Measurements of Transverse Beam Diffusion Rates in the Fermilab Tevatron Collider

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1. INTRODUCTION

THE TRANSVERSE BEAM DIFFUSION RATE vs. particle oscillation amplitude was measured in the Tevatron using collimator scans (Figure 1). All collimator jaws except one were retracted. As the jaw of interest was moved in small steps, the local shower rates were recorded as a function of time. By using a diffusion model, the time evolution of losses could be related to the diffusion rate at the collimator position. Preliminary results of these measurements are presented.

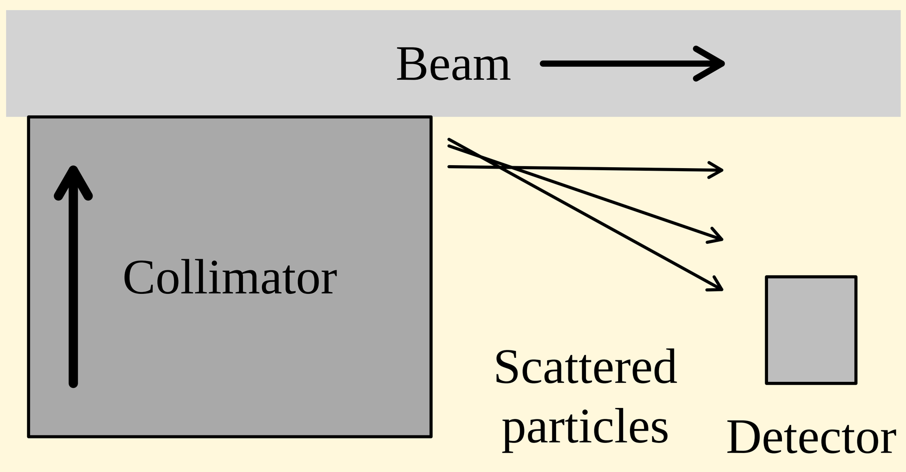

Figure 1: *Schematic layout of the apparatus.*

Phenomena related to stochastic transverse beam dynamics in circular accelerators can be described in terms of particle diffusion [1]. It was demonstrated that these effects can be observed with collimator scans [2]. For the Tevatron, a detailed description of the collimation system can be found in Ref. [3]. Collimator jaws define the machine aperture. If they are moved towards the beam center in small steps, typical spikes in the local shower rate are observed, which approach a new steady-state level with a characteristic relaxation time (Figure 2). When collimators are retracted, on the other hand, a dip in losses is observed, which also tends to a new equilibrium level. These phenomena were used to estimate the diffusion rate in the beam halo in the SPS at CERN [4], in HERA at DESY [2], and in RHIC at BNL [5]. Similar measurements were carried out at the Tevatron in 2011 to characterize the beam dynamics of colliding beams and to study the effects of the novel hollow electron beam collimator [6].

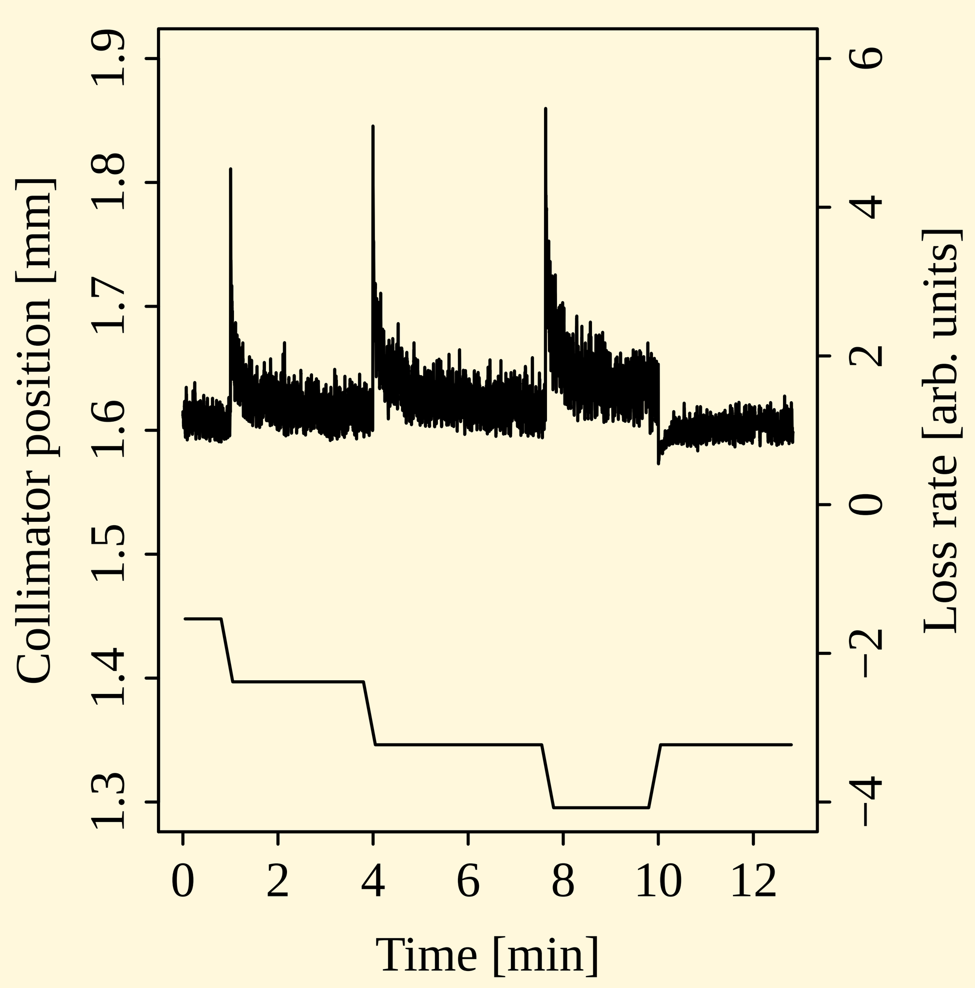

Figure 2: *Example of the response of local loss rates to inward and outward collimator steps.*

2. MODEL

A diffusion model of the time evolution of loss rates caused by a step in collimator position was used to interpret the data [7]. It builds upon the work presented in Ref. [2] and its main assumptions: constant diffusion rate within the range of the step and linear halo tails. These two hypotheses allow one to obtain analytical expressions for the solutions of the diffusion equation and for the corresponding loss rates as a function of time. Our extended model addresses some of the limitations of the previous model and generalizes it in the following ways: (a) losses before, during, and after the step are predicted; (b) different steady-state rates before and after are explained; (c) determination of the model parameters (diffusion coefficient, tail population, detector calibration, and background rate) is more robust and precise.

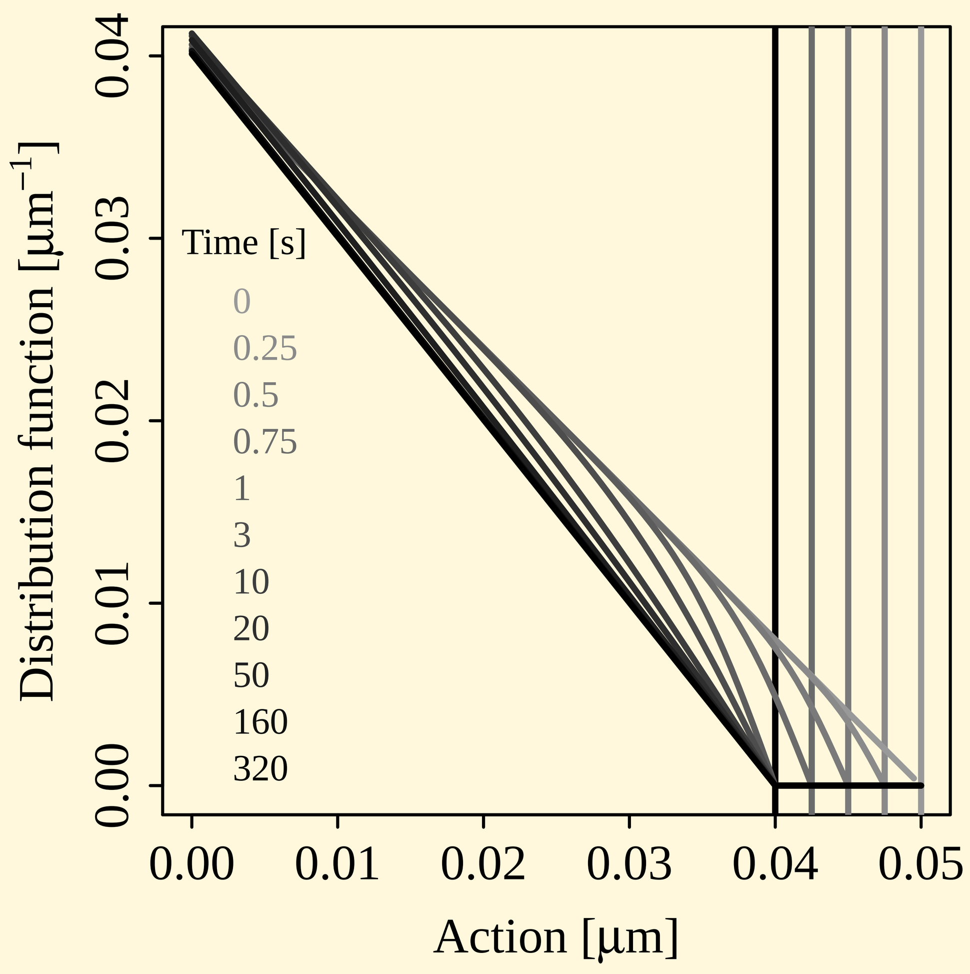

Figure 3: *Calculated evolution of the distribution function during an inward collimator step. The vertical lines represent the positions of the collimator vs. time. Collimator action varies between $J_{ci} = 0.05\ \mu$m and $J_{cf} = 0.04\ \mu$m in a time $\Delta t = 1$ s. The initial and final slopes of the tails are $A_i = 0.8\ \mu\text{m}^{-2}$ and $A_f = 1\ \mu\text{m}^{-2}$. The diffusion coefficient is $D = 10^{-5}\ \mu\text{m}^2/\text{s}$.*

Under the hypotheses described above, the diffusion equation can be solved analytically using the method of Green's functions, subject to the boundary condition of vanishing density at the collimator and beyond. Details are given in Ref. [7]. An example of the evolution of the phase-space density according to this model is shown in Figure 3. Local losses are proportional to the gradient of the distribution function at the collimator.

3. DATA ANALYSIS

The model is used to interpret the measured shower rates. Parameters are estimated from a least-squares fit to the experimental data. An example is shown in Figure 4.

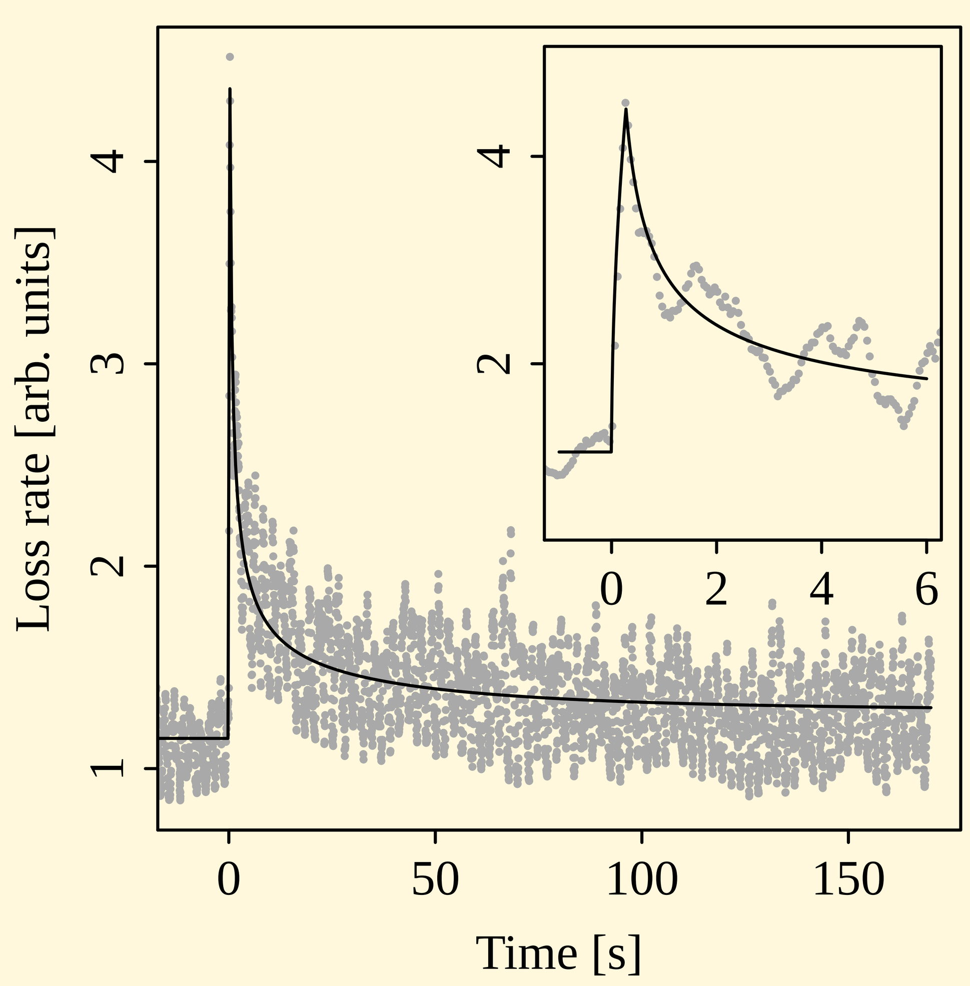

Figure 4: *Example of least-squares fit of the model to the observed loss rates during an inward collimator step.*

The model explains the data very well when the diffusion time is long compared to the duration of the step. With this technique, the diffusion rate can be measured over a wide range of amplitudes. At large amplitudes, the method is limited by the vanishing beam population and by the fast diffusion times. The limit at small amplitudes is given by the level of tolerable loss spikes.

4. RESULTS

Several collimator scans were performed at the Tevatron during 2011. The goal was to observe the effect on diffusion of beam-beam forces and of the hollow electron beam scraper. An example of the strong dependence of the diffusion rate on amplitude is shown in Figure 5. The experiment was done at the end of a regular collider store. Experimental conditions are summarized in Table 1. Every 2 to 3 minutes, the F48 vertical antiproton collimator was moved inward by 50 μm in 0.2 s. At the location of the collimator the amplitude function was $\beta_y = 29$ m and the r.m.s. beam size was $\sigma_y = 320\ \mu$m.

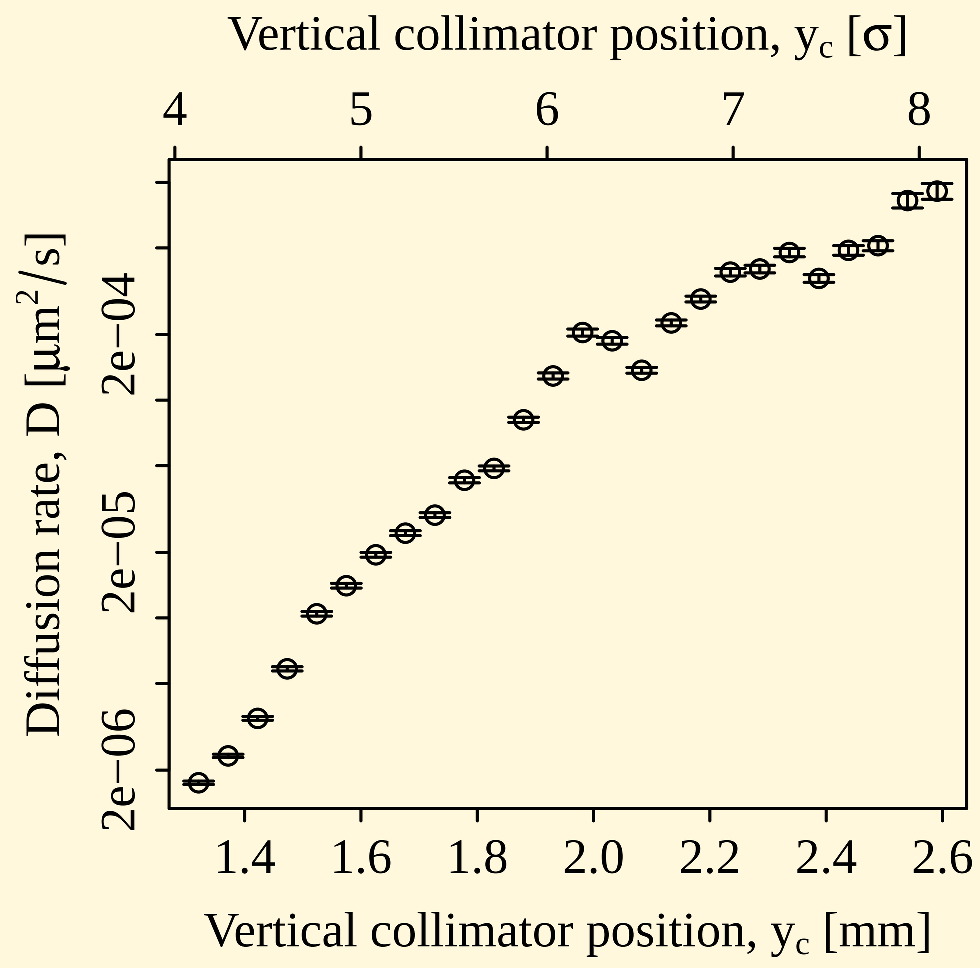

Figure 5: *Measurements of the transverse beam diffusion rate with a vertical antiproton collimator scan (Tevatron Store 8527, 25 February 2011).*

Table 1: *Summary of experimental conditions for the diffusion measurement shown in Figure 5: instantaneous luminosity, $\mathcal{L}$; average number of protons and antiprotons per bunch, N^p and N^a; average transverse emittances (95%, normalized), ε_x^p, ε_y^p, ε_x^a, and ε_y^a; average longitudinal emittances, ε_z^p and ε_z^a; average momentum spreads, δ_p and δ_a; average incoherent tunes, Q_x^p, Q_y^p, Q_x^a, and Q_y^a; chromaticities, Q'_x and Q'_y.*

$\mathcal{L}$	N^p	N^a	ε_x^p	ε_y^p	ε_x^a	ε_y^a
$1/(\mu\text{b s})$	10^{11}	10^{11}	μm	μm	μm	μm
27	1.67	0.326	38.0	42.7	26.2	21.7

ε_z^p	ε_z^a	δ_p	δ_a
eV s	eV s	10^{-4}	10^{-4}
7.18	6.97	1.753	1.708

Q_x^p	Q_y^p	Q_x^a	Q_y^a	Q'_x	Q'_y
0.5888	0.5888	0.5861	0.5862	4.0	4.4

In this experiment, the diffusion rate grows with the 9th power of amplitude, or $J^{4.5}$. It exibits some structure, possibly related to the nonlinearities of the machine. A detailed comparison of the diffusion rates for antiprotons with and without collisions is under way. For the bunches affected by the hollow beam scraper, this technique provided the first direct evidence of halo diffusion enhancement (about a factor 10).

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