TEVATRON END-OF-RUN BEAM PHYSICS EXPERIMENTS

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Abstract

Before the Tevatron Collider Run II ended in September of 2011, a number of specialized beam study periods were dedicated to the experiments on various accelerator physics concepts and effects during the last year of the machine operation. The study topics included collimation with bent crystals and hollow electron beams, diffusion measurements and various aspects of beam-beam interactions. In this report we concentrate on the subject of beam-beam interactions, summarizing the results of beam experiments. The covered topics include offset collisions, coherent beam stability, effect of the bunch-length-to-beta-function ratio, and operation of AC dipole with colliding beams.

INTRODUCTION

Over the course of the Tevatron Collider Run II, the accelerator program has seen a remarkable success. Many novel Accelerator Physics (AP) ideas were studied and applied at the collider as well as at other machines of the complex, which resulted in the dramatic progress of the luminosity production [1]. The peak luminosity exceeded the Run II project goal and ultimately reached 4.3×10^{32} $cm^{-2}s^{-1}$, and more than 11 fb^{-1} of integrated luminosity was delivered to the High-Energy Physics (HEP) experiments [2]. During the last two years, the machine was operating in a stable configuration, which provided Fermilab's accelerator experts with an opportunity to plan and carry out beam physics experiments for the benefit of future machines. There was a strong interest from other accelerator laboratories including BNL, CERN and LBNL to study a number of AP topics at the Tevatron before it is switched off forever.

The majority of AP studies were carried out concurrently with collider operation, either parasitically during HEP stores, or during short (1-3 hour) end-of-store periods minimizing the use of precious machine time and impact on the luminosity production. Some studies, however, required special beam conditions or were deemed unsafe for parasitic mode and thus demanded dedicated machine time. It was decided to group the experiments into compact two-week periods, in which the special AP stores would be interleaved with normal HEP operation. This approach allowed the studies to be planned at more convenient time of day, and provided time for immediate analysis and discussions of the experimental data.

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Two such AP study periods were scheduled and carried out in 2011: the first one in May was dedicated to crystal collimation [3], hollow electron beam lens [4], and diffusion measurements [5]; the second in August was devoted to beam-beam-related experiments. In this report we summarize the results of the beam-beam AP study period.

The initial list of experimental proposals was collected and prioritized at a one-day workshop at Fermilab in 2010 [6], and then was further reduced to five items: operation of AC dipole with colliding beams, coherent beam-beam modes, effect of transverse separation, effect of bunch length to beta-function ratio, and effect of external noise on beam-beam interactions.

The studies made use of 43 hours of machine time over the two-week period, with the actual beam time equaling 35 hours and the rest spent on set-up and failure recovery. Eleven special beam fills were used for experiments.

EXPERIMENTAL CONDITIONS

In normal HEP operation Tevatron was filled with 36 bunches of each (proton and antiproton) particle species. The fill pattern had a three-fold symmetry with three trains of 12 bunches. The beams collided head-on at two main interaction points (B0 and D0 IPs) spaced by one third of the ring circumference. Outside of the main IPs the beams were separated transversely with the use of electrostatic separators, and would interact at 70 long-range interactions with separation ranging from 6 to 10 beam sigma. Since our experiments concentrated on head-on interaction, the number of long-range collisions was reduced by filling the machine with 3 bunches of each type. Thus each bunch had only four long-range IPs at ~10 sigma, and their effect can be neglected.

Electron cooling in the recycler ring reduced the emittance of antiproton bunches before their injection into the Tevatron. As a result, it was possible to achieve almost equal beam-beam parameters of the two beams albeit with significantly (up to a factor 2) different transverse dimensions. Unfortunately, the electron cooling was not operational during much of the study period. This significantly hampered our ability to study coherent beam-beam modes but provided suitable conditions for experiments on weak-strong effects.

Table 1 lists the typical beam parameters during the beam-beam studies. Other parameters relevant to the studied effects were the feta-functions at the main IPs β^*=30 cm, and the betatron tune working point Qx=20.584, Qy=20.587 for protons and Qx=20.570, Qy=20.575 for antiprotons.

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Table 1: Beam Parameters (* with electron cooling off).

Parameter		Value
Protons per bunch		2.8×10^{11}
Antiprotons per bunch		$0.8\ (0.4^*)\times10^{11}$
Proton emittance (95% normalized)		22 μm
Antiproton emittance		8 (14*) μm
Proton bunch length		0.51 m
Antiproton bunch length		0.45 m
Proton momentum spread		1.4×10^{-4}
Antiproton momentum spread		1.2×10^{-4}
Hourglass factor		0.61
Beam-beam tune shift	protons	0.015 (0.005*)
	antiprotons	0.019

OFFSET COLLISIONS

It was indicated by numerical simulations [7] that a transverse offset of the colliding beams could lead to emittance growth caused by coherent beam-beam effect. Weak-strong simulations, at the same time, predicted that transverse separation leads to intensity lifetime degradation with the losses peaking at the offset of 1-1.5σ [8]. We performed scans of horizontal and vertical beam-beam separation at B0 IP (with beams colliding head-on at D0) observing the beam intensity, emittance and luminosity at both experiments. The scans demonstrated that a) no emittance growth occurs for the Tevatron parameters. This is substantiated by the fact that specific luminosity at D0 stays constant during the scan; b) the intensity decay rate peaks at 1-1.5σ (Fig. 1, 2); c) the effect on beam life time is negligible up to the offset of 0.4-0.5σ. In all cases the losses were mostly observed in the weak (antiproton) beam. The peak losses were at the level of 1% per hour, however measurements indicate that the effect can be partially mitigated by the change of tune working point.

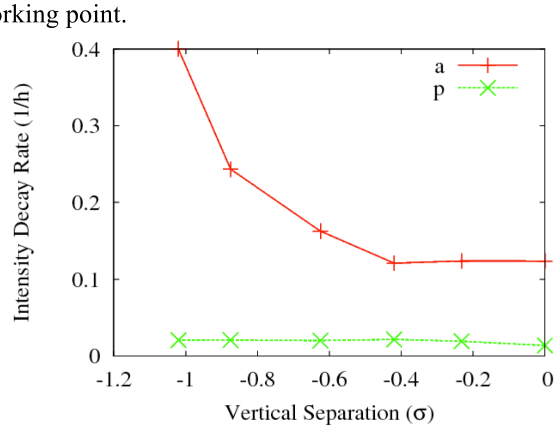

Figure 1: Beam intensity decay rate as a function of vertical beam-beam separation at one collision point. 'a'-antiproton data, 'p'- proton data.

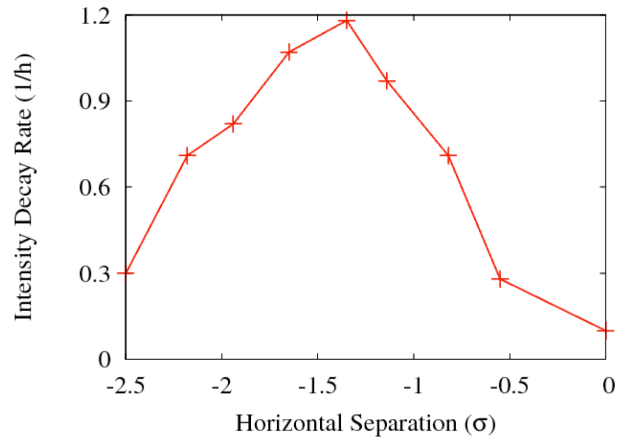

Figure 2: Antiproton beam intensity decay rate as a function of transverse beam-beam separation at one collision point.

COHERENT STABILITY

Colliding beams represent a system of coupled oscillators with their eigen-frequencies determined by beam and machine properties. Interplay of the machine impedance and coherent beam-beam oscillations could create conditions for instability of some of the coherent modes [9]. We planned to explore the behavior of the coherent beam-beam modes in the presence of collective instability. However, the lack of electron cooling of antiprotons prevented experiments in strong-strong regime. Hence, we concentrated on the studies of the stabilizing effect of beam-beam force nonlinearity.

Due to the danger of head-tail instability, the Tevatron normally operated with the chromaticity C=+14 without collisions and +5 at collisions. Earlier work [10] indicated that the nonlinearity of beam-beam interaction results in stabilization of head-tail instability through Landau damping.

We performed a direct measurement of the threshold betatron tune chromaticity with and without beam-beam interaction. A train of 3 nominal intensity proton bunches was injected in the machine and the current of chromaticity correction sextupoles was gradually lowered until an instability was observed. The head-tail instability was very fast slightly above C=0, causing a quench. Similar experiment with colliding beams demonstrated very clearly that *whenever beam-beam interaction is present, any chromaticity value could be dialed in without causing the head-tail instability*. The stabilizing effect was fully independent of the choice of the tune working point.

Due to the absence of fast triggered data acquisition we were unable to perform quantitative measurement of the instability growth rates. Also, studies of the effect of beam brightness were not performed due to unavailable bright antiprotons.

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EFFECT OF BUNCH LENGTH

Theoretical work by Alexahin [11] predicted that the so-called phase averaging in collisions of bunches with finite length should mitigate certain beam-beam resonances and improve beam lifetime. We measured the dependence of particle lifetime on the ratio of beta-function at the IP to the bunch length σ_z. This was achieved by varying the β^* via shifting the collision point longitudinally, while keeping the bunch length constant. The results of the measurement are presented in Figs. 3 and 4. A clear dependence of the lifetime on β^*/σ_z is observed. The increase in proton losses is symmetrical with respect to the direction of the IP shift, while there is significant asymmetry in the measurement for antiprotons. This feature could be explained by the asymmetry of position of horizontal and vertical beta-function minima in the antiproton beam optics.

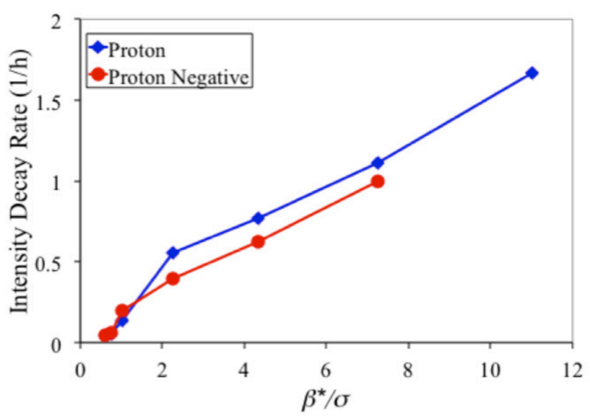

Figure 3: Proton beam intensity decay rate as a function of β^* to bunch length ratio.

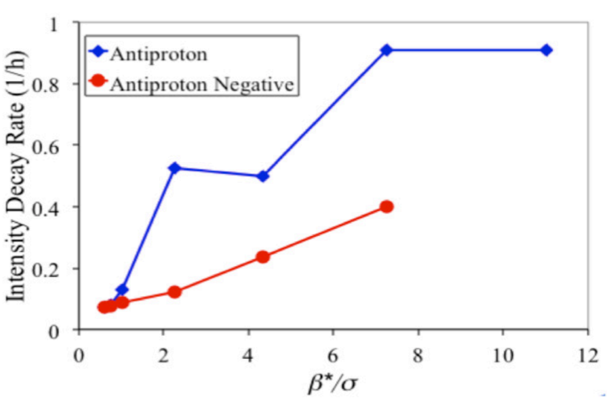

Figure 4: Antiproton beam intensity decay rate as a function of β^* to bunch length ratio.

AC DIPOLE WITH COLLIDING BEAMS

AC dipole is a device that adiabatically excites transverse oscillations of the beam. Turn-by-turn detection of these oscillations allows restoring the beam optics [12]. The interest in performing studies at the Tevatron was to demonstrate that the AC dipole could be operated with colliding beams, offering the possibility to measure incoherent tune shift, dynamic optics distortions (beta-beating caused by beam-beam), and perhaps nonlinear effects such as the tune shift vs. amplitude. The goal of the measurement was to excite the "weak" beam through the strong beam using the AC-dipole.

The Tevatron experimental procedure had several deficiencies: a) the weak-strong arrangement of the beams had to be reversed since the BPM system operates in a turn-by-turn mode for protons only. This was done by using the lowest possible proton intensity against nominal low emittance antiprotons; b) owing to the low beam intensity, the BPM signal was quite noisy; c) the strong betatron coupling of the machine lattice complicates the mode picture and negatively affects the signal detection. These issues disallowed good quantitative measurements. In particular, the beta-beating restored from the AC dipole kick turn-by-turn data, were quite noisy.

Despite the above-mentioned issues, the studies were successful to demonstrate that AC dipole could be safely operated with colliding beams, driving oscillation amplitudes up to 4 beam sigma. No instability or emittance growth was observed after multiple excitations.

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