Initial design of a ϕ factory

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Abstract

An initial design is presented of a high luminosity (10^{32} $cm^{-2}s^{-1}$) e^+e^- collider which will cover the energy range of 400 to 800 MeV. The primary physics goal of such a machine would be the production of large numbers of ϕ(1020)-mesons, allowing detailed studies of a.o. CP violation in the K-$\bar{K}$ system. The intention is to use the existing 500 MeV electron-linac of NIKHEF to inject electrons and positrons into a two ring collider. One interaction region is foreseen in a dispersion free mini-beta insertion. On the basis of a specific lattice critical items will be discussed which may limit the performance of the storage ring.

Introduction

In recent years much interest has been shown in the physics potential of "ϕ-factories", high luminosity e^+e^- colliders optimized for the production of large numbers of ϕ(1020)-mesons [1-3]. In particular precision measurements of CP-violation in the kaon system would be possible with such machines. Experimental arguments indicate that a luminosity of at least $10^{32}cm^{-2}s^{-1}$ is required for this purpose [4] Although storage rings have been built that cover this energy range the luminosities achieved are orders of magnitude smaller than the above figure. A dedicated collider of which the luminosity is optimized at a beam energy of 510 MeV is therefore required. The existence of a high intensity 500 MeV electron linac at NIKHEF has triggered discussions to complement this machine with a small e^+e^- storage ring of center of mass energy around 1000 MeV. In this paper the emphasis will be on the requirements and limitations of the storage ring to achieve the design luminosity of 10^{32} $cm^{-2}s^{-1}$.

Collider design

General guidelines for the design of a high luminosity e^+e^- collider are given in several papers [5-8]. The main requirements are: one or two interaction regions, a mini-beta insertion, short bunch separation and high emittance. This leads to a two-ring design, where the two beams are separated by electrostatic separators. In an interaction region, free of dispersion, the luminosity is given by:

$$L = \pi B(1+k^2)f\gamma^2\epsilon_x\Delta\nu_y^2/(r_e^2\beta_y^*)$$

Here B is the number of bunches, f the revolution frequency, γ the usual relativistic factor, $r_e = 2{\cdot}8\ 10^{-15}$ m is the classical radius of the electron, β_y is the vertical beta value at the interaction point, ϵ_x is the horizontal emittance, k is the coupling factor and $\Delta\nu_y$ the beam beam tune shift. For the last one in our studies the value 0.04 was taken, although higher values up to 0.06 have been reported.
In this formula optimum coupling $k = \sqrt{\beta_y^*/\beta_x^*}$ is implied. The beam current corresponding to this luminosity is given by: $I = 2er_e\beta_y^*L/(\gamma\Delta\nu_y)$. The energy dependence of the luminosity following from these formulae is illustrated in fig.1 for the lattice described in the next paragraph. Two limiting cases are shown: 1) the natural emittance $\epsilon_x \alpha E^2$ leading to $L \alpha E^4$ and 2) a fixed emittance value giving $L \alpha E^2$.

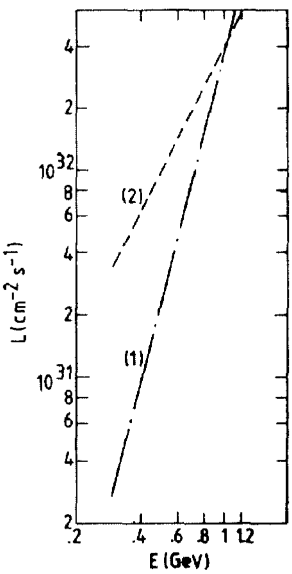

Fig. 1 Luminosity for the ϕ-factory. Curve (1): with natural emittance, curve (2): constant emittance

It is seen that in this specific case a luminosity of 10^{32} requires a 4-fold increase of the emittance compared to the natural one. Since this emittance is not yet restricted by the aperture of the machine, the possibility of increasing the emittance will be crucial in our discussions.

Lattice design

A schematic drawing of the proposed machine is given in Fig. 2. It has two rings, one above the other, in the same tunnel. Electrostatic separation is done in the mini-beta insertion. Although each ring is essentially a one-superperiod machine, it was tried to maintain the highest degree of regularity. Therefore the common building block is a 3 m 90 deg phase advance FODO cell, with or without bending magnets. This is most forgiving for misalignment errors and tollerances on magnets and provides good dynamic aperture. The machine has two types of double achromats each consisting of 4 cells: two groups fully equiped with bends, two groups are half full with bends. The latter achromat consists of two identical 180 deg phase advance sections, each with a full and an empty cell. Fig. 3 shows the lattice functions. In fact the double achromatic behaviour is realized within three cells, since a non-zero dispersion can only be achieved in the bending magnets. The empty cell in the middle of this achromat has non-zero dispersion. Here (Robinson) wigglers are to be positioned for increasing the emittance and luminosity. Furthermore the empty cells in the dispersion free straight are used as "tuning cells" for realizing the desired choice of the working point. Moreover the dispersion free straigth section opposite to the interaction region is suitable to accomodate the injection equipment, RF, etc. The micro-beta insertion obviously is the only section not employing the standard FODO building blocks. Calculations are based on the optics program DIMAD [9].

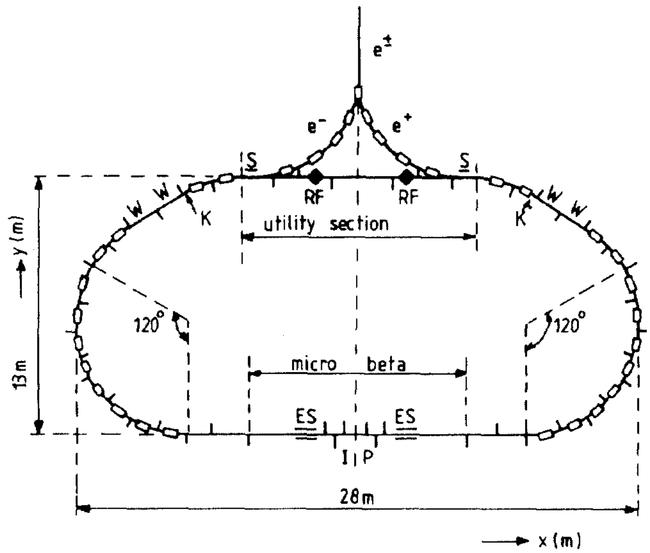

Fig. 2 Machine lay-out

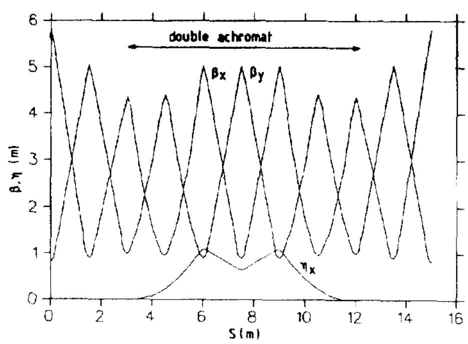

Fig. 3 Lattice functions in 2nd double achromat

The mini-beta insertion

A mini-beta insertion, optimized at the ϕ-resonance, has been designed using triplet focusing. It provides beta-values of: $\beta_y = 1$ cm, $\beta_x = 20$ cm. The vertically focusing quad nearest to the interaction region is 40 cm away from this collision point and is 30 cm long. Table 1 gives some data for the mini-beta insertion quadrupoles. The distance between the triplet quadrupoles is 20 cm. The maximum vertical beta-function is 25 m.

Table 1.

Mini-beta quad data				
Name	length (cm)	half aperture (cm)	poletip induction at 510 MeV (T)	focal length (cm)
qid1	30	3	- 0.55	37.4
qif1	20	3	0.70	- 40.7
qid2	20	3	- 0.31	87.8

Beam separation between e^+ and e^- beams is accomplished by means of electrostatic separator plates followed by a magnetic septum. There are 15 bunches, i.e. bunch separation 4.75 m. Separator plates are within half this distance from the IP. Fig. 4 shows the separation system. Separator plates 0.6 m long with 25 kV/cm provide a deflection of 2.75 mrad and $\Delta y = 0.8$ mm separation for a 510 MeV beam. This fullfills the requirement $\Delta y > 2\sigma_x$ [10].

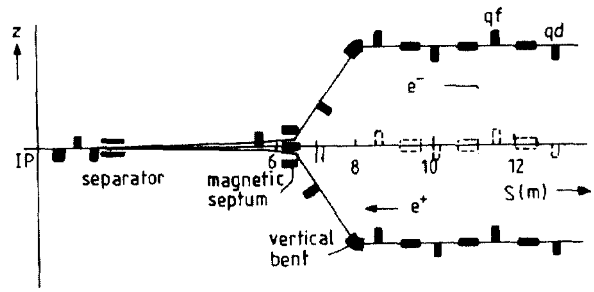

Fig. 4 Interaction region

The vertically defocusing quadrupole following the separator enhances the deflection angle, giving rise to a beam separation of several cm at the septum. Chromatic effects caused by the insertion quadrupoles are corrected by two families of sextupoles in the arcs only in the two full cell double achromats. This does not seriously afect the dynamic aperture as shown by the absence of geometric aberations doing tracking over many tunes [11].

RF, bunch length and energy spread

The bunch length σ_l in the ϕ-factory must be shorter than the micro-beta value at the interaction point, in order not to cause an increase of the effective spotsize along the bunch during collision. This requires RF parameters with a combination of a high harmonic and a high acceleration voltage. A Cornell-type superconducting cavity [12] is adopted operating at 1.5 GHz and with peak acceleration voltage of 1 MV. This provides bunches less than 1 cm long for a relative RMS energy spread $\sigma_\varepsilon = 10^{-3}$ at 510 MeV. The natural energy spread of the machine, $\sigma_\varepsilon = \alpha\ (I_3/I_2)\ J_\varepsilon^{-\frac{1}{2}}$, *with* I_3 *and* I_2 *the synchrotron radiation* integrals and J_ε the longitudinal damping partition number, equals $\sigma = 3.2 \times 10^{-4}$. We note that this is smaller than we need at the ϕ-resonance, which is 4.2 MeV wide. With $\sigma_\varepsilon = 10^{-3}$ we would loose 7% counting rate. A summary of the machine parameters for this machine is given in Table 2.

It is seen that the luminosity is a factor of 4 smaller than required. An increase of the luminosity to 10^{32} by enhancing the emittance would lead to problems with the Keil-Schnell-Boussard criterion for the threshold of the longitudinal micro-wave instability.

$$I_p \lesssim \frac{2\pi(E/e)\alpha}{|Z/n|}\,\sigma_\varepsilon^2,$$

where $I_p = ecN_b/(\sqrt{2\pi}\,\sigma_l)$ is the instantaneous peak current in the bunch belonging to N_b particles, E is the beam energy, α the momentum compaction factor, Z the longitudinal impedance, n the mode number and c the velocity of light.

Inserting numbers: with $L = 10^{32}$ cm s^{-1} one finds $N_b = 2.35\ 10^{10}$ and $I_p = 45$A, leading to $|Z/n| \lesssim 0.4\ \Omega$. Such a low impedance will be hard to realize; a more realistic value is $|Z/n| = 2\ \Omega$ [3].

The KSB criterion can in this case only be satisfied by increasing the energy spread by a factor of 2 to 3, i.e. $\sigma_\varepsilon \gtrsim 7.4 \times 10^{-4}$.

Summarizing: in order to reach $L = 10^{32}$ cm^{-2}s^{-1} the emittance has to be increased by a factor 4.2, and the energy spread by a factor of 2 to 3.

Table 2.

Machine parameters		
Beam energy	400-800	MeV
Circumference	71.2	m
Bending radius	1.9	m
Number of interaction regions	1	
RF frequency	1.5	GHz
Circulating current °)	58	mA/beam
Number of bunches	15	/beam
Number of particles °)	5.75×10^{9}	/bunch
Radiation loss °)	3.1	keV/turn
RF peak voltage	1	MV
RF beam power °)	0.18	kW/beam
Momentum compaction	0.05	
Betafunctions β_x^*	0.2	m
β_y^*	0.01	m
Natural emittance °)	63.3	nm
Tuneshift	0.04	
Luminosity °)	2.4×10^{31} cm^{-2} s^{-1}	

°) at 510 MeV

Emittance increase

The emittance in the machine may be changed by modifying factors in the relation $\epsilon_x \alpha\ (I_5/I_2)J_x^{-1}$ where J_x is the horizontal damping partition number and I_2 and I_5 are synchrotron radiation integrals. In our existing lattice design a number of possibilities has been investigated to enhance the emittance.

1. Reducing the bending radius of all dipoles to 1 m, instead of 1.9 m. This requires a field of 1.67 T at 510 MeV and provides an increase in the emittance by a factor 1.76 and in the energy spread by a factor 1.42. This opition requires super-conducting coils for higher collision energies.

2. Double achromats with μ = 60 deg phase advance rather than 90 deg enhance the emittance by a factor 2.9, in agreement with approximate relation $\epsilon_x\ \alpha\ \mu^{-3}$.

3. Two dipole wigglers in each appropriate achromat, with a block length of 10 cm and field 1.4 T provide a gain in emittance by a factor 1.6 and in relative energy spread by a factor 1.3, due to changes in I_2, I_3 and I_5. Optical distortions induced by the wigglers can be compensated by the empty cell quadrupoles of these achromats.

4. Drastic changes in the emittance can be obtained by Robinson wigglers in these achromats. A change of J_x from 1 to 0.25 can be realized with four wigglers of modest size. This does somewhat reduce the energy spread. Independent measures to increase the energy spead have not yet been looked at in detail. One may consider the use of stochastic RF.

Touschek lifetime

One of the main factors limiting the overall beam lifetime is the Touschek effect. The lifetime in case the emittance is increased by a factor 4.2 is given in fig. 5 for the natural energy spread, and for an energy spread of 10^{-3} respectively. Calculations were done with our code Touschek. At lower energies the multiple Touschek effects may further increase the emittance and actually prolonge the lifetime. The beam lifetime due to gas scattering has not yet been calculated however based on the experience with other machines this should exceed several hours.

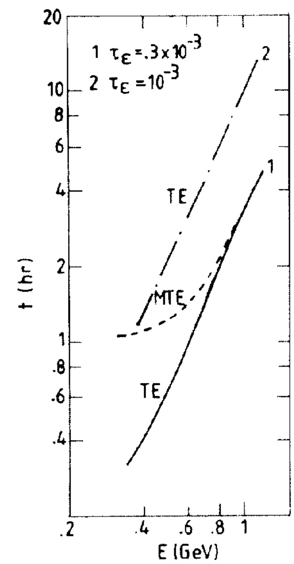

Fig. 5 Touschek lifetimes

Conclusion

Luminosity figures have been given for a ϕ-factory collider based on a detailed initial lattice and machine design. A luminosity L = 10^{32} cm^{-2} s^{-1} or higher is feasible.

Acknowledgement

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