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A high Luminosity e^+e^- Collider with a Crossing Angle

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Abstract

In this paper an e^+e^- collider with a crossing angle is discussed. It is shown, that for flat beams a crossing in the horizontal plane is preferred. The basic parameters for a machine with a luminosity of $10^{34} s^{-1} cm^{-2}$ are given.

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1 Introduction

For the next generation colliders high energy physics requires a luminosity two orders of magnitude higher than presently achieved, for e^+e^- machines as well as for hadron colliders.

In order to achieve a luminosity above $10^{34}s^{-1}cm^{-2}$ for the future hadron colliders such as the LHC and the SSC it is intended to bring two beams with a large number of bunches into collision. To avoid crossings outside the physics experiments the beams collide with a small angle [1,2,3]. In the design for the future high luminosity e^+e^- colliders a crossing angle has been excluded because of the painful experience with DORIS, where the beams were colliding with a vertical angle [4]. The existence of strong synchro-betatron resonances was observed with a limiting effect on the performance of DORIS.

Since then no e^+e^- storage ring operated with a crossing angle. It is not yet understood which maximum crossing angle can be tolerated. Not much work has been done on problems related to a crossing angle for e^+e^- colliders since the DORIS experiments, whereas different groups are working on the maximum value for the crossing angle which can be tolerated for future hadron colliders [5,6,7]. For e^+e^- collider one suggestion is the crab crossing geometry, which can suppress synchro-betatron resonances [8].

In this paper we discuss an e^+e^- collider with a crossing angle. It is shown that for flat beams a horizontal crossing angle is better than a vertical one. The crossing angle can be as small as about 1 mrad. It is not yet clear if such an angle is tolerable, but at least it can be said that this angle is small compared to the vertical crossing angle at DORIS.

The basic design principles for an e^+e^- collider with a crossing angle are the following:

- Both beams have many bunches, circulating in two distinct vacuum chambers. The distance between two bunches is in the order of 0.5 m.
- The emittances of the beams are very low.
- The intensity per bunch is very small.
- The total current is high.
- The beams collide with a 'small' crossing angle in order to avoid parasitic bunch crossings.
- Because of the small emittance a small diameter of the vacuum chamber in the physics experiments is feasible.
- Because of the small emittance the dynamic aperture does not need to be large.

Here we only consider a collider with both beams having the same energy. First we show how the basic parameters for such a collider are derived. Then we discuss some aspects of the interaction with a crossing angle. In an example the basic parameters for a B-factory with a luminosity of $10^{34}s^{-1}cm^{-2}$ are given.

2 The basic equations

The luminosity of a collider is given by :

$$L = \frac{N^2 \times f}{4\pi \times \sigma_x \times \sigma_z} \quad (1)$$

with :

N...Number of particles per bunch.

f...Number of crossings per second.

σ_x, σ_z ...beam dimensions at the interaction point in both planes.

This equation is valid for head-on collision. It is approximately true if the crossing angle is small, which is assumed in the following.

With the definition $\kappa = \sigma_z/\sigma_x$ the luminosity and the tune shifts are :

$$L = \frac{N^2 \times f}{4\pi \times \sigma_x^2 \times \kappa} \quad (2)$$

$$\delta Q_x = \frac{r_e \times N \times \beta_x}{(2\pi \times \sigma_x^2) \times (1 + \kappa) \times \gamma} \quad (3)$$

$$\delta Q_z = \frac{r_e \times N \times \beta_z}{(2\pi \times \sigma_x^2) \times \kappa \times (1 + \kappa) \times \gamma} \quad (4)$$

with γ the relativistic factor and r_e the classical electron radius. The beam-beam effect limits the tune shift to a value between 0.03 and 0.05. The optimal luminosity is achieved with the same tune shift in both planes : $\delta Q_x = \delta Q_z$ which requires for the ratio of the beta functions at the IP : $\beta_z/\beta_x = \kappa$.

The beam size at the interaction point for a given tune shift can be expressed in the following way :

$$\sigma_x = \sqrt{\frac{r_e \times N \times \beta_x}{2\pi \times (1 + \kappa) \times \delta Q_x \times \gamma}} \quad (5)$$

In conventional e^+e^- storage rings with a small number of bunches the emittance of the beam is large. This allows to have strong bunches without reaching the beam-beam limit. The equations below show how a collider with many bunches is optimized : the total current is limited by the power requirements because of the energy loss due to the synchrotron radiation. The current is distributed between many bunches. The emittance is reduced to keep a high luminosity and to keep the beam-beam tune shift close to the maximum possible value.

The required number of particles per bunch for a given luminosity is (from eq.2 and eq.5)

:

$$N = \frac{2 \times L \times r_e \times \beta_y}{f \times \gamma \times (1 + \kappa) \times \delta Q_x} \quad (6)$$

and the required horizontal emittance :

$$\epsilon_x = \frac{r_e^2 \times \beta_x \times \kappa \times L}{\pi \times \gamma^2 \times (1 + \kappa)^2 \times \delta Q_x^2 \times f} \quad (7)$$

The last equation shows, that the emittance is inversely proportional to the bunch frequency.

3 An interaction region with a crossing angle

The geometry around the interaction point is defined in fig.1. The distance between two bunches is given by s_b , the first parasitic crossing point is $0.5 \times s_b$ away from the interaction point. For a drift space (no quadrupoles) the β -function is given by: $\beta(L) = \beta^* + L^2/\beta^*$, β^* is taken at the interaction point.

The minimum crossing angle is determined by the requirement to have a large enough separation at the parasitic crossing points. The distance between the beams at the parasitic crossing is given by $d = L \times \alpha$. This distance expressed in units of the beam size σ should be larger than a certain minimum value, i.e. $d/\sigma(L) \geq (d/\sigma(L))_{min}$.

For $L \gg \beta^*$ the beam size increases linearly with the distance from the interaction point : $\sigma(L) = (L \times \sigma^*)/\beta^*$ and the separation d/σ_L becomes constant. A reasonable assumption for the separation is $(d/\sigma(L))_{min} = 10$ for the interaction points at a distance $L \gg \beta^*$. For one or two parasitic crossing points a smaller separation can be tolerated.

One finds for the minimum crossing angle respecting the condition for the separation :

$$\alpha_{min} = (d/\sigma(L))_{min} \times \frac{\sigma^*}{\beta^*} \quad (8)$$

with σ^* the beam size and β^* the value of the β function at the interaction point. For the required separation of 10σ the crossing angle is $\alpha = 10\sigma^*/\beta^*$.

A large crossing angle reduces the strength of the parasitic beam-beam crossings, but increases the strength of the synchro-betatron resonances. In first order this strength is proportional to [4] :

$$R = \frac{\alpha}{2} \times \frac{\sigma_l}{\sigma^*} \quad (9)$$

with σ_l the r.m.s. bunch length.

R gives the separation of a small amplitude particle at a longitudinal displacement of σ_l when the bunch centres collide (see fig. 2). In the case of a zero crossing angle the parameter R vanishes.

More recent studies show that in the case of very flat beams and a large crossing angle in the vertical plane the resonance strength saturates [9]. In the following we continue the discussion with the approximate formulas.

We assume that a certain crossing angle can be tolerated, corresponding to the parameter $R = R_{max}$. Then a combination of (8) and (9) yields a condition for the ratio of the bunch length to the beta function at the interaction point :

$$\frac{\sigma_l}{\beta^*} = \frac{2 \times R_{max}}{(d/\sigma(L))_{min}} \quad (10)$$

In order to evaluate this expression numerically, some assumptions about the value of R_{max} and $(d/\sigma(L))_{min}$ have to be made. We assume for R_{max} a value of 0.1, about five times smaller than at DORIS. For the separation at the parasitic crossing points we require $(d/\sigma(L))_{min} = 10$. This yields for the ratio of the bunch length and the beta function a value of 0.02. With a bunch length of 1 cm, the minimum beta function is 50 cm. In a geometry with a vertical crossing this condition is impossible to fulfill : for flat beams the vertical beta function is only about 1 cm. Therefore a horizontal crossing is mandatory.

Even if synchro-betatron resonances are not considered, a horizontal crossing is preferable. With nominal coupling the required crossing angles in both planes are identical. It is well known that the beam-beam effect leads to an increase of the vertical emittance and to non Gaussian tails in the vertical particle distribution. If a geometry with a vertical crossing angle is chosen, the angle must be larger than the angle calculated with nominal coupling to have a certain security margin.

4 Example for a B-factory with a luminosity of $10^{34} s^{-1} cm^{-2}$

We assume the following parameters :

Beam energy : $E = 5.3$ GeV for both beams.

Gamma factor : $\gamma = 10372$.

Bunch distance : $s_b = 1.2$ m.

Frequency of the collisions : $f = 500$ MHz.

Beta functions at the interaction point : $\beta_x = 50cm$ and $\beta_y = 1cm$.

Coupling : $\kappa = 0.02$.

Tune shifts : $\delta Q_x = 0.05, \delta Q_z = 0.05$.

Bunch length : $\sigma_l = 1\text{cm}$.

Classical electron radius : $r_e = 2.8179 \times 10^{-15}\text{m}$.

Using these parameters we find :

Number of particles per bunch : $N_b = 2.13 \times 10^{10}$.

Horizontal emittance : $\epsilon_x = 1.805 \times 10^{-8}\text{m} \times \text{rad}$.

Bunch sizes at the interaction point : $\sigma_x = 95\mu\text{m}, \sigma_z = 1.9\mu\text{m}$.

Crossing angle in the horizontal plane : $\alpha = 1.90\text{mrad}$.

Separation at the first parasitic crossing point : $d = 5.1 \sigma$.

Separation at the next crossing point : $d = 7.7 \sigma$.

Parameter for the strength of the synchro-betatron resonances : $P = 0.1$

Current in one beam : $I = 1.7 \text{ A}$.

The separation at the first two parasitic crossing points is 5.1 and 7.7σ . These values are probably sufficient for a small number of crossing points. Further away the separation reaches the required value of 10σ .

5 Conclusions

For an example design of a B-factory with two beams of the same energy the crossing angle is 1.9 mrad . A collider with beams of different energies can be designed following the same principles. The angle is substantially smaller than the angle used at DORIS, and the synchro-betatron resonances are expected to be weak. Nevertheless, simulations and experiments are needed to study if an angle of this order is acceptable. It is also of interest to compare the strengths of the synchro-betatron resonances generated by a crossing angle with those generated by nonvanishing dispersion at the interaction point. If detailed studies show that this crossing angle is not acceptable, a crab crossing geometry can be employed. The fields in the crab cavities are very moderate due to the small value of the crossing angle.

An angle of 1.9 mrad leads to a beam separation of 9.5 mm after a distance of 5m . This is too small to install elements to separate the two beams into different vacuum chambers. Therefore an additional separation is needed to increase the distance between the two beams. This could be done with electrostatic separators, either in the horizontal or in the vertical plane.

The masking of the physics detectors against synchrotron radiation is probably easier in an interaction region with a crossing angle, as it was found at Cornell studying the synchrotron radiation background for different interaction region geometries [10].

In many ways such a collider resembles more to a synchrotron light source than to a conventional storage ring : small emittance, many bunches, high total current. It has to

be studied, if beams with so many bunches are stable, and if a feedback system can be designed to damp coupled bunch instabilities. A detailed layout of the interaction region is required to calculate the minimum possible β function.

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Fig.1 Geometry around the interaction region with a crossing angle.

Fig.2 Geometry of the interaction point when the bunch centres collide