How to Reach High Luminosity?

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1 Introduction

How to reach high luminosity? is a question that successively the particle physicist, the accelerator designer and the machine experimenter have to face. The particle physicist and the machine designer have an essential job to do in common, namely to set 'reasonably optimistic' performance targets. This initial estimate will be the future yardstick to judge the performance of the machine after it has been built. Once the collider is built, the accelerator experimenter—often the same as the one who designed it—is supposed to achieve at least the design performance. At the same time the particle physicist is eagerly asking for the beam.

The aim of this lecture is more to give a survey of the problems to be solved, than to present a detailed scientific account of each of the effects which limit the performance. The main arguments leading to the basic choice of parameters are presented with insistence on the interrelation between the different effects.

2 Luminosity Definition

By definition the luminosity is the number of events produced by the collisions, per second, for events with a cross section of one square centimeter. Since a typical cross section unit is one nanobarn (1 nb $= 10^{-33}$ cm^2), a luminosity $\mathcal{L} = 10^{33}$ cm^{-2} s^{-1} only produces one such event per second, in which case the luminosity is said to be one inverse nanobarn per second. The figure that one quotes as luminosity is in general the peak luminosity of the machine, expressed in cm^{-2} s^{-1} which mostly interests machine designers.

Luminosity integrated over a week (see Fig. 1), or at least several runs is what physicists are interested in; it is often measured in inverse picobarn. Note that one inverse picobarn is one thousand times larger than one inverse nanobarn. In MKS unit: 1 pb^{-1} = 10^{40} m^{-2}.

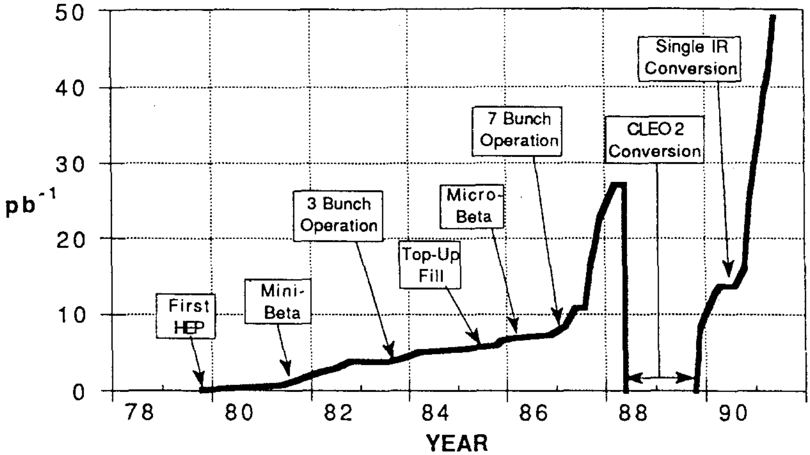

Fig. 1. CESR integrated luminosity per week

3 Performance

The performance of some of the most modern e^+e^-colliders is presented in Table 1. The world luminosity record ($\mathcal{L} = 2.10^{32}$ cm^{-2} s^{-1}) is presently—and presumably for a number of years—the property of the CESR machine at Cornell. It is interesting to see how this has been achieved. Figure 1 extracted from the presentation of D. Rice at the recent BEPC upgrade workshop [2] shows that with 12 years of constant effort the luminosity of CESR has been improved by a factor 100. The recipes are given in the figure: smaller beta at the Interaction Point, more bunches and only one Interaction Point.

The top-up fill mentioned in Fig. 1 corresponds to the injection of only the missing current at the end of the run rather than a complete refill. In fact the filling—or topping-up—time is an essential ingredient of the performance of a collider, it not only allows an increase of the average luminosity, but—more important— it allows the machine development sessions to be very efficient and consequently speeds up the rate of improvements. The dead time between two physics runs is obviously shorter if the injectors are powerful enough, that is if the injection is made at full energy and if the positron source can provide the several ampere required by factories in a short time. All factory designs include a full energy injector.

One more element cited by D. Rice [2] explains the performance of CESR: one quarter of the machine operating time is reserved for machine studies. This implies an extremely powerful team of machine experimenters, working in shifts. In spite of this large fraction of machine study time one can see from Fig. 1 that several months of hard work are required between the commissioning of an upgrade and the corresponding luminosity increase. In the case of the CLEO II conversion, the graph indicates that six months after the stop scheduled for the modification of the detector, the machine performance was still reduced to

Table 1. Peak luminosities of e^+e^-colliders*

Collider		BEPC	CESR	PETRA	TRISTAN	LEP
Peak luminosity	$\mathcal{L}$ (10^{30} cm^{-2} s^{-1})	7.	200	20	14	13
Beam-beam parameter	ξ_v	0.028	0.039	0.04	0.034	0.036
Energy	E (GeV)	2.2	5.3	17	32	46
Number of I.P.		2	1	4	1	4
Current per bunch	I_b (mA)	5	14	5	4	1
Number of bunches	n_b	1	7	2	2	4
Vertical β at I.P.	β_v^* (m)	0.1	0.015	0.06	0.1	0.05

* Data mainly extracted from Ref. [1]

half the performance achieved before the stop; life has not always been easy at CESR.

4 Design Process

The choice of the main parameters is made with the permanent preoccupation of leaving enough flexibility in the machine for progressive luminosity improvement by the accelerator experimenter.

4.1 Simulations

The search for the optimum values of beam dynamics parameters is made using simulation programs and a number of workshops have been dedicated to these. The major problem to simulate large numbers of turns without loosing the properties of conservation attached to Hamiltonian motion (Liouville theorem or more generally simplecticity) has been solved. Considerable progress has been made in introducing all possible effects in the simulation, including hardware imperfections. The simulation programs are now an essential tool of the designer. Nevertheless the predictive power of simulation programs in the search for the optimum working point (Q_h, Q_v) for example is not very good. Several machines have had to change their working point to reach their maximum luminosity.

The reason, or the consequence, is that the difference in the performance of the various colliders is not clearly understood. Experience proves that the luminosity is limited by various effects taking place in the bunch crossing and measured (in first approximation) by the tune shift induced in beam one by the space-charge effect of beam two. The beam-beam tune shift parameter (ξ) of most e^+e^- colliders is given in Table 2. A number of attempts have been made to find scaling laws applying to the variation of this parameter with energy, number of interactions or damping decrement. There may be a trend towards higher beam-beam parameter values with energy, and towards lower values with increasing number of interaction points, but even those apparently reasonable trends are not obviously confirmed by the performance of existing colliders. The maximum value of the beam-beam parameter has a remarkably constant value, varying between 0.025 and 0.06 in most cases, for a range of energy of two orders of magnitude, with the corresponding differences in damping time, synchrotron frequency and natural emittances; this over the 20 years which separate ADONE and LEP. It is nevertheless difficult to predict the beam-beam parameter and therefore the luminosity of a new machine to better than 30–40%.

4.2 Equations

The detail design of a collider is complex involving the simultaneous solution of a large number of equations. At the end of this school you will have a case full of them. The performance of a collider can nevertheless be described using a small number of key equations.

The first one is the luminosity definition, simplified to the case where the colliding bunches have the same number of particles N, and the same rms horizontal and vertical beam size at the interaction point, σ_h and σ_v:

$$\mathcal{L} = \frac{N^2 f}{4\pi\sigma_h\sigma_v} n_b \tag{1}$$

where f is the revolution frequency, and n_b the number of bunches. The fraction is sometimes called the single-bunch luminosity.

The second equation concerns the beam-beam parameter. This is denoted by ξ and its value is

$$\xi_v = \frac{r_e}{2\pi}\frac{\beta_v^*}{\gamma}\frac{N}{\sigma_v(\sigma_h + \sigma_v)} \tag{2}$$

where r_e is the classical electron radius. In e^+e^- accelerators the vertical beam size is negligible compared to the horizontal one so that the last fraction can be simplified. For the same reason the beam-beam parameter in the horizontal plane is less constrained.

The third equation is a result of the combination of the two above equations where the number of particles per bunch has been replaced by the single-bunch current I_b, using: $I_b = eNf$, where e is the electron charge. Then:

$$\mathcal{L} = \frac{1}{2er_e}\frac{\gamma\xi_v}{\beta_v^*} n_b I_b \tag{3}$$

Most of the high-luminosity constraints are present in this equation. Comparing with the successive CESR upgrades we see the beneficial effect of mini-beta's: lowering β_v^*, of many-bunch operation: increasing n_b and, as already mentioned, the effect on the ξ parameter of working with a single interaction point. The

Table 2. Beam-beam tune shift of e^+e^-colliders*

Collider	Energy (GeV)	ξ_v	Nb of IP
VEPP-2M	0.5	0.050	2
DCI	0.8	0.041	2
ADONE	1.5	0.070	6
SPEAR	1.2	0.018	2
	1.9	0.056	2
	2.1	0.055	2
BEPC	1.6	0.035	2
DORIS-2	5.3	0.026	2
VEPP-4	5.0	0.050	1
KEK-AR	5.0	0.030	2
	5.0	0.045	1
CESR	4.7	0.018	2
	5.0	0.022	2
	5.3	0.026	2
	5.5	0.028	2
	5.4	0.020	2
	5.4	0.035	1
PEP	14.5	0.045	6
	14.5	0.065	2
	14.0	0.050	1
PETRA	7.0	0.014	4
	11.0	0.024	4
	17.0	0.040	4
TRISTAN	30.4	0.034	4
LEP	45.6	0.035	4

* Data mainly extracted from Ref. [4]

place where the optimization of all these parameters raises the most delicate problems is the interaction area, but before discussing this we must consider the idea of the double-ring collider, which opens the way for large luminosity improvements.

5 Bunch Spacing

Of all the quantities in equation (3) the only one susceptible of increasing the luminosity by an order of magnitude, as requested by the new factory specifications, is the number of bunches (or its equivalent in this case, the bunch spacing around the ring). This is possible in two ways, either put more bunches in a single ring—The CESR solution—or have the two beams in two different rings, solution selected for future modern factories.

5.1 The Pretzel Scheme

The seven bunches of CESR circulating in the same ring, cross in 14 places around the ring. If nothing was done, the tune shift induced by the beam-beam effect in each of the crossings being of the order of 0.04, the total beam-beam tune spread would be $\delta Q = 14 \times 0.04 = 0.56$ and most of the beam would probably be lost in a few turns. The solution adopted by CESR—the so-called Pretzel scheme—is to have the two beams circulate on different orbits so that at the crossing points not used for experiments they are separated. At these parasitic crossings the beam-beam effect is considerably reduced by this separation, but it is still present so that one cannot increase the number of bunches at will. Moreover, each of the beams have to be accommodated in a smaller part of the vacuum chamber and the nonlinear optics are severely complicated by the requirement to 'comfortably' install two beams on two different trajectories inside the same vacuum chamber. Still, if you can, with time and effort, accommodate the two beams, you have a chance to win the world race for luminosity, which CESR did.

5.2 The Double-ring Collider

With the two beams each installed in their own vacuum chamber, the beams only see each other in the interaction area, the limitation to the number of bunches is now in the separation scheme in the interaction area. The obvious disadvantage is the cost of the installation of two rings instead of one. Also some specific problems have to be solved: the mechanical and magnetic stability of the two rings have to be carefully checked in order to avoid that the two beams move or vibrate at the collision point where the beam sizes are only a few microns.

The double ring makes it possible to avoid collisions in the arcs. However, in factories the bunch spacing considered is a few meters only as indicated in Table 3. The separation of the beams must be made in the interaction area. tab2

6 Low-beta Section

To achieve high luminosity low beta values are required at the interaction point. The assembly of elements used to achieve this, starting from the regular lattice, is called the low-beta section, or the interaction area optics. It usually includes, starting from the interaction point: a quadrupole doublet, a matching section, a dispersion suppressor, and a set of skew quadrupoles in order to compensate the effect of the detector solenoïd. In the case of double rings a set of beam separators is required. When the separation is made in the vertical plane a vertical dispersion matching is required. This in itself is an interesting exercise with the requirement to simultaneously match ten parameters. In the case of

Table 3. e^+e^-factories

Collider		ϕ-factory[1]	τ-c factory[2]	B-factory[3]	Z-factory[4]
Energy	(GeV)	.5	2.5	9	45
Circumference	(m)	98	360	2199	26659
Max. beam current	(A)	5.3	.5	1.5	0.027
Bending radius	(m)	1.5	12	165	3100
Energy loss per turn	(MeV)	0.01	0.2	3.6	260
Radiation losses/ring	(MW)	0.01	0.1	5.3	7
Rms bunch length	(cm)	3	.7	1	2
β-function at IP	(cm)	4.5	1	3	5
Beam-beam parameter		0.04	0.04	0.03	0.03
Bunch spacing	(m)	4.2	12	1.26	740

[1] Daphne[5]
[2] τ-charm project[6]
[3] High energy ring of SLAC design[7]
[4] High luminosity LEP with 36 bunches[8]

the B-factory this must be done separately for two different energies, and with elements common to the two beams close to the interaction point. The solutions proposed should be transparent enough that the experimenter can understand, measure, and correct possible imperfections.

Several considerations influence the design of the linear optics in the low-beta section:

- *Chromaticity*
  The very strong quadrupoles required in low-betas will focus more low energy particles of the beam than high-energy ones. This effect (the chromaticity induced by the low-beta optics) must be corrected to prevent head-tail instabilities. This correction is made using sextupoles, which reduce the dynamic aperture.
- *Quadrupole strength*
  The scaling laws for the quadrupole doublet of the low-beta optics (see e.g. Möhl [3]) indicate that in order to decrease the beta value by a factor a, and keep the chromaticity constant, the distance of the first lens to the interaction point must be reduced by the same factor a. In this scaling the quadrupole length is reduced by a, the k-value is multiplied by a^2, the aperture by $a^{1/2}$, so that the pole field is multiplied by $a^{3/2}$. This explains the fact that most designs select the superconducting technology for the low-beta quadrupoles.

– *Detector forward acceptance*

By pushing the quadrupoles closer and closer to the interaction point one increases the solid angle where the detector is blind, which makes the interpretation of events more uncertain. Quadrupoles with minimum transverse dimensions are therefore favored. This explains the choice of permanent magnet quadrupoles in some designs.

– *Detector masking*

The detector must be protected from stray radiation to avoid excessive background. Two sources of background must be considered: the synchrotron radiation and the circulating beam interaction with the residual gas or the vacuum chamber. Their effect is analyzed using tracking programs which include routines to describe the secondary particle production when the incident particle hits an obstacle. It is only recently that the comparison between simulations and actual measurements at LEP or DESY have proved satisfactory. The result of the study is a set of masks placed at convenient positions, close to the interaction point, to stop the incident particles. The situation is particularly delicate in the case of B-factories where the vertex detection imposes a small radius of the vacuum pipe at the interaction point. Moreover the vertex detector is itself extremely sensitive to radiation damage.

– *Mechanical layout*

It must be possible for the low-beta quadrupoles installed inside the detector to be removed or reinstalled when the detector is being repaired or replaced. This, together with the requirement to install in the minimum possible space the cooling of superconducting quadrupoles, and the required pumping speed close to the masks where the desorption is important, imposes severe constraints on the mechanical design of the machine parts inserted in the detector.

– *Separation*

The aim of separation is not only to send the two beams into their respective rings, but also to separate the beams as close as possible to the interaction point. This is to allow the injection of as many bunches as possible with a minimum number of crossings at places where the beams are separated but not yet isolated in their own vacuum chamber; these are called distant crossings. How distant these should be is still a matter of debate. For separation in the horizontal plane it seems that a distance d equal to 7 to 9 rms of the horizontal distribution at the point of crossing is sufficient, for vertical separation figures ranging from 3 to 7 times the rms of the horizontal beam size have been quoted. In any case the question must be solved for each particular collider because the parasitic crossing effect on luminosity depends very much on a number of other parameters such as the main beam-beam tune shift, the working point selected, the number of useful and of parasitic crossings etc. This is one of the many applications of simulation programs.

The separation is made using electrostatic deflectors in equal energy machines, and magnetic deflectors in B-factories where the two beams have different energies. This is the reason why B-factories have smaller bunch longitudinal distances: the separation is easier.

Optimization of the luminosity can only be attacked once these various effects have been understood and their consequences introduced in the design. This in general requires several rounds of successive versions of design. The final design and construction will be made keeping in mind these various possibilities so that they can be tested in the machine during the experimental search for maximum luminosity.

7 Radio-frequency Systems

A number of considerations enter into the design of factory RF systems. The latter are one of the key elements in the design of Z- and B-factories because of the enormous amount of synchrotron radiation losses.

- *Synchrotron radiation*
  The energy loss per turn due to synchrotron radiation scales as E^4/ρ where ρ is the average bending radius in the machine. The optimization of the machine gives a bending radius approximately proportional to the square of the energy so that the energy loss per turn is also approximately proportional to the square of the energy. Two single-cell accelerating cavities are required for DAPHNE whereas LEP requires a total of 640 cells in phase one.
  Not only the voltage required from the RF system can be very high, but the circulating current of these colliders is around one ampere, with the consequence that the RF power to be delivered to the cavities is very large indeed (Table 3). For this reason a double-ring Z-factory is not proposed, it would consume too much RF power.
- *Bunch length*
  In order that all particles cross at the waist of the low beta, the bunch length must be short compared to the value of β^*. How short the bunch should be is not clear. Experiments at CESR demonstrated that, when the bunch length is limited by the RF voltage available, the optimum value of β^* is equal to the rms bunch length. For the designer the question is rather: how short should be the bunch to maximize the luminosity at a given β^*? There are some indications that the bunch length should be shorter than β^* by a factor between 1.5 and 2. Since the RF voltage required varies with the inverse of the square of the rms bunch length, the RF specification depends very much on the answer given to this question.
- *Transient beam loading*
  The beam ionizes molecules of the residual gas, the ions collect in the potential well of the electron beam and induce blow-up by the space-charge effect. In order to eliminate the ions one suppresses a number of bunches in the circulating beam, the ions are destabilized by this 'hole' in the potential well and no longer accumulate. This hole, in turn, induces a considerable transient beam loading in the RF system at the revolution frequency. The

net effect is to modulate the RF voltage, the RF phase and therefore the longitudinal position of the bunch crossing in the interaction area. This is not acceptable. The solution is first to introduce a hole in the positron beam to equilibrate the transient so that the bunches cross at the interaction point, and second to arrange a low level RF control which can live with these powerful transients. The Z-factory bunches are too distant to allow ion collection but in the ϕ-factory the circumference is too short to install a hole so that the ions will have to be cleared using clearing electrodes.

- *Beam loading*
  Apart from this transient beam loading effect, the low-level-RF engineer of the large current colliders is faced with a new problem linked to the high circulating beam current. Due to the beam loading at the fundamental frequency, which is not in phase with the required voltage, the RF cavity must be detuned so as to present a matched load to the RF source. This detuning can be as large as one revolution frequency in a machine with a large radius (small revolution frequency) and large current. The large impedance of the detuned cavities will excite the first mode (m = 1, n = 1) of longitudinal multibunch instabilities. The corresponding dipole oscillation of the bunch must be controlled by a feedback system within the RF low-level control.
- *RF technology*
  The debate between normal and superconducting cavities is still open for these machines with the exception of the ϕ-factory were the normal conducting cavities are sufficient and the Z-factory were the conversion to superconducting cavities is underway. Normal conducting cavities consume more power for less accelerating voltage and present a higher impedance to the beam. They are reliable, simple to operate and not sensitive to synchrotron radiation. Recent experience with superconducting cavities in TRISTAN and LEP show a large sensitivity of superconducting cavities to the circulating current. The plans are, in general, to start with normal conducting cavities at lower luminosity and to test progressively superconducting cavities. This was the procedure for LEP and could be the procedure for future τ-charm and B-factories.

The RF specialist must combine the competence of the accelerator physicist, of the low-level-electronics engineer and of the high-power specialist. In this domain, as in all others, the designer should prepare the hardware for the adjustments or modifications he will have to make when his work changes from designer to experimenter during the commissioning stage, and later development.

8 Instabilities

Several types of instabilities can reduce the beam current in operational conditions. The catalogue of these instabilities, and of the correction technique has been made in detail. In his lecture J. Gareyte [9] provides some advice: 'The most important phase (of the correction of instabilities) is the process of understanding, which requires good observation skills coupled to a thorough knowledge of the theoretical models'.

Instabilities can affect the longitudinal or transverse motion, they come in two types: single bunch or multibunch. They are induced by the wake fields left after the passage of the bunch through the various sections of the vacuum envelope. A quantity called impedance has been introduced which measures the ratio between the volts applied to the beam due to these wake fields and the beam current. In the longitudinal case this ratio is measured in ohms. In the transverse case it is the beam transverse displacement which is both the source and the result of the instability so that the transverse impedance is measured in ohms per meter of transverse displacement.

- **Single bunch**
  Single-bunch effects require that the action is made in a short time, during the bunch passage. In the frequency domain this is equivalent to a broad-band effect. The instability is therefore characterized by the broad-band part of the impedance. This comes from the vacuum chamber resistive wall itself but is often dominated by broad-band resonant structures like bellows, kickers or instrumentation. Longitudinal instabilities induce longitudinal blow-ups and therefore bunch lengthening. The threshold can be increased by increasing the RF voltage. Transverse instabilities of the simple head-tail modes are stabilized by using positive chromaticity. The transverse, head-tail, mode-coupling instability, where two head-tail modes couple, is usually destructive. No cure has been found.

- **Multibunch**
  These instabilities are generated when a coherent pattern of transverse or longitudinal oscillations of all bunches around the ring enters into resonance with a parasitic mode of oscillation of the RF cavities (or other similar resonant equipment). A single mode of oscillation could be easily damped by damping the resonant mode in the cavity, or by a feedback system measuring the bunch position and feeding back with the proper phase a deflecting or accelerating force onto the beam, or by both actions simultaneously. The difficulty is that with a large number of bunches there is a large number of such resonant patterns covering a large frequency band. Similarly there are many parasitic Higher-order Modes (HOM) of oscillations of the cavities capable of entering into resonance with the rotating patterns. The damping of HOM in the accelerating cavities is indispensable because the strength of the resonance can be so big that blow up occurs before the bunch phase has changed enough for the feedback system to be efficient. The bandwith and power requirements for the feedback system are at the limit of present technologies. Prototypes are being built using digital feedback techniques [10].

– **Beam current**
The highest beam current ever reached in an e^+e^-storage ring is less than one ampere, this in extreme conditions with large beam blow-up. The circulating current in factories is of the order of one ampere. [1] The various effects at the origin of this blow-up (mainly instabilities) are now well understood and accelerator physicists have estimated that the risks in entering this new working condition are acceptable, providing the conditions stated by J. Gareyte are fulfilled.

9 Non-conventional Schemes

Two proposals do not follow the traditional scheme of head-on collisions at zero dispersion: the Cornell CLNS laboratory has decided to investigate and propose a crab-crossing scheme, at Novosibirsk studies of monochromators open the way for a proposal where the classical regime of beam-beam interaction is modified. In Cornell Yuri Orlov is investigating the possibility to have mm long bunches cross in mm low beta to reach still higher luminosity.

9.1 Crab-crossing

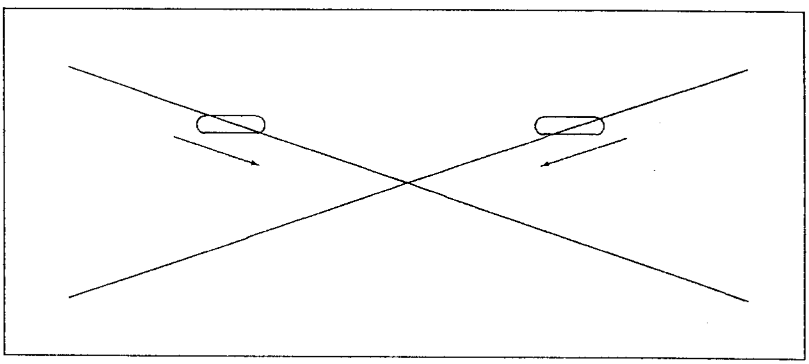

Fig. 2. Crab-crossing scheme

This scheme [12] was initially proposed [11] for linear colliders. The aim is to have the bunches cross at an angle in the interaction point. This provides the most efficient separation. In order to avoid the corresponding problem of the excitation of synchro-betatron resonances when the bunches do not perfectly overlap during the collision, the colliding bunches are tilted on their orbit (Fig.

[1] The Z-factory current must be limited to lower values to avoid excessive radiation losses with the corresponding problems of power consumption and cooling. The ϕ-factory will have 5 A of circulating current.

2). This way, the collision in the center of mass is made head-on even though the bunches cross at an angle.

The bunches are tilted by an RF cavity working in a deflecting mode, with a phase adjusted to zero at the center of the bunch so that the head and the tail are deflected in opposite directions. A second cavity placed at the other side of the interaction region, at a betatron phase advance of π with respect to the first deflection, restores the bunch to its normal trajectory. The scheme presents several difficulties:

- *Tolerances:* The deflection phase and amplitude of the two deflecting cavities must be adjusted with precision in order to avoid a residual angle of crossing, or a residual oscillation inducing synchro-betatron resonances.
- *Betatron phase advance:* A betatron phase advance error between the two compensated cavities has the same effect as an amplitude difference between them: synchro-betatron resonances are excited.
- *Parasitic modes:* The deflecting mode in a normal cavity is not (unlike the accelerating one) the mode of oscillation of the cavity with the lowest frequency. Therefore the corresponding lower-order modes are more difficult to damp and the cavities add to the general ring impedance which is already at the limit in these machines.

The advantages are also numerous:

- *Small bunch spacing:* The separation is so fast that a bunch distance of the order of the RF wavelength (60 cm with 500 MHz) can be considered.
- *Simpler low-beta design:* only one quadrupole is common to both rings which makes the low-beta design easier, and probably the background protection and masking as well.
- *Energy variation:* The absence of magnetic separation allows the two rings to work at a variety of energies. Collisions at equal energies are possible.

The Cornell laboratory (in collaboration with KEK) has already invested a large effort in the design of single-cell superconducting cavities which are an essential ingredient of this scheme. First prototypes are being tested. Moreover the CLNS laboratory can make experiments with CESR, the highest luminosity collider in operation. First indications are that the sensitivity to errors of the angle crossing scheme is not so severe as was feared. Experiments are continuing. A number of studies and experiments have been performed in various laboratories on this scheme, which is proposed for the high-luminosity version of the ϕ-factory under construction at Frascati.

9.2 Monochromators

The Novosibirsk laboratory has published [13] a study on a scheme which, at the origin, was invented [14] to insure a better energy resolution of the observed collisions. It turns out however that this scheme modifies the beam-beam interaction so that the current equations of luminosity limitation are no longer valid.

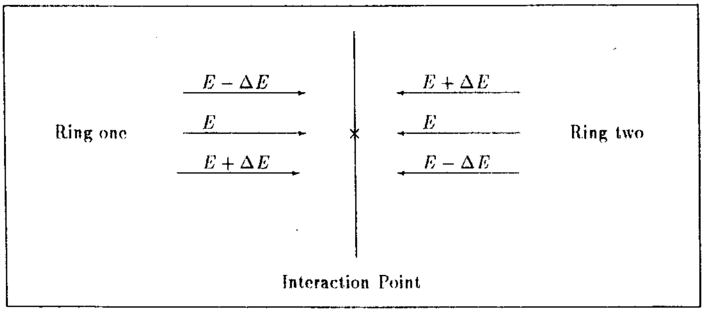

Fig. 3. Monochromator scheme

The idea is to take advantage of the two rings to install at the interaction point energy dispersions of opposite sign. In this way (see Fig. 3), particles with opposite energy difference collide so that the energy in the collision is always $2E$. The horizontal beam size at the interaction point is now dominated by the energy dispersion and no longer by the emittance.

The risk is obviously the excitation of synchro-betatron resonances, reason for which the dispersion function is usually made precisely equal to zero at the interaction point. The authors however make the point that to excite synchro-betatron resonances one needs nonlinearities in the betatron phase space and that if the emittance is reduced by a large enough factor, a monoenergetic part of the beam will only sample a very small horizontal fraction of the beam-beam force, so that these nonlinear terms will be considerably reduced. The linear part of the force (the beam-beam tune shift) is no longer a measure of the nonlinear terms so that this parameter does not have the same physical signification.

The scheme [15] has been applied to the tau-charm factory and combined with a proposal to achieve polarization in the same rings.

Obviously one should examine in detail this new scheme, and its consequences, before reaching conclusions. The scheme does not benefit from the several decades of experience accumulated in e^+e^- colliders. Other obstacles are no doubt on the way, but it is still one of the very few options left for trying to improve the luminosity of colliders. If a two-ring collider (Tau-charm or B-factory) is built one day with only one interaction area used, a monochromator could be tested using the second crossing point.

9.3 Micro-betas and Bunch Compression

Working at Cornell, Yuri Orlof has proposed [16] to further reduce, by an order of magnitude, the value of beta at the Interaction Point: β^*. Simultaneously a reduction of the bunch length is required in order to make good use of the low-beta value all over the bunch. In the proposed scheme this is achieved by using a classical bunch compression technique combining an RF cavity, which provides an energy modulation from the head to the tail of the bunch, and a magnet where the variation of trajectory with energy achieves the bunch compression. A reverse system re-establishes the original bunch length around the ring. A preliminary design of the interaction area is described, with due consideration to chromatic effects. The results of a number of simulations are given where essential effects are analyzed. The conclusion requires only one sentence: 'The main preliminary result of the simulation is that the tune map of the luminosity $\mathcal{L} = \mathcal{L}(Q_x, Q_y)$ in this design is at least as good as the maps of usual colliders. The luminosity is $\mathcal{L} = 10^{35}$ cm^{-2} s^{-1}.

10 Conclusion

In order to be competitive, there is a tendency for proposals for new colliders to announce rather high values for the expected luminosity. Past experience with electron colliders has proved that it is extremely long and painful to achieve the design peak luminosity once the machine is built. This is even more true with the large size of high energy machines. Still one should design for a high luminosity in order to avoid that the luminosity is limited by under-design rather than by more fundamental problems. The recipe used in all proposals is to keep the design flexible enough that the experimenter can try a variety of parameter sets. The hope is that in the future the simulation programs will make it possible to do a large part of this search on the computer.

In other words it is far easier to give a lecture on how to achieve high luminosity than to actually work on it for days and nights in a control room.

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