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Observations on the Luminosity Lifetimes and Emittance Growth Rates at the Tevatron

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Abstract

A record luminosity of $4.2\,10^{31}$ has been reached at the Fermilab $p-\bar{p}$ collider. The lifetime of this luminosity at the beginning of the store is about 10 hours. This lifetime can be explained by the measured loss of anti-protons and protons due to collisions and emittance growths. We report on transverse emittance growth rates based on our Synchrotron Light Monitor. Longitudinal emittance growth rate measurements are based on the TeV Sampled Bunch Display data. It is shown that Intra Beam Scattering is a significant source of emittance growth rates. 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 peak luminosity.

INTRODUCTION & INSTRUMENTATION

The luminosity lifetime is a critical factor in reaching high integrated luminosity at any collider[1]. In this paper, we summarize the results based on various Tevatron instruments and 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 uncertainties in the measured offsets coming from the non-uniform beam structure, the precision of this device is adequate to establish the correlations shown below. The Sampled Bunch Display (SBD)[4] is used to measure the longitudinal profile of every bunch in the Tevatron ring. This device 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 Wires (FWs)[5]. These wires create background at the experiments, so we do not fly them during the stores. Instead, we use the Synchrotron Light Monitor (SL)[6], which measures the transverse beam profile in each plane without perturbing the beams. This device reports each bunch transverse size every 15 seconds. The emittances reported by FWs and the SL are reproducible with a typical rms of a few percent. However, the systematic error, or absolute scale uncertainty, is much larger (on the order of 30%), as indicated by the effective emittance measurement deduced from the luminosity counters[7]

The data is collected via the Sequenced Data Acquisition (SDA) system. The stores we consider here are from August 2002 through May 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 [1, 7]. For a given $p\,\bar{p}$ pair of bunches, this Luminosity is

$$\mathcal{L} = \frac{f\,N_p\,N_{\bar{p}}(6\beta_l\gamma_l)}{4\,\pi\,\beta^*\,\epsilon_{eff}}\,\mathcal{H}(\sigma_z/\beta^*)$$

where f is the revolution frequency (47.713 KHz), $N_p\,N_{\bar{p}}$ the proton and anti-proton bunch intensities, $\beta_l\gamma_l$ are the Lorentz boost factor (1,045 at 980 GeV) and β^* is the beta function at the interaction point (IP). $\mathcal{H}$ is the hourglass factor, derived from the SBD bunch length measurements. The effective emittance ϵ_{eff} is expressed in terms of the 95%, normalized beam emittances $\epsilon_p\,\epsilon_{\bar{p}}$ as

$$\epsilon_{eff} = 1/2\,\sqrt{(\epsilon_p+\epsilon_{\bar{p}})_x\,(\epsilon_p+\epsilon_{\bar{p}})_y}$$

Therefore, 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:

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

$$2/\sigma_p(d\sigma_p/dt)/(1.+\epsilon_a/\epsilon_p)\;+\;1/\mathcal{H}d\mathcal{H}/dt$$

where λ_a, λ_p are the anti-proton and proton bunch intensity lifetimes, respectively. σ_a and σ_p are the beam widths, averaged over both transverse planes[1].

Each of these terms can be determined from data. The proton lifetime can be much shorter than the inverse collision rate at the interaction points. The cause for such occasional short proton lifetimes is not known for certain (slightly incorrect closed orbits, betatron tunes, or non-linear resonance whose effects are possibly amplified by beam-beam forces). 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 $\approx\;25$ hours for all three planes. The self-consistency of this simple derivation has been checked by comparing the measured luminosity lifetime to the sum of

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

these other quantities, as shown in figure 1. Although reasonably good agreement is obtained (5 to 15%, relative, on the luminosity lifetime), the effective emittance growth rate is significantly different than the measured (SL) emittance growth rate. This is shown for a good store in figure 2.

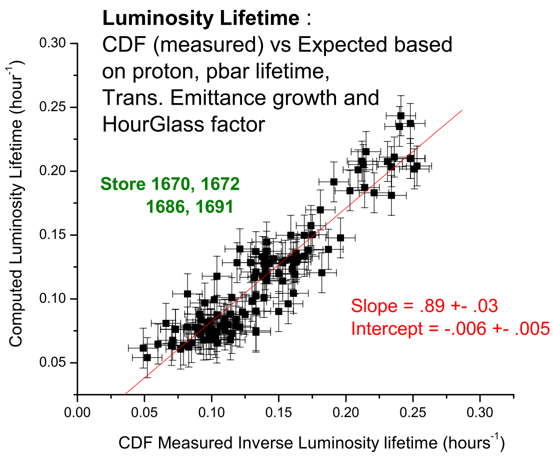

Figure 1: Correlation plot showing the predicted (based on various emittance and intensity detectors) vs measured luminosity lifetime. One data point corresponds to one $p\bar{p}$ bunch in a given store. This data was taken during August 2002. Similar results have been obtained on recent stores.

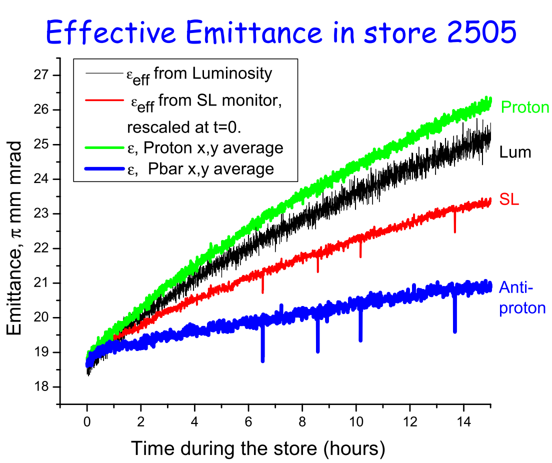

Figure 2: The effective emittance deduced from Luminosity measurement, averaged over all 36 bunches is shown as a function of time during the store. Also shown is the average proton and anti-proton emittances, reported by the SL front-end, re-scaled by a fixed factor, and the effective emittance deduced from this SL data. Data was taken May 3, 2003.

EMITTANCE GROWTH PHENOMENOLOGY

We now concentrate on the emittance growth rate factors. Such growth rate $r_\epsilon = 1/\epsilon \, d\epsilon/dt = 2 r_\sigma = 2/\sigma \, d\sigma/dt$ [2] 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. Note that, to first order, these growth rates are insensitive to fixed scale factors in the bunch size measurements. Various sources of emittance growth have been considered. We list them here in order of decreasing importance, starting with the proton beam:

- Based on modeling, Intra-Beam scattering (IBS) plays a leading role. Tentative evidence from the SL and SBD data is shown in the latter part of the paper.
- Poor vacuum in the Tevatron: The un-coalesced (small longitudinal emittance bunches) proton beams have a lifetime of about 500 hours. From this and direct pressure measurements, we concluded that the beam heating from multiple scattering on residual gas is small compared to IBS predictions.
- We measured the low-level phase noise in the r.f. system and wrote a simple numerical simulation model of the longitudinal dynamics with such noise. There is satisfactory agreement between measured noise spectral density and this model, once IBS is taken into account[8]
- Other possible sources 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. The longitudinal dampers stabilize the bunches during the stores. They do not affect such slow diffusion processes.

For the anti-proton beam, IBS is less intense because the bunch intensity is about 6 to 10 times smaller than for the proton beam. However, we strongly suspect that beam-beam effects plays a leading role[9]. In any event, the transverse emittance growth for the anti-proton beam is typically less pronounced than for the proton beam. In some cases, beam-beam effects in conjunction with a slightly wrong betatron tune causes beam losses instead of emittance growth, given the tight dynamical aperture.

We now show that these observed $r_{\epsilon(x,y,z)}$ growth rates, for the proton bunches are qualitatively and semi-quantitatively consistent with IBS predictions. The grow rates reported from now on have been measured for the first 2.5 hours of the stores, where such effects are maximized. The correlation between the horizontal and longitudinal growth rates shown on figure 3 is statistically significant, although there is a lot of fluctuation bunch to bunch and store to store. A similar correlation between the vertical and horizontal growth rates has also been observed.

[2] in absence of dispersion

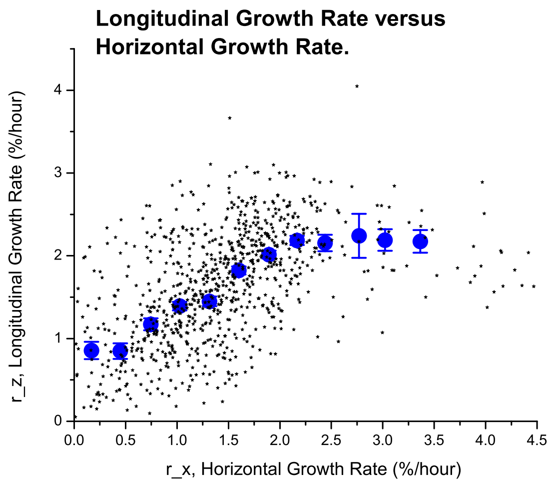

Figure 3: Correlation plot showing the longitudinal vs horizontal relative bunch size growth rates. Out of 15 stores, all but two stores showed some correlations. For each of these 13 stores, there is a probability of only a few percent that the apparent correlation is not real.

The comparison of data vs the IBS model is shown in figure 4. The correlation between predicted and measured values is statistically significant, once we reject the stores or bunches for which the proton loss rate is anomalously high compared to the expected loss due to collisions at B0 and D0. Semi-quantitative agreement is also observed in the transverse planes. In the absence of betatron coupling, IBS predicts no growth rate in the vertical plane. Since we are running with significant betatron coupling, emittance growth is indeed observed in both transverse planes. Despite the reduction of the growth rate in the horizontal plane due to this coupling effect, the IBS prediction for most of the stores are significantly above the measured values, in the horizontal and longitudinal plane. We suspect that residual beam losses could account for this discrepancy. Note also that we still have an unresolved discrepancy between the effective emittance growth rates and the measured (SL) emittance growth rates (see above) .

CONCLUSION

The Luminosity lifetime at the beginning of good stores (i.e., small unknown beam losses) is about 10 hours, and increases to 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 a degree of confidence in the model describing various luminosity upgrade scenarios[1]. We are planning to operate the collider at a peak luminosity of $3.3\ 10^{32}$ by raising both proton and anti-proton beam intensities, while preserving the current emittances. Under these circumstances, IBS is significant for both beams. The luminosity lifetime will then be $\approx$ 6 hours.

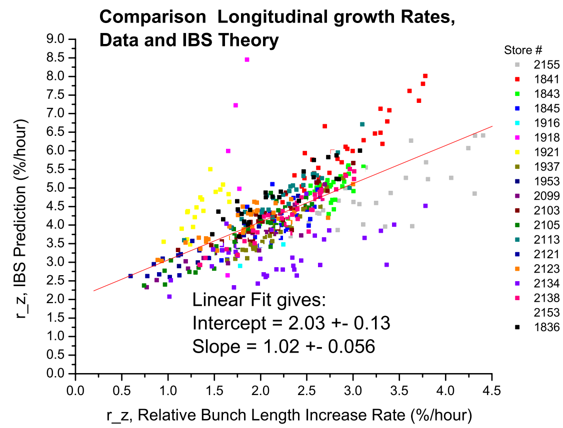

Figure 4: Correlation plot between the measured and IBIS-predicted longitudinal relative bunch size growth rates.

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