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# Beam losses at injection energy and during acceleration in the Tevatron.

T. Sen, J. Annala, P. Lebrun, R. Moore, V. Shiltsev, M. Syphers (FNAL);
W. Fischer (BNL), F. Schmidt, F. Zimmerman (CERN)

*Abstract*

Protons and anti-protons circulate on helical orbits in the Tevatron. At injection energy (150 GeV) the lifetimes of both species are significantly lower on the helical orbits compared to lifetimes on the central orbit but for different reasons. There are also significant beam losses in both beams when they are accelerated to top energy (980 GeV)- again for different reasons. We report on experimental studies to determine the reasons and on methods of improving the lifetimes and losses for both beams.

## INTRODUCTION

Beam losses on the Tevatron ramp have been significant since the beginning of Run II (March 1, 2001). In the last year they have become the most significant contributor to the Tevatron inefficiency. Losses on the ramp can not be attributed to a single effect. Several phenomena take place - e.g., losses due to shaving on a physical aperture, dynamic aperture (DA) effects due to machine nonlinearities, reduced DA due to beam-beam effects, loss of the DC beam, reduction of RF bucket area, etc. Figure 1 shows the variation of several parameters on the ramp in store 2328 (March 16, 2003, initial peak luminosity $40.6\times10^{30}$ cm$^{-2}$s$^{-1}$).

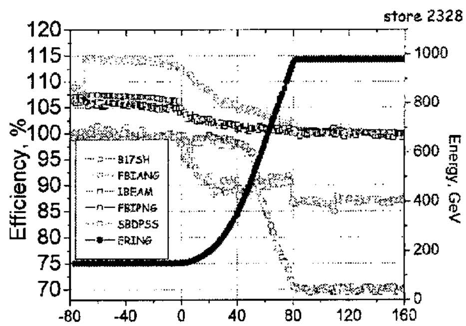


Figure 1: (color).Transfer efficiencies during the ramp in store 2328.

Two dedicated experiments were done, the first in September 2002 and the second in January 2003 to identify the mechanisms that cause protons to be lost during the ramp. In both experiments, only proton bunches were injected and ramped. The conditions in the Booster and the Main Injector were adjusted so that the bunches had different intensities and emittances.

The ramp lasts a little longer than 80 seconds. The largest beam loss occurs during the initial part of the ramp. We zoom in on the longitudinal dynamics in this part of the ramp. The bucket area at the start of the ramp is about 4.3 eV-sec, then decreases for the first 10 seconds to a minimum around 4.0 eV-sec before increasing to a final value of 10.4 eV-sec at 977 GeV. Figure 2 shows the bucket area for the first 20 seconds of the ramp. The synchronous phase required for the area of an accelerating bucket is calculated from the energy. It is evident that the energy data is not smooth during the ramp which results in a non-smooth bucket area. Therefore we have fitted the calculated area by a cubic polynomial curve in the least squares sense and the smoothed area curve is shown in Figure 2. Also shown in this figure is the smoothed beam intensity curve (also a cubic polynomial fit to the noisy FBIPNG data ) during this portion of the ramp. We observe that a large fraction of the beam loss occurs during the stage when the bucket area is decreasing. This is to be expected since the bunches injected into the Tevatron are long and almost fill the bucket at 150 GeV. This suggests that changing the ramp parameters to increase the bucket area in the first 10 seconds may be helpful. Apparently one attempt last year at doing this was not successful and did not reduce the beam losses.

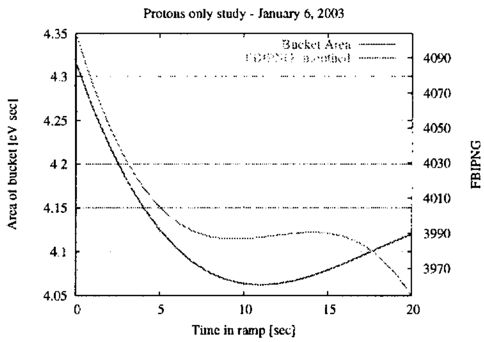


Figure 2: (color) The bucket area and the beam intensity during the initial stages of the ramp. These curves represent smoothed fits through the values at each second. Note that a large portion of the beam loss occurs while the bucket area is shrinking.

## BEAM STUDY WITH ANTI-PROTONS ONLY

In the pbar only study we observed that these antiprotons were indeed much more stable than with protons present. The large nonlinearities and the very large emittances in all 3 planes are not terribly important given that a) only one species is present, b) the currents are low (not true for protons) and c) the helix is chosen such as to avoid the tight aperture (this seems to be better fulfilled for the antiprotons compared to the protons). A detailed study for all 36 bunches on the front porch shows that the lifetime is quite high, i.e. between 10.6h and 25h (average 17.4h), even so the helix seems optimized for the antiprotons we find a sizable correlation ($R^2 \sim 0.43$) of the lifetime with the vertical emittance in agreement with the expectations due to a severe limitation in the vertical plane, however the correlation with the horizontal emittance is much smaller but still measurable; we do not find any correlation with the bunch-length, although it varies a lot. On the ramp we can make some general conclusions: once the ramps start the total beam current reduces by about 8.5% while the NG current stays constant which defines the fraction of the beam that is outside of the bucket; the average losses on the ramp are very small and within the noise of the measurement; during the squeeze the average loss is about 4%; lastly, the lifetime after the squeeze is 600 hrs for IBEAM and 160 hrs for NG.

## DIFFUSION MODEL

A simple model of constant phase space diffusion can shed light on the subject. By looking at the evolution of the particle intensity over time, it is evident that the extent of the antiproton distribution closely resembles the available aperture, whether it is physical or dynamic. For diffusion in one degree-of-freedom, the problem can be cast in terms of dimensionless variables $\tau \equiv (R/W_a)t$ and $Z \equiv W/W_a$, where $R$ is the rate of change of the Courant-Snyder invariant, $W$, of a particle and $W_a$ is the value of $W$ corresponding to the limiting aperture (i.e., the admittance). The solution to the diffusion equation is[1]

$$N(\tau) = 2\sum_n \frac{c_n}{\lambda_n} J_1(\lambda_n) e^{-\lambda_n^2 \tau/4} \qquad (1)$$

where the $\lambda_n$ are the zeroes of the Bessel function $J_0(z)$, and the $c_n$ are given by

$$c_n = \frac{1}{J_1(\lambda_n)^2} \int_0^1 f_0(Z) J_0(\lambda_n \sqrt{Z}) dZ \ , \qquad (2)$$

$f_0(Z)$ being the initial particle phase space distribution (assumed to be radially invariant).

In order to match the observed shape of the antiproton intensity variation in the Tevatron, the initial distribution needs to have an rms size comparable to the available aperture ($\sigma \approx a$). Once the correct shape has been established, the ratio of emittance growth rate to initial emittance sets the time scale: $\tau = 2(\dot{\epsilon}/\epsilon)(\sigma/a)^2 t$.

In the Tevatron, the observed shape of the antiproton intensity curve over 15 minutes suggests that this time scale corresponds to $\tau \approx 0.04$ and that $a \approx \sigma$, or a rather uniform distribution in the available phase space. The antiproton beams coming from the Main Injector have transverse emittances (95%, normalized) of about $20\pi$ mm-mrad, are rather Gaussian, and the available transverse aperture is approximately $3\sigma$ or so. Also, the necessary emittance growth rate would have to be $\dot{\epsilon} \approx 16\pi$ mm-mrad/hr, exceedingly large.

However, if we apply the same type of analysis to the longitudinal degree-of-freedom we find much more reasonable numbers. Namely, for an approximately uniform beam (after coalescing) entering a 4 eV-sec bucket, and a growth rate of 1/3 eV-sec/hr – all very consistent parameters for the Tevatron – then we get $\tau \approx 2$ (0.33 eV-sec/hr/4 eV-sec)(0.25 hr)) = 0.042. This suggests that the behavior of the beam lifetime at injection is governed more by longitudinal effects.

It should be noted in passing that the observed "$e^{-\sqrt{t}}$" behavior of the antiproton intensity is completely explained by the simple diffusion model. Using Eq. 1 and taking differing numbers of terms in the sum, we plot $N(\tau)$ over the range of interest of $\tau$ as well as $e^{-\sqrt{\tau}}$ in Fig. 3 . For this plot, we assume a uniform initial distribution within the aperture.

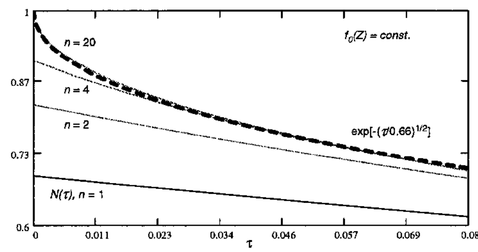


Figure 3: $N(\tau)$ using 1, 2, 4, and 20 terms in the sum. Also plotted is $e^{-\sqrt{\tau/0.66}}$.

## CONCLUSIONS

In two dedicated experiments we examined the losses of protons during the ramp. In the first experiment of September 24, 2002 we found that the losses were most strongly dependent on the longitudinal emittance. For example, uncoalesced bunches which had the smallest longitudinal emittance lost less than 2% of their intensity during the ramp. At the other extreme, coalesced bunches with the largest longitudinal emittance lost about 12% of their intensity and furthermore their longitudinal emittance decreased by about 20% after the ramp. This implies that particles from the longitudinal edges were lost. We found a weaker dependence of the loss on bunch intensity and vertical emittance.

In the second experiment on January 6, 2003 we attempted to isolate the dependence of the loss on the individual parameters in a controlled fashion. This time we also obtained the longitudinal profiles of the bunches at 150 GeV both on the central orbit and on the helix and again at 980 GeV. The longitudinal dampers were not turned on so the longitudinal oscillations of the bunches were not damped. We found that the most rapid loss occurs during the first 10 seconds of the ramp when the bucket area is decreasing - see Figure 2. Again we found that the loss during the ramp was determined overwhelmingly by the longitudinal emittance and the longitudinal profile. Short coalesced bunches with nearly Gaussian profiles had the smallest losses ($< 2\%$) while long oscillating bunches had losses around 10%. We found very little dependence on the bunch intensity. The same was true when we accelerated two proton bunches on the anti-proton helix.

We conclude that the losses of protons during the ramp can be minimized if the longitudinal emittances are as small as possible and the bunches attain an equilibrium distribution before the start of the ramp. This would require better coalescing in the Main Injector, perhaps with the addition of longitudinal dampers. It might also help to turn on the longitudinal dampers during the ramp in the Tevatron.

## REFERENCES


[1] D.A. Edwards and M.J. Syphers, *An Introduction to the Physics of High Energy Accelerators*, Section 7.2, Wiley, New York (1993).