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e+e- FACTORIES - THE NEXT GENERATION

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Abstract

Through most of the history of electron-positron colliding beam storage rings, actual performance has lagged significantly behind design performance figures. Rarely have design parameters been met or exceeded, usually only after significant modifications of the machines. With the latest generation of electron positron factories we are beginning to see design parameters achieved in the original configuration of the machine. This change reflects the tremendous knowledge accumulated over years of studies and experience with these machines. The next generation of lepton factories will reach a luminosity beyond 10^{35} cm^{-2}-sec^{-1}. The designs must take into account effects that are just at their thresholds in present machines. New techniques to reach high space charge density at the interaction point and large collision currents will play critical roles in these colliders. The experience over the past few years gives good confidence that, carefully planned, these machines will achieve design luminosity.

1 INTRODUCTION

Although the concept of using colliding beam machines for high energy physics research was considered as early as 1943 [1] by Rolf Wideroe, the luminosity was thought to be inadequate. After the alternate gradient focussing principle was elucidated Kerst suggested [2] in 1956 that this situation had changed.

> "The possibility of producing interactions in stationary coordinates by directing beams against each other has often been considered, but the intensities of beams so far available have made the idea impractical. Fixed-field alternating-gradient accelerators offer the possibility of obtaining sufficiently intense beams so that it may now be reasonable to reconsider directing two beams of approximately equal energy at each other. In this circumstance, two 21.6 BeV accelerators are equivalent to one machine of 1000 BeV."

A few years later AdA in Frascati and the Princeton-Stanford ring at Stanford University stored their first beams, followed shortly by VEP-1 in Novosibirsk. The first e+e- collisions were observed in AdA, then at Orsay. [3] Others quickly followed. Each of these machines encountered and (usually) overcame some of the limiting effects which are now standard material for every student of accelerator physics.

Although many problems were solved, the achievement of predicted luminosities was elusive. Each machine seemed to have its particular features which prevented reaching performance levels more common today. As these effects, many of them component engineering matters, were understood, and beam diagnostic instrumentation coupled with computational power improved, performance began to approach predicted levels.

Today we have two newly constructed machines that started up and reached, or nearly reached, first stage design luminosity within a year and a half. As these and other machines push into their next stage of performance, they will encounter new problems as they enter a regime of higher beam currents and bolder interaction region configurations. The answers to these challenges will in turn pave the road for the next generation of e+e- colliders.

Before leaping ahead to the future, let us look in more detail the development of e+e- colliders to date.

2 THE PATH TO E+E- FACTORIES

2.1 First Steps: AdA, Princeton-Stanford, VEP-1

The first stored electron beam was accomplished in AdA, then at Frascati, in May, 1961. [4] Because of slow injection, however, accumulation of useful currents had to wait until the machine was moved to Orsay where a high intensity linac was available.

Meanwhile a few high energy physicists were building an dual ring e-e- machine at Stanford. The Princeton-Stanford machine stored its first beam in March, 1962. [5] While the only physics from this machine was a test of QED by e+e- pair production, a plethora of machine physics phenomena were revealed.

The desorption of large amounts of gas from synchrotron radiation striking the wall was among the first observations. This photodesorption effect is well known and a chamber wall conditioning plan is now built into the commissioning of every electron storage ring.

The "long range wake instability," now called resistive wall instability, was observed and cured with octupole magnets. The coherent beam-beam instability was seen and cured by separating the tunes of the two machines. The beam-beam performance was seen to degrade when the beam-beam tune shift reached around 0.025. This was, coincidentally, about the limit the designers quoted. They assumed the limit would be when the tune was shifted to the half-integer, and put in a factor of 10 for conservatism!

The field of accelerator engineering wasted no time establishing itself with the need to build 24 m of ultra-high vacuum chamber and injection kickers with a flat-topped 80 ns wide pulse.

One of the interesting ironic "non-discoveries" was the head-tail instability. The designers felt it would be a good idea, on general principles, to correct the chromaticity to zero, thus leaving the discovery of the head-tail instability to the Adone machine physicists. The first physics results from the Princeton-Stanford machine were presented in 1963.

Once AdA was moved to Orsay where a "high intensity" injector was available, electron-positron collisions were observed via single photon production in early 1964 with 10^7 particles stored in each beam.

As the beam intensity increased in AdA the accelerator physicists noticed a decrease in beam lifetime which was exacerbated as the stored beam density was increased. This phenomenon was explained by Bruno Touschek, as being caused by intra-beam scattering combined with the relativistic boost given to motion in the longitudinal direction.

Accelerator physics measurements at VEP-1 include strength and width of linear and non-linear resonances, and beam-beam effects on losses on resonances and vertical emittance blow up [6,7]. Elastic scattering and double-brehmstrahlung experiments were performed at the VEP-1 collider in Novosibirsk in 1965-67 [8].

2.2 Higher intensities, Collective Effects

High Energy Physics with e+e- colliders started in earnest with the storage rings VEPP-2 in Novosibirsk, ACO in Orsay, and ADONE in Frascati. These rings also reached beam intensities where collective effects are serious impediments to performance.

Almost immediately after turn on the beam intensity at ADONE was limited by a transverse instability, soon explained and named the head-tail instability by Pellegrini and Sands.

VEPP-2 quickly encountered a coherent longitudinal instability cured by proper tuning of the RF cavities. ("Robinson" instability). Observations of instabilities from parasitic modes in ion pumps circuits were also reported and were cured by bypassing the plates to a terminating resistor. [9]

The 0.51 GeV ACO storage ring at Orsay incorporated the first detector using a solenoidal magnetic field. Both anti-solenoid and skew-quad compensation were tested. Some luminosity degradation as solenoid field increased could not be avoided, but solenoid compensation worked much better than skew quad compensation. [10] However, only two pairs of skew quads were used, which do not provide full compensation at the interaction point.

An unexplained bunch lengthening accompanied by an increase in the energy spread was reported in both ACO and ADONE [11]. This was later explained as the microwave instability caused by mixing of the coherent longitudinal modes.

2.3 The Bridge to 10^{33}

The next machines to be built, SPEAR, DORIS, CEA Bypass, and D.C.I. formed the transition to today's e+e- factories. Charge densities increased as bunches were shortened for compatibility with low beta insertions and wake field effects became critical to reaching design performance. The criteria for vacuum chambers were refined to reduce the size of steps and gaps to millimeter levels. During this period the CEA Bypass overcame a complex injection process to achieve colliding beams, and in the process introduced the low beta insert to the storage ring community. A bold attempt to compensate the beam-beam space charge was made at Orsay with the DCI dual ring machine.

The original design luminosity for SPEAR [12] was 7 x 10^{32} cm^{-2}-sec^{-1} at 2.3 GeV with 250 mA circulating current. Low beta (5 cm) inserts for the interaction regions were designed to reduce the effect of high space charge in the beam-beam interaction.

A plethora of preventative devices was built into SPEAR to combat instabilities observed in the previous generation of colliders. These included: variable dispersion in the arcs to control emittance, β_V^* variable from 5 to 50 cm, sextupoles for chromaticity correction, octupoles to provide Landau damping, electrostatic quadrupoles to split the tunes of the electron and positron beams, and a fast transverse feedback system.

Collective effects were seen immediately in SPEAR, and after installation of higher frequency RF to shorten the bunch length, SPEAR became the test bed for longitudinal single bunch effects – both inductive and turbulent bunch lengthening.

DORIS began life with 2 rings vertically stacked and the beams of 480 bunches each crossing one another with a 24 mrad vertical crossing angle.[13,14] The beams were more round than flat with comparatively large values for the interaction point amplitude functions (β^*). While many of the now common collective phenomena (coupled bunch instabilities from RF cavity modes, turbulent bunch lengthening, ion trapping) were observed in DORIS, luminosity was ultimately limited by the unfavorable crossing angle geometry and the need to spread the synchrotron frequencies between bunches with a sub-harmonic cavity to avoid coupled bunch instabilities. The spread in tunes made it impossible to avoid the additional resonances engendered by the crossing angle. Investigations on DORIS of the effects of the crossing angle, as well as strength of satellite resonances, have provided valuable additions to the storage ring knowledge base.

DORIS II used a single ring with reduced magnet gaps to extend the energy to 5.3 GeV to reach the Y resonances of the newly discovered b quark. Operating with a single bunch, DORIS II reached a luminosity of 3 x 10^{31} cm^{-2}-sec^{-1} at 5.2 GeV [15], fueling the production of many publications on B physics by the ARGUS and Crystal Ball collaborations.

The conversion of the Cambridge electron synchrotron to a storage ring required many innovative solutions [16] to the problems imposed by tight funding. SPEAR and subsequent machines quickly emulated the low-beta insertion first developed at the CEA. Damping quadrupole magnets were needed to correct the damping partition numbers in the combined function ring. A low impedance RF cavity reduced beam-cavity interactions.

Although the filling time was short (roughly 10 minutes) the low currents limited luminosity to around 3 x 10^{28} cm^{-2}-sec^{-1} at 2.5 GeV beam energy, limiting physics results to a measurement of R in this energy range [5].

The incoherent beam-beam effect was found to be a primary limitation to collider performance. Elimination of the space charge effects could lead to higher luminosity. This was the objective of the two-ring machine D.C.I. at LAL in Orsay. The two rings each had circulating electron and positron bunches, but moving in opposite directions so that when the 4 beams came together at the interaction point, the net average space charge was zero. In practice, however, beam densities were limited to values similar to the uncompensated condition. Computer simulations [17] later suggested that the loss of tune spread from the beam-beam interaction reduced Landau damping of the coherent beam-beam instabilities, lowering their threshold charge densities.

2.4 The Desert

The natural next step was to increase the energy of the machines to look for evidence of higher mass particles. Accordingly, PEP [18], PETRA [19], and TRISTAN [20] were conceived with target energies per beam of 15, 23, and 20 (later 30) GeV.

These machines were essentially scaled up versions of the previous generation of colliders. The increasing critical energy of synchrotron radiation called for careful shielding of accelerator components, and those machines that had lower energy injectors would struggle with complicated energy ramps through long strings of RF cavities with their parasitic modes.

However, Nature did not smile on these machines, and they made no discoveries comparable to the J/Ψ or Y. Although where was some hope of finding the 6^{th} quark after the discovery of the Y meson in 1977, this was to be reserved for the much higher energy reach of the p-pbar colliders.

As with all other colliders, though, these machines made their contributions to the accelerator physics field.

PEP hosted the development of several feedback and beam diagnostic systems [21] as well as beam-beam measurements with various optics and numbers of collision points [22,23]

PETRA injected at 7 GeV and ramped a beam by a factor of 3 in energy through many RF cavities. Control of dispersion in these cavities proved to be crucial in determining the current limit, prompting detailed investigations of beam stability and interaction with parasitic impedances.

TRISTAN was the first storage ring to install and operate with a substantial number of superconducting RF cavities [24]. Use of SC RF lead to an increase in beam energy to over 30 GeV.

2.5 And a collection of others

During this period several other storage rings were constructed – VEPP-4 [25] in Novosibirsk, CESR [26] at Cornell University, and BEPC in Beijing. The first two of these facilities were constructed to operate in an energy range a factor of 2-3 above SPEAR, VEPP-2M, ACO and ADONE, but below PEP, PETRA, and TRISTAN. They were favored by Nature with the B meson well within their energy range. BEPC was designed after SPEAR, but with the goal of reaching significantly higher luminosity.

2.6 Across the Desert

The first study of a collider with energy well above existing designs was started in 1976 at CERN.[27] A detailed design was finished in mid-1978 [28] for a 70 GeV/beam machine which could be extended to 100 GeV with superconducting RF cavities. The magnets would be designed to reach 130 GeV. Economic considerations limited the injection energy to 20 GeV, implying a long and sensitive ramp with beam each filling cycle.

In addition to it's production of copious quantities of Z_0's (along with the Stanford Linear Collider in the US). LEP eventually installed the world's largest RF system with 272 4-cell superconducting cavities. As with TRISTAN, LEP used the s.c. cavities to extend its energy range – to over 100 GeV in LEP's case. [29]

The very high energy electrons lost nearly 3 GeV per turn to synchrotron radiation, producing the highest damping decrement (fraction of particle transverse amplitude damped between interaction points) of any machine – over 0.003 – giving a valuable point on the luminosity performance vs. damping decrement plot. [30]

3 FACTORIES AT THE MILLENIUM

3.1 A change of course

Until the mid-1980's the frontier of particle accelerators was defined by center-of-mass energy. As the Standard Model took shape, thanks in part to the discovery of Charmed and B mesons, the physics interest turned toward precision measurements. The increasing cost of maintaining progress on the energy frontier also fueled this trend. The precision, or luminosity frontier rapidly gathered recognition.

The friendly competition between the ARGUS /Crystal Ball and CLEO /CUSB groups at DESY and Cornell, both studying the decays of the B meson, provided additional drive to increase luminosity as quickly as possible. While DORIS II was pushing all systems to their limits to reach the Υ (4S) resonance at a beam energy of 5.3 GeV, CESR enjoyed the good luck to be designed with optimum luminosity at 8 GeV, leaving room in operating parameters for innovative luminosity improvements.

In working through the practical details of putting a second bunch in each ring, the CESR accelerator staff realized it would take very little additional effort to add several bunches. After installation of 4 horizontal electrostatic separators and 6 months of intensive machine studies, routine HEP operation with 3 bunches per beam began in October 1983. After modifications to the RF cavity power windows, operation with 7 bunches per beam began in early 1987. Meanwhile, permanent magnet quadrupoles had been installed in the interaction region to lower β_V^* below 3 cm without excessive chromaticity or aperture requirement. These [31], and other improvements brought CESR to a luminosity of 10^{32} cm^{-2}-sec^{-1} in 1989, a world record at that time.

By 1990 the rush to the luminosity frontier was fully developed. The B Factory session in the 14^{th} International Conference on High Energy Accelerators (1989) included papers referring to 6 potential B factories and one Φ factory. In 1990 the DAΦNE Φ Factory was approved and a detailed design began in 1991 [32].

3.2 The Asymmetric Colliders

The headline physics in the studies of B meson decay is the characterization of CP violation in this system. Analyses indicated that roughly an order of magnitude less luminosity would be needed to characterize CP violation if the collisions took place a frame of reference with a relativistic boost. By the mid 1990's, there were 3 detailed proposals for asymmetric B factories, at KEK, SLAC, and Cornell. After a US review, funding was awarded for the SLAC proposal, and almost simultaneously KEKB [33] was approved.

The asymmetry of beam energy introduced a new collection of challenges beyond those of rings with ampere currents and micron beam dimensions at the interaction point. The interaction region (IR) of the asymmetric colliders became an accelerator physics and engineering exercise not seen before. A few aspects are:

- Low β* optics for two different energy beams
- Separation of the beams to limit parasitic crossing effects
- Kilowatts of synchrotron radiation striking nearby chambers
- Solenoid compensation for the two beams
- Limited space for diagnostics, vacuum pumps, etc.
- Exacting field quality requirements for magnets with strict geometry constraints
- Small vertex chambers which must be protected from multiply scattered photons.

A few of the design machine parameters for PEP-II and KEKB are shown in table 1 below.

	PEP-II		**KEKB**	
Parameter	**LER**	**HER**	**LER**	**HER**
Beam Energy [GeV]	3.1	9.0	3.5	8.0
Circumference	2199.32 m		3016.26 m	
β* (V) [cm]	1.5	2.0	1.0	1.0
β* (H) [cm]	37.5	50	33	33
ε_H (nm-rad)	64	48	18	18
Beam-beam param. (ξ_X,ξ_Y)	0.03, 0.03		0.039, 0.052	
Bunch spacing	4.2 nsec		2.0 nsec	
Crossing angle	0.0 mrad		±11 mrad	
Beam cur. [A]	2.14	0.99	2.6	1.1
Luminosity [cm^{-2}-sec^{-1}]	3 x 10^{33}		1 x 10^{34}	

Table 1 – Comparison of PEP-II and KEKB asymmetric B factories

The interaction regions of PEP-II and KEKB are shown in Figure 1 below. The primary differences are the separation scheme and the beam emittance. The magnetic separation method is feasible in PEP-II because of the larger energy asymmetry, and permits head-on collisions. The crossing angle separation in KEKB reduces synchrotron radiation somewhat (though it can still be quite strong from quadrupoles). The smaller emittance, both horizontal and vertical, in KEKB allows closer spacing of masks and somewhat more flexibility in IR design, but at the expense of smaller charge per bunch.

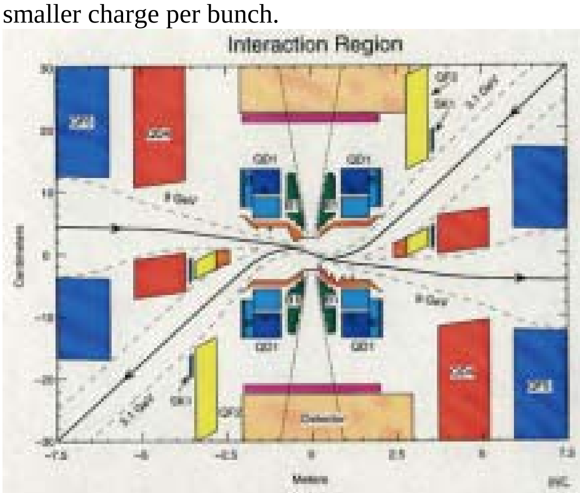

Figure 2 – PEP-II Interaction Region layout

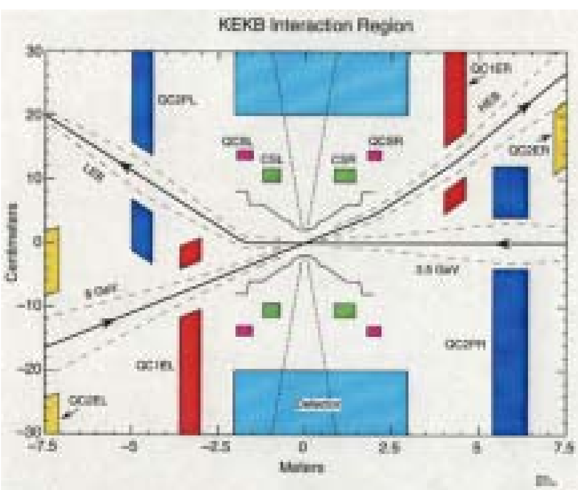

Figure 3 – KEKB Interaction Region layout

3.3 Luminosity Performance

Very few colliders have ever achieved their original design luminosity. Most fall a factor of 2 to 3 short, some more. A look at several aspects of performance will highlight some of the challenges to the realization of high luminosity.

While the incoherent beam-beam effect is often felt to be a rather hard limit, most machines have felt the effects of other limits.

CESR was limited to a (vertical) beam-beam parameter of 0.025 for many years until changing to a single interaction point and eliminating a large horizontal dispersion at the interaction point. A value of 0.04 was then rapidly reached, but substantial additional tuning was required to increase ξ_V further to 0.05-0.06. Reducing β* and adding bunches with separation using the “pretzel” scheme brought further increases in luminosity.

With its large energy range, LEP has been limited by low energy instabilities and also by emittance limits imposed by IR masks required to tame the high energy synchrotron radiation. LEP is outstanding in that it achieved the original design luminosity in something near it’s original configuration.

LEP later set a world record for beam-beam parameter in a flat beam e+e- collider*, recording ξ_V = 0.083 at 98 GeV beam energy[30].

Most machines operating in the 1990’s, save possibly LEP, have had to struggle to achieve adequate compensation of the experiment solenoid. This is an area where better instrumentation and analysis technique will be important. Table 2 below shows the ratio of solenoid field times length to the particle momentum, “Bρ”, for this group of machines.

Detector	**Solenoid rotation**
CESR (CLEO)	0.33
LEP – 46 GeV (Aleph)	0.06
DAΦNE (KLOE)	1.4
PEP-II LEB (BaBar)	0.58
KEKB LEB (Belle)	0.51

Table 2 – Relative strengths of solenoids (BL/p_{beam})

Both PEP-II and KEKB faced similar problems in solenoid compensation. In addition, the “electron cloud instability,” first seen at the KEK Photon Factory, [34] proved to be an important effect on performance.

Both asymmetric B factories were designed with the electrons in the high energy ring so the effects of ion trapping would be reduced. In fact, the electrons trapped by the positrons proved to be a performance limiting phenomenon. The ante-chamber design of PEP-II reduced the severity of the ECI, which made its presence known by a vertical blowup of the beam. Still, solenoid magnets and additional “micro gaps” in the train of bunches had to be used to reach the present level of performance. KEKB has installed solenoids over 1200 m of the ring with another 400 m where solenoid installation is possible with significant effort. The knowledge from these machines will benefit the next generation of factories.

* An impressive beam-beam parameter of 0.5 was reported at this conference by HERA machine physicists colliding e- on protons.

3.4 Beam-beam effects

Equation 1 below is a convenient expression for the luminosity of a storage ring containing the beam-beam effects in ξ, (linear) optics effects in β, and the beam current in I:

$$L = 2.17 \times 10^{32} (1+r) \frac{I E_0 \xi_V}{\beta_V^*} \qquad (1)$$

where the luminosity, *L*, is in the usual c.g.s. units, r is the vertical to horizontal beam size ratio at the interaction point, I current/beam [A], E_0 beam energy [GeV], ξ_V the beam-beam parameter, and β_V* the vertical focusing function at the interaction point [m].

Of the 4 available variables, r is often left small since round beam optics are difficult to implement, though there is some evidence [38] that the accompanying sacrifice in β_V* may pay off.

Each of the three remaining variables may be optimized, often independently, but with some coupling between them when pushed to the extreme.

The beam-beam parameter, ξ_V, is chosen in a design, but the value actually achieved depends on many details of the design and implementation. Figure 4 shows the beam-beam parameters, and linear tune shift parameters, δQ_V, for the e+e- factories in operation last year.

If ξ_V varied proportional to beam energy E_0 in a single machine, as often observed, then it would be proportional to damping decrement $d^{1/3}$. A fit to a modified[1] data set yields a $d^{0.05}$ dependence with much shallower slope, though the exponent could be somewhat larger with a different fit[2].

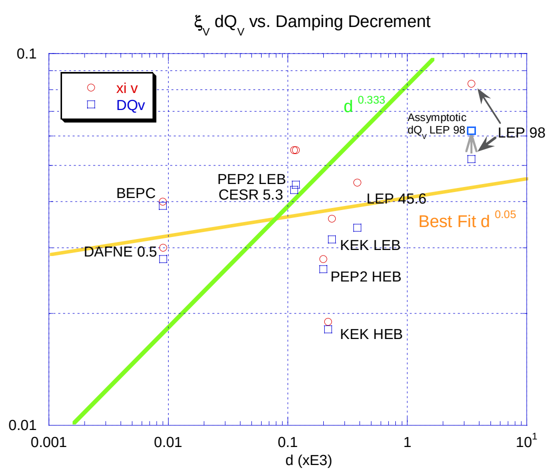

Figure 4: ξ_V and δQ_V vs. damping decrement. Values for the asymptotic value for LEP 98 are shown since they may better represent intrinsic beam-beam performance.

The experience from these machines provides some guidance for future designs. One might argue that designing a machine with ξ_V or δQ_V well above the trend line would require some justification. On the other hand, experience has shown that a wide variety of phenomena can reduce ξ_V below these values.

4 THE NEXT GENERATION

In making the conceptual design for a machine with a luminosity of 10^{35} or higher, we may use equation (1) to set goals for the beam current, focusing, and expected beam-beam performance. While the "free" parameters are conceptually independent, in practice there is interaction, particularly when pushing the parameters to near limits.

4.1 Challenges to parameter optimization

The following is a list of potential limiting effects for these parameters. The symbols in parenthesis indicate limits to or limits by one of the other parameters.

I (beam current): RF power, s.r. absorber dissipation, beam-wall instability, electron cloud instability, intra-beam scattering (ξ_V), bunch lengthening (β_V*).

ξ_V (beam-beam parameter): limited radiation effects (damping, excitation), beam instabilities (I), optics errors, nonlinearities (β_V*), experiment solenoid, low beam aspect ratio (r).

β_V* (vertical focusing function at i.p.): aperture, chromaticity, bunch length (I), magnet strength limits, physical space limits

r (beam aspect ratio at i.p.): magnet limitations (β*), chromaticity, aperture, non-linearities, max gain x2

4.2 Present performance and improvements

One expects that the present generation of colliders has exploited each of these parameters to the extent deemed feasible at the time of design. Therefore to make orders of magnitude improvement one must have new ideas in either or both the areas of accelerator physics and engineering.

Achievements to date and suggestions for further improvements to luminosity parameters are listed below.

I (beam current): Over 2 amps have been stored in PEP-II LER, and over 1 amp in each DAΦNE ring. Further increases could be obtained by keeping beam cross section large in the arcs, raising thresholds for the ECI, and a clever idea for more efficient damping (less power radiated).

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[1] The fit was done to δQ_V since the scatter in points was lower. The KEKB HER point was not included since it is known to be low due to E.C.I. effects in the LEB.

[2] The measured value for LEP 98 was used. Using the asymptotic value would increase the exponent.

ξ_V (beam-beam parameter): PEP-II and CESR operate in the ξ_V = 0.05-0.06 regime, LEP has reached 0.083. More damping/randomization of transverse motion, better optics correction, crab cavities, and fast filling could lead to higher values of the beam-beam parameter.

β_V* (vertical focusing function at i.p.): KEKB operates with β_V^* = 7 mm. Lower values may be reached through magnet and optics development, alternative focusing schemes, local longitudinal focusing, lower impedance vacuum chambers and compromises with the detector design.

r (beam aspect ratio at i.p.): Operating colliders use nearly flat beams. Round beam R&D is being carried out at BINP, Novosibirsk and Newman Lab, Cornell University. IR optics and beam separation must be further developed for factory level round beam performance.

4.3 Where to build?

This question is asked not in respect to location, but for the energy of the factory. The clear options include Phi, C-Tau, B, Z_0, W and Top factories. Polarization would be beneficial for the C-Tau factory physics, and potentially lower background for a Z_0 factory. Monochromatization may be useful for a C-Tau factory operating on the narrow resonances. We accelerator builders will need guidance from the high energy physicists, which will likely come only after a significant data sample from the present B factories has been analyzed.

While some aspects of design will depend on the energy chosen, many are applicable across the energy range. An example would serve as a reference point.

4.4 A 10^{36} Luminosity B Factory

John Seeman put together a conceptual design [35] with parameter list for a B factory providing a 2 order-of-magnitude improvement in luminosity above existing machines. This collider design is for the Y(5S). Some of the primary parameters are shown below.

Parameter	HER (e+)	LER (e-)
Beam Energy [GeV]	10.5	2.81
Circumference [m]	2425	
Sync. Rad. pwr [MW]	21.2	5.1
Beam current [A]	5.5	20.5
Number of bunches	5600	
β* V/H [cm]	0.12/10	0.12/10
Bunch length [cm]	0.14	0.12
Crossing angle [mrad]	+4.5	-4.5
Beam lifetime [min]	4.2	3.2
Beam-beam param.	0.11	0.11
Luminosity [cm^{-2}-sec^{-1}]	10^{36}	

Seeman's design incorporates all of the experience acquired in construction, commissioning, and operation of PEP-II. Several aspects of the design depart from the norm.

Positrons are in the high energy beam to reduce the effects of the electron cloud instability. No completely effective cure has yet been found for this instability of high current positron rings. The trapping of ions, which has prompted designers of the present generation of asymmetric factories to put the positrons in the LER, will presumably be overcome by a filling scheme that avoids debilitating trapping until the current is high enough to destabilize all relevant ion species.

A second, more radical departure from custom, is to design for a rather short beam lifetime (~4 minutes). This allows relaxing of constraints in several areas such as Touschek lifetime (permits smaller beam dimensions) and beam-beam parameter. The injection system, including a plan to inject essentially continuously, becomes an integral part of the design.

Another feature is a large bending radius (279 m in the HER) to reduce synchrotron radiation power at the high currents. While this leads to longer damping time ($\propto \rho R$), the longer revolution time means longer time between collisions, so the damping decrement scales only as $1/\rho$, and the larger radius should have very little effect on achievable beam-beam parameter.

The beam separation must be rapid with a bunch spacing of only 42 cm. A ± 4.5 mrad crossing angle plus a permanent magnet dipole beginning 30 cm from the interaction point followed by a large offset superconducting quadrupole separate the beams horizontally by about 15 σ_X at the first parasitic crossing.

The vacuum system will have to be carefully designed to avoid damage from the beam higher order modes and synchrotron radiation. This design proposes to eliminate bellows, constraining the vacuum chamber mechanically to avoid squirming.

The RF system is similar to those of the present B factories with the exception of the heavy beam loading.

The injection process must be carefully crafted from the source through the storage ring and detector. With 5.5 x 10^{12} particles lost per second in the LER, the injector must dribble in a constant current. The injection process must not cause excessive background in the detector, so the phase space occupied by the injected particles must avoid any exposed parasitic crossings, masks, and other apertures in the IR where the physical aperture is limited.

Lastly, Seeman points out several specific areas for future study:

- Effects of the short beam lifetime and continuous injection on the physics detector
- Interaction region layout
- Longitudinal beam stability at high currents
- Parameters of the bunch-by-bunch feedbacks
- Tradeoff between beam-beam parameter ξ and beam lifetime

4.5 Energy Frontier Machine

A study of a collider with energy reach substantially beyond that of LEP has been underway for several months. This machine could be sited in a large (240 km circumference) tunnel which could later be used for a post-LHC hadron collider [36]. The c.m. energy range would be 100 to 400 GeV, and the physics would be low-mass Higgs, large sample Z_0 physics, and possibly a study of physics around the t-tbar threshold.

With a synchrotron radiation power budget of 100 megawatts, a luminosity of 10^{33} cm^{-2}-sec^{-1} might be reached with 12.6 mA per beam. The damping decrement would be huge, on the order of 0.01.

4.5 Bolder Innovations

In addition to the resourceful features of the example above, other, bolder concepts could alleviate some of the difficulties caused by high currents, short bunches, chromaticity, etc.

Carrying short bunches around a large ring puts demands on kilometers of vacuum components. The bunches could be locally shortened by placing high gradient RF cavities on either side of the IR with a anisochronous insertion to shorten the bunch locally at the interaction point at the expense of increased energy spread. Orlov suggested [37] a compression scheme using crab cavities followed by a synchro-betatron coupled insertion to shorten the bunch without increase in energy spread. This scheme calls for large kicks from the crab cavities, and complex optics insertions.

e+e- colliders have typically operated with flat beams (width much greater than height) at the i.p. Round beams may have some advantages. There is some indication that round beams are capable of withstanding much higher tune shifts from the beam-beam interactions than flat beams [38,39]. Their downside is that low β interaction regions are much more difficult to design for round beams than flat, and they are less tolerant to crossing angles because of their large longitudinal to transverse beam size ratio.

Another innovative idea is the Linac boosted storage ring. [40] Here a pairs of superconducting RF cavities are placed either side of the IR to boost the energy of the colliding beams just before collision, then decelerate them before they travel through the arc. The pairs of cavities are coupled together so the reclaimed energy is recycled. The beams then pass through the bending magnets at relatively low energy to reduce synchrotron radiation losses. Additional damping could be provided by wiggler magnets or a novel scheme such as optical stochastic cooling [41,42]. Besides requiring exotic damping methods, the energy transferred between the cavities is quite large (decelerating a 10 A beam from 5 to 3 GeV would imply 20 GW of power transfer!)

5 CONCLUSION

A steady increase in luminosity has been maintained since the first storage rings of about a factor of 20 every 10 years (Figure 5). Building an e+e- storage ring system providing 1 to 2 orders of magnitude increase in luminosity beyond planned performance of present day machines is a challenging but plausible task. The experience from commissioning and operation of DAΦNE, PEP-II and KEKB is providing a necessary and adequate basis for this design.

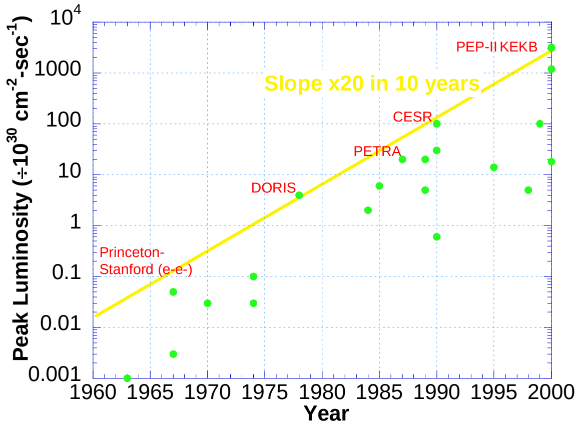

Figure 5 – The trend in peak luminosity 1960-2000

There are many topics that can be studied, both theoretically and by accelerator machine studies, which will be important for the next machine(s) to be built. These should get underway as soon as possible.

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