Electron-Positron Particle Factories

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Abstract

Around the world studies for new e^+e^- collider projects spanning the center of mass energy range 1-11 GeV are being enthusiastically pursued. Thirteen "factory" projects in seven countries have been mentioned. Common among them is the goal of achieving 50-100 times the luminosity currently achieved at their respective CM energies. This goal presents severe technical challenges in terms of beam stability, synchrotron radiation power density and power and accelerator produced backgrounds in the detectors. The common features and special aspects pertaining to the low, medium and high energy parts of the range are pointed out and discussed.

Introduction

Two great scientific and technological successes are now playing strongly together to inspire proposals for next logical steps in particle physics: the Standard Model and e^+e^- colliding beam technology. The inclusiveness and robustness of the Standard Model on the one hand and its limitations and incompleteness as a fundamental theory on the other hand cry out for precision tests, particularly precision measurements of rare modes. Advances in e^+e^- collider technology, such as achievement of the long sought goal of $10^{32}cm^{-2}sec^{-1}$ luminosity give hope that our knowledge base is now substantial enough to support the two orders of magnitude luminosity increases needed to carry out these measurements. Such high luminosity colliders have come to be known as particle factories. Factories at the energy of the Phi, J/psi and Upsilon resonance neighborhoods are being discussed. The luminosity needed at the 1.5, 4 and 11 GeV(CM) depend in detail on the physics to be studied at each energy. One will not be surprised to learn, however, that significant improvement in precision, as well as access to decays too rare now to be studied, requires 50 to 100 times more luminosity than now available and that the needed luminosity scales with the elementary cross-section. This can be seen by examining Fig.1 which shows the energy dependence of the e^+e^- cross-section and Fig. 2 which shows the luminosity of existing and planned machines over the relevant energy range. The knowledge base gained by experience with these existing machines makes it appear just possible to achieve the luminosities now desired although further studies and R/D will be required to support this appearance.

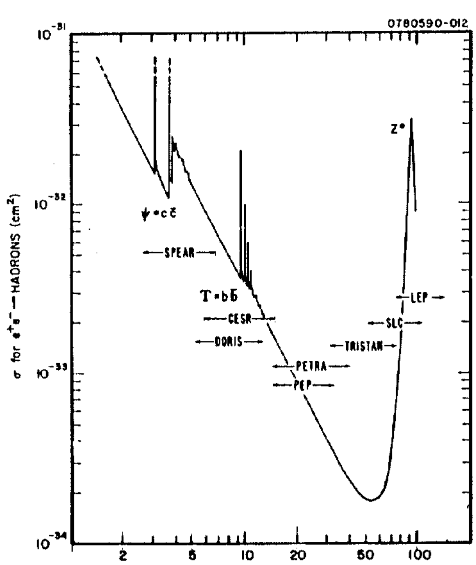

Fig. 1.

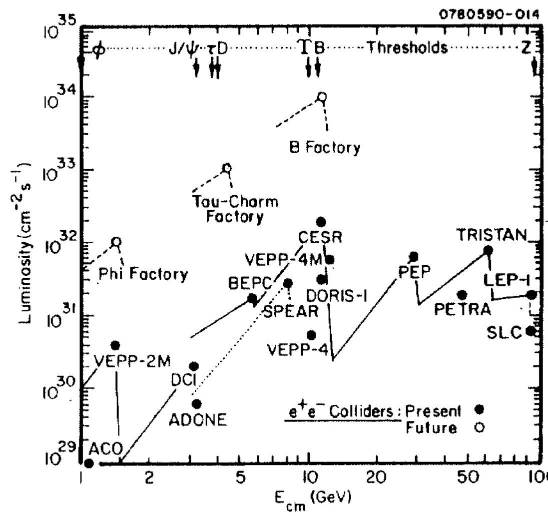

Fig. 2 The luminosity of present and future colliders.

Common Technical Challenges

A sense of the challenges to be encountered can be gained by study of Table 1 which displays abbreviated example parameter lists typical of the machines being studied. Both storage ring and storage ring-linac combinations have been considered in searching for satisfactory concepts to meet the luminosity needs defined above. In this section we will emphasize the storage ring concepts, generalizing somewhat in a later section to encompass the ring on linac designs.

Table I

Example Parameter Lists for "Factories" of Three Energies

Beam Energy(GeV)	0.51[ϕ]	2.2[τ/c]	5.3[B]	5.3[Today]
Luminosity($10^{32}cm^{-2}s^{-1}$)	1	10	100	1
Circumference(m)	12.9	329.9	768	768
σ_V^*, σ_H^*(micron)	90,900	14,284	3.9,255	4.9,400
σ_L(cm)	2.7	0.6	1.0	1.7
β_V^*, β_H^*(cm)	5,50	1,20	1,65	1.5,100
ξ	0.05	0.04	0.03	0.02
n_e($10^{10}e$/bunch)	22	16.3	7.3	18
n_b(bunches)	1	21	640	7
N($10^{11}e$/beam)	2.2	34.2	467	12.6
I(Amp/beam)	0.8	0.5	2.9	0.08
$< Z/n >$(ohm)	2.0	0.32	0.65	1.0
ΔE/turn(keV)	14.1	173	1040	1040
Vcav(MV)	0.1	32	10.6	7.8
α(momentum compaction)	0.12	0.04	.009	0.015
λ_{rf}(cm)	86	86	60	60
Q_V, Q_H, Q_S	3.1,1.8,0.007	7.8,8.9,0.19	9.7,10.7,0.05	9.4,8.4,0.06
θ(mr-crossing angle)	0	0	±10	0
τ_E, τ_V, τ_H(ms)	2.2,3.1,1.9	14,28,28	13,26,26	13,26,26
SR pwr. density(kW/m)	4.2	1.1	7.2	0.2
E_H(10^{-7}m-emittance)	18.0	4.2	1.1	1.6

Three parameter lists can hardly do justice to thirteen different concepts each with their different, ingenious approaches to the technical problems but some general features can be made evident. At each energy the designers are attempting to raise luminosity by increasing currents and current densities to the maximum possible extent permitted by the restraints imposed by the detector and by accelerator physics and technology particular to that energy range. This statement can be made more precise by reference to the basic luminosity relation.

$$L = \frac{N_1 N_2 f_c}{A} \qquad (1)$$

with $N_{1,2}$ being the numbers of particles in the colliding bunches, f_c the rate of which they collide and A the cross-sectional area of the counter circulating beams, assumed equal, at the collision point. Accelerator physics and technology puts limits on these variables (Table II) as well as variables only implicit in this formula.

Table II

Variable	Limit
$N_{1,2} < \hat{N}$	single bunch instability $[< \frac{Z}{n} >]$
$f_c < \hat{f}$	parasitic collision avoidance, detector dimension
$\check{A} < A > \hat{A}$	lens technology, dynamic aperture, background
$N \cdot f_c < \hat{I}$	multibunch instabilities $[< \frac{Z}{n} >$,Q], power density
$N/A < (\frac{\hat{N}}{A})$	beam-beam nonlinear focussing

Other important variables can be exposed by writing the tune spread, introduced into the beam by the effects of beam-beam focussing during the collisions.

$$\Delta Q_j = \frac{r_c}{2\pi}\frac{N\beta_j^*}{\gamma\sigma_j(\sigma_V + \sigma_H)}, \quad \beta^* << \sigma_L \qquad (2)$$

Long experience shows that for confinement and collision configurations tried to date, the achievable ΔQ_j will be in the range 0.02 to 0.06. Formulas (1) and (2) can be combined to give

$$L = 2.17 \times 10^{34} \frac{\Delta Q_V}{\beta^*[cm]}(1 + \frac{\sigma_V}{\sigma_H})E_{bm}[GeV] \cdot I_{bm}[A][cm^{-2}s^{-1}] \quad (3)$$

Here we have explicitly introduced the strength of the focusing at the collision point, β^* and the energy of the beam E_{bm}. E and L are fixed by physics goals. Fortunately the "natural" luminosity as limited by the beam-beam effect is proportional to E, partially compensating for the decrease of the elementary cross-section with E^2.

Evidently there is a premium on achieving the tightest possible focussing or lowest β^*. There are limits to β^* from both technology and physics. Lens strengths are limited by achieveable magnetic fields, a matter of materials, and allowed sizes, a matter of detector configurations because small β^* corresponds to placement of the IP lenses within the detector. In addition, small β^* corresponds to relatively large chromaticity which must be compensated by strong sextupoles which in turn limit the dynamic aperture of the confinement system if storage rings are used. There are further limits, partially implied above. When $\sigma_L \sim \beta^*$ the beam size varies significantly over the collision volume which increases the tune spread for particles residing in the longitudinal extrema of the bunch.[1] For example, a particle at $5.3\sigma_L$ in a configuration with $\beta^*/\sigma_L = 1$ will have a 2.8 times more severe ΔQ than a particle at beam center. If $\beta^*/\sigma_L = 0.5$ the factor will be doubled. Most, but not all, currently operating e^+e^- colliders have $\beta^*/\sigma_L \sim 2-7$. Several of the projects now near proposal have $\beta^*/\sigma_L \sim 1$. Evidence from machines now operating with $\beta^*/\sigma_L \sim 1$, while difficult of interpretation[2], show that this circumstance must be better understood before expected $< \Delta Q >$ can be assessed. There is of course the geometrical consequence of luminosity reduction[1] for $\beta^*/\sigma_L \lesssim 1$ which must also be taken into account.

A possibility mentioned frequently for enhancing the combination $\frac{\Delta Q}{\beta^*}(1 + \frac{\sigma_V}{\sigma_H})$ is to employ round beams rather than the more common flat beams. Simulations indicate the possibility for some help there.[3]

Two other limits to σ_L must also be considered. Not only is the beam area density constrained by the beam-beam limit but the volume density is constrained by intrabeam scattering in a single bunch in which particles are scattered out of the rf bucket and lost, the Touschek effect[4].

$$\frac{1}{\tau_T} \propto \frac{N}{\sigma_H\sigma_V\sigma_L} \cdot \frac{1}{\gamma^2} \qquad (4)$$

The linear charge density is also limited by the longitudinal single bunch instability through

$$\frac{N}{\sigma_L} \leq \sqrt{\frac{\pi}{2}}\frac{\alpha}{r_c}\gamma\frac{< \frac{\Delta E}{E} >^2}{< \frac{Z_L}{n} >} \cdot 377 \qquad (5)$$

where α is the momentum compaction factor. For bunch lengths less than 1cm the possibilities for $< Z_L/n >$ enhancement by coherent synchrotron radiation need to be examined.[5]

Another potentially limiting effect is that of ion trapping in the potential well of the electron beam. This can lead to enhanced residual gas density at the beam core and thus enhanced loss due to scattering and bremsstrahlung as well as to ion-beam instabilities. These effects will tend to limit the allowable bunch separation in a single beam and thus the average current. Some experience in dealing with such instabilities has been gained and some methods for its avoidance explored[6]. However, more studies will be needed before storage rings with small bunch separations can be designed with complete confidence.

Particular Technical Challenges

Configurations

In attempting to enhance f_c and I_{bm} while avoiding parasitic beam collisions and excessive accelerator produced backgrounds, designers have found that both detailed local IR geometry and overall layout are of importance. In Fig. 3 below are shown examples of the configurations being considered, the details of which will depend on the energy and detector configurations.

Linac on ring configurations have been considered at both ends of the range of energies. The use of a linac from which the beam need not be saved may offer advantages through the decoupling of beam parameters and consequent design freedom. In those situations where ion effects may limit electron beam performance of a storage ring, they can be eliminated by using the linac as e^- accelerator against an e^+ storage ring. A severe constraint on such schemes is linac beam power leading to de-

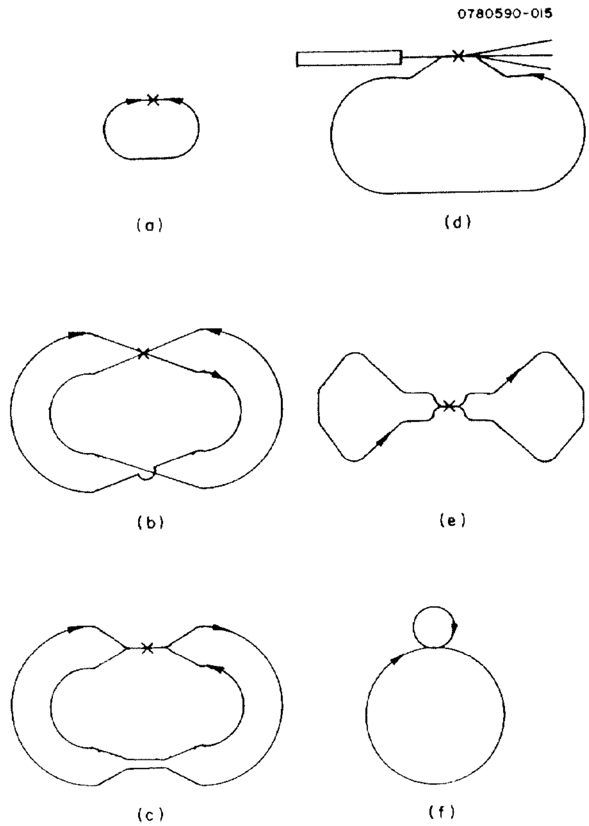

Fig. 3

(a)very small ring, high f_o, (b) independent rings with angle crossing, (c) independent rings with head-on crossing, (d) linac on ring, (e) figure of eight, (f) large ring small ring.

signs in which the linac beam is violently disrupted at the IP. Because the practical consequences for such designs for achievable luminosity and background to luminosity ratio are untested by experience, it seems unlikely that a new factory facility based on this idea will be risked. It should be noted, however that two of the phi factories now under consideration have full energy injection linacs and it has been proposed to use them, at a subsequent stage, to test the linac on ring configurations as it can be done at little additional cost. Further development of the linac on ring idea is likely to await such explorations.

Phi Factories

At the low end of the energy scale we have the Phi-factories with luminosity goals of 10^{32} or more. Both small radius single bunch single ring, multi-bunch dual ring, figure of 8 and linac on ring configurations are being studied. Constraints peculiar to this low end of the energy range are, depending in detail upon the configurations, β^* limited by chromaticity, σ_L limited by single bunch longitudinal instability and the Touschek effect which is the major lifetime limit. As maximization of beam-beam tune spread is believed to require zero dispersion at the IP, chromaticity arising from final focus lenses must be corrected remotely. As the final focus system occupies a relatively large portion of the circumference that means that the needed sextupole corrections will be relatively lumpy, thus limiting dynamic aperture. Suggestions for ameliorating this effect have recently been made.[7] In smaller rings the injection, rf and IP equipment also occupy a relatively large part of the circumference making the achievement of low $< \frac{Z_L}{n} >$ very difficult.

Tau-Charm Factories

At four times the beam energy of the Phi factories the Touschek effect is easily avoided and as IR to circumference ratio is more favorable one may hope to use strong quadrupoles to their fullest while maintaining suffiecient dynamic aperture. To capitalize on the small ($\sim 1cm)\beta*$ achievable a very short bunch length is required in the face of a relatively large momentum compaction factor. This requires a high rf voltage which will make difficult the needed impedance control for such short bunch maintenance. The relatively large bunch spacings required in head-on collision versions leads to large emittances for which the synchrotron radiation background consequences need careful assessment. Angle crossing could alleviate this circumstance if needed.

B-Factories

Having the highest luminosity requirements, these factories have the highest currents required and thus average current related problems will tend to dominate. Since emittances (beam sizes) are strictly limited by need to control synchrotron radiation background at the IP the only recourse in achieving the needed average current is to use many closely spaced bunches. This close spacing has several consequences. First, head on collisions without close parasitic crossings become virtually impossible in most configurations. Second, multi-bunch instabilities even up to higher order bunch shape changing modes will be dangerous requiring close attention to minimuzing rf system impedances and to design of efficient feedback systems in both longitudinal and transverse directions. Third, in schemes employing an e^- storage ring, ion collection and consequent instability will need special design considerations.

An additional complication has also been introduced in that part of the B physics could benefit by a moving CM in the lab frame. Proposals to achieve this with independent storage rings or linac on ring have considered energy asymmetries in the range 7×4 to 12×2.5. As the asymmetry affects the detection as well as the accelerator design, optimization of this variable is particularly difficult. Currently those emphasizing CP violation physics seem to favor 8×3.5 while those focussing on B_s mixing favor higher asymmetries.

In tau-charm factories $1cm$ β^* could be achieved by involving superconducting quadrupoles alone. At the 2 times higher beam energies needed for B production one will need to add advanced permanent magnet quadrupoles very close to the IP to achieve the needed β^*. Dynamic aperture considerations will be important here too.

A particularly intractable part of B-factory design has been the control of accelerator produced backgrounds at the detector both due to SR and to lost particles. These effects are so strong that even though primary hits of particles and SR can be avoided, secondary and tertiary processes can provide enough flux in the detector to confuse real events and even cause radiation damage. While this is an extremely detailed subject as yet not widely mastered and well supported with neasurements, a few general observations can be made.

With regard to SR it turns out that schemes with bending magnets very close to the IP as in magnetic separation schemes for asymmetric beam energies including quads offset with respect to the incoming beam axis, are exceedingly difficult. Additionaly, there is a maximum beam emittance above which even IR quadrupoles centered on the incoming beams produce excessive x-ray flux in the detector inner chambers. A better configuration, from the background point of view is one in which the beams cross at a small angle, the common quadrupoles closest to the IP being centered on the incoming beams. Success with such a scheme hinges on the , as yet untried, success of the Palmer-Oide crab crossing scheme. In any event it will be necessary to arrange the geometry such that radiation fans from the opposing beams be deflected to opposite sides to avoid backscattering into the detector from the closest in SR masks as in Fig. 4.

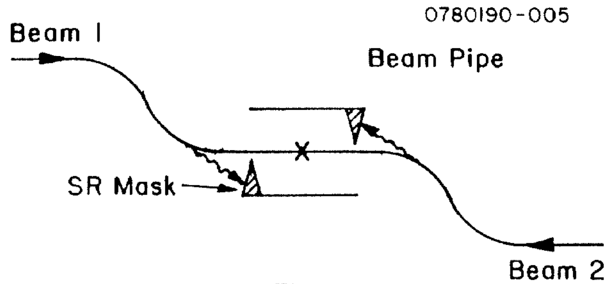

Fig. 4.

With regard to lost particles it is important to arrange the IR optics to focus particles with significant energy deviations, i.e. $\Delta p/p \sim 1\%$ through the detector pipe. In general and unfortunately, it appeats that with the best designs, residual gas pressures of better than 10^{-9} torr will need to be maintained throughout the IR and somewhat upstream to lessen large angle coulomb scattering and bremsstrahlung in these critical areas.

R/D Needs

As each one of the factory projects will push beyond present technical cability, some R/D to provide a foundation for that push will be necessary. This R/D encompasses computer simulation studies, beam experiments with existing colliders and laboratory development work. Common threads run through R/D needed for factories at all three energies discussed: A few are listed below

- the behavior of the beam-beam effect at $\beta^* \sim \sigma_L$ must be better understood through simulation and measurements.
- quick, reliable algorithms for computing particle and SR background must be developed and tested at existing machines to give confidence in their use as a design tool.
- sharp reductions in ring impedances must be effected by improved designs for cavities and other vacuum system components.
- ways must be found to reduce vacuum chamber pressures in the face of significantly increased wall power fluxes.
- potential of crab crossing and necessary tolerances must be understood

Conclusion

The physics motivation for obtaining 50-100 fold luminosity increases in the phi to B mass range is high. e^+e^- collider experience over the past few years has taught us much that will be useful in this next step. Even though no obvious reason why these goals are impossible or impractical has emerged, much hard work remains to be done and new problems and new ideas come up almost daily. Given the manifest enthusiasm of the proponents and the great knowledge base and skills that have been acquired in the past decade one has reason for optimism that the most well conceived of these projects now before us will successfully go forward.

Studies and Projects Underway

Type of Factory	Country/Institution (Collaborators)	Special Features
Phi	Italy/Frascati	Dual rings, possibility for SC linac on ring
	USSR/Novisibirsk	Figure 8 Polarization
	USA/UCLA	One ring possibility for N.C. linac on ring
Tau-Charm	Spain/Seville(CERN, Orsay, SLAC)	dual ring
	USSR/ITEP, Dubna(Novisibirsk)	
B(asymmetric)	Germany/DESY	large ring, small ring
	Japan/KEK	dual rings
	Switzerland/CERN.PSI	dual rings
	Switzerland/CERN	s.c. linac on ring
	USA/CEBAF	s.c. linac on ring
	USA/Cornell	dual rings, s.c. rf
	USA/SLAC	dual rings
	USSR/Novosibirsk	dual rings narrow $\Delta E/E$

References

1. S. Milton, The Hour Glass Effect, CBN 89-1, Cornell Univ. 1989.
2. D. Rice, Luminosity Performance for CESR with small β^*, International Conference on High Energy Accelerators, Tsukuba 1989.
3. S. Krishnagopal and R. Siemann, A Comparison of Flat Beams with Round, CBN 90-2, Cornell, 1990.
4. H. Bruck, Accelerateurs Circulaires de Particules, Presses Universitaires de France 1966.
5. J. Bisognano, Impedance and Wakefields Beyond Cutoff, Proc. of 1988 Linear Accelerator Conference, CEBAF Report 89-001, June 1989.
6. J. Marriner et. al., Experiments and Practice in Beam Shaking, Particle Accelerators v.30, pp. 13-20, Gordon and Breach, 1990.
7. M. Cornacchia and K. Halbach, Study of Modified Sectupoles for Dynamic Aperture Improvement in Synchrotron Radiation Sources, SLAC Pub.-5096, Oct. 1989.