Results from Beam Diffusion and Collimation Measurements in Preparation for Fermilab Tevatron Crystal Extraction

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Abstract

In order to extract stored beam from the Tevatron Collider in a controlled and transparent manner, protons must be diffused from the core of the beam into the lattice of the bent crystal without inducing higher background rates in the high energy physics detectors CDF and D0. The experimental study of diffusion, collimation, and detector backgrounds are part of the larger effort of the Fermilab experiment E853. Reported in this paper are results showing the effect of RF noise on beam size evolution, proton diffusion from the beam core, and detector backgrounds.

I. INTRODUCTION

In preparation for the Fermilab Tevatron crystal extraction experiment 853 [1] parasitic colliding beam studies and some dedicated proton only experiments were performed. The purpose of this work was to perform preliminary exploratory experiments on the effect of RF noise and collimation on a proton beam and on the background rates measured in the high energy physics detectors CDF and D0.

Three basic sets of experiments were performed. First, the effect of RF noise on the beam in the absence of collimation (but in the case where protons spill out of the RF buckets confining the bunches) is studied during a proton only store at 900 GeV. Second, the effects of a steel collimator during the above RF noise induced diffusion is observed in the same store. Finally, a test of collimation with a unbent crystal during a normal colliding beam store is reported.

II. EXPERIMENTAL SETUP

The Tevatron stores 6 proton and 6 antiproton counter-rotating bunches at 900 GeV. At the crystal the horizontal dispersion and beta are 2.02 m and 90.8 m respectively. The transition gamma has a value of approximately 18. The synchrotron frequency is 39 Hz. Typical beam dimensions are an rms horizontal betatron width of 0.60 mm, an rms horizontal divergence of 166 μr, an rms bunch length of 60 cm (2 nsec), and an rms relative energy spread of 166×10^{-6}.

The RF system is split into two sets of 4 cavities each. Four cavities accelerate either protons or antiprotons, but generate a net voltage of zero for the other beam. This is accomplished by spacing pairs of cavities 90° apart at the RF frequency 53.104705 MHz (bucket length of 18.8 nsec). Each beam sees a net RF voltage of 1.1 MV/turn (corresponding to an RF bucket half height of 446 MeV). External noise (white in the band between 50 and 100 Hz) was added to the RF amplitude program to induce longitudinal dilution. An external voltage of 10 V changes the RF voltage by 100 kV (10%). Applied at twice the synchrotron frequency, this noise causes quadrupole oscillations and longitudinal diffusion.

There are a series of steel collimators in the ring. They are oriented both vertically and horizontally, where the horizontal collimators are placed on the radial inside of the vacuum chamber. This orientation allows the steel to intercept particles which have fallen out of an RF bucket and are decelerating due to synchrotron radiation emission at the rate of 5 eV/turn toward the radial inside. A single horizontal silicon unbent crystal sits on the radial outside for studies.

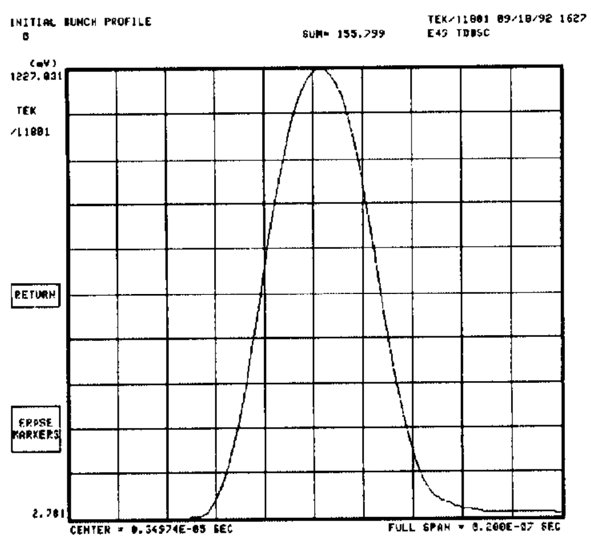

Figure 1: Initial longitudinal beam distribution as measured by a broadband resistive wall monitor and oscilloscope. The scale of the time axis is 2 nsec/div.

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III. MEASUREMENTS

A. Diffusion without Collimation

Two levels of external random noise were applied to the RF amplitude program. The first experiment was performed with an rms external voltage of 500 mV, which corresponds to a rms RF gradient fluctuation of 5 kV/turn. Due to the proton diffusion caused by this noise and the fact that the separatrix of the bucket acts as an aperture, the longitudinal density distribution of the beam changes into a new equilibrium shape. Figures 1 and 2 show the longitudinal shape of a typical proton bunch before and after RF amplitude noise was applied. Note that the equilibrium shape has a narrower FWHM than the initial distribution, but has many more particles at large amplitude near the bucket separatrix (the left and right edges of the plot).

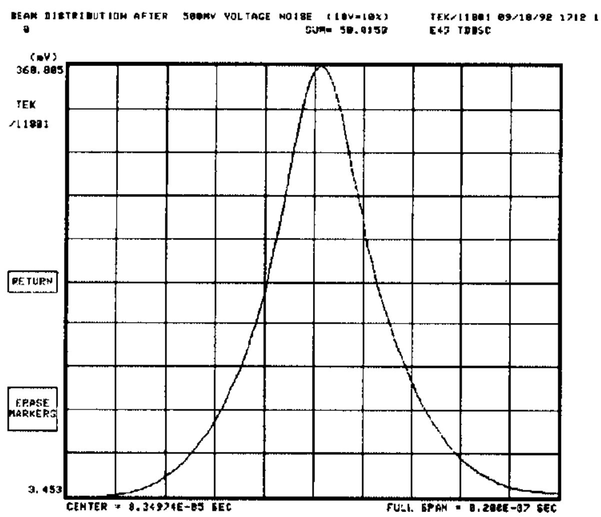

Figure 2: Equilibrium longitudinal distribution generated by RF amplitude noise and the RF bucket separatrix. The scale of the time axis is still 2 nsec/div.

Once the equilibrium shape of the longitudinal bunch distribution was established, an exponential particle loss rate was established. In the 5 kV/turn case, the relative proton loss rate was 1.4×10^{-3}/sec (over 3 orders of magnitude to large a rate). This corresponds to an intensity time constant of 12 minutes.

The next experiment used a reduced external noise level of only 50 mV, corresponding to an RF voltage jitter of 500 V rms. Figure 3 shows the DC and bunched beam intensities vs. time during the study. The equilibrium loss rate in this case was measured to be 1.6x10-5/sec (for a time constant of 17 hours). The nominal intensity time constant for the protons in the Tevatron Collider varies anywhere from 40 to 120 hours, depending on beam-beam effect variations store to store. Note that a factor of 10 reduction in noise amplitude was responsible for a factor of 100 reduction in the proton loss rate. The DC beam (total beam intensity in the accelerator, both bunched and unbunched) lags the bunched beam loss (the sum total intensity in the 6 primary proton RF buckets) due to the fact that the 5 eV/turn deceleration rate of each proton requires approximately an hour for the particles to hit the inside edge of the horizontal aperture.

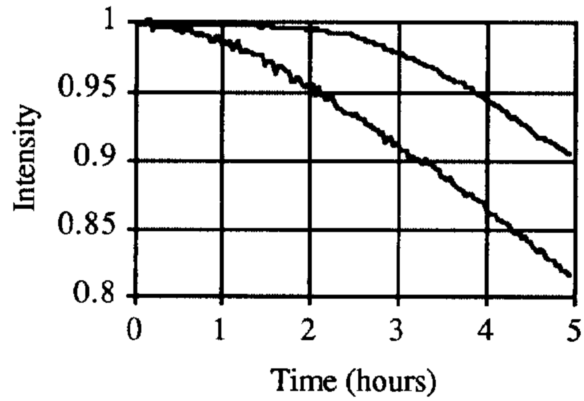

Figure 3: DC beam (top) and bunched beam (bottom) normalized intensity vs. time during RF amplitude noise excitation at the 500 V rms/turn level.

During the latter measurement the bunch length was monitored. One of the potential negative impacts of this extraction technique is that the external noise will increase the bunch length. Since the vertex detectors of the collider experiments and the β^* at the interaction point are comparable to the bunch length, lengthening would cause a reduction in luminosity. While the rms bunch length increased from 55 cm to 75 cm (see figure 4), the FWHM bunch length decreased from 150 cm to 140 cm. This seemingly contradictory result is due to the shape change in the longitudinal bunch distribution. Since the core width (as measured by the FWHM parameter) is basically unchanged, there is no adverse effect of crystal extraction on luminosity.

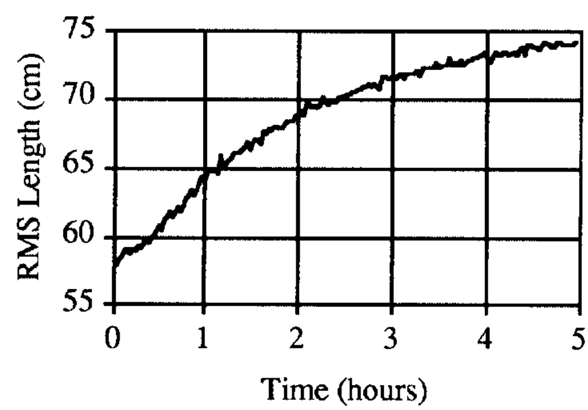

Figure 4: Proton bunch length vs. time during the period when 500 V rms/turn of RF amplitude noise was being applied. At this noise level it takes approximately 6 hours for the bunch length to come to an equilibrium value.

B. Collimation without Diffusion

Before addressing the question of background counting rates in the high energy physics detectors in the presence of externally driven diffusion and collimation, it is useful to measure the diffusion rate during typical colliding beam conditions. This measurement is carried out by monitoring the rate at which single protons are deposited into the CDF high energy physics detector when a momentum aperture defining horizontal collimator (a collimator in a region of high dispersion) is retracted by a small distance. By measuring the time it takes for the loss rate to return to its original value, the average diffusion rate can be calculated.

In this experiment a collimator was retracted by 100 μm. It was observed that the proton loss rate in the CDF detector initially dropped from approximately 4 kHz to 2 kHz, and then required 2000 seconds to approach the original loss level again. Therefore, the diffusion rate was measured to be 0.01 Angstroms/turn. If a crystal replaced the collimator, this would be the average diffusion rate which would be observed at the face of the crystal.

C. Steel Collimator

Again applying an rms RF amplitude noise level of 500 V/turn, a steel horizontal collimator was place next to the beam. Since the edge of the bucket in the horizontal plane (the bucket half height times the horizontal dispersion) is 1 mm from the center of the beam, and the total bunch width at the crystal is 0.7 mm, a collimator would have to scrape away almost half of the beam intensity before it would become the dominant bunched beam aperture. But since the collimator is on the radial inside, it will eventually intercept all of the diffused beam particles. Even though the above noise level induces a loss rate 10 times that which is desired for crystal extraction, the maximum proton background rate measured in the CDF detector was 5 kHz. Depending on the value of luminosity, a background rate below 10 to 5 kHz is considered acceptable.

In addition to slowing down the extraction rate, it should be possible to employ other collimators as "shadows". These collimators are not primary apertures, but they intercept particles which have interacted with the primary aperture and have either large betatron or energy deviations.

D. Silicon Crystal Collimator

In order to assure that the measurements made with the steel collimator were meaningful for crystal extraction calculations, an unbent silicon crystal was installed in the Tevatron. Unfortunately, the crystal was installed on the radial outside of the accelerator, so that it cannot intercept DC beam. On the other hand, large betatron amplitude particles will strike the silicon crystal as their momentum error increases.

Under the same diffusion conditions as the previous section and using the silicon crystal as the primary aperture, it was found that the CDF loss increased from approximately 2 kHz to 10-15 kHz. Again, remember that this diffusion rate is 10 time that desired for crystal extraction experiments.

At this point, a steel horizontal collimator at the A0 location was brought in as a shadow. The proton background rate in CDF decreased immediately to a value of approximately 5 kHz. Upon removal of the A0 collimator, the losses rose immediately to the 10-15 kHz level again.

IV. CONCLUSIONS

It has been shown in this paper that the diffusion and collimation required to simulate the effects of crystal extraction have little or no deleterious effects on a high energy physics collider experiment. Therefore, it should be possible to perform parasitic studies of crystal extraction during the next Tevatron collider run. In addition, major concerns regarding the compatibility of crystal extraction and collider physics have been answered.

At the accelerator physics level, it has been learned that the momentum spread is so large and the dispersion so small that a horizontal collimator cannot supersede the RF bucket separatrix as the dominant aperture in the Tevatron Collider. Therefore, in order to simulate the crystal extraction process to be employed in the SSC, it will be necessary in the Tevatron to either decrease the longitudinal emittance of the proton bunches or increase the local horizontal dispersion at the crystal. Both solutions are currently under study.

V. REFERENCES

1. G. Jackson, "Extraction from the Fermilab Tevatron using Channeling with a Bent Crystal", Proc. 1993 Part. Acc. Conf., Washington D.C. (1993).