The Recycler Ring Beam Life Time and Emittance Growth

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Beam Life Time and Emittance Growth: Physical Processes

Recycler Ring Parameters

Vacuum Residual Gases

Beam Life Time: Beam-gas Interactions

- Beam life time computations
- Results for various scenarios
- A brief history of life time measurements

Emittance Growth:

- Beam-gas interactions
- Effect of Main Injector Ramping
- Dependence on initial beam condition
- Understanding emittance growth: some digressions

Summary and Outlook

Recyler Ring: Parameters

Recycler Design acceptance = 40 $\pi \times 10^{-6}$ **m-r**
Average $\overline{\beta}$ **around the ring = 40 m**
Average physical radius = 0.023 m

Beam energy = 8.89 GeV
Beam energy acceptance = $\pm$ **89 MeV**
Average beam particle γ **= 9.48**
Average beam particle β **= 0.998**
Classical proton radius $r_p = 1.53 \times 10^{-18}$ **m**
Classical electron radius $r_e = 2.82 \times 10^{-15}$ **m**

Initial beam distribution (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.**
For initial beam of 10$\pi \times 10^{-6}$ **m-r,** $\sigma = 11.53 \times 10^{-3}$**m-r. Here a is the half aperture (0.023 m).**

Recyler Ring: Residual Gases

- **Pressure profile inside the beam pipe varies differently for different gases**
- **Based on Terry Anderson's Vacuum Model: Residual gases (Region 636-639)**

Gas	Min. Pres. [Torr]	Max. Pres. [Torr]	Design report [Torr]
H_2	4.9E-11	1.2E-10	1.0E-10
H_2O	1.8E-11	7.6E-11	—
CO	1.7E-12	1.3E-11	(0-2)E-12
Ar	8.9E-12	1.1E-11	—
CH_4	2.4E-11	7.9E-11	—
CO_2	3.8E-12	2.9E-11	—
$Unknwon$	4.5E-13	3.4E-12	(0-2)E-12
Total	1.1E-10	3.3E-10	1.002E-10

- **Tabulate life times for various cases:(a) If water content reduces by a factor of 5; (b) If the actual pressure level worsens by a factor of 2; (c) Each gas component scenarios etc.**
- **Treat the 'unknown' component as Nitrogen.**

Beam-gas Interactions

Physical Process:

- Single Coloumb Scattering
- Excitation of atomic electrons by the beam
- Bremstrahlung - proton emits a photon and the gas atomic nucleus left unexcited
- Nuclear scattering by strong force
- Multiple Coloumb Scattering - via emittance growth (the dominant contribution)

Single Coloumb Scattering

Use the Rutherford scattering cross section:

$$\frac{1}{\tau_{sc}} = \frac{-1}{N}\frac{dN}{dt} = \beta c \sum_j \sigma_j n_j$$

where the summation is over gas species. The cross section is:

$$\sigma_j = \frac{4\pi Z_j^2 r_p^2}{\beta^4 \gamma^2 \theta_{max}^2}$$

where r_p, the classical radius of the proton;

$$\theta_{max} = \sqrt{\frac{Acceptance}{\pi \beta_{avg}}}$$

Life time due to single scattering:

$$\frac{1}{\tau_{sc}} = \frac{4\pi r_p^2 c}{\beta^3 \gamma^2 \theta_{max}^2} \sum_j Z_j^2 n_j$$

Using the above parameters, $\theta_{max} = 0.325$ mr and $\tau_{sc} = 1.47 \times 10^3$ hours for minimum pressure case and 4.98×10^2 hours for the maximum case.

Not a factor by itself unless the vacuum gets significantly worse!

Inelastic Scattering

There are three contributions to the inelastic case:

- **Excitation of atomic electrons from momentum transfer from beam particles:**

  $$\sigma_{ee} = 4\alpha\{\frac{4}{3}Zr_e^2 \mathrm{In}\frac{1194}{Z^{2/3}}[\mathrm{In}(E/\epsilon_m)-(5/8)]+\frac{1}{9}(Zr_e^2)[\mathrm{In}(E/\epsilon_m)-1]\}$$

  where E is beam particle energy and ϵ_m, the maximum energy loss by the beam particle.

- **Bremsstrahlung - proton emitts a photon and the nucleus of gas atom left unexcited:**

  $$\sigma_{br} = 4\alpha\{\frac{4}{3}Z^2r_p^2 \mathrm{In}\frac{183}{Z^{1/3}}[\mathrm{In}(E/\epsilon_m)-(5/8)]+\frac{1}{9}(Z^2r_p^2)[\mathrm{In}(E/\epsilon_m)-1]\}$$

  This process is negligible compared to other two!

- **Nuclear scattering by strong force (no simple expression from QCD - only approximate parametrization):**
  $\sigma_{nc}(H) = 40$**mb;** $\sigma_{nc}(C) = 344$**mb;** $\sigma_{nc}(Ar) = 921$**mb**
  $\sigma_{nc}(N) = 387$**mb;** $\sigma_{nc}(O) = 429$**mb**

Now with the relevant Recyler parameters:

$\tau_{in-em} = 3.26 \times 10^3$ **hours (Minimum)**
$\tau_{in-nu} = 6.98 \times 10^3$ **hours (Minimum)**
$\tau_{in-em} = 1.06 \times 10^3$ **hours (Maximum)**
$\tau_{in-nu} = 1.98 \times 10^3$ **hours (Maximum)**

Multiple Coloumb Scattering

The mutiple coloumb scattering causes emittance growth of the beam. We have to solve the diffusion equation 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 $= \epsilon/\epsilon_a =$ **emittance/acceptance, and** $\tau =$ **tR**$/\epsilon_a$ **with R, the diffusion coefficient.**

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

The general solution:

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

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** $J_0(Z)$**. The total beam particle as a function of time:**

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

Multiple Coloumb Scattering - Cont'd

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

The beam life time as a function of time:

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

Using the small angle limit of the Rutherford scattering cross section, parametrization of atomic and nuclear radii:

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

Using Table I and the relevant Recycler parameters:

$$< \dot{\theta}^2 >= 4.23 \times 10^{-12} \ \mathrm{rad}/\mathbf{sec} \ \mathbf{(Minimum)}$$
$$< \dot{\theta}^2 >= 1.25 \times 10^{-11} \ \mathrm{rad}/\mathbf{sec} \ \mathbf{(Maximum)}$$

$$\tau_{asym} = 1.51 \times 10^2 \mathrm{hours} \ \mathbf{(Minimum)}$$
$$\tau_{asym} = 5.11 \times 10^1 \mathrm{hours} \ \mathbf{(Maximum)}$$

Life Time Summary

Life time estimations for various cases:

- **Maximum and minimum pressure cases:**

Physical Process	Minimum Pressure [hours]	Maximum Pressure [hours]
Single Coloumb	1.47×10^3	4.98×10^2
Inelastic Scatt.	3.26×10^3	1.06×10^3
Mult. Coloumb	1.51×10^2	5.11×10^1
Nuclear Scatt.	6.98×10^3	1.98×10^3
Total Life Time	1.29×10^2	4.34×10^1

- **Some possible scenarios: Relative to maximum case**

Physical Process	$n(H_2O) \times 1/5$ [hours]	$n(all\ gases) \times 2$ [hours]
Single Coloumb	6.50×10^2	2.49×10^2
Inelastic Scatt.	1.34×10^3	5.28×10^2
Mult. Coloumb	6.67×10^1	2.56×10^1
Nuclear Scatt.	2.57×10^3	9.89×10^2
Total Life Time	5.67×10^1	2.17×10^1

- **Vacuum improvements: Reduce water by baking etc.**

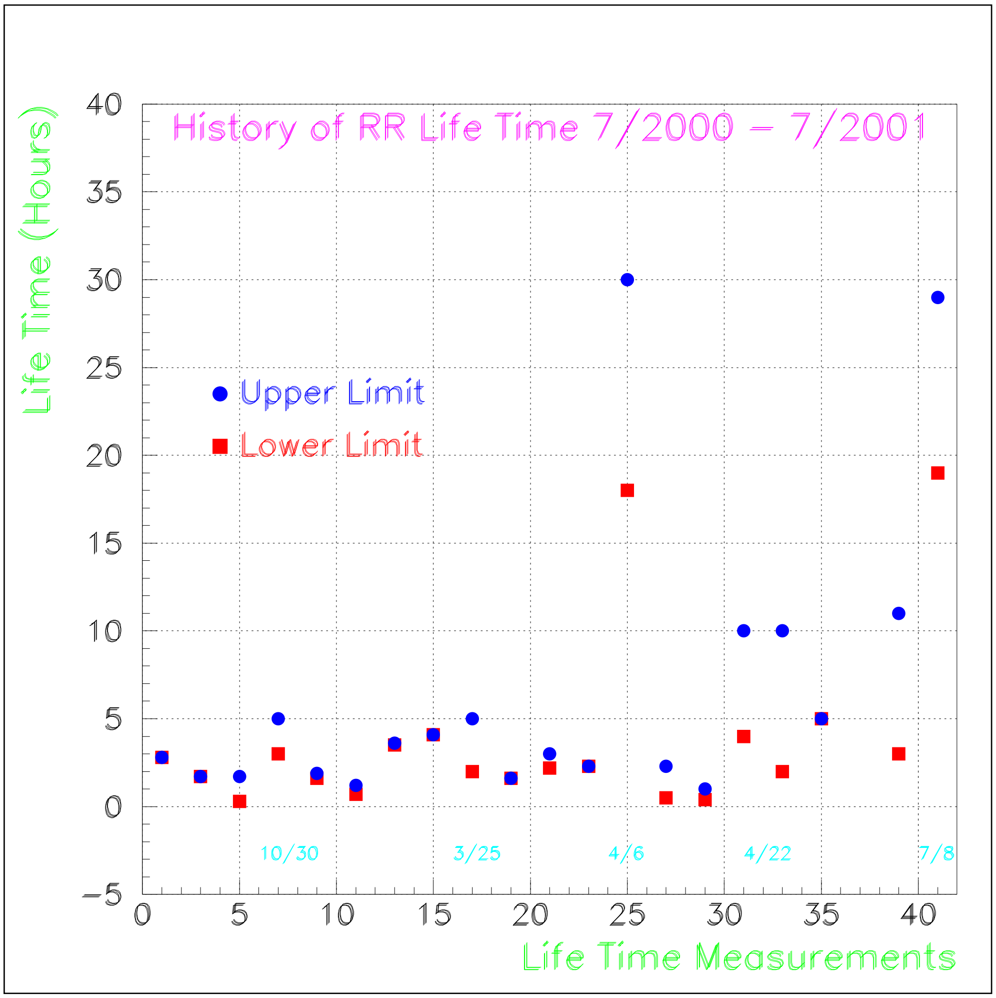
Life Time Summary - Continued

- **More possible scenarios: Relative to the maximum pressure case**

Scenario	Sin. Col. [hours]	Inelastic [hours]	Multiple [hours]	Nuclear [hours]	Total [hours]
Max. case	4.98×10^2	1.06×10^3	5.11×10^1	1.98×10^3	4.34×10^1
$n(H_2) \times 2$	4.91×10^2	9.74×10^2	5.04×10^1	1.85×10^3	4.26×10^1
$n(H_2O) \times 2$	3.85×10^2	8.34×10^2	3.95×10^1	1.53×10^3	3.36×10^1
$n(CO) \times 2$	4.62×10^2	9.93×10^2	4.75×10^1	1.84×10^3	4.04×10^1
$n(Ar) \times 2$	4.11×10^2	9.27×10^2	4.23×10^1	1.84×10^3	3.61×10^1
$n(CH_4) \times 2$	4.20×10^2	8.27×10^2	4.32×10^1	1.53×10^3	3.65×10^1
$n(CO_2) \times 2$	4.09×10^2	9.08×10^2	4.20×10^1	1.67×10^3	3.58×10^1
$n(N_2) \times 2$	4.93×10^2	1.05×10^3	5.06×10^1	1.96×10^3	4.30×10^1

- **The table clearly shows that reducing water content by baking will be a good thing!**
- **We should also try to reduce Ar, CH_4, and CO_2 if possible!**
- **The Recycler Technical Design Report life time is $1.66 - 1.67 \times 10^3$ depending on the ratio of CO/N_2.**

Brief History of RR Life Time



- **04/06/01:** **Scrapped, adiabatically debunched beam**
- **07/08/01:** **Quite time - No MI ramping and kickers are off**

Brief History of RR Life Time

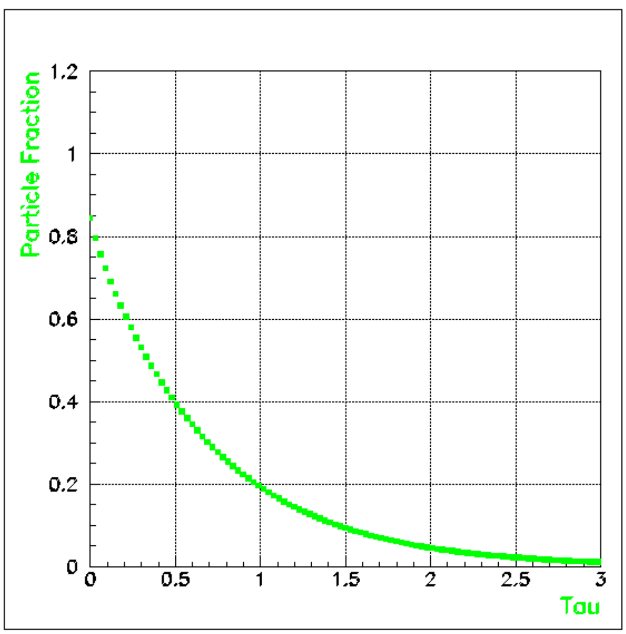
Date	Life Time [hours]	Comment
07/10/00	2.8	Beam intensity life time
08/22/00	1.7	Start-up studies
10/24/00	0.3-1.7	Bunched and debunched beam
10/30/00	3.0-5.0	New tune settings
10/31/00	1.6-1.9	With and without cooling
01/08/01	0.7-1.2	Start-up - no optimization
01/13/01	3.5-3.6	With noise source on and off
01/14/01	4.1	DC beam life time
03/25/01	2.0-5.0	With and no MI ramping - tune-up
03/28/01	1.6	MI scrapped beam (30 %)
04/04/01	2.2-3.0	With 2 hours of stored beam
04/05/01	2.3	With 1.5 hours of stored beam
04/06/01	18.0-30.0	Scrapped, adiabatically debunched
4/13-6/01	0.5-2.3	Tune vs life time studies
04/19/01	0.4-1.0	For different quad settings
04/20/01	4.0-10.0	RR scrapped beam - emittance studies
04/22/01	2.0-10.0	With and with out quite time
05/12/01	5.0	May start-up - first 15 minutes
6/9-19/01	3.0-11.0	Life time and emittance studies - PAC
07/08/01	19.0-29.0	Quite time - no MI ramping/kickers

Emittance Growth: Beam-gas Interactions

The emittance growth in the case of beam-gas multiple scattering is obtained by:

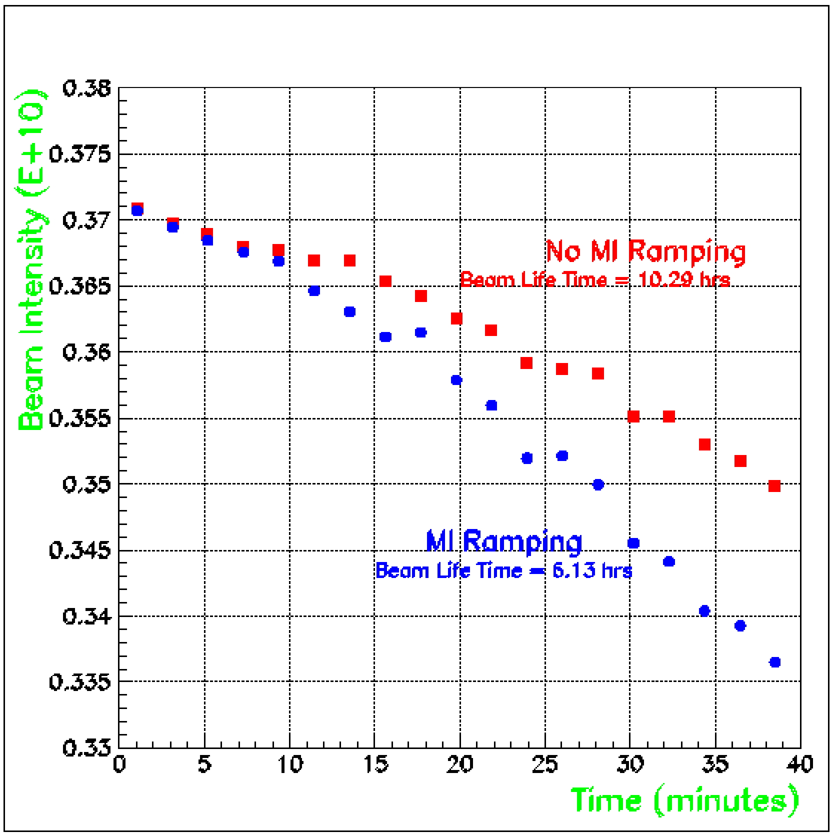
$$\frac{d\epsilon_N}{dt} = \frac{\pi\beta\gamma}{2}\beta_{avg} < \dot{\theta}^2 >$$

Using the above estimates for $< \dot{\theta}^2 >$, the emittance growth due to beam-gas multiple scattering as $4.80 \times 10^{-2}\pi$ mm-mr/minute for the minimum case and $1.42 \times 10^{-1}\pi$ mm-mr/minute for the maximum case.



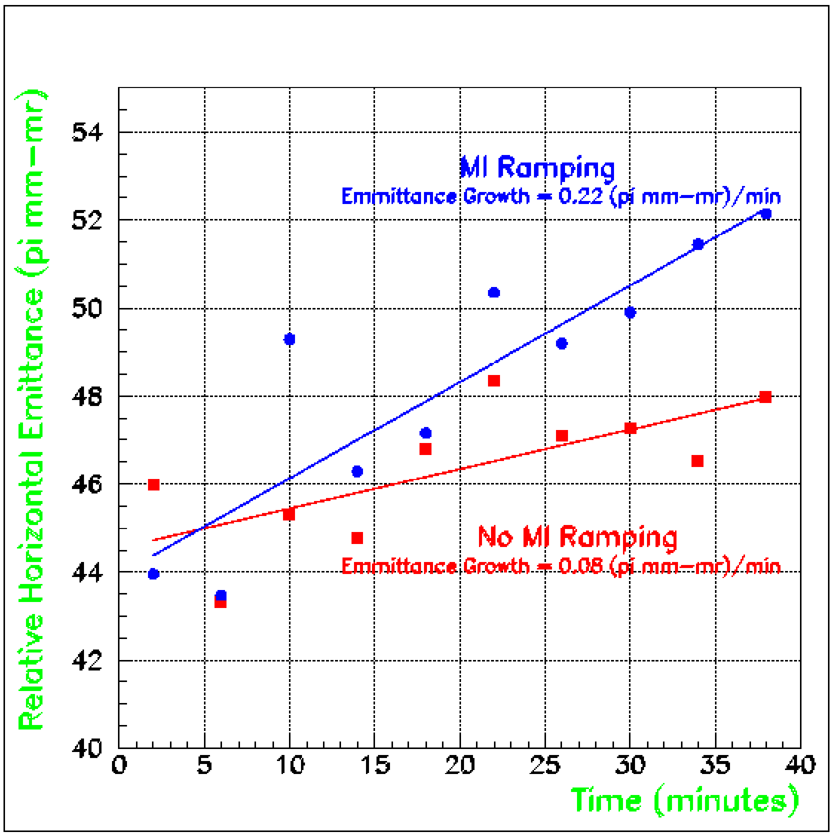
Emittance Growth: Effect of Main Injector Ramping - Beam Intensity

Have measured the beam intensity in the Recycler Ring as a function of time while the Main Injector is ramping and while not ramping with identical Recycler setups.



Emittance Growth: Effect of Main Injector Ramping - Emittance

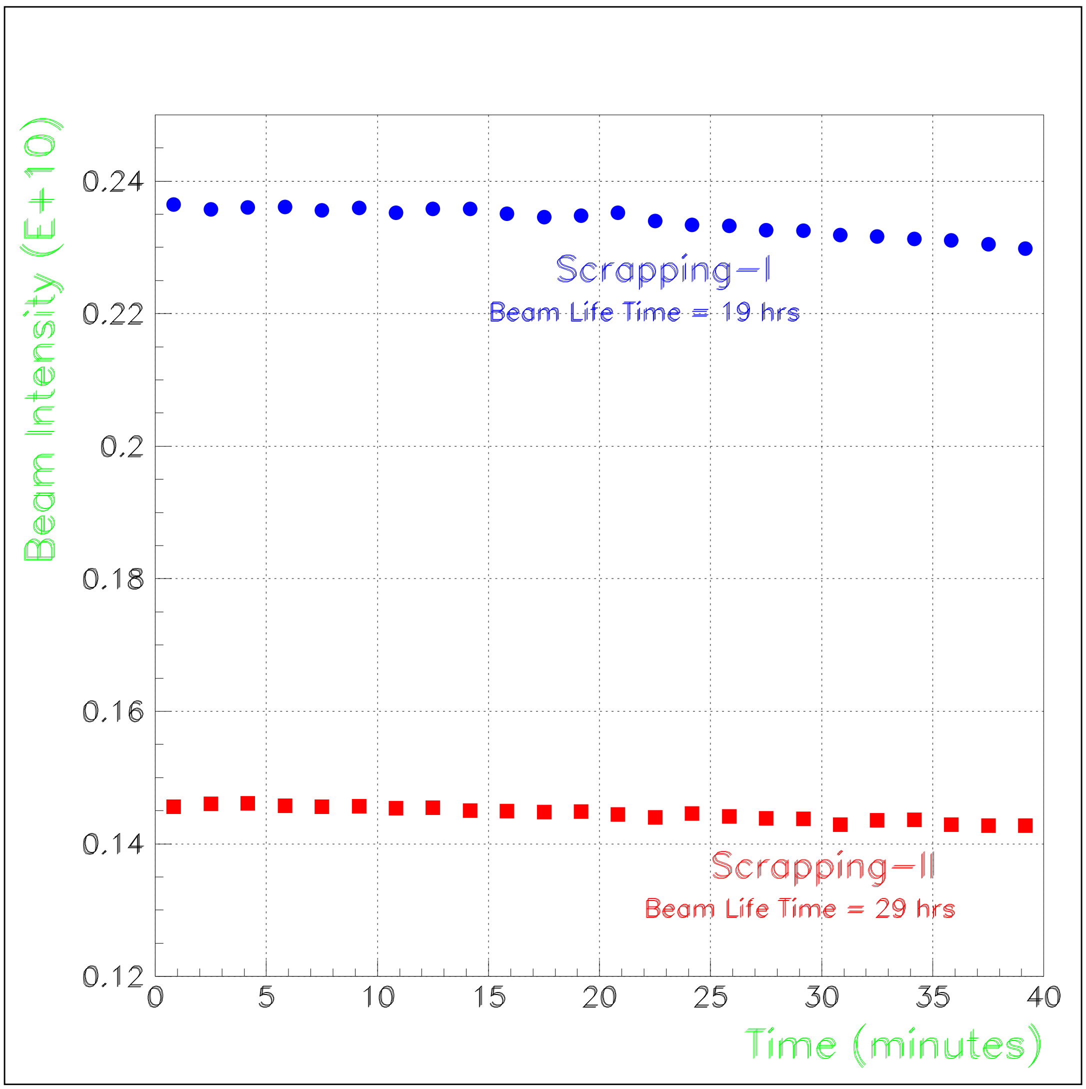
Have measured the emittance growth in the Horizontal plane as a function of time while the Main Injector is ramping and while not ramping with identical Recycler setups.



The growth rate of 0.08 pi mm-mr/minute (no ramping) is consistent with that of maximum pressure case 0.14 pi mm-mr/minute!

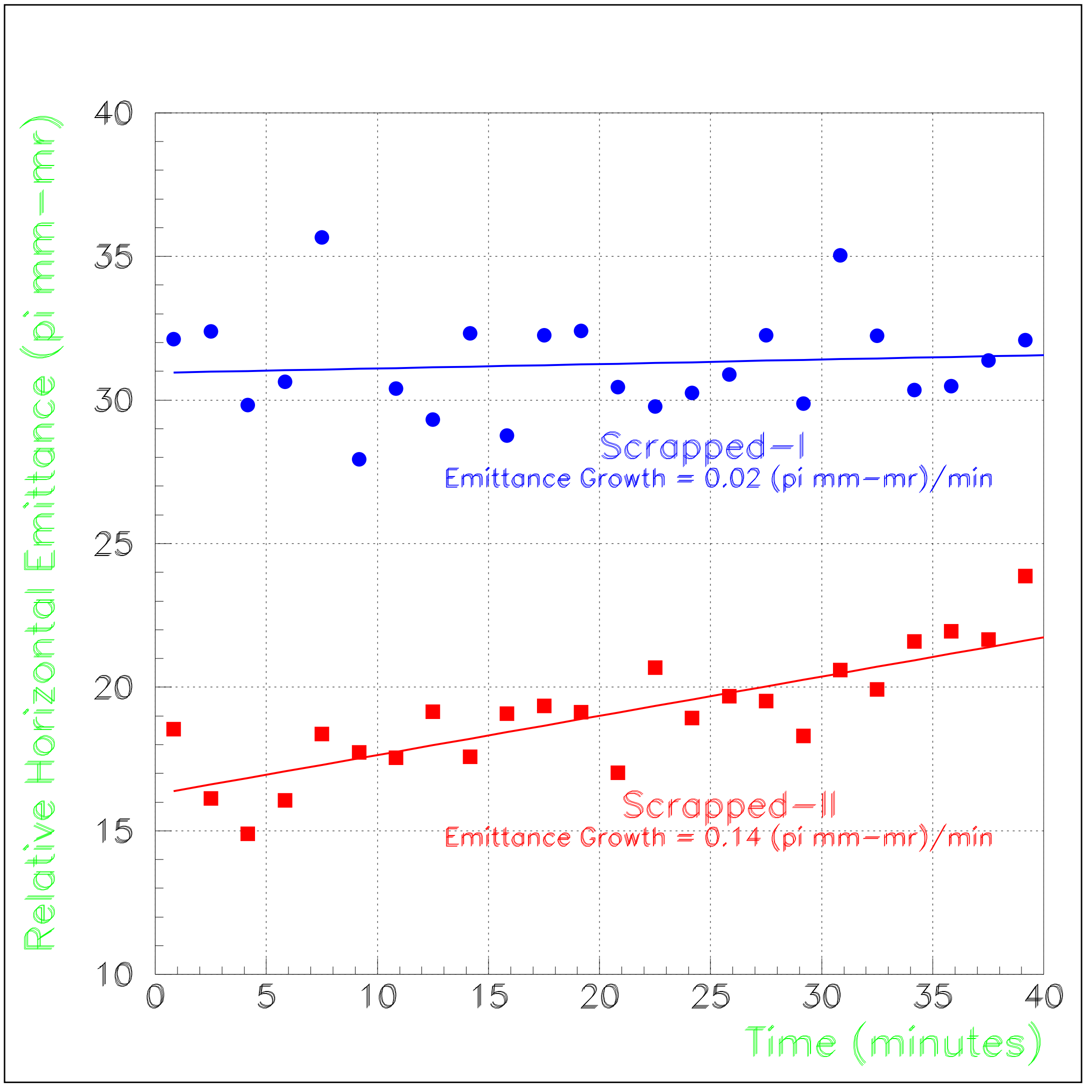
Beam Intensity Loss: Variation of Initial Beam Emittance

The loss of beam intensity dependence on the initial beam emittance can be studied using different amount of scrapping.



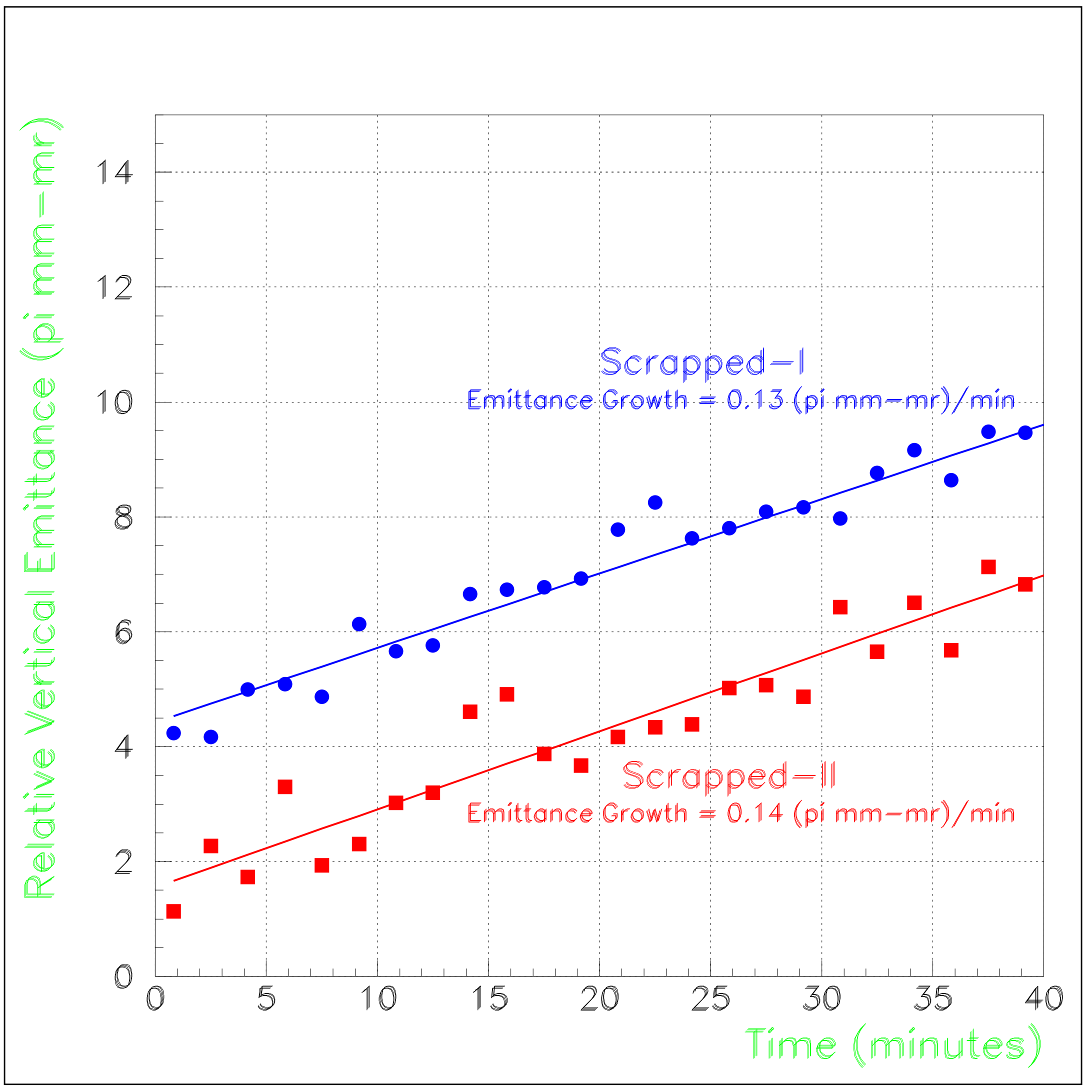
Horizontal Emittance Growth: Variation of Initial Beam Emittance

The horizontal emittance growth dependence on the initial beam emittance can be studied using different amount of scrapping.



Vertical Emittance Growth: Variation of Initial Beam Emittance

The vertical emittance growth dependence on the initial beam emittance can be studied using different amount of scrapping.



Emittance Growth: Random Musings

- **Some numbers to ponder - conincidence? ...**
  Emittance growth predicted by the worst case vacuum scenario = 0.14π mm-mr/min
  Best scrapped beam horizontal emittance growth = 0.14π mm-mr/min
  Best scrapped beam vertical emittance growth = 0.14π mm-mr/min

- **If you take the above numbers seriously ...**
  $\Rightarrow$ 6-7 π mm-mr/hour! Our proposed cooling rate is $\approx$ 1 π mm-mr/hour. So we need to control emittance growth somehow!

- **Decomposing emittance growth: Vacuum + non-vacuum components**
  (a) Fit beam intensity - $I_0 e^{-t(1/\tau_{vac}+1/\tau_{nvac})}$
  (b) Emittance growth - linear vacuum part + ??

Summary and Outlook

We are beginning to understand the issues affecting the emittance growth and RR beam life time - considerable progress since the Beams Division Retreat in 12/00. The best life time observed so far is about 30 hours during quite time. The worst case vacuum scenarios seem to indicate that vacuum is playing a prominent role in determining the present obesrved RR life time. More work is needed to sharpen the conclusions.

RR Life Time:

- **RR Vacuum model can be further improved - work in progress**
- **Still need to involve beam structure in vacuum computations - intrabeam scattering**
- **Improving RR vacuum - bake more!**
- **Need more monitoring devices on selected locations: Ion gauges, RGA**

Emittance Growth:

- **Many factors to be studied: Dynamic aperture, Non-linearities, Tunnel vibrations, Power supply noise, Lattice deffects**
- **A lot more to come ....**