2E

CERN - SL 90-12 AP

C₁

EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN-SL/90-12 (AP)

CERN LIBRARIES, GENEVA

22 MAY 1990

CM-P00049315

Report of the Working Group on Beam-Beam Effects

Eberhard Keil

Abstract

This report summarizes the discussions and conclusions of the Working Group on Beam-Beam Effects during the Workshop on Beam Dynamics Issues of High-Luminosity Asymmetric Collider Rings, held at the Lawrence Berkeley Laboratory, Berkeley CA, USA, from 12 to 16 February 1990. The discussions were organized around four topics: (i) The relative advantages of round beams compared to flat beams, (ii) Energy transparency which deals with the question of which beam parameters have to be made equal although the beam energies are different in the two rings, (iii) The simulation of the beam-beam effect, (iv) Experiments in existing e^+e^- colliders to check the design concepts for future asymmetric colliders. The overall conclusions arrived at by the working group can be found at the end.

Geneva, Switzerland

25 April 1990

1 Introduction

The discussions of the Working Group on Beam-Beam Effects were organized around four topics in discussion groups. The topics and the participants are shown below. The discussion leaders are printed in *italics*.

- Round beams versus flat beams: *Furman*, Krishnagopal, Woods
- Energy transparency: *Chao*, Chattopadhyay, Chin, Kim, Sessler, Tennyson
- Simulation: *Courant*, Channell, Dell, Gerasimov, Hirata, Johnson, Ruggiero
- Experiments: *Seeman*, Cornelis, Kikutani, Rice, Rivkin, Schmidt

The first two topics are concerned with physics issues, the second two topics deal with tools which are used to resolve them. This summary is organized by discussion groups. The overall conclusions can be found at the end.

2 Round Beams versus Flat Beams

The physical argument in favour of round beams goes as follows: Assuming for simplicity equal horizontal and vertical rms radii of the two beams, i.e. $\sigma_x^+ = \sigma_x^- = \sigma_x$ and $\sigma_y^+ = \sigma_y^- = \sigma_y$, the luminosity L is given by:

$$L = \frac{N^+ N^- f k}{4\pi \sigma_x \sigma_y} \quad (1)$$

The vertical beam-beam tune shift parameters $\xi_y^\pm$ are given by:

$$\xi_y^\pm = \frac{N^\mp r_e \beta_y^\pm}{2\pi \gamma^\pm (\sigma_x + \sigma_y) \sigma_y} \quad (2)$$

Here, N^+ and N^- are the intensities of the positron and electron bunches, respectively, $f k$ is the bunch collision frequency, r_e is the classical electron radius, $\beta_y^\pm$ are the vertical amplitude functions at the collision point(s) and $\gamma^\pm$ are the beam energies in units of the electron rest energy.

Eliminating one bunch intensity $N^\mp$ from Eq. (1) and introducing the beam aspect ratio $r = \sigma_y/\sigma_x$ yields the following expression which clearly displays the parameters entering into the performance of a B factory:

$$L = \frac{N^\pm f k \xi_y^\pm \gamma^\pm}{2r_e \beta_y^\pm} (1 + r) \quad (3)$$

We see that, all things being equal, the luminosity for round beams with $r = 1$ is nearly a factor of two higher than for flat beams with $r \ll 1$. This geometrical factor is one of the main arguments on favour of round beams.

Whether it is permitted to assume that other things, and in particular the beam-beam strength parameter ξ_y and the amplitude functions at the collision point(s) $\beta_y^\pm$ remain the same when the B factory design is changed from flat beams to round beams is debatable. The evidence on the maximum value of ξ_y will be discussed below. The minimum value of $\beta_y^\pm$ and many other topics related to the choice between flat and round beams were discussed by the Lattice Working Group.

2.1 Maximum value of ξ_y

For flat beams, the maximum achievable beam-beam strength parameter ξ_y was observed in all e^+e^- storage rings, and computed by several simulation programs. The proceedings of workshops in Santa Margherita di Pula, Sardinia, Italy [1] and Novosibirsk, USSR [2] contain discussions of these subjects. At this workshop, J. Tennyson reviewed incoherent beam-beam effects [3], K. Hirata reviewed coherent beam-beam effects [4], and D. Rice reviewed the present experimental data [5]. The highest experimentally observed beam-beam strength parameters fall into the range $0.02 < \xi_y < 0.04$. The results of simulation programs fall into the same range. It is generally agreed that simulation programs yield results in agreement with observations in well-tuned e^+e^- storage rings.

The only experimental data for the beam-beam strength parameter ξ_y for machines with round beams come from the DCI storage ring in Orsay, France. The observed maximum values for ξ_y fall into the range $0.035 < \xi_y < 0.041$ [6]. Further experiments on round beams will soon be done in the CESR e^+e^- storage ring at Cornell University, Ithaca NY, USA. Recent two-dimensional simulations, i.e. without synchrotron oscillations, for the case of round beams were made by Krishnagopal and Siemann [7] who find a maximum value of $\xi_y \simeq 0.1$ for a carefully optimized operating point in a machine with round beams. Chin [9] has made a comparison between a machine similar to the LBL/SLAC B factory proposal and finds $\xi_y \simeq 0.04$ with flat beams, and $\xi_y \simeq 0.035$ with round beams at the same working point. In both cases, a blow-up of the beams is observed, indicating that the maximum value of ξ_y is reached. The factor of three discrepancy between the simulation results needs clarification.

2.2 Distribution functions

It is generally accepted that the observed beam-beam limit in existing e^+e^- storage rings is related to the fact that the tails of the distribution functions, and in particular the vertical distribution function, drop less rapidly than a Gaussian distribution. The increased population of the tails in turn causes a reduction of the beam lifetime and/or an increase of the particle background in the experiments surrounding the collision point(s). Such tails have also been observed in simulations [8]. Chin [9] has compared the tails for round and flat beams, and found a striking difference: The vertical distribution for flat beams has a pronounced non-Gaussian tail while the vertical distribution for a round beam continues to have a Gaussian shape up to the beam-beam limit.

Since, for round beams, the horizontal and vertical emittance are about the same, the two transverse energies are also nearly identical. Hence, coupling between the two planes, caused e.g. by nonlinear beam-beam driven resonances, cannot transfer much energy from one plane to the other. For flat beams, the horizontal emittance is one to two orders of magnitude higher than the vertical one, and this transfer of horizontal energy into the vertical plane is indeed possible.

2.3 Miscellaneous Points

The shorter tails for round beams do not necessarily imply that the vertical aperture in a machine with round beams can be smaller than in a machine with flat beams. The consequences of the choice of the aspect ratio r on the interaction region design, the masking of synchrotron radiation, the separation of the two counter-rotating beams, etc. was studied by the Lattice Working Group.

It is unlikely that the horizontal and vertical amplitude functions β_x and β_y in a machine with round beams can both be made as small as the vertical amplitude function β_y in a machine with flat beams. This may offset any gain due to the geometrical factor of two and of a higher maximum beam-beam strength parameter ξ_y .

A particle in one beam executing synchrotron oscillations meets the oncoming bunch of the opposite beam at varying positions s along the beam direction. Even with head-on collisions, this causes a modulation of the beam-beam parameter for flat beams since $\sigma_y(s) \propto \sqrt{\beta_y(s)}$, neglecting the variation of $\beta_x(s)$ and $\sigma_x(s)$, as can be seen in Eq. (2). This tune modulation is absent for round beams because $\beta_x(s)$ and $\beta_y(s)$, and $\sigma_x(s)$ and $\sigma_y(s)$ vary such that Eq. (2) becomes independent of s .

2.4 Conclusion for round versus flat beams

The following conclusions may be drawn concerning the choice between round and flat beams:

- The beam-beam effect which seems to favour round beams over flat beams is only *one* of *many* aspects entering into the choice.
- A *fair* comparison of the results of simulation programs is needed.
- Results of more experiments in existing machines are eagerly awaited.

3 Energy Transparency

3.1 Issue

Energy transparency addresses the question what beam and machine parameters must be made equal in the two rings of an asymmetric B factory in order to achieve optimum performance although the two beams have different energies. This problem was first raised by Chin [10] who put forward the following conditions:

- Same beam radii at the interaction point:

$$\sigma_x^- = \sigma_x^+ \quad \sigma_y^- = \sigma_y^+ \quad (4)$$

- Same nominal beam-beam strength parameters:

$$\xi_x^- = \xi_x^+ \quad \xi_y^- = \xi_y^+ \quad (5)$$

- Same damping decrements $\delta^\pm$, i.e. same ratios of time between collisions and synchrotron radiation damping time:

$$\delta^- = \delta^+ \quad (6)$$

This condition implies that the damping decrement in the low energy ring is increased beyond its natural value by adding wiggler magnets.

- Same betatron phase modulation due to synchrotron oscillations with bunchlength σ_s and tune Q_s :

$$\left(\frac{\sigma_s Q_s}{\beta_x}\right)^- = \left(\frac{\sigma_s Q_s}{\beta_x}\right)^+ \quad \left(\frac{\sigma_s Q_s}{\beta_y}\right)^- = \left(\frac{\sigma_s Q_s}{\beta_y}\right)^+ \quad (7)$$

Hirata and Keil [11] [12] studied the centre-of-mass motion of colliding bunches in an asymmetric collider with K^+ bunches in one and K^- bunches in the other ring, in linear approximation by computing the stability of the eigenvalues of the coupled bunch motion due to the beam-beam collisions in one interaction point, and by multi-particle tracking. They find sum resonances which are driven by the total current and occur when the tunes Q^+ and Q^- satisfy the relation:

$$K^- Q^+ + K^+ Q^- \leq n \quad (8)$$

Here K^+ and K^- are assumed to be relatively prime, and the $\leq$ symbol indicates that the resonance occurs just below the arbitrary integer n . If there are variations in the bunch intensities within the beams, also integral and half-integral resonances are driven when the tunes satisfy the relations:

$$K^\pm Q^\pm \leq n \quad (9)$$

$$K^\pm Q^\pm \leq n + \frac{1}{2} \quad (10)$$

- Avoiding these closely spaced resonances when $K^\pm \gg 1$ requires that the two circumferences are the same, leading to the condition:

$$C^+ = C^- \quad (11)$$

If one requires that the driving terms for synchro-betatron resonances due to the beam-beam collisions are also equal, one gets the following conditions which are considered important when the expressions involved are of order unity, and unimportant when they are small compared to unity:

- Same driving term due to beam-beam collisions at the crossing angle α , where σ_c is the rms beam radius in the plane of the crossing:

$$\left(\frac{\alpha \sigma_s}{2\sigma_c}\right)^- = \left(\frac{\alpha \sigma_s}{2\sigma_c}\right)^+ \quad (12)$$

- Same tune modulation due to chromaticities $Q'_x = dQ_x/dp/p$ and $Q'_y = dQ_y/dp/p$:

$$\left(\frac{Q'_x \sigma_e}{Q_s}\right)^- = \left(\frac{Q'_x \sigma_e}{Q_s}\right)^+ \quad \left(\frac{Q'_y \sigma_e}{Q_s}\right)^- = \left(\frac{Q'_y \sigma_e}{Q_s}\right)^+ \quad (13)$$

Chin[10] finds that the high energy beam blows up the low energy beam when only Eqs. (4) and (5) are satisfied. When the damping decrements are made equal, i.e. when Eqs. (6) are satisfied, the blow up of the low energy beam is significantly reduced. When the tune modulations are also made equal, i.e. when Eqs. (7) are satisfied, the behaviour of the two beams is almost equalized, and the blow up both beams is small for nominal beam-beam strength parameters up to $\xi_0 = 0.05$. Tennyson[3] has made a comparison between machines with equal and unequal damping rates in the two rings, and finds a small difference in the luminosity. Clearly, the discrepancy between these simulation results needs to be understood.

3.2 Opinion

The following questions related to energy transparency have been examined, with the following results:

1. Is there more physics in the energy transparency conditions than reducing the problem of simulating two rings with different energies and different parameters to the problem of simulating two rings with the same energy and identical parameters? We believe that this is not the case.
2. Are the energy transparency conditions *sufficient*? We believe that they are.
3. Are the energy transparency conditions *necessary*? We don't know for sure, but our consensus is that not all conditions are necessary.

The problem of energy transparency needs further work, by simulation since no asymmetric machine exists. An approach where one starts with small deviations from energy transparency and sees how one has to change parameters such as to recuperate the good performance of transparent machines appears most promising.

4 Simulation

4.1 Weak-Strong versus Strong-Strong Simulation

The relative merits of simulating the beam-beam effect in the weak-strong and the strong-strong approximation were discussed. In the former simulation, a weak beam of test particles collides with a strong beam whose parameters, i.e. average position and beam radius, do not change with time. The strong beam only provides the forces acting on the weak beam. In the latter case, both beams exert forces on each other and their parameters are allowed to change due to the forces. Tennyson made the argument that calculating the beam parameters from the modest number of particles in the simulation, typically a few hundred, causes numerical noise which might disturb the simulation. This argument can be overcome by simply exponentially averaging the beam parameters over about a damping time.

4.2 Bunch Slicing

In order to achieve the expected performance, the vertical amplitude function β_y in modern B factory designs is no longer large compared to the bunch length σ_s . Therefore, the amplitude functions $\beta_x(s)$ and $\beta_y(s)$ and the betatron phases $\mu_x(s)$ and $\mu_y(s)$ vary significantly over the length s of the collision region. Siemann and Krishnagopal [7] have taken this into account by dividing the bunches into S slices along the beam axis. They find that the emittance of the weak beam is increased much less when the strong beam is divided into $S \geq 3$ slices. By now, bunch slicing has become general practice in beam-beam simulation programs.

4.3 Lifetime, Background, Tails

Multi-particle simulation is a good tool for obtaining data for the dynamic evolution of the beam radii, and therefore of the luminosity in e^+e^- colliders [1] [2]. However, obtaining good statistical data on lifetime, background and tails of distribution functions is very time-consuming because the particles spend only a small fraction of their time at large amplitudes.

Lifetime, background and tails are not only influenced by the beam-beam effect proper, but also by the aperture and the non-linearities of the storage ring lattice which therefore should also be taken into account. A simulation by Jackson and Siemann [13] has shown that the effect of the non-linearities on the core of the beam and the luminosity of CESR was small. Gerasimov [14,15] has used a different technique to obtain equilibrium distribution functions for oscillatory systems under the influence of quantum excitation, damping, and isolated non-linear resonances.

We were reminded rather forcefully by an experimental particle physicist that the background for experiments in a real machine is not reproducible and very sensitive to its fine tuning. Therefore, no attempts should be made to define a standard distribution function with non-Gaussian tails, e.g. for the calculation of synchrotron radiation hitting the vacuum chamber next to the interaction points.

4.4 New Material

New material was presented about the following aspects of beam-beam simulation:

- Hirata, Moshhammer, Ruggiero and Bassetti presented an irreducible set of parameters and symplectic equations for the beam-beam effect in six dimensions [16].
- Channell treats the beam-beam effect as a discrete Lie-Poisson system, sets up a system of equations of motion for the moments of the distribution function, and follows them by tracking [17]. The computer code which contains this procedure runs faster than multi-particle tracking. It does not include quantum excitation and damping.
- Kikutani has a promising technique to calculate the beam-beam force from the particle distribution, based on Fourier transforms and Green functions [18]. It could replace the traditional approach of obtaining the beam-beam force from a Gaussian density distribution with variable mean and standard deviation.

- Zholents and others presented simulation results for a machine in which the horizontal beam radius is dominated by the contribution of synchrotron oscillations, i.e. $D\sigma_e \gg \sqrt{E\beta}$ [19]. They find that the beam-beam limit is about the same as for a machine where the dispersion vanishes at the interaction point.

4.5 Unanswered Questions

Standard test data describing an existing machine with a large collection of experimental data should be developed and used for all existing and future simulation programs. Programs which do not reproduce the experimental data should be rejected.

A comparison between existing simulation programs should be made, including the input data, phenomena included, algorithms, etc.

A standard simulation code should be developed which can be used by anybody who wants to simulate the beam-beam effect. It should have the reliability of standard beam-optics codes.

5 Experiments

The discussion group on experiments considered the following experiments:

5.1 Beam-Beam Strength Parameter ξ_{max} versus Energy

A very puzzling experiment in the VEPP-2M machine at Novosibirsk [20] yielded the maximum value of the beam-beam strength parameter ξ_{max} as a function of the energy for two different settings of the wiggler magnets. The observed values of ξ_{max} were nearly the same although the difference in the damping times was large. To clarify the dependance of ξ_{max} on the damping times, systematic experiments should be done in LEP between 20 and 46 GeV and in PEP between 7 and 14 GeV. Whenever possible, the damping rates should be varied with wiggler magnets located both in places where the horizontal dispersion vanishes and in places where it does not. The following quantities should be carefully recorded: Luminosity L versus current I – horizontal and vertical emittances E_x and E_y – bunchlength σ_z , and relative energy spread σ_e – tunes Q_x , Q_y , and Q_s – amplitude functions β_x and β_y at the n_x interaction points – dispersions D_x and D_y and their derivatives at the interaction points – beam radii σ_x and σ_y – density distributions – nature of current limitation (beam-beam, background, lifetime, etc.) – closed orbit – frequencies of coherent modes – lifetime and shape of single beam – coherent and incoherent damping times.

5.2 Round Beam Tests

The following questions should be included in experiments on round beams in CESR and possibly other machines: Maximum beam-beam strength parameter ξ_{max} – shape of tails in distribution function – stability of saturated regime – limit on inequality of bunch currents. These experiments should be done both on the coupling resonance where the equality of beam radii is achieved by coupling, and off the coupling resonance where this equality is achieved by some other means.

If we are serious about round beams we should get an interaction region in some machine rebuilt to handle round beams in the region of parameter space considered for asymmetric B factories.

5.3 Crossing Angle and Crab Crossing

Tests in CESR, Sp $\bar{p}$ S, PEP, etc. should answer the following questions:

- At what crossing angle do the beams behave differently from head-on collisions, and how does this observation compare to theoretical predictions?
- Do crab cavities work?

5.4 Beam separation at Interaction Points

Data exist around the world, most recently at Novosibirsk, on the minimum beam separation needed at the interaction points. These data are relevant to the design of asymmetric B factories because of the close encounters between bunches near to the interaction point due to the small bunch spacing. These data should be checked and outstanding tests should be completed.

5.5 Tail Distribution

The density in transverse phase space $\rho(x, x', y, y')$ should be measured as a function of energy E , current I and beam-beam strength parameter ξ , and the following questions should be answered::

- Are there differences between round and flat beams?
- What are the growth time, overshoot and relaxation time after bringing the beams into collision?

5.6 Disruption Parameter

The disruption parameter D is the ratio of the bunch length σ_s to the focal length F of the lens representing the focusing due to the oncoming bunch. It is used in the design of linear colliders and related to the beam-beam strength parameter ξ_y by the following equation:

$$D = \frac{4\pi\sigma_s\xi_y}{\beta_y} \quad (14)$$

The question whether D is a better indicator of the strength of the beam-beam forces than ξ_y should be answered. It enters into the synchro-betatron coupling by the beam-beam effect. The relevance of the Bassetti parameter, i.e. the ratio of the energy loss or gain due to the beam-beam collisions compared to the energy fluctuation due to the emission of synchrotron radiation between the collisions should be checked. The bunchlength σ_s and the amplitude function β_y should be varied and any changes in the beam-beam parameter ξ_{max} should be observed.

5.7 Importance of Tests

Future B factories, be they symmetric or asymmetric, aim at luminosities between one and two orders of magnitude higher than existing e^+e^- colliders. Therefore, it is important for their design, that new and untried design concepts are verified by experiments on existing machines as much as possible. Beam time for such experiments will have to be found at machines which already operate with a full schedule. Modifications of these machines needed for specific experiments will have to be funded. Therefore, beam time and funds for such experiments should be requested at a high level of laboratory management and be used at the highest possible efficiency by good preparation, coordination and collaboration.

5.8 Simulations

All of the independent simulation codes should predict the results of all these tests before they are done, for two reasons: Beam time on existing machines is expensive, and applying simulation codes to experimental situations will sharpen our understanding of the codes.

6 Conclusions

The findings of the beam-beam working group concerning the design and the performance of asymmetric B factories may be summarized as follows:

- The choice between round beams and flat beams is mainly an engineering issue. No miraculous improvements in the maximum permissible beam-beam strength parameter ξ are to be expected.
- Imposing the many conditions required by energy transparency is one way of solving the associated beam-beam problems, but most likely not the only one.
- Simulation of the beam-beam effect is again under active development in several places, after an interruption of nearly ten years.
- Experiments must be performed in existing machines to answer many of the open questions. They need the active support of the community to obtain the necessary funding and beam time.
- Beam-beam effects are but one aspect entering into the design and performance of asymmetric B factories.

This report summarizes the work of all participants in the Working Group on Beam-Beam Effects. Their names are listed in the Introduction. References to specific contributions to the Workshop are given below. It was a pleasure to chair this Working Group.

References

- [1] J.M. Jowett, M. Month and S. Turner, eds., Nonlinear Dynamics Aspects of Particle Accelerators, Lecture Notes in Physics No. 247, Springer-Verlag Berlin, Heidelberg, New York, Tokyo 1986.

- [2] N.S. Dikansky and D.V. Pestrikov, eds., Third Advanced ICFA Beam Dynamics Workshop, Novosibirsk 1989, to be published.
- [3] J. Tennyson, these proceedings.
- [4] K. Hirata, these proceedings.
- [5] D. Rice, these proceedings.
- [6] R. Chehab, A. Jejcic, J. Le Duff, M.P. Level, P. Marin, D. Potaux, M. Sommer, H. Zyn-gier, Proc. 11-th International Conf. on High-Energy Accelerators (Geneva 1980) 702.
- [7] S. Krishnagopal and R. Siemann, Proc. 1989 IEEE Particle Accelerator Conf. (1989) 836.
- [8] S. Myers, in ref. [1], 176.
- [9] Y.H. Chin, these proceedings.
- [10] Y.H. Chin, LBL Report 27665 (1989).
- [11] K. Hirata and E. Keil, Physics Letters **B232** (1989) 413.
- [12] K. Hirata and E. Keil, CERN/LEP-TH/89-76, to be published in Nucl. Instr. Meth.
- [13] G. Jackson and R. Siemann, Proc. 1987 IEEE Particle Accelerator Conf. (1987) 1011.
- [14] A.L. Gerasimov, Inst. of Nuclear Physics, Novosibirsk, Preprint 87-100 (1987).
- [15] A.L. Gerasimov, Physics Letters **A135** (1989) 92.
- [16] K. Hirata and F. Ruggiero, these proceedings.
- [17] P.J. Channell, these proceedings.
- [18] E. Kikutani, these proceedings.
- [19] A. Zholents, these proceedings.
- [20] P.M. Ivanov, to be published in ref. [2].