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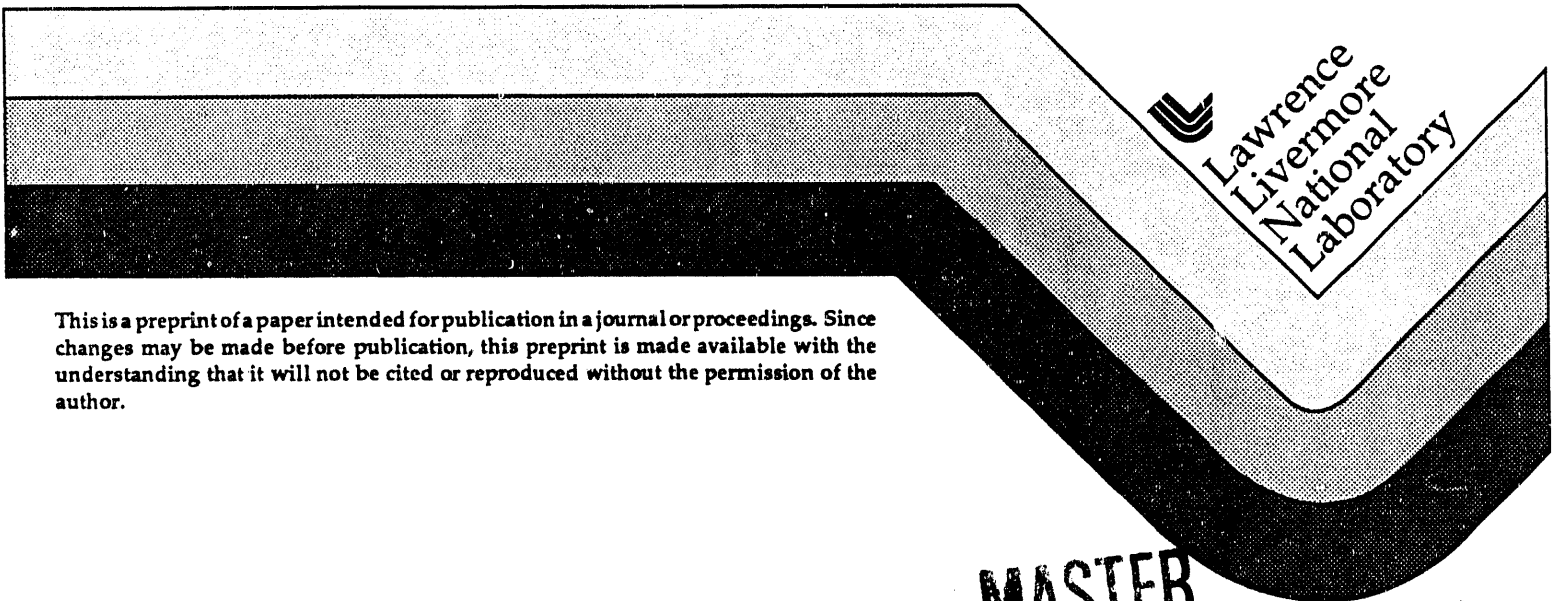
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## Vacuum Requirements for Heavy Ion Recirculating Induction Linacs

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# VACUUM REQUIREMENTS FOR HEAVY ION RECIRCULATING INDUCTION LINACS\*

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**Abstract:** We examine the requirements of the vacuum system for the LLNL/LBL recirculating induction linac concept. We reexamine processes, including beam stripping, background gas ionization, intra-beam charge exchange and desorption of gas molecules from the wall due to the incident ionized gas molecules and stripped ions, in the context of the proposed recirculator. We discuss implications for the vacuum system layout and estimate the cost of such a system.

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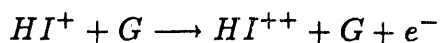
## I. Introduction

In a recirculating heavy ion induction accelerator, the residence time of an ion beam in the accelerator can be a factor of ten or more longer than in a linear accelerator, due to the lower average accelerating gradient in the recirculator. This requires an allowed background gas density in the recirculator that is lower by a factor roughly equal to the ratio of the residence times. In addition, the beam will desorb gas molecules from the wall, and will propagate, on subsequent laps around the recirculator, through the beam-induced desorbed gas, placing more stringent requirements on the vacuum pumping rates. A number of processes have been identified in previous work (cf. refs. 1-4) which cause loss of the heavy ion beam; we shall rely heavily on this work. As in previous work a number of uncertainties exist in our knowledge of cross sections and desorption coefficients. The main purpose of this paper is to make our best estimate of how severe the vacuum and pumping requirements might be in a heavy ion recirculator used as the driver for an inertial confinement fusion power plant. In particular, we will focus on the recirculator design presented by Yu et al at this conference.

## II. Processes

For the purpose of this paper, we consider four processes which have been identified in ref. 3 as contributing to possible losses of the heavy ion beam: Stripping, Background Gas Ionization, Beam Induced Gas Desorption, and Beam-Beam Charge Exchange. We briefly review these processes:

**Stripping:** Stripping occurs when an electron is stripped off of a heavy ion, upon an interaction with a gas particle:



Here  $HI$  represents heavy ion and  $G$  stands for gas molecule. In the recirculator, due to the presence of the bending magnets, a particle of a charge state that is higher or lower

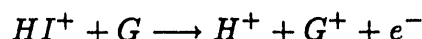
by one electron charge will be lost in a distance that is short compared to the ring radius. The cross-section for stripping and excitation in the Born approximation  $\sigma_{sB}$  is calculated in ref. (5) and graphed in ref. (4) and is given approximately by:

$$\sigma_s < \sigma_{sB} \cong \begin{cases} 1.0 \times 10^{-17} (Z_b/92) \beta^{-2} \text{ cm}^2 & (\text{N}_2) \\ 1.0 \times 10^{-18} (Z_b/92) \beta^{-2} \text{ cm}^2 & (\text{H}_2) \end{cases} \quad (1)$$

Here  $\text{N}_2$  and  $\text{H}_2$  are the background gasses,  $Z_b$  is the atomic number of the heavy ion beam, and  $\sigma_s$  is the stripping cross-section alone. This cross-section is valid for large ion velocities ( $v_i \gg \alpha c$  where  $\alpha$  is the fine structure constant and  $c$  is the speed of light). At low energies, the cross section increases with increasing energy. At intermediate energies a broad peak in the cross section occurs.

Where the exact turn-over occurs is uncertain. Low energy experimental data (refs. 6 and 7) indicates that for Uranium ions ( $Z_b = 92$ ) being stripped by  $\text{N}_2$  background gas at energies around 1-2 MeV the cross section already appears quite flat and is around  $1.0 \times 10^{-15} \text{ cm}^2$ .

**Gas Ionization:** Here a beam particle ionizes a background gas particle:



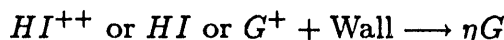
The Born cross section for excitation and ionization  $\sigma_{ionB}$  is given in ref. (5) as:

$$\sigma_{ion} < \sigma_{ionB} \cong 1.2 \times 10^{-16} (Z_b/92)^{2/3} \beta^{-2} \text{ cm}^2 \quad (2)$$

Here  $\sigma_{ion}$  is the actual ionization cross section. Again, low energy data of lighter ions suggests that the maximum may be as low as  $\sim 10^{-15} \text{ cm}^2$  for beam particles of atomic mass  $A_b \cong 200$  on molecular nitrogen gas (cf. e.g. ref. 8).

As pointed out in ref. (3) gas ionization does not directly lead to beam loss, but rather indirectly through interactions with the walls, leading to increased gas density.

**Beam Induced Gas Desorption:** Here the ionized gas particles, in the presence of the strong radial electric field of the heavy ion beam are driven to the wall with energies up to tens of keV's. There they desorb  $\eta$  gas molecules per incident gas ion:

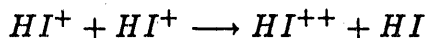


As indicated above stripped or neutralized heavy ions also may contribute to desorption of wall molecules.

The energy gain  $E_{ion}$  of the ions due to the space charge of the beam is approximately  $(2I/\beta_i c) \ln[b/a] = 18 \text{ keV } (I/180\text{A}) (.3/\beta) (\ln[b/a]/0.7)$  where  $I$  is the beam current,  $\beta_i c = v_i$  is the ion beam velocity,  $b$  is the pipe radius and  $a$  is the average beam radius. At these energies sputtering coefficients  $\eta$  are by refs. (9) and (10) experimentally measured to be on the order of a few  $\cong 5$ . These sputtering coefficients are found from specially treated clean surfaces. The actual surfaces found in a recirculator may be "dirtier," but may in fact be cleaned by the process of beam desorption. Large uncertainty exists in our knowledge of  $\eta$ . In ref. (10) an empirical formula for sputtering coefficients as a function of energy, heavy ion and target species is given, with coefficients determined from experimental data, so

that an extrapolation to high energy may be attempted. For lead ions ( $A=207$ ) impinging upon iron targets ( $A=56$ ) with energies of 1 to 10 GeV, impinging normally upon the surface, the desorption coefficient is calculated to be  $\sim .05$  to  $.002$  respectively, decreasing inversely with energy. As the energy increases the ions penetrate deeper within the metal surface and therefore desorb fewer surface atoms. However, as pointed out in ref. 11, the ions will not have normal incidence. In a recirculator, neutralized or stripped ions will have glancing incidence and can dislodge many surface particles, increasing the effective  $\eta_{HI}$  by several orders of magnitude. A possible solution is to ensure that the stripped or neutralized heavy ions strike surfaces at normal incidence by placing circular apertures or scrapers periodically within the beam pipe. Minimum grazing angles  $\theta$  of the heavy ions impinging upon the surface are of the order  $(\Delta r/R)^{1/2}$ , where  $\Delta r$  is the clearance distance between beam and pipe, and  $R$  is the recirculator radius. In order to intercept the misguided ions, scrapers would need to have an aspect ratio (radial extent  $\Delta r_{scrapers}$  divided by the distance between scrapers  $L_{scrapers}$ )  $\geq \theta$ . So  $L_{scrapers} \leq \Delta r_{scrapers}(R/\Delta r)^{1/2}$ . For the large ring of ref. 12,  $R \cong 400$  m and  $\Delta r \cong 3$  cm, the maximum spacing would be about 3.5 m, (for  $\Delta r_{scrapers} = \Delta r$ ). Much smaller  $\Delta r_{scrapers}$  is possible (to avoid intercepting the beam) with correspondingly smaller  $L_{scrapers}$ .

**Beam-Beam Charge Exchange:** In this process two singly charged heavy ions interact transferring one electron, resulting in a doubly charged ion and a neutral ion.



Experimental data exists for singly charged bismuth ( $Z_b = 83$ ,  $A_b = 209$ ) in the energy range of interest (refs. 13 and 14). We parameterize their cross-section measurements approximately as:

$$\sigma_{ce} \cong \begin{cases} 2.1 \times 10^{-16} (E_{cm}/10\text{keV})^{-62} \text{cm}^2 & \text{if } E_{cm} < 19\text{keV} \\ 1.8 \times 10^{-16} (E_{cm}/10\text{keV})^{-94} \text{cm}^2 & \text{if } E_{cm} > 19\text{keV} \end{cases} \quad (3)$$

Here  $E_{cm}$  is the energy in the heavy-ion center of mass frame. Note that  $\sigma_{ce}$  also includes beam ionization,  $HI^+ + HI^+ \longrightarrow HI^{++} + HI^+ + e^-$ , which contributes (to a lesser extent) to beam loss as well.

### III. Background Gas Evolution

The fluid equations may be used to understand the evolution of the gas density within the accelerator pipe. We follow a similar line of reasoning that is pursued in the study of proton storage rings, such as the Intersecting Storage Ring (ISR) at CERN (e.g. refs. 15-17).

The continuity equation (assuming variation only in  $z$  and  $t$ ) becomes:

$$\frac{\partial}{\partial t} n_g + \frac{\partial}{\partial z} n_g v_z = \mu \sigma_s v_i n_b n_g - \frac{S_{lin}}{A_p} n_g + q_{eff} \quad (4)$$

Here,

$$\mu = \left[ \frac{\sigma_{ion}}{\sigma_s} \eta_G + \eta_{HI} \right] \left[ \frac{V_{beam}}{V_{pipe}} \right], \quad (5)$$

$n_g$  = background gas number density,  $n_b$  = heavy ion beam number density,  $v_b$  = heavy ion velocity,  $v_z$  = z-component of background gas fluid velocity at time  $t$  and position along acceleration direction  $z$ ;  $S_{lin}$  = linear pump strength (dimensions unit volume per unit time per unit distance),  $A_p$  = cross-sectional area of pipe =  $\pi b^2$ , where  $b$  = pipe radius;  $q_{eff} = q + q_{ce}$  is the sum of the intrinsic outgassing rate per unit distance along the accelerator  $q$  and the outgassing rate due to desorbed gases from heavy-ions which have been lost due to charge exchange  $q_{ce}$ . Note that  $q = 2Q_o/b$  where  $Q_o$  = intrinsic outgassing rate per unit surface area and  $b$  is the pipe radius;  $q_{ce} = \eta_{HI} n_b^2 \sigma_{ce} v_{cm} (V_{beam}/V_{pipe})$ ;  $\eta_{HI}$  and  $\eta_G$  are the desorption coefficients due to heavy ions and gas ions, respectively;  $V_{beam} =$  the total volume of the beam =  $\pi a^2 v_i \Delta t$ , where  $a$  = beam radius,  $\Delta t$  = pulse duration;  $V_{pipe} =$  volume of the pipe =  $\pi b^2 C$  where  $C$  = the circumference of the recirculator;  $v_{cm}$  is the average thermal velocity of the ions in the comoving ion frame.

In eq. (4) the left hand side represents the normal conservation of particles. In addition, on the right hand side there are sources (the first and third terms) and sinks (the second term). The second term represents the effect of distributed (linear) pumps. The first term arises from the desorption of wall molecules by stripped beam particles and ionized background gas particles, while the third term represents intrinsic outgassing plus desorption of wall molecules from beam-beam charge exchange.

The momentum equation (again assuming variation only in  $z$  and  $t$ ) is:

$$\frac{\partial}{\partial t} n_g v_z + \frac{\partial}{\partial z} n_g v_z^2 = -\frac{v_z n_g}{\tau} - \frac{kT}{m_g} \frac{\partial n_g}{\partial z} \quad (6)$$

Here,  $\tau$  = mean time between wall collisions,  $k$  = Boltzmann's constant and  $T$  = gas temperature, and  $m_g$  = the mean mass of the gas molecules.

The second term is the ram pressure term of the background gas and is ignorable, and the first term is the inertial term. The time  $t_s$  for sound traveling at the sound speed  $c_s$  to cross the distance between vacuum pumps  $L$  is usually much less, than the residence time  $t_{res}$  in the recirculator. Since some fraction of  $t_{res}$  is the timescale over which density changes are of interest, we also ignore the first term in the momentum equation. The third term represents the effects of the collisions of gas particles with the walls of the pipe, i.e. the conductance of the pipe, and for timescales of interest, this term is balanced by the pressure gradient (cf. ref. 18):

$$n_g v_z \cong -\frac{\tau kT}{m_g} \frac{\partial n_g}{\partial z} \quad (7)$$

Using eq.(7) to eliminate  $v_z$  the continuity equation becomes:

$$\frac{\partial n_g}{\partial t} = \mu \sigma_s v_i n_b n_g - \frac{S_{lin}}{A_p} n_g + q_{eff} + \frac{\tau kT}{m_g} \frac{\partial^2 n_g}{\partial z^2} \quad (8)$$

The boundary conditions at the lumped pump locations at  $z = \pm L/2$  require that gas flow into the pump aperture is matched by the gas being pumped out: (cf. ref. [16]):

$$S_{lump} n_g|_{z=L/2} = 2n_g v_z A_p|_{z=L/2} = \frac{2\tau kT A_p}{m_g} \frac{\partial n_g}{\partial z}|_{z=L/2} \quad (9)$$

Here  $L$  = the distance between lumped pumps,  $S_{lump}$  = the lumped pumping speed (with dimensions of unit volume per unit time).

Averaging over the distance between pumps,  $L$ , yields an equation for the  $z$ -averaged gas density  $\bar{n}$ :

$$\frac{d\bar{n}}{dt} = \mu\sigma_s v_i n_b \bar{n} - \frac{S_{lin}}{A_p} \bar{n} + q - \frac{S_{lump}}{A_p L} n_g|_{z=L/2} + q_{eff} \quad (10)$$

Now the gas density at a vacuum pump is some fraction  $f$  of the average gas density:  $n_g|_{z=L/2} = f\bar{n}$  where,

$$f \cong \begin{cases} 1 & \text{if } t_{diff} \ll t_{pump} \\ \frac{\pi^2}{4} \frac{t_{pump}}{t_{diff}} & \text{if } t_{diff} \gg t_{pump} \end{cases} \quad (11)$$

Here  $t_{pump} = LA_p/S_{lump}$  = a lumped pumping time,  $t_{diff} = 3L^2/(v_t^2\tau)$  = the diffusion time of a gas particle through the pipe due to wall collisions, and  $\tau = 2a/v_t$  = the time between wall collisions. The factor  $f$  was obtained by assuming a nearly  $\cos(\pi z/L)$  dependence and is correct to within a factor of order unity. Physically, if the pumps are sufficiently close together, or the pump strengths are sufficiently weak, there will be a small density gradient, and the pumps will act as if they are distributed uniformly along the pipe. We may define an effective total linear pump speed  $S_T = S_{lin} + fS_{lump}/L$  and an effective net pumping time  $t_{net} = A_p/(\mu n_b \sigma_s v_i A_p - S_T)$  for which the average gas density equation becomes:

$$\frac{d\bar{n}}{dt} = q_{eff} + \frac{\bar{n}}{t_{net}} \quad (12)$$

Note that  $t_{net}$  is positive (and is thus an exponential growth time) if the gas desorption rate outpaces the pumping rate.

#### IV. Beam Evolution Equation

As discussed in section II, stripping and charge exchange lead to losses from the beam:

$$\frac{dn_b}{dt} = -\sigma_s v_i n_b \bar{n} - \sigma_{ce} v_{cm} n_b^2 \quad (13)$$

We assume that the fractional beam loss is small (even though this may lead to large changes in background gas density). Let  $n_b(t) = n_{b0} - \delta n_b$ . Define  $x = \delta n_b/n_{b0}$ , then eq. (13) becomes:

$$\frac{dx}{dt} \cong \sigma_s v_i \bar{n} + \sigma_{ce} v_{cm} n_{b0} \quad (14)$$

#### V. Approximate Solutions to the Coupled Beam/Gas Equations

In addition to assuming that the fractional beam losses are small ( $x \ll 1$ ), we tentatively make a number of simplifying assumptions to facilitate solution of the coupled equations, (12) and (14). (1). We assume the the quantities  $\sigma_s v_i$ ,  $\sigma_{ion} v_i$ ,  $\sigma_{ce} v_{cm}$ ,  $\eta_{HI}$ , and  $\eta_G$  are constants equal to their average values during the transit of each of the

four rings. (2) We make plausible assumptions about the ionization and stripping cross-sections:  $\sigma_s = \text{Min}[1.0 \times 10^{-15}, 3.0 \times 10^{-18}(Z_b/92)\beta^{-2}] \text{cm}^2$  and  $\sigma_i = \text{Min}[1.0 \times 10^{-15}, 3.0 \times 10^{-17}(Z_b/92)^{2/3}\beta^{-2}] \text{cm}^2$ . Here, the cross-sections are reduced from eqs. (2) and (3) by a factor  $\sim 3$  to take account of the probable lower mean molecular weight of the gas and the inclusion of excitations in the Born cross sections. Using assumption (1), equation (12) has the solution:

$$\bar{n} = -q_{eff}t_{net} + (n_{go} + q_{eff}t_{net}) \exp(t/t_{net}) \quad (15)$$

Here  $n_{go} = \bar{n}$  at  $t = 0$ . Inserting eq. (15) into eq. (14) yields:

$$x = (-\sigma_s v_i q_{eff} t_{net} + n_{bo} \sigma_{ce} v_{cm}) t + \sigma_s v_i t_{net} (n_{go} + q_{eff} t_{net}) (\exp[t/t_{net}] - 1) \quad (16)$$

After the pulse duration  $\Delta t$  the fraction of the beam that is lost to the walls is denoted  $x_f$ . The gas density at  $t = 0$  that is required to obtain a beam loss of  $x_f$  is found by solving eq. (16) for  $n_{go}$ :

$$n_{go} = \frac{x_f + (\sigma_s v_i t_{net} q_{eff} - n_{bo} \sigma_{ce} v_{cm}) \Delta t}{\sigma_s v_i t_{net} (\exp[\Delta t/t_{net}] - 1)} - q_{eff} t_{net} \quad (17)$$

If  $n_{go}$  is greater than given by eq. (17) the beam loss will be greater than  $x_f$ . We have found for the lowest pumping rates,  $t_{net} > 0$ , i.e. the gas density increases exponentially during the pulse despite relatively large vacuum pumps. In that case the gas density is maximum at  $t = \Delta t$  and has value  $n_{gmax}$  given by:

$$n_{gmax} = -q_{eff} t_{net} + (n_{go} + q_{eff} t_{net}) \exp[\Delta t/t_{net}] \quad (18)$$

We may use the relatively large dead time between pulses  $t_d$  ( $> \sim .1$  s) to reduce the gas density back to  $n_{go}$ . Defining the total pump time  $t_s = A_p/S_T$ , the final density at the end of the dead time  $n_{gf}$  is given by:

$$n_{gf} = q t_s + (n_{gmax} - q t_s) \exp[-t_d/t_s] \quad (19)$$

Requiring that  $n_{gf} = n_{go}$  eqs. (18) and (19) may be used to solve for  $n_{go}$  to give:

$$n_{go} = \frac{q t_s - (q_{eff} t_{net} + q t_s) \exp[-t_d/t_s] + q_{eff} t_{net} \exp[\Delta t/t_{net} - t_d/t_s]}{1 - \exp[\Delta t/t_{net} - t_d/t_s]} \quad (20)$$

In eq. (20), the beam loss  $x_f$  did not constrain the value of the initial density, only the requirement that it return to its original value in a time equal to  $t_d + \Delta t$ . In fig. (1), we plot the required  $n_{go}$  in eqs. (17) and (20) as a function of the total linear pump rate  $S_T$ , for parameters that characterize the large ring of ref. 12. It is apparent that as the pump rate is increased a larger initial gas density can be tolerated for a given  $x_f$  while a smaller initial gas density is actually obtained. The value of  $S_T$  at the intersection of the curves  $S_{crit}$  represents the minimum value of  $S_T$  for which the beam loss is no more than  $x_f$ . The evolution of the gas density, for a pump rate  $S_T = S_{crit}$  is plotted in figure (2), again for large ring parameters. Having obtained the effective pump rate  $S_T$ , we may use eq.(11)



to determine the minimum distance  $L_{min}$  such that the pumps are pumping on essentially the average density  $\bar{n}$ .

For each of the four rings of the recirculator, we calculate some of the required pumping parameters based on the model we have described. In table 1, we list these parameters, as well as some of the assumed parameters we have employed. Note that we have assumed only a 2.8 % loss in the high energy ring where the impact of beam loss on efficiency is greatest, whereas we tolerate a 10 % loss of particles in the low energy ring where cross sections are largest but where beam loss is less costly. We estimate the cost of such a system, by assuming a unit cost of \$ 9 / (1 s<sup>-1</sup>), which we estimate is achievable using cryopumps. As can be seen, required, initial densities (corresponding to initial pressures at 300 K) are ~ a few times 10<sup>-10</sup> torr, effective pumping rates are in the 100's to 1000's of 1 s<sup>-1</sup> m<sup>-1</sup> and costs are in the 10's of millions of dollars. This seems to indicate that vacuum technology development and vacuum costs will not require a disproportionate share of recirculator resources. Since there are large uncertainties in our knowledge of cross sections, sputtering coefficients, and other parameters, our intent is to use this type of analysis to indicate the sensitivity on pumping rates and cost on these coefficients, so that future experimental or theoretical work can be focused on the most sensitive of these parameters.

### Acknowledgements

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### Figure Captions

1. The gas density at the entrance of a beam pulse into the large ring of ref. (12) is plotted as a function of the linear pump rate  $S_T$ . The dashed curve is the required initial density (eq. 17) necessary to obtain a given fractional beam loss  $x_f$ . The solid curve (eq. 20) is the initial gas density that is obtained at the given pump rate. The curves indicate that as the pump rate is increased a larger initial gas density can be tolerated to achieve a given  $x_f$ , while a lower gas density is actually achieved. The minimum pump rate required to obtain  $x_f$  occurs at the intersection of the two curves.
2. Evolution of the gas density as a function of time, at the minimum pump rate (see figure 1) and parameters of the large ring of ref. (12) (see table 1).

### Table Caption

1. Parameters of the four rings of the recirculator of ref. (12).

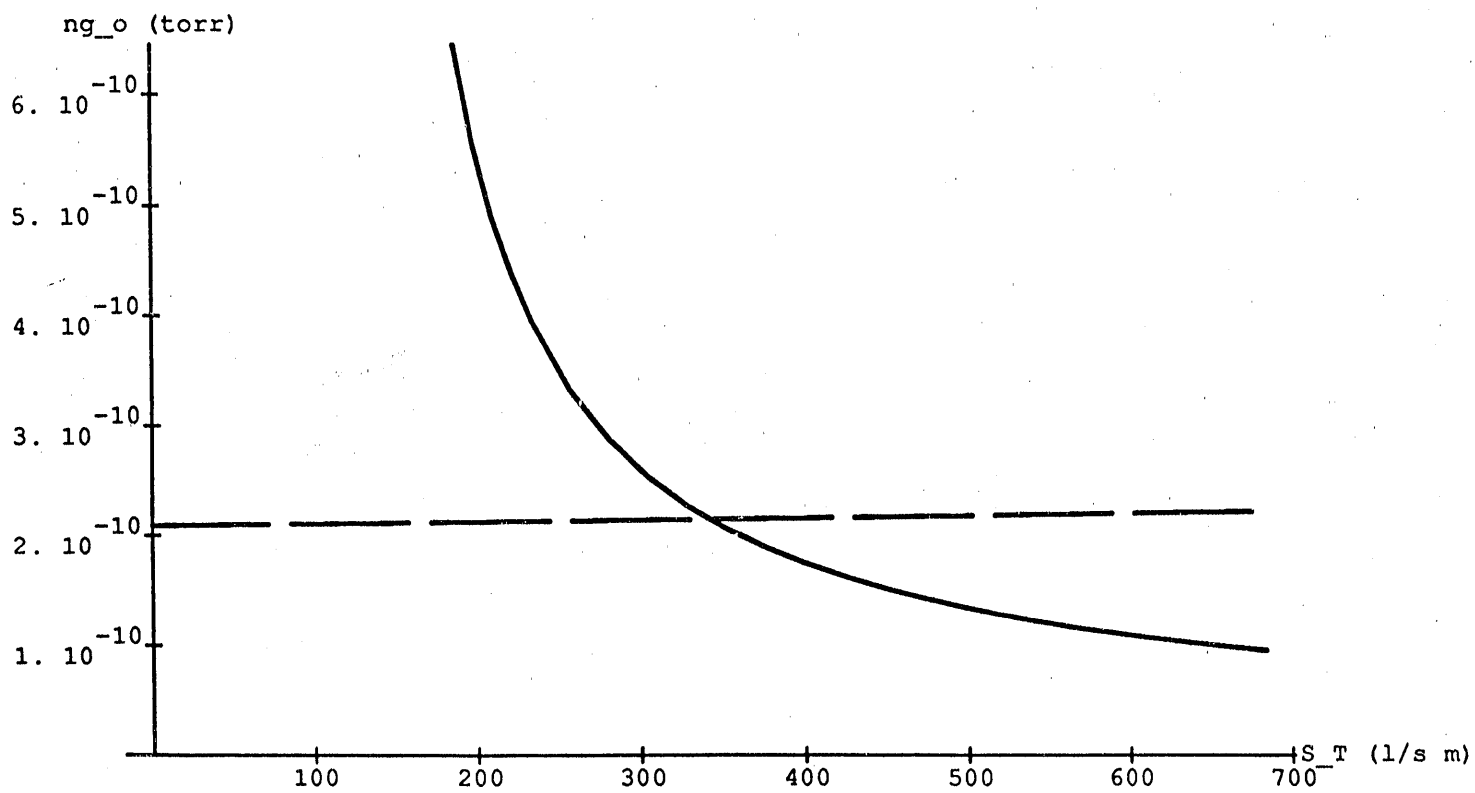


Figure 1.

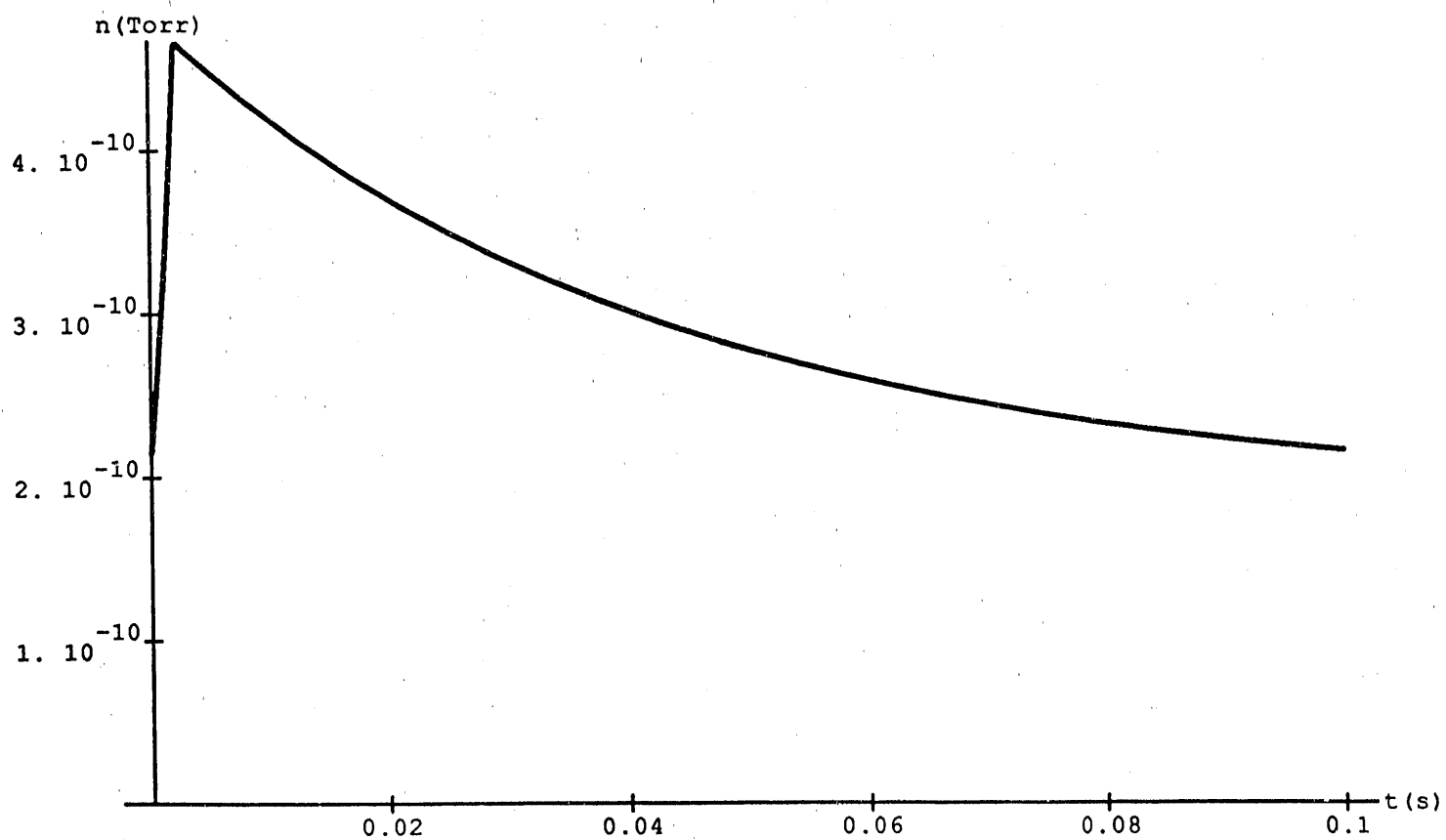


Figure 2.

Table 1 : Vacuum Parameters for the Recirculator Rings of Ref. 12

	IR	LER	MER	HER
Allowed Beam Loss	.10	.10	.05	.028
Charge Exchange Loss	0.0	0.0	.0003	.018
Outgassing Rate (T l/s cm <sup>2</sup> )	10 <sup>-11</sup>	10 <sup>-11</sup>	10 <sup>-11</sup>	10 <sup>-11</sup>
Stripping Cross Sec. (cm <sup>2</sup> )	1. 10 <sup>-15</sup>	1. 10 <sup>-15</sup>	9. 10 <sup>-16</sup>	8. 10 <sup>-17</sup>
Ionization Cross Sec. (cm <sup>2</sup> )	1. 10 <sup>-15</sup>	1. 10 <sup>-15</sup>	1. 10 <sup>-15</sup>	8. 10 <sup>-16</sup>
Chrg. Exchng. Cross Sec. (cm <sup>2</sup> )	4. 10 <sup>-18</sup>	1. 10 <sup>-17</sup>	2.5 10 <sup>-17</sup>	1.8 10 <sup>-16</sup>
Desorption Coeff. (Gas)	5	5	5	5
Desorption Coeff. (Heavy Ion)	4	2	.3	.01
Initial Gas Density (torr)	1.1 10 <sup>-10</sup>	1.3 10 <sup>-10</sup>	2.7 10 <sup>-10</sup>	2.2 10 <sup>-10</sup>
Final Gas Density (torr)	3.0 10 <sup>-9</sup>	7.1 10 <sup>-9</sup>	6.6 10 <sup>-10</sup>	4.7 10 <sup>-10</sup>
Effective Pump Rate (T l/s m)	960	830	240	342
Max. Dist. Betwn Pumps (m)	1.6	1.4	2.2	1.9
Total Cost of Vacuum Pumps (10 <sup>6</sup> \$)	2.9	2.1	2.0	8.0
$E_{cm}$ (keV)	.013	.068	.34	7.7
$E_{av}$ (MeV)	11.5	60.0	300	3000
$I_{av}$ (A)	2	16	29	182
Pulse Length <sub>av</sub> ( $\mu$ s)	74	18	3.5	.55

**END**

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