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New Techniques for Particle Accelerators

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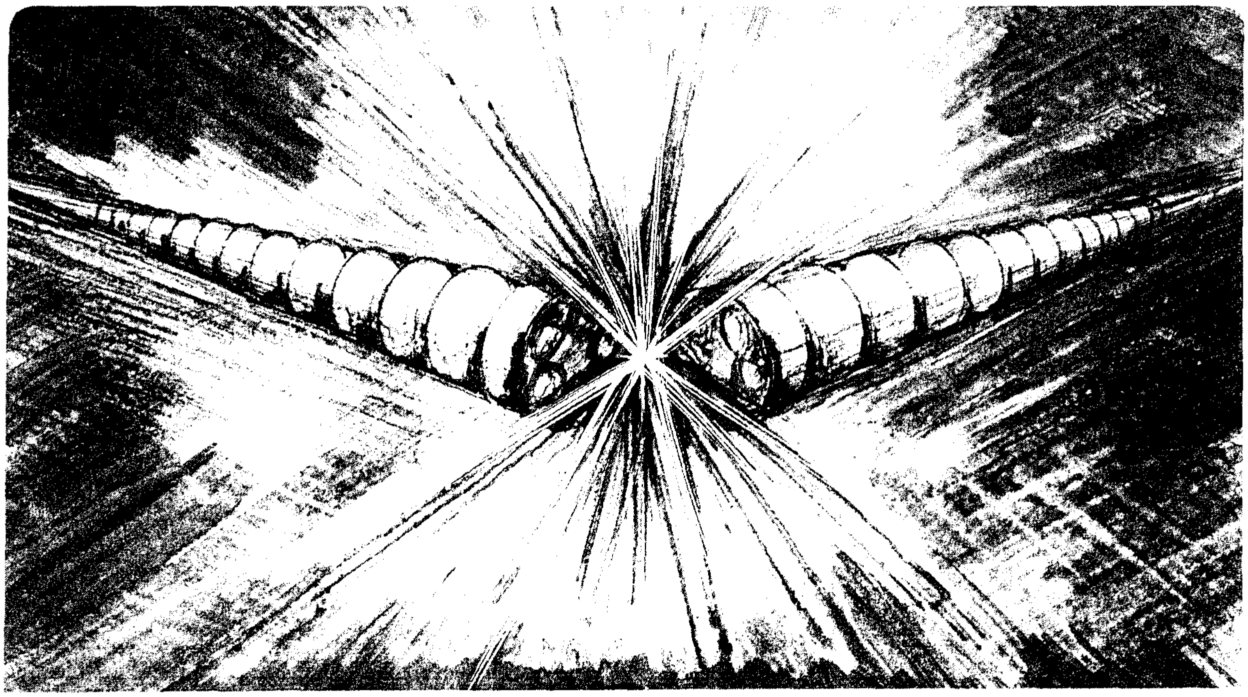

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NEW TECHNIQUES FOR PARTICLE ACCELERATORS*

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Abstract

A review is presented of the new techniques which have been proposed for use in particle accelerators. Attention is focused upon those areas where significant progress has been made in the last two years—in particular, upon two-beam accelerators, wake-field accelerators, and plasma focusers.

I. Introduction

Although novel methods for acceleration have been considered for a very long time, it was at Los Alamos in 1982, at the first Workshop on The Laser Acceleration of Particles[1], that efforts were made to systematically characterize the various concepts. Subsequent workshops in that series, at Malibu[2], at Madison[3], and at Lake Arrowhead[4] have detailed the very large progress made, during the decade, on advanced accelerator concepts. During the same period, a series of workshops was held in Europe: at Oxford[5], at Frascati[6], and at Orsay[7]. The interested reader will wish to study much in these seven volumes.

I want, in this review, to discuss the present state of novel concepts. I must do that with only a minimum of repetition, while making my presentation accessible to many. Not easy ! Rather than work within the general framework developed at Los Alamos I simply list, in Table 1, the concepts that still remain viable at this date. The Table has many references; not a complete list, but enough as to allow the reader to enter the original literature without too much difficulty. (As a result, detailed ideas will not be further referenced in this review.) Into the list in Table 1 has been built my personal prejudice, for I have ordered concepts, with the most interesting devices, the most likely ideas to come to fruition, in my opinion, listed first in each Category. (Naturally the concepts that I work on are high on the list, but any other ordering would be less than honest.)

Table I. New Techniques for Particle Accelerators

I. Accelerator Concepts

1. Two-Beam Accelerator (Relativistic Klystron)[8]
2. Two-Beam Accelerator (Free-Electron Laser)[9]
3. Plasma Wake-Field Accelerator[10]
4. Wake-Field Accelerator (Cu structures, dielectrics)[11]
5. Switched Power Accelerator[12]
6. Plasma Beat-Wave Accelerator[13]
7. Plasma Implosion Accelerator[14]
8. Inverse Free-Electron Laser[15]
9. Inverse Cherenkov Accelerator[16]

II. Power Sources

1. Klystrons[18]
2. Crossed Field Amplifiers[17]
3. Binary Pulse Compression[19]
4. CARMs[20]
5. Gyroklystrons[21]
6. Gyrocons[22]

III. Focusing, Compensation, Damping

1. Plasma Lens[23]
2. Adiabatic Compressor[24]
3. Plasma Compensation[25]
4. Plasma Damper[26]

Some of the concepts are receiving very little work (such as I-5, I-7, I-8, I-9) while a few are receiving good effort, but have not yet yielded to this effort (such as I-6). Let me leave aside Category II, on the grounds that the work is not sufficiently "new", although we well-realize that often significant progress, really important progress, is made on things which aren't considered novel. In the first Category considerable work, and considerable progress over the last two years, has been achieved on I-1 to I-4; we shall go into these four concepts in some detail in Sections II and III. Category III consists of devices which aid in accelerator technology, but are not concepts for acceleration. (Back in 1982 we didn't even consider this Category.) Some of the most likely prospects for early realization are in this Category and we shall go into III-1 and III-2 in some detail in Section IV.

II. Two-Beam Accelerators

The Two-Beam Accelerator (TBA) was first proposed in 1982. Since that time a great deal of work has been done on the concept. Basically, an intense low-energy beam is employed to repeatedly produce microwaves which are then used to accelerate a beam to high energy. The concept is shown schematically in Figure 1.

Four versions have been developed: two employ a free electron laser (FEL) as the power converter (from electron beam power to microwaves) (TBA/FEL), and two employ a relativistic klystron (RK) as the power converter (TBA/RK). Two replenish the beam power with induction acceleration, and two with superconducting cavities.

The heart of the Two-Beam Accelerator is the power generation unit. These units could be used, individually, as power sources. Generally, the units seem too expensive (although that may not really be the case; the units, Relativistic Klystrons or Free-Electron Lasers, have the advantage that they are known to work). One can imagine putting a few units together, even mixing them up (the "after burner" concept); if one uses a large number of units then one arrives at a TBA.

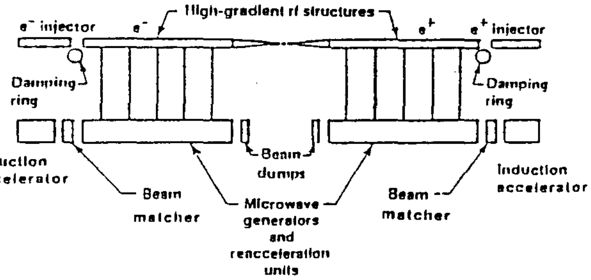

Fig. 1. Schematic of a Two-Beam Accelerator. The low energy drive beam provides power to the high energy beam. Reacceleration is provided by induction units or with superconducting RF cavities. Conversion of beam energy to microwaves is provided by either relativistic klystrons or free-electron lasers.

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I would like to first, very briefly, review the status of the power generation units, and then turn to some TBA concepts.

1. Free-Electron Laser

The first experiment was done by the LLNL/LBL group in 1986. I remind you that, operating at 35 GHz, and using 850 A of 3.5 MeV electrons, they generated over 1 GW of peak power corresponding to an efficiency greater that 34%. Recently the KEK group has started an experimental program to generate 11.4 GHz radiation with an FEL.

2. Relativistic Klystron

A great deal of work has been done on the Relativistic Klystron (RK), with perhaps the most interesting results those of the LLNL/SLAC/LBL group. They have been able, operating at 11.4 GHz, and using a 550 A, 1.3 MeV electron beam sent through a multi-cavity klystron, to extract 290 MW of peak power in a pulse of about 50 ns, corresponding to an efficiency of 40%. The CERN group is building a facility for studying the generation of microwaves at 28 GHz.

3. Concepts

In the RK version of the TBA the microwaves may be easily transferred from the drive structure to the high gradient structure (HGS). The FEL is a very effective source of microwaves, but the extraction is non-trivial. On the other hand an RK can only be made to work up to some critical frequency (which seems to be close to the experimental studies at 11.4 GHz). Operation at higher frequencies has distinct advantages of economy in capital cost and operating cost, but seems to require an FEL.

The most straightforward method of extracting microwaves is with a "septum coupler". However, this approach, in a very restricted experimental study, was observed to be limited by breakdown at low microwave intensity. Theoretical studies of microwave extraction have resulted in a number of possible configurations, no one of which is ideal.

An interesting method for removing microwaves, in a RK, has been proposed by H. Henke. This method employs a drive cavity and a high gradient structure in close resonance, so that beats between the two structures result in transfer of energy from the driver structure to the HGS. In the coupled cavity version of the TBA/FEL, the method proposed by Henke (for an RK) is used in the FEL version. In addition, the coupled cavity TBA can be operated in a mode where the energy of particles is close to constant, which is quite advantageous as has been emphasized by R. Pantell.

In order to employ beats between the drive structure and the HGS there must be cavities that "hold" the microwave field for a significant fraction of the beat cycle. In the usual FEL the microwave field is travelling with roughly the same velocity as the particles, but it is possible to have a phase velocity that allows for slippage of one wave while traversing one period of the wiggler (the well-known FEL resonance condition) and yet have a group velocity that is zero, i.e. allows the electromagnetic pulse to remain stationary in space. In short, one can operate an FEL in the "strong slippage" regime, and that is just what is employed in the coupled cavity scheme.

Putting all these ideas together, we arrive at the configuration shown in Figure 2. Experiments are being done at Northstar, and are being considered by UCLA, MIT, and LLNL.

III. Wake-Field Accelerator

Wake-field accelerators employ a large charge (the "drive beam") or a photon pulse (the "drive pulse") to create fields in a structure, which fields are then employed to accelerate a small charge to high energies. Typically, the small charge is just a few RF cycles behind the drive beam, and the structure is either made of conventional materials or is a plasma. Equivalently, one can think that the drive particles leave behind a wake which accelerates the following group of particles. In short, an intense beam of low energy drives a few charges to high energy.

Clearly, conservation of energy requires that the accelerated charge must be smaller than the drive charge. The wake-field theorem, also based only upon conservation of energy, has much stronger implications. It says that if a point charge is sent through a passive structure on the same trajectory as the drive charge, also assumed to be a point charge, then the accelerated particles can gain, at most, twice the energy of the drive particles. This tends to defeat the whole concept. All wake-field schemes attempt to circumvent the theorem either by shaping the drive beam or by employing different trajectories for the drive and accelerated beams. (In addition "staging" is employed.) A measure of the degree of circumvention of the theorem is the "transformer ratio", which typically is designed for structures made of conventional materials to be 10, or so, rather than 2.

Another general theorem is the Panofsky-Wentzel theorem which relates the radial variation of the longitudinal wake (the accelerating force) to the longitudinal variation of the transverse wake (the focusing, or defocusing, force). This theorem must be carefully observed when making a structure which will provide acceleration and (only modest) focusing.

1. Copper Structures and Dielectric Structures

A wake-field transformer, of copper, and with the drive beam a circular beam and the accelerated beam on axis, as shown in Figure 3, has been developed by the DESY group. A drive beam of 6 bunches, each of 5 nC, and separated by 2 ns, resonantly excited the structure and accelerated particles. The inferred gradient was 1.2 MeV/m over 16 cm. The DESY group has plans to build a large transformer driven by 90 bunches and with a transformer ratio of 35.

The Argonne group has explored the use of a dielectric tube, which has the distinct advantage of simplicity and compactness. In Figure 4 is shown the tube used in an experiment, the measured wake, and the theoretical wake. A drive beam of 2 nC, and length 25 ps, was driven through a tube of length 50 cm with radius 1.3 cm. The dielectric, having a constant of 6, had an inner radius of 0.6 cm. The measured gradient was 0.3-0.5 MeV/m, which is in excellent agreement with the theory.

There has been controversy, over the last year, about transverse wakes in a dielectric structure, but all parties now agree in that there is a wake whose value is about the same as in a copper accelerating structure. Nevertheless, dielectric structures may be of interest. They must be resonantly excited (because the heating is excessive in regular, resonant, excitation) and hence must be employed as wake-field structures. A major concern is electric breakdown, and that remains to be studied experimentally, but it seems unlikely that a gradient in excess of a few hundred MeV/m can be attained (but that value is nevertheless of interest). A second major concern is that of transverse stability of the accelerated beam, which must be very good if micron size beams are to be brought into collision. The Argonne group has plans to build a large dielectric wake-field transformer having a transformer ratio of 1.5 and attaining 1 GeV.

2. Plasmas

Wake-fields in plasmas have been observed at Argonne where with a plasma of 30 cm length and density of 10^{13} cm^{-3}, and a beam of 5×10^{11} cm^{-3}, they measured a gradient of 5 MeV/m.

Subsequent work at KEK was done in a plasma of 2-9 x 10^{11} cm^{-3}, and length of 75 cm. Using a 5 bunch comb of 1 nC pulses separated by 10 cm, they measured an acceleration, at the last bunch, of 7 MeV/m.

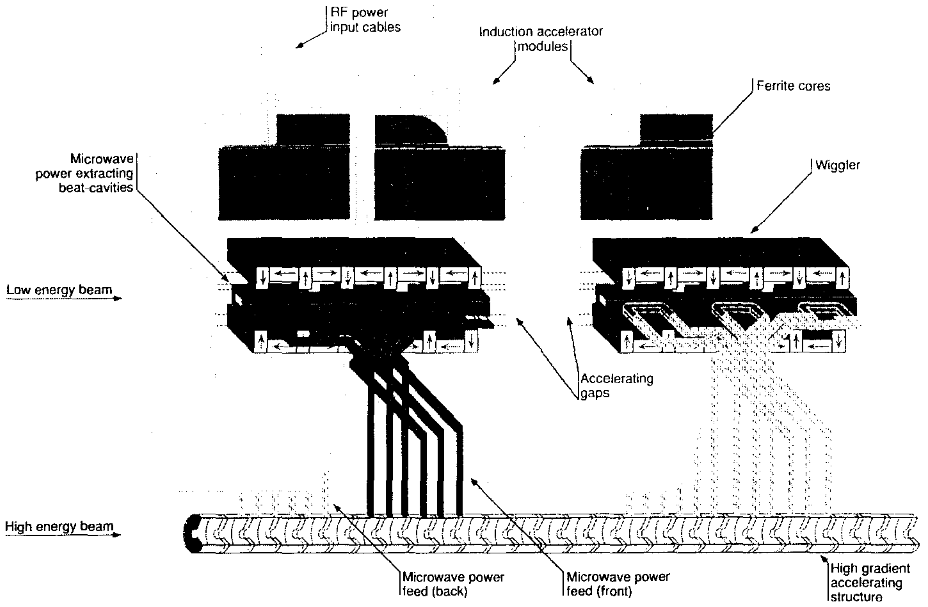

Fig. 2. Schematic of a Coupled Cavity version of the Two-Beam Accelerator with re-acceleration by induction units and microwave generation is by means of a free-electron laser. The coupling to the high gradient structure is by means of waveguides.

In order to obtain a high transformer ratio, one can contemplate drive bunches which are shaped so that the bunch intensity ramps up and then drops to zero quickly (in less than the ω_p^{-1} time). Thus plasmas give the hope of achieving very large gradients (of the order of 10 GeV/m) and transformer ratios of tens. An experiment to achieve 100 MeV, in 7 cm (gradient of 1 GeV/m) and a transformer ratio of 7, is being considered by UCLA.

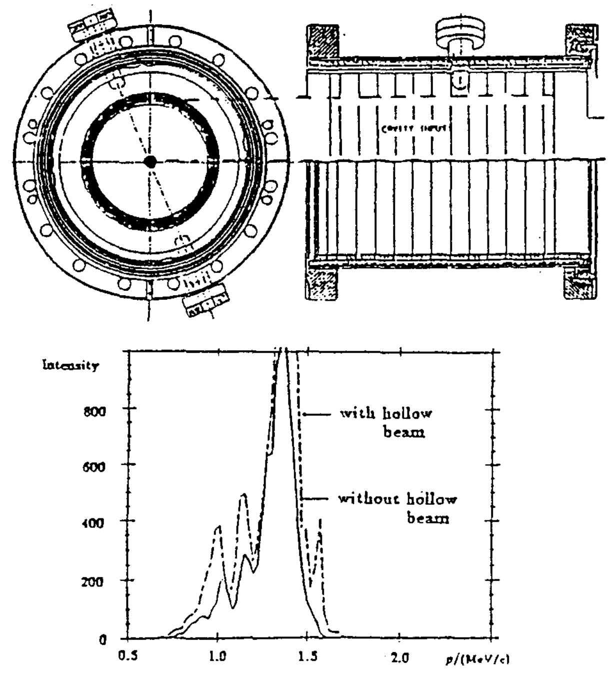

Fig. 3. The wake-field accelerator developed by the DESY group. A drive beam of 6 bunches, each of 5 nC, and separated by 2 ns, resonantly excited the structure and accelerated particles. The inferred gradient was 1.2 MeV/m over 16 cm. (Bialowons, et al 1987)

IV. Plasma Focusing

Plasma lenses, and the adiabatic focuser, both focus relativistic beams because the plasma shields out the beam's electric field. Since the electric and magnetic forces cancel, to order γ^2 in a freely propagating beam, shielding of the electric force leaves the magnetic force to focus the beam. This force can be very large; in a collider (where the beam is intense and focused to a very small radius) the resulting force is many orders of magnitude greater than can be achieved with conventional focusing elements.

At low density a plasma shields the electric forces, and not the magnetic. At high density it can shield both, which is the basis for the proposal of a plasma compensator that can reduce beamstrahlung. This idea will not be discussed here. (Item III-3)

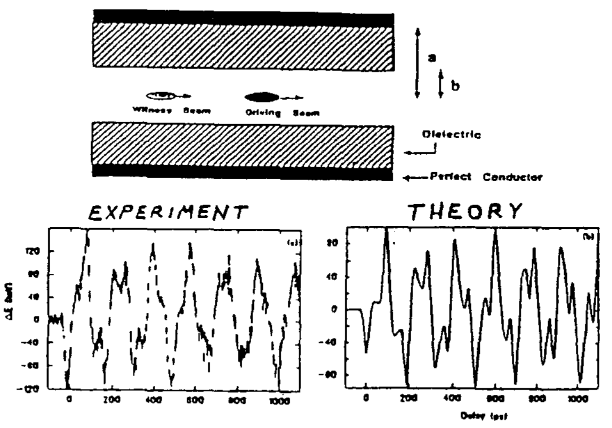

Fig. 4 . The dielectric wake-field experiment of the Argonne group. A drive beam of 2 nC, and length 25 ps, was driven through a tube of length 50 cm and a=1.3 cm, b=0.6 cm, and dielectric constant 6. The measured gradient was 0.3-0.5 MeV/m. (Gai, et al 1988)

The plasma density can either be higher than the beam density (overdense case) or lower than the beam density (underdense case). In the first case, since the beam is a perturbation, the plasma dynamics (which is the hard part of the problem) is easy. Furthermore, beams of both signs of charge experience almost the same behavior, for plasma electrons either move a bit in (so as to compensate the beam charge when the beam is positive) or they move a bit out (again to compensate the beam charge when the beam is negative). The plasma ions hardly move, since they are massive.

In the underdense case, and for a negatively charged beam, the plasma electrons get blown out of the beam, and even beyond that, so as to make a channel of ions. The motion of the plasma is clearly non-linear, and it is hard to analyze. A representation of the phenomena is shown in Figure 5. Because, in the laboratory frame, the focusing is simply due to the plasma ions, this is often called ion focusing. It has been shown, in many experiments, to be effective. Perhaps the most dramatic demonstration of ion focusing has been at Livermore, where a beam of electrons, of 10 kA, has been transported for more than 50 m.

In the underdense case the behavior of the beam very much depends upon the sign of charges in the beam. At first sight, the lens would seem not to be effective for positively charged beams, but numerical simulations show that plasma electrons are pulled in to the beam, make a very non-linear lens, but still provide some focusing.

1. Plasma Lenses

In the overdense case, the focusing from a plasma lens depends upon the beam current. Thus there are strong spherical aberrations as well as a longitudinal variation of the focusing. Both effects limit the degree of focusing possible; i.e., the beam spot size which is achievable. All in all, and especially remembering that the background will be greater in this case, an overdense plasma seems less attractive than an underdense plasma.

In the underdense case, the focusing force does not depend upon the beam density (provided, only, that the plasma channel radius is larger than the beam radius), and hence the lens has fewer aberrations. (The beam pulse must be short enough so as to avoid ion motion.) A numerical example, for the SLAC linear collider, SLC, has a lens of only 0.6 cm with a focal length of 1.0 cm. It can focus a beam of electrons, of initial radius 6 μm, down to 0.5 μm and a beam of positrons, of initial radius 6 μm, down to 1.2 μm. It produces a luminosity in excess of the design luminosity. Background is, of course, an element of the lens, but perhaps it is not excessive; i.e., detectors can be designed to operate despite the background.

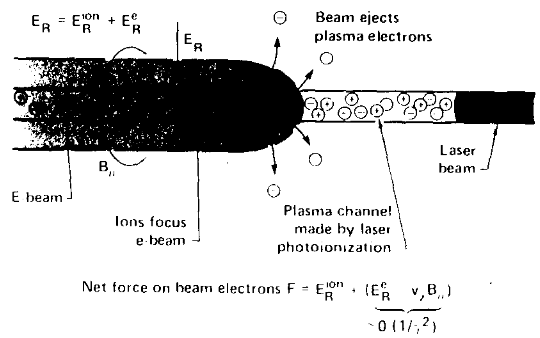

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Fig. 5. A drawing showing the behavior of a pre-ionized plasma channel down which a beam of electrons is sent. The drawing represents an underdense situation. The plasma electrons move out of the beam, forming a plasma channel inside of which the plasma ions focus the beam. The plasma focusing can be very strong.

2. Adiabatic Focuser

The adiabatic focuser is a variation of an underdense plasma lens in which the focusing is ever-increasing along the beam trajectory. This has the consequence that the beam is focused down to an ever-smaller size. In fact, the focuser is remarkably insensitive to particle energy; a consequence of the fact that the focusing is continuous. Thus it is possible to focus beams down to very small sizes; in fact sizes that are unobtainable with discrete lenses. The fact that there is a limit for discrete lenses, and evaluation of this limit, is due to Oide.

If the beam is large then, while oscillating in the adiabatic focuser, it radiates its energy away before it is compressed to a small size. If it is small enough, then it can be compressed beyond the Oide limit. The critical size is given in terms of a critical normalized emittance, which only involves fundamental constants, and is $(3^{3/2}\ 15^3\ \lambda_c)/(2^3\ 4^2\ 22\ \alpha^3)$, where λ_c is the Compton wavelength and α is the fine structure constant. Numerically the critical emittance is 6.17×10^{-6} m, which is a very attainable value. Numerical examples of adiabatic focusers have been produced, but no experiments have yet been done.

V. Conclusion

The Two-Beam Accelerator (TBA) is rather close to having "pay off". Two forms of the central elements (conversion of beam energy to microwaves) have been established, and experimental study of re-acceleration will be done in the near future. Considerable effort, both theoretical and experimental, is being put into the TBA by a number of different groups, and we can look forward to further progress.

Wake-field accelerators have been built and the central concept shown to be correct. Conventional material structures would seem to have limited applicability, although there is interest in pursuing this work in a number of places. Plasmas have considerable potentiality, but clearly the time scale is long. Further work would appear to be merited, and may be done at a number of places.

Plasma focusing devices have been studied theoretically, and shown to have considerable promise. The effect has been experimentally observed, but only as a side effect in wake-field studies. One would hope that a significant experimental program will soon be mounted so as to study the many features theoretically described, but I know of none planned. I do know of talk at LBL, UCLA, ANL, and KEK.

Finally, there are many new techniques for particle accelerators and, even a decade after formalization of the field, many old concepts still remain viable, while new concepts appear at a steady rate. It is important to note that some concepts have the suggestion of early promise, while others—requiring very much longer development—have the potentiality of significantly advancing our capabilities. We can look forward to ever-more progress as a good number of investigators (even more would be welcome) work on, and a good amount of support (of course, not enough) goes into, these activities.

I am pleased to acknowledge the work of my many colleagues upon which this review is based.

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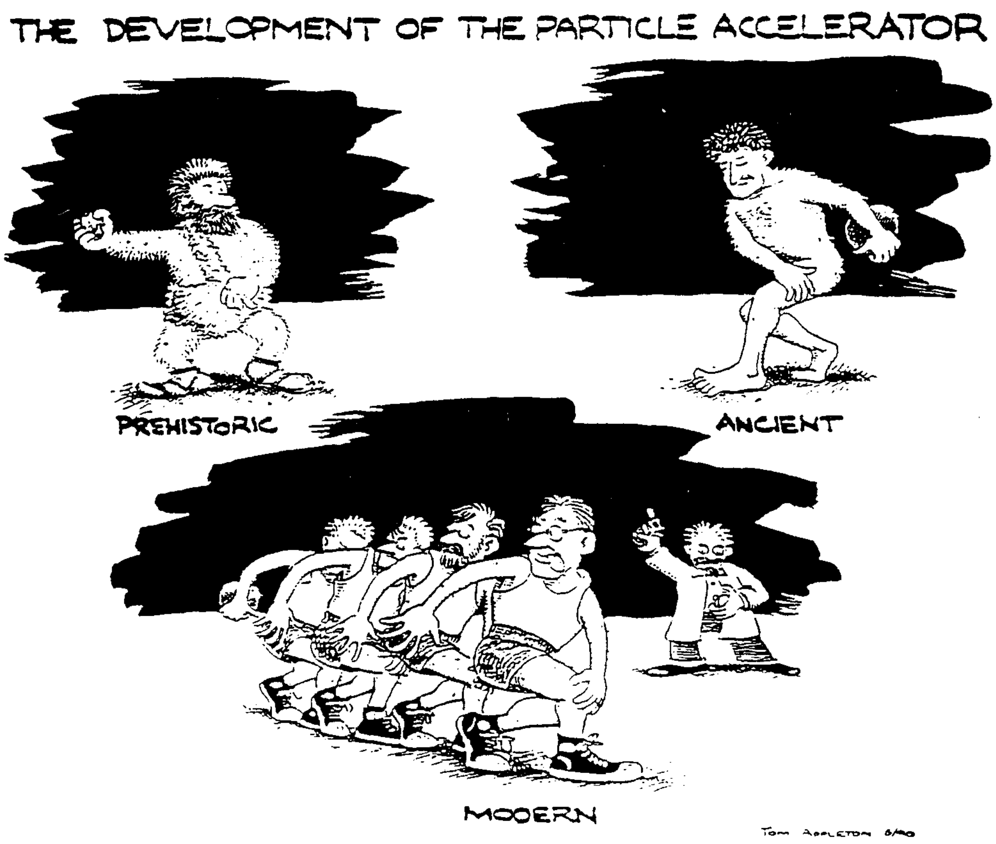

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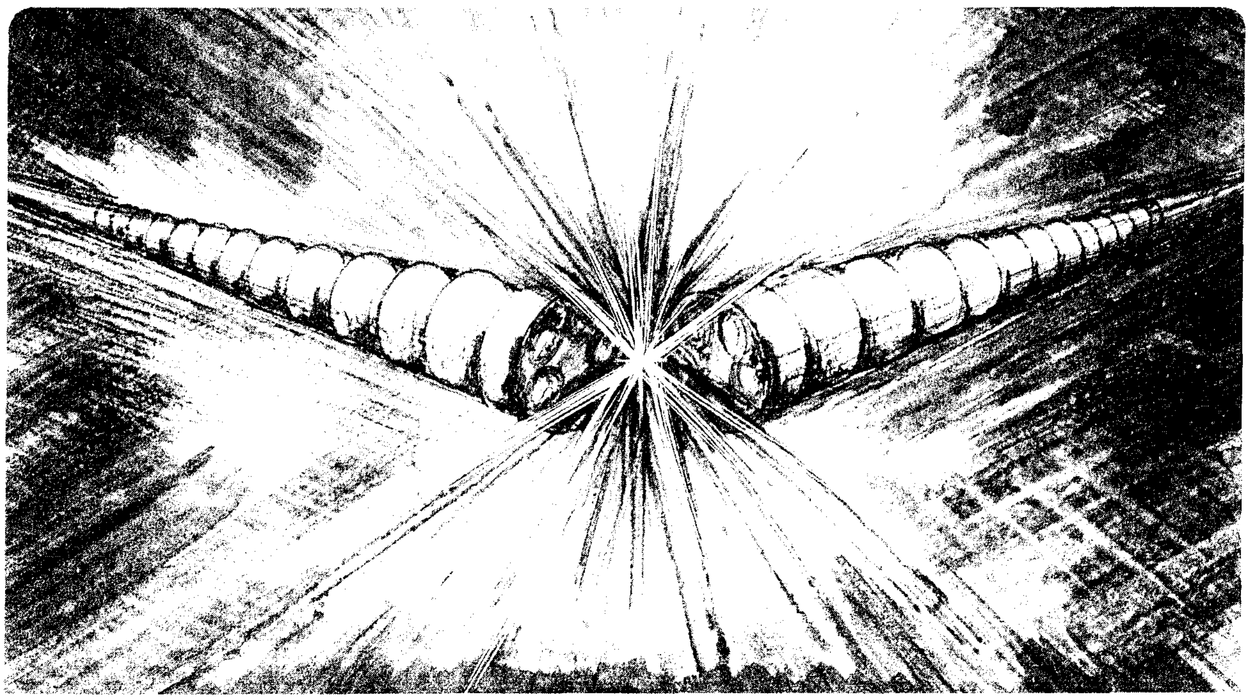

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Beam Dynamics Issues of High-Luminosity Asymmetric Collider Rings*

• Andrew M. Sessler

• **Abstract**

The beam dynamics issues presented by a high-luminosity asymmetric electron collider ring (such as is required for a B meson factory) are described. Attention is focused on lattice aspects, on single-beam effects, and on beam-beam interaction effects. The overall conclusion is that a facility with a beam of (about) 3 GeV in one ring and a beam of (about) 9 GeV in a second ring having a luminosity of between 10^{33} and 10^{34} $cm^{-2}s^{-1}$ is a feasible concept.

1. Introduction

The desire to study, in great detail, the B-$\bar{B}$ system and, in particular, to study the CP-violation in that system, has motivated the development of very high-luminosity asymmetric collider rings.[1] The development of such a collider presents new challenges to accelerator physicists, and in order to explore and assess the beam dynamics issues that this quest raises, a Workshop on the subject was called by the Lawrence Berkeley Laboratory and the Stanford Linear Accelerator Center in February of this year.[2]

The physics to be done at a B Factory requires an integrated luminosity of more than 30 fb^{-1}/year.[1,3] This is equivalent to a collider delivering a luminosity of at least $3x10^{33}$ $cm^{-2}s^{-1}$ for a third of each year (10^7 seconds). The required luminosity is larger than the present performance of colliders, in the same energy range, by a factor of at least 30. In addition, the collider must have a center of mass energy of 10-11 GeV with beam energy ratios of up to 5 to 1. (If the collider is symmetric in energy, then the luminosity required is larger than that given above, by an additional factor of about 5.) From the machine physicist's point of view the extrapolation in luminosity is much more of a challenge than the extrapolation from symmetric colliders to asymmetric ones.

In this article, we shall draw heavily upon the Workshop. On the very closing day of the Workshop, a small group of physicists gathered together and attempted to summarize

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the conclusions in a succinct form. The first section of their Summary is attached to this article.

Beam dynamics issues may conveniently be broken into three categories. The first is that having to do with "single particle" phenomena. Under this comes the design of a proper focusing lattice, RF acceleration, injection, extraction, radiation damping, quantum fluctuations, etc.

The second category consists of single-beam phenomena arising from the many-body aspects of a beam. Within this category are conventional "space charge phenomena" (negligibly small at relativistic energies), and also rather sophisticated phenomena such as intrabeam scattering, synchro-betatron mode coupling, and single- and multi-bunch coherent instabilities.

The third category consists of those phenomena that result from the interaction between beams where the non-linear forces are the primary source of concern.

In this paper we shall consider the beam dynamics of B Factories by discussing, in turn, single-particle phenomena, single-beam phenomena, and beam-beam phenomena. We shall not be concerned with various "practical" issues such as injection, e^+ production, vacuum, etc. They are, of course, important. We do note that the large luminosity implies a short beam lifetime and hence a dedicated injector and (probably) the ability to take data while "topping off" the beam. We start, first, with some general considerations.

2. General Considerations

Some of the elements that must be considered by the machine physicist are shown in Figure 1. Of course, we are not starting from scratch; circular colliders have been built, and carefully studied, for two decades. It is quite appropriate to ask in that context what must be done differently from that which has been done in existing colliders in order to achieve the performance specifications of a B Factory. In fact, this mode of reasoning is very simple, and almost unique in its results, so that all of the various proposals for B Factories (see Section 6) are quite similar in general nature.

The reasoning begins as follows: The beam-beam interaction puts a limit on the luminosity created by one bunch (meeting one bunch of the other beam) which we presently do not know how to exceed. We can make this limit as large as possible by focusing the beams to very small size at the crossing point ("low β^*"). But to get the required very large luminosity with a reasonable beam emittance will still require many bunches in each beam. Because of the many potential near crossings (even with the separation that can be achieved electrostatically) the collider needs to have two rings.

What are the consequences of this direction for the design? The first thing with which we must be concerned is multi-bunch effects, and we shall discuss this more in Section 4. Suffice it to note here that, due to the large current in each ring, there are severe multi-bunch instabilities and they must be handled by strong feedback systems. Even then it is critical to reduce their growth rates in the first place by proper design of RF cavities with reduced higher-order mode response. A second major consequence of the design is that the bunches must be separated rather close to the interaction point (because unwanted crossings must be avoided and the many bunches are close together). If the collisions are head-on—and experience suggests that the deleterious aspects of the beam-beam interaction are greatly enhanced if the crossing is not head-on—then powerful magnets are required near the crossing point and these produce synchrotron radiation background from which the detector must be shielded. We shall discuss this in Section 3. Alternatively, the crossing could be at an angle, but appear as if it is head-on; this approach would employ the suggestion by Bob Palmer of "crab crossing" (described below).[4] This scheme, which has not yet been studied very extensively, does not require the use of separation magnets and consequently is good from a masking point of view, but requires strong crab RF cavities near the interaction point. The technical feasibility of this scheme is unknown at this time. Being able to focus both a high energy beam (HEB) and a low energy beam (LEB) by a common set of magnets in the interaction region (IR) implies a novel and challenging feature of asymmetric machines. A third consequence of the design is that the very low β^* implies a concomitant need for very short bunches and, hence, a very powerful radio frequency system. It is clear from both the above that the RF system must be of special design that can deliver a large amount of power and voltage to the beam with a minimum number of cavities.

There are other consequences of our design direction, and some of them will be touched upon below. Much more can be found in the various design study documents being produced in the laboratories mentioned in Section 6, but the major consequences are as listed above and depicted in Figure 2. One cannot help but notice from Figure 2 and Figure 1, where all the issues seem to converge on the IR layout circle, that the design of the interaction region optics plays a central and crucial role in any high-luminosity collider design. No other aspect is as intricately connected to all others as is the interaction region.

3. Lattices

Perhaps one should start with consideration of the beam-beam interaction, for that is central to a B Factory design. Fortunately, however, the consequences of this subject can be summarized very succinctly, and that allows us to proceed in the logical order of designing a collider for single-particle effects and then, subsequently, concerning ourselves with many-particle phenomena. Of course, life is not that simple and there must be continual interchange between the experts in lattices and in many-body phenomena.

The physics of single-particle behavior in colliders has been set out in the classic work by Matt Sands.[5] Although that work is 20 years old, it includes just about everything one needs to know to design a collider. We shall not go through considerations that are well known, such as betatron tune, chromaticity, dispersion, radiation damping times and emittance, although all of these are needed to design a collider. (For example, we shall not comment upon the required beam emittance which is low, but in the range that has already been achieved.) Rather, we shall comment only in a very general way, upon the novel features that enter into B Factory design.

Perhaps the central complicating feature of the design is that there must be two rings. (Not completely new ground; think of the ISR, or HERA.) Thus the interaction region, with its separation of particles, and its production of a very low β^* at the crossing point is the most difficult part of the design. Of course, one must be concerned with chromaticity corrections, making straight sections in which wigglers can be inserted to produce and control low beam emittance and short damping times, and the myriad of other things that go into a lattice design. But the main complication comes about with designing the interaction region.

The difficulty is in the combined aspect of producing a low β^* and separating the beams, while at the same time not producing too much synchrotron radiation very near the interaction point. The low β^* can be produced by powerful focusing quadrupoles, but as the beams are separated, the one that is off-center in the quadrupole feels a large field and consequently bends and radiates. (The one on-center also radiates, but only because of its finite size.) In an obvious way, any dipole magnets that are employed to separate the unequal energy beams also produce synchrotron radiation from both beams. Rather strong magnets are needed to get prompt separation (as one moves away from the interaction point) because of the close bunch spacing.

A number of different suggestions have been made, and presently are being explored, for the interaction region geometry (see Section 6). In Figure 3 we have indicated the essential elements of two of these suggestions. As of this writing, no completely acceptable solution has been produced, although there is no reason to believe that one cannot be achieved. Of course, there needs to be considerable attention to the quality and nature of the required synchrotron radiation masks and the sensitivity of the detector to radiation. In addition to synchrotron radiation, there is the background from lost particles which is strongly affected by the beam-beam interaction that is the primary mechanism for putting particles into the tail of beam distributions.

One issue in the design is whether the beam is flat (aspect ratio of say 40 to 1) or round. It is unclear how much one gains in the beam-beam interaction with round beams (as discussed in Section 5) and it appears to be more difficult to design an interaction region with a round (but small cross section) beam rather than with a flat beam (very small vertically, but big horizontally), thus the obvious advantage, of a factor of two, in round beams versus flat beams is washed out. Also in favor of flat beams, there appears to be less synchrotron radiation in that case because the required focusing gradients are lower than those needed to produce round beams. Presently, there is no unanimity of thought on the subject of round vs. flat beams.

Still another aspect of the interaction region is whether or not the collisions are head-on or crossing at an angle. Certainly a non-zero crossing angle reduces the masking problem greatly, but crab crossing, which would be necessary, has not yet been tried. In Figure 4 we indicate the nature of crab crossing. The luminosity of a head-on configuration would be maintained in the crossing case but, much more importantly, the transverse beam-beam kick does not couple to the longitudinal degree of freedom of the particles, and hence the beam-beam interaction is no different in the crossing case than in the head-on case. Study and simulations of the effects of crab crossing, in synergism with beam-beam effects, is just starting. Most projects are not "counting on crab crossing," but are allowing for the possibility of incorporating this feature in the future (i.e., by having S-bends in the case of head-on collisions).

4. Single-Beam Phenomena

The subject of single beam instabilities has been well-studied through the years in connection with storage rings and colliders. The new synchrotron radiation sources are being built with very short bunches (so as to get good time resolution of the radiation) and with very small emittance bunches (so as to have very bright sources). Their construction has been based upon our knowledge and experience with colliders, but the frontiers of research on single beam instabilities are now being pushed by the people concerned with synchrotron radiation sources.[6]

A comprehensive discussion of intense beam phenomena can be found in many laboratory design study reports and, in particular, in two recent papers.[7,8] One must consider the longitudinal microwave instability, transverse mode-coupling instability, and coupled-bunch instabilities. It is the last that are the most serious. They are driven by the impedance of the RF cavities and for the regime of total current under consideration for a B Factory, have growth times for the worst modes on the order of a millisecond. (Recall that synchrotron radiation demands RF cavities with power in the 10 MW range.) Such rapid instabilities must be controlled by very powerful feedback systems; that is, systems of wide bandwidth and having considerable amplifier power. It is not novel to employ such systems (they are presently used on a number of machines) but the present demands on power and bandwidth are in excess of current practice.

Because coupled-bunch instabilities need to be reduced as much as possible, there is the need to reduce the impedances of the higher modes in the RF cavities as much as possible. This can be accomplished by making the cavity bore large, damping the higher-order modes, and using as few cavities as possible (i.e., operate at a high gradient). The last demands the ability of "windows" to transmit great RF power, and that requires new technology. The issue of room temperature or superconducting cavities is not yet settled. Notice that the crab-cavities (which will give increased impedance, and therefore are a negative element in the crab crossing scheme) will likely be superconducting cavities as they demand voltage, but do not demand power.

Finally, we should mention other single-beam phenomena that are not limiting, but need to be considered in the design. These include radiation damping, quantum excitation, intra-beam scattering, Touschek scattering, and gas scattering. For example, consideration is being given to whether the vacuum chamber should be made of aluminum and have an antechamber to absorb the synchrotron heating, or whether it is allowable to have a single chamber made of copper.

Of more than passing interest is the collection of ions in the electron beam. This matter is well-known, but still not entirely understood. The clearing of unwanted ions (without introducing excessive impedance from the clearing electrodes, which will drive various instabilities) or without losing luminosity, as will be the case if one imposes a long gap in the train of bunches, is possible, but not easy.

5. Two-Beam Phenomena

The beam-beam interaction is the heart of any collider. But the beam-beam coherent electromagnetic interaction—a particle of one beam interacting with the total electric and magnetic fields of the other beam—is an unwanted component of the collision and, very importantly, puts a severe limit on the operation of the collider. The beam-beam interaction has been studied, both theoretically and experimentally, for decades.[9] This effect is often treated in the "weak-strong" approximation, which consists of one particle interacting with a prescribed intense beam. A proper analysis must, however, include strong-strong phenomena such as coherent beam-beam effects and instabilities.

The beam-beam effect is usually quantified in terms of the linear lens effect of one beam on the other. It is clear, of course, that any linear effect can be compensated and that it is really the *non-linear* part of the interaction (which is proportional to the linear lens effect) that is important. Luminosity, L, of a collider is given by

$$L = \frac{N^+ N^- f k}{4\pi\sigma_x\sigma_y} \qquad (1)$$

where N^+, N^- are the bunch particle numbers, f is the frequency of rotation, k is the number of bunches in the collider, and σ_x , σ_y are the horizontal and vertical beam sizes, respectively, (assumed the same in the two rings). The vertical beam-beam strength parameter, ξ_y, is given by

$$\xi_y^{\pm} = \frac{N^{\mp} r_e \beta^{*\pm}_y}{2\pi\gamma^{\pm}\left(\sigma_x+\sigma_y\right)\sigma_y} \tag{2}$$

where r_e is the classical electron radius, γ is the energy of the beam in units of rest mass energy, and the β^* value is introduced explicitly.

Combining these formulas we arrive at

$$L = \frac{fk(1+r)}{2r_e}\left[\frac{N^+\gamma^+\xi_y^+}{\beta^{*+}_y}\right]^{1/2}\left[\frac{N^-\gamma^-\xi_y^-}{\beta^{*-}_y}\right]^{1/2} \tag{3}$$

where r is the aspect ratio of the beams (1 for round, 0 for flat). In deriving this formula it has been assumed that the beam-beam interaction in the vertical direction is the limiting phenomenon. The beam-beam strength parameter, ξ, both experimentally and theoretically, is within the range 0.03 to 0.06. Thus we see that high luminosity requires high beam current and low β^* (and that these two quantities can be varied arbitrarily provided the beam size is properly adjusted). There are, of course, other limits on the low β^* value and the beam current.

At first sight, it appears that round beams are better than flat beams (by a factor of two), and this effect may be even greater than is explicit if ξ depends on the beam aspect ratio. At present, the dependence of ξ on aspect ratio is moot. It appears to be more difficult to make a low-β^* lattice for round beams than for flat beams, by about a factor of two, which removes the obvious advantage of round beams. Thus it is unclear at this time whether round beams offer any advantage over flat beams.

The beam-beam interaction will be more severe if the bunch is comparable to, or long or longer than, the β^* at the crossing point. This is because β^* increases quickly (quadratically with distance) as one moves away from the crossing point. Thus it is necessary to have short bunches which requires lots of RF voltage. In fact, the necessary length of bunches precludes making β^* very small (and hence limits the amount of luminosity possible with a single pair of bunches).

The beam-beam interaction tends to throw particles out to large amplitudes and this results in short beam lifetime and aggravated detector background. Radiation damping has the opposite effect and it is true that a collider performs better when the radiation damping is large. Just how much damping is required for various operating conditions is not yet clear. It is a matter under study at this time.

The beam-beam interaction can also lead to motion of the beam as a whole (rather than the incoherent effect discussed above). It is important to avoid coherent instabilities, and that appears possible in practice. Finally, then, all projects are not considering moving into new ground with the beam-beam interaction (except in having β^* very small; i.e. of the order of the bunch length), but plan on obtaining the improved luminosity over present colliders by means of having many bunches.

6. Projects

There is great interest, throughout the world, in the development of a B Factory. Serious design studies are now under way at six different institutions; namely, Cornell in Ithaca[10], KEK in Tsukuba[11], INP in Novosibirsk[12], CERN in Geneva (in collaboration with the Paul Scherrer Institute)[13], DESY in Hamburg[14], and SLAC/LBL in Stanford[15]. Four of the projects are based on existing rings; namely PEP at SLAC, the ISR at CERN, CESR at Cornell, and PETRA at DESY. In addition, there are studies, at CERN[16] and at CEBAF[17], of a linac colliding with a ring.

The projects are still in a very preliminary state, with some of them hoping to have a reasonably firm parameter list before the end of the year. It appears at present that there is a convergence of design parameters (linac options aside) so that there is considerable similarity among the various projects. (A year ago, one could not have said that.) To illustrate the range of parameters under study, we show in Table 1 the present design parameters of three of these projects. It seems likely that many of the parameters will change before the projects become actual proposals. The SLAC/LBL parameters are for round beams, but that group is now developing a flat-beam case, which may be what it actually proposes. The Cornell group plans to start with a symmetric collider and then go to an asymmetric case. (The asymmetric case is the one listed.) The Novosibirsk beams have correlated dispersions at the interaction point that result in a "narrowing" of center-of-mass energy spread. This may be desirable from an experimental point of view, but may worsen the beam-beam effect. The last is being studied right now, with initial results looking encouraging.

In conclusion, the construction of a B Factory to study B Meson physics and CP-violation in that system seems, from the beam physics point of view, to be feasible, but challenging. Feasibility studies are now under way to quantify the challenge.

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Figures

Fig 1. A diagram showing the various phenomena, and their major interconnections, that must be considered in designing a high-luminosity circular collider. Of course, at some level, every circle is connected to every other circle. Technical feasibility is a dominant consideration and is included, really, at all levels by "knowing what can, and cannot, be done". Notice that cost, which in the last analysis is the determining factor, is completely left out of the diagram. (Figure due to Maury Tigner.)

Fig 2. The logical steps that one takes in designing a high-luminosity collider. Some explanation, and further analysis, are given in Section 2 of the paper along with further details in Sections 3, 4, and 5.

Fig 3. The design of the interaction region of a collider is still in a state of flux, with a number of interesting ideas being considered, but with no consensus as to how best to proceed. One possibility is an S-bend, head-on configuration, which is shown in Fig. 3a. This appears to be good for masking of the detector, while allowing for subsequent modification so as to have crossing at an angle. Other ideas include a configuration where the high-energy beam goes through the centers of focusing quadrupoles, use of combined function magnets, and "tilting" of the detector solenoid so as to facilitate beam separation. In Fig. 3b we show a three dimensional bend (S-vertically and C-horizontally), a "propeller blade" crossing which might be quite advantageous as far as masking is concerned.

Fig 4. A diagram of "crab crossing" which shows how by tilting the bunches (by half the crossing angle, which typically is about 25 mrad) the crossing appears "head-on" in a moving frame (up in the diagram). Notice that one needs to tilt the bunches and then un-tilt them after the crossing. Powerful RF cavities are required to do the necessary gymnastics and they have to be reasonably close to the interaction point and carefully adjusted to avoid introducing synchro-betatron resonances.

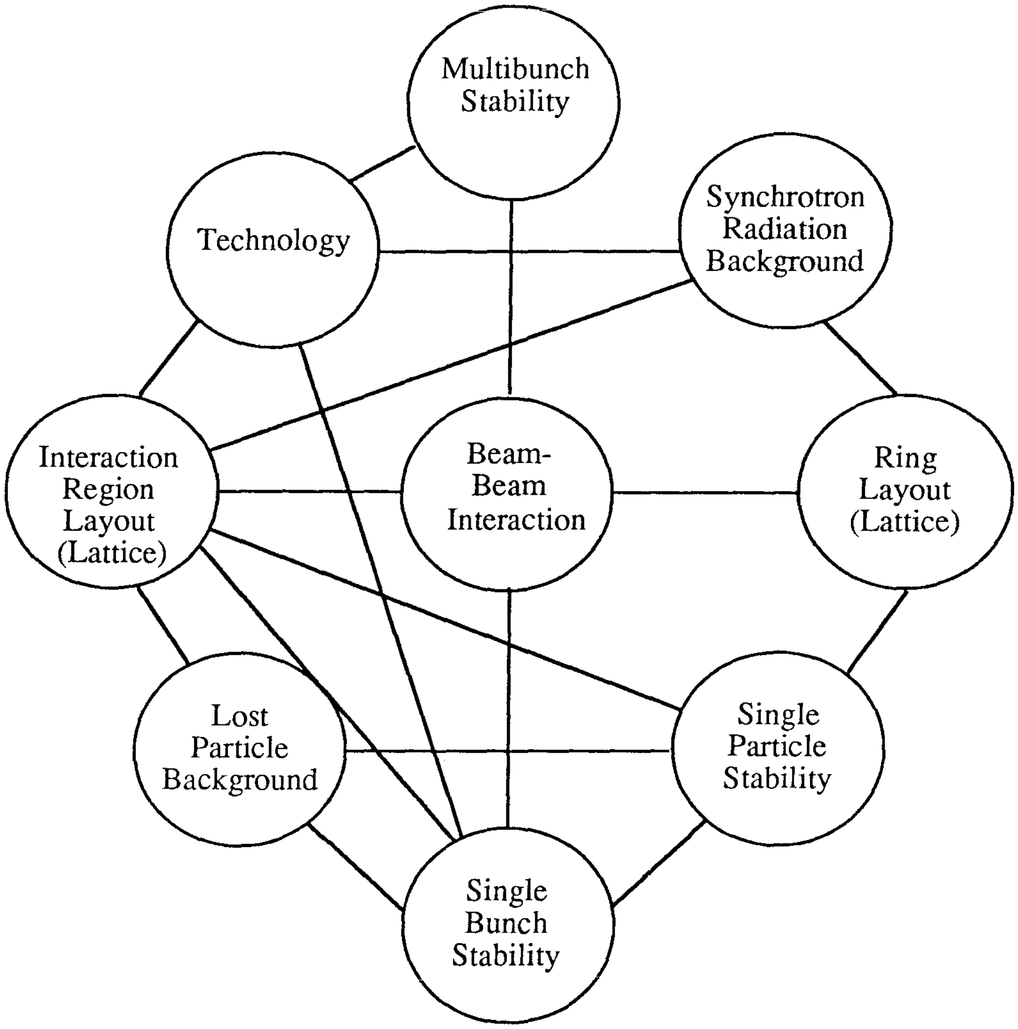

Multibunch Stability
Synchrotron Radiation Background
Technology
Interaction Region Layout (Lattice)
Beam-Beam Interaction
Ring Layout (Lattice)
Lost Particle Background
Single Particle Stability
Single Bunch Stability

Fig. 1

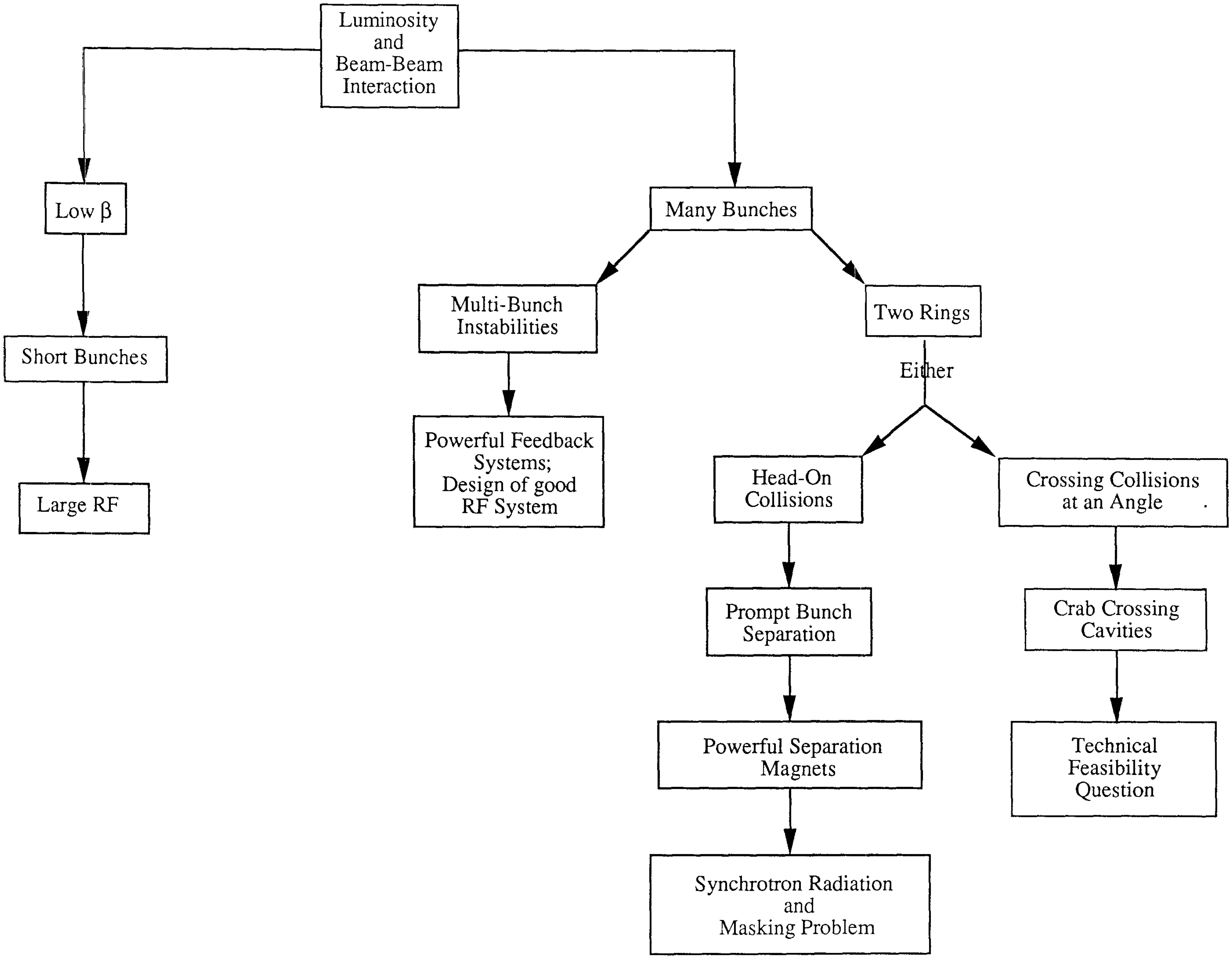

Luminosity and Beam-Beam Interaction
Low β
Short Bunches
Large RF
Many Bunches
Multi-Bunch Instabilities
Powerful Feedback Systems; Design of good RF System
Two Rings
Either
Head-On Collisions
Prompt Bunch Separation
Powerful Separation Magnets
Synchrotron Radiation and Masking Problem
Crossing Collisions at an Angle
Crab Crossing Cavities
Technical Feasibility Question

Fig. 2

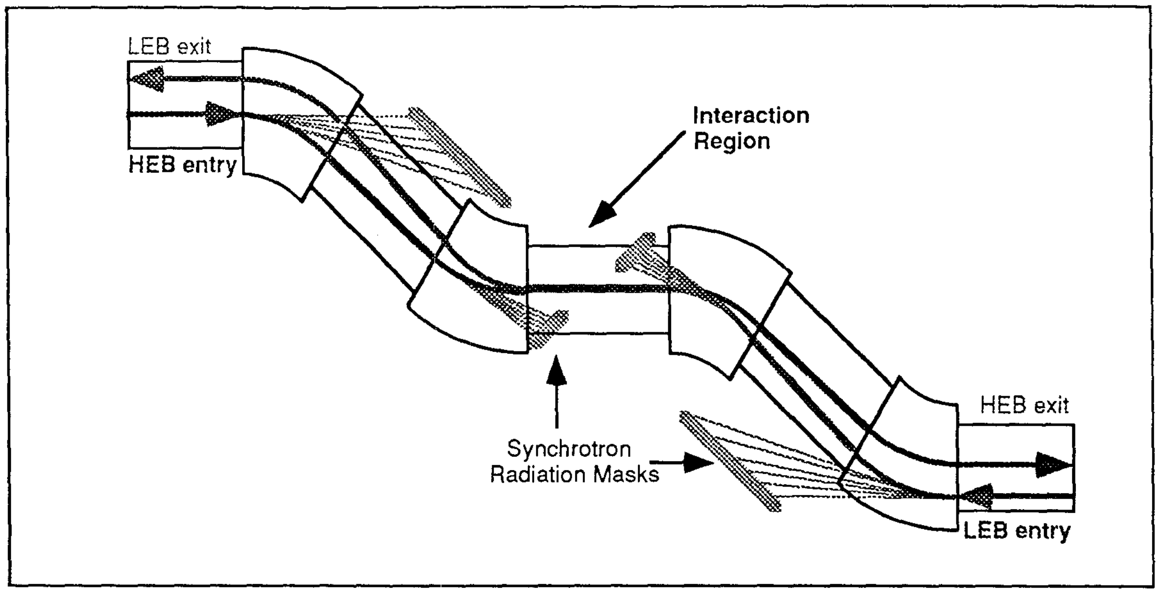
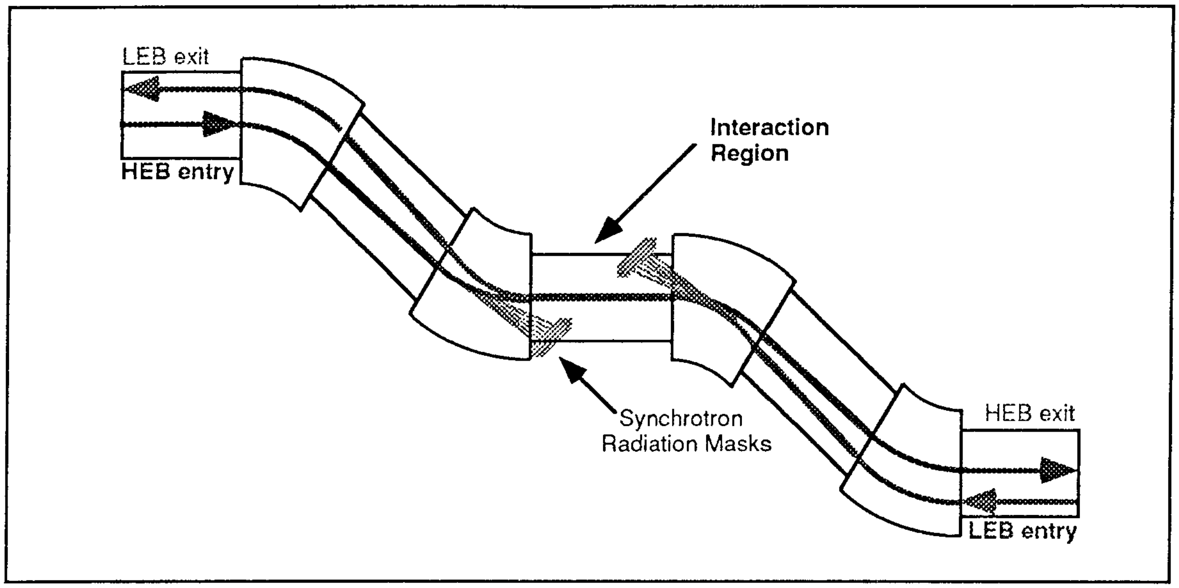

LEB exit
HEB entry
Interaction
Region
Synchrotron
Radiation Masks
HEB exit
LEB entry

Fig. 3a

Vertical S-Bend



Horizontal C-Bend

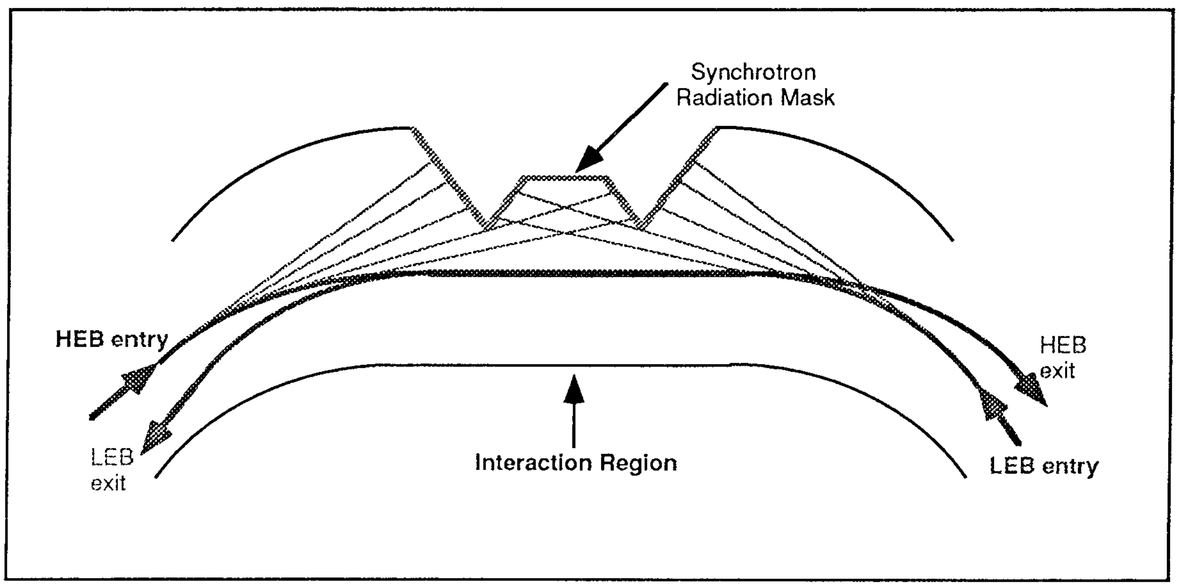


Fig. 3b

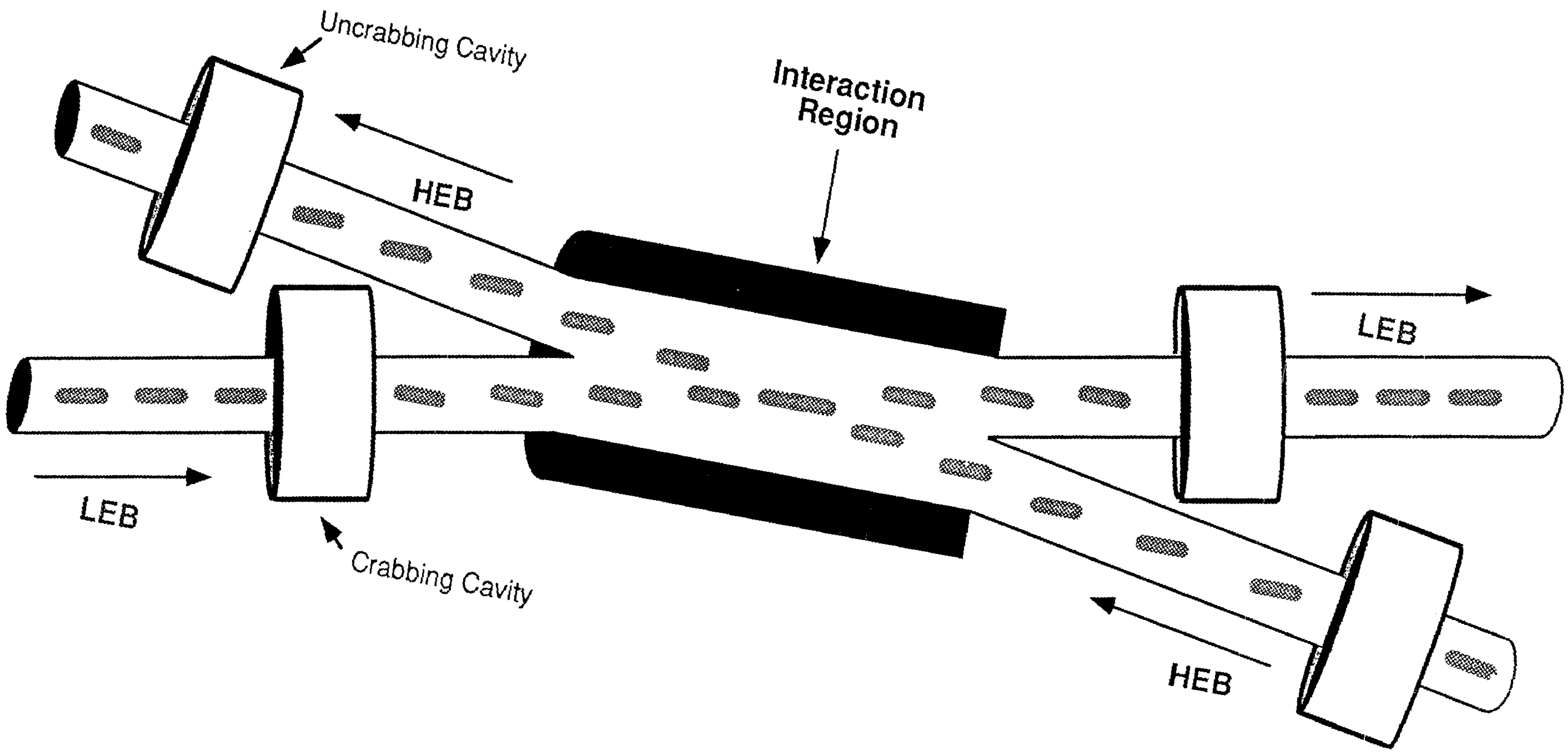

Uncrabbing Cavity
Interaction Region
HEB
LEB
LEB
Crabbing Cavity
HEB

Fig. 4

Table I. Typical Parameters of B Factory Projects

	SLAC/LBL[f]		Novosibirsk[c]		Cornell[a]	
	Low-energy ring	High-energy ring	Low-energy ring	High-energy ring	Low-energy ring	High-energy ring
Energy, E [GeV]	3.1	9	4.3	6.5	3.5	8.0
Circumference, C [m]	2200	2200	655	655	768	768
Number of bunches, k_B	1296	1296	156	156	96	96
Particles per bunch, N_b [10^{10}]	7.88	5.44	9	6	37	16
Total current, I [A]	2.23	1.54	1	0.7	2.19	0.96
Emittance ε_x [nm·rad] ε_y [nm·rad]	 66 66	 33 33	 8 0.25	 6.5 0.25	 78 78	 78 78
Bunch length, σ_l [mm]	10	10	7.5	7.5	18	18
Momentum spread, σ_p [10^{-4}]	9.5	6.1	10	10	3.6	8.4
Damping time $\tau_{x,y}$ [ms] τ_E[ms]	 32.3 17.3	 37 18.5	 17 –	 13 –	 26 13	 26 13
Beta functions at IP β_x^* [cm] β_y^* [cm]	 3 3	 6 6	 60 1	 60 1	 3 3	 3 3
Betatron tune horizontal, υ_x vertical, υ_y	 37.76 35.79	 21.28 18.20	 29 20	 26 13	 7.04 7.04	 10.7 10.7
Synchrotron tune, Q_s	0.039	0.053	0.028	0.028	0.05	0.05
Momentum compaction, α	0.00115	0.00245	0.002	0.002	2.02	0.88
RF parameters frequency, f_{rf} [MHz] voltage, V_{rf} [MV]	 353.2 10	 353.2 25	 500 8.8	 500 15	 500 2.2	 500 11.3
Nominal beam-beam tune shift ξ_{ox} ξ_{oy}	 0.03 0.03	 0.03 0.03	 0.012 0.05	 0.012 0.05	 0.045 0.045	 0.045 0.045
Luminosity, L [$cm^{-2}s^{-1}$]	3×10^{33}		5×10^{33}		5×10^{33}	

WORKSHOP ON BEAM DYNAMICS ISSUES OF HIGH-LUMINOSITY ASYMMETRIC COLLIDER RINGS

Summary*

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General Conclusions

1. An asymmetric B-Factory is here defined to be an e^+e^- storage ring collider capable of 10^{33}-10^{34} cm^{-2} s^{-1} luminosity in the center of mass energy range 10-11 GeV with beam energy ratios of up to 4 to 1. Based on studies of designs for such machines at eight laboratories around the world, there is no known reason to expect that such a facility cannot be built. No completely satisfactory conceptual design for such a facility exists at this time, however. Technical issues requiring further study and resolution are discussed in this report.

2. There is no question that e^+e^- collisions with luminosities in excess of 10^{32} cm^{-2} s^{-1} can be achieved in the 10-11 GeV center of mass energy regime. The success of a B-Factory hangs upon achieving 30 to 100 times this luminosity. Due to uncertainties in scaling of detector backgrounds, the beam-beam tune shift limits, or multibunch instabilities, and because the requisite extrapolation in luminosity is large, the facility designs need to be sufficiently conservative that they can be easily adjusted to accommodate the possible need for larger currents or modified collision geometry, beam energy ratio and emittances.

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8. DESY, Germany
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* Includes only the General Conclusions. The complete Summary will be published in the Proceedings of the Workshop on Beam Dynamics Issues of High-Luminosity Asymmetric Collider Rings, AIP Conference Proceedings (1990).