# Summary of the Working Group on IR Design, Beam-Beam Interaction and Optics

F. Zimmermann
*CERN, 1211 Geneva 23, Switzerland*

The Factories'03 ICFA Beam Dynamics Workshop was held at SLAC from October 13 to 16, 2003. The workshop was organized in three working groups. In this report, I summarize the highlights of the working group on interaction-region (IR) design, beam-beam interaction and optics, emphasizing the suggestions for future studies and pointing out the open questions.

## 1. INTRODUCTION

The working group convened for three consecutive days. The first day was devoted to the IR, with several presentations on design issues and limitations at PEP-II and KEKB, as well as at their Super-B upgrades, and at eRHIC. The second day addressed beam-beam issues, with talks covering simulations for PEP-II, KEKB, VEPP-2N, measurements at PEP-II, analytical estimates, the interplay of beam-beam interaction and electron cloud, the compensation of parasitic collisions by electro-magnetic lenses, experience with negative alpha lattices and luminosity optimization of proton colliders using super-bunches. The third day first looked at a few specific optics questions, mainly for PEP-II and eRHIC. This was followed - in a joint session with the rf working group - by presentations on the exciting upgrade plan of PEP-II, on a novel rf focusing scheme for DAFNE, and on a further analytical approach to the combined effect of beam-beam interaction and an electron cloud or space charge. In total 22 presentations were given in this working group, namely 6 on the IR design, 10 on the beam-beam interaction, and another 6 in the final session on optics and upgrade recipes.

## 2. IR DESIGN

The IR session started out with design issues for the eRHIC Interaction Region, presented by C. Montag. In eRHIC, 10 GeV electrons will collide with 100 GeV/nucleon Au ions. Both beams are polarized. A small ion-beam emittance is maintained by electron cooling. There is no crossing angle. The presently favored optics solution considers flat beams with a 4:1 ratio in the IP beta functions of the proton beam (1 m and 0.26 m). For the electron beam, the IP beta functions are 0.19 m in both planes, while the emittances are different. The nominal tune-shift parameters are $\xi_{x,y}$=0.031, 0.061 for the electrons and $\xi_{x,y}$=0.0074, 0.0037 for the protons. The proton rms bunch length is 15 cm. The final quadrupole magnets are combined function magnets with dipole windings that facilitate the separation of the two beams. The synchrotron radiation (SR) in the IR region is quite moderate, if compared with the B factory-upgrade plans. The SR fan from the combined-function magnets carries a power of 1 kW with a critical energy of less than 11 keV. The power hitting the septum was minimized in the optics design. Beam-beam simulations were performed for a slightly reduced proton current, corresponding to an electron tune shift $\xi_{x,y}$=0.05. The tentative time schedule foresees commissioning around 2013. In the discussion, A. Zholents and M. Furman pointed out that two-ring colliders with unequal circumferences may suffer from an enhanced number of resonances, and that this problem had been studied both by K. Hirata and E. Keil [2] and also by A. Aleksandrov and D. Pestrikov [3].

M. Sullivan next discussed possible upgrades to the PEP-II Interaction Region [4]. The motivation of the PEP-II IR upgrade is to reduce $\beta_y^*$, from 12.5 mm via 8.5 mm down to 6.5 mm at a higher current in 2006/7. An optional crossing angle of +/-3.25 mrad is contemplated. The crossing angle would reduce the amount of synchrotron radiation generated in the IR, and it would also lower the beam-beam effect from the parasitic collisions, possibly allowing one to fill every rf bucket. Depending on whether or not a crossing angle is included, two alternative upgrade options are under investigation. The first option replaces the last 20 cm of the final permanent dipole magnet B1 by a quadrupole field, in which case the loss in bending angle is compensated by a crossing angle. This change in the magnet layout moves the vertical focusing closer to the collision point. At the same time it minimizes the hardware changes required. The second option increases the strength of the quadrupole magnet QD1, without changing its position, which can be accomplished by using a higher-strength permanent magnet. In this case, the head-on collisions are kept. For both options, the adequacy of the existing synchrotron-radiation (SR) shielding is ensured by preserving the present beam orbits within a few mm. Only a few chambers need more careful attention, e.g., at the multi-tipped LER mask the SR power increases from the present level of 30 W/mm to 65 W/mm. About 165 kW of SR power will be generated inside the permanent IR magnets, with a critical energy of about 40 keV. A detailed parameter study is necessary to decide between the two options. In particular, the trade off in luminosity degradation due to the crossing angle on the one hand and due to the parasitic beam-beam encounters on the other hand needs to be investigated more carefully. Higher-order mode (HOM) heating in the IR is another item requiring further consideration.

A. Seryi reviewed recent impressive progress in PEP-II IR alignment [5]. His study was motivated by an apparent strong correlation between the settings of the IR orbit correctors controlled by an automated feedback and the beam current, which hinted at IR magnet motion. A possible mechanism is that synchrotron radiation increases the temperature of the magnets or their supports. The ensuing thermal expansion could then change the magnetic centre of the IR quadrupoles with respect to the beam. To study this phenomenon, a comprehensive suite of alignment diagnostics has been installed in the PEP-II IR. This diagnostics comprises tilt meters, hydrostatic sensors from BINP, a stretched wire, and a laser tracker system, mounted on both sides of the collision point. Position data taken for several magnets allow a reconstruction of the observed orbit motion. A. Seryi showed a movie illustrating the motion of magnets left and right of the collision point. The magnet motion sampled over a few days exhibits typical amplitudes of 100 microns and a raft pitch of the order of 30 μrad. As expected, the motion of the magnets is correlated with the beam current. The characteristic "warm-up time constant" is about 10-15 minutes. The motion on the left side of the interaction point (IP) is much larger than on the right side. It is caused by the LER SR shine. Presently a more refined model of the magnet motion is under development. Such model might eventually be used for a feed-forward orbit correction. The list of possible remedies also includes mechanical design modifications and, especially, the isolation of the magnets from the vacuum chamber. In addition, now that the source of the motion is understood, it is possible to optimize the orbit feedback and orbit correction so as to efficiently react to this particular source of perturbation.

M. Sullivan next reviewed design principles for Super-B factory interaction regions [6]. To alleviate the SR load, the incoming beam is commonly placed on axis, so that SR is generated mainly downstream of the IP. The final quadrupole Q1 is shared, so that one beam is always bent in this magnet. The second quadrupole Q2 must be a septum magnet, and a typical design criterion is to provide a beam separation by at least 100 mm at this magnet. The beam-pipe radius at the septum is minimized. The strong solenoid field of the detector requires that the final quadrupole be either a permanent magnet or superconducting. To ensure adequate shielding from background, collimators, masks and shielding walls are installed. A generic Super-B factory may have a vertical IP beta function $\beta_y^*$=1.5 mm and a crossing angle of +/-12 mrad. Operating with every rf bucket filled, it can provide a luminosity of $10^{36}$ $cm^{-2}$ $s^{-1}$. The final quadrupole Q1 may need to be offset so as to minimize the torque experienced in the solenoid field of the detector, as was elaborated in discussions with reference to B. Parker's plenary presentation [7]. The high current implies non-negligible background as well as substantial amounts of HOM and SR power. Even resistive losses in the chamber components become important. An asymmetric elliptical IR chamber was suggested as one option for improving the vertex resolution, that at the same time maintains a sufficient horizontal aperture and does not intercept the SR fan in the immediate vicinity of the IP. Longitudinally tilted quadrupoles were also contemplated by the audience, for balancing constraints from optics, SR, magnet torque and beam separation. The SR fan in the PEP-II design studies is based on a beam envelope of 10σ, which is augmented by a rough model of beam tails, where the tail population is estimated from the assumed beam lifetime.

The IR design for Super-KEKB was described in detail by Y. Funakoshi. The beam current in the two KEKB rings is limited by the present rf system to maximum values of 9.4 A and 4.1 A, respectively. The horizontal beta function will be squeezed from 33 to 20 cm, and the vertical beta function will be 3 mm (about 6 mm at the moment). The crossing angle will moderately be increased from 11 to 15 mrad, maintaining the present electron orbit in the IR region and only modifying the positron orbit. The horizontal emittance must be increased from 18 nm to 24 nm, which optimizes the luminosity according to strong-strong beam-beam simulations. The rms bunch length is reduced to 3 mm, i.e., the same value as the decreased $\beta_y^*$. The ring acceptance might prove marginal for the positron emittance from the linac, which motivates studies of a dedicated positron damping ring. The acceptance of the ring depends on the beta function at the injection point. For low values of $\beta_y^*$, the energy acceptance becomes a problem. The KEKB final quadrupole QC1 is superconducting and of compact size. For the envisioned beam currents of 9 and 4 A, the synchrotron radiation power in the quadrupole bores is of the order 100-200 kW with a critical photon energy of 55 keV. The aperture requirements are estimated considering a beam size of 3σ and a contribution from the closed orbit. The latter takes into account orbit drifts, artificial bumps, and "iBump tuning". The closed-orbit component was estimated from the operational experience at KEKB, where the IP offset varies by +/-0.73 mm, which translates into +/-0.37 mm at Super-KEKB. The IP angle in KEKB fluctuates by +/-0.5 mrad. Dynamic beta function and dynamic emittance are also included in the aperture calculations. In Super-KEKB crab cavities will be installed on either side of the IP, whereas in the present KEKB only a single crab cavity is foreseen per ring. A charge switch between the two rings is under consideration as a method to combat the electron cloud. The effect of parasitic collisions in Super-KEKB needs a re-evaluation.

F. Zimmermann [8] recommended more serious consideration of a Raimondi-Seryi final focus [9] for the future factories and factory upgrades. Such system would offer a truly local correction of chromaticity, where the chromaticity sextupoles are placed next to the low-beta quadrupoles. Implying a nonzero dispersion here, this scheme may require a non-vanishing slope of dispersion at the IP, or, else, the dispersion must be cancelled by a dipole downstream of the low-beta quadrupoles. A system of this kind was proposed by P. Raimondi and A. Seryi for the Next Linear Collider in 2000, and it has meanwhile been adopted for most linear-collider projects, such as NLC, CLIC, and, possibly, TESLA. The local correction provides for much improved chromatic properties, in particular a larger off-momentum dynamic aperture. While the original design was made for a single-pass collider, an exploratory design was also generated for the challenging parameters of a 30-TeV muon collider by P. Raimondi [10]. This design demonstrated a superb performance also over multiple turns. Though already the pioneering article by Raimondi and Seryi [9] suggested to adopt this type of system for factory colliders, apparently nobody has so far seriously taken up this proposal, though it may well offer a superior solution for the proposed IR upgrades. In addition, any practical implementation and operational experience at a factory might benefit the linear-collider optics design. One possible reservation relates to the slope of the dispersion at the IP, whose impact could be studied in beam-beam simulations. Presumably it is small compared with the effect of a typical crossing angle.

## 3. BEAM-BEAM INTERACTION

The beam-beam session started with A. Valishev, who described simulations of the beam-beam interaction for round beams [11]. The motivation of colliding round beams is the direct gain of a factor $(1+\sigma_x/\sigma_y)^2$~4 in luminosity, and the added potential of further pushing the beam-beam limit. In 1995, a successful test of round-beam collisions was conducted at CESR [12], where a tune shift of 0.09 could be established. If the emittances, IP beta functions, and tunes in the two planes are equal, there is a perfect rotational symmetry, and an additional integral of motion thereby exists. The driving terms of all betatron coupling resonances are also eliminated. The round beams can be focused by solenoids (at low or moderate beam energies), which simultaneously rotate the eigenplanes of motion. Three operation modes are possible: the normal round-beam case, a Moebius lattice, and a flat configuration. Round-beam collisions will for the first time be demonstrated at the VEPP-2000 machine, which employs 13-T solenoid fields made from a combination of NbSn and NbTi superconductors. The nominal beam-beam tune shift for this project is $\xi$~0.075. Beam-Beam simulations for VEPP-2000 were performed by the codes LIFETRAC [13] and BBSS in weak-strong and strong-strong mode [14], including lattice-sextupole nonlinearities. A dynamic aperture problem was found for $\beta^*$~6 cm. Hence, the VEPP-2000 design value of $\beta^*$ was increased to 10 cm. A convenient feature of round beams is that tune scans are purely 1-dimensional. The strong-strong code revealed coherent dipole oscillations for some tune values, with an amplitude of about $1\sigma$, that were accompanied by beam-size growth and mode mixture. Both planes were affected by these oscillations. The first beam in VEPP-2000 is expected at the end of 2004. Responding to a question by A. Zholents, A. Valishev explained that the tolerance to optics errors is rather loose and that a beta beating of 5% may be acceptable. The prototype round-beam collider VEPP-2000 will provide useful experience for the VEPP-5 charm-tau factory, described by A. Skrinsky in a plenary talk [15].

Beam-beam simulations for PEP-II were discussed by Y. Cai [16]. His simulation code has been benchmarked with K. Ohmi's code BBSS. Y. Cai employs a reduced boundary region [17] and he makes use of parallel computing, which gains a factor 20 in speed. Following an approach developed by K. Ohmi and M. Tawada at KEK, it performs a longitudinal linear interpolation after equal-area slicing. Dynamic beta and dynamic emittance are approximated by the Hirata-Ruggiero formula [18], which well reproduces simulations by the LEGO code. We note that an improved expression for the dynamic emittance has been published by A. Otboyev and E. Perevedentsev [19]. The simulated tune scan shows that the luminosity is sensitive to the horizontal tune of the Low Energy Ring (LER). Close to the ½ integer resonance, the vertical beam size in the LER is much reduced. A simulated scan of luminosity versus beam current revealed a limitation due to beam loss in the vertical direction for both beams. Indeed only the vertical beam size blows up for increasing current. The measured dipole tune spectrum is in good agreement with the simulated spectrum. If a crossing angle is present, the simulated spectrum shows evidence of coherent "tail-tail motion" or synchro-betatron resonances. The crossing angle is modeled by a symplectic rotation instead of the non-symplectic Lorentz boost [20]. The simulation shows a rather dramatic decrease in luminosity with crossing angle, far above the purely geometric reduction. It also suggests that a reduced vertical beam size, corresponding to a factor 100 in spot-size aspect ratio, may yield 65% higher luminosity. If one also decreases the vertical IP beta function, the bunch length and the damping time, by a factor of two each, a luminosity of $2\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ appears possible. Y. Cai's simulations closely reproduce the actual KEKB and PEP-II performance, lending some confidence to the luminosity predictions for the upgrades and Super-B factories.

J. Gao presented an analytical estimation of beam lifetimes limited by beam-beam interaction in circular colliders [21]. He first computed the dynamic aperture due to a single multipole. The resulting expression has been verified in numerical simulations for Super-ACO. The formula was then extended to the dynamic aperture from several multipoles acting together, and, finally, to that from the beam-beam interaction, by expanding the latter into multipoles. By this procedure, a maximum tune shift for the beam-beam interaction due to the dynamic aperture was obtained. Using the standard formula for the quantum lifetime, the dynamic aperture translates into a beam lifetime, whose dependence on the radiation damping time was emphasized. The round-beam tune-shift limit was found to be about 1.9 times the limit for flat beams. As an alternative approach, J. Gao has also computed the maximum tune shift allowed by the emittance blow up. This alternative calculation relates to the second beam-beam limit. Comparison with experimental data often shows a satisfactory or good agreement for both approaches, but for a few cases the predicted limit has been exceeded in reality. The effect of the crossing angle was also studied. Only a 20% luminosity reduction from the crossing angle was inferred for KEKB. An application of this method was presented by J. Gao in a later talk (see further below). It was suggested by F.-J. Decker to modify the beam distribution in ring colliders like PEP-II, so as to change the multipole content of the beam-beam interaction in a favourable way. More details of Gao's approach can be found in the literature, e.g., in Ref. [22].

C. Biscari gave a brief review of the experience with negative alfa lattices so far [23]. Measurements were reported from UVSOR, Super-ACO and KEKB. In most cases the microwave-instability threshold for $\alpha<0$ occurred at a lower current than for $\alpha>0$. D. Rice suggested to compare the thresholds in terms of line density rather than as a function of current. An extrapolation to DAFNE was given.

W. Kozanecki summarized the beam-beam experience at PEP-II [24]. He remarked that the design current ratio of PEP-II was 2.9/1, and thus far from the actual ratio of 1.3/1. In the present operating condition, with tunes near the ½ integer, the vertical electron beam size and the horizontal positron beam size blow up with increasing beam current. A bunch-to-bunch variation due to the electron cloud is clearly evident. Typically, the 1st and 3rd bunch in a train have a higher luminosity. Why the 3rd bunch has a better luminosity than the 2nd is not fully understood. For a long time, PEP-II was operated with mini-gaps, which were meant to clear the electron cloud. Recently, a better luminosity was achieved without introducing such mini-gaps for a bunch spacing of 6.3 ns. In the quest for higher luminosity, the bunch spacing is being decreased. Filling every 2nd rf bucket (4.2 ns spacing), the luminosity decreases by 20-25% after the first 5-10 bunches. In another pattern where the bunch spacing alternates between 2 and 4 rf buckets, the luminosity of the second bunch in each "pair" exhibits a non-monotonic evolution along the bunch train. The effect of parasitic collisions is visible as a pronounced (~20%) increase in luminosity for the 1st and last bunch in a train. The variation of the beam-beam induced tune shift of the positron beam was measured to be about 0.004 for a change in electron-beam current from 1.07 to 0.81 A, corresponding to a total electron-beam tune shift of 0.08-0.11. Typical PEP-II beam-beam studies are conducted by holding one beam current constant and varying the current of the other beam. For the old tune settings, used until summer 2003 (the horizontal positron tune was near the 2/3 resonance), the positron beam blew up as its own charge was being varied, but there was little dependence on the charge of the opposing beam. Nevertheless, at that time the pure presence of the electron beam was essential to observe the positron blow up. It is possible that the vicinity of the 3rd integer resonance and the combined effect of beam-beam interaction and electron cloud may have been the cause of this 'self-induced' beam-size increase. For the present tunes, near the ½ integer, the vertical electron beam size depends on the positron beam current and the horizontal positron beam size on the electron current. The blow up is sizable, of the order of 40-100%. The horizontal size of the luminous region was reduced by about 40% after the change of tune. It was pointed out that this most likely is not an evidence for the dynamic beta effect, as the dynamic beta reduction should almost exactly be cancelled by the dynamic emittance increase.

K. Ohmi discussed quasi-strong-strong beam-beam simulations [25], a simulation scheme first proposed in Ref. [26]. Recent strong-strong simulations for present KEKB operating parameters have shown that the beam-beam limit is due to an incoherent phenomenon, associated with a change in the shape of the beam distribution to a new stationary form, which no longer is Gaussian [27]. The quasi-strong-strong simulation consists of a cycled weak-strong simulation, by which the stationary beam distribution is approached. The final luminosity agrees to within 15% with that obtained by a real strong-strong simulation. A typical simulation uses 10000 particles and 500 turns, or 5 million particle-turns. Both strong-strong and quasi-strong-strong simulations demonstrate that the tail of the beam distribution plays an important role for the beam-beam effect. In K. Ohmi's simulation also the synchrotron radiation strongly contributes to the beam-beam limit. The diffusion of particles seems to be greatly enhanced by the radiation excitation, which might be related to the 'resonance streaming' of Tennyson [28]. The simulation predicts a higher beam-beam limit for proton beams, which appears to be contrary to common wisdom. K. Ohmi suggested that a "mismatch" of the proton beams in the real world could be responsible for this discrepancy.

F. Zimmermann described a weak-strong model for the combined effect of beam-beam interaction and electron cloud [29]. This model was already presented in Ref. [30], but newly computed results for PEP-II parameters were added at the occasion of this workshop. The calculation represents the bunch by a few equally charged macro-particles, typically 3 or 4. It is assumed that the primary effect of the beam-beam interaction is to introduce a Gaussian variation of the betatron tune along the bunch, which is approximated by a parabolic dependence of the tune on the longitudinal position. This assumption is based on simulation results from the HEADTAIL code [31], which have shown that such an additional tune variation due to beam-beam (or space charge) can have a dramatic impact on the electron-cloud instability [30]. In the analytical model, the effect of the electron cloud is twofold. It gives rise to a wake coupling successive macro-particles and it causes an additional tune shift along the bunch. As a first rough approach to this problem, the wake is considered to be constant, independent of the distance between the macro-particles, and the electron-cloud tune shift is taken to rise linearly along the length of the bunch. The calculation is an extension of the two-particle model for a regular head-tail instability as discussed, e.g., in [32]. The model predicts that the beam-beam tune shift can further destabilize the beam in the presence of an electron cloud. The agreement between model and simulation should improve with an increasing number of macro-particles.

M. Biagini reported on parasitic collisions and beam-beam parameters at PEP-II and its upgrade [33]. For a +/- 3.5 mrad crossing angle, the Piwinski angle in the future PEP-II would be 60% larger than in CESR, but still more than three times lower than in the present KEKB. A large crossing angle reduces the strength of unwanted beam-beam interactions at the parasitic collision points, but at the same time, according to strong-strong beam-beam simulations, it decreases the maximum tune shift that can be achieved at the primary collision point. M. Biagini computed the individual beam-beam tune shifts for each parasitic collision and for various bunch spacings. These tune shifts determine the minimum separation required and hence the minimum crossing angle. A crossing angle appears necessary, since without it the parasitic vertical tune shifts would be larger than the tune shift induced at the main IP. The beam-beam tune shifts were computed for different crossing angles and for various $\beta^*$. The luminosity was kept constant by scaling the main IP tune shifts, decreasing the bunch lengths accordingly. The dependence of the tune shifts on $\beta^*$ is weak, while there is a strong sensitivity to the crossing angle. In addition to the parasitic tune shift, strong-strong beam dynamics must be taken into account. It was remarked by the audience, that the simulations considered a bunch length that was a factor 2 too large, which will exaggerate the deleterious effect of the crossing angle. The simulations should be repeated. M. Biagini closed with two questions and one recommendation: (1) Is it favorable to use a smaller number of bunches, reaching the same peak luminosity for a constant tune shift? (This question followed up on a similar suggestion by M. Placidi.) (2) Can one really obtain 6.5 mm long bunches in the present PEP-II layout? (3) Future 3-D strong-strong simulations must include the parasitic collisions.

F. Zimmermann discussed the possibility of using electro-magnetic lenses for compensating the effect of the parasitic collisions [34]. At the LHC, where parasitic collisions also are a concern, their number is much higher than for the e+e- factories, namely 120 in total with 30 around each of four collision points. Simulations suggest that these long-range collisions can reduce the dynamic aperture to a value of 4-6$\sigma$. The force of the long-range collisions equals that of a current-carrying wire at a certain transverse distance, parallel to the beam. Thus, a compensation of the long-range force by two wires for either beam around each IP was proposed by J.-P. Koutchouk [35] and this scheme has been validated in computer simulations [36]. A prototype of such a wire was built and installed in the CERN SPS in 2002. The wire can be fed with up to 300 A dc current. In the present set up, this wire may reproduce the combined effect of all long-range collisions in the LHC, for a "worst case" scenario, where the long-range forces around the two main IPs add up linearly. So far three machine experiments were performed in 2002 and three further in 2003. The measured tune shifts and orbit distortions, induced by powering the wire, are well understood and allow a precise determination of the beam-wire distance. Preliminary measurements of beam lifetimes and losses indicate that the LHC parameters are close to an edge, e.g., if the crossing angle is reduced by10% the beam lifetime is less than 4 h). A prime observation is a shrinkage of the transverse emittance induced by the wire excitation, which can be understood in terms of the reduced dynamic aperture. The dependence of the final emittance on wire current and beam-wire distance has been explored. Using a calibration measurement based on mechanical beam scraping, the dynamic aperture could be expressed in terms of rms beam sizes. A scaling law proposed by J. Irwin for the SSC [37] was confirmed experimentally, namely that the dynamic aperture varies linearly with the square root of the bunch population. Extrapolating the measured data to the LHC and invoking some additional scaling assumptions, the dynamic aperture in the LHC could be as low as 2$\sigma$. However, part of the experimental data may reflect the limited mechanical aperture in the SPS at a beam energy of 26 GeV/c, where most of the measurements have been performed. Direct diffusion measurements have started. They have proven challenging until now, due to problems related to the signal quality of the photomultiplier tubes, the maximum speed of the scraper and the flexibility of the acquisition software. Two further wire devices will be installed in 2004, one adjacent to the first one, and the other in a different sector of the SPS. These additional wires can be used to compensate the effect of the first wire, thus both demonstrating the compensation technique and also probing its tolerances against various types of errors. The new devices are equipped with wires in the horizontal plane, in the vertical plane, and in the diagonal plane, which shall also allow comparing the performance of various alternating crossing schemes that are being considered for the LHC IPs.

F. Zimmermann then gave a brief review of super-bunches for hadron colliders [38]. The idea of superbunch colliders is inspired by the outstanding performance of the CERN ISR. It was recently taken up by K. Takayama and colleagues [39]. At CERN it is studied in view of a possible LHC upgrade [40,41]. The main motivation is that the luminosity of a conventional hadron collider, operating with round and nearly Gaussian bunches colliding at two separate IPs with alternating planes of crossing can be increased in proportion to the bunch current, while keeping a constant beam-beam tune shift by enlarging the product of bunch length and crossing angle, $\sigma_z\theta$ [42]. Choosing a uniform longitudinal profile instead of a Gaussian, an additional factor $\sqrt{2}$ is gained. Making use of these dependences and operating either with a large Piwinski angle or, preferably, with longitudinally flat (intense long) 'super-bunches' the LHC luminosity can be increased about 10 times to $10^{35}\text{cm}^{-2}\text{s}^{-1}$ for the same total tune shift and beam current. As an additional benefit from the super-bunches, there would neither be PACMAN bunches, nor an electron cloud build up inside the vacuum chamber [40]. Therefore, super-bunches would not only increase the LHC luminosity, but at the same time they would overcome two of the biggest challenges of the nominal LHC.

## 4. OPTICS

D. Wang discussed the lattice design of the electron ring of eRHIC [43]. The goals of this project include an electron beam energy of 5-10 GeV, a luminosity of $10^{32}$-$10^{33}$ $cm^{-2}s^{-1}$ for ep collisions and of $10^{30}$-$10^{31}$ $cm^{-2}s^{-1}$ for eAu collisions. The eRHIC is conceived as a ring-ring collider based on RHIC, augmented by a new electron ring, which has a three time smaller circumference. Both beams will be polarized. Electrons may be generated from a polarized source. If instead of electrons, positrons are stored in this ring, they will be polarized by synchrotron radiation at 10 GeV. The product of synchrotron radiation power and radiation time is a constant, which requires a trade off between contradicting requirements. The Sokolov-Ternov polarization time for the present design is 21 minutes. The beam-beam tune shift is higher than in HERA. Round beam collisions become attractive, but have proven difficult to achieve in actual lattice designs, in particular with regard to electron polarization. They remain an option for the future. The last quadrupole, Q1, is placed 0.8 m from the IP. A new quadrupole design was created by B. Parker for a previous optics version with round beams. With round colliding beams a rather large crossing angle of several mrad is required, implying a high voltage for the crab cavities. An anti-symmetric solenoid-dipole pair serves as spin rotator between the arc and the IP and it is effective over a wide energy range. The working point is chosen just above the integer to preserve polarization in the ring (the spin tune is near 0.5). For dynamic-aperture computations, the LEGO [44] and SAD [45] codes were used and benchmarked against each other. SAD predicts a larger dynamic aperture than MAD [46]. For the present flat-beam solution, the IR geometry and SR power look feasible. The design optimization is still ongoing. In the subsequent discussion, A. Zholents and others pointed out, as before for C. Montag's talk, that according to studies by A. Aleksandrov and D. Pestrikov [3] and by K. Hirata and E. Keil [2], the coherent beam-beam effects may compromise the performance of unequal-circumference rings. Purportedly, this issue was also investigated by D. Shatilov for the PEP-N project [47]. Similarly, Y. Cai has simulated the performance of a ring-linac collider and he found a 10% effect [48], as is illustrated in Fig. 1.

Y. Yan presented the optics diagnostics and correction of beta beating at PEP-II [50] using a model-independent analysis (MIA) [49]. The MIA procedure assumes that the quadrupoles, sextupoles, beam-position monitors (BPMs) etc. are all located at the right locations. It then creates a virtual accelerator by adjusting magnets strengths, BPM calibrations and offsets. The input to MIA are 4 independent high-resolution multi-turn orbits (acquired while exciting either one of the two eigenplanes at two different betaton phases). The extraction of beta functions from the phase advance may break down for a coupled lattice. The optics correction is accomplished by a few knobs containing a limited set of key magnets. Y. Yan pointed out that the 'real machine responds very well to MIA'. Solenoid errors are fitted by normal and skew quadrupole variables; tilt angles and coupling ellipses are included. The MIA residual error in the interaction region (IR) is larger than that in the arcs. The LER beta beat was easily fixed using the trombone and global skew quadrupoles. The net success rate of MIA so far is 2 out of 3 or 66.67%. The beta beating in the HER still remains for the moment, but a global skew problem (wrong polarity of all skew quadrupoles) could be confirmed. MIA provides a summary page with condensed optics information. Further improvements in MIA may still be needed, in particular for the IR. A similar application of MIA for beta-function measurements is described in [51].

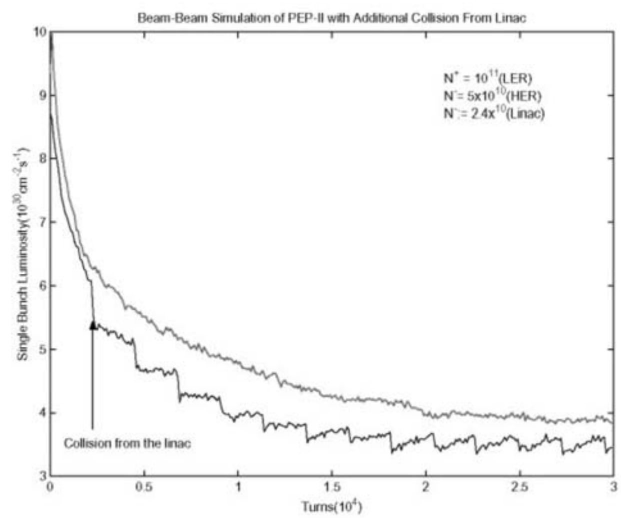


Figure 1: Simulated luminosity as a function of turn number for PEP-II with (lower curve, blue) and without (upper curve, red) an additional ring-linac collision at 60 Hz [Courtesy Y. Cai, unpublished].

The next speaker, F.-J. Decker, discussed orbit bumps in PEP-II for luminosity optimization [52]. In the PEP-II IR there are large BPM offsets of 9-10 mm in magnitude. Each time when this region was steered flat, the performance degraded. The scale of this problem is stupefying. A 0.2 kG skew quadrupole field is known to change the luminosity by 3-5%. This field is equivalent to a 250 micron offset in a sextupole. A 10-mm offset corresponds to 40% of the strength of a regualar quadrupole. The deflection from the sextupole can be stronger than the deflection needed to make a bump. Both the offset in the plane of the bump and the coupled part of the bump, in the orthogonal plane, must be closed. Bumps introduced at high current in certain regions of the PEP-II LER could result in more than 20% increase of luminosity [53]. Electron cloud or wake field were invoked as possible explanations. It was not a non-linear problem, as the region in question contained neither sextupoles nor skew quadrupoles. Another suggestion is that the effect might have been caused by the change in path length induced by the bump. F.-J. Decker speculated that for the present optics and tune it might be possible to steer the orbit flat all around the machine and then introduce special bumps to optimize the luminosity. A "short-cut" in the chicane due to the bumps may have changed the horizontal offset in the sextupoles all around the machine. The optimum amplitude of a bump often is "one-sided", which means the luminosity decreases steeply in one direction and is flat in the other. The bumps seem to have less effect after the tune was moved to the ½ integer. Other, unwanted bumps are generated by the global orbit feedback (GOF). Sometimes these accidental bumps became as large as 17 mm, at one point causing a vacuum leak. D. Rice suggested that the effect of the bumps could be related to dispersion in the rf cavities and to the excitation or compensation of synchro-betatron resonances. It was proposed to systematically explore the effect of localized bumps all around the PEP-II ring.

The final three talks by A. Gallo, J. Seeman and J. Gao were held in a joint session with the working group on rf, feedback, and collective feedbacks, chaired by J. Corlett, who was assisted by D. Teytelman and P. McIntosh.

A. Gallo presented the innovative concept of strong rf focusing [54]. The desire to reduce the length of the bunches is motivated by the fact that the luminosity scales roughly as the inverse bunch length, due to the hourglass effect. Unfortunately, for short bunches one easily reaches the microwave threshold (Boussard criterion). The standard approach to generate short bunches requires a very high RF voltage and a small impedance. Strong RF focusing represents a promising alternative, which may also avoid the microwave instability, likely encountered for short bunch lengths. This scheme resembles a magnetic bunch compressor. The synchrotron tune is close to the ½ integer resonance. Optimum values for longitudinal beta functions, bunch length at the IP, energy spread, rf voltage and wave length are easily determined. The bunch length is not constant during one turn, but varies dramatically around the ring, assuming a minimum at the collision point. Wake field sources are preferably located near the rf, on the opposite side from the IP. The rf energy acceptance must be reconsidered. For the contemplated DAFNE2 upgrade, the energy acceptance is 1.1% at the IP and 0.45% at the rf. The variation of the acceptance and bunch length around the ring must be taken into account for Touschek and IBS calculations. The wake potentials depend strongly on the bunch length, often as the third inverse power. The sign of the momentum compaction is important for the onset of instability. A proposed 'wiggling' machine is constructed by adding inverse bends. This design can achieve a 2 mm bunch length for DAFNE2. A bunch length of 1mm would require a more exotic lattice. There are not many free parameters left. RF frequencies above 500 MHz are not suitable, since they would imply too low an energy acceptance. It is perhaps worth to be mentioned that as early as 1969 the longitudinal motion in electron storage rings for large synchrotron tunes was studied by A. Piwinski [55], who already derived expressions for the variation of bunch length and energy spread around the ring.

J. Seeman next outlined the future very high luminosity options for PEP-II [56]. His extrapolation is based on the experience from the present PEP-II and KEKB, namely that asymmetric beam energies work, and that beam-beam tune shifts of 0.08-0.10 can be reached. The PEP-II luminosity will be increased by storing 4 times more bunches (bunch spacing 0.6 ns), by increasing the bunch current 2 or 3 times, and by accepting 50% larger tune shifts, which can be sustained with continuous injection. In addition the vertical beta function will be decreased by a factor 2-3 down to 1.5-3 mm. A bunch-by-bunch feedback system operating at a sub-ns time scale will be necessary. It has already been designed by the group of J. Fox and its components are being prototyped. The beam energy asymmetry is decreased in order to save beam power. For fiscal year 2008, beam currents of 4.5 A positrons and 2 A electrons appear within reach, with a vertical IP beta function of 6 mm, and every 2nd RF bucket filled. This can provide a luminosity of 2-3x$10^{34}$ $cm^{-2}$ $s^{-1}$, but the particle physicists are asking for $10^{36}$ $cm^{-2}$ $s^{-1}$. Higher luminosity is accomplished as follows. The HER energy is decreased from 9 to 8 GeV, and the HER current is ramped up to 4.8 A. The LER energy is increased from 3 to 3.5 GeV, which requires a new vacuum chamber for the LER. The LER current will be 11 A. The SR flux in the LER can be softened by adding bending magnets and by increasing the magnet bore. The number of bunches will be 3400, the vertical beta function at the IP 2.2 mm, and the beam-beam tune shift 0.15. The corresponding site power is 120 MW, supporting a luminosity 5x$10^{35}$ $cm^{-2}s^{-1}$. An advanced upgrade option foresees a new RF frequency, e.g., 952 MHz, and more bunches. With 1.8 mm bunch length, a crossing angle of 15 mrad, 6900 bunches, and $\beta_y^*$=1.5 mm, the luminosity becomes $10^{36}$ $cm^{-2}s^{-1}$, still for a 120 MW site power. J. Seeman showed an intriguing plot of site power versus luminosity for the two RF frequencies, clearly revealing a substantial gain by the 952 MHz system. The steep increase of either curve at a certain power level indicates a fundamental limitation, which he baptized the 'Rice limit' after David Rice. He pointed out that further issues related to high luminosity factories and the particle physics at such machines will be discussed in an upcoming KEK-SLAC workshop at Oahu, Hawaii, mid-January 2004.

The last talk by J. Gao on the analytical treatment of nonlinear beam dynamics [57] extended the approach of his earlier presentation [22] so as to include the effects of wigglers, space charge and electron cloud on the dynamic aperture. For the wigglers, he illustrated his calculations with the example of Super-ACO. Similar to the beam-beam tune-shift limit derived in [22] he computed a limit from the space-charge effect, choosing the TESLA damping ring as a prominent example. The combined effect of the electron cloud and the beam-beam interaction was treated in an analogous way. J. Gao's result suggests a further reduction of the beam-beam dynamic aperture due to the electron cloud. Considering PEP-II, he computed that the beam-beam tune shift limit would be reduced from 0.045 to 0.01 by the electron cloud. Everybody agreed with his final conclusion that analytical treatments are helpful in addition to numerical simulations.

## 5. DISCUSSION

The working group was asked to respond to several charges (shown in bold italics below), and arrived at the following answers.

***Explore and document the operational experience of present interaction regions. Can interation regions with a $\beta_y^*$ of 2-3 mm be designed? Evaluate procedures for measuring and controlling IP optics parameters.***

These questions were only partially answered, though in lively discussions. The working group considered achieving the short bunch length of 2-3 mm for future colliders to be the real challenge, which includes the generation of such bunches, the associated higher-order mode power, the bunch lengthening, CSR instability, and Touschek lifetime.

A related set of challenges concerns the IR itself. The IR limits the bunch length, due to HOM heating of critical components, and it limits the IP beta function, due to the restricted apertures. The IR also greatly affects the optics modelling, the optics tuning, coupling and diagnostics, which have been a problem for both PEP-II and DAFNE. The question was asked what the right balance is between hardware solutions and software modelling, e.g., a more modular and more expensive IR might allow more precise modelling and a better optics control. It was proposed to seriously consider the Raimondi-Seryi IR layout for the next round of factory upgrades. The first step in this direction would be to design a prototype optics, with truly local chromatic correction, and compare its dynamic aperture with that of a conventional layout. A. Seryi expressed interest in pursuing this type of solution. The effect of the possible slope of the IP dispersion function should be studied as well in beam-beam simulations, and Y. Cai will likely take on this enterprise for PEP-II.

***What are the present limits of the beam-beam interaction?***

The working group came up with a long list of limitations, which comprises the damping, bunch shapes (F.-J. Decker suggested to create a transversely uniform bunch to remove beam-beam nonlinearities), bunch length, beam lifetime, lattice nonlinearities, IP tuning, coupling, the vertical IP beta function, parasitic crossings, crossing angle, travelling focus (J. Gao), and electron cloud.

***Trade-off between parasitic collisions and crossing angle?***

Head-on collision are difficult to realize with short bunch spacings, due to the strength of parasitic collisions. It was debated whether there exists a limit on the Piwinski angle, as possibly suggested by some of the strong-strong beam-beam simulations. To find the optimum parameter choice, the dependence of the specific luminosity on the bunch spacing shoud be studied. M. Placidi proposed to collect data for various colliders (PEP-II, KEKB, DAFNE) and to see, whether they suggest a scaling law; if the optimum number of bunches is not too large, perhaps the crossing angle and parasitic collisions can be entirely avoided in a certain range of parameters. It was proposed to benchmark the strong-strong simulations suggesting a dramatic effect of the crossing angle against data from an actual machine, e.g., DAFNE, where the crossing angle might be varied between 10 and 20 mrad and the bunch length could be changed by a 3rd harmonic RF system.

J. Gao asked about experience with, or considerations on, the **pinch effect** in storage rings. He pointed to a paper by A. Chao [58]. It was remarked that P. Chen's and K. Yokoya's work [59] might be relevant for this question as well. The pinch effect appears similar to the notion of a travelling focus in linear colliders [60]. The audience and J. Gao raised three questions: (1) Is it important? (2) Can it be useful? (3) How does it scale with energy?

***What are the next steps in understanding the beam-beam interaction and how to increase the tune shifts?***

The next step is an extension of strong-strong beam-beam simulations so as to include the parasitic collisions, and to determine the optimum crossing angle for a given bunch spacing. K. Ohmi and Y. Cai will rise to this challenge. The tune shifts could be increased by a variety of means: RF focusing, crab cavities, round beams in conjunction with an improved dynamic aperture, wire compensation of the parasitic collisions, electron lens, or two collision points with mutual cancellation.

It was next debated whether and where the **strong RF focusing** idea could be tested in practice. A meaningful experiment should approach a synchrotron tune near 0.5. For CESR the maximum synchrotron tune is 0.1-0.2 at 1.5 GeV, while the DAFNE2 design value is 0.4. Some other candidate storage rings that came to mind are the SLAC damping ring, PETRA, DORIS, or the new SPEAR-III. During the 2000 Chamonix workshop, such test was proposed for LEP at injection by A. Hofmann, but, unfortunately, LEP no longer is available.

***Are there new operational issues that can help control beam tails and backgrounds?***

Octupoles are not useful for increasing the tune shift (J. Seeman tried them unsuccessfully at CESR and SPEAR), but at DAFNE the octupoles help for lifetime and background. Specifically, they increase the beam lifetime by about 20%.

Finally, the **electron cloud** was also discussed, in particular the question why DAFNE does not observe any electron-cloud effects. The DAFNE bunch spacing is 80 cm, the bunch current 20 mA, and the bunch population about $4\times10^{10}$. It was suggested that DAFNE should try to produce an electron cloud, by reducing the number of bunches, increasing the bunch population, e.g., by a factor of 2, and possibly filling every RF bucket. The situation at CESR was also discussed. There the bunch spacing is 3.6 m, or 12 ns, and for normal operation up to 5 bunches are stored in a row ('mini-trains'). For a dedicated study, an arbitrary number of positron bunches could be produced in CESR, and bunch populations of $3\times10^{11}$ are feasible. CESR has an Al beam-pipe without an antechamber.

D. Rice suggested, for future reference, to compile a list of all existing strong-strong beam-beam simulation codes, including their main features and possible benchmarks against operating colliders or other simulation programs. This compilation is displayed in Table 1. Some related references are [14,17,61,62,63,64,65,66].

Table 1:Strong-Strong Beam-Beam Simulation Codes

| Author | Institute | Name | Angle | Paras. | Optics errors | SR | Bench - mark w code | Bench- mark w collider |
|---|---|---|---|---|---|---|---|---|
| A. Kabel | SLAC | nameless | No | Soon | No | Yes | Cai | ? |
| J. Qiang | LBNL | BEAMB EAM3D | Yes | Yes | Yes | Yes | Cai, Ohmi | RHIC Tevatron |
| K. Ohmi | KEK | BBSR | Yes | No | Yes | Yes | Cai, Qiang | KEKB, PEP-II |
| Y. Cai | SLAC | nameless | Yes | No | Yes | Yes | Ohmi, Kabel | PEP-II, KEKB |
| J. Rogers | Cornell | Odysseus | Yes | Yes | Yes | Yes | No | CESR |
| S. Krish-nagopal | CAT Indore | CBI | No | No | No | Yes | No | (PEP-II?, LHC) |
| J. Shi | Kansas | ? | ? | Yes | Yes | ? | ? | (LHC) |
| W. Herr, F. Jones | CERN/ TRIUMF | BeamX | Yes | Yes | Partly | No | No | (LHC) |

## 6. CONCLUSIONS

For the next generation of factories several exciting novel design concepts have been proposed. Most of these will likely be tested soon, such as strong RF focusing, round-beam collisions, Raimondi-Seryi final focus for factories, beam-beam compensation schemes, etc. Significant progress is visible not only in the experimental beam-beam diagnostics, but also in the strong-strong beam-beam modeling, where simulations now closely reproduce observed luminosities and limiting tune shifts, and where, for typical optimized working points, the main limitation seems to arise from an incoherent effect. A few open questions still remain to be answered, such as the optimum choice of crossing angle or bunch spacing, and the best approach to produce a short bunch length. The present IR layouts work well. They provide a solid basis for the upgrades. Interesting news were also reported on lattice designs, optics diagnostics, tuning, and magnet motion. In summary, the progress at the operating electron-positron colliders is impressive, as evidenced by the recent remarkable improvements in their performance and understanding. The factories community has all reason to look optimistically towards the future.

## Acknowledgments

I would like to thank John Seeman for inviting me to chair this working group, my associates Michael Sullivan and Yunhai Cai for their precious help in organizing and managing the sessions, and John Corlett for the fruitful collaboration with the rf working group. I also thank Yunhai Cai and Kazuhito Ohmi for helpful informations.

## References

[1] C. Montag, “eRHIC Interaction Region Design,” these proceedings.

[2] K.Hirata, E.Keil, “Barycentre Motion of Beams due to Beam-Beam Interaction in Asymmetric Ring Colliders,’’ NIM A292, 156-168 (1990).

[3] A.Aleksandrov, D.Pestrikov, “Coherent Beam-Beam Oscillations in Asymmetric Colliders,’’ EPAC90, Nice (1990).

[4] M.Sullivan, “Upgrades to the PEP-II Interaction Region,” these proceedings.

[5] A. Seryi, “PEP-II IR Alignment,” these proceedings.

[6] M.Sullivan, “Super-B Factory Interaction Regions,” these proceedings.

[7] Y.Funakoshi, “IR Design for Super-KEKB,” these proceedings.

[8] F.Zimmermann, “Raimondi-Seryi Final Focus for Factory IRs?,” these proceedings.

[9] P.Raimondi, A. Seryi, “A Novel Final-Focus Design for Future Linear Colliders,” Phys. Rev. Lett. 86, pp. 3779 (2001).

[10] P.Raimondi, F. Zimmermann, “Performance of a Compact Final-Focus System for a 30-TeV Muon Collider,” SL-Note-2001-020 AP; contribution to the ‘6-Month Feasibility Study on High Energy Muon Colliders,’ A. Caldwell and B. King (eds.), ISBN: 1-58949-020-7, Rinton Press (2001).

[11] A.Valishev, “Simulations of Beam-Beam Interaction for Round Beams,” these proceedings.

[12] E.Young et al., “Collisions of Resonantly Coupled Round Beams at the Cornell Electron-Positron Storage Ring (CESR),” PAC 97 Vancouver (1997).

[13] D.Shatilov, “Beam-Beam Simulations at Large Amplitudes and Lifetime Determination,” Part. Accel. 52, pp. 65-93 (1996).

[14] K.Ohmi, “Simulation of Beam-Beam Effects in a Circular e+e- Collider,” Phys. Rev. E, 62, pp. 7287-7294 (2000).

[15] A.Skrinsky, “New Colliders at Novosibirsk,” these proceedings.

[16] Y.Cai, “Beam-Beam Simulation for PEP-II,” these proceedings.

[17] Y.Cai et al., “Simulation of the Beam-Beam Effects in e+e- Storage Rings with a Method of Reducing the Region of Mesh,” PRST-AB 4, 011001 (2001).

[18] K. Hirata, F. Ruggiero, “Treatment of Radiation in Electron Storage Rings,” LEP Note 611 (1988).

[19] A.V. Otboyev, E.A. Perevedentsev, “Self-Consistent Beta Functions and Emittances of Round Colliding Beams,” PRST-AB 2, 104401 (1999).

[20] K.Hirata, “Analysis of Beam-Beam Interactions with a Large Crossing Angle,” Phys. Rev. Letters 74, 12, p. 2228 (1995).

[21] J.Gao, “Analytical Estimation of Beam-Beam Interaction Limited Lifetimes in Circular Colliders,” these proceedings.

[22] J.Gao, "Analytical Estimation of the Beam-Beam Interaction Limited Dynamic Apertures and Lifetimes in e+e- Circular Colliders," NIM A 463, pp. 50-61 (2001).
[23] C.Biscari, "Negative Alfa Experience," these proceedings.
[24] W.Kozanecki, "Beam-Beam Experience at PEP-II," these proceedings.
[25] K.Ohmi, "Beam-Beam Limit Estimated by Quasi-Strong Simulation," these proceedings.
[26] K.Ohmi, K.Hirata, N.Toge, "Quasi-Strong-Strong Simulations for Beam-Beam Interactions in KEKB," Proc. 5th EPAC, Sitges (1996).
[27] K.Ohmi, "Summary of Beam-Beam Effects," these proceedings.
[28] J.Tennyson, "Resonance Transport in Near-Integrable Systems with Many Degrees of Freedom," Physica 5D, 123-135 (1982).
[29] F.Zimmermann, "Weak-Strong Model for the Combined Effect of Beam-Beam Interaction and Electron Cloud," these proceedings.
[30] G.Rumolo and F.Zimmermann, "Electron Cloud Instability with Space Charge and Beam Beam," Int. Workshop on Two-Stream Instabilities, KEK, Tsukuba, 2001, and CERN-SL-2001-067 (2001).
[31] G.Rumolo and F.Zimmermann, "Practical User Guide for HEADTAIL," CERN-SL-Note-2002-036 AP (2002).
[32] A.Chao, "Physics of Collective Beam Instabilities in High Energy Accelerators," J. Wiley (1993).
[33] M.Biagini, "Long-Range Beam-Beam Interactions in PEP-II," these proceedings.
[34] F.Zimmermann, "Compensating Parasitic Collisions using Electro-Magnetic Lenses," these proceedings.
[35] J.-P.Koutchouk, "Principle of a Correction of the Long-Range Beam-Beam Effect in LHC using Electromagnetic Lenses," LHC Project Note 223 (2000); Proc. PAC2001 Chicago, p.1681 (2001).
[36] F.Zimmermann, "Weak-Strong Simulation Studies for the LHC Long-Range Beam-Beam Compensation," in 'Contributions of the SL Division to the Workshop on Beam-Beam Effects at Fermilab', LHC Project Report 502 (2001).
[37] J.Irwin, "Diffusive Losses from SSC Particle Bunches due to Long-Range Beam-Beam Interactions," SSC-233 (1989).
[38] F.Zimmermann, "Short Review of Super-Bunches for Hadron Colliders," these proceedings.
[39] K.Takayama et al., "Superbunch Hadron Colliders," PRL 88: 144801 (2002).
[40] F.Ruggiero, G.Rumolo, F.Zimmermann, Y.Papaphilippou, "Beam Dynamics Studies for Uniform Hollow) Bunches or Super-Bunches in the LHC: Beam-Beam Effects, Electron Cloud, Longitudinal Dynamics, and Intrabeam Scattering," Proc. RPIA2002 Tsukuba, and CERN LHC Project Report 627 (2003); see also the same authors at PAC2003 Portland, Oregon (2003).
[41] O.Bruning et al., "LHC Luminosity and Energy Upgrade: A Feasibility Study," CERN LHC Project Report 626 (2002).
[42] F.Ruggiero, F.Zimmermann, "Luminosity Optimization near the Beam-Beam Limit by Increasing Bunch Length or Crossing Angle," PRST-AB 5:061101 (2002).
[43] D.Wang, "Lattice Design of the Electron Ring of eRHIC," these proceedings.
[44] Y.Cai, "LEGO: A Class Library for Accelerator Design and Simulation," ICAP98 Monterey, eConf C980914:6-10 (1998).
[45] "SAD: Strategic Accelerator Design", home page *http://acc-physics.kek.jp/SAD/sad.html*
[46] H.Grote, C.Iselin, "The MAD Program (Methodical Accelerator Design) Version 8.4: User's Reference Manual," CERN-SL-90-13-AP-REV.2 (1991).
[47] D. Shatilov, "Beam-Beam Study for PEP-N Project," comment by J. Seeman (no reference provided).
[48] Y.Cai, "Beam-Beam Simulations for a Linac-Ring Collider," unpublished.
[49] J.Irwin, C.X.Wang, Y.Yan, et al., "Model-Independent Beam Dynamics Analysis," Phys. Rev. Letters 82: 1684-1687 (1999).
[50] Y. Yan, "PEP-II Beta-Beat Fixes with MIA," these proceedings.
[51] C.-X.Wang, et al., "Phase Advance and Beta Function Measurements using Model-Independent Analysis," PRST-AB 6, 104001 (2003).
[52] F.-J.Decker, "Orbit Bumps in PEP-II to Maximize Luminosity," these proceedings.
[53] F.-J.Decker, et al., Orbit Distortions and Bumps in the PEP-II LER Ring," EPAC'02 Paris, p. 289 (2002).
[54] A.Gallo, "Strong RF Focusing: a Possible Approach to Get Short Bunches at the IP," these proceedings.
[55] A.Piwinski, "Synchrotron Oscillations in High-Energy Synchrotrons," NIM 72, pp. 79-81 (1969).
[56] J.Seeman, "Future Very High Luminosity Options for PEP-II," these proceedings.
[57] J.Gao, "Analytical Treatment of Nonlinear Beam Dynamics," these proceedings.
[58] A.W.Chao, Y.Kamiya, "Bunch Shape at IP and the Pinch Effect," SLAC-CN-218 (1983).
[59] K.Yokoya, P.Chen, "Beam-Beam Phenomena in Linear Colliders," 1990 US-CERN School, Hilton Head Island, So. Carolina (1990).
[60] V. Balakin, "Traveling Focus Regime for Linear Collider VLEPP," Proc. LC91 workshop on Linear Colliders, Protvino 1991, Vol. 1, p. 330 (1991).
[61] S. Krishnagopal, R. Siemann, "Coherent Beam-Beam Interactions in Electron-Positron Colliders," PRL 67, 18, p. 2461 (1991).
[62] J. Qiang, et al., "Strong-Strong Beam-Beam Simulation using a Green Function Approach," PRST-AB 5: 104402 (2002).
[63] W. Herr, M.P. Zorzano, F. Jones, "A Hybrid Fast Multipole Method Applied to Beam-Beam Collisions in the Strong-Strong Regime," PRST-AB 4: 054402 (2001).

[64] J. Shi, D. Yao, "Colective Beam-Beam Effecst in Hadron Colliders," PRE62, 1258-1265 (2000).
[65] A. Kabel, "Parallel Simulation Algorithms for the 3-Dimensional Strong-Strong Beam-Beam Interaction," PAC2003 Portland Oregon (2003).
[66] E.B. Anderson, J. Rogers, "ODYSSEUS: A Dynamic Strong-Strong Beam-Beam Simulation for Storage Rings," ICAP98 Monterey, eConf C980914:122-126 (1998).