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

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Abstract

A peaked, record luminosity of $4 \times 10^{31}$ 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 $2 \times 36$ 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:

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

where $\lambda_a$, $\lambda_p$ are the antiproton and proton bunch intensity lifetimes, respectively. $\sigma_a$ and $\sigma_p$ are the beam width, average over both transverse planes' $\epsilon_a$ and $\epsilon_p$ are the transverse 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 component in determining this luminosity lifetime: the $\bar{p}$ lifetime is typically 16 hours against $\approx 100$ hours for the proton beam. The emittance terms contribute to $\approx 60$ hours ($\bar{p}$ and $p$) in the transverse planes (average) and $\approx 80$ hours longitudinally. The self consistency of this simple derivation has been checked by comparing the measured inversed luminosity 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 growth become significant.

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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 luminosity lifetime.

**OBSERVATIONS OF EMITTANCE GROWTH AND INTRA BEAM SCATTERING**

We now concentrate on the proton emittance growth rates. This growth rate \( r_e = 1/\epsilon \frac{d\epsilon}{dt} = 2 \sigma_x = 2/\sigma \frac{d\sigma}{dt} \) is typically a few percent per hour, in all three planes, at the beginning of the store. \( r_e \) itself decays with an approximate half-life of 5 hours. The growth rates reported from now on have been measured for the first 21/2 hours into the stores. The correlation between the horizontal and longitudinal growth rates shown on figure 2 is statistically significant, 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 \( r_{e(x,z)} \) are qualitatively and quantitatively 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 \( \beta = 1 \))

\[
\frac{dr_e}{dt} = \frac{\epsilon_s}{\epsilon_s} \frac{d\epsilon_s}{dt} = \frac{L_c N_0 r_0^2 A_{x_{av}}}{4 \sqrt{2} \gamma^3 \sigma_x \sigma_y \sqrt{\sigma_x^2 + \sigma_y^2}}
\]

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, \( \approx 1.7 \times 10^{11} \). \( \gamma \) is the Lorentz relativistic factor, 1045. \( r_0 \) is the classical radius of the proton, 1.53 x 10^{-15} mm. \( \sigma_{x,z} \), the rms sigma bunch length, expressed in sec, \( \approx 2 \) nanoseconds. \( \sigma_x \) is the effective horizontal beam size (Gaussian \( \sigma \)), average over the entire ring, respectively, taken to be:

\[
\sigma_x = \sqrt{(\epsilon_{g,x} \beta_{x,av}) + (D_{xav}^2 \sigma_p^2)}
\]

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

\( \sigma_y \) is the vertical beam size, average over the entire ring. \( \theta_x, \theta_y \) is the angular spread of the beam (one \( \sigma \)), excluding the contribution from dispersion, once again, average over the entire ring, in the horizontal and vertical planes, respectively. \( A_{x_{av}} \) is length-wise average of the following combined Twiss function,

\[
D_{xav}^2 + (D_{xav}^2 \beta_x + \alpha_x D_{xav})^2 \beta_x
\]

Likewise, longitudinally, we have,

\[
\frac{dr_e}{dt} = \frac{L_c N_0 r_0^2 \Gamma^2}{4 \sqrt{2} \gamma^3 \sigma_x \sigma_y \sqrt{\sigma_x^2 + \sigma_y^2}}
\]

where \( \Gamma_x \) is \( (\sigma_x c)/\sigma_p \).

The comparison data/IBS model is shown on figure 3. Once again, the correlation between predicted and measured values is statistically significant, once we reject the store or bunches for which the proton lifetime is anomalously short due to losses unrelated to collisions at 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 significantly above the measured values. We suspect that residual beam losses could account for that discrepancy. 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 negligibly small compared to IBS.
- Other possible effect such as non-linear resonances 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 losses) 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 (∼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. (∼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 \times 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 \approx 5.4 hours.

REFERENCES


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