Review of Studies of Electron-Positron Factories

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Abstract

Research in elementary particle physics based on accelerators exhibits nowadays two complementary trends: the first points towards unexplored high energy regions, the second searches the answers to fundamental theoretical questions through high resolution experiments, based on the detection of a very large number of events in the energy range already covered by existing accelerators. Following the latter direction, high luminosity electron-positron colliders optimized at the center of mass energies of the quark-antiquark resonances Φ (1 Gev), J/ψ (4 GeV) and Υ ("upsilon", 11 GeV), where the cross section for particle production is high, are being proposed by several laboratories in the world. The luminosity requirements of such "factories" exceed by two orders of magnitude the results obtained by operational accelerators, mainly limited by beam-beam interaction. To achieve this goal, substantial changes to the classical scheme of single ring colliders with few crossings are under study, spanning from compact structures with extremely high current density, to double intersecting rings with a large number of bunches interacting only one or two times per turn with the other beam. Experimental requirements on the geometry of the crossing region, such as center-of-mass momentum and magnetic fields for produced particles detection, set additional challenges to the design. The main accelerator physics and technology issues of electron-positron factories are discussed, advantages and drawbacks of possible collider schemes are compared, and the status of the existing proposals is reviewed.

1. INTRODUCTION

Strong interest has been demonstrated by the high energy physics community towards the realization of high luminosity electron-positron colliders optimized around the center of mass energy of the hadronic resonances Φ (1 GeV), J/ψ ("τ/charm", 4 GeV) and Υ ("beauty", 11 GeV). The large cross section at the peak of the resonances enables the production of high hadron fluxes, and this is the reason for the name of "factories" assigned to these projects. Due to the relatively low energy required, the typical size of such colliders is often compatible with the possibilities of small, national, laboratories, in contrast with the huge financial and technical effort required for the realization of colliders beyond the energy range already covered by existing machines. On the other hand, the experiments proposed in this "low" energy range are always very high precision measurements of physical quantities, the most important being the study of CP violation, or search for rare decay modes of the resonant state, and a common feature to such proposals is the requirement for very high luminosity, typically two orders of magnitude above the performance of existing storage rings ($4\times10^{30}cm^{-2}s^{-1}$@1.02GeV at VEPP2M [1], $7\times10^{30}cm^{-2}s$-1@4.4GeV at BEPC[2], $1.8\times10^{32}cm^{-2}s^{-1}$ @10.6GeV at CESR [3]). The experiments are in most cases extremely sensitive to the backgrounds created by the machine, such as synchrotron radiation and lost particles, and even radiation damage of experimental setups my become one of the constraints to be respected in the collider project. The high luminosity is a common requirement for the three kinds of factories: a peculiarity for the Υ decay physics is the requirement for different energies in the two beams (asymmetric B-factories), while τ/charm factories are characterized by the need of very good energy resolution, to match the tiny width of the J/ψ resonance.

To achieve the strong improvement required for the luminosity, new structures are proposed for the factories, as alternatives to the standard layout of a single storage ring with counterrotating electron and positron beams: the preferred one is based on the use of two separate rings with one or two interaction regions, but also small superconducting single rings or superconducting electron linacs against positron storage rings have been considered.

2. MACHINE PHYSICS OVERVIEW

2.1. *Luminosity*

The luminosity of an electron-positron collider is

$$L = f\frac{N^+N^-}{A} \tag{1}$$

where N^+ and N^- are the numbers of electrons and positrons in a single bunch of the machine, f the collision frequency and A an "effective" interaction cross section, which, in the simple case of equal beam sizes of the two beams and gaussian horizontal and vertical distributions, takes the simple form

$$A = 4\pi\sigma_x\sigma_y \tag{2}$$

Beam-beam interaction limits the maximum number of particles stored in a single bunch. A good probe for the intensity of the perturbation is the linear tune shift

$$\xi_{x,y} = \frac{r_o\ N\ \beta_{x,y}}{2\pi\gamma\ \sigma_{x,y}\ (\sigma_x+\sigma_y)} \tag{3}$$

where r_o is the classical electron radius, γ the energy of the beam in units of the electron rest mass and $\beta_{x,y}$ the betatron functions at the interaction point (IP).

From the experience on existing storage rings and from the results of beam-beam numerical simulations, it can be stated that the tune shift cannot exceed a maximum value ξ_o, whose value, averaged over the experimental results from operating machines does not depend on energy and is

$$\xi_o = 0.038 \pm 0.013 \tag{4}$$

The tune shift can reach its maximum value in both planes if

$$\frac{\beta_y}{\beta_x} = \frac{\varepsilon_y}{\varepsilon_x} = \frac{\sigma_y}{\sigma_x} = k \tag{5}$$

where ε_x and ε_y are the horizontal and vertical emittances and k is the coupling factor in storage rings without vertical bendings. In this configuration the luminosity is optimized: combining (1) and (3) under the assumption (5) one finds for the luminosity and the number of stored particles the following expressions

$$L = f\,\pi\,\gamma^2\,\xi_o^{\,2}\,\varepsilon_o\,\frac{1+k}{r_o^{\,2}\,\beta_y} \qquad N = 2\,\pi\,\gamma\,\varepsilon_o\,\frac{\xi_o}{r_o} \tag{6}$$

where ε_o is the sum of the horizontal and vertical emittances of the beam. Formula (6) shows that, keeping the other parameters constant, the achievable luminosity scales with the square of the beam energy. This behaviour is almost compensated by the decrease of the hadron production cross section: the typical luminosity requirements for the factories are $>10^{32}$ for the Φ, $\approx 10^{33}$ for the τ-charm and $\approx 10^{34}$ for the beauty.

The limit imposed by beam-beam interaction can be overcome in colliders where one or both beams are lost after crossing at the IP, thus allowing strong beam-beam interaction, which largely exceeds the above mentioned limits for conventional storage rings. In these colliders, the beams sizes at the IP are pushed to the minimum value allowed by the achievable emittance. The beams are strongly focused by the interaction itself, and numerical simulations predict a "pinch effect" that increases the luminosity beyond the value foreseen in (1). Proposals have been put forward both for linac on linac and for superconducting electron linac on positron storage ring schemes. These solutions are limited by beam power considerations, and, of course, superconducting structures have been proposed [4]. In the first case the main difficulties come from the beam emittance and from the positron production: a damping ring is inserted in the structure to improve positron emittance, while the electron beam is used both to produce luminosity at the IP and for positron conversion. The hybrid solution [5] is based on the strong disruption of a weak electron beam on an intense stored positron beam with very small emittance. This scheme exploits the experience based on small emittance storage rings for synchrotron radiation, and, although no experimental data are available on such kind of interaction, it seems the most promising.

As already mentioned, an improvement of about two orders of magnitude in luminosity, with respect to existing machines, is required for the factories. In the absence of new basic ideas to improve the luminosity, the proposals for new machines push the parameters appearing in (6) towards their technically achievable limits. Table 1 shows typical values of these parameters for double ring projects in the three energy ranges.

Table 1
Design parameters for e^+e^- factories

	Φ [6]	τ/Charm [7]	Beauty [8] e^+	Beauty [8] (common)	Beauty [8] e^-
Energy (GeV)	0.5	2.5	3.1		9.0
Luminosity ($cm^{-2}\,s^{-1}$)	5.0×10^{32}	6.10^{32}		3.10^{33}	
Collision frequency (MHz)	368.2	30.0		238.2	
Horizontal linear tune shift	0.04	0.05		0.03	
Vertical linear tune shift	0.04	0.007		0.03	
Number of particles per bunch	8.9×10^{10}	1.2×10^{11}	5.9×10^{10}		4.1×10^{10}
Number of filled bunches	120	30		1658	
β_x at IP (cm)	450.0	1.0	37.5		75.0
β_y at IP (cm)	4.5	15.0	1.5		3.0
Vertical dispersion at IP (m)	0	±0.4		0	
Crossing angle (mrad)	20	0		0	
Horizontal emittance (m)	1.0×10^{-6}	3.6×10^{-9}	9.7×10^{-8}		4.8×10^{-8}
Vertical emittance (m)	1.0×10^{-8}	0.2×10^{-9}	3.9×10^{-9}		1.9×10^{-9}
σ_x at IP (mm)	2.12	6.0×10^{-3}		0.19	
σ_y at IP (mm)	2.12×10^{-2}	0.4		7.6×10^{-3}	
Coupling factor	0.01	0.06		0.04	

2.2 Betatron Function at the Interaction Point

The luminosity is inversely proportional to one of the two betatron functions at the interaction point ($k\beta_x$ can be put in formula (6) instead of β_y): the vertical one is usually preferred, according to (5), for small values of the coupling factor k. The slope of the betatron function in the interaction straight section grows linearly from the crossing point to the first magnetic element and is inversely proportional to its value at the IP, so that a strong focusing quadrupole triplet is necessary on each side to maintain it within reasonable limits. These quadrupoles limit the solid angle covered by the experimental setup, and are a source of chromatic effects, which must be corrected by means of sextupoles in the arcs where the dispersion does not vanish. The sextupoles make the lattice strongly nonlinear, with a consequent restriction of the stable area for betatron oscillations (dynamic aperture).

The most important limitation to the value of β at the IP is the condition that it must not be smaller than the bunch length, since otherwise the particles would cross at positions where, due to the increase of the betatron function, the beam-beam limit would be exceeded. Small bunch lengths call for very high voltage in the R.F. system, and, anyway, there will be a limit coming from the microwave instability [9], which mainly depends on the peak current and the longitudinal broadband impedance in the ring. The vacuum chamber must be carefully designed, in order to avoid contributions to such impedance coming from any parasitic cavity, such as bellows, pumping ports, injection elements and so on. The R.F. cavity itself is in principle an important source of longitudinal impedance, and special designs are being carried on to overcome this difficulty. Two harmful implications of a small bunch length are, on the other hand, the larger sensitivity to single bunch longitudinal instabilities and the reduction of single beam lifetime due to the Touschek effect (intrabeam scattering), which is inversely proportional to the bunch volume. For conventional structures the achievable bunch length (and the β function at the IP) is few centimeters.

A solution to the small bunch length problem is suggested by the idea of the "quasi-isochronous storage ring" scheme [10], where the linear part of the momentum compaction is made as small as to maintain the stability of synchrotron oscillations. In this way the betatron function can be decreased to few millimeters.

2.3. Collision Frequency

Operating colliders in the energy range of the factories are all single rings, where electrons and positrons are stored in opposite directions, and an obvious way to improve the luminosity is to store many bunches in the ring. The first difficulty of having many bunches in a single ring collider is that the lattice should provide many interaction points with small β's, and, as explained before, this would lead to unacceptable chromatic limitations. Moreover, it has been observed that the maximum tune shift per crossing depends on the number of crossings per revolution, and scales roughly with the inverse square root of this number. In order to optimize the luminosity at a single interaction point (IP), it is therefore necessary to separate the beams at the unwanted "parasitic" crossings, and the number of possible separations is typically twice the number of betatron oscillations per turn. Since the wavelength of these oscillations is much longer than the R.F. buckets (which set the maximum number of bunches in the ring), this becomes a practical limit to the collision frequency for single rings.

Most of the proposals are therefore based on machine designs where the beams travel in two independent rings, with one or two crossings where the experimental setups are located. For such machines the collision rate is limited, in principle, by the R.F. frequency, typically in the range of $3\div5\times10^8$ Hz, the maximum number of storable bunches being equal to the R.F. harmonic of the revolution period. In the double ring scheme the beam-beam interaction limits the maximum current stored in single bunches, and the luminosity is proportional to the number of circulating bunches. The total stored current and the synchrotron radiation power are therefore very large, setting challenging requirements on the vacuum system design and making damping of longitudinal instabilities a crucial point for reliable machine operation. Sophisticated bunch-to-bunch digital feedback systems are under study to match these needs [11].

Multibunch beams travelling in opposite directions near the IP cross each other at multiples of half the distance between bunches, where the β functions are much larger and the beam-beam limit would be exceeded. It is therefore necessary to separate the beams at these "parasitic" crossings, and this can be more easily accomplished in the beauty factories, where the two beams have different energies, so that a couple of bending magnets around the IP can give the two beams different deflections. These magnets must, however, be located very near the IP, at a distance smaller than half the distance between bunches, and they become a dangerous source of synchrotron radiation backgrounds.

Parasitic crossings contribute to beam-beam interaction: the additional incoherent tune shifts are given by

$$\xi_x = -\frac{r_o N \beta_x}{2\pi\gamma d^2} \qquad \xi_y = \frac{r_o N \beta_y}{2\pi\gamma d^2} \tag{7}$$

where d is the distance between the centers of mass of the two bunches at the parasitic crossing point, and they must be kept much smaller than the tune shifts from the IP crossing. Beam-beam simulations including parasitic crossings [8] should be performed to assess the minimum required separation.

Electrostatic separation or crossing at an angle must be provided in the case of equal energy beams (Φ and τ/charm factories). The first solution is rather difficult from the technical point of view, because the required deflection is large, and therefore, due to the limitations on the maximum attainable voltage, the plates must be long; the spacing between bunches must be increased and the contribution of the plates to the broadband longitudinal impedance is strong.

Crossing at an angle is, in principle, prone to synchrotron-betatron coupling which may strongly reduce the luminosity [12]. This drawback can be overcome by the Crab-crossing scheme [13], where the trajectories cross at an angle, but the bunches are tilted by transverse R.F. fields by the same angle so that they "see" each other head-on. However, it has been shown that harmful effects of the crossing angle θ can be neglected, if the following condition is satisfied (σ_l is the longitudinal r.m.s. bunch length)

$$\theta_{x,y}\,\sigma_l < \sigma_{x,y} \qquad (8)$$

and this may be a good approach for flat beams crossing at an angle in the horizontal plane, the tolerable angle being in the order of 10^{-2} rads [6]. On the other hand, condition (8) is also a strict tolerance on the maximum angle between the two beams in the vertical plane, due to their tiny vertical size.

High collision frequency can be obtained also with small, superconducting, single storage rings with one or two bunches. The proposals based on this concepts are however limited to the Φ-factories, because of the small energy of the ring: in this case collision frequencies around 20 MHz can be realized [14,15] . To compensate for the smaller collision rate, these proposals are based on very small betatron functions at the IP, with a large number of particles per bunch. The major drawbacks of this approach are the very short beam-beam decay rate (proportional to the luminosity divided by the total number of particles in the ring), the small space available for the experimental setup and the complexity of chromatic correction.

2.4. *Beam emittance*

Formula (6) shows that large emittance is beneficial to luminosity in the case of tune shift limited colliders: this is the case for the Φ-factories, where wigglers are proposed both to increase the emittance and to contribute additional damping, since beam-beam interaction observations suggest that the tune shift limit increases with the amount of radiated power [16]. The price to pay comes however from the increase in stored current, with strong implications on beam stability and vacuum requirements.

A large emittance lattice is less favourable in the high energy region (B-factories), where the radiation problem is much more troubling and the ratio of luminosity to stored particles per bunch is better by an order of magnitude.

Small emittance is also required in τ/charm factory projects where "beam monochromatization" is proposed [7] to enhance hadron production at the resonance. In this scheme the idea is to have very small betatron contribution to the beam size at the interaction point together with a strong energy/position correlation, in such a way that the sum of the energies of the interacting particles is much less spread out than the particle energies themselves. This approach leads to a peculiar set of machine parameters, as it can be observed in Table 1.

Small beam emittance is also foreseen in linac-linac [4] and electron linac against positron storage ring, where the electron beam is lost after interaction and the positron beam is brought near the maximum tune shift calculated for conventional two rings structures [5].

2.5. *Coupling*

A factor two in luminosity could be gained, as shown in (6), by working with the stored beams in full coupling. The question if the maximum tune shift can be influenced by the shape of the interacting beams is still open, since some numerical simulations predict that round beams can help in reaching larger tune shifts. No experimental evidence is however available to support this prediction.

Full coupling requires the two β functions at the IP to be of the same in order to obtain the maximum luminosity: this is an additional difficulty to the design of the low-β section, strong focusing in both planes being required. As a consequence, the chromaticity is increased and the chromatic correction more complicated. A solution to this problem is suggested by the Novosibirsk Φ-factory proposal [14], where round beams are foreseen and a solenoidal field around the IP is used both to focus the beams and as energy analyzer for the experimental setup.

3. INTERACTION REGION GEOMETRY AND BACKGROUNDS

A crucial point in the design of the factories is the interaction region geometry and its protection from machine backgrounds, such as synchrotron radiation photons or lost particles from beam-gas or intrabeam scattering. A fundamental requirement to the layout of the machine around the crossing point is the availability of free space for the experimental setup, which should subtend a solid angle as close as possible to 4π to avoid loosing substantial sensitivity in the observation of CP-violating processes. Low-β focusing at the IP is realized with quadrupole triplets and these quadrupoles limit the solid angle available for the detector. Compact structures, realized with permanent magnets, are a common feature to many projects, because they are able to provide the best compromise between internal aperture and external dimensions. In the case of beam crossing at an angle, the maximum angular separation is constrained by condition (8), and the two beams are not far enough at the end of the drift space around the IP to allow the realization of independent focusing triplets. The two beams travel therefore together in a common vacuum chamber and off-axis in the focusing triplets. The lattice is designed in such a way as to improve the separation and help the final splitting of the two rings [6]. For the asymmetric schemes, the design of the IP lattice is more complicate, since the first quadrupoles are common to both beams, and they are more efficient on the low energy one: the high energy beam must therefore be focused mainly by upstream quadrupoles where the two rings are completely independent.

Longitudinal magnetic field in the detector is also required, so that complicate correction schemes must be designed, especially in the case of the low-energy Φ-factories when small coupling is foreseen. Longitudinal field compensators and tilted quadrupoles are necessary to ensure the correct shape and position for the beams at the IP.

Protection against backgrounds in the detector vacuum chamber is one of the main items in B-factory designs. Strict tolerances are set on the number of background particles hitting the detector [8], both for dead-time and radiation damage reasons. Typical limits are in the order of 0.1 particles/cm$^2\mu$s. To achieve this goal, despite the large number of circulating particles, the interaction region must be protected by masking targets that are the result of thorough investigation and tracing from any possible source of direct or reflected photons and lost particles. The design of the masking system is strongly advantaged in the case of small emittance beams, and this is the main reason for the usual choice, in the majority of B-factory projects in the direction of a large number of bunches with relatively small emittance and number of particles per bunch.

4. CONCLUSIONS

As a consequence of the strong interest demonstrated by the high energy physics community towards the above described research field, several proposals have been forwarded by many laboratories in the world: particular emphasis is put on beauty-factories, also because they can be realized as upgrades of operating machines. Linac on Linac [4], Linac on ring [5,17,18] and double storage rings [8,19,20,21,22,23] have been studied and proposed.

Two projects based on the double ring scheme are being studied in the τ/charm energy range [7,24,27], and five in the Φ region, two of them proposed as compact single rings [14,15]. The other three are double ring systems [6,25,26]: one of them, the Frascati Φ-factory DAΦNE [6], has been funded and is under construction.

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