Luminosity and intensity lifetimes

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Based on W. Fischer, M. Bai, M. Harvey, C-A/AP/235 (2006)

Machine Advisory Committee, November 15 – 17, 2010

Beam parameters for polarized proton operation in Run-5

quantity	unit	value
proton energy	GeV	100.0
relativistic γ	...	106.6
revolution time T	μs	12.8
bunches per beam N	...	56–111
bunch intensity N_b	10^{11}	0.39–1.05
normalized emittances ϵ_n (95%)	mm mrad	12–43
transverse tunes (Q_x, Q_y),	...	(28.68,29.69)
rf gap voltage	kV	300
rms bunch length	m	0.5–1.2
number of head-on bb interaction n_{IP}	...	3
initial beam-beam parameter ξ/IP	...	0.001–0.005

Parameters at the beginning of the store

Beam loss due to luminosity

Assumptions:

- beam loss due to luminosity occurs by losing both protons involved
- no emittance growth

Particle loss per beam:

$$n_{\mathrm{IP}} N_{\mathrm{bunches}} \frac{\mathrm{d}N_b(t)}{\mathrm{d}t} = -\mathcal{L}(t)\sigma_{\mathrm{tot}}$$

$$\begin{aligned} N_b(t) &= \frac{N_b(0)}{1+t/\tau} \\ \mathcal{L}(t) &= \frac{\mathcal{L}(0)}{(1+t/\tau)^2} \end{aligned}$$

with

$$\begin{aligned} \tau &= \frac{N_{\text{bunches}} N_b(0)}{n_{\text{IP}} \mathcal{L}(0) \sigma_{\text{tot}}} \\ &= \frac{2\pi}{3\gamma} \frac{\epsilon_n \beta^*}{n_{\text{IP}} f_{\text{rev}} N_b(0) \sigma_{\text{tot}}} \end{aligned}$$

and

$\sigma_{\text{tot}} = 50\,\text{mbarn}$ (S. Eidelman et al., Phys. Lett. B 592, 1. Fig. 40.11 (2004)),

$$\tau = 1400\,\text{h}$$

Beam loss due to rest gas inelastic scattering

Beam lifetime due to inelastic scattering off molecular nitrogen (N. V. Mokhov, V. I. Balbekov, Handbook of Accelerator Physics and Engineering):

$$\begin{aligned} \frac{1}{\tau} &= -\frac{1}{N_b}\frac{\mathrm{d}N_b}{\mathrm{d}t} \\ &\approx 800\,\mathrm{sec}^{-1}\mathrm{Torr}^{-1}\frac{\beta}{C}\int_0^C P(s)\,\mathrm{d}s \end{aligned}$$

For

$$\begin{aligned} \langle P \rangle &= 30\,\mathrm{nTorr} \\ L_{\text{warm sections}} &= 652\,\mathrm{m} \\ \sigma_{\text{loss}} &= 0.296\,\mathrm{barn} \end{aligned}$$

$$\tau = 191\,\mathrm{h}$$

Emittance growth from rest gas elastic scattering

$$\frac{1}{\tau_{\epsilon_n}} = \frac{1}{\epsilon_n}\frac{\mathrm{d}\epsilon_n}{\mathrm{d}t} = \frac{6\gamma}{\epsilon_n}\frac{1}{C}\int_0^C \beta(s)\Theta^2_{\text{restgas}}(s)\,\mathrm{d}s$$

with

$$\Theta^2_{\text{restgas}}(s) = \frac{4\pi r_p^2 c}{\gamma^2} n Z(Z+1)\ln(183 Z^{-1/3})$$

For N_2 at 300 K,

$$\frac{1}{\tau_{\epsilon_n}} \approx 0.88\,\text{sec}^{-1}\text{Torr}^{-1}\frac{L_{\text{warm sections}}}{C}\frac{\langle\beta P\rangle}{\epsilon_n\gamma}$$

Using 2.7 nTorr nitrogen equivalent,

$$\tau_{\epsilon_n} = 17\,\text{h}$$

Emittance growth from beam-beam elastic scattering

$$\frac{1}{\tau_{\epsilon_n}} = \frac{1}{\epsilon_n}\frac{\mathrm{d}\epsilon_n}{\mathrm{d}t} = \frac{9}{2}\gamma n_{\mathrm{IP}}\frac{f_{\mathrm{rev}}N_b}{\epsilon_n^2}\sigma_{\mathrm{el}}\Theta_{\mathrm{bb}}^2,$$

with

$$\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}t} \propto \exp(-b|t|) = \exp\left(-\frac{\Theta^2}{2\Theta_{\mathrm{bb}}^2}\right)$$

$$t \approx -p^2\Theta^2.$$

RMS scattering angle:

$$\Theta_{\mathrm{bb}} = \frac{1}{p\sqrt{2b}}$$

Using $b = 11.9\,(\mathrm{GeV/c})^{-2}$ and $\sigma_{\mathrm{el}} = 8\,\mathrm{mbarn}$,

$$\Theta_{\mathrm{bb}} = 2.1\,\mathrm{mrad}$$

$$\tau_{\epsilon_n} = 6600\,\mathrm{h}$$

Emittance growth from intrabeam scattering

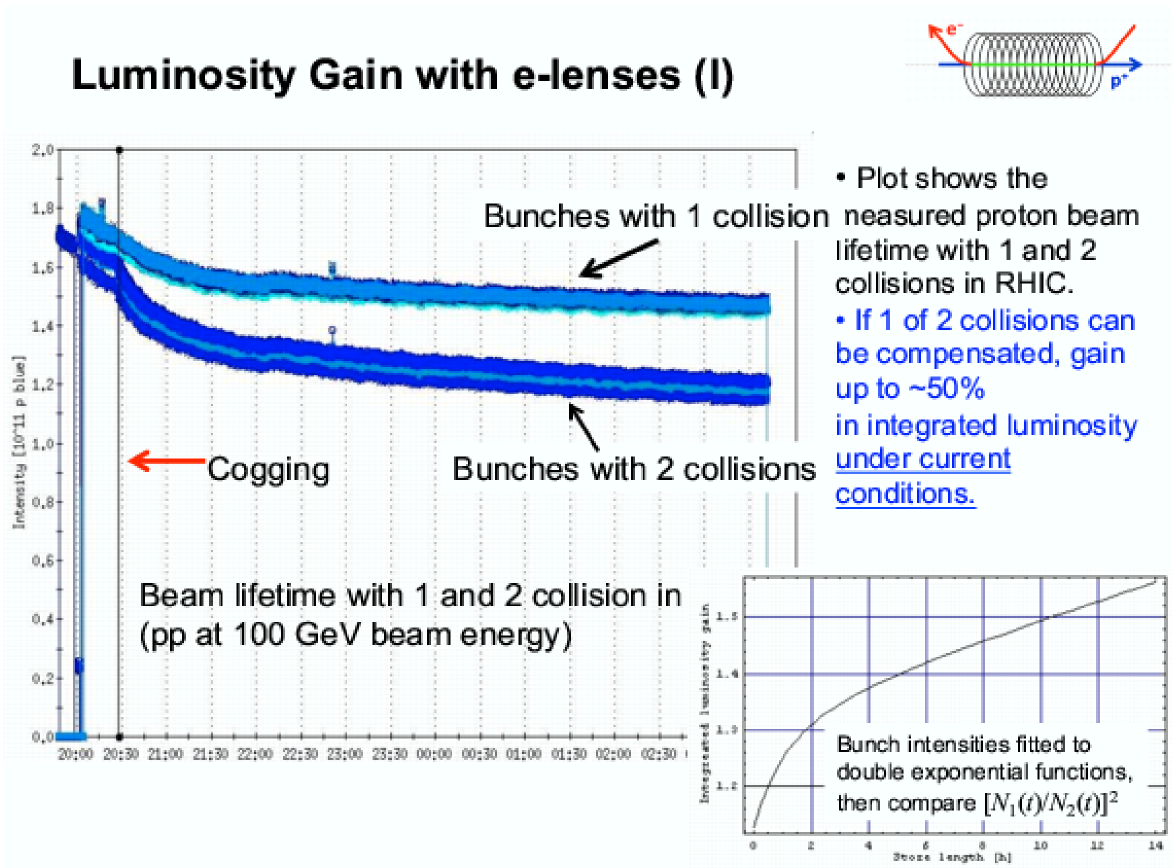
Emittance growth times

$$\frac{1}{\tau_{x,y,z}} = \frac{Z^4}{A^2} C_{x,y,z} \frac{N_b}{\gamma \epsilon_x \epsilon_y \epsilon_z}$$

Calculations with the BETACOOL code yield

$$\tau_x = \tau_y = 255\,\mathrm{h},\ \tau_z = 20\,\mathrm{h}$$

Bunch intensity evolution with 1 and 2 collisions



Beam-beam effect manifests itself as difference between bunches that experience 1 and 2 collisions

Total calculated and measured lifetimes

	unit	measured	calculated
beam lifetime τ_{N_b}	h	90/57	172
transverse emittance growth time τ_{ϵ_n}	h	18	16
longitudinal emittance growth time τ_{ϵ_s}	h	7.6	20
luminosity lifetime $\tau_{\mathcal{L}}$	h	12	13

Measured lifetimes refer to long-lived component in double-exponential fit

Transverse emittance growth rates and luminosity lifetime agree well, but beam longitudinal emittance growth rate and lifetime are factor 2 off