Ionization Issues at the Fermilab Recycler

Daniel R. Broemmelsiek

Fermilab, P.O. Box 500, Batavia, IL 60510

The knowledge of the residual gases in the Recycler vacuum is much more detailed than at the time of the Technical Design Report (TDR). In light of the known composition of the residual gases, ionization issues for high current antiproton beams are revisited. Cross-section calculations for the molecules found in the residual gas analysis of the Recycler are detailed. The motion of the resultant positive ions due to the static electric field of the antiproton beam are studied along with the expected ion clearing electrode currents.

Introduction

Eventually, the antiproton beam in the Recycler will ionize the residual molecules in the vacuum chamber. Negligible momentum is transferred to the positive ions, which will be trapped in the transverse potential well created by the negatively charged beam[1]. The recycler beam parameters are summarized in Table 1.

Table 1: Recycler Beam Parameters

Parameter	Value
Antiproton Intensity [#]	$4 \bullet 10^{12}$
Circumference [m]	3319.398040
Beam Energy [GeV]	8.89
Average beam velocity	.998
Average boost	9.48

Recent studies have measured the composition of the residual gases in the Recycler. The content by species and the maximum pressure given by a model of the pressure profile in the Recycler are shown inTable 2.

Ionization Cross Sections

Table 2: Recycler Pressure Profile and Residual Gas Composition

Gas Species	Content [%]	Max Press. [10^{-11} torr]
H_2	67.22	12.0
H_2O_2	21.13	7.6
CO	3.36	1.3
Ar	0.02	1.1
CH_4	0.05	7.9
CO_2	6.53	2.9
Unknown (N_2)	0.89	0.34

Ionization cross-sections for proton collisions are parameterized[2] for several elements and molecules. The parameterization is,

$$\sigma_I = \left(\sigma_I^{-1} + \sigma_I^{-1}\right)^{-1} \quad (1)$$

$$\sigma_L = 4\pi a_0^2 C x^D \quad (2)$$

$$\sigma_H = \frac{4\pi a_0^2}{x}\left(A \ln(1+x) + B\right) \quad (3)$$

Table 3: Target Species and Values of Fitted Parameters for Proton Impact Data

Target	*Z/A*	*A*	*B*	*C*	*D*	Reliability§
Ar	0.45059	3.85	1.98	1.89	0.89	b
H_2	0.99216	0.71	1.63	0.51	1.24	b
N_2	0.49976	3.82	2.78	1.80	0.70	a
CO	0.49982	3.67	2.79	2.08	1.05	a
CO_2	0.49989	6.55	0.00	3.74	1.16	a
CH_4	0.62334	4.55	2.07	2.54	1.08	b

§**a:** <10%, **b:** 10-25%

where the subscripts, L and H, designate the low and high-energy regimes. The quantity x is the

$$x \equiv \frac{T}{R_{\mathrm{RY}}} \tag{4}$$

ratio,

$$T \equiv \frac{m_e(\beta c)^2}{2} \tag{5}$$

with

such that T is the kinetic energy of an electron with the velocity of the proton beam. R_{RY} is the Rydberg energy. The coefficients *A*, *B*, *C* and *D* are fitted parameters to proton-impact ionization data[2], Table 3. Data for H_2O exist, however, in a different format and it is assumed that water will eventually be removed.

Neutralization Times

Supposing that both the beam and secondary particles are singly charged and that the gas and beam densities are constant, after neglecting recombination, neutralization times can be written as,

$$\tau_{\mathrm{N}} = \frac{1}{n_g \sigma_{\mathrm{I}} \beta c} \tag{6}$$

where n_g is the density of the gas. The gas density is related to the absolute pressure through Loschmidt's number, $\mathrm{L_g} = 3.54 \times 10^{22}\,\mathrm{m}^{-3}\,\mathrm{torr}^{-1}$.

Ion Bounce Frequency

The equation of motion for ions trapped in the electric field generated by the beam charge density is,

$$\mathrm{A}\, m_{\mathrm{p}} \ddot{r} = \mathrm{Z} e E_{\mathrm{beam}}(r) \tag{7}$$

where r is the distance from the center of the beam distribution. For a round Gaussian beam of width σ, the electric field is approximated by,

$$\begin{aligned} E_{\mathrm{beam}} &= \frac{\lambda}{2\pi\epsilon_0} \frac{1 - e^{-\frac{1}{2}\left(\frac{r}{\sigma}\right)^2}}{r} \\ &\approx \frac{\lambda}{2\pi\epsilon_0}\left[\frac{r}{\sigma} - \frac{1}{4}\left(\frac{r}{\sigma}\right)^3\right] \end{aligned} \tag{8}$$

giving the linear equation of motion near the center of the beam as,

$$\ddot{r} + \left[\omega_{\mathrm{b}}^2 - \frac{1}{4}\left(\frac{r}{\sigma}\right)^2\right] = 0 \tag{9}$$

where ω_{b} is the linear ion bounce frequency defined as,

$$\omega_b^2 = \frac{Ze|\lambda|}{4\pi\epsilon_0 A m_p \sigma^2} \quad . \tag{10}$$

All higher order terms in Equation (9) are even powers of r/σ. Larger amplitude motions occur with smaller oscillation frequencies. Table 4 lists the neutralization times and ion bounce frequencies in the linear approximation for those gases listed in Table 2.

Table 4: Neutralization times and Linear Ion Bounce Frequencies. Gaussian width is taken as 2.3mm.

Gas	τ_N [sec]	ω_b [MHz]
H_2	11.4	3.76
H_2O_2	48.5	5.58
CO	366	3.96
Ar	99.3	3.96
CH_4	13.6	4.43
CO_2	26.9	3.96

Ion Clearing Currents

At current residual gas concentrations, there will be complete ionization of the antiproton beam within minutes. The ions are in thermal equilibrium with negligible momentum transfer from the antiprotons and therefore have thermal longitudinal velocities. The rms velocity for the Maxwell-Boltzmann distribution is,

$$v_{rms} = 15800\sqrt{\frac{T}{M}} \ \frac{\text{cm}}{\text{sec}} \tag{11}$$

where T is now temperature in $^\circ K$ and M is the molecular weight of the gas species.

Using the case of molecular hydrogen at $300\,^\circ K$, the ion current passing any point in the Recycler will be ~10nA for a store of 10^{11} unbunched antiprotons. This is approximate since the geometry of the beam-pipe has been ignored which could cause ions to be trapped in deep potential wells. However, 10nA can be taken as a scale of the expected ion clearing current drawn by any one of the 416 clearing electrodes in the Recycler.

Conclusions

While the ionization cross-sections calculated here are different from the TDR, they agree with other[3] cross-section calculations. No discussion has been made here of longitudinal RF gaps in the beam distribution as this issue has not changed since the TDR. Such RF gaps still only destabilize the low mass ions and are intrinsic to operations of the Recycler.

The linear ion bounce frequencies are all similar in magnitude to the synchrotron revolution frequencies for typical barrier RF buckets in the Recycler. The bounce frequencies are not similar to the betatron oscillation frequencies.

---

[1]Martin Reiser, *Theory and Design of Charged Particle Beams* (John Wiley & Sons, Inc., New York, NY 1994.)

[2]M.E. Rudd, Y.-K. Kim, D.H. Madison and J.W. Gallager, *Rev. Mod. Phys.* **57**, p.965 (1985)

[3]Steve Werkema, **FNAL Seminar**, *Recent Developments in Understanding Trapped Ion Phenomena in the Fermilab Antiproton Accumulator.*