Fermilab FERMILAB-Conf-01/189-E July 2001

A STUDY OF EMITTANCE GROWTH IN THE RECYCLER RING

K. Gounder, B. C. Brown, C. Gattuso, M. Hu, D. Johnson,
J. Marriner, S. Mishra, S. Pruss, M. Yang, FNAL, Batavia, IL 60510, USA.

Abstract

We investigate processes contributing to emittance growth in the Fermilab Recycler Ring. In addition to beam-gas multiple scattering, we also examine other external factors such as Main Injector ramping affecting the emittance growth.

1 RECYCLER RING

The Recycler Ring [1] located in the Main Injector tunnel at Fermilab is designed to be a storage facility for antiprotons as a part of Run II luminosity upgrade program. The Recycler Ring (RR) is being commissioned using protons. Beam emittance growth can be caused by many factors such as injection mismatch, lattice properties, beam structure, dynamic aperture, tunnel vibrations, power supply noise, Main Injector ramping as well as beam-gas effects. This study investigates the effect of beam-gas interactions and other external factors such as Main Injector ramping etc. on emittance growth in the Recycler Ring. The relevant RR parameters are listed in Table 1.

Table 1: Recycler Ring Paramaters

Paramater	**Value**
Acceptance (mm-mr)	40π
Average β (m)	40.0
Average beam pipe radius (in m)	0.023
Beam energy (GeV)	8.89
Average beam β	0.998
Average beam γ	9.48
Maximum energy loss (GeV)	0.089

2 EFFECT OF BEAM-GAS SCATTERING

We estimate the beam emittance growth due to multiple coloumb scattering of the beam particles (protons) with the residual gas atoms present in the beam pipe. The injected beam is assumed to be Gaussian:

$$f(Z) = \frac{a^2}{2\sigma^2} e^-(a^2/2\sigma^2)Z$$

with $Z = \epsilon/\epsilon_a$ ranging from 0.0 to 1.0. With an initial beam of $10\pi \times 10^{-6}$ m-r, $\sigma = 11.53 \times 10^{-3}$m-r. Here ϵ, ϵ_a denote emittance and Recyler acceptance respectively while a is the half aperture equal to the average radius of the beam pipe (0.023 m).

The RR ultra high vacuum is maintained by a regular array of ion and titanium sublimation pumps (TSP). The pressure at a point inside the beam pipe varies significantly depending on the distance from the pump locations. The pressure profile has been computed for each component of the gas present in the beam pipe. The maximum and minimum pressure for each gas are listed in Table 2. For life time estimations, we treat the 'unknown' component as Nitrogen.

Table 2: Vacuum Gas Composition

Gas	**Content** [%]	**Min. Pres.** [Torr]	**Max. Pres.** [Torr]
H_2	67.22	4.9E-11	1.2E-10
H_2O	21.13	1.8E-11	7.6E-11
CO	3.36	1.7E-12	1.3E-11
Ar	0.02	8.9E-12	1.1E-11
CH_4	0.85	2.4E-11	7.9E-11
CO_2	6.53	3.8E-12	2.9E-11
$Unknwon$	0.89	4.5E-13	3.4E-12
Total	100.00	1.1E-10	3.3E-10

The mutiple coloumb scattering of beam particle causes emittance growth of the beam. As a result, protons are lost via diffusion across the boundary of the allowed particle distribution in the beam pipe. Therefore, we should approach this problem by solving the diffusion equation [4] for a particle distribution f:

$$\frac{\partial f}{\partial \tau} = \frac{\partial}{\partial Z}(Z\frac{\partial f}{\partial Z})$$

subject to the boundary conditions:

$$f(Z,0) = f_0(Z)$$

$$f(1,\tau) = 0$$

where Z = ϵ/ϵ_a = emittance/acceptance, and τ = tR/ϵ_a with R, the diffusion coefficient. The diffusion coefficient R is given in terms of scattering angle θ by:

$$R = \beta_{avg}\langle\dot{\theta}^2\rangle$$

The general solution of the above equation can be written as:

$$f(Z,\tau) = \sum_n C_n J_0(\lambda_n\sqrt{Z})e^{-\lambda_n^2\tau/4}$$

with coefficients C_n:

$$C_n = \frac{1}{J_1(\lambda_n)^2}\int_0^1 f_0(Z)J_0(\lambda_n\sqrt{Z})dZ$$

where λ_n is nth root of the Bessel function $J_0(Z)$. Now we can obtain the total beam particles as a function of time:

$$N(\tau) = \int_0^1 f(Z,\tau)dZ = 2\sum_n \frac{C_n}{\lambda_n} J_1(\lambda_n) e^{-\lambda_n^2 \tau/4}$$

The life time due to multiple coloumb scattering can be now computed using the standard expression:

$$\tau_{mc} = -\frac{N(\tau)}{dN(\tau)/d\tau}$$

The beam life time varies with time and normally reaches an asymptotic value [5]:

$$\tau_a = \frac{4\epsilon_a}{\lambda_1^2 R}$$

.

To compute $<\dot{\theta}^2>$, we use the small angle limit of the Rutherford scattering cross section, parametrization of atomic and nuclear radii:

$$<\dot{\theta}^2> = \frac{8\pi r_p^2 c}{\gamma^2\beta^3} \sum_j n_j Z_j^2 \mathrm{In}[\frac{38360}{(A_j Z_j)^{1/3}}]$$

with A_j denoting the atomic weight of jth gas component. Using Table 2 and the relevant Recycler parameters in Table 1, we obtain $<\dot{\theta}^2> = 4.23 \times 10^{-12}\ rad/s$ for the case of minimum gas pressure and $1.25 \times 10^{-11}\ rad/s$ for the maximum pressure case.

The emittance growth is obtained by:

$$\frac{d\epsilon_N}{dt} = \frac{\pi\beta\gamma}{2}\beta_{avg} <\dot{\theta}^2>$$

.

Now using the above estimates for $<\dot{\theta}^2>$, we compute the emittance growth due to beam-gas multiple scattering as $8.00 \times 10^{-4}\pi$ mm-mr/s for the minimum case and $2.37 \times 10^{-3}\pi$ mm-mr/s for the maximum case.

3 THE EFFECT OF MAIN INJECTOR RAMPING

The Main Injector plays a pivotal role in the Fermilab accelerator complex for accelerating, decelerating and transferring beams between the Booster, Antiproton Source, Accumulator, Recycler Ring and the Tevatron. The Recycler Ring is located in the upper section of the Main Injector tunnel and is separated by an average distance of only about 2m. Therefore while the Main Injector is ramping, the stray fields may affect the beam in the Recycler Ring where shielding by μ-metal may not be adequate.

To measure the effect of Main Injector ramping, we have measured the beam intensity and the emittance growth in horizontal plane in the Recycler Ring as a function of time while the Main Injector is ramping and while not ramping with identical Recycler setups. The relative emittance meaurement was done using Schottky detectors [6]. The beam intensity in the Recycler Ring with and with out the Main Injector ramping vs time is plotted in Figure 2. The beam intensity falls off more rapidly while the Main Injector is ramping than compared to the case of no ramping. The beam life time obtained by fitting the beam intensity as a function of time is 6.13 hours while ramping and 10.29 hours while not ramping.

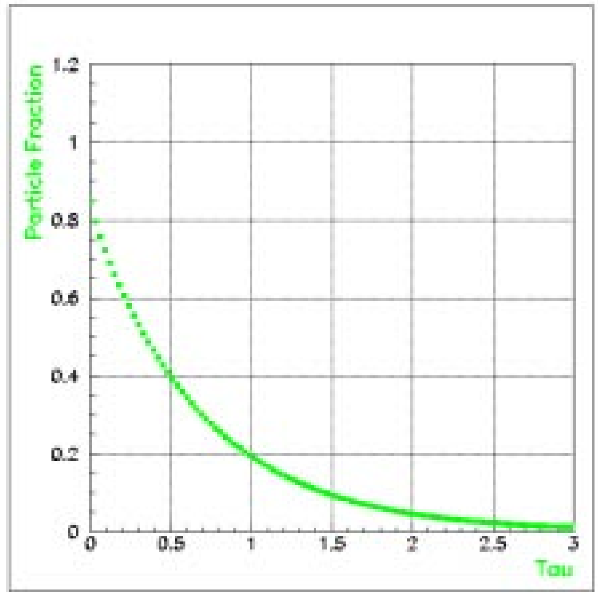

Figure 1: The particle fraction a function of $\tau = tR/\epsilon_a$ due to multiple coloumb scattering process. The beam particles are lost via diffusion across the boundary of the allowed particle distribution in the beam pipe.

The relative horizontal beam emittance vs time is shown in Figure 3 for the cases of Main Injector ramping and not ramping. The emittance growth rates are obtained by fitting a straight line to the data. The rate is 0.22 π mm-mr/minute while ramping and is only 0.08 π mm-mr/minute while not ramping. The result is consistent with those obtained from the beam intensity measurements.

4 OUTLOOK

In this study, we have considered two of the many processes contributing to the emittance growth in the Recycler Ring. Comparing the overall growth rate with that obtained from multiple scattering of beam particles with residual gases in the beam pipe, we can conclude that Main Injector ramping along with other factors are playing significant roles.

5 REFERENCES

[1] Gerry Jackson, "The Fermilab Recycler Ring Technical Design Report", November 1996, Fermilab-TM-1991.

[2] A. G. Ruggiero, Fermilab Pbar Note 54, November, 1979.

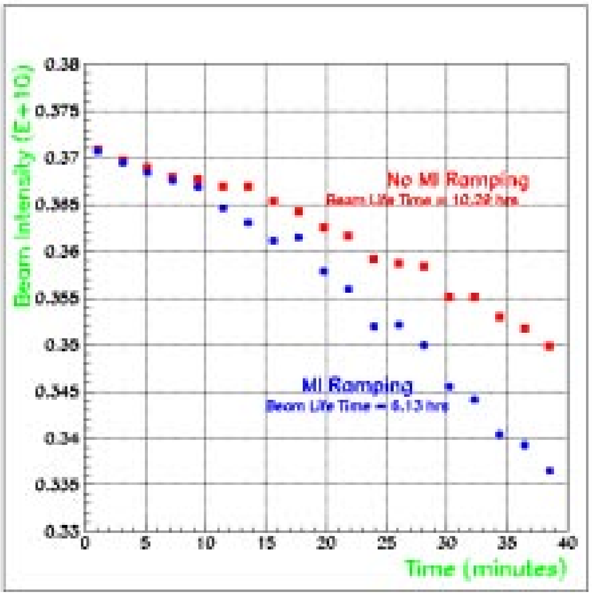

Figure 2: The effect of Main Injector ramping on the Recycler beam. The life time is determined by fitting an exponential form to the relevant beam profile. The Recycler beam pipe is being shielded from the stray fields caused by the Main Injector ramping.

[3] A. Wurlich in "CERN Accelerator School 1994", CERN-94-01.

[4] D. Edwards and M. Syphers, "An Introduction to Physics of High Energy Accelerators", John Wiley and Sons, 1993. .

[5] For details, K. Gounder et. al, "Recycler Ring Beam Life Time" in PAC2001 conference proceedings.

[6] M. Hu et. al., "The Fermilab Recycler Diagnostics", in PAC2001 conference proceedings.

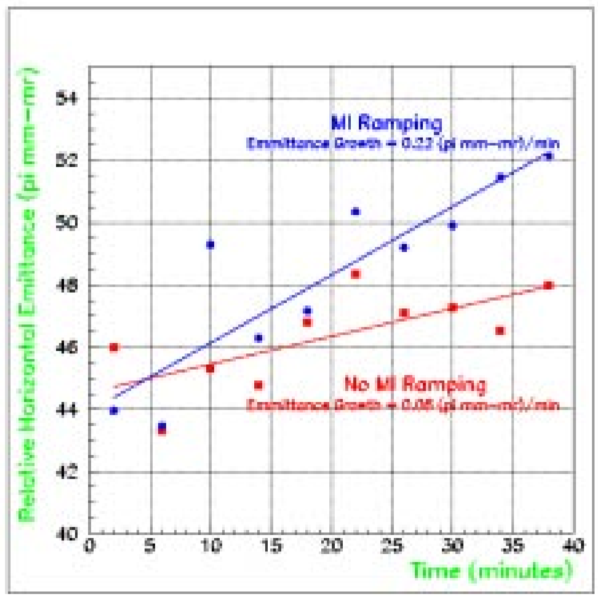

Figure 3: The Main Injector ramping more than doubles the emittance growth in the Recycler Ring. The relative emittance is measured using Schottky detectors.