Observations on the Luminosity Lifetimes, Emittance Growth Factors and Intra-Beam Scattering at the Tevatron

P. Lebrun, V. A. Lebedev, V. Shiltsev, J. Slaughter
FNAL, Batavia, IL 60510, USA

Abstract

A peaked, record luminosity of $4.\,10^{31}$ has been reached at the Fermilab $p - \bar{p}$ collider. The lifetime of this luminosity at the beginning of the store is about 9 to 10 hours. This lifetime can be explained based on the anticipated loss of antiprotons and protons due to collisions and emittance growths. We report on transverse emittance growth rates based on our Synchrotron Light Monitor. Longitudinal emittance measurements are based on the TeV Sample Bunch Display data. It is shown that Intra Beam Scattering is a significant source of emittance growth. We comment on other possible factors for these observed emittance growth rates. Finally, we comment on future luminosity lifetimes, as we hope to further increase our peaked luminosity.

INTRODUCTION & INSTRUMENTATION

The Luminosity lifetime is evidently a critical factor in reaching high integrated luminosity at any collider[1]. In this paper, we summarize the results based on various Tevatron instruments on the various factors determining the luminosity lifetime for the $p/,\bar{p}$ Tevatron collider.

The luminosity is measured by the CDF Cerenkov Luminosity Counter(CLC)[2]. The bunch intensities are measured by the Fast Bunch Integrator (FBI) connected to a wall current monitor [3] Although this is not the optimum way to determine the bunch intensity due to electronic noise and errors in the analog integration, the precision of this device is adequate to establish the correlations shown below. The Sample Bunch Display (SBD) [4] is used to measure the longitudinal profile of every bunch in the Tevatron ring. This devices samples at 2 GHz, performs Gaussian fits and reports a measurement of the bunch length for the 2×36 bunches every 3 seconds or so. The transverse emittances are measured at the beginning of the High Energy Physics phase (e.g., when the beam collides) with the Flying Wire[5] These wires do create severe background at the experiments, so we do not fly them during the stores. Instead, we use the Synchrotron Light Monitor (SincLite)[6], which measures the transverse beam profile in each planes without perturbing the beams. This device reports each bunch transverse size every 15 seconds. Finally, beam loss counters were used to verify that anomalously short beam lifetime were not due to some unknown FBI instrumentation effects.

The data is collected via the Sequenced Data Acquisition system [7] and has been taken in October 2002 through March 2003.

LUMINOSITY LIFETIME

The Luminosity $\mathcal{L}$ recorded by the Collider detectors (CDF and D0) can be compared to the computed ones based on bunch intensities and emittances[8]. The normalized collision rate change vs time for a given pair of bunches (or the inverse of the luminosity lifetime) can be expressed as the following sum:

$$1/\mathcal{L}\, d\mathcal{L}/dt = 1/\lambda_a + 1\lambda_p + 2/\sigma_a(d\sigma_a/dt)/(1.+\epsilon_p/\epsilon_a) +$$

$$2/\sigma_p(d\sigma_p/dt)/(1.+\epsilon_a/\epsilon_p) \;+\; 1/FdF/dt$$

where λ_a, λ_p are the antiproton and proton bunch intensity lifetimes, respectively. σ_a and σ_p are the beam width, average over both transverse planes[1] and ϵ_a and ϵ_p are the trnsverse emittances. F is the hour glass factor, derived from the SBD bunch length measurements.

Each of these terms can be determined from data. The proton lifetime can be much shorter than the inverse collision rate due to poor machine tuning (slightly mispaced collimators or orbits, betatron tunes or chromaticities). For other "good stores", the proton lifetime is the smallest componenent in determining this lumisosity lifetime: the $\bar{p}$ lifetime is typically 16 hours against $\approx> 100$ hours for the proton beam. The emitance terms contribute to ≈ 60 hours ($\bar{p}$ and p) in the transverse planes (average) and ≈ 80 hours longitudinally. The self consistency of this simple derivation has been checked by comparing the measured inversed luminoisty lifetime to the sum of these other quantities 1. Although reasonably good agreement is obtained (5 to 15%, relative, on the luminosity lifetime), the effective emittance growth rate indirectly reported by the FBI and CDF detectors (CLC) is significantly larger than the measured (SL, SBD) emittance growth rates.

The dominant contribution to this lifetime is the lifetime of the antiproton beam, and occasionally, the proton lifetime. When the Tevatron is well tuned, such proton losses are greatly reduced and the contributions from emittance gowth become signficant.

[1] We assume here that the horizontal and vertical emittance are not too different from each other, which is the case.

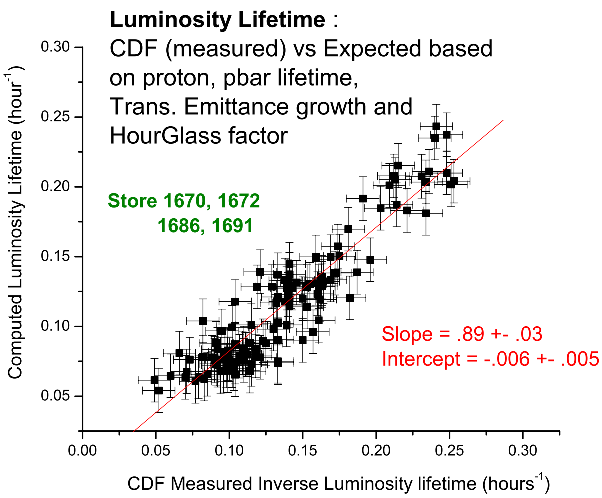

Figure 1: Correlation plot between the predicted (based on various emittance and intensity detectors) vs measured luminoisty lifetime.

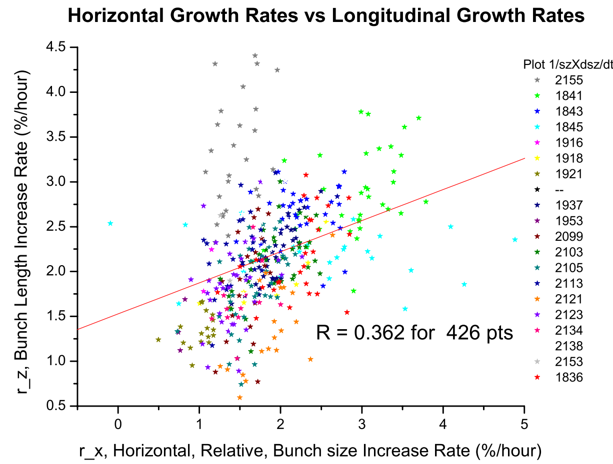

Figure 2: Correlation plot between the longitudinal and horizontal, relative, bunch size growth rates.

OBSERVATIONS OF EMITTANCE GROWTH AND INTRA BEAM SCATTERING

We now concentrate on the proton emittance growth rates. This growth rate $r_\epsilon = 1/\epsilon\, d\epsilon/dt = 2\, r_\sigma = 2/\sigma\, d\sigma/dt$ is typically a few percent per hour, in all three planes, at the beginning of the store. r_ϵ itself decays with an approximate half-life of 5 hours. The grow rates reported from now on have been measured for the first $2^{1/2}$ hours into the stores. The correlation between the horizontal and longitudinal growth rates shown on figure 2 is statistically signficant, although there is a lot of fluctuations bunch to bunch and store to store. A similar correlation between the vertical and horizontal growth rates has also been observed.

We now show that these observed $r_{\epsilon(x,z)}$ are qualitatively and quantatively consistent with Intra Beam Scattering (IBS). We compute these quantities taking into account the proper averaging of the dispersion and betatron function, including the straight section. For elliptical beams, the emittance growth rate in the horizontal plane is (in the ultra-relativistic regime where $\beta = 1$.)

$$r_{\epsilon,x} = \frac{d\epsilon_x}{dt} = \frac{L_c\, N_0\, r_0^2\, Ax_{av}}{4\,\sqrt{2.}\,\gamma^3\,\sigma_\tau\,\sigma_x\,\sigma_y\,\sqrt{\theta_x^2 + \theta_y^2}}$$

where L_c is the coulomb logarithm, taken in this calculation to be 28.108. N_0 is the number of proton per bunch at low beta, $\approx 1.7\,10^{11}$. γ is the Lorentz relativistic factor, 1045. r_0 is the classical radius of the proton, $1.53\,10^{-15}$ mm. σ_τ, the rms sigma bunch length, expressed in sec, $\approx$ 2 nanoseconds. σ_x is the effective horizontal beam size (Gaussian σ), average over the entire ring, respectively, taken to be:

$$\sigma_x = \sqrt{(\epsilon_{g,x}\,\beta_{x,av}) \;+\; (D_{av}^2\,\sigma_p^2)}$$

$\epsilon_{g,x}$ is the geometrical emittance (at one σ of the distribution!). Thus, σ_x includes the contribution due to dispersion. The lattice beta $\beta_{x,av}$ and dispersion D_{av}^2 functions are averaged over the entire lattice.

σ_y is the vertical beam size, average over the entire ring. θ_x, θ_y is the angular spread of the beam (one σ), excluding the contribution from dispersion, once again, average over the entire ring, in the horizontal and vertical planes, respectively. Ax_{av} is length-wise average of the following combined Twiss function,

$$\frac{D_x^2 \;+\; (D_x\,\beta_x \;+\; \alpha_x\,D_x)^2}{\beta_x}$$

Likewise, longitudinally, we have,

$$r_{\epsilon,z} = \frac{d\epsilon_s}{\epsilon_s\,dt} = \frac{L_c\, N_0\, r_0^2\, \Gamma_s^2}{4\,\sqrt{2.}\,\gamma^3\,\sigma_\tau\,\sigma_x\,\sigma_y\,\sqrt{\theta_x^2 + \theta_y^2}}$$

where Γ_s is $(\sigma_\tau\, c)/\sigma_p$

The comparison data/IBS model is shown on figure 3. Once again, the correlation between predicted and measured values is statistically signficant, once we reject the store or bunches for which the proton lifetime is anomalously short due to losses unrelated to collisions ar CDF or D0. IBS predicts no growth rate in the vertical plane, contrary to observation. However, it should be noted that we currently run the Tevatron with a high betatron coupling. The IBS prediction for most of the stores are signficantly above the measured values. We suspect that residual beam losses could account for that discrepency. The lattice function and measured emittances also have large uncertainties.

Other possible source of emittance growth have been considered.

- The longitudinal dampers stabilize the bunches during the stores. They do not affect such slow diffusion processes.
- We measure the low-level phase noise in the r.f. system and wrote a simple numerical simulation model of the longitudinal dynamics with such noise. The emittance growth was found to be small compared to IBS.
- Poor vaccum n the Tevatron: The uncolaesced (small longitudinal emittance bunches) proton beam has a lifetime of about 500 hours. From this, and direct pressure measurements, we concluded that the beam heating from multiple scattering on residual gas was found to be neglibly small compared to IBS.
- Other possible effect such as non-linear resonnances or beam-beam effects have also been considered. However, we do not have firm quantitative results, due to the inherent complexity of such simulation.

CONCLUSION

The Luminosity lifetime at the beginning of good (small machine lossses) store is about 9 to 10 hours, and get longer as reaches about 15 to 20 hours at the end of the store. This lifetime is quantitatively ($\approx 15\%$, relative) understood in terms of beam losses and emittance growth. We compared these emittance growth rates with the IBS prediction and found semi-quantitative agreement. ($\approx 50\%$) This work allows us to have some confidence in the model describing various luminosity upgrade scenarios[1]. We are planning to operate the collider at a peaked luminosity of $3.3\,10^{32}$ by raising both proton and antiproton beam intensities, while preserving the current emittances at injection. Under these circumstances, IBS is significant for both beams. The Luminosity lifetime will then be ≈ 5.4 hours.

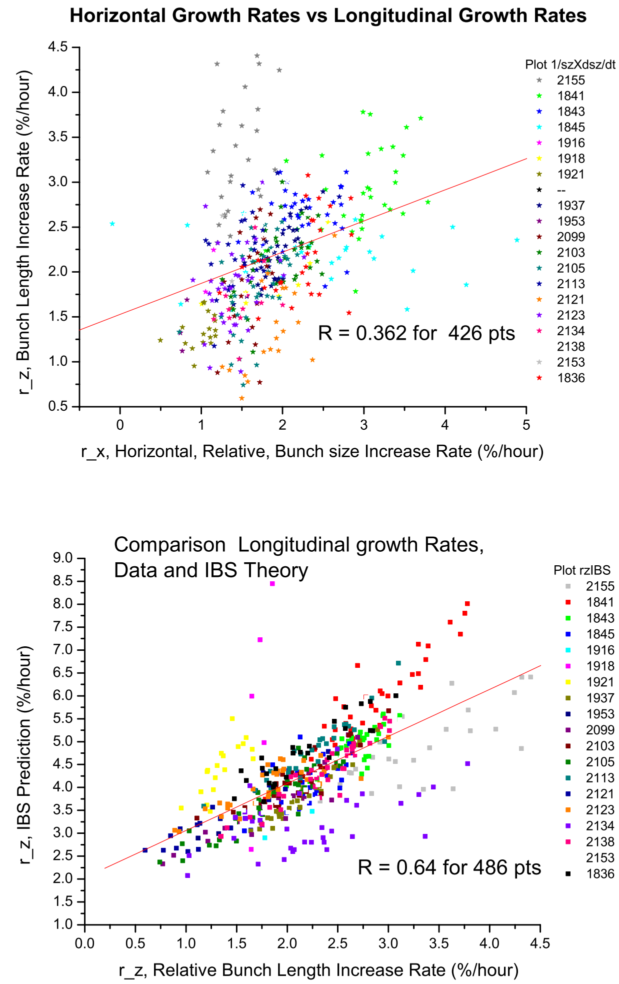

Figure 3: Correlation plot between the measured and IBS-predicted horizontal (top) and longitudinal (bottom) relative bunch size growth rates.

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