oscillation, just as in the Accumulator.

2) Maintain a gap in the longitudinal beam distribution to destabilize the ions. This requires the constant use of a set of barrier bucket pulses to maintain an empty section of beam azimuth.

3) Employ clearing electrodes to sweep away ions from the beam potential well. In the Recycler there are two beam position monitors in each half cell which will be used as clearing electrodes.

Ion Clearing with a Longitudinal Gap

Maintaining a gap in the beam distribution destabilizes low mass ions due to the fact that the time periodicity of the instantaneous beam current has the same effect on the ions as if the ions were circulating in a circular accelerator experiencing a comparable lattice. Assume that the beam is not neutralized, and that the ions have thermal kinetic energies. Then only the electric field from the beam has a significant impact on the ion motion. Since this force is attractive, an ion of mass M undergoes a radial oscillation about the beam centroid described by the differential equation

$$\ddot{z} + \frac{e^2 \lambda_b}{4\pi \varepsilon_o \sigma_r^2 M} z = 0$$

Let ω_i be the ion angular frequency **indicated** in this harmonic oscillator equation. At the antiproton intensity of $4\text{x}10^{12}$ molecular hydrogen $\mathbf{H_2}$ has a ion angular frequency of **$4\text{x}10^6$ rad/s**. At this rate the small amplitude H_2 ion undergoes **7.13** transverse oscillations for every one antiproton revolution around the Recycler. If T_b is the length of the beam distribution and T_g is the length of the gap, then the matrix equation describing the one-turn map of the ion coordinates (z,v) is

$$\begin{pmatrix} z \\ v \end{pmatrix}_{n+1} = \begin{pmatrix} \cos(\omega_i T_b) & \frac{1}{\omega_i}\sin(\omega_i T_b) \\ -\omega_i \sin(\omega_i T_b) & \cos(\omega_i T_b) \end{pmatrix} \begin{pmatrix} 1 & T_g \\ 0 & 1 \end{pmatrix} \begin{pmatrix} z \\ v \end{pmatrix}_n$$

The stability of the ions is determined by the condition that the trace of the one-turn matrix

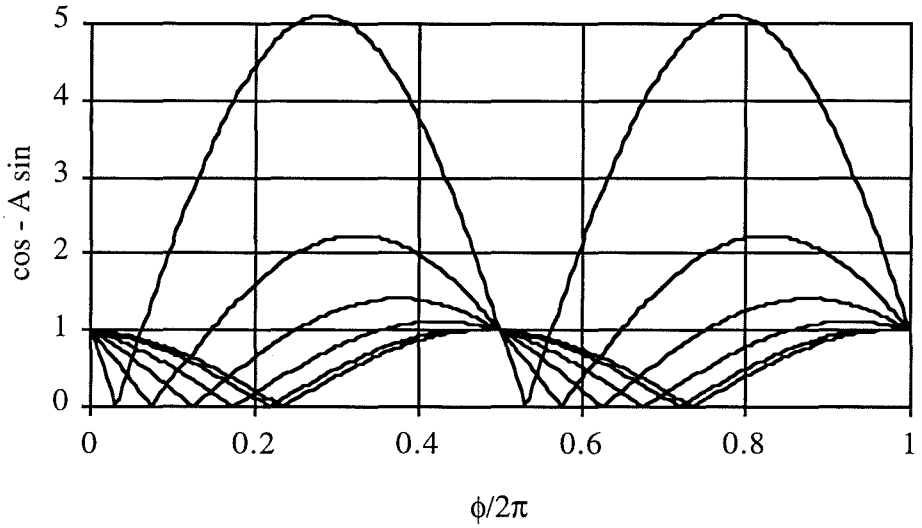
$$\begin{pmatrix} \cos(\omega_i T_b) & T_g \cos(\omega_i T_b) + \frac{1}{\omega_i}\sin(\omega_i T_b) \\ -\omega_i \sin(\omega_i T_b) & \cos(\omega_i T_b) - \omega_i T_g \sin(\omega_i T_b) \end{pmatrix}$$

be

$$\left|\cos(\omega_i T_b) - \tfrac{1}{2}\omega_i T_g \sin(\omega_i T_b)\right| \le 1$$

Let $A = \omega_i T_g/2$ and $\phi = \omega_i T_b$. The magnitude of this equation for various choices of A over the full 2π range of ϕ is shown in the figure below. Note that the ion motion is unstable when the curve is greater than unity. Since ϕ

depends critically on the precise beam intensity, it is very hard to control accurately enough to always guarantee that the it is in a region of instability. On the other hand, for values of A of approximately 5 or greater, the ion is generally unstable independent on the detailed beam intensity.



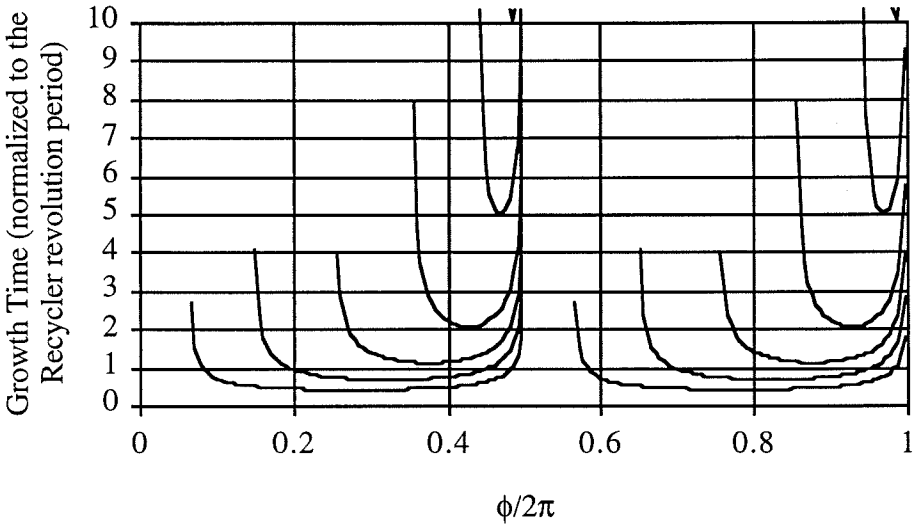
Map of equation 2.5.13 for various choices of the defined parameter A over the full 2π range of ϕ. The values for A are 5 (top), 2, 1, 0.5, 0.2, and 0.1 (bottom).

For the case again of molecular hydrogen H_2, the value of A for a **2** μsec long ion clearing gap is **5**. For the minimum operational current when only the recycled beam is in the accelerator A drops to **2** for the same size clearing gap. As will be seen in the sections on intrabeam scattering and stochastic cooling, it is desirable to compress the beam longitudinally as much as possible, to at most half of the Recycler circumference. Under these conditions with only recycled antiprotons the factor A is again greater than **11**. For stacking from an empty Recycler, assuming transfers of intensities greater than or equal to $2\text{x}10^{11}$ antiprotons, if the 1.6 μsec beam pulse length from the Accumulator is maintained with barrier buckets the minimum value for A is greater than **6**. On the other hand, with an atomic number of 28, either CO or N_2 are almost always expected to be stable in the presence of the ion clearing gap.

For unstable ions the growth rate of their oscillation amplitudes about the beam is

$$\tau = \frac{T_o}{\cosh^{-1}\left(\left|\cos(\omega_i T_b) - \frac{1}{2}\omega_i T_g \sin(\omega_i T_b)\right|\right)}$$

where T_o is the revolution period of the antiprotons in the Recycler. For values of A and f where the beam motion is unstable the value of the growth rate is calculated and plotted in the figure below. Note that the for most of the phase space the growth time is roughly equal to the revolution period.



Map of equation 2.5.14 when the beam motion is unstable. The values for A are 5 (bottom), 2, 1, 0.5, 0.2, and 0.1 (top).

If it is assumed that the ion amplitude growth time is also the characteristic time it takes for the ion to be cleared from the beam, then the equilibrium ion longitudinal density λ_i is described by the equation

$$\lambda_i = R_i \tau$$

For the case of $\tau = T_o$ and the value of R_i for H_2 listed in a table above, the equilibrium ion longitudinal density is **291 H_2 ions/m**!

It should be pointed out that larger amplitude ions see a net field which is different from that assumed in the above linearized theory. In the cases of marginal growth linearized growth rates the net reduction in focusing experienced by the ions may slow down or halt their escape from the beam.

Ion Clearing with Clearing Electrodes

In the case of H_2 where ϕ and A do not lead to unstable oscillations around the antiproton beam, and for the case of CO and N_2 in general, another method of ion clearing is required. This is the purpose of the clearing electrodes. A pair of clearing electrodes on opposite sides of the vacuum chamber with opposite voltage generate a transverse electric field. When that electric field is greater than the maximum radial electric field generated by the beam, any ions between the electrodes are stripped away from the beam.

Taking the derivative of the beam generated electric field with respect to radius and setting the result equal to zero, the radius at which the electric field is maximum is calculated to be

$$r_{max} = 1.585\,\sigma_r$$

Substituting this result into the electric field equation yields the result

$$E_{max} = \frac{0.45\,e\,\lambda_b}{2\pi\varepsilon_o\,\sigma_r}$$

With an antiproton intensity of **$4x10^{12}$** in the Recycler, the maximum radial electric field is found to be **675 V/m**. The largest effective separation d of the clearing electrodes across the vacuum chamber is **9.5 cm**. The minimum voltage across the electrodes is related to this separation and the maximum radial electric field according to

$$V_{min} = E_{max}\,d$$

Plugging in the above number, the minimum voltage per electrode is approximately **32 V**.

The ions are traveling with kinetic energies determined by their temperature, which is equal to room temperature 300°K. The table below contains a summary of the ion velocities, and for future reference when ion propagation in the gradient magnets are discussed their cyclotron orbit in a 1.5 kG magnetic field.

RMS thermal ion velocity and rms cyclotron orbit radius as a function of gas species assuming room temperature. The cyclotron orbit radius assumes the **1.5 kG** magnetic field in the Recycler gradient magnets. The overvoltage is the amount of additional voltage required to accelerate an rms ion into the negative electrode, thereby eliminating the ion from the beam.

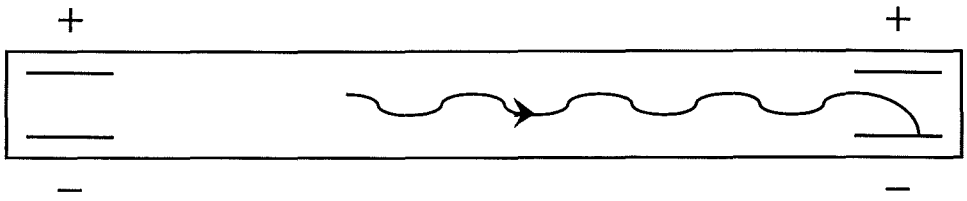
Gas	Atomic Mass	rms Velocity [m/s]	rms Cyclotron Radius [mm]	Overvoltage [V]
H_2	2	1113	0.15	0.0013
$CO+N_2$	28	297	0.58	0.0013

In order to assure that the ions leave the beam while they ballistically traverse the clearing electrodes, an additional accelerating voltage greater than the above 32 V is necessary. The electrodes are 1' long. Assume that a particle traveling at the rms velocity straight down the center of the vacuum chamber must be deflected enough to strike the negative electrode. The additional voltage required per electrode for each species of gas to perform this task is listed in the right most column in the above table. It is truly negligible.

Mean free path calculation assuming the effective molecular diameter to be $2x10^{-10}$ m. The point of this calculation is to verify that the ion motion in the beam is ballistic in nature, since the mean free path is much longer than the vacuum chamber and the distance between clearing electrodes.

Gas	Pressure [nTorr]	Gas Density [m^{-3}]	Mean Free Path [m]
H_2	0.1	$3.5x10^{12}$	$2.3x10^{6}$
$CO+N_2$	0.002	$7.1x10^{10}$	$1.1x10^{8}$

As shown in the above, the motion of ions is not significantly affected by other ions in the range of pressure that is found in the Recycler vacuum system. Therefore, it is not unreasonable to assume that a molecule ionized in the beam will travel unmolested longitudinally. This geometry, with the approximate relative geometry between two clearing stations in a Recycler half cell, is shown in the figure below.



Sketch of an ionized molecule with an initial longitudinal velocity in a geometry very similar to that inside a Recycler half cell.

The clearing electrodes act as a black hole, eliminating every ion that traverses them. If the distance between the clearing electrodes is L_{ce}, and the rms velocity of an ion is σ_v, then the average time τ it takes an ion heading toward a particular electrode to be eliminated from the beam is

$$\tau = \frac{L_{ce}}{\sigma_v}$$

Plugging in this result yields an estimate of the equilibrium average trapped ion density between the clearing electrodes. Using previously present values for the relevant parameters, the calculations of this average ion density for each gas species is listed in the table below. The worst case density is **10,000x** lower than expected at neutralization.

Calculation of the equilibrium ion longitudinal density assuming a distance between clearing stations of 6 m.

Gas	Clearing Time [ms]	Ion Density [m^{-1}]
H_2	5.3	1.4×10^5
$CO+N_2$	20	5.2×10^4

Ion Clearing from the Magnets

When a gas molecule is ionized inside a magnet, the ions execute very tight horizontal cyclotron oscillations around the magnetic field lines. If these magnets were pure dipoles, the only mechanism for ion transport to the clearing electrodes would have been ExB drift generated by the space charge radial electric field of the beam. At the radial field maximum of **675 V/m**, for a relatively improbable ion more than a sigma away from the beam center, the drift velocity is 675 / 0.15= **4500 m/s**. But the small amplitude ions can see an order of magnitude smaller electric field, and for the case of low beam intensity the electric field is yet again another order of magnitude smaller. On the other hand, that still leaves a factor of **100x** lower density than expected if the beam were completely neutralized.

In addition, the gradient portion of the Recycler bend magnets introduce ∇B drift. As an ion executes horizontal cyclotron orbits, the gradient in the dipole field causes these orbits to have a horizontal position dependent radius of curvature. This causes the particle to drift longitudinally. The drift velocity v_d depends on the cyclotron radius r_c, the field gradient g, and the cyclotron frequency f_c according to the equation

$$v_d = \pi f_c \, g \, r_c^2$$

The table below contains the results of this calculation for the gas species of interest. The gradient for the normal cell Recycler gradient magnets is **2.5 m^{-1}**. Note that compared to the neutralizing ion density of **1.2×10^9 m^{-1}**, the H_2 density in the magnet is almost unaffected whereas the $CO+N_2$ density is a factor of 20x below neutralization. Taking into account the fact that the gradient magnets make up approximately half of the ring, this indicates that with clearing electrodes only that $CO+N_2$ neutralization can be avoided. Both the gap and electrodes seem to be needed for H_2.

Calculation of the equilibrium ion longitudinal density in a gradient magnet assuming ∇B drift as the mechanism for trapped ion loss. The expected average equilibrium ion densities in the magnets are also calculated.

Gas	Cyclotron Freq. [MHz]	Drift Speed [m/s]	Magnet Ion Density [m^{-1}]
H_2	1.1	0.19	5.2×10^8
$CO+N_2$	0.082	0.22	5.2×10^7

Vacuum Specification

The beam tube vacuum pressure requirement is determined by antiproton intensity lifetime, antiproton emittance growth, and ion trapping considerations. The emittance growth rates should be small compared to the anticipated intrabeam scattering growth rates. The intensity lifetime should be long enough insure that the stacking rate necessary to achieve the required antiproton intensity is not increased by more than a few percent. Because vacuum pressures always improve with time, the specification quoted in this section will apply to the initial pressure needed for reasonable operations.

The transverse normalized 95% emittance growth rate is determined by multiple Coulomb scattering with the nuclei of the residual gas in the beam tube. Assuming a relativistic beam, the equation describing this growth rate can be written as

$$\dot{\varepsilon}_n = \frac{3\langle\beta\rangle}{\gamma_r}\left(\frac{15\ \mathrm{MeV}}{mc^2}\right)^2 \frac{c}{L_{rad}}$$

where $<\beta>$ is the average beta function of the accelerator, γ_r is the relativistic energy of the beam, and L_{rad} is the radiation length of the gas at a given temperature and pressure. Radiation length values at standard temperature (0 °C) and pressure (760 Torr) are listed below.

Radiation lengths for the two constituent molecules commonly found in a high vacuum stainless steel system such as that expected for the Recycler ring.

Gas	Radiation Length (g/cm^2)	Density @STP (g/l)	Radiation Length (m)
H_2	61	0.090	6800
$CO+N_2$	38	1.25	300

Normalized 95% emittance growth rate for each component gas in a high vacuum system.

Gas	Partial Pressure (nTorr)	Radiation Length (m)	Emittance Growth Rate (π mmmr/hr)	Emittance Growth Time (hrs)
H_2	0.1	5.2×10^{16}	0.05	200
$CO+N_2$	0.002	6.0×10^{15}	0.05	200

Assuming an average beta function value of 30 m and a kinetic energy of 8 GeV, the emittance growth rates for the same constituent vacuum gasses are listed in the above table. Note that the measured and expected ratio of hydrogen to nitrogen/carbon monoxide is set at 50:1. As will be shown later, these pressures are the result of measured outgassing rates and calculated pumping speeds. In order to calculate an emittance growth time, a base emittance of 10 π mmmr is assumed.

The stochastic cooling system is anticipated to have an emittance cooling time of approximately 4 hours. From the above table it is can be shown that maintaining an average $CO+N_2$ partial pressure of less than 0.1 nTorr is necessary for Recycler operations.

Nuclear interaction lengths for the two constituent molecules commonly found in a high vacuum stainless steel system.

Gas	Nuclear Int. Length (g/cm^2)	Density @STP (g/l)	Nuclear Interaction Length (m)
H_2	51	0.090	5700
$CO+N_2$	88	1.25	704

Intensity lifetime due to nuclear interactions with each component gas in a high vacuum system.

Gas	Partial Pressure (nTorr)	Nuclear Interaction Length (m)	Antiproton Loss Time (hrs)	Antiproton Loss Rate (10^{10}/hrs)
H_2	0.1	4.3×10^{16}	40,000	0.0063
$CO+N_2$	0.002	1.4×10^{17}	250,000	0.0010

The other consideration is particle lifetime. The two mechanisms which remove particles from the ring are nuclear interactions and large angle Coulomb scattering (Rutherford scattering).
Nuclear interactions are typically broken down between elastic and inelastic scattering. Though a portion of the elastically scattered particles would stay in the accelerator, it is easier to take the worst case assumption that they are all lost. In that case the total cross-sections, characterized as a nuclear interaction length, is used. In the above table the lifetime and particle loss rates are calculated using a base intensity of 250×10^{10} antiprotons in the Recycler.

Single large angle Coulomb scattering angles greater than the angular acceptance of the Recycler occur with a frequency described by the equation

$$\sigma_{el} = \frac{2\pi r_p^2 Z^2}{\gamma_r^2} \frac{\beta_y}{A_y}$$

The lifetime associated with this cross-section is

$$\tau_{el} = \frac{1}{n_{gas}\, \sigma_{el}\, \beta c}$$

The results of these calculations are listed in the table below.

Intensity lifetime due to large angle Coulomb scattering.

Gas	Partial Pressure (nTorr)	Cross-Section (mbarns)	Antiproton Loss Time (hrs)	Antiproton Loss Rate (10^{10}/hrs)
H_2	0.1	17	30,000	0.008
$CO+N_2$	0.002	870	30,000	0.008

In conclusion, even though its partial pressure is lower than the hydrogen, the $CO+N_2$ is comparable in both the particle loss and the emittance growth rate. A partial pressure less than $1x10^{-10}$ Torr is desirable for those species.

Outgassing of Stainless Steel

The spacing and pumping speed of the lumped ion-sputter and titanium sublimation pumps in a traditional Fermilab system is determined by the outgassing rate of gas molecules from the surface of the stainless steel vacuum tube. Because the cost of the vacuum system scales with the number of pumps, minimizing this outgassing rate is very desirable.

Upon chemically cleaning a stainless steel tube and performing a 150°C bake after system assembly, a hydrogen surface outgassing rate of $1x10^{-12}$ T-l/cm^2-sec is achievable. At this point the only other gas in the system is CO+N_2, which comes dominantly from the ion pumps and ion gauges. The hydrogen comes from diffusion of molecules out of the bulk of the stainless steel material. The key to reducing the cost of the Recycler vacuum system is to eliminate this bulk hydrogen.

High concentrations of hydrogen exist in stainless steel because of one step in it's production, when the steel is quenched in a hydrogen atmosphere. It has been found [R. Calder and G. Lewin, Brit. J. Appl. Phys. **18**, 1459 (1967)] that the hydrogen can be removed by heating the stainless steel in a good vacuum (<10^{-6} Torr) at a temperature of approximately **500°C**. Using this technique, measurement results at Fermilab with a 30 m test vacuum system have found hydrogen surface outgassing rates of **$2x10^{-13}$ T-l/cm^2-sec**, even though it turns out that the ultimate pressure during the bake was only 10^{-3} Torr and multiple vacuum accidents during studies. More details concerning the hydrogen degassing oven and its operation can be found later in this talk.

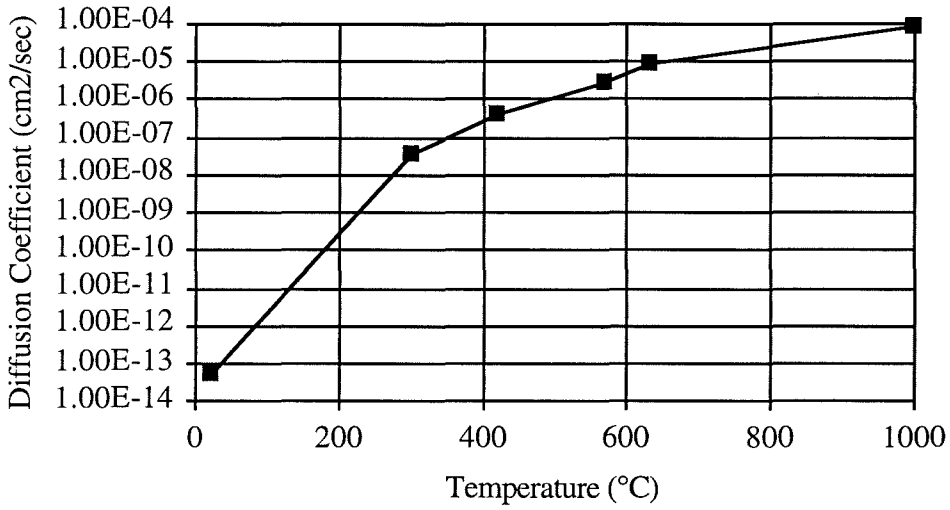
The calculation of time and temperature vs. hydrogen degassing of stainless steel is rather straightforward. Assume that an infinite slab of stainless steel of thickness d is placed in a perfect vacuum and heated to some temperature T. The one dimensional diffusion equation describing this situation is

$$D\frac{\partial^2 c}{\partial x^2} = \frac{\partial c}{\partial t}$$

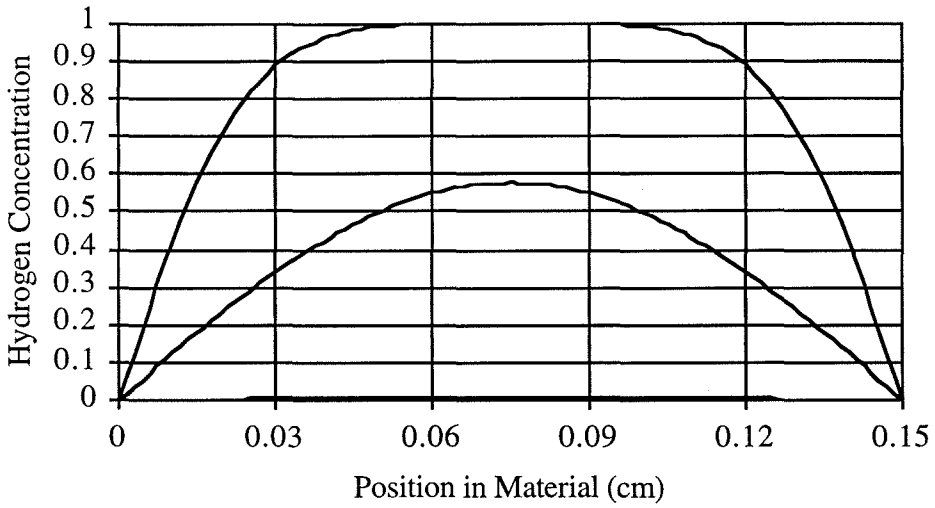
The diffusion coefficient D as a function of some typical outgassing temperatures is plotted in the figure on the next page.

The initial condition is that the stainless steel is uniformly saturated with hydrogen at some initial concentration c_o. As compared to an atmospheric hydrogen concentration of **1.4×10^{-4} T-l/cm^3**, the initial concentration found in 300 series austentic stainless steels is **0.3 T-l/cm^3**. Outside of the slab it is assumed that a perfect vacuum exists. The solution of the differential equation with these boundary conditions can be written in terms of an infinite sum

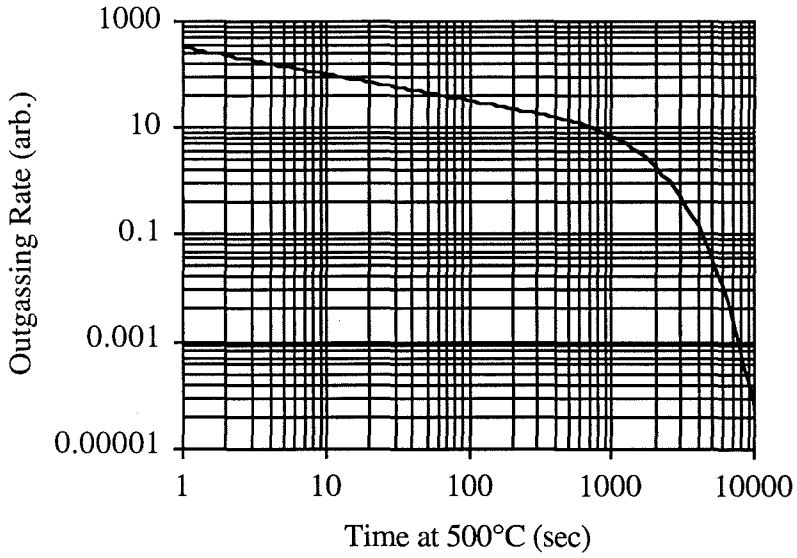
$$c(x,t) = c_o \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{1}{(2n+1)} \sin \frac{\pi(2n+1)x}{d} \exp\left[-\left(\frac{\pi(2n+1)}{d} \right)^2 Dt \right]$$



Hydrogen diffusion rate as a function of temperature in stainless steel. The data points are at typical degassing temperatures. The lines are for the purpose of interpolation.



Hydrogen concentration profile across the beam tube wall as a function of time at 500°C. In the beginning the concentration is uniform and scaled to unity. The curves show the concentration profiles after 60 sec, 10 minutes, and 1 hour. After 3 hours the concentration is $1x10^{-7}$.



Hydrogen outgassing rate after cooldown as a function of the time spent at 500°C for degassing.

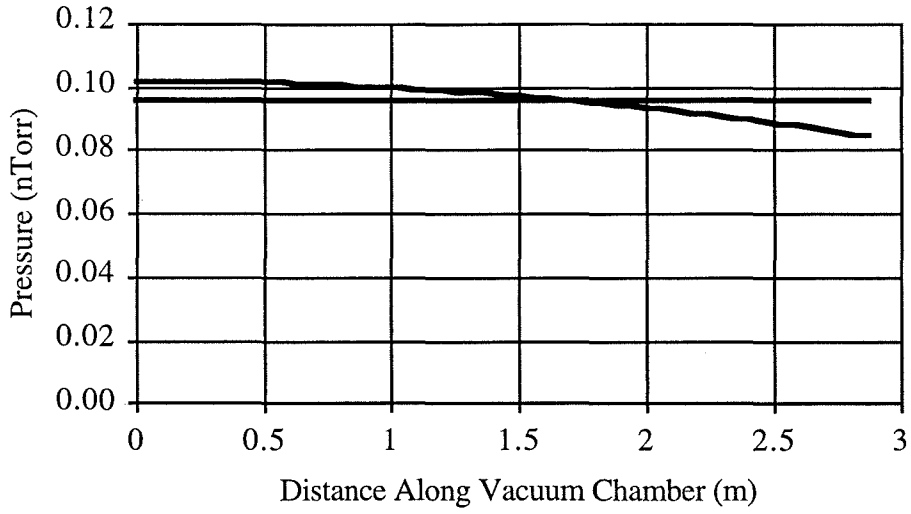
For the case of Recycler vacuum chamber, using a diffusion coefficient of **$1x10^{-6}$ cm²/sec** (500°C) and a thickness d of 0.065" (approximately 1.5 mm), the concentration profile through the vacuum tube wall as a function of position in the wall and time at temperature is plotted above.

Pressure Calculations

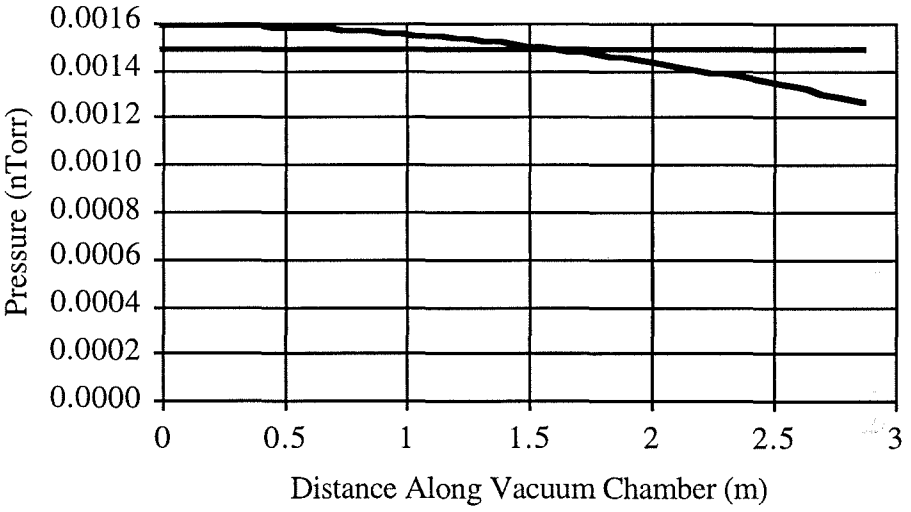
Parameters expected to describe the vacuum system in the Recycler ring. This spacing corresponds to three 30 liter/sec pump (either ion or titanium sublimation) per half cell, where the pumping speed (assuming ion pumps) was derated to account for saturation and low pressures at the pump.

Parameter	H_2	$CO+N_2$
Lumped Pump Pumping Speed (L/s)	30	10
Surface Outgassing Rate (T-L/s-cm^2)	$2x10^{-13}$	$1x10^{-15}$
Distance between Lumped Pumps (m)	5.75	5.75
Total Width of Elliptical Pipe (inch)	3.75	3.75
Total Height of Elliptical Pipe (inch)	1.75	1.75
Molecular Mass of the Gas	2	28
Specific Conductance (m-L/s)	100	28
Specific Outgassing Rate (T-L/s-m)	$4.4x10^{-10}$	$2.2x10^{-12}$
Pressure at Lumped Pumps (nTorr)	0.084	0.0013
Pressure Halfway between Pumps (nTorr)	0.100	0.0016
Average Pressure (nTorr)	0.096	0.0015

The ion pumps to be used are 30 liter/sec pumps, but the actual pumping speeds are derated because of the low pressures and assuming that the pumps are nitrogen saturated during pumpdown. The majority of the pumps are of the titanium sublimation variety, which have much lower ultimate pressure and much higher typical pumping speeds. The present titanium sublimation pumps are also planned to have a speed of at least 30 liter/sec. The following figures show the dependence of pressure on position in the beam tube. Note that the average pressures described are much lower than assumed in the lifetime discussions above.



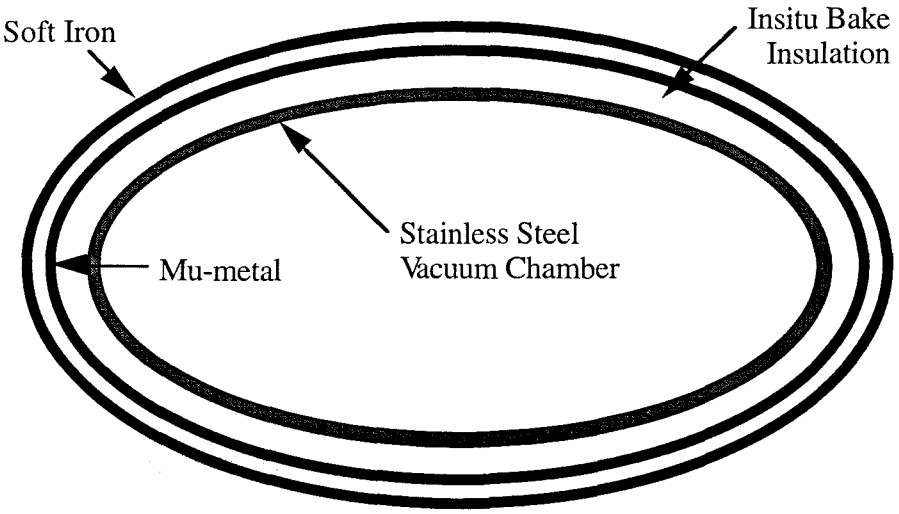
Hydrogen partial pressure as a function of distance along the vacuum tube. The origin is the symmetry point halfway between any two pumps. The horizontal line designates the average pressure.



$CO+N_2$ partial pressure as a function of distance along the vacuum tube. The origin is the symmetry point halfway between any two pumps. The horizontal line designates the average pressure.

Magnetic Shielding

There are many sources of time-dependent magnetic fields which if left unshielded would modulate the closed orbit position and tune of the Recycler beam. Therefore, it has been decided to generate a hermetic seal of magnetic shielding around the Recycler vacuum chamber. In order to save money the insitu bake insulation and the magnetic shielding have been merged into the same effort. Because of this link to the insitu insulation, and because of the need to integrate the shielding with the vacuum fabrication, magnetic shielding is one of the responsibilities of the vacuum Recycler group. A sketch of the geometry of the magnetic shielding and insitu bake insulation is displayed in the following figure. The regions of vacuum chamber occupied by magnets do not require shielding due to the thick flux return they employ.



Sketch of the integrated magnetic shielding and insitu bake insulation for the Recycler ring.

The dominant sources of stray time-dependent magnetic fields at the Recycler tunnel position are:

1) Main Injector magnet fringe fields. These have been measured to be no more than 2 Gauss at the Recycler position [A. Mokhtarani & P. Mantsch, MTF-94-0052 (1994)].

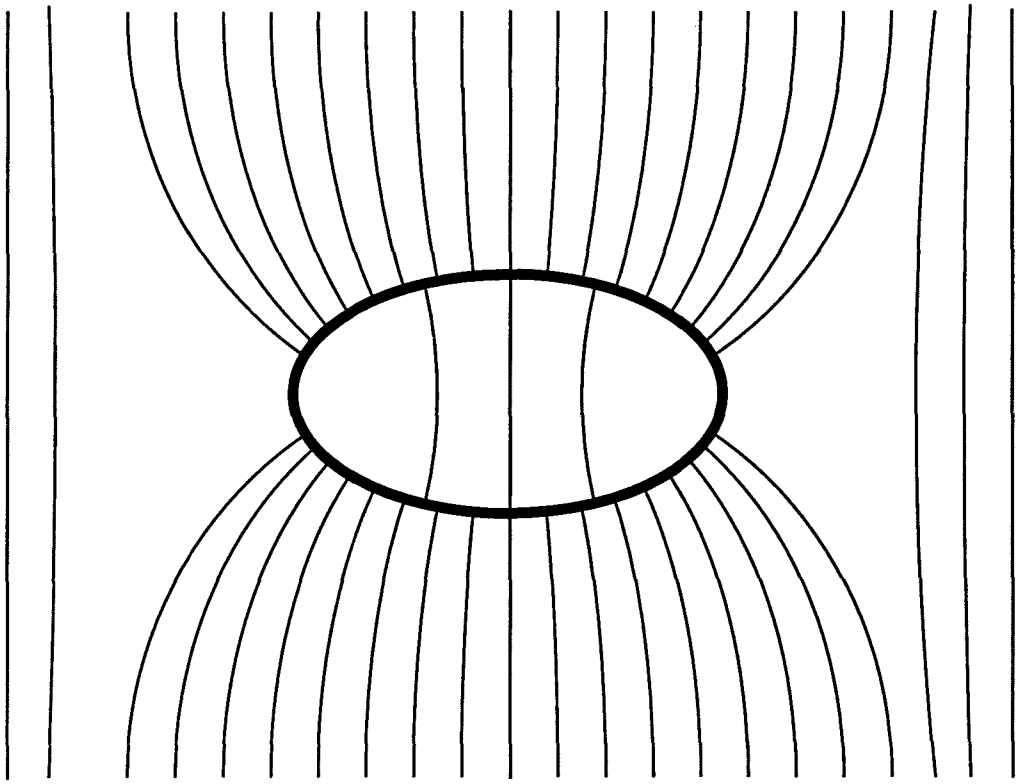
2) Main Injector magnet bus bypasses. By calculating the dipole field generated by a pair of busses near the wall at the Main Injector elevation, a maximum field of 2 Gauss is calculated.

3) Uncompensated quadrupole loop current. The focusing and defocusing quadrupole circuits are each single loops around the tunnel. Therefore, the net current difference between these loops will generate a net magnetic flux through the wetland inside the Main Injector. More important, it would generate approximately 4 Gauss at the Recycler beam pipe.

4) High current cables in trays. One example would be Lambertson cables. Estimates generate fields as high as 5 Gauss.

In order to firm up these estimates and to identify any unanticipated source of field, a flux measurement experiment is being designed for the Main Ring tunnel at the comparable elevation of the Recycler. Another purpose of this test is to measure the actual field attenuation one obtains from magnetic shielding. There is some doubt as the validity of more detailed calculations of magnetic shields in the milliGauss field range. It is because of these doubts that only semi-quantitative calculations are presented below.

A system capable of shielding the beam to an extent comparable to the dipole field strength criterion is necessary. The fields in the gradient magnets is specified to have a maximum allowable error of 5×10^{-4} in a field of 1.5 kG. This corresponds to approximately 1 Gauss over roughly 4 m. In order to assure that systematic or random effects from the time dependent fields are negligible, especially in alignment sensitive regions such as the stochastic cooling pickups, a stray field goal at the Recycler beam of 10 mG has been specified.



Sketch of magnetic field lines from the tunnel being drawn into the soft iron shield around the beam pipe. Note that due to the finite permeability of the iron, approximately 0.1% of the flux continues through to the beam.

When a layer of soft iron is wrapped around an otherwise non-ferric material such as the beam pipe, the higher permeability of the iron pulls magnetic flux lines from an area approximately double the width of the iron geometry. In the case of the Recycler, this covers an area almost 8" across. The plan is to use a layer of soft iron which is 6 mils thick. Therefore, the peak magnetic field in the soft iron is approximately 670 times larger than the ambient field. Since the saturation field of the soft iron is 20 kG, this puts an upper limit on the magnetic field at the Recycler of 30 Gauss. This is 5-10 times higher than anticipated. In specific locations in which there are known or discovered high magnetic field generating devices, extra shielding can be added to prevent the soft iron from going into saturation.

The problem with the above solution is that even when not in saturation, the soft iron has a finite permeability of approximately 3000-5000. Therefore, some fraction of the ambient tunnel magnetic flux still penetrates to the beam. For time-dependent fields the maximum level of attenuation is approximately 1000x. It is for this reason that mu-metal is inserted as an addition layer between the beam pipe and the soft iron.

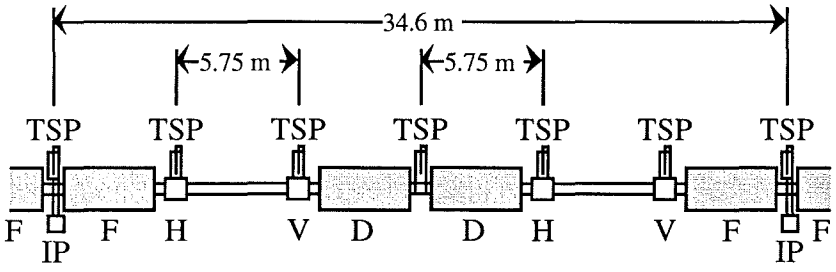
The disadvantage of mu-metal is that it's saturation level is on 8 kG. On the other hand, it's permeability is in the range of 12,000-400,000. At fields up to 3 kG and frequencies up to 60 Hz, field attenuation factors of 100,000x are achievable [Amuneal Manufacturing Corp., "Complete Guide to Magnetic Shielding"]. The plan for the Recycler is to use a mu-metal layer which is 4 mil thick. Over basically the same area, the maximum residual field inside the soft iron which the mu-metal can shield is 2 Gauss. By design, this field matches the leakage expected through the soft iron just as it begins to seriously saturate.

The power spectrum of the magnetic fields in the tunnel below 60 Hz should be dominated by 0.5 Hz from the basic Main Injector ramp plus the first 10-100 harmonics needed to reproduce the more complex, non-sinusoidal current waveforms found in most correctors, busses, and specialty devices (such as Lambertsons). At these frequencies both the soft iron and mu-metal still behave as if exposed to a constant magnetic field.

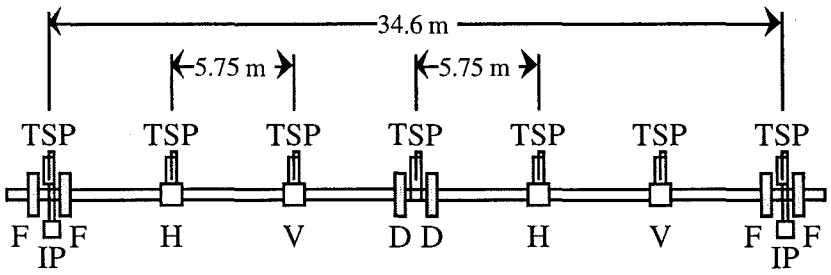
Vacuum Hardware Overview

There are 208 half cells in the Recycler ring. Because of the low outgassing rates accessible with the hydrogen degassing technique described earlier in this talk, a vacuum pressure two orders of magnitude lower than the Main Injector can be achieved with the same number of pumps. In this discussion the type, placement, and processing of Recycler ring vacuum components are reviewed.

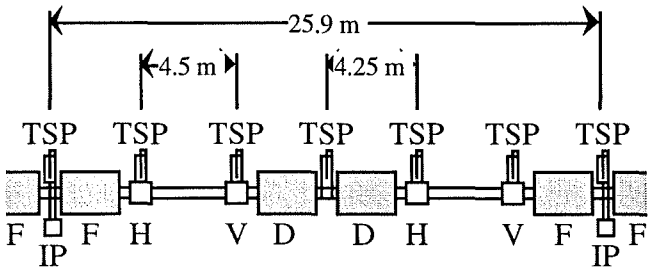
In the Main Injector there are 6 ion pumps per cell and the length of vacuum sectors is approximately 500' (150 m). In the Recycler there will be one ion pump per cell, for a total of 104 ion pumps. There will be 6 titanium sublimation pumps (TSPs) per cell to achieve an average of pressure of approximately $1x10^{-10}$ Torr. The benefit of TSPs are lower cost and lower ultimate pressures. Since the length of normal cells is 34 m and the length of dispersion cells is 26 m, the longest vacuum sector possible if the isolation valves are spaced every 8 cells apart is 270 m. Therefore, the total number of sector valves is $104 \div 8 = 26$. Figures 3.2.1 through 3.2.3 contain sketches of the vacuum system in normal arc cells, straight section cells, and dispersion suppression arc cells.



Sketch of the vacuum system in a normal arc cell. The horizontal (H) and vertical (V) beam position monitors have attached to them titanium sublimation pumps (TSP) in order to maintain a low average pressure and to minimize the number of welds in the tunnel.



Sketch of the vacuum system in a normal straight section cell. Except for the fact that the quadrupoles are much shorter than the gradient magnets in the normal arc cell, nothing is different with respect to the previous figure.



Sketch of the vacuum system in a dispersion suppresser cell.

With the exception of the MI-60 phase trombone straight cells which need additional vertical aperture and hence a round 3" O.D. beam tube, the Recycler vacuum tube is a 1.75" inside height by 3.75" inside width ellipse. It is produced by crushing a standard 3" O.D. beam tube with a wall thickness of 0.065".

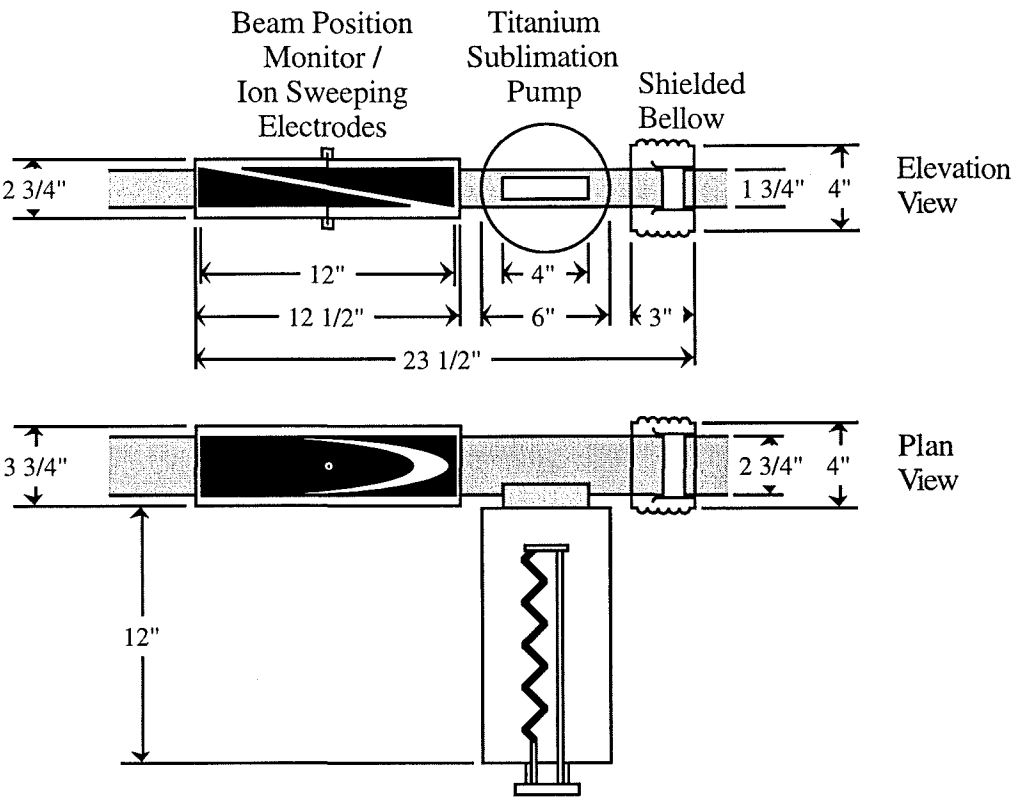
Beam Position Monitor Assemblies

In order to minimize the cost of the vacuum system, it is necessary to minimize the number of welds in the tunnel. This means generating as many pre-fabricated assemblies in industry and staging areas as possible. In addition, if possible it is good to merge multiple functionalities into the same component. For instance, the beam position monitor (BPM) can also act as an ion clearing electrode.

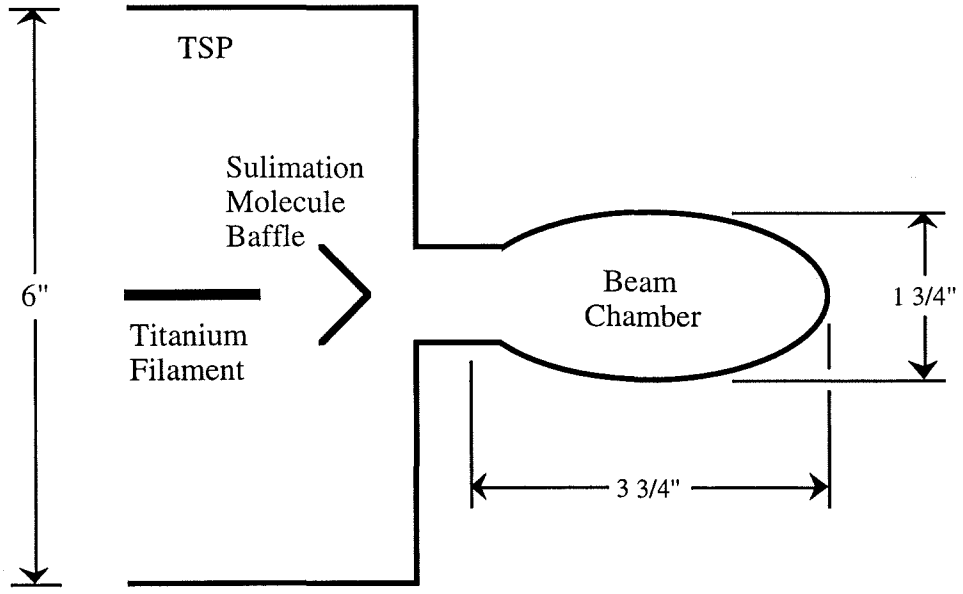
Another innovation is the use of titanium electrodes in order to get ion pumping from the BPMs. The sputtering yield for 500 eV argon ions bombarding metalic surfaces have been measured (Maissel, Physics of Thin Films, Vol. 3, p.73). Whereas the coefficients for aluminum and steel are 1.05 and 1.10 respectively, the coefficient for titanium is only 0.51. Therefore, titanium seems to be the prefered electrode material, with the side benefit that the sputtering which does occur creates a fresh surface which allows the titanium surface to pump.

Because both protons and antiprotons are injected into the Recycler for operations, commissioning, and studies, the beam position monitors need to be bi-directional. Capacitive split-tube electrodes are optimum in a geometry where the transverse beam size is comparable to the electrode dimensions. Capacitive electrodes are also perfect for the creation of ion clearing electrodes. In order to minimize the impedance effects of the BPMs, the electrodes are shaped to match the vacuum chamber, the outer wall of the BPM is the same shape as the electrodes and only large enough to stand off the 700 V of ion clearing voltage. For the same reasons, the gaps between the electrodes and vacuum chamber wall are minimized without compromising the capacitance (sensitivity) of the electrodes.

At each BPM locations a bellow is required to absorb the length increase which occurs in the vacuum system when it is insitu baked at 150°C. In order to simply the beam pipe positioning stands and installation, the bellows are always located to the outside of both BPMs in a half cell. As shown in the figure below, between the BPMs and bellows are TSPs. The TSP port is a rectangular slot 4" long and 1" high centered on the horizontal edge of the chamber (see the second figure below). The horizontal edge of the vacuum chamber supports the minimum of the image current distribution, so therefore this geometry has the lowest impedance impact while simultaneously maximizing the conductance to the pump itself.



Elevation and plan views of the BPM assemblies which each include a TSP and shielded bellows. A vertical BPM is shown, which is on the downstream side of each half cell.

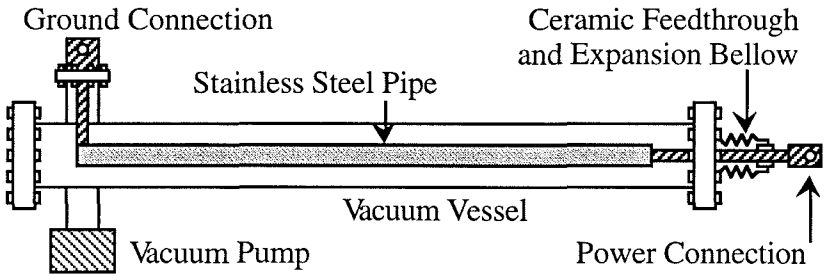


Beam's eye cross-section view of the TSP and its connection to the beam tube.

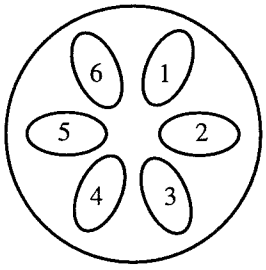
Hydrogen Degassing Oven

Before the hydrogen degassing is performed, the tubing is washed and cleaned internally with solvents. The tubing is then sent over to a former superconducting coil collar hydraulic press used for crushing the pipe into the correct elliptical shape. The design profile has an inner full height of 1.75 in. and a full width of 3.75 in.

In order to achieve this vacuum system configuration and achieve an average vacuum of approximately $1x10^{-10}$ Torr, it is necessary to hydrogen degas every component. The test oven shown in the figure below will be used for specialty pieces such as 1.5" diameter tubing for gauges. The 3" diameter tubing used to generate the vacuum chamber itself needs to be processed at a rate of approximately one half cell per day in order to keep up with the projected rate of magnet production. This criterion requires three 20' pipes per day. As shown below, by creating a new oven which has a 12" diameter, a total of six pipes per day could be processed. Since the processing requires that the tubing stay at a temperature of 500°C for approximately 12 hours and the time constant of the heating and cooling is approximately 4 hours, one batch of six pipes per day is a convenient processing rate.



Sketch of the test oven which will still be used to process specialty tubing.



Profile of the crushed 3" tubing in the 12" diameter production oven proposed to generate an average of 2 half cells of tubing per day.