A SUMMARY OF CARE-HHH-APD PRESENTATIONS ON BEAM-BEAM EFFECTS & BEAM-BEAM COMPENSATION AT THE LHC

J. P. Koutchouk, CERN, Geneva, Switzerland

Abstract

This paper aims at summarizing five years of activities of the CARE-HHH network on one of the prominent limitations of hadron colliders.

INTRODUCTION

The beam-beam effect is a basic limitation to increasing the peak and integrated luminosity of colliders. This is the case in the Tevatron and RHIC and is the expected limit in the LHC. The topic was therefore discussed in several CARE-HHH events:

2002	LHC IR Upgrade Collaboration Meeting, CERN
2004	HHH-2004, CERN
2005	LUMI-05, Arcidosso
2006	LUMI-06, Valencia
2007	• Contributions to US-LARP workshop on beam-beam compensation, SLAC • BEAM-07, CERN • IR-07, Frascati
2008	• Meeting on beam-beam effect and compensation, CERN • This HHH08 meeting

Some 60 presentations on the beam-beam effects have been given, by 26 different authors: N. Abreu/BNL, Y. Alexahin/FNAL, K. Cornelis/CERN, U. Dorda/CERN, W. Fischer/BNL, M. Furman/LBNL, W. Herr/CERN, A. Kabel/SLAC, V. Kamerdzhiev/FNAL, J.-P. Koutchouk/CERN, V. Lebedev/FNAL, Y. Luo/BNL, C. Milardi/INFN-LNF, K. Ohmi/KEK, S. Peggs/BNL, T. Pieloni/CERN, F. Pilat/BNL, J. Qiang/LBNL, P. Raimondi/INFN-LNF, F. Ruggiero/CERN, T. Sen/FNAL, W. Shiltsev/FNAL, G. Sterbini/CERN, E. Tsyganov/UT Southwestern, A. Valishev/FNAL, F. Zimmermann/CERN.

The goal of this summary is an attempt at drawing perspectives from the available material (transparencies of the talks were used). Given the complexity of this field where the understanding is often qualitative, several interpretations are possible. The author evidently takes responsibility for the selection of material restricted around a few topics and for some interpretations proposed. The RHIC contributions are reported in [1].

PHENOMENOLOGY AND BEAM-BEAM LIMIT

Definition of the beam-beam limit

The beam-beam limit is specified here as the maximum total beam-beam tune spread (or shift) that the beams can stand without a significant decrease of lifetime. This definition seems to cover the observations in the present generation of hadron colliders. Other criteria holding in the past or for electron rings can be different, e.g. limitation by an increasing background to the experiments (ISR), flip-flop effects (several electron machines)...The value of the beam-beam limit for the head-on beam-beam effect is taken from experience in former or existing hadron colliders. The long-range beam-beam effect due to the large number of bunches in the Tevatron and LHC introduces an additional complexity. It is taken into account by putting a limit on the total combined tune spreads arising from the head-on and long-range effects. Possible limitations of this criterion are the somewhat arbitrary maximum transverse amplitude considered for the tune spread calculation and disregarding resonant effects. These limitations together with the empirical value of the beam-beam limit should lead us to critically review the present observations. Luminosity predictions indeed depend on the square of the assumed beam-beam limit.

Value of the beam-beam limit

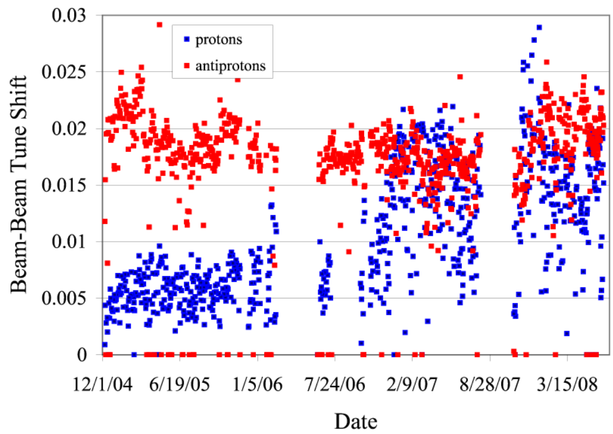

Figure 1: Beam-beam tune shift at the Tevatron, from [4]

The limit on the beam-beam tune spread assumed for the LHC upgrade is 0.01 for the combined effect of head-on and long-range beam-beam detunings [2]. This value was considered as operational in the SppbarS (though calculated for a maximum amplitude of 4σ instead of 6σ used in the LHC). The RHIC beam-beam tune shift is presently equal to this value [3]. While the head-on beam-beam tune shift at the Tevatron appeared to be limited slightly above this value, recent progress has significantly changed the situation (figure 1). Although the spread is large, a number of runs shows head-on beam-beam tune shifts above 0.025 with an average around 0.015. This outstanding performance has been obtained in presence of numerous long-range perturbations occuring all around the machine, in a more complex scheme that that of the LHC. There are therefore good reasons to believe that the beam-beam limit could be well above the LHC performance assumptions. Taking into account the square law dependence of the luminosity on the beam-beam tune shift, the best achievement observed at the Tevatron would be sufficient to implement the full LHC luminosity upgrade, increasing the luminosity by about one order of magnitude.

Limitations of the concept of beam-beam limit

Already in 2004, the Tevatron experience showed clearly that the beam-beam performance cannot be simply characterized by the beam-beam tune shift or spread [5]. The phenomenology is quite complex and seems to depend on a large number of parameters (quality of the optics and accuracy of its control, modulations, noise,…). A few examples from observations or simulations illustrate this complexity:

- In the Tevatron, a good matching of the proton and antiproton transverse emittances is favorable for high performance, as anticipated (Figure 2) from [6].

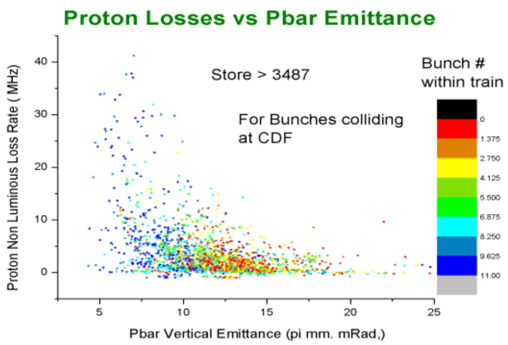

Figure 2: Correlation between proton loss rate and pbar beam size, from [6].

However, a stronger beam-beam effect (higher antiproton intensity) is surprisingly not detrimental to the luminosity loss rate (Figure 3) from [6]

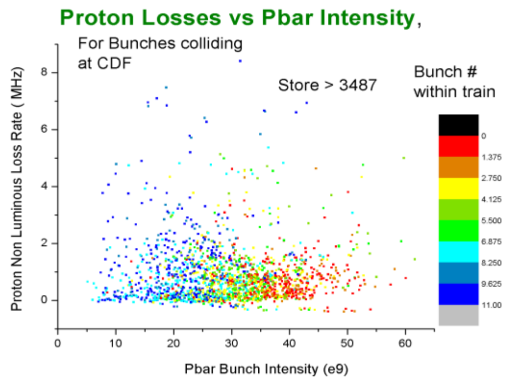

Figure 3: Correlation between proton loss rate and pbar intensity, from [6].

- The long-range beam-beam effect appears in simulations to enhance the diffusion and the emittance growth much faster than its contribution to the criterion of detuning would indicate.

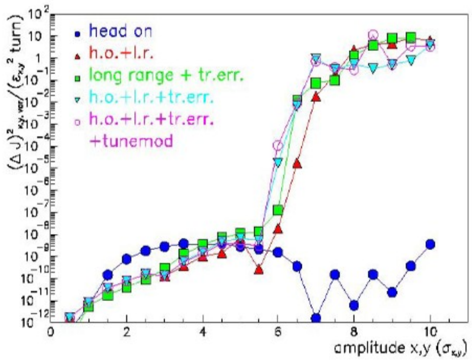

Figure 4: Onset of strong diffusion due to the long-range beam-beam effect, from [7]

Figure 4 from [7] shows the qualitatively different effect of the long-range perturbations on the diffusion towards larger amplitudes using a simplified model. While the head-on beam-beam effect is basically stable for all initial amplitudes, the long-range beam-beam effect causes the onset of a strong diffusion above a 6σ initial amplitude for the LHC. Figure 5 from [8] shows that, in a more complete model, the perturbation is not limited to the large amplitude tails but contributes as well to an emittance growth of over 2% in about 10 seconds of coasting time while again no growth is observed when only the head-on effect is at work.

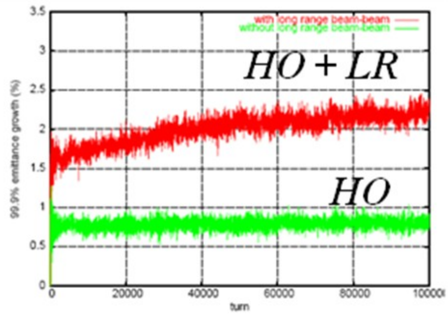

Figure 5: LHC predicted emittance growth over 100000 turns, from [8]

Even more intriguing is the numerical observation reported in [9] by the same author: The long-range beam-beam effect enhances strongly the emittance blow-up due to an imperfect overlap at the collision point by a fraction of the beam size. Figure 6 shows no significant consequence of a horizontal separation by 0 to 0.4σ when only the head-on beam-beam effect is at work. However, when the long-range beam-beam effect is added, a detectable blow-up appears for a parasitic separation of 0.1σ.

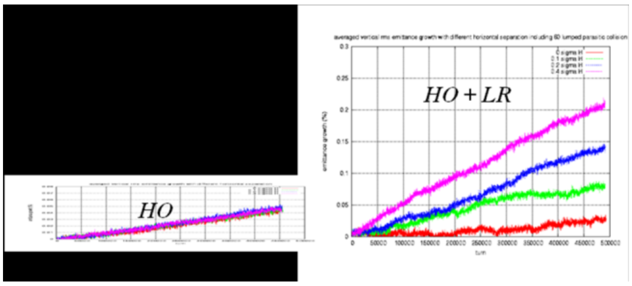

Figure 6: Predicted vertical emittance growth in LHC [9] for a parasitic beam separation of 0, 0.1, 0.2 and 0.4σ with head-on only (HO) and head-on and long range. The vertical scales are identical.

- Another set of simulations [10] shows again the peculiar effect of the long-range beam-beam perturbations in the LHC, this time evaluated on the beam intensity decay rate. Figure 7 shows that the head-on or long-range beam beam effect in isolation does not cause a detectable intensity loss over 10^7 turns (15 minutes of coasting time). However both combined cause a loss of 3.5% that is easily detectable even though it is not dramatic. Figure 8 shows the transverse spectra. There is clearly no indication from these spectra that the combined effects of head-on and long-range beam-beam should significantly increase the beam loss rate.

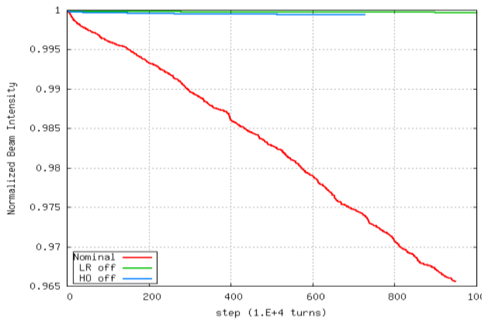

Figure 7: Intensity vs time; red: nominal, green: LR off, blue HO off, from [10]

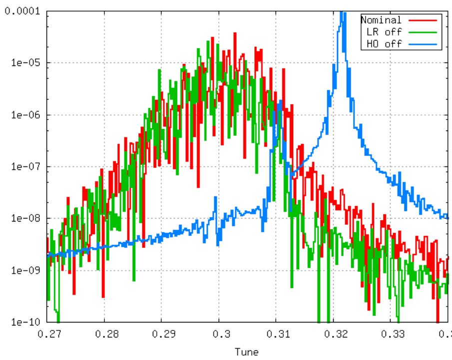

Figure 8: Transverse spectrum with same color convention, from [10]

- The long-range beam-beam effect can be simulated with good precision by the effect of a wire carrying the corresponding electric current. Such experiments were done in the SPS and RHIC. An interesting outcome is shown on Figure 9 from [11]. The long-range beam-beam effect tends to cut the beam tails much like a scraper would do. Here the wide beam injected by mismatching a transfer line quadrupole suffers an emittance reduction by a factor 3 while the peak intensity is only reduced by 15%.

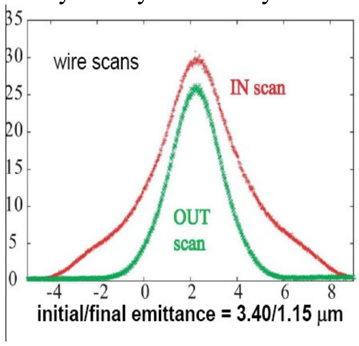

Figure 9: Transverse beam profile before and after excitation of a long-range beam-beam effect, from [11]

Combination of crossing planes

The baseline LHC design included provisions (aperture, orbit correctors) for beam crossing in arbitrary planes. However, the late requirement of a beam screen in the low-beta triplets, decreasing their already tight aperture, imposed freezing the crossing planes. The footprint criterion, including nominal and pacman bunches, privileged the default scenario of alternate crossing proposed for the SSC. The tracking of the diffusive aperture, backed by SPS experiments using two wire compensators, tends to show that the situation is more complex. At least for equal initial conditions in the two transverse planes, tracking shows that non-alternate crossing appears better in terms of diffusive aperture (Figure 10 from [12]) for nominal bunches. The situation in terms of frequency map appears less decidable (Figure 11 from [11]). Detailed tracking not reported in CARE-HHH [13] confirmed a marginal difference for alternating or non-alternating crossings.

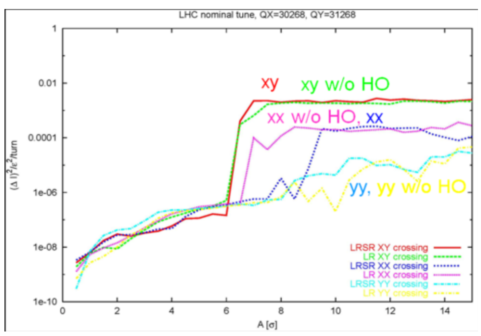

Figure 10: Diffusive aperture versus crossing scheme, from [12]

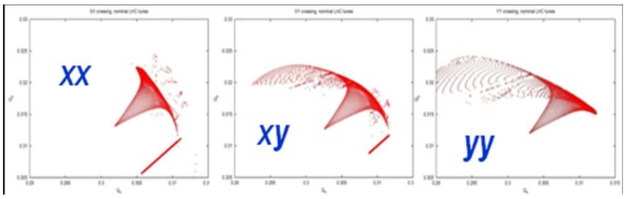

Figure 11: Frequency maps versus crossing scheme, from [11]

Further tracking [14] for emittance blow-up and calculation of resonance excitation confirms that only the LHC machine can provide a definitive answer: the XX crossing causes larger tune spread but limited resonance excitation, while the XY crossing causes a narrower tune spread but excites more resonances with observation of halo formation.

Minimum beam separation

It was found long ago that the many long-range encounters occurring in the LHC require a beam separation of at least 9.5σ. For the LHC upgrade, the early separation scheme option requires a few encounters (4 to 12) to occur at the smallest separation compatible with a long beam lifetime. Such a scenario had not been considered. Hints, observations and tracking results are summarized below:

SppbarS [15]	7 LR's @ 6σ + 1 LR @ 3.5σ	OK for years with ultimate LHC bunch charge
Tevatron [16]	4 LR's @ 5.3σ	5% to 10% integrated luminosity gain when increasing separation by 10%
RHIC experiments [17] [18]	1 LR @ 4σ	Losses observed
	4 LR's @ 5σ	Lower lifetime with one exception
	1 to 10 LR's @ 5 to 9σ	Onset of losses; threshold very sensitive to working point.
RHIC simulations [19]	4 LR's @ 5σ	Not possible
LHC design	17 LR's @ 7σ + 1 LR @ 5σ	Safe in simulation
SPS wire experiment [20]	4 LR's @ 5σ	Appears safe; more LR's create a lifetime reduction
LHC 2D+ simulations [21]	8 LR's @ 5σ	Comparable to SppbarS if other LR's are at 13σ rather than 9.5σ

The overall picture is not quite consistent, whether from simulations or observations. An important weight should be given to the SppbarS results as they were reproduced for years. The observations of the Tevatron should be considered as hints, as the long-range encounters occur all around the ring at positions where the dispersion does not vanish, causing a more perturbed dynamics. An interesting observation by three authors is the very high sensitivity of the results to other parameters: tunes, resonances, betatron coupling. This might explain the discrepancies. This topic clearly requires more data and understanding.

Effect of large Piwinski angles

Two options of the LHC upgrade, the LPA (large Piwinski angle) and the early separation with leveling require Piwinski angles in the range of 2 to 3.5, instead of the nominal value of 0.4. Such large angles are feared to produce lifetime issues due to synchro-betatron coupling. Weak-strong and strong-strong simulations so far show no luminosity loss in the scenarios tested [22]:

- The LPA was investigated with head-on and long-range beam-beam effects and shows no luminosity loss for the required bunch charge of 4.9 10^{11} (Figure 12). Increasing the bunch charge by 20% creates an observable loss.

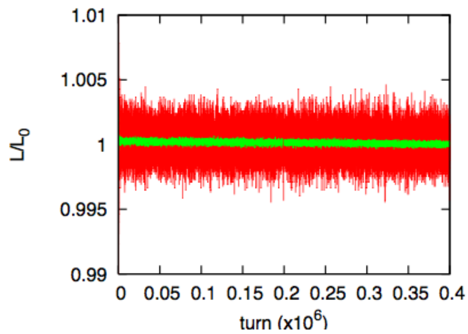

Figure 12: Luminosity loss for the LPA option, from [22]

- The early separation with luminosity leveling was investigated with the head-on beam-beam effect only. Figure 13 shows a large margin in bunch charge. No conclusion can be drawn until the long-range effect is included.

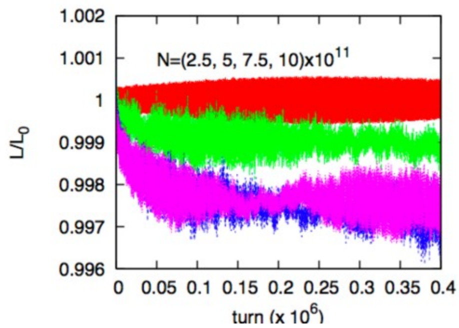

Figure 13: Luminosity loss for the early separation option, from [22]

SIMULATIONS AND PREDICTABILITY

There are three complementary ways to study the beam-beam effect, each with advantages and drawbacks:

- The dedicated experiments: naively, this should be the preferred and most reliable method to advance the understanding of the beam-beam effect. In practice, experiments with hadrons are very delicate: the sensitivity to "hidden" parameters is large and may bias the results. The duration of the experiments excludes repeating measurements to reach statistical significance. Hence error bars are generally missing.
- The observations during operations: statistical significance is obtained however with limited ability to disentangle parameters.
- Simulations: its strength is the ability to study the importance of each model parameter. There are three main limitations: i) the relevance of the model to the real physics, ii) the accuracy and speed of the computational method, iii) the ability (mostly inability) to compute observables that set the beam-beam limit in practice (development of tails, lifetime, background to the experiments).

The presentations made in all CARE-HHH-APD workshops show a significant progress in the past decade. There is a large number of codes with clear progress in computational methods and speed. Attempts at calculating the beam lifetime are made with some qualitative agreement. Quoting Andreas Kabel and Tanaji Sen, calculation of observables is within reach and results are encouraging...

The uncertainties on the models that are so important for the beam-beam effect however will remain with us until the calculation speed can be increased by one or two orders of magnitude to allow many tests of hypotheses. Simulations tuned to one given machine show a predictive power in a reasonably small range of parameters.

WIRE COMPENSATION

Compensation in simulations

The wire compensation of the long-range beam-beam effect had been proposed to suppress or weaken the process known in simulation to limit the LHC performance. Since then, several studies of its performance and robustness were made either by simulation by several authors or experimentally in the SPS and planned at RHIC. The latest calculations [23] confirm the compensation efficiency (Figure 14).

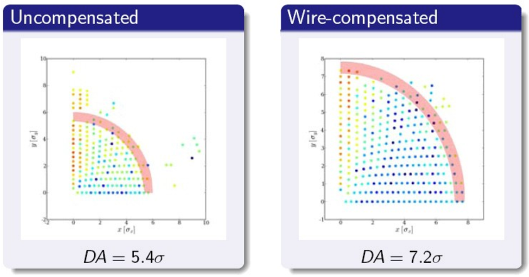

Figure 14: Increase of dynamic aperture by wire compensation, from [23]

Compensation in experiments

For the time being, experimental results are available from the SPS. Figure 15 shows results obtained in 2004 [11]. Very similar results were measured in 2008.

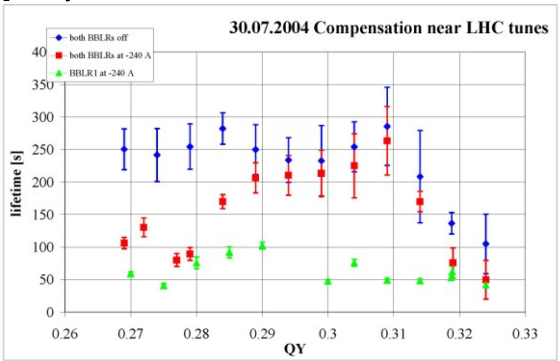

Figure 15: Beam lifetime versus tune for 1) blue: no long-range effect, 2) green: with long-range effect, 3) red: with compensated long-range effect, from [11]

There is a nearly perfect compensation over the interesting tune range; however, compensation unexpectedly partially fails for lower tunes. This is presently attributed to an imperfect compensation related to limitations in the SPS set-up. Figure 15 shows as well that the tunes .31/.32 found optimal for the head-on beam-beam effect is not optimal for the long-range beam-beam effect. This would be consistent with SppbarS observations [15].

Robustness in simulation

Several authors investigated in simulation the sensitivity of the compensation to imperfections. It appears to be robust against errors in beam-wire distance and errors in wire current. The current stability however needs to be better than 10^{-3} [24] that is very easy to achieve for a dc current but remains an extreme challenge for a pulsed version. Figures 16 and 17 illustrate the robustness against position errors and tunes, the latter expected from the locality of the correction.

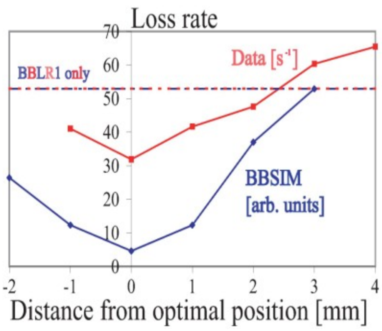

Figure 16: Experimental and simulated loss rate for errors in wire position, from [5] (the rms beam size in the SPS is typically 2 mm)

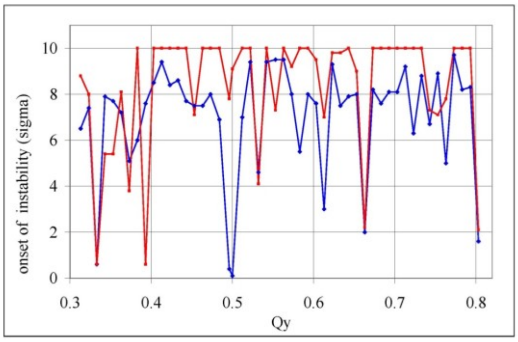

Figure 17: Compensation robustness versus tune, from [23]

Application in Dafne

The first operational application of wire compensation was done in Dafne to compensate its long-range beam-beam effect [26]. Contrary to LHC, a local correction was not possible. Hence, only an optimum could be found. Figure 18 shows the amplitude plane without/with compensation and with compensation with the opposite sign. The improvement is striking.

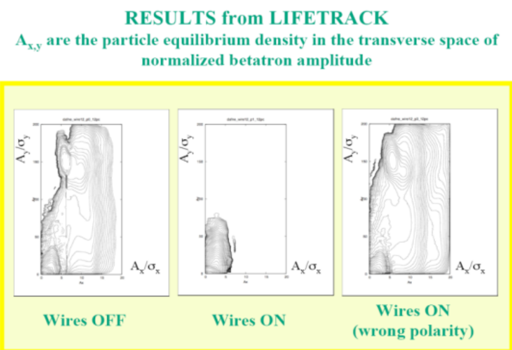

Figure 18: Impact of the compensation on the amplitude plane, from [26]

The observed effect of the beam was a significant increase of lifetime (Figure 19), the suppression of sudden blow-ups and a reduction of background, but no increase in luminosity. The wire compensation resulted in a gain in integrated luminosity by 30%.

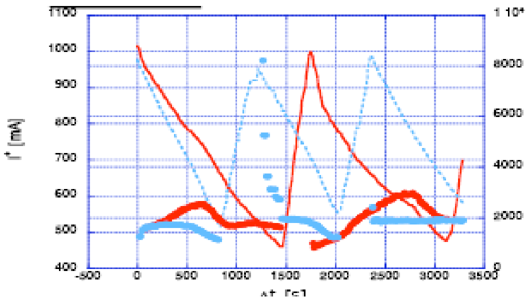

Figure 19: Beam current versus time without (blue) and with (red) wire compensation, from [26]

Compensation of Pacman bunches

The compensation of pacman bunches requires a pulsed compensator with a turn-to-turn stability better than 10^{-3}. This problem has challenged a number of experts but has not found a solution so far. However, simulations have shown that an optimization of the dc wire current can be found to significantly increase the stability of both nominal and pacman bunches [27].

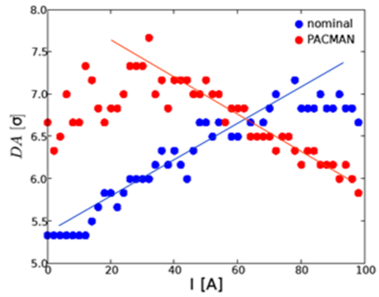

Figure 20: Mitigation of nominal and pacman bunch correction with a dc wire compensator, from [27]

For a pulsed device, an interesting option offering possibly more stability from turn to turn was proposed by F. Caspers. Its principle, based on an RF oscillator modulated by the requested waveform is shown on Figure 21. A first experimental set-up was put together [27] but the studies are presently not taken over.

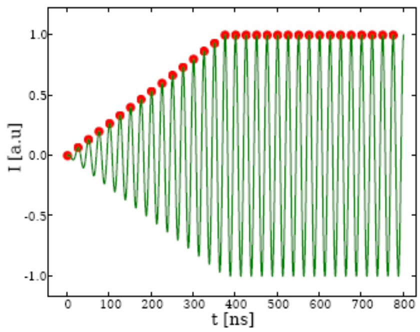

Figure 21: Principle of a RF wire compensator operating at the bunch frequency, from [27]

ELECTRON LENS COMPENSATION

The electron lens compensation (TEL) has the potential to correct both the head-on and long-range beam-beam effects. Its more involved and expensive implementation favors application for head-on compensation. However, applications to the compensation of the long-range beam-beam effect in the case where wires cannot be used (encounters at reduced distance, like in the early separation scheme) are as well of interest.

Performance at the Tevatron

The first striking result obtained at FNAL is a demonstration that the TEL is reliable, after 6 years of operations. The fluctuations of the electron beam current are sufficiently small not to create a detectable proton emittance blow-up. The TEL has thus gained a status of a collider instrument. It has been used so far as a pulsed quadrupole to equalize the tunes of all bunches. This has improved the beam and luminosity lifetimes, as shown on Figures 22 [28] and 23 [29].

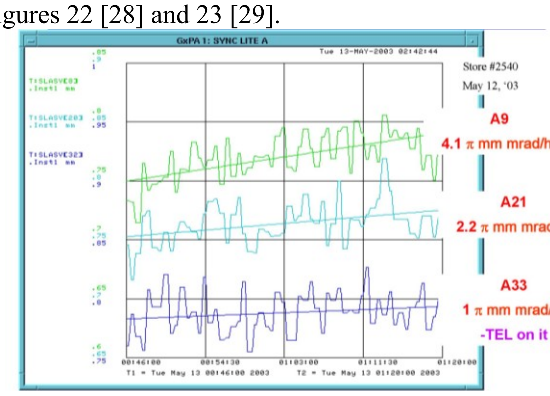

Figure 22: Emittance versus time: A33 bunch blow-up suppressed by the TEL correction, from [28]

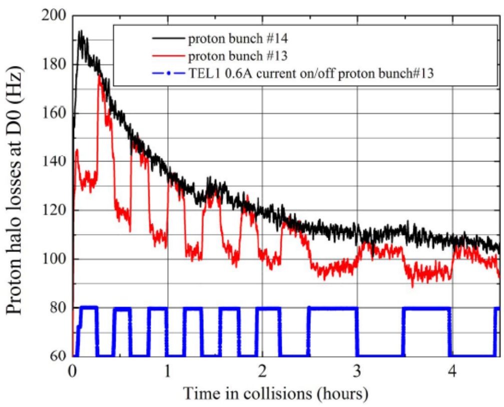

Figure 23: Halo losses versus switching on and off the TEL, from [29]

Potential for the LHC

The potential of an electron lens to alleviate the head-on beam-beam limit in the LHC was already anticipated as early as 1993 [30]. With the demonstration of feasibility in the Tevatron, it becomes worth investigating its benefit in the LHC. Figure 24 from [31] shows the efficient footprint compression to be expected from the electron lens.

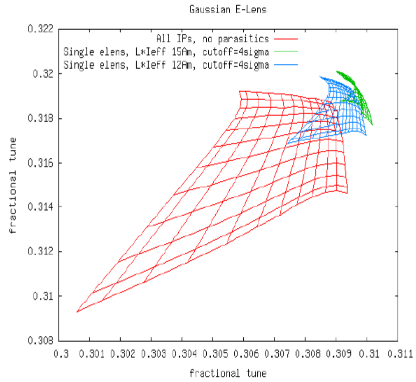

Figure 24: Initial and compressed footprints for two electron currents, from [31]

In fact, the efficiency of the electron lens grows rapidly with the beam-beam tune shift. It becomes appealing for the SLHC (Figure 25 from [10]).

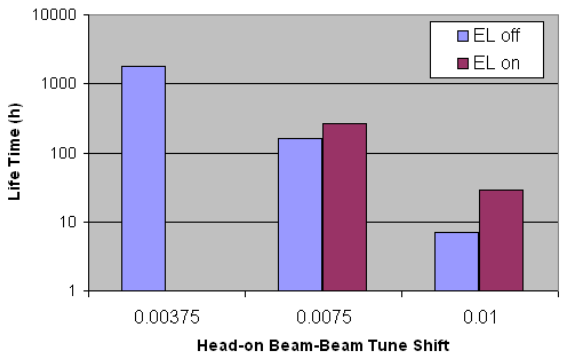

Figure 25: Lifetime gain to be expected from electron lens correction in the LHC versus beam-beam tune shift, from [10]

Robustness of compensation

For a complete correction, the electron lens should be installed at the collision points or in phase with them. This cannot be done in general and the compensation will occur at a betatron phase shift that will not be optimal. Simulations [10] show nevertheless a significant improvement even for the worst phase of 90 degrees. This is likely to show that the footprint compression dominates over resonance excitation when compensating the head-on beam-beam effect in the case studied.

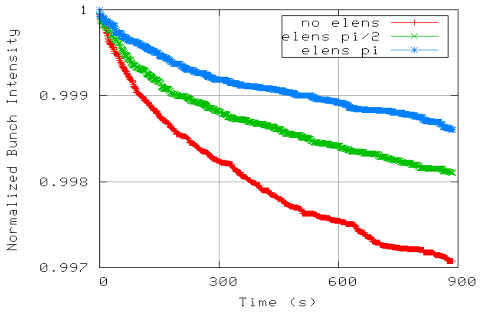

Figure 26: Intensity decay in time for 3 scenarios of elens compensation, from [10]

CONCLUSIONS

This paper has touched a number of aspects of the beam-beam problem but left aside some other aspects of importance, such as the coherent beam-beam effect, flat beam scenarios, importance of second-order chromaticity, uminosity levelling... The communications made in the CARE-HHH-APD workshops were considered, ignoring for practical reasons the literature published elsewhere. Hence the conclusions shall be relative to the CARE-HHH-APD framework that, nevertheless, groups a critical mass of beam-beam considerations and expertise. Given the number of aspects, we shall attempt some conclusive remarks per aspect.

The beam-beam limit

The operational experience of the Tevatron is an invitation to reconsider the value of the beam-beam limit used so far for the LHC upgrade, with the potential to double it if the LHC parameters can reach the domain where the bunch length reduces the beam-beam perturbation.

The long-range beam-beam effect

It appears significantly more perturbing and "unpredictable" than a footprint criterion would indicate. One should consider in upgrades increasing the low-β triplet aperture to allow more than the nominal or scaled 10σ beam separation. Alternatively, the wire compensation can be applied to mitigate the consequences of the present tight LHC triplet aperture.

Crossing schemes

The best scheme leading to the highest beam-beam limit appears to be undecidable by simulations. Provisions for recovering the flexibility in using any scheme should be incorporated in upgrade designs.

Minimum beam separation

The available information does not allow yet concluding. A new simulation effort is on-going (Herr-Kaltshev) and dedicated experiments in RHIC would be of highest value.

Large Piwinski angle

No show stopper was identified for LHC upgrade scenarios. More simulations are needed, to include all perturbations and study diffusion in tails. Would existing hadron machines allow experimenting these large angles?

Simulations

This is a key tool for beam-beam studies. Its results should always be considered with due care given its inherent limitations.

Wire compensation

Its efficiency and robustness are sufficiently established to consider an implementation in LHC in dc mode. A pulsed compensation should bring an added value. The principle of an RF device appears attractive. Its feasibility remains to be demonstrated. There is presently no effort on this issue.

Electron lens compensation

This remarkable instrument is not anymore an exotic idea but a reliable device, compatible with the requirements of a storage ring. It will gain full acceptance when its use as non-linear compensator will have been experimented in the Tevatron. It has a significant potential for the LHC.

ACKNOWLEDGMENTS

The author wishes to thank all experts of the field for the many interesting and enriching interactions that this series of workshops has allowed and the workshop organizers for having given this opportunity for all of us. We acknowledge the support of the European Community: FP6-CARE, contract RII3-CT-2003-506395.

REFERENCES

[1] W. Fischer, this workshop.
[2] F. Ruggiero *et al.,* LHC Luminosity and Energy Upgrade: a Feasibility Study, LHC Project Report 626, p. 4, 2002.
[3] W. Fischer, private communication, April 2008.
[4] A. Valishev, Tevatron experience with reduced distance encounters, CARE-HHH-APD Working meeting on LHC beam-beam effect and compensation, CERN, 28 August 2008.
[5] T. Sen, Beam-beam simulations, CARE-HHH-2004 workshop, CERN.
[6] P. Lebrun, quoted in [5]
[7] F. Zimmermann, Beam-beam effects for LHC and LHC upgrade scenarios, US-LARP Beam-Beam Workshop, SLAC, 2007.
[8] J. Qiang, quoted in T. Sen, Beam-beam studies in the LARP framework, CARE-HHH-APD Working meeting on LHC beam-beam effect and compensation, CERN, 28 August 2008.

[9] J. Qiang, Beam-beam simulations for RHIC and LHC, 2007 US-LARP beam-beam workshop, SLAC.
[10] A. Valishev, Benefits of e-lens in LHC, CARE-HHH-APD Working meeting on LHC beam-beam effect and compensation, CERN, 28 August 2008.
[11] F. Zimmermann, Open issues from the SPS Long-Range Experiment, US-LARP Beam-Beam Workshop, SLAC, 2007.
[12] F. Zimmermann, Beam-beam compensation schemes, HHH-2004, CERN.
[13] W. Herr, Dynamic behaviour of nominal and pacman bunches for different LHC crossing schemes, LHC Project Report 856, 2005.
[14] K. Ohmi, Collision with a crossing angle; large Piwinski angle, BEAM-07, CERN.
[15] K. Cornelis, SPS experience with reduced distance encounters, CARE-HHH-APD Working meeting on LHC beam-beam effect and compensation, CERN, 28 August 2008.
[16] A. Valishev, Tevatron beam-beam phenomena and counter-measures, US-LARP Beam-Beam Workshop, SLAC, 2007.
[17] N. Abreu, Beam-beam with a few long-range encounters at short distance, CARE-HHH-APD BEAM07, 2007.
[18] W. Fischer, N. Abreu *et al.,* An overview of RHIC beam-beam experiments, CARE-HHH-APD Working meeting on LHC beam-beam effect and compensation, CERN, 28 August 2008.
[19] U. Dorda, Beam-beam issue for LHC phase I and II, CARE-HHH-APD IR07, 2007.
[20] G. Sterbini *et al.*, SPS wire experiments in 2008, to be published.
[21] G. Sterbini, A simplified 2D+ model for tracking the beam-beam effect in the D0 scheme, CARE-HHH-APD Working meeting on LHC beam-beam effect and compensation, CERN, 28 August 2008.
[22] K. Ohmi, Large Piwinski angle studies, CARE-HHH-APD Working meeting on LHC beam-beam effect and compensation, CERN, 28 August 2008.
[23] U. Dorda, LHC with long-range compensation, US-LARP Beam-Beam Workshop, SLAC, 2007.
[24] several sources quoted in J.P. Koutchouk, Overview of wire compensation for the LHC, CARE-HHH-APD Working meeting on LHC beam-beam effect and compensation, CERN, 28 August 2008.
[25] F. Zimmermann, Progress of beam-beam compensation schemes, CARE-HHH-APD LUMI05, Arcidosso, 2005.
[26] C. Milardi *et al.,* Dafne lifetime optimization with octupoles and compensating wires, CARE-HHH-APD IR07, Frascati, 2007.
[27] U. Dorda, Beam-beam and emittance growth with wire compensators, CARE-HHH-APD Beam07, CERN, 2007.
[28] W. Shiltsev, quoted in [12]
[29] W. Shiltsev, Electron lenses for compensation of beam-beam effects, HHH-CARE-APD BEAM07, CERN, 2007.
[30] E. Tsyganov, Electron beams for the compensation of beam-beam effect in hadron colliders, US-LARP Beam-Beam Workshop, SLAC, 2007.
[31] A. Kabel quoted in T. Sen, Beam-beam studies in the LARP framework, CARE-HHH-APD Working meeting on LHC beam-beam effect and compensation, CERN, 28 August 2008.