RECENT STUDIES OF THE BEAM-BEAM INTERACTION WITH PARASITIC COLLISIONS: EXPERIMENTS

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Abstract

Long-range beam-beam interactions are expected to limit the maximum achievable luminosity in colliders with several thousand high-current bunches. In this report we summarize recent experiments with focus on parasitic collisions in the Tevatron, SPS, LEP, CESR, the B-factories, and RHIC. Compensation schemes and the relevance of these findings to the LHC will be discussed.

1 INTRODUCTION

Both existing and future colliders call for increasing the number and intensity of bunches to maximize the total luminosity. The counter-rotating bunches must be separated on either side of the interaction points (IPs) and in the collider arcs. However, bunches which are separated by only a few sigma experience long-range beam-beam forces, which may compromise the total number of bunches. Moreover, in accelerators operating with as many as possible bunches, these long-range interactions are expected to eventually limit the achievable bunch intensities and hence the luminosity.

Long-range beam-beam interactions introduce various complications beyond those seen with the usual short-range interactions. These include additional non-linearities, additional shifts in the bunch tune, and coupling generated between the bunches. Operational difficulties may also arise due to the separation schemes; e.g. large crossing angles, strong separator fields, dispersion generated by the separators, or coupling introduced by the detector solenoids with displaced orbits.

Irregularities in the bunch fill pattern give rise to additional concerns. At the LHC, gaps in the fill patterns will be present to avoid beam loss due to the rise and fall times of the injection and abort kickers and possibly for alleviation of ions and/or electron clouds. Such gaps introduce for the different bunches multiple tune footprints which depend on the proximity to the gap(s), different orbits, lifetimes, and luminosities, potential changes in coherent beam-beam modes, and operational concerns due to the differences in bunch properties.

In this report we summarize selected observations from existing colliders pertaining to parasitic collisions (PCs). Common features of the observations will be stressed as will those issues pertinent to operation of the LHC, which has a design fill pattern consisting of over 2800 bunches per beam and up to 120 PCs (15 on each side of 4 IPs).

2 SEPARATION SCHEMES

Long-range interactions are avoided by maximizing the separation between those pairs of bunches not intended for primary collisions. Existing single ring colliders have been adapted to accommodate multiple, widely spaced bunches by the introduction of sine-like closed orbit distortions for separating the beams using electrostatic separators in the accelerator arcs. Distortions in a single plane, so-called “pretzel” orbits, were introduced at CESR, LEP, and the SPS, while at the TeV, appropriately phased distortions were applied in both transverse planes in so-called “helix” orbits.

Alternatively, localized trains of bunches have been used where the PCs are avoided using electrostatic, or magnetic, separation (LEP) or using a crossing angle (CESR) at the IPs. Double-ring colliders (PEP2, KEKB, RHIC, LHC) allow to increase the number of bunches (with the separation scheme at the IPs as for bunch trains) and long bunch trains without the complications introduced by the common vacuum chamber.

3 EXPERIMENTAL OBSERVATIONS

The experimental data on long-range interactions are classified in terms of symmetric or asymmetric collision geometries. *Symmetric interactions* are those long-range interactions arising from collisions between bunches which experience beam-beam forces that are independent of the bunch structure of the opposing beam; i.e. the presence (or absence) of an opposing bunch. These occur given widely spaced bunches, which have PCs via a pretzel or helix collision scheme, or in the regime of closely spaced bunches near the middle of bunch trains. *Asymmetric interactions* are those arising from collisions between bunches where the absence of an opposing bunch affects the ensuing dynamics. For example, with 5 bunches per train, only the middle 3 bunches experience symmetric long-range interactions considering only the first PC on either side of the IP. At the LHC with multiple PCs [1], the concepts of “collision schedules” and equivalence classes has been developed [2,3].

3.1 Symmetric Long-Range Interactions

The most recent experience with long-range beam-beam effects comes from the Tevatron [4,5], which is a single ring collider with helical orbits for separating the beams. Present operations use 3 trains of 12 bunches with electrostatic separation in the IPs and 70 PCs in the arcs. Significant improvements [5] were recently accomplished by increasing the distance of closest approach of the two beams at the PCs from 1.8σ to 2.7σ during the transition between the helix optics used at injection and that used in collision. Measurements [5] of the beam currents shown before and after this improvement are shown in Fig. 1. After this correction the sudden drop in antiproton beam intensity seen near the center of the plots was eliminated.

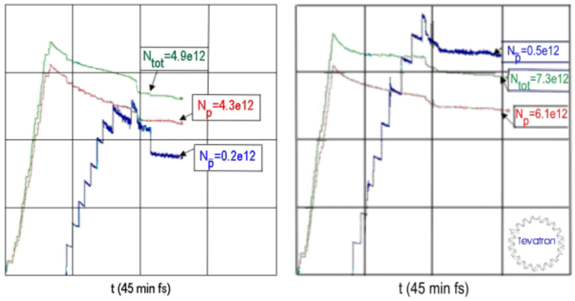

Figure 1: Beam currents during injection into the Tevatron before (left) and after (right) modifications for better separation of the PCs (courtesy V. Shiltsev, 2002).

Measured [5] single-bunch antiproton (pbar) intensities in collision with protons (p) at the Tevatron are shown at injection energy (150 GeV) in Fig. 2. In this measurement, batches of 4 pbar bunches were injected with each batch having different emittances. The particle losses experienced by the largest bunches are due to the long-range interactions. With a 4σ bunch separation, the protons act as a "soft collimator" on the pbar beam [5].

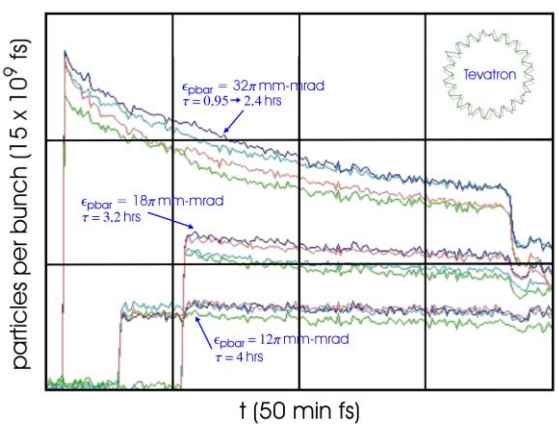

Figure 2: "Soft-collimation" effect of the protons on the antiprotons due to PCs at the Tevatron (courtesy V. Shiltsev, 2002).

Similar collimation effects were observed [6] earlier in the SPS p-pbar collider, a single-ring accelerator operating with 6 widely spaced bunches separated using a horizontal pretzel orbit outside the IPs. The beam separation was >6σ at all but one (of 9) PCs where the separation was only 3.5σ. As shown in Fig. 3, when the separation of the PCs was reduced by a factor of 2, the detected losses of the proton beam increased [6]. The influence of the high-order (13^{th} and 16^{th}) resonances on the proton beam was also visible.

At the newly commissioned, double-ring collider RHIC, PCs are nominally absent as the present bunch spacing is large. Recently however poor beam lifetimes have been attributed to long-range interactions [7,8] as shown in Fig. 4, which depicts the currents of two Au beams versus time. When the rf loops were closed an rf frequency difference was introduced which caused the IP to move longitudinally. As verified independently [8] this produced a tune modulation and ensuing beam loss, which has since been eliminated using transverse separation at the IPs.

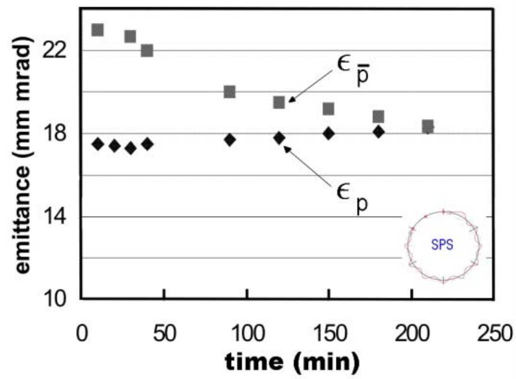

Figure 3: Proton beam backgrounds in the SPS before (diamond) and after (squares) the separation of the PCs was reduced by a factor of 2 [6].

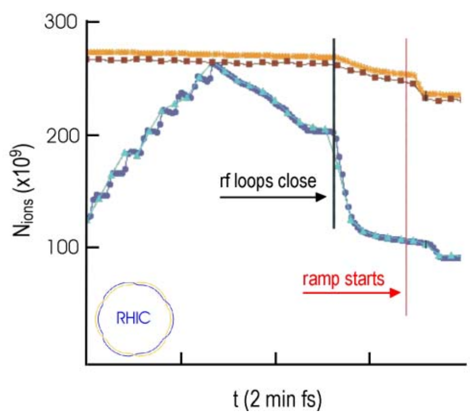

Figure 4: Beam loss due to PCs caused by a difference in rf frequencies of the beams in RHIC (courtesy W. Fischer, 2002)

3.2 Asymmetric Long-Range Interactions

Asymmetric beam-beam interactions are characterized by bunch properties which depend on their location within a bunch train. Usually the collision parameters are adjusted for maximum luminosity for the majority of the bunches. However, the singular properties of the outermost bunches could with time conceivably affect neighboring bunches - hence the expression "pacman bunches".

Asymmetric interactions were studied at LEP [9-11], which was a single-ring collider operating successfully for many years with continued refinements aimed at increasing the total number of bunches. In studies prior to the final upgrade, the pretzel scheme was abandoned in favor of localized bunch trains separated at the IPs using electrostatic separators. The luminosity measured [9] for each of 4 bunches in a single train is shown in Fig. 5 obtained from a beam-beam scan for which the relative vertical separation between the beams at the IP was varied in discrete steps. The curves were obtained using a self-consistent analysis of the beam-beam kicks experienced (or not experienced) on either side of the IP.

From these and subsequent studies many important conclusions may be drawn [9-11]. The end bunches have orbits, chromaticities, and tunes which are different from those undergoing symmetric interactions so the maximum luminosity is different for different bunches resulting in a net lower total luminosity. Not shown (but taken into account in the analysis) is that different bunches had different total currents as it was found difficult to fill the outermost bunches with colliding beams – an effect that has also been observed at other colliders. It is worth noting that the orbit offsets alone cannot account fully for the measured variations in the specific luminosity.

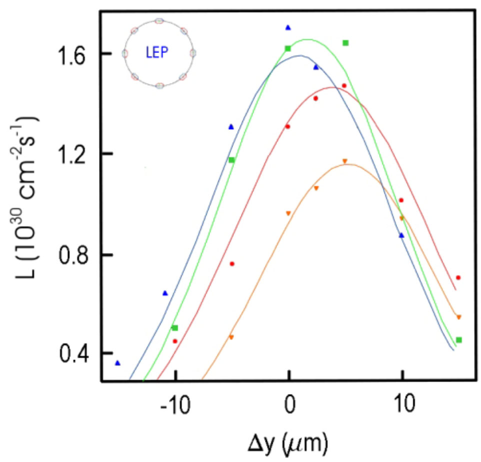

Figure 5: Luminosity scan at LEP during initial studies with 4-bunch train operation (courtesy W. Herr, 2002).

Similar studies with 2- and 3-bunch, bunch trains were later performed at LEP [10,11]. With 2 bunches per train, the orbit deviations could be made symmetric (still with asymmetric collisions) and the performance of single bunch operation was restored. Comparisons between collision geometries led to the further important observation that the maximum achievable beam-beam tune shift was dependent on the train length [10,11].

This train-length dependence of the maximum tune shift was measured directly at CESR using variable length bunch trains as shown [12] in Fig. 6. Operating with a single ring and pretzel optics in the arcs, the measured luminosity as a function of average bunch current is shown with 4 bunches and 5 bunches per train with a total of 9 trains in both cases. The maximum tune shift was observed to be 10% higher with 4, as opposed to 5, bunches per train [12].

In separate studies at CESR with similar conditions, the integrated and specific luminosity per bunch and the integrated current were measured [13]. These data, plotted as a function of the location within the bunch train, are shown in Fig. 7 (car 1 designates the first bunch in each of the 9 bunch trains, for example). From these data was concluded [13] that the variations in luminosity were due both to the different bunch currents in each car and to the different bunch sizes. As at LEP, the imperfect overlap of the outmost bunches at the IP was insufficient to explain the measured specific luminosities of these bunches.

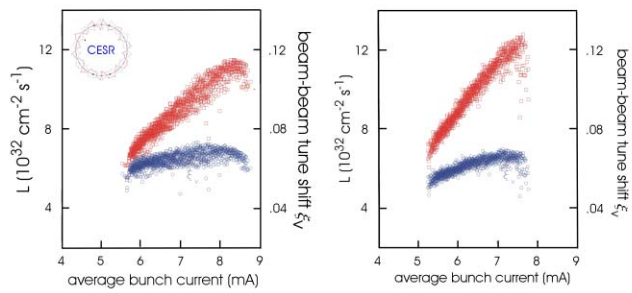

Figure 6: Luminosity and beam-beam tune shift achieved at CESR with 9 trains of 4 (left) and 5 (right) bunches per train (courtesy D. Rubin, 2002).

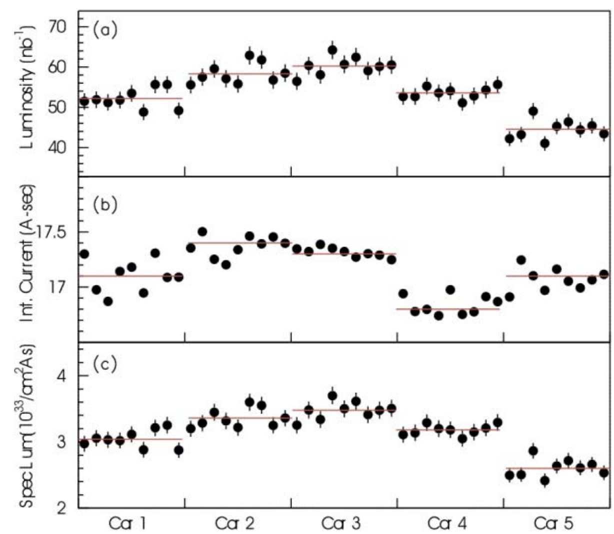

Figure 7: Integrated luminosity (a), integrated current (b), and specific luminosities (c) sorted according to location within the bunch train as measured at CESR with conditions similar as Fig. 6, right (courtesy M. Billing, 2002).

An effect which may prove crucial for future compensation schemes is shown in Fig. 8 from CESR, which shows the time-dependence of the relative orbit displacement of the different cars [13]. In this measurement the relative vertical position of each bunch was measured, averaged over location within the bunch train (a car), and plotted as a function of time. From these data, variations of up to 0.5σ were detected between cars. Of note is that the last of such bunches (car 5) evidenced a dramatically different behavior compared to the other cars. Such asymmetry between for leading and lagging bunches has been observed also at LEP and the B-factories. A conclusive explanation for this effect awaits.

Worth mentioning are recent data from the B-factories, which collide in separate rings positrons on electrons. Both the KEKB and PEP-II accelerators operate with high–intensity, multibunch trains much like that envisioned for the LHC but with fewer PCs. While PACMAN-*like* effects are observed in both accelerators, the limitations of both accelerators are primarily driven by electron clouds. This not forseen instability is expected to be present also at the LHC and may similarly constrain the optimal bunch distributions (fill patterns).

At PEP-II, while luminosity variations between bunches have been observed there is no direct evidence to date that PCs degrade the luminosity. Dedicated experiments [14] performed at KEKB showed no luminosity degradation due to PCs with the nominal +/- 11 mrad crossing angle.

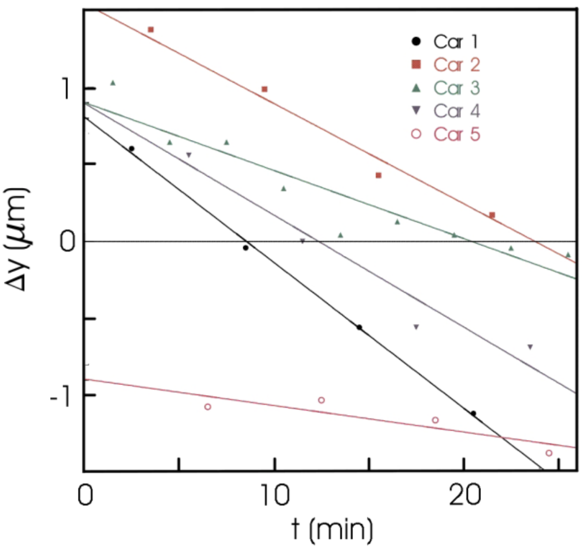

Figure 8: Measured relative displacement between beams at the IP versus time measured at CESR (courtesy M. Billing, 2002).

3.3 Other recent observations

It is conceivable that perturbations of the bunch properties at the end of bunch trains, even if not caused by PCs, may potentially aggravate the already complicated long-range beam-beam dynamics. In the worst possible case, eventually the current and/or luminosity degradations generated at the end of bunch trains could migrate towards train center slowly affecting adversely the properties of all bunches. In Fig. 9 is shown the measured [15,16] bunch-by-bunch luminosities at PEP-II. The distribution, which was uniform at the start of collisions, evidenced irregularities by the end of the store in those bunches immediately following the abort gap.

This effect was studied further using bunch-by-bunch measurements of the individual beam size of one of the beams. The measurements [15,16] are shown in Fig. 10. In this case (similar to observations from KEKB), one of the beams evidenced a sudden and persistent change in beam size. At PEP-II such adversely affected bunches also evidenced poor lifetime. The change in beam-beam tune shift of such bunches has yet to be measured.

4 POTENTIAL CURES

To alleviate orbit variations between bunches, the existing bunch-by-bunch feedback was modified at CESR [17]. The differential motion of the bunches was detected and used to kick each bunch relative to the opposing bunch. The initial results [17] appear promising for the future.

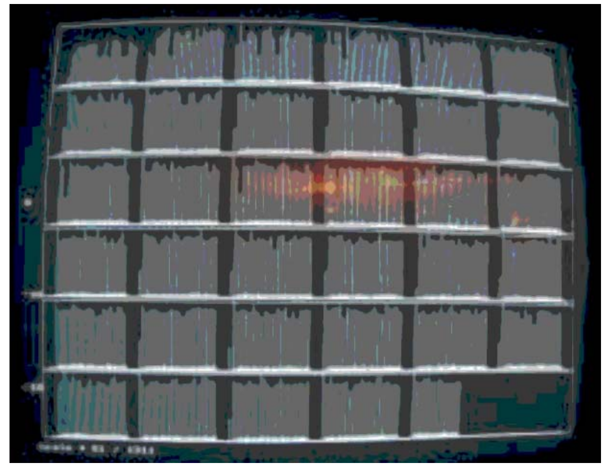

Figure 9: Bunch-by-bunch luminosity measured at the end of a store at PEP-II (courtesy R. Holtzapple, 2002).

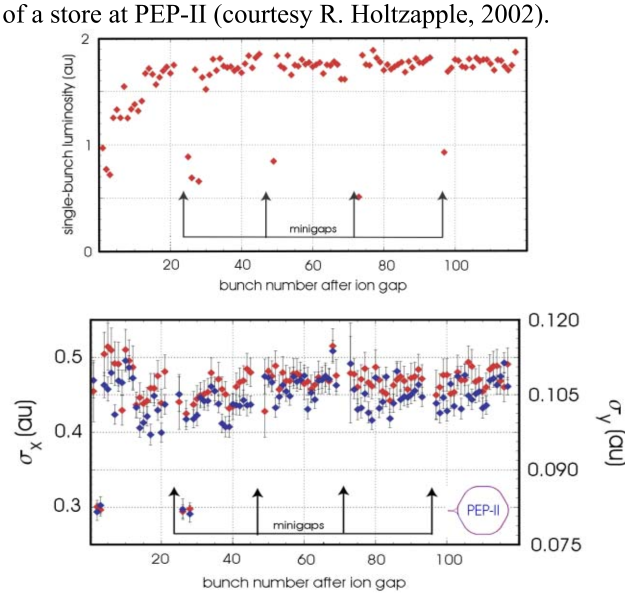

Figure 10: Bunch-by-bunch luminosity and beam size measured as a function of position at PEP-II (courtesy R. Holtzapple, 2002).

At Fermilab, suppression of bunch-to-bunch tune spread (linear) and intrabunch tune spread (nonlinear compensation) are envisioned using an electron lens [18]. Initial results are encouraging and further experimental data are eagerly awaited.

For the LHC, first and foremost is envisioned a scheme of alternate crossings [1,19] for the even number of IPs. By symmetry, by alternating the sign of the crossing angle the forces on the particles are cancelled at successive pairs of interaction points. Additionally the feasibility of an electromagnetic lens [20] is under study. In this case the 1/r dependence of the long-range beam-beam force is to be compensated by a wire providing the same electric field dependence. Experimental verification of the viability of this elegant scheme awaits.

It is expected that both the electron lens and the electromagnetic lens may be used to correct PC effects by appropriately pulsing (in time and amplitude) the required compensation [18,20]

Lastly, as shown [21] in Fig. 11, coherent centroid motion of the beams may be Landau damped via the tune spread generated by the beam-beam interaction. Not only may coupled bunch instabilities be damped, but possibly also coherent modes generated by strong-strong interactions between both primary and parasitic bunches.

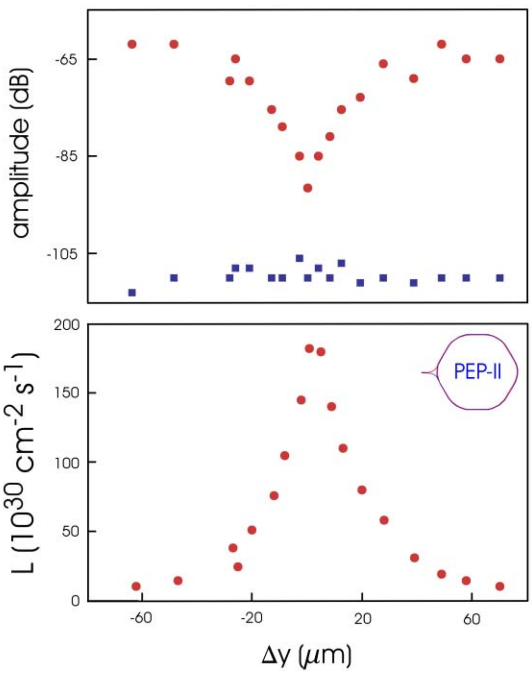

Figure 11: Measured horizontal (squares) and vertical (circles) instability amplitude (top) and luminosity (bottom) versus relative beam separation at the PEP-II IP with transverse bunch-by-bunch feedback turned off.

5 OUTLOOK

A common observation (LEP, CESR, TeV, PEP-II) involves the difficulty achieving and/or maintaining the desired bunch currents with PCs present. The variations in bunch currents, particularly at the end of bunch trains, have been significant with beams in collision. Fortunately, such difficulties are not expected to limit the LHC, where it is envisioned that the beams will be sufficiently well separated during injection. However, with the beams then brought transversely into collision the "soft collimation" effects (SPS, TeV) could introduce such intensity variations between bunches.

An important feature of the LHC design, not yet tested experimentally, involves the small rms spread between the betatron phase of the PCs; while the phase difference varies from 2.0-88.5 degrees, 80% of the PCs have an rms phase difference of only 0.4 degrees [20]. In the worst case, the PACMAN effects might add coherently. On the other hand, the small rms variation is precisely that required for compensation of beam-beam effects using the electromagnetic lens [20].

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