Summary of the Snowmass Accelerator Group M2 on e⁺e⁻ Circular Colliders

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Report on the future of e⁺e⁻ Circular Colliders for the M2 Accelerator Group at Snowmass 2001.

A.   Participants of the M2 Accelerator Group at Snowmass 2001:

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B.   Charge for the M2 e⁺e⁻ Circular Colliders Group for Snowmass 2001:

Perform a survey of the present status as well as the vision of the future promises of the various electron-positron circular colliders. The colliders to be covered include those currently in operation, currently under construction, or envisioned as a possibility of the future, and in the US and abroad. Special emphasis should be placed on the clear identification of the beam physics limits and technological limits, and an examination of the extent that they have been address by past research or need to be addressed by future research. Identify new and promising ideas even though they may need additional work. These issues should be addressed for all the leading technical realizations of the circular positron-electron colliders. Finally, the group should summarize in a brief report the highest priority research topics for different technological realizations of circular electron-positron systems and give an approximate timetable for key R&D development [1]. The group is also asked to provide a comprehensive presentation to high-energy and accelerator physicists in plenary sessions during the Snowmass workshop.

C.   Executive Summary of the Snowmass Accelerator Group M2 on e⁺e⁻ Circular Colliders

C.1   Overview:
The status, future plans, and research issues for the existing and future e⁺e⁻ circular colliders were discussed. The operational or recently operating colliders studied were BEPC, CESR, DAFNE, KEKB, LEP, PEP-II, VEPP-2M, and VEPP-4. Upgrade plans for CESR-c, PEP-II, and KEK-B were presented. The future circular colliders studied were BEPC-II, PEP-N, Super-B-Factory (SBF), VEPP-2000, VEPP-5, and VLLC. These colliders cover a center of mass energy range of 1 to 370 GeV and a luminosity range of 10^{31} to 10^{36}/cm²/s.

C.2   Outlook:
The working group felt that the HEP community should give strong support to the operation and proposed upgrades of these medium energy colliders as these accelerators are a very necessary and healthy component of the full landscape of high energy physics.

C.3   Present Colliders and Upgrades:

The present colliders deliver data to their respective detectors at an unprecedented rate. The B-factories have reached luminosities of $3\text{-}4\times10^{33}$ /cm^2/s and deliver integrated luminosity at rates in excess of 4 fb^{-1}/month. The recent rapid turn-on of the two B-Factories, PEP-II and KEKB, has shown that modern accelerator physics, design and engineering can produce colliders that rapidly reach their design luminosities and deliver integrated luminosities capable of frontier particle physics discoveries.

The present colliders are planning upgrade programs to extend their data production capabilities. PEP-II and KEK-B with "ongoing upgrade programs" should reach luminosities of a few times 10^{34}/cm^2/s in a few years. More aggressive plans may follow allowing luminosities of order 10^{35}/cm^2/s by the end of the decade. Plans are in place at CESR to extend the energy range of the collider to 1.5 GeV < E < 5.6 GeV with the installation of damping wigglers (CESR-c). Luminosities of $2\text{-}3\times10^{32}$/cm^2/s should be achievable at the lowest energies and $1\text{-}2\times10^{33}$/cm^2/s at the highest. Experience at CESR over the last two decades demonstrates that steady upgrades to existing colliders are extremely cost-effective and productive.

C.4   New Colliders:

The demonstrated success of e+e- factories over the last several years provides confidence that higher luminosities can be achieved in several energy regimes, which are now demanded by the need for precision measurements in particle physics. The proposed new colliders are designed to cover energy ranges where additional data is needed and to explore the energy frontier.

Two machines, VEPP-2000 (under construction) and PEP-N (under consideration), will provide precision R measurements in the energy range $1<E_{cm}<3$ GeV. These machines are inexpensive and complement well the ongoing programs.

With the success of the present B-Factories, ideas for a future very high luminosity B-Factory or Super-B-Factory (SBF) are under consideration. In the likelihood that B-TeV and LHC-B will be in operation by the end of the decade, a B-physics program based at an e+e- collider would very likely require a luminosity approaching 10^{36}/cm^2/s to be competitive. This performance level would require improvements significantly beyond planned upgrades of present facilities. Recent studies provide support that such a collider could be built.

VLLC is a proposed energy frontier collider (up to $E_{cm}= 370$ GeV) to be located in the VLHC tunnel. This machine is in the early stages of consideration and many design issues remain. Several of the questions for this accelerator are: Are one or two rings needed? What is the injection energy and injection system? Is polarization required and achievable? What is the energy range of the main ring? Is an e-p option desired? The rational and timing for the VLLC must take into account the overall planning of an e^+e^- linear collider.

C.5   Connections to other facilities:

Research and development for high luminosity e+e- colliders has direct applicability to other frontier accelerators including linear colliders, synchrotron light facilities, and FELs. Some of the common accelerator physics issues are wiggler-dominated rings, beam dynamics of bunch trains, multi-bunch feedback systems, and interaction region designs.

C.6   Suggested collider research needing strong community support:

C.6.a   Interaction region design:

The upgrades of many existing colliders and all future colliders require improvements in the design and operation of the interaction region (IR) for both the accelerator and the detector.

Nearly all future IRs require reduced beta functions forcing the interaction region quadrupoles to be moved closer to the collision point. Chromaticity, beam separation, and detector backgrounds are concerns. The recent invention of small cross section superconducting quadrupoles for a HERA upgrade has provided new possibilities for low beta interaction regions for e+e- colliders.

All present colliders use vertically flat beams at the interaction point. Round beams at the collision point may allow higher beam-beam tune shift limits and a higher luminosity but, perhaps, with increased backgrounds. For example, a Super-B-Factory may need round beams. CESR-C will test round beam operation in the next year.

Two beam separation issues in the IR include crossing angles, parasitic crossings, lost particle and synchrotron radiation backgrounds, low beta functions, and HOM power generation in the separation

"crotches". More work is needed in this area. Research is especially needed to enable evaluation of the generated HOM power and optimization of the vacuum hardware for HOM reduction.

There is a desire to reduce the radius of the interaction region Be chamber from the present 2-2.5 cm radius towards 1 cm to improve particle tracking. Beam heating and detector backgrounds may become significantly worse and further research is needed.

C.6.b   Beam-beam interaction:

The beam-beam interaction ultimately sets the luminosity limit in e^+e^- circular colliders. Many methods are used to increase the limit or reduce its effects. For example, reduced beta functions at the collision point allow more beam current with the same tune shifts.

The beam-beam issues with round beams require further experimental and theoretical work as the potential luminosity gain is substantial.

Increasing the basic beam-beam tune shift limits in e^+e^- circular colliders involves careful orbit, coupling, and dispersion control. The empirical optimization of these lattice conditions should be better understood and systematized, if at all possible.

Several new colliders will be reworked to operate at lower than the design energy and will use very strong wiggler magnets to increase radiation damping and the beam-beam tune shifts. These wigglers add strong lattice nonlinearities to the accelerator. Understanding the effects of these wigglers for colliders (as well as linear collider damping rings) is needed.

Diagnostics and tuning techniques of these high luminosity colliders are essential to achieve/maintain their performance. More new devices and algorithms must be developed both for present and future machines.

C.6.c   Very high current beams:

For future high luminosity B-Factories the beam currents must be increased by up to an order of magnitude. These high currents will require many additional RF cavities resulting in higher impedance and stronger instabilities. The longitudinal and transverse feedback systems will likely need substantial improvements. The combination of the energy storage cavities and longitudinal feedback needs study.

Stress fatigue of vacuum chambers from high current temperature cycling is now an important factor in B-Factories and future studies will lead to improvements in the design of vacuum chambers.

The power consumption of the future machines may reach upwards of 100MW. Efforts to reduce the wall power needed to produce the luminosity should be encouraged.

C.6.d   Accelerator physics:

Several new accelerator physics issues affect ring operation and need study. The electron cloud instability (ECI) can enlarge a positron beam and reduce the luminosity along the bunch train. Vacuum chamber solenoids are only a partial cure for ECI. Thus, additional cures must be investigated.

High current B-Factories will enter a regime where the Touschek effect significantly reduces the beam lifetime and, perhaps, Intra-Beam Scattering (IBS) will enlarge the transverse and longitudinal beam sizes. Measurements of IBS and calculations do not always agree, suggesting the need for theoretical improvement. In particular, calculations that take into account x-y coupling and transverse enlargement are needed.

Finally, further advances in bunch-by-bunch instrumentation are required to enable understanding of the underlying limitations to machine performance.

D.   The scientific program at the Snowmass Workshop on Positron-Electron Circular Colliders

July 3 (Tuesday)	S. Henderson	"CESR: Present status and near term future"
	K. Oide	"KEKB: Present status and near term future"
	M. Sullivan	"PEP-II Present status and near term future"
	C. Biscari	"Status of DAFNE"
July 4 (Wednesday)	M. Tigner	"CESR-C: a tau/charm collider"
	J. Seeman	"Luminosity of 10**35 in PEP-II"
	U. Wienands	"Vacuum Systems for High Luminosity e+e- Colliders"
	S. Ecklund	"HOM Heating in Interaction Regions"

July 5 (Thursday)	Joint meeting with T9 Diagnostics
	A. Fisher "Survey of Diagnostics for Circular e+e- Colliders"
	D. Sagan "Lattice Correction and Diagnostics"
	F. J. Decker "Beam Variations along a Long Bunch Train"

July 6 (Friday)
R. Assmann "LEP Lessons Learned"
T. Sen "Design of an e+e- collider in the VLHC tunnel"
M. Sullivan "PEP-N collider"
A. Skrinsky "e+e- colliders at BINP, Russia"

July 7 (Saturday)
U. Wienands "Feedback Systems in High Luminosity e+e- Colliders"
J. Seeman "Ideas on a 10**36 Luminosity B-Factory"

July 9 (Monday)
Joint meeting with T1 Interaction Region on IR designs
M. Sullivan "PEP-II IR Upgrade"
D. Rubin "CESR-C Interaction Region"
J. Seeman "IR for a 10**36 Collider"

July 10 (Tuesday)
S. Henderson "Resistive Wall Effect for a High Luminosity B-Factory"
J. Seeman "A PEP-N Design Based on a Cu Linac"

July 11 (Wednesday)
Joint meeting with T5 Beam Dynamics on Intra-Bunch Scattering
P. Colestock "IBS Code Comparison"
F. Pilat "RHIC Experiments"
K. Kubo "KEK IBS Experiments"

July 13 (Friday)
J. Norem "Technology Challenges of a e+e- collider in the VLHC tunnel"
T. Sen "Summary of the spring 2001 workshop on an e+e- VLHC"

July 14 (Saturday)
Joint meeting with T5 Beam Dynamics on beam-beam interaction
Morning:
J. Seeman "Survey of Beam-Beam Effects"
F. Willeke "Strong Beam-Beam Experiments"
V. Shiltsev "Results of Beam-Beam Compensation Experiments"
Y. Cai "Methods and Issues in Beam-Beam Simulation"
Afternoon:
A. Burov and Y. Derbenev "Beam Rounders in Circular Colliders"
S. Henderson "Round Beam Experiments in CESR"
M. Palmer "Beam-Beam Interaction at CESR"
J. Rogers, A. Romano "Beam-Beam Interaction at CESR-C"

July 16 (Monday)
Y. Ohnishi "Luminosity of 10**35 in KEKB"
F. J. Decker "Possible Ways to Large Beam-Beam Tune Shifts"

July 17 (Tuesday)
Joint meeting with T3 group
M. Liepe "RF Control for Large SRF System"
A. Hutton "Large SRF Systems at CEBAF/JLab"
K. Hubner "Large SRF Systems at LEP"
F-J. Decker, A. Hutton "Recirculating Linear Colliders"

July 18 (Wednesday)
Discussion of Snowmass summary document for the M2 Group

E.   General History and Outlook on Circular e^+e^- Colliders

Circular e^+e^- colliders have had a long history in the world starting in the mid-1960s with the Stanford–Princeton e^-e^- Collider in the United States and the VEP e^+e^- collider in Russia. The tradition has been carried on with many colliders, up to the present day accelerators of 2001 with BEPC in China, CESR in the US, DAFNE in Italy, PEP-II in the US, and KEKB in Japan. CESR, PEP-II and KEK-B toast the highest luminosities in the world of 1 to 4 x 10**33/cm2/s. All of the above mentioned colliders have been either on the energy frontier or on the luminosity frontier. The particle physics results produced with these colliders have been great and quite varied: the discovery of a new quark, a new lepton, lifetimes of many particles, CP violation, precise mass values of particles, and the number of families of quarks, just to name a few. There are a wide variety of physics measurements remaining to do with this class of accelerator and there are many physicists with strong desires to do so.

To keep these accelerators at the frontier of particle physics, the luminosity must be continually increased. History over nearly forty years has shown a factor of twenty to twenty-five increase in luminosity every decade. There are many ideas under development that should keep this trend going. For example, there are upgrades planned for CESR to extend its energy range. There are ongoing luminosity upgrades planned for PEP-II and KEKB to achieve luminosities exceeding 10^{34}/cm^2/s in a few years. BEPC will likely be upgraded to the 10^{33}/cm^2/s level. These upgrades will be adequate for the next round of particle physics in the upcoming decade. These modest upgrades will cost in the range of 5 to 30 M\$ for the US projects.

In about ten years, significantly more luminosity will be needed in the e+e- B-Factory colliders to track the expected data rates in the hadron colliders. Studies are underway to determine what is needed to get PEP-II and KEKB to a luminosity approaching 10^{35}/cm^2/s. These upgrades, if warranted, are more substantial and will likely require expenditures on the order of 50 to 250 M\$.

Another approach is to take what has been learned in the present colliders and the previous generations to design a ultra-high luminosity B-Factory with substantially higher performance, say, in the range approaching 10^{36}/cm^2/s. The hardware that such an accelerator will likely need is well beyond an upgrade to an existing B-Factory but could well use most of the existing infrastructure. The studies for such a collider will take several years and the costs may be on the same order as the original collider facility.

Finally, on the energy frontier, studies have started for placing an e^+e^- collider in the proposed VLHC tunnel with beam energies of about 185 GeV. Given the long history of e^+e^- colliders, a reasonable design can be made with some confidence. How such an accelerator fits in with a linear collider that has a more extendable energy range has to be decided.

All these upgrades and proposed new facilities require significant research and development to reach their goals. A few of the major research topics are multi-ampere beam currents, multi-megawatt x-ray loading of vacuum chambers, multi-bunch beam instabilities, interaction region designs with two different intense beams, and increased performance from the beam-beam interaction. The results of these studies are fully shared between world laboratories but are a necessary part of each program. The accelerator field, in general, has made great advances with these research topics over the past years and the expectation for success with the next round of improvements is very good.

F.   Status of Present and Future Positron-Electron Circular Colliders

F.1   BEPC and BEPC-II:

Presently, BEPC [2] has a luminosity of about 10^{31}/cm^2/s at 4 GeV in the center of mass. Data is steadily being supplied to the particle physics detector.

For the future, there have been several upgrade plans presented over the past years to increase the luminosity in BEPC to make an accelerator with significantly higher luminosity. The present plan [2] is for BEPC-II, a two-ring collider with a luminosity up to 1.55 x 10^{33}/cm^2/s with beam energies of 1.89 GeV. This new collider will use superconducting RF cavities at 500 MHz, superconducting interaction region quadrupoles similar to those in HERA, a 1.5 cm βy*, crossing angle with +/- 11 mrad, 93 bunches, and an upgraded detector. The estimated cost of this collider upgrade and detector improvements is about 80 M\$. A decision on this facility is expected in the fall of 2001.

F.2   CESR:

At present, the Cornell Electron Storage Ring (CESR) [3] operates on and near the Y(4S) resonance. An 8-month luminosity production run was recently completed in which a peak luminosity of 1.3×10^{33} /cm^2/sec was achieved.   Integrated luminosity was delivered at peak rates of 73 pb^{-1}/day and 1.5 fb^{-1}/month providing 11.2 fb^{-1} for the 8-month run. Prior to the luminosity run, the integrated luminosity production rate was improved by a factor of ~3 over previous CESR records from a combination of improved operational efficiency, better beam-beam tune shift performance and the ability to store and collide higher beam currents.

Improvements in operational efficiency were realized by improvements to the CESR injector intensity and CESR injection efficiency, operating with shorter high-energy-physics run lengths and adjustments to the operating schedule that maximized scheduled colliding beam operation.   The integrated luminosity relative to that which would have been obtained by operating at peak luminosity with 100% duty factor averaged ~45% during the run.

The beam-beam tune shift parameter in CESR has been increased by a factor of 2 in 9 years of continual machine development. Beam-beam tune shift parameters, ξ_y, of 0.06-0.07 were routinely achieved in the recent running period. The improved performance can be attributed to several factors. Improved understanding and correction of the machine optics has been realized with the implementation of a fast betatron-phase and transverse coupling measurement and correction system. This system has allowed rapid optics measurement and correction cycles, which has enabled experimentation with modified optics, and allowed rapid diagnosis of non-linearities and optical errors. Continued attention to the machine survey and correction of magnet alignment errors has contributed to the improved performance. Finally, aggressive exploration of machine parameters (working point, chromaticities, pretzel amplitude, vertical and horizontal orbits, electron-positron tune differences, coupling correction by skew quadrupoles) has resulted in substantial improvement in the tune shift parameter.

CESR is configured for bunch-train operation. In the recent running period, each beam consisted of 45 bunches, arranged in nine trains, each of which was populated with five bunches spaced by 14 ns. In recent years, a longitudinal coupled-bunch instability was overcome with the installation of a bunch-by-bunch longitudinal feedback system and the replacement of CESR's normal conducting cavities with four 500 MHz single-cell superconducting cavities. In addition, a number of improvements to the vacuum system were implemented, including a scheme for positioning the sliding joints in order to minimize higher-order-mode heating. Beam currents were subsequently increased and reached a total colliding beam current of 750 mA.

CESR continues to push the limits of what can be accomplished in a single-ring collider. The most severe limitation, the parasitic beam-beam interaction, limits the performance of this machine. Due to the bunch-train operation of the collider, different bunches in a train are subjected to a different set of parasitic interactions and differential optical parameters result. Two of the most vexing manifestations are the introduction of differential bunch-by-bunch orbit displacements at the collision point (by as much as ½ σ_y) and differential bunch-by-bunch tunes ($\Delta Q \approx 0.003$). These two effects make increases in bunch current less productive, as the beams are separated further at the IP and the footprint in the tuneplane is increased, which in turn results in poor lifetimes of some bunches. Efforts to combat these destructive effects are focusing on bunch-by-bunch orbit adjustments provided by the vertical feedback system, and the development of an RF quadrupole to shift the tunes of bunches according to their position in a train.

The future plans for CESR are to install a new interaction region optics that will be complete in summer 2001. These new optics, based on high-gradient superconducting quadrupoles, will allow a reduction in the vertical focusing parameter, β_y^*, (presently 2 cm) below 1 cm.   Additional superconducting RF cavities are being prepared to provide the RF voltage necessary to reduce the bunch length accordingly. In the present optics, the parasitic crossing point nearest the interaction region places a limit on the bunch current. In the new optics, the beta-functions at this crossing point will be reduced to values typical of the machine arcs, thus removing this limitation. Additionally, equal horizontal and vertical beta functions at the IP (approaching 3 cm) are possible, allowing further tests of round-beam collisions.

A plan to extend the operating energy range of CESR has emerged which will allow precision QCD and charm physics measurements to be performed. This upgrade to CESR, known as CESR-c, calls

for the installation of damping wigglers to allow operation in the energy range $1.55 < E_{beam} < 5.6$ GeV. The present design calls for 18m of 2.1T super-ferric wigglers, providing transverse damping times at 1.88 GeV which are twice those at 5.3 GeV. The same bunch-train scheme used at Y(4S) energy will be employed for low-energy operation, but the current per bunch is reduced in proportion to the energy to maintain the same parasitic beam-beam tune shifts. The increase in damping time reduces the beam-beam tune shift parameter by ~25 %. With a reduction in β_y^* to 1 cm, the resulting luminosity at E=1.88 GeV will be 2.7×10^{32} /cm^2/sec while at high-energies, luminosity up to 2×10^{33} /cm^2/sec may be possible. The introduction of strong wigglers into the lattice leads to large octupole non-linearities that reduce the dynamic aperture. These non-linearities and their possible compensation with octupole correctors are presently under study.

CESR will be performing tests in the near future that bear on the designs of future machines. The transformation of CESR to low-energy operation provides an important test of the beam-dynamics in a wiggler-dominated ring, the results of which are important for damping ring designs for linear colliders. Secondly, the follow-up experiments on round-beam collisions at CESR, this time with small beta-functions at the IP, are another important test of round-beam collisions as a potential route toward higher luminosities, not only at CESR, but at other colliders as well.

F.3   DAFNE:

The present plan of DAFNE [4] at Frascati, Italy, is to collide beams for particle physics. DAFNE is a two-ring collider located at INFN Frascati, Italy, operating on the φ-resonance (E$_{cm}$ = 1.02 GeV) as a Kaon Factory. DAFNE has achieved a peak luminosity of 3.2×10^{31}/cm^2/sec and integrated luminosity production rates of 1.5 pb^{-1}/day and 20 pb^{-1}/month. In typical collision conditions, each beam consists of 50 bunches with 0.8A per beam. The DAFNE design spells out two phases: in the first, a peak luminosity of 1×10^{32} /cm^2/sec is achieved with 1A currents in each beam, while in the second phase, the beam currents are increased to 5A per beam resulting in a luminosity of 5×10^{32} /cm^2/sec. In each case, a beam-beam tune shift parameter $\xi_y = 0.04$ and a vertical focusing parameter $\beta_y^* = 4.5$ cm are assumed.

The peak beam-beam tune shift parameter recorded to date is 0.018 which is less than half the design tune shift parameter. A number of performance limitations have been encountered, most of which are related in some way to the low beam energy. First, the strong detector solenoid field demands very careful coupling compensation in the KLOE interaction region. The beam is rotated by ~40° in traversing the solenoid, so careful compensation must be achieved with compensating anti-solenoids and the low-beta quadrupole tilts. The original design called for 1% vertical to horizontal emittance ratio, but even this level was found to limit the beam-beam tune shift parameter. By detailed search for coupling sources and careful solenoid compensation, an emittance ratio of 0.2% has been achieved.

Secondly, non-linear fields in the wigglers, sextupoles, correctors and magnet fringe-fields degrade the beam-beam performance. In particular, it has been found that the magnitude and sign of the cubic non-linearity plays a critical role, since the amplitude-dependent tune shift can either increase the tune-spread or decrease the tune-spread, resulting in more or less Landau damping. As a result, the cubic non-linearity affects directly the dynamic aperture, particularly in the presence of the beam-beam interaction. Operationally, the cubic non-linearity has been observed to vary over a wide range, even changing sign, depending on the lattice functions and closed orbits. A dominant source of octupole non-linearity is due to the wigglers. In the near-term, additional octupoles will be installed to provide tunability, and the wiggler poles will be shimmed.

A third effect arises from operation of the collider with two interaction regions. The second low-beta IR introduces chromaticity that must be compensated with strong sextupoles. In addition, the beams are separated vertically in the second IP, and it has been observed that the correctors used for the separation bump introduce coupling and non-linearities. A new optics has been designed in which the second IP is "detuned." The β^* has been increased which reduces the IR chromaticity, and a larger separation is achieved with weaker correctors.

Two bunch-by-bunch feedback systems are in use; the longitudinal system has been operating successfully since initial commissioning. A vertical feedback system was recently installed to combat a vertical instability that was observed at only a few hundred mA. Both feedback systems are operating

well; beam currents in excess of 1A have been stored in each ring. A horizontal feedback system is in preparation.

The beam lifetime and backgrounds are dominated by Toushek scattering. Additional scrapers are being considered to shield the detector from lost Touschek particles. Due to the (anticipated) short lifetimes, frequent filling is required. DAFNE operates with interleaved electron and positron filling cycles in which the beams remain in collisions and the detector continues to take data.

The DAFNE luminosity goal calls for 200pb^{-1} delivered to KLOE by the end of 2001, 500 pb^{-1} by the end of 2002 to allow a measurement of ϵ'/ϵ to 10^{-3}. They plan to deliver 10 pb^{-1} to the DEAR detector at the second IP by the end of 2002. To achieve these goals requires further reduction in the coupling, detuning the second IP, further exploration of the working point, octupole compensation and increasing the stable beam current.

F.4   KEKB:

KEKB [5] at the KEK Laboratory in Japan has been very successfully operating with the BELLE detector since May 1999. The KEKB operation for this year was stopped on July 16 for the scheduled summer shutdown. During this year the Belle detector collected an integrated luminosity of about 22.3 fb^{-1}. The total integrated luminosity from the beginning of its operation is about 33.1 fb^{-1}. The present record peak luminosity is 4.49 x 10^{33} /cm^2/sec that was recorded on July 3, 2001. The record integrated luminosity per shift is 84.1 pb^{-1} that was recorded in the owl shift of June 16. The daily integrated luminosity of the best day (July 9) is 232 pb^{-1}. The integrated luminosity of the best successive 7 days (Jun. 11 ~17) is 1492 pb^{-1}. The monthly integrated luminosity of the best month (May) is 4760 pb^{-1}. All of these values are logged luminosity by the Belle detector.

Before the startup of the beam operation in this year, KEKB installed more solenoid coils in the LER. About 430m of the ring were covered with the solenoid field at this time. After the scheduled winter shutdown of about 20 days, the KEKB started up on January 16, 2001. The luminosity increased gradually and reached 2.9 x 10^{33} /cm^2/sec in the middle of March. At the end of 2000, the record of the peak luminosity was 2.26 x 10^{33} /cm^2/sec. Prior to this increase of the luminosity, the betatron-tunes were changed at the beginning of February according to beam-beam simulations. The fractional part of vertical tunes of the both rings changed from around 0.10 to 0.60. It is believed that the luminosity improvement came from suppression of the LER single beam blowup by the solenoid field. The increase of the luminosity at the end of March, however, was clearly brought by the change of the tune. The horizontal tune of the LER was changed from around 45.52 to 45.51. The vertical tune was also changed from 43.60 to 43.58. Although an amount of the tune change was small, the luminosity showed an immediate increase and exceeded 3 x 10^{33} /cm^2/sec for the first time. After this, the luminosity increased gradually with fine tuning and reached 3.4 x 10^{33} /cm^2/sec at the middle of April. In the middle of April, the KEKB operation was interrupted for replacing the HER movable masks with those of a new version. Before this replacement, the HER beam current was restricted by the tolerable HOM power of the masks. After the replacement, the HER beam current could be increased from around 590 mA to 700 mA or more and the luminosity was increased up to around 3.8 x 10^{33} /cm^2/sec at the beginning of May. At the end of May, the vertical beta function of the LER at the IP was squeezed from 7mm to 6.5 mm. At the beginning of June, the vertical tune of the LER was changed from around 43.58 to 43.57, and the LER beam current was increased from around 880mA to 920mA. Due to these changes, the peak luminosity exceeded 4 x 10^{33} /cm^2/sec. At the end of June, the luminosity was once again increased up to 4.49 x 10^{33}/cm^2/sec that is the current record for the peak luminosity of the KEKB. Prior to this luminosity increase, the circumference of the rings changed day by day and a way was established to compensate this change with chicane magnets in LER and a change of the RF frequency. There is some possibility that the circumference compensation system contributed to the stability of the beam operation and to the increase of the peak luminosity.

Beam injection rates are gradually improving, although the fluctuation of the rates is still rather large. Typical injection rates are 1 ~ 1.9 mA/sec for a positron beam and 1 ~ 4mA/sec for an electron beam. Some experiments were tried for two-bunch injection of the positron beam. From the beginning of the next run, which will be started on Oct. 1, the two-bunch injection is expected to be available in normal operation.

During this summer 2001 shut down, some hardware changes are planned. Additional solenoid coils of about 250m in the LER will be installed. The movable masks in the HER will be replaced with

thinner ones to avoid damage from beam interception. The vacuum chamber of the HER near the IP will be replaced with a new version that has more vertical aperture and a more powerful water cooling channels.

The luminosity in the 2001-2002 long run will be pushed toward the design luminosity of 10^{34}/cm^2/s with more current and smaller beam sizes in year 2004. There is a study under way to increase the luminosity in KEKB toward 10^{35}/cm^2/s to make a SuperKEKB with bunch lengths and βy* on the order of 3 mm and 10 A in the LER and 3 A in the HER. There are issues with power usage, vacuum chamber heating, and coherent synchrotron radiation. The LOI for the SuperKEKB will be presented to the HEP community in the winter of 2001.

F.5   PEP-II:

PEP-II [6] is an e+e- collider with asymmetric energies (3.1 and 9 GeV) in a 2200 m tunnel at the Stanford Linear Accelerator Center. The collider produces B mesons to study CP violation as well as other physics topics. PEP-II was completed in 1998 with the first luminosity generated in July of that year. The installation of the BaBar Detector was finished in May 1999. The two beams collide at a single point in the IR2 hall where the BaBar detector is located.

The salient design features of the PEP-II collider design are LER-above-the-HER rings with head-on collisions but with dipoles bends near the collision point for beam separation. PEP-II has new copper RF cavities at 476 MHz with HOM damping, strong bunch-by-bunch feedback systems, many bunches (1658), high stored charges (2.1A x 0.75 A), permanent magnet interaction region quadrupoles and dipoles, and the use of the existing SLAC linac as an injector but with new transport lines.

The PEP-II e+e- collider has been operating for over two years with the BaBar detector at the energy of the Upsilon 4S resonance. The PEP-II run with BaBar is going very well. The luminosity has reached 113% of design or 3.4x 10^{33}/cm^2/s in July, 2001, and an integrated luminosity per day of 172% of design or 229 pb^{-1} occurring also in July, 2001. The total delivered integrated luminosity to date is 42 fb^{-1}. This luminosity has been achieved with vertical and horizontal beta functions of 12.5 cm and 50 cm, respectively. With time, the beam currents in PEP-II have been raised to increase the number of bunches and the luminosity. The peak luminosity was reached with 729 bunches with a positron current of 1.6 A and an electron current of 0.9 A. The bunch lengths are about 13 mm. The beam-beam tune shift limits are approaching 0.05-0.07 horizontally and 0.03-0.05 vertically, well above the design values. The data delivered by PEP-II has allowed the BaBar detector to definitively establish CP violation in the B-meson system, which was published during Snowmass 2001.

There are several accelerator physics issues that are being addressed for the present PEP-II. The "electron cloud instability ECI" enlarges the positron beam size at high currents. The ECI effect is reduced by solenoidal magnetic fields of about 30 gauss on the vacuum chambers. The solenoids have been wound over about half the PEP-II LER and the remainder will be wound on the accelerator over the next six months. The effect on the positron beam from the ECI inside the dipoles and quadrupoles is under study.

There are several beam heating issues in PEP-II. One of the bellows near the beryllium vacuum chamber at the interaction region inside BaBar over heats with beam current. This heating comes from local HOM power and also from the nearby crotch chamber. There are plans to remove some of the beam heating by replacing the crotch vacuum chamber with a design with a smoother transition and to improve the heat removal of bellows located near where the beams are separated in the summer of 2002. Direct cooling of the affected bellows will be added in summer 2004 when the support tube will be removed to replace silicon vertex wafers. There are also heating problems with the bunch-by-bunch feedback kickers. This heating will be relaxed by replacing the electrical feed-throughs with more sturdy units.

The beam-beam interaction is one of the limits to the luminosity and reducing the betas at the interaction point and finding a better tune location are underway. The tunes will soon be moved to near the half integer to take advantage of the dynamic beta effect. These tunes allow a higher beam-beam tune shift. Also, an improvement of the empirical skew quadrupole adjustments will lead to smaller spot sizes and more luminosity per beam ampere.

There are several longer range upgrade plans in place to raise the luminosity. The number of bunches can be doubled requiring twice the beam currents. Raising the LER and HER beam currents will require the addition of several RF stations in each ring. The installation of these new stations will be phased over several years. The number of beam aborts from short radiation bursts in BaBar and from the RF system need to be reduced. There are plans to lower beta y* at the interaction point from 1.25 cm to 0.7 cm.

A lower beta will require the reduction of the bunch length to about 7 mm using more RF cavities, lower momentum compaction lattices or, perhaps, adding third harmonic cavities. More vacuum chambers will have to be replaced within 50 m of BaBar that will eventually be over heated by beam fields. Finally, the longitudinal feedback kickers will need a more robust design with the higher beam currents.

The present accelerator development plan for PEP-II is envisioned to lead to a luminosity of 5 x 10^{33}/cm^2/s by July 2002. The near term future of PEP-II is to run continuously through to the end of June 2002 with the plan of integrating 100 fb^{-1}. A three-month down in summer and fall 2002 is needed to replace several vacuum chambers near the IR, install two new RF stations, and to repair the Instrumented Flux Return (IFR) of BaBar. Over the next five years, the luminosity for PEP-II should approach $2x10^{34}$/cm^2/s. The long range goals for PEP-II are to provide 0.6 ab^{-1} by the year 2007 and 1.0 ab^{-1} in year 2010.

Taking advantage of PEP-II experience, design R&D has started for a higher luminosity B-Factory with 100 times larger event rate. See Section F.8 below. The research for this new accelerator will take several years.

F.6   PEP-N:

The PEP-N project [7] is a proposed new e+e- collider at SLAC to operate in the center of mass energy range of 1.0 GeV to 3.1 GeV. PEP-N consists of a new Very Low Energy electron Ring VLER (<800 MeV) to collide with the PEP-II e+ Low Energy Ring LER (3.1 GeV) parasitically to PEP-II operation for BaBar. Since the e+ ring has a fixed energy, the very low energy ring needs an energy range of 100 MeV to 800 MeV. This collider would likely be placed in Experimental Hall 12 of the PEP-II complex and have its own dedicated 800 MeV e- injector. The peak luminosity should reach 2 x 10^{31}/cm^2/s.

In more detail, PEP-N is an "e$^+$ e$^-$ --> N Nbar or multi-hadrons" collider based at PEP-II. The plan is to collide the 3.1 GeV LER e+ beam against a 0.1 to 0.8 GeV electron beam stored in a new very low energy ring (VLER). The PEP-II LER is assumed to be operated for full BaBar operation with design parameters. The small electron storage ring has a circumference of 45.36 m and is located in straight section IR12 of PEP-II. The electrons are injected from a 40 m-long linac also located in IR12 of PEP-II. The luminosity of this collider is estimated to be above 10^{31} /cm^2/s at a VLER energy of 500 MeV without affecting BaBar data collection.

The collider straight section IR12 in PEP-II is relatively large, has good floor space both inside and outside the radiation enclosure, and has a large counting house. Both PEP-II rings are relatively simple in this straight section. The hall is 20 m along the beam line and about 12 m wide inside the radiation wall. A new 800 MeV linac would inject bunches of $3.6x10^{9}$ electrons into every second ring RF bucket spaced 4.2 ns apart, as in PEP-II. The linac would be mounted on the floor of IR12 and extend into the "proton" alcove to form four 12 m "girders" with 200 MeV acceleration each. Injection could be at 120 Hz if needed but 1 Hz is planned. At 1 Hz, the injection time is 36 seconds.

The PEP-N collision point is located in the center of the IR12 straight, but could be displaced a meter if the detector needs additional longitudinal space. A large bore dipole at the IP is used to separate the beams in the two rings and for detector momentum analysis. The vacuum system is relatively simple as the synchrotron radiation power is low, less than a kilowatt. The RF system is a single cavity (which exists as the prototype cavity for PEP-II). The VLER has two straights: one for the IP and one injection-RF-feedback straight. The LER ring would have to be slightly modified for this collider. The present LER quadrupole at the location of the collision point would be moved and reinstalled about 6.3 m upstream. A new symmetrical quadrupole would be added 6.3 m downstream. The IP beta functions in the LER are about a meter rather than a few centimeters as in traditional colliders. Thus, the chromaticity in the LER will not change very much and the present LER sextupoles are sufficient. The beam-beam tune shifts for the LER from PEP-N will be very low, about 0.004, which should not affect PEP-II operations. PEP-N will operate in a "parasitic mode" for about 9 months per year.

If the average peak luminosity over a year using different energies is about 3 x 10^{30}/cm^2/s and the ratio of average to peak luminosity over long times including down times is about 0.5, then an integrated luminosity of about 35 pb^{-1} is expected each year. Design work on PEP-N is continuing and with a major external review to be held in Fall 2001.

F.7   LEP:

The LEP collider at CERN [8] completed operations on Nov. 2, 2000, after 11 years of running. LEP operated on the Z-resonance (E_{beam} = 45 GeV) until 1995, when the beam energy began to be increased to approach the W^+W^- production threshold (E_{beam} = 80 GeV). W-pair production was observed in 1996. The beam energy was continuously increased over the next 4 years in an attempt to reach the highest possible center-of-mass energy in order to search for the Higgs Boson. LEP eventually reached a peak energy of 104.5 GeV.

The beam current at 45 GeV was initially supported by a normal-conducting RF system providing 16 MW of RF power. Increases in energy were made possible by the continuous installation of super-conducting cavities. After an upgrade to the cryogenics system, the ultimate RF system was capable of providing 36 MW with 288 superconducting cavities operating at gradients of 7.5 MV/m. The maximum beam energy depended on the optimization of several parameters: the available RF voltage, the RF trip rate, the RF voltage overhead, the horizontal damping partition number (which was adjusted to tune the horizontal beam size), and the average bending radius (which was adjusted with horizontal correctors). In traditional operation, a two-klystron overhead was maintained to allow for RF trips without loss of beam. To achieve the highest energy, LEP was operated with no klystron margin even as the RF trip rates increased due to the high gradient operation of the cavities.

The peak luminosity of 9.7×10^{31} /cm^2/sec was recorded in 1999 at E_{beam} = 98 GeV which compares with a peak luminosity of 1.5×10^{31}/cm^2/sec at 45 GeV. The increase is due to increased bunch currents, an orbit correction algorithm that minimized the vertical dispersion, and a higher beam-beam tune shift. The experience at LEP provides valuable insight into the importance of the damping decrement on the tune shift limit. At 104 GeV, the damping time is 60 turns and a tune shift parameter of 0.083 was achieved, whereas at 45 GeV, the damping time is 720 turns and a beam-beam tune shift of 0.045 was achieved. It is important to note that at high energy, the saturated tune shift limit was never observed. A simple model of the dependence of the beam-beam tune shift on bunch current provided an estimate of the asymptotic tune shift limit of 0.12. Taken with the data at 45 GeV, it was found that the beam-beam tune shift scales with damping decrement, λ, as $\xi_y \propto \lambda^{0.4}$, which is close to the simple expectation of $\xi_y \propto \lambda^{0..33}$. The scaling of the tune shift limit with damping is important for estimating the luminosity of the VLLC, as well as estimating the tune shift limit in machines which operate over a large energy range (such as CESR-c).

The single-bunch current in LEP was ultimately limited by the transverse-mode-coupling instability (TMCI) at the injection energy. A number of improvements over the years helped to increase this threshold current: the injection energy was increased, the synchrotron tune was increased and the transverse impedance of the ring was reduced with the installation of super-conducting cavities. A factor of two increase in threshold current was realized over the years so that the current was finally limited to about 1 mA/bunch.

The experience at LEP has provided a number of important contributions to accelerator physics and technology. To name a few, the operation of a large superconducting RF system, the technology of niobium sputtered on copper cavities, beam-beam performance in the presence of strong radiation damping, and various lattice function measurement and correction techniques.

F.8   Super B-Factory:

Initial parameters of a very high luminosity e^+e^- B-Factory or Super B-Factory (SBF) [9, 10] are being developed incorporating several new ideas from the successful operation of the present generation e^+e^- accelerators. A luminosity approaching 10^{36} cm^{-2}s^{-1} appears possible. Furthermore, the ratio of average to peak luminosity may be increased by 30% due to continuous injection. The operation of this accelerator will be qualitatively different from present e^+e^- colliders due to this continuous injection.

The next generation e^+e^- B-Factory will likely operate at the Upsilon (4S) with a center of mass energy of 10.58 GeV and with the same energy asymmetry as present. For the present study, the PEP-II tunnel geometry was used as well as the PEP-II beam energies of 9.0 and 3.1 GeV. The choice of energy asymmetry is, at this time, an open question as a larger energy asymmetry makes the beam separation at the interaction region easier but the makes the RF costs higher. To increase the luminosity about two orders of magnitude, the beam currents must be raised an order of magnitude and the beam cross sectional area reduced an order of magnitude while keeping the beam-beam tune shifts under control. The parameters in Table 1 below are self-consistent but further overall optimization can be made.

The detailed parameters of an SBF are shown in table below. The design choices and constraints are many. The two beam energies force two separate rings. There is one collision point. The circumferences are equal due to beam-beam interaction reasons. Round beams may be used to increase the beam-beam tune shifts. However, flat beams have traditionally worked well but may reduce the peak luminosity by a third given the same currents. Several RF frequencies ranging from 300 to 1000 MHz are considered but 476 MHz was used below as that is the present PEP-II frequency. The number of RF cavities must be increased with the beam current. Every RF bucket has a bunch.

The interaction region for an SBF is similar to that of PEP-II but must be longitudinally shortened to keep the peak betas in the interaction region quadrupoles as low as possible. Since the bunches are significantly shorter in this accelerator, a crossing angle is used at the collision point to help separate the beams. The beam lifetimes will be low forcing injection to be continuous. Continuous injection will also allow the beam-beam tune shift limits to be increased. The HER will store positrons to reduce the effects of the electron cloud instability. The very high electron current in the LER will likely remove all collected ions. If not, clearing electrodes may have to be installed. The vacuum chambers may need to be continuous extrusions, welded together to minimize impedance issues and reduce the number of fragile vacuum elements such as bellows and vacuum valves.

TABLE 1 10^{36} Collider Parameters based at the PEP-II tunnel

Parameter	High Energy Ring (HER)	Low Energy Ring (LER)
Beam energy (GeV)	9.0	3.1
Beam particle	e+	e-
Center of mass energy (GeV)	10.58	10.58
Circumference (m)	2200	2200
RF Frequency (MHz)	476	476
RF Voltage (MV)	50	30
Synch. Rad. Power (MW)	23	12
Number of bunches	3492	3492
Total beam current (A)	6.6	19.2
Beta * (y/x) (cm)	0.32/0.32	0.32/0.32
Emittance (y/x) (nm)	22/22	22/22
Momentum Compaction	0.001	0.0013
Bunch length (mm)	3.5	3.5
Approx. AC power (MW)	50	27
Beam lifetime (min)	5	5
Injection particles per pulse	7.3×10^{10}	5.3×10^{10}
Continuous injection rate (Hz)	20	80
Beam-Beam tune shifts	0.14	0.14
Luminosity (/cm^2/s)	10^{36}	10^{36}

The observed beam-beam tune shifts in PEP-II are approaching 0.07. The expected tune shifts in this new accelerator should be larger for two reasons. Theoretical and experimental evidence indicates that round beam operation of the collision point will increase the tune shifts by about a factor of about two. However, there may be increased backgrounds from round beam operation but significantly more backgrounds are expected from other sources as well. Furthermore, it has been observed in PEP-II during routine running that by adjusting the tunes the luminosity can be increased significantly (~10%) at the expense of the beam lifetime. (This beam lifetime will be called the beam-beam lifetime.) Higher luminosity for the same current means higher tune shifts. It is believed that this new accelerator can take advantage of continuous injection to push the beam-beam tune shifts to significantly higher values and consequently the beam-beam lifetimes to significantly lower values.

The interaction region will likely have a similar geometry to that of PEP-II. The cone angle separating the accelerator and detector components can be the same at about 300 mrad. The focusing

quadrupoles must be as close to the interaction point (IP) as possible to reduce the peak beta functions in those quadrupoles. The LER quadrupoles for this accelerator can be moved significantly closer to the IP than in PEP-II using superconducting Q1 and Q2 magnets with stronger gradients. A good design choice for these magnets is similar to those used in the HERA e- ring upgrade. The HER quadrupoles can also be moved closer because the LER quadrupoles have been moved. A crossing angle of about +/- 5 mrad is used to help separate the beams at the first parasitic beam-beam crossing. The beams are horizontally separated by about 12 σ_x at the first parasitic crossing.

The RF system design can be similar to that of KEKB or PEP-II but with an order of magnitude larger scale. The longitudinal beam dynamics will be difficult with the large beam currents. To keep the beams stable, it is likely that the solutions used for KEKB (storage cavities) and for PEP-II (strong bunch-by-bunch feedbacks) will both be needed.

The HER vacuum system must dissipate over 16 kW/m of synchrotron radiation power. The chambers will likely be made with an antechamber with a continuous built-in photon stop. The design of the bellow (expansion) modules will be very difficult for these high currents and short bunch lengths. Instead, the plan is to use a concept investigated for the PEP-II rings but not implemented. The vacuum system would be a continuous extrusion welded together with no bellows but with rigid supports to constrain thermal stresses.

The beam lifetime has several components including luminosity, vacuum, Touschek, beam-beam and dynamic aperture. A total beam lifetime of about 4 to 5 minutes for each beam, hence the need for continuous injection.

Many studies must be done over the next few years to bring these ideas closer to a practical accelerator. A few of the more important topics are listed. 1) The effects of the short beam lifetime and continuous injection on the physics detector. 2) The interaction region layout with round beams, higher detector fields, and smaller IP chamber. 3) A flat beam IR option, 4) The longitudinal beam stability at high currents. 5) The parameters of the bunch-by-bunch feedbacks. 6) The beam-beam interaction allowing a higher beam-beam tune shift but with a shorter beam lifetime.

F.9   Electron-Positron Collider Activities at the Budker Institute of Nuclear Physics, Novosibirsk:

The VEPP-4M collider is in operation at BINP [11]. This collider is expected to cover the beam energy range 1<E_{beam}<5 GeV with a luminosity of $2x10^{31}$/cm^2/sec at 5 GeV. The present emphasis is on the energy range between the ϕ and J/ψ resonances. Damping wigglers have been installed to enhance the luminosity at low energy.

The VEPP-2M collider which operated since 1974 in the energy range 0.4<E_{cm}<1.4 GeV completed operation in 2000. The machine reached a peak luminosity of $4x10^{30}$/cm^2/sec on the ϕ resonance and delivered a total of 80pb^{-1} in its lifetime. This machine was decommissioned to make room for the new VEPP-2000 collider that will be capable of higher energy collisions (1 <E_{cm} <2 GeV) and higher luminosity. The VEPP-2M machine has been removed and VEPP-2000 is now under construction.
 The design luminosity of $1x10^{32}$/cm^2/sec relies on the large beam-beam tune shift (ξ_y = 0.075) which may be achieved by colliding round, rather than flat, beams at the interaction point. Superconducting solenoids are placed on either side of two interaction points. Each pair rotates the planes of betatron oscillations by 90° so that vertical and horizontal motion toggle on each half-turn, resulting in full emittance coupling. With equal horizontal and vertical beta functions at the IP, round beams result. The round beam operation of VEPP-2000 will be another important test of the round colliding beam concept for increasing the beam-beam tune shift limit in e+e- colliders.

The VEPP-5 collider has been proposed as a two-ring high luminosity tau/charm collider with maximum center-of-mass energy of 5 GeV. There are three operating scenarios envisioned. In the first, a luminosity of 10^{34}/cm^2/sec is achieved with round beam collisions. In the second, longitudinal beam polarization is possible at a reduced luminosity of 10^{33}/cm^2/sec. In a third mode, a monochromatization scheme is used for studying narrow states. In this mode, a mass resolution of ΔM = 50 keV can be achieved at luminosities of 10^{32}/cm^2/sec. The injector complex for VEPP-5 is already constructed.
A design is in place for a ϕ-factory to be built in the VEPP-5 injector complex based on a "four-wing" design.

F.10   An e$^+$e$^-$ Collider in the VLHC Tunnel:

An energy frontier e$^+$e$^-$ collider (the Very Large Lepton Collider, VLLC) located in the Very Large Hadron Collider tunnel is under discussion [12]. The machine design is based on an extrapolation of the technology used in LEP. The energy range of 90<E$_{cm}$<200 GeV would provide large samples of Z^0's, allow studies of a light Higgs, high resolution studies of the $t\bar{t}$ threshold and searches for light SUSY states. Some of the parameters of the machine are summarized in Table 2.

Table 2:   Parameters of a Very Large Lepton Collider

Beam Energy (GeV)	185 GeV
Circumference	233 km
Luminosity	7x10^{33} /cm^2/sec
β_y^* , β_x^*	0.01, 1.0 m
Beam-beam tuneshift	0.14
Dipole Field at 45 GeV, 185 GeV	57, 238 Gauss
Total SR Power	100 MW
RF Voltage	4.6 GV

A luminosity of 7x10^{33}/cm^2/sec is expected with 12.6 mA in 126 bunches. A 100 MW synchrotron radiation power limit is assumed for the purposes of machine design. The RF system operates at 352 MHz and would use cavities of niobium sputtered on copper operating at 8 MV/m. The placement of RF cavities in the ring is chosen to minimize the sawtooth effect on the closed orbit. The electron and positron beams would probably be confined in separate rings and brought into collision at a single interaction point to avoid the destructive effects of the parasitic beam-beam interaction. The dipole field is 57 Gauss at injection and 238 Gauss at full energy. Shielding the beam at low-energy from stray fields, such as fringe-fields from the VLHC magnets is a concern.

The question of the achievable beam-beam tune shift parameter in such a high-energy accelerator is an interesting one. Experience at LEP shows that the tuneshift scales with damping decrement, saturating at 0.12 for LEP parameters at 100 GeV. This suggests that a large tune shift of 0.14 for the VLLC could reasonably be expected.

There are several important issues that are under consideration for this machine. First, the transverse-mode coupling instability (TMCI), important at low-energy, will ultimately place a limit on the single bunch current. Careful attention to the vacuum chamber design is required to minimize the transverse impedance in this large ring, and injection at the highest possible energy is necessary. An energy of 45 GeV would be required for injection, so the injector for the VLLC could operate as a Z-factory in itself capable of a luminosity of 1x10^{33} /cm^2/sec.

The requirements imposed by TMCI place special importance on minimizing the impedance of the vacuum chamber. As a result, a "no-bake, no-bellows" vacuum system has been proposed to reduce the impedance. Advantage has been taken of the high critical energy of the SR emission (u$_c$ = 450 keV) by placing SR absorbers outside the vacuum chamber. The SR photons penetrate a 1mm thick Al window so that the SR power is absorbed in copper blocks external to the vacuum chamber. This novel design simplifies the chamber cooling and also reduces the outgassing.

Many questions remain: What is the injection energy and injector system? What polarization is required and achievable? What is the energy range of the main ring? Is an e-p option desired? What does an optimized Z factory look like? What is the cost? Clearly, this machine makes sense only in the context of a VLHC. Additionally, the rationale and timing must take into account the overall planning of an e+e-linear collider.

F.11   An Asymmetric Collider at the ψ''

Initial studies on the possibility of an asymmetric e$^+$e$^-$ collider at the ψ'' has started [13] to look for small mixing between D^0 and it antiparticle. This accelerator would collide a 50 GeV positron beam

against a 142 MeV electron beam at a 90 degree crossing angle to allow for the decaying D^0 mesons to be cleanly measured. The optimum accelerator parameters and layout are under study.

G.   Research Topics for Circular Colliders

Here is a discussion of research topics that deserve the attention of the accelerator physics community to advance the luminosity and energy frontiers of e^+e^- colliders, as described above.

G.1   Interaction Region Issues:

The competing requirements of ever-higher colliding beam currents, and precision tracking with low detector backgrounds, brings interaction region design to the forefront of research topics for future e^+e^- colliders. A great deal of information and experience on the machine-detector interface has been gained in the design and operation of the present-day B-factories. This experience provides a strong foundation for tackling the machine-detector interface problems, which need to be solved in order to extend the performance of the existing machines, and to successfully operate future high-luminosity colliders.

The IR research topics, which need further attention, fall into four broad categories: achieving smaller β^*, beam separation, machine-detector real-estate, and beam-generated detector backgrounds. Naturally, these categories are heavily inter-related.

Detector backgrounds are the primary concern of interaction region design. In addition to the (well-known) sources of detector backgrounds, lost particles from beam-gas scattering and scattered synchrotron radiation, new sources of background will be apparent in the future machines under discussion. For example, the SBF proposes to operate in a short-lifetime mode, in which the beam current is replenished through continuous injection. The losses in such a machine will be orders of magnitude more severe than in present machines.   Indeed, luminosity itself will present a significant "background." The operation of low-energy machines requires careful consideration of Touschek losses (as is already observed at DAFNE).   Continued effort in understanding the sources of beam-generated backgrounds and in understanding the loss mechanisms is essential for the development of future machines. Finally, the detector technology must advance in-step with increased luminosity performance. New technologies must be identified to handle the increased radiation levels and high occupancies.

Colliders have continued to improve their luminosity by reducing β^*. A smaller focusing parameter requires placing the strong IR quadrupoles closer to the interaction point (IP), in order to limit the peak β-function in the IR. The combination of strong quadrupoles and large β-functions generates chromaticity, which must be compensated by stronger sextupoles in the machine arcs. These strong sextupoles eventually limit the machine's dynamic aperture. Recently, it has been proposed (for the VLLC IR) to design interaction region optics with a finite η', in order to achieve local chromaticity compensation in the IR. Such a scheme should be carefully evaluated in simulation and with experiments at a colliding-beam facility.

Ever stronger and smaller IR quadrupoles are required to produce small β-functions at the IP. Quadrupoles of small cross-section are an essential requirement from the standpoint of detector tracking solid-angle. As the focusing quadrupoles are moved closer to the IP, their cross-section must shrink to avoid infringing on the detector solid-angle. Recently, small cross-section super conducting quadrupoles were constructed for the HERA upgrade. Quadrupoles of this type may soon find use in the interaction regions of e^+e^- colliders.   Research should be directed towards incorporating such magnets in future IR designs.

There is a desire amongst the experimentalists to further reduce the central detector beampipe radius in order to improve particle-tracking performance. The choice of beampipe radius is determined primarily from detector background concerns. Research should be directed toward understanding the fundamental limitations in the beampipe radius.

There is active interest in exploring round colliding-beams as a path towards higher luminosity. An interaction region optics optimized for round-beams presents significant challenges to the IR detector background shielding design. The very large β-functions in the IR give rise to potentially large synchrotron radiation backgrounds.   Further effort should be devoted to shielding designs which make possible high-current round-beam collisions.

Separation of the two colliding beams presents another complication in the interaction region design. The geometry of the IR is determined largely from consideration of the IR parasitic crossings. These in turn may require crossing-angles to generate increased separation. The crotches, which take each beam to its own vacuum chamber beyond the collision point, absorb large synchrotron radiation power, and generate large HOM power. Simple scaling from present day power levels leads to uncomfortably high power deposition. Further effort in the design and modeling of the IR geometry is needed to accommodate higher beam currents in the future.

G.2   Beam-Beam Interaction Issues:

The ultimate luminosity performance of e+e- colliders is limited by the beam-beam interaction. In more than three decades experience with e+e- collider operation much has been learned, but the fundamental limitations of the beam-beam interaction remain unclear. Experience at CESR shows that the beam-beam tuneshift limit in a particular collider is not pre-ordained nor fundamental; indeed, through active exploration of parameters and careful attention to the linear optics and coupling, the beam-beam tuneshift parameter may be steadily increased over the course of time. This is evidenced by the increase in the beam-beam tuneshift parameter in CESR of a factor of two in the last decade.

The good beam-beam performance of the B-factories, achieved rather soon after turn-on, gives confidence that future machine designs can also plan on better beam-beam performance than was achieved in the previous generation of e+e- colliders.

Improvement in the beam-beam performance of the existing machines depends on very careful manipulation and control of the closed orbit, linear optics, dispersion, and x-y coupling. Much empirical "tuning" is required to achieve optimum beam-beam performance. Often, the effects of empirical tuning lie beyond the reach of our present diagnostic capabilities. Thus, achieving good luminosity performance remains part "art" and part "science". The detailed inter-relation between the closed-orbit, linear optics, coupling and luminosity needs to be unraveled. More effort needs to be devoted to real-time monitoring and correction of the critical optical parameters, since they play such an important role in the ultimate performance. Appropriate diagnostics and correction algorithms need to be developed which automate machine "tuning" and the maintenance of good machine performance. The lack of control of these critical parameters is evidenced by the number of accelerator operations staff that are required to maintain a collider at peak performance.

The recent experience at LEP, which revealed the dependence of the beam-beam tune shift limit on the damping decrement, points toward one route for improved beam-beam performance. The LEP result has obvious implications for the luminosity achievable in the VLLC. Is there a way to harness this capability at lower energies?

With the introduction of strong damping wigglers to the lattice, colliders may be operated at energies lower than was originally designed. These wigglers introduce strong lattice non-linearites that impact the single-beam and beam-beam dynamics. More effort is needed in understanding the implications of these strong non-linearities, and in the mitigation of their effects.

Interest in the collision of round beams (rather than flat) as a route toward increasing the beam-beam tune shift limit has been around for more than a decade. Experiments at CESR showed a factor of two improvement in the beam-beam tune shift limit with the collision of round beams. Further experiments are forthcoming at CESR and VEPP-2000. It remains to be seen if round-beam collisions can be harnessed for real luminosity production. Further work, both experimental and theoretical, is justified given the potential luminosity gain.

For specialty colliders of the future, beam-beam studies of a linac beam colliding with a ring beam and two rings of different energies colliding should be studied to expand our design capabilities.

Finally, the field seems to be entering a new era in strong-strong beam-beam simulations. We are beginning to see simulation results that include the full complexity of the beam-beam interaction, together with detailed particle transport. These simulations are beginning to shed new light on the beam-beam interaction itself, as well as aid in the understanding and operation of the existing colliders. We have the opportunity to learn with the combination of powerful simulations and data from several operating colliders. The field should take advantage of this situation both to improve the luminosity of the operating machines, and to further understand the fundamental limitations of the beam-beam interaction.

G.3   Very High Current Beams:

A major direction for future e^+e^- colliders is to raise the beam currents to increase the luminosity. For example, in future high luminosity B-Factories the beam currents must be increased by an order of magnitude. As a result, many accelerator issues arise including stronger beam instabilities, stress fatigue in components, large wall plug power, RF power generation, and RF frequency choices.

The largest burden for higher currents falls on the RF system. The higher currents will require additional RF cavities and stations resulting in higher impedance and stronger instabilities. The larger system will require additional inter-station control. The bunch lengths need to be shortened and the additional RF voltages will shorten the bunch but also increase the synchrotron frequencies. In general, the overall RF frequency needs to be chosen to minimize energy use and instabilities. The use of energy storage cavities will be investigated to minimize longitudinal instabilities.

The power consumption of the future machines may reach upwards of 100 MW. The higher power comes from increased synchrotron radiation power as well as HOM power and resistive wall losses from the shortened bunch lengths. Thus, efforts to reduce the wall power for the increased luminosity are highly encouraged. Vacuum chamber designs emphasizing lower impedance will also be crucial.

The electron cloud instability (ECI) can transversely enlarge a positron beam, e.g. in a B-Factory, or heat vacuum chambers, e.g. in the LHC. Further studies are needed to find the full extent of this effect in various accelerators and to find cures. Beam chamber solenoids of order 30 gauss have been found to be a partial cure. However, high current colliders will need future improvements that include solving the ECI issues inside the dipole and quadrupole magnets. The optimum material and surface geometry (roughness) for the vacuum chamber surface also need further study.

With the proposed higher currents in the next round of B-Factories, the longitudinal and transverse feedback systems will need significant upgrades. The currents will be an order of magnitude higher and the coupled bunch modes more unstable. The combination of energy storage cavities and bunch-by-bunch feedbacks may solve the longitudinal instabilities. How these two cures work together has not been studied. The transverse feedback will also need increased strength. Kicker structures will need an improved design as the beam heating will be too high if the present existing structures are used.

Finally, stress fatigue of vacuum chambers from temperature cycling from the high beam currents is now an important factor in B-Factories. Future studies will lead to improvements in the design of vacuum chambers that can be exposed to larger temperature extremes and more cycles. Continuous injection may help reduce this situation. New designs of vacuum pumps and pumping plenums may also reduce the chamber impedance and allow more beam current.

G.4 Basic Accelerator Physics:

Future colliders will surface new accelerator physics effects as well as reemphasize several old effects. These effects include optical lattices, instabilities, radiation damping, beam-beam interaction, and low and high field magnets effects.

The electron cloud instability (ECI) can enlarge a positron or proton beam size and reduce the luminosity along the bunch train. This effect arises when electrons trapped in the positively charged beam interact with individual bunches to cause instabilities. Vacuum chamber solenoids are a partial cure for ECI by keeping the electrons from the beam, but only at present in the drift vacuum chambers. Additional cures and reductions must be investigated, calling for new simulations, experiments, and chamber studies. The studies of ECI around the world are growing each year as more accelerators are seeing or will see the effects of ECI.

High current B-Factories, CESR-c, VEPP-2000, VLLC, and other accelerators will enter a regime where the Touschek effect significantly reduces the beam lifetime and, perhaps, a related effect, Intra-Beam Scattering (IBS), will enlarge the transverse and longitudinal beam sizes. The parameters of these present and proposed accelerators are being carefully studied in light of Touschek and IBS. The theory of Touschek and IBS is constantly being improved and future improvements are needed as measurements of IBS and calculations do not always agree. For example, in intra-beam scattering calculations, x-y coupling should be added and the transverse discrepancy between the Piwinski and Mtingwa-Bjorkan codes should be determined.

Studies of the longitudinal beam dynamics of multi-bunches are needed for the next generation of higher current B-Factories. The closely spaced bunches will interact more strongly with the RF cavities and the resulting instabilities must be minimized and managed.

Further advances in bunch-by-bunch instrumentation are required to enable understanding of the underlying limitations to machine performance. Luminosity, tunes, beam sizes, current, current losses, dipole motion, and head-tail oscillations are some of the bunch-by-bunch measurements that are needed along the beam trains. The bunches are spaced only a few nsec apart.

Several new colliders will be rebuilt to operate at lower than the design energy and will use very strong wiggler magnets to increase radiation damping as well as the beam-beam tune shifts. These wigglers add strong lattice nonlinearities to the accelerator lattice, which need further investigation. These studies are also of interest for light sources and linear collider damping rings.

The proposed electron-positron rings for the VLHC will need to inject at very low energies and, thus, low dipole fields. The method to make a stable beam with these very low field magnet strengths is not clear as the dipole magnetic fields will be comparable to the earth's field. Furthermore, the overall lattice design must take into account many factors. For example, the lattice magnet spacing of the VLLC should be the same as for the low energy VLHC to allow for e-p collisions in the future.

Finally, optical lattices which are flexible enough to allow independent adjustment of momentum compaction, dispersion, damping times, and beta functions are needed. These adjustments will aid in the changes in the accelerator collider to optimize the beam-beam parameters and, thus, the luminosity.

H.   Acknowledgements

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