Report from Working Group T5: Beam Dynamics

M. Blaskiewicz
Brookhaven National Laboratory
K.-J. Kim
The University of Chicago and Argonne National Laboratory
S. Y. Lee
Indiana University

Speakers and Participants

R. Assmann, R. Baartman, V. Balbekov, K. Balewski, K. Bane, D. Barber, W. Barletta, J. Berg, M. Berz, M. Blaskiewicz, A. Bogacz, C. Bohn, D. Bruhwiler, A. Burov, Y. Cai, A. Chao, C. Chen, P. Colestock, F.-J. Decker, W. Decking, Ya. Derbenev, A. Dragt, G. Dugan, J. Ellison, D. Errede, R. Fernow, M. Furman, A. Garren, J. Gallardo, S. Geer, J. Griffin, S. Habib, G. Hansen, K. Harkay, S. Heifets, K. Heitmann, S. Henderson, T. Hill, I. Hofmann, J. Holmes, Z. Huang, J. Irwin, A. Jackson, L. Jin, P. Johnson, A. Kabel, D. Kaplan, E. Keil, K.-J. Kim, H. Kirk, G. Krafft, D. Krop, K. Kubo, P. Lebrun, S.Y. Lee, D. Lehman, S. Lidia, A. Luccio, R. Macek, S. Machida, K. Makino, J. Marriner, A. Mikhailichenko, F. Mills, M. Minty, S. Nagaitsev, B. Nash, D. Neuffer, E. Ng, T. Nobukazu, K. Pacha, M. Palmer, R. Palmer, V. Papadimitriou, Z. Parsa, S. Peggs, G. Penn, F. Pilat, M. Pivi, C. Prior, S. Pruss, J. Qiang, H. Qin, P. Raimondi, U. Ratzinger, T. Raubenheimer, J. Rogers, A. Romano, T. Roser, R. Ruth, R. Ryne, R. Samulyak, D. Schulte, P. Schwandt, J. Seeman, T. Sen, A. Seryi, J. Shi, Y. Shimosaki, A. Skrinsky, L. Spentzouris, G. Stupakov, D. Sutter, K. Takayama, V. Telnov, P. Tenenbaum, A. Thiessen, V. Tsakanov, M. Venturini, N. Walker, C.-x. Wang, M. Watanabe, F. Willeke, M. Witherel, A. Wolski, J. Wurtele, A. Wolski, M. Xiao, M. Zisman

ABSTRACT

During the last several decades there have been tremendous advances in the power and the techniques of particle accelerators. In parallel, there have been remarkable advances in the understanding of how charged particle beams interact with themselves and with external environments. The current status of *beam dynamics* is such that some of the mathematical tools for the collective instabilities, phase-space dilutions and beam cooling methods, nonlinear phenomenon, etc. have become practical design tools for currently operating accelerators. As we contemplate the next generation of large-scale accelerator projects, there are more challenges ahead, both in improving the predictive power of the current calculations as well as in developing new topics. This report is a summary of the discussions of the Beam Dynamics (T5) Working Group at Snowmass on the progress and challenges for the beam dynamics of future accelerators.

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Executive Summary

Though great progress has been made, instabilities remain important. For lepton machines the prevention and damping of transverse mode coupling instability (TMCI) is crucial; it has yet to manifest in hadron machines but care is needed. An effective damping scheme is needed and fully coupled calculations will help weed out ineffective methods. This is true for all stability calculations. All relevant electromagnetic processes including, for example, detuning wakes should be examined. With its small revolution frequency, electrodynamics of the VLHC involves new sorts of quasi-static effects that deserve special attention.

Electron clouds are dangerous both from the transverse two-stream instability that can result and the increased heat load in cryogenic systems. Recent data suggest significant survival of low-energy electrons striking the vacuum chamber. This must be studied since the estimate of both the cryoload and cloud density could increase by an order of magnitude.

Studies on the electron-cloud instability are progressing. A linear response model agrees well with the existing data from positron rings, though why PEP-II and KEKB see the instability in different planes is unexplained. A comparison of calculated and experimental scaling laws is warranted. A nonlinear theory appears necessary to explain the instability scaling laws in the PSR.

Space-charge effects play a significant role in proton booster synchrotrons. Widespread supercomputing allows for new levels of prediction and control, but better theoretical models should be sought as well. With its large radius and small emittance, space charge affects the TESLA damping ring. Beam rounders are used in the TESLA damping ring design to reduce the vertical tune shift. This is a new and exciting territory.

The principles of intrabeam scattering (IBS) are well understood, and it is time to develop a complete implementation. The reported discrepancies between IBS estimates (up to a factor of two) are almost certainly due to the use of approximate formulas and experimental uncertainties. Both RHIC and ATF/KEK will provide detailed verification of the IBS theory, particularly the distinctive behavior below and above transition.

All sources of beam degradation must be tightly controlled to realize high-luminosity linear colliders. Techniques for controlling wakefield-induced beam breakup (BBU) have been developed both for single-bunch and multibunch phenomena. Emittance degradation due to mismatch and filamentation can be reduced by precision alignment and control of all vibration sources.

Minor perturbation of the bunch tails (banana effect) could lead to significant luminosity reduction due to the complex interaction of the colliding beams. Methods to mitigate the effect are being explored. The influence of strong damping wigglers in damping rings on nonlinear beam dynamics needs to be fully understood.

Beam cooling techniques are useful to achieve high luminosity operation in many colliders. Stochastic cooling in the microwave frequency range is routinely used in antiproton accumulators. The principles of electron cooling have been extensively demonstrated for low-energy hadron beams. High-energy electron cooling will be implemented in the Fermilab Recycler Ring. This will be important to the high-luminosity operation of the Tevatron. High-energy electron cooling may also be implemented for luminosity enhancement in RHIC and PETRA using electron beams generated by a superconducting linac with energy recovery. Optical stochastic cooling using high-power laser amplifiers may provide a drastic increase in cooling rate.

To realize muon colliders with reasonable luminosities, ionization cooling by a factor of 10^6 in the 6D phase space is needed. This is being intensively studied. Neutrino factories do not require longitudinal cooling. Transverse cooling in a linear cooling channel involving liquid hydrogen absorbers, rf cavities, and a solenoidal focusing lattice looks feasible. It requires a new regime of beam dynamics due to large aperture beam transport, strong nonlinearities, and the role of angular momentum. Two major simulation codes, GEANT4 and ICOOL, have been developed and cross-checked. Efforts are underway to provide an analytic understanding of the ionization cooling starting from a linear description and systematically adding nonlinear effects. Longitudinal cooling via emittance exchange is under study. Several schemes have been proposed.

In the past, weak-strong beam-beam simulation codes have been valuable for the design and operation of high-luminosity colliders, such as LEP. Strong beam-beam simulation codes have recently been developed into powerful tools for the study of beam-beam effects in high-luminosity colliders. These codes have been used to compare and optimize the operation of PEP-II, KEKB, and CESR. Besides the optimization of these high-energy colliders, the codes can be used to study effects, such as coherent beam-beam modes on beam instabilities, the scaling law of beam-beam tune shift vs damping decrement, and correction schemes. Compensation schemes include wire correctors to compensate the long-range beam-beam effects for the LHC and electron lenses to compensate beam-beam effects for antiprotons in the Tevatron. These are important experiments. Experimental studies of beam-beam effects with round beams should be carried out. The schemes the of round-beam transformer, and of fully coupled betatron motion, should be further studied.

Sophisticated map methods have changed the way we design accelerators. The parallel development of pure theory and real-world applications provides a model for the study of beam dynamics. Maps can provide fast and reliable tracking and accurate modeling for nonlinear resonances. This played a key role in the design and construction of B-factories. It is expected that this design tool will be used in future high-luminosity colliders. Notable improvements in the elimination of chromatic aberrations at the IP of a linear collider have been achieved.

Accelerator development for high brightness requires instrumentation pushed to the sensitivity frontier. Employing model independent analysis (MIA), the sensitivity of instrumentations can be greatly enhanced. This technique, coupled with computing power, will become an indispensable tool in large accelerator complexes.

Techniques in polarization preservation have matured by using full snake, partial snake, and rf dipole. Experiments in medium-energy accelerators such as the AGS and RHIC will test spin dynamics at the high energy frontier. Some of these issues are the rf spin flip, snake resonances, spin chromaticity, and spin diffusion. Electron polarized sources with a high quantum efficiency will continue to play important roles in future linear colliders. A polarized positron source may be obtained from the pair production of circular polarized photons.

1. Transverse Impedance and Stability in Rings

Impedance issues appear solvable in principle [1] The usual strategy of rough approximation followed by more refined estimates is sound. Detuning wakes, which are generalizations of the Laslett image coefficients, should be considered as well. This is particularly important for large machines where the betatron tune spread due to detuning wakes can rival the spread due to chomaticity. For the very largest machines, like VLHC, the usual separation between DC and high-frequency phenomena becomes blurred. This is tractable but requires some work. Also, for large machines the calculated tune shifts can be of order unity, which will require new ways of thinking about feedback. Also, as machines evolve, the fraction of the impedance due to interaction regions will increase. Teamwork between builders and experimenters will be needed to optimize experiments.

For lepton machines a major study issue is the prevention and/or damping of the fast head-tail or transverse mode coupling instability (TMCI) [2]. Reactive feedback has been tried, with limited success. Whether or not this is a fundamental limitation is an important issue. Special care needs to be exercised when the sychrotron tune becomes large. Synchrobetatron resonances with $Q_\beta - mQ_s = k$ can exist for small values of m, and a distributed system of kickers and pickups may be required. In any case, the interaction between the beam and the damping system should be modeled self-consistently including realistic passbands and delays. This is a straightforward extension of current techniques but significant work nonetheless. Calculations for the proposed VLHC would be of interest.

Recent observations at the ESRF point toward bunch intensities five (5) times beyond the TMCI threshold [3]. This is very important and warrants man-years of research.

The inclusion of detuning wakes should become commonplace in simulations. The analogous analytic work is valuable as well. PEP-II results, with multibunch tune shifts five times larger than expected, could point to a significant midrange impedance that has been missed. In general these midrange wakes with bandwidths of order of the bunching frequency need to be included correctly in a nonrigid, multibunch analysis.

For hadron machines the TMCI may soon appear. A guarded stance is prudent and efforts toward accurate predictions of TMCI are warranted.

In many hadron machines, as well at the TESLA damping ring, direct space charge is the largest collective force. Up to now, completely neglecting the space-charge force has led to good agreement between prediction and experiment, but good reasons why they have been neglected are absent. Simulations with space-charge effects are large-scale computational problems, and it is not clear that the requisite algorithms exist, *e.g.*, symplecticity combined with adequate resolution and speed. Analytic work assuming highly idealized models has provided some insight, but new ideas are needed.

1.1. Talks

1. M. Blaskiewicz: Transverse Impedance and Instabilities in Rings

2. K. Harkay: Transverse Bursting Modes in the APS

2. Electron Clouds

When free electrons within the vacuum chamber are accelerated by the electric field of the beam a two stream, transverse instability may ensue [4]. This electron cloud instability is present in both hadron and positron machines but, due to the sign of the electric field, less likely with electron beams. There are two fundamental lines of research.

The generation of the cloud involves the liberation of primary electrons via photoemission, losses, or stripping of the background gas. When the primaries are accelerated by the field of the beam, they can strike the vacuum chamber wall with sufficient energy to liberate more electrons. The surface physics of the wall is complicated and one generally resorts to measurements to characterize the system. The secondaries generally have a few electron-volts of kinetic energy, and the cloud evolves under the influence of its self-electric field between bunch passages. One critical area of research is characterization of the wall interaction for low electron impact energies, since this largely determines the number of free electrons that survive the gap between bunches. This affects both instability thresholds and the cryogenic heat load, where applicable. For the LANL PSR, rough calculations show an order of magnitude increase in electrons surviving the gap when reasonable, low-energy reflection probabilities ~ 0.8 are included. The instability has been extensively studied in the PSR, SPS, PEP-II and KEKB. A noticeable exception is the ISIS synchrotron, which sees no instability. It is presumed that its wire cage within the vacuum chamber plays a fundamental role, but serious calculations remain to be done.

A myriad of experimental studies on the PSR and the various positron rings have been suggested. Generally, these are valuable experiments but it is also important to analyze the data carefully and publish new findings. Funding for data analysis might prove more valuable than regular beam time. A timely characterization of the electron cloud is particularly important for the LHC, since the cryogenic heat load could be strongly influenced by electrons striking the wall.

The second line of research involves the instability. For short positron bunches, a linear response model agrees fairly well with existing data. More extensive measurements of scaling, with, *e.g.*, rf voltage, are needed to test the viability of linear response models.

In the PSR the instability threshold follows simple scaling laws (R. Macek, PAC01). The maximum number of stored protons is proportional to the rf voltage and is independent of the bunch length. While the linear scaling with voltage is consistent with linear response, the lack of dependence on bunch length seems to require a nonlinear treatment. However, the simple scaling laws suggest that the complex behavior exhibited by the signals from the electron cloud are not fundamental to the instability. This is fortunate, since detailed dependence on several parameters will make predictions for future machines very difficult.

Future research on the experimental side needs to include a better characterization of secondary emission, especially at low energy. This is several man-years of experimental research but is of negligible cost compared with a major project. Other experimental questions include:

- Why is a horizontal electron flux seen in the 1.2-T vertical bends of the PSR?

- Why is no electron cloud instability seen in DAΦNE?

- What are the electron cloud densities within the beam?

- How does the coherent betatron tune shift vary along a bunch train?

On the theoretical side a realistic approach is needed. One must accurately model the observed scaling laws before claiming understanding. The PSR scaling laws with voltage and bunch length are fundamental. On the positron side, the fact thap PEP-II and KEKB see the instability in different planes must be explained. Other avenues of theory are difficult to predict in advance but it is likely to take tens of man-years of effort. The reward, in terms of building machines close to but below threshold, will greatly outweigh the salaries of a handful of theorists.

2.1. Talks

1. M. Furman: Electron Cloud Effects
2. J. Seeman: Suggested ECE Calculations
3. G. Stupakov: Possible Effects with Electron Beams
4. R. Macek: New Data from the PSR
5. M. Blaskiewicz: Difficulties with a Linear Response Model for PSR

3. Space Charge

With the advent of widespread supercomputing, the prediction and control of space-charge forces is experiencing a renaissance [5]. Reliable simulations of short-term behavior are in hand, and long-term problems, related mainly to booster synchrotrons, seem almost tractable.

From the analytic point of view the situation is similar. For high-intensity linacs the importance of matching and the deleterious effects of mismatch are well explained by considering a few low-lying modes associated with the space-charge force. In booster synchrotrons the fractional detuning is only a few percent and the modes of interest generally correspond to relatively high-order resonances. Here too, one hopes the theorists will succeed in formulating a reasonable picture.

With its large circumference and small emittance, space-charge forces are important in the TESLA damping ring. Beam rounders, which are accelerator versions of optical quarter-wave plates, are used to reduce the vertical tune shift. This is new territory and study topics include the creation of halos, driven by coherent oscillations and chromatic abberations.

3.1. Talks

1. I. Hoffman: Longitudinal Space Charge and Instabilities
2. W. Decking: Space Charge in the TESLA Damping Rings

4. Longitudinal Instabilities

At first glance the longitudinal instability problem looks simpler than the transverse problem. However, longitudinal instabilities quickly go nonlinear (E. Shaposhnikova, PAC01) . Since stability thresholds depend on the longitudinal phase-space distribution, an initially unstable bunch can quickly stabilize with only a small increase in emittance. Additionally, stability thresholds can have a sensitive dependence on machine impedance. For example, calculations show that adding an inductive impedance of $Z/n = i0.1\Omega$ could double the stable intensity of the SLC damping rings. Another point of interest is the possibility that we might be able to simulate the effect of broadband Z/n far more efficiently than is normally done. This bold statement follows from work on numerical solutions to the Vlasov equation wherein a 100 by 100 grid can faithfully model systems up to 1/4 of the Nyquist frequency. Compare this situation with the usual macroparticle simulations where the rms statistical error scales as $\sqrt{N_{bin}^3/N_{macro}}$! A hybrid technique by C. Prior seems to integrate the best of both worlds and deserves careful consideration. Generally, the accelerator community would benefit by a greater interaction with outstanding mathematicians.

4.1. Talks

1. K. Bane: Single Bunch Longitudinal Instabilities

5. Beam Breakup

Beam breakup (BBU) occurs in linacs when coherent betatron oscillations of leading particles create wakefields that resonantly drive trailing particles. BBU is usually driven by dipole modes in the accelerating structure. Long-range BBU is a multibunch effect, driven by wakefields that persist between bunches, while short-range BBU is due to short-range wakefields that cause breakup within a single bunch.

Long-range BBU can be suppressed by designing the rf structure so that the net dipole wakefield is small for multibunch spacings. This is especially important in the NLC design, where long-range wakefields are suppressed by a combination of detuning and damping.

No effective damping scheme for short-range wakefields is known, and it is necessary to modulate the betatron tune along a bunch to suppress short-range BBU. Since short-range wakefields always kick trailing particles in the same direction as the offset of the head particles, stronger focusing of the tail particles suppresses BBU. This can be accomplished by introducing a correlated energy spread (BNS damping) or by using rf quadrupoles. For both NLC and TESLA it is important to calculate the efficiency of BBU suppression schemes, since small correlated offsets could yield banana-shaped transverse distortions, which will reduce luminosity.

5.1. Talks

1. G. Stupakov: Beam Break up Instability in Linacs

2. S. Heifets: Beam Instability and Microbunching due to Coherent Synchrotron Radiation

6. Emittance Preservation in Linear Colliders

In a linear collider, intense, high-brightness electron beams are produced, accelerated, and focused to a nanometer spot for collisions with opposing positron beams. To realize and maintain high luminosity, all sources of beam degradation and fluctuation in the entire accelerator chain must be tightly controlled [6, 7]. Significant progress has been made during the last decade on accelerator techniques for production and manipulation of high-brightness beams so that linear colliders with 500 GeV center of mass energy and a luminosity of a few times $10^{34}\ cm^{-2}\ s^{-1}$ appear technically feasible. The progress has been beneficial also to other applications requiring high-brightness linacs, such as x-ray free-electron lasers for the fourth-generation light sources.

6.1. Damping Ring Performance

The main causes of the damping ring performance in producing low-emittance beams are the instabilities driven by impedances and electron clouds, and also the intrabeam scattering. These phenomena have been modeled extensively and efforts are underway to test the modeling predictions at existing electron storage rings for synchrotron light sources and e+e- circular colliders. One of the prominent features of damping rings is a long, high-field wiggler for enhanced damping. The effects of these wigglers on nonlinear beam dynamics need to be understood thoroughly with a realistic 3-D field configuration model. In the TESLA damping ring, the space-charge effect could be significant due to its long circumference and high bunch intensity, as discussed in the instability section.

6.2. Emittance Degradation in Linacs

Two main causes of emittance degradation in linacs are wakefield-induced beam breakup (BBU) and filamentation of mismatched beams. Misalignment of the accelerating structures must be tightly controlled to suppress wakefields. The BBU effect is significant in the NLC linac due to the small aperture of the x-band rf structures. However, the suppression of the single-bunch BBU by the BNS damping is well-known and has been tested experimentally [2]. The multibunch BBU can be controlled by suitably detuning the accelerating structures. The BBU effects are not thought to be a problem in TESLA due to the large aperture.

Emittance degradation due to mismatch can be limited by precision alignment and control of all vibration sources including the ground motion. These topics have been studied very thoroughly from the machine-operation perspective by the collider design teams.

6.3. Sensitivity to Beam Profiles

For strongly disruptive collisions, the luminosity could be sensitive to small distortions of beam profiles not evident from the value of the projected emittances [8]. Such distortions could develop, for example, from the residual BBU effects that are left uncompensated. This is clearly an important topic that needs to be more fully investigated.

6.4. Talks

1. T. Raubenheimer: Accelerator Physics Review of Emittance Correction & Preservation in Rings and Linacs

2. R. Assmann: Comparison of Beam Dynamics in the NLC/JLC, CLIC and TESLA Main Linacs

3. N. Walker: Emittance Preservation in Beam Delivery Systems

4. D. Schulte: Correlated Emittance Growth and Luminosity Sensitivity

5. A. Kabel: Coherent Synchrotron Radiation, Theory and Experimental Results

6. P. Tenenbaum: Beam-based Alignment Techniques and Algorithms; Overview and NLC-Specific

7. D. Schulte: CLIC-Specific

8. V. Tsakanov: TESLA-Specific

7. Cooling of Hadron Beams

Beam cooling is useful for high-luminosity operation of hadron colliders. Two main techniques are stochastic cooling [9] and electron cooling [10]. In stochastic cooling, errors in phase-space coordinates of beam samples containing a finite number of particles are detected and corrected repeatedly. In electron cooling, hadron beams are cooled via interaction with co-moving, cold electron beams. Stochastic cooling has been routinely used for antiproton accumulation in p-$\bar{p}$ colliders. Electron cooling has been effective for low-energy ion machines. At present, cooling is not considered for LHC and higher energy p-p machines. However, recently there has been increased interest in electron cooling at collision energies in large heavy ion machines such as RHIC [11] and PETRA [12].

7.1. Stochastic Cooling

Stochastic cooling with microwave circuits with a few GHz bandwidths has been remarkably efficient for anti-proton accumulation, allowing the construction of the p-p̄ colliders. However, the bunched-beam stochastic cooling has proved to be challenging for practical implementation due to the presence of coherent signals. A leap in the capability of stochastic cooling may be achieved by employing optical amplifiers developed for high-power lasers and periodic magnets (undulators) as the pick-up and kicker devices, opening up new applications in ultrashort electron beams and in high-energy muon colliders. Proof-of-principle experiments of optical stochastic cooling in a low-energy electron storage ring would be highly desirable.

7.2. Electron Cooling

Electron cooling was originally invented to realize p-p̄ colliders. However, its main application has been in cooler rings of low-energy ion beams. Recently, however, interest in high-energy electron cooling is growing. At Fermilab, an electron cooling system is being installed in the 8.9-GeV p̄ recycler ring using electron beam from a 5-MV Pelletron [13]. Studies for continuous electron cooling of ion beams at collision energy at RHIC and PETRA are underway. These applications will require high-brightness, MeV to GeV electron beams of tens of megawatts of power. Such beams can be produced by a storage ring or by a system based on an rf photocathode gun and superconducting linear accelerators with a recirculation path for energy recovery. High-power, energy recovery linacs of similar capabilities have been proposed for applications in high-power free-electron lasers, and experience from theses machines will be very valuable.

7.3. Solenoidal Optics

The study of beam cooling has spurred development of sophisticated beam dynamics techniques. Development of advanced microwave pick-up and kicker devices for stochastic cooling is one example. Another is the development of novel electron optics employing solenoidal and quadrupolar lenses in high-energy electron cooling [14], leading to a better understanding of the role of the angular momentum in beam dynamics. This in turn led the idea of a beam rounder with which a flat beam can be transformed into a round beam [15]. As mentioned before, a beam rounder may help to extend the tuneshift limits of colliders. Also, a beam flatter, which is a beam rounder in reverse, could be useful for linear collider applications.

7.4. Talks

1. A. Skrinsky: Cooling of Hadron Beams, Critical Issues
2. S. Peggs: Diffusion in Hadron Storage Ring
3. J. Marriner: A Review of Stochastic Cooling
4. S. Nagaitsev: Electron Cooling at FNAL
5. K. Balewski: High Energy Electron Cooling at DESY

8. Intrabeam Scattering

Intrabeam scattering (IBS) is the process in which small-angle Coulomb scattering in the beam rest frame leads to relaxation of beam distribution in storage rings, coupling all three degrees of freedom for both electron and hadron beams. In an electron storage ring, IBS can limit the ultimate phase-space density as radiation damping, quantum excitation, and IBS yields an equilibrium beam distribution. In a hadron storage ring, IBS can determine beam lifetime due to diffusion in the absence of any damping mechanism.

8.1. Theory

The theory of IBS was pioneered by Piwinski and is summarized in Ref. [16]. Bjorken and Mtingwa [17] provide an alternate approach to IBS based on the S-matrix formalism. The two theories in general agree with each other once the lattice variation is taken into account in Piwinski's theory, for example, by substituting $\eta_{x,y}^2/\beta_{x,y}$ with the $\mathcal{H}_{x,y}$ function.

8.2. New Experiments

Experiments at newly constructed electron and hadron rings will provide opportunities for a detailed verification of the IBS theory. In the RHIC experiment [18, 19], longitudinal and transverse beam sizes of gold ions are recorded at the injection (below transition) and at the store (above transition). Reasonable agreement between the measured longitudinal growth times and IBS calculations is found (within a factor of two). Below transition, the beam grows transversely (i.e., no transverse shrinkage is observed), consistent with the expected IBS behavior in a strong-focusing lattice. Above transition, the observed transverse growth times are far larger than those obtained from IBS calculations. This discrepancy is currently attributed to the beam-beam or nonlinear effects in the interaction region.

The Accelerator Test Facility (ATF) at KEK is a prototype damping ring for future e+e- linear colliders that demands very low transverse emittances. Recent single-bunch characterization [20, 21] shows that the vertical emittance at the design current appears to have grown by a factor of three over the zero-current result (accompanied by $\sim$ 80% growth in the horizontal emittance and the energy spread). This result is unexplained so far by IBS calculations, although there is evidence that IBS plays important roles (the energy spread increases when the vertical emittance is decreased using a dispersion correction). Thus, either the effect of IBS is much stronger than predicted by calculations, or there are errors in the measurements (of tiny vertical emittances).

The KEK measurements also show how the beam evolves under the combined influences of the radiation damping and IBS. The energy spread first decreases due to radiation damping. The IBS effect is suppressed during this period because the vertical emittance is large. As the vertical emittance becomes small due to damping, the energy spread then increases as the IBS rate becomes significant.

More benchmarking measurements will also be needed. Motivated by these measurements, a self-consistent treatment of IBS and longitudinal wakefields based on the numerical solution of the Vlasov-Fokker-Planck equation is being carried out [22].

8.3. Future Developments

The predictions of Piwinski theory and Bjorken-Mtingwa theory could differ in details up to a factor of two. It is time to remove this discrepancy. In particular, it should be possible and interesting to identify the precise steps where the two theories start to diverge from each other.

The starting point of the IBS analysis is the Landau's collision integral, the validity of which is based on two assumptions; that the scattering process is local and that the dielectric response can be taken to be the vacuum response. Both of these assumptions may need to be revisited for beams of very high densities in future accelerators.

The distinctive behavior below and above transition may be a very interesting test of different relaxation paths and should be experimentally confirmed. Under the smooth lattice approximation, a kinetic invariant exists because the kinetic energy is conserved in the Coulomb scattering process. Thus, IBS has different behaviors depending on whether the beam energy is below or above the transition energy. Below transition, the beam behaves like a gas in which energy is transferred from the hotter dimension (usually transverse) to the cooler dimension (usually longitudinal) and tends to a "thermal" equilibrium in the beam's rest frame. Above transition, emittance in every dimension can grow simultaneously and an equilibrium does not exist because of the negative mass effect. Well above transition, the transverse emittance growth is dominated by the change in the betatron closed orbit when the momentum of the particle is varied during the scattering (dispersion effect), similar to the emittance growth caused by quantum excitation in an electron storage ring. Thus intrabeam scattering in accelerators provides opportunities of testing how the relaxation paths of statistical systems differ under different external constraints.

8.4. Talks

1. P. Colestock: Introduction to Intrabeam Scattering and Critical Issues
2. M. Venturini: Intrabeam Scattering Theory, A Survey
3. A. Kabel: Quantum Corrections to IBS
4. A. Burov: An Analytic Approach to IBS
5. C. Bohn: Chaotic-Mixing in Charged-Particle Beams and Galaxies
6. K. Bane: Results from KEK-ATF
7. K. Kubo: SAD implementation of IBS, and Results from KEK-ATF
8. F. Pilat: Results from RHIC

9. Ionization Cooling of Muon Beams

Muon colliders, if developed, will make it possible to construct a lepton collider of TeV center of mass energy that is so compact it will fit within the boundaries of current HEP laboratories such as BNL. To realize a muon collider with a useful luminosity, however, the muon beams collected from pion decays must be cooled by a factor of 10^6 in 6-D phase-space volume, or a factor of 100 in each of the three emittances in three spatial directions, in the short time before the muon decay. The only known way to accomplish this at this time is ionization cooling, in which the transverse and longitudinal components of the beam momentum are decreased when passing through an ionizing medium and its longitudinal component is restored by subsequent acceleration [23, 24]. A conceptual design for ionization cooling of transverse emittance at 200 MeV/c has been worked out, consisting of a sequence of absorber vessels, rf cavities, and solenoidal focusing magnets of alternating polarities. A direct cooling of the longitudinal emittance is difficult due to heating from energy straggling. On the other hand, indirect cooling via an emittance exchange system should be possible, in principle. However, a practical design has not been worked out yet.

An intermediate step towards a muon collider is a neutrino factory, for which cooling is desirable but not essential. Designs of neutrino factories have been developed in considerable detail recently in the feasibility study I [25] and II [26].

9.1. Cooling of the Transverse Emittances

An ionization cooling section consists of a repetitive arrangement of absorber vessels, rf accelerating cavities, and focusing elements. Due to the large acceptance required, the focusing is most suitable with cylindrically symmetric solenoidal fields. To minimize the heating from multiple scattering, the absorbing medium is chosen to be liquid hydrogen (LH2). The focusing lattice should be designed such that the beta function is as small as possible at the location of the absorbers. The frequency of the rf cavities must be low to allow for a large beam diameter, and the accelerating gradient should be high to compensate for the large ionization loss. In order to avoid building-up of canonical angular momentum, the direction of the solenoidal field should be reversed at least once along the cooling channel.

Several configurations for transverse cooling have been proposed. The most studied configuration is known as the super-FOFO scheme, which is a straight channel of unit cells [25]. In this scheme, the direction of the solenoidal field is reversed once in each cell with the minimum beta occurring at the cross-over point. The solenoid direction alternates also from cell to cell. The magnitude of the field profile is optimized for the maximum momentum acceptance by avoiding the integer resonances. An attempt to simplify the cooling configuration is the single or double flip scheme, in which the field reversal takes place only once or twice [27]. These schemes are interesting alternatives to the super-FOFO scheme and need to be evaluated further by more detailed study. A ring configuration for cooling has also been proposed [28]. However, much work will be necessary to determine whether a practical cooling system based on a ring can be designed.

9.2. Emittance Exchange

The ionization process normally leads to an increase in the energy spread either because the derivative of the ionization loss with respect to the momentum has a wrong sign or because the effects of straggling are too strong. However, the longitudinal emittance may still be cooled indirectly by introducing a dispersion section in which the beam is spread transversely according to its momentum and placing a wedge absorber so that the higher-momentum particles pass through more material. Several schemes for generating dispersion systems have been proposed: bent-solenoid [29], helical wiggler [30], or ring cooler [28]. However, a practical system with sufficient performance has not been found yet.

9.3. Beam Dynamics Study

Ionization cooling has been modeled by two simulation codes: Geant4, based on C++ and ICOOL, based on Fortran [31]. These codes take into account the ionization loss, multiple scattering via the Moliere method, straggling, and particle motion in solenoids and rf cavities. Much progress has been made in code development and debugging. The results from these two entirely independent codes agree with each other, giving credence to the reliability of the codes.

An effort to develop an analytic understanding of the beam dynamics of ionization cooling is in progress. A systematic parameterization of the 6-D beam moments taking into account the solenoidal symmetry and coupled equations describing the evolution of these moments equations have been derived. For transverse cooling, these equations lead to coupled evolution equations for emittance and angular momentum [32]. Nonlinear effects and transverse-longitudinal correlation are also beginning to be systematically classified.

9.4. Talks

1. D. Kaplan: Overview of Cooling
2. P. LeBrun: Basic Formulae for Scattering, Energy Loss and Straggling
3. D. Neuffer: Transverse Cooling Theory and Simulation
4. C.X. Wang: Linear Theory of 6D Ionization Cooling
5. G. Hansen: 6D Simulation Survey
6. S. Geer: Cooling Experiment Issues
7. V. Balbekov: Double Flip Channel with Parabolic Absorber
8. J. Gallardo: Sensitivity Analyses
9. M. Berz: Normal Form Methods and Optimization for Nonlinear Properties
10. A. Bogaz: Ionization Cooling in Axially Symmetric Channels
11. R. Palmer: Acceptance in SFOFO Lattice
12. A. Garren/H. Kirk: Ring Simulation
13. S. Berg: Wedgeless Emittance Exchange
14. K. Makino: Nonlinearities and Fringes

10. Beam-Beam Interaction

The electromagnetic fields generated by the high brightness colliding bunches can cause strong perturbation to particle motion in accelerators. The perturbation caused by the beam-beam collisions is called the beam-beam effect.

The beam-beam interaction can cause beam dilution, halo formation, coherent dipole oscillations, bunch shape distortion, lifetime reduction, luminosity degradation, etc.

Almost all colliders operate at the beam-beam limit set by a tolerable background in detector, nonlinear resonances, beam lifetime, etc. On the other hand, beam-beam interaction for e^+e^- linear colliders can enhance luminosity by the pinch factor.

10.1. Circular Colliders

The tolerable beam-beam tune shift depends on the tune clearance of leading nonlinear resonances of the storage ring, damping decrement, and tune spread of the bunch. As the damping decrement becomes larger, the beam-beam interaction is less susceptible to nonlinear resonances. Typically it is limited to about 0.02 for hadron colliders, 0.05 for electron colliders. For example, the beam-beam tune-shift parameter of the LEP at 104 GeV achieved 0.083 at a damping decrement of about 1.6×10^{-2} per revolution.

1. Crossing angle

Many colliders are forced to collide beams with crossing angles. Some of these accelerators are KEKB and LHC. The effects of the beam-beam effects due to a horizontal crossing angle is determined by the X-parameter $X_{bb} = \theta_{\rm x}\sigma_s/\sigma_x$, where $\theta_{\rm x}$ is the crossing angle, σ_s is the rms bunch length, and σ_x is the rms bunch width.

First of all, the luminosity is reduced with a nonzero crossing angle. More importantly, the beam-beam interaction with a nonzero crossing angle can induce synchro-betatron coupling. So far, the experience of KEKB has shown little detrimental beam-beam effects due to a large collision crossing angle. However, it is important to note that there is a loss in collision luminosity. Crab-crossing will be installed in the KEKB to enhance luminosity for head-on collision with finite crossing angle.

2. Beam-beam effects of round beams

It seems that a round beam can provide larger tolerance of beam-beam tune shift. Round beam experiments at the CESR indicated that the beam-beam tune shift limit is increased to 0.09. Recently, Derbenev proposed a beam rounder transformer. This beam transformer should be studied.

In 1994, Talman proposed a Möbius insert for storage ring with round beam geometry. Unfortunately, first phase experiments have not been successful. It would be worthwhile to understand the beam dynamics problems.

3. Simulations

In recent years, numerical beam-beam simulations have made much progress in speed and accuracy. It is possible to realistically compare numerical simulations with experimental data. In particular, these particle-in-cell (PIC) codes can be used to provide better operational conditions for high-luminosity colliders such as CESR, PEP-II, and KEKB. The simulation can also help understand PACMAN and flip-flop effects.

Since the PIC codes have become powerful collider design tools, they can be used to understand the scaling law of maximum tune shift as a function of the damping decrement. In fact, the scaling law depends on the beam operational condition. If the maximum beam-beam tune shift is determined by a nonlinear resonance for a given damping decrement, the scaling law may exhibit devil's staircase.

The PIC codes have also been applied to study beam-beam effects for LHC. Betatron resonances can trap coherent beam-beam motion into resonance islands and induce large emittance dilution. Selection of betatron tunes is critical to the stability of collider operation.

4. Compensation of beam-beam effects

The beam-beam compensation has been under consideration since the 1970's. Recently, the Tevatron electron lens (TEL) project considered the correction of linear and eventually nonlinear beam-beam tune effects with two electron lenses. At present, scientists are trying to understand the effects of electron lenses on beam lifetime and emittance.

Correction wires have also been considered for the correction of the long range beam-beam effects in LHC. The correction wires have been successfully implemented in compensating sextupoles due to the eddy current in the rapid cycling accelerators, e.g., the AGS Booster, and in compensating magnetic multipoles for high-intensity accelerators, e.g., the ISR. The correction of wires for beam-beam interaction can provide a smaller betatron-tune footprint for different bunches in the collider.

10.2. Linear Colliders

High luminosity in linear colliders requires the collision of intense e^+ and e^- bunches. The intense electromagnetic field induced by colliding beams affects the particle motion of electrons and positrons in the colliding bunches. There are two strong field beam-beam effects: the disruption and the bremsstrahlung effects.

The disruption is associated with the focusing effects of a charged particle by the mean field of the oncoming bunch. This can alter the beam sizes of colliding bunches and affect the luminosity. The bremsstrahlung can cause charged particles to radiate in the strong quadrupole field in the countercolliding bunches. Because the radiation is a quantum process, the bremsstrahlung effect causes spread in center of mass energy of the collider and contributes to detector background.

The current design of the luminosity enhancement factor for a linear collider is about $H_D \approx 1.5$.[1] The strong electromagnetic field can also cause kink instability and multibunch crossing instability for colliding beams with an initial offset. The offset can grow exponentially.

Too high a bremsstrahlung parameter will cause a very large energy spread to the colliding beams. The design value for the NLC is about 0.11 for 500 GeV, and 0.29 for 1000 GeV.

10.3. Summary on beam-beam effects

Strong beam-beam simulation codes have been recently developed into powerful tools in the study of beam-beam effects in high-luminosity colliders. These codes have been used to compare and optimize the operation of PEP-II, KEKB, and CESR. Besides optimizing these important high-energy colliders, the codes can be used to study (1) the role of coherent beam-beam modes on beam instabilities, (2) the scaling law of beam-beam tune shift vs damping decrement, (3) the effects of nonlinear resonances, (4) the ultimate limit of the beam-beam tune shift, (5) effects of various correction schemes on beam-beam effects, etc.

There are two methods proposed to compensate beam-beam effects. The wire-corrector has been proposed to compensate the long-range beam-beam effects for the LHC. Electron lenses have been proposed and tested to compensate beam-beam effects for antiprotons in the Tevatron. These experiments should be fully tested for future higher-luminosity colliders.

Experimental studies of beam-beam effects with round beam should be carried out. The schemes of a round-beam transformer, or a fully coupled betatron motion, should be further studied for the benefit of future colliders. These experiments should be planned and systematically carried out in next few years.

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[1] The SLC has reached $H_D \approx 2$.

10.4. Beam-Beam Codes

The following table is a partial list of strong-strong beam-beam tracking codes.[2]

Table of (some) strong–strong beam–beam codes			
name	hadr./lept.	principle type of simulation	contact
	phase space	method for collective force	institute
	lepton	operator splitting PF & Fokker–Planck	R. Warnock
	2–D	various Vlasov–Poisson	SLAC
`Odysseus`	lepton	macroparticles	J. Rogers
	6–D	core: PIC; halo: soft Gaussian; long.: slices	Cornell
`BBDeMo`	hadron	weighted macroparticles (WMPT)	M. Vogt
	2–D & 4–D	Hybrid Fast Multiple (HFMM)	UNM
`BBPF`	hadron	Perron–Frobenius (PF) operator	M. Vogt
	2–D (& 4–D)	FFT	UNM
	hadron	macroparticles	W. Herr
	4–D	HFMM	CERN
	hadron	macroparticles	J. Shi
	4–D	PIC	UKansas
BBP	lepton	macroparticles	Y. Cai
	4–D	PIC & FFT, cycl. red. & reduced mesh	SLAC
`CBI`	lepton	macroparticles	S. Krishnagopal
	4–D	PIC	CAT, India

10.5. Talks

1. J. Seeman: Survey of Beam-Beam Effects
2. E. Keil: Beam-Beam Interaction in LEP and Scaling Law
3. V. Shiltsev: Results of Beam-Beam Compensation Experiments
4. Y. Cai: Methods and Issues in Beam-Beam Simulations
5. T. Sen: Summary of Beam-Beam Workshop at Fermilab
6. G. Hoffstaetter: Beam-Beam Experiments in ep Collider at HERA
7. S. Henderson: Round Beam Experiments in CESR
8. M. Palmer: Beam-Beam Effects at CESR
9. J. Rogers and A.P. Romano: Beam-Beam Interaction in CESR-C
10. A. Burov, Ya. Derbenev: Beam Rounders in Circular Colliders
11. A. Bogacz: Linear Betatron Coupling
12. J. Shi: Chaotic Coherent Beam Oscillations Due to Beam-Beam Interactions in Hadron Colliders
13. J. Ellison: Averaged Vlasov Equation for Strong Beam-Beam
14. F.J. Decker: Ideas in Minimizing Beam-Beam Effects

[2]Special thank to Jim Ellison for the compilation of this table.

11. Nonlinear Dynamics, Lie Algebra, TPSA, and Chaotic Dynamics

Particle motion in high-energy accelerators is usually dominated by the linear effects, where we design dipole magnets for bending and quadrupole magnets for beam focusing. However, high field magnets have intrinsic nonlinear multipoles, and thus the Hamiltonian is nonlinear, which is usually nonintegrable. Since the particle motion depends on its momentum, chromatic aberration can also be important. Normally, particles orbit in an accelerator for about 10^{10} turns, chaotic motion can cause particle loss, bunch dilution, and other radiation hazard problems. Nonlinear beam dynamics is important in the design and construction of storage rings for high quality beams.

In the past three decades, many innovative methods, e.g., Lie Algebra, Differential Algebra (DA), Truncated Power Series Algebra (TPSA), etc., have been developed to study nonlinear beam dynamics. In the past few years, many nonlinear beam dynamics computer programs, such as MARYLIE, COSY-infinity, Z-library, etc., were developed and have been implemented in the study of nonlinear beam dynamics problems for high-energy colliders.

11.1. Recent Developments

1. MARYLIE

The MARYLIE program has implemented a new method for computing charged particle transfer maps based on surface (boundary value) data [33]. This option can provide a better description for particle beam tracking in a general configuration of a magnetic field map.

Employing the Cremona map for symplectic map tracking has shown that the speed of particle tracking can be improved by a factor of ten in comparison with the element-by-element particle tracking [34].

2. Differential Algebra and the truncated power series algebra (TPSA)

Development of the COSY-infinity code, based on Differential Algebra, has continued. It will create a new interface to MatLab. COSY-infinity has been used to study many dynamical systems such as orbit of near-earth asteroids, particle tracking in the muon cooling channel, and LHC dynamical aperture.

3. Applications of MAP tracking to LHC dynamical aperture

Much efforts has been devoted to studying the dynamical aperture using MAP tracking for high-energy colliders. For LHC, dynamical aperture simulations have been done systematically. Correction schemes can also be devised by using the map tracking. Recently, Shi found that the nonlinear field errors of the insertion region triplets can be effectively corrected by four lump correctors up to a decapole [35]. Since the colliding beams have a 300 μrad crossing angle, local multipole correction may not be effective in restoring the dynamical aperture.

11.2. Model Independent Analysis (MIA)

The statistical analysis in the model independent analysis (MIA) has dramatically increased the sensitivity of BPMs. It can be used to detect weak imperfections in the machine. This method has been successfully applied to study the effect of wakefields in linacs (e.g., the SLC) and perturbation of betatron motion in storage rings (e.g., PEP-II). With an increased sensitivity, the method may be used to measure the nonlinear map.

11.3. Summary

Sophisticated map methods have changed the way we design accelerators. The parallel development of pure theory and real-world applications provides a model for the study of beam dynamics. Maps can provide fast and reliable tracking and accurate modeling for nonlinear resonances. This plays a key role in the design and construction of B-factories. It is expected that this design tool will be used in future high-luminosity colliders. However, it is worth pointing out that the behavior of particle motion near the dynamical aperture is not well understood.

The statistical analysis in the model independent analysis (MIA) has dramatically increased the sensitivity of BPMs. It can be used to detect weak imperfections in the machine. Through this sensitivity, nonlinear maps may someday be measured.

Experimental measurements of nonlinear resonances has been used to invent innovative beam manipulation schemes, such as slow extraction, rf dipole beam modulations, beam transfer functions, double rf systems, rf voltage and phase modulations, etc. Future beam dynamics experiments should be planned and carried out for the understanding of nonlinear maps.

The representation of the symplectic group Sp(6) has potential applications for systematically treating dissipative dynamical systems. Further studies should be interesting.

A global accelerator network should be formed to lead the way for code collaboration and cross-checking of these codes.

11.4. Codes

The following table provides a partial list of lattice design and nonlinear tracking codes for beam dynamics.

Name	Author/Contact	Method/Purpose
MAD	F.C. Islin	Lattice, optics, tracking
SYNCH	A. Garren	Lattice, optics, tracking
TRANSPORT	K. Brown, D. Carey, F.C. Islin	Optics of transport line
Turtle	K. Brown, F.C. Islin	Multi-particle simulation
DIMAT/DIMAD	R.Servranckx, K. Brown	Optics
Trace3D		Tracking
Comfort	M.D. Woodley, M.J. Lee, etc	Optics
TEAPOT	R. Talman	Optics and tracking
PATRICIA	H. Wiedemann	Particle tracking
PARMELA		Space charge tracking
PARMILA		Space charge tracking
ELEGANT	M. Borland	Optics, tracking, CSR
PATH	Lombardi	Space charge, multiparticle cooling tracking
ICOOL	R. Fernow	Ionization cooling channel tracking
MARYLIE	A. Dragt	Lie algebra, tracking
COSY-infinity	M. Berz	DA, tracking
Zlib	Y. Yan	TPSA tools, tracking
UAL	N. Malitesky	Unified accelerator library
SIXTRACK	F. Schmidt	TPSA tools, tracking
LIELIB	E. Forest	Lie algebra package, tracking
LEGO	Yunhai Cai	TPSA tools, tracking

11.5. Talks

1. A. Dragt: Computation of Transfer Maps for Arbitrary Geometry Using Boundary Value Data
2. J. Irwin: Using MIA (Model Independent Analysis) Together with Other Standard Tools to Unravel Accelerator System and Accelerator Beam Behaviors
3. J. Shi: Global Compensation of Nonlinear Field Errors with Minimization of Nonlinearity in Poincaré Map of a Circular Accelerator
4. M. Berz: Recent Advances in Differential Algebraic Methods
5. A. Dragt: Cremona Map in One Turn Map for LHC Long Term Tracking
6. A. Dragt: Representation of Symplectic Group and Its Applications
7. K. Makino: Recent Applications of COSY to Nonlinear Beam Dynamics
8. R. Baartman: End Effects of Transport Elements
9. H. Haseroth: CERN Cooling Package PATH
10. J.S. Berg: Future MAD Developments

12. Effects of Chromatic Aberration

The local compensation of chromatic aberration in the insertion region (IR) can be achieved by generating dispersion functions with carefully located sextupole and octupoles [36]. This represents a substantial improvement in the chromatic aberration correction in dramatically reducing the length of the beam delivery system in the linear collider.

In circular colliders, the chromatic aberration is usually globally compensated by families of sextupoles in the arcs. Systematic analysis can be carried out by minimizing the chromatic half-integer stopbands and stopbands of geometric aberration. However, the local chromatic aberration correction concept can also be implemented in circular colliders, particularly when the β^* is squeezed to a very small value [37]. In fact, the local chromatic correction concept in the horizontal plane can be tested in RHIC and PEP-II, where the IRs have built-in correctors with nonzero horizontal dispersion function.

12.1. Talks

1. P. Raimondi: Chromatic Aberration and Corrections
2. C. Johnstone: Design of IP Region for the Muon Colliders

13. Beam Measurement and Manipulation

Beam measurements play a key role in the understanding and improvement of beam quality and machine performance. Laser interferometry has provided beam size measurement down to the order of tens of nanometers. Using statistical analysis in the model independent analysis (MIA), the sensitivity of beam position monitors has increased two orders of magnitude. Such methods can be used to diagnose the effect of wakefield, errors in magnets, alignment error, and possible nonlinearity, etc.

Many innovative beam measurement methods have been invented in the past. Some of these are

- beam transfer functions for measuring the longitudinal and transverse impedance and the intrinsic frequency of particle motion,
- beam-based measurements of machine alignment,
- Poincaré maps and surface-of-section for determining the machine tune, nonlinear resonance, dynamical aperture, etc.
- beam profile measurements for beam emittance and distribution,
- beam echo measurements for determining the particle diffusion rate,
- Schottky signal for determining the frequency spectrum and momentum spread,
- synchrotron light monitor and streak camera,

- rf modulation to dipoles, quadrupoles, and rf cavities, etc.

Based on these beam measurement methods, various beam manipulation techniques have been developed. Some of these are

- feedback systems for collective beam instabilities,
- beam-based alignment,
- voltage and phase modulations for overcoming coupled bunch instabilities,
- beam cooling,
- rf dipole modulation for overcoming the depolarization resonances and providing betatron tune measurements,
- minimization of stopband widths (linear coupling, chromatic stopbands, nonlinear resonances, etc.) by using correction magnets,
- optical matching for minimizing the quadrupole mode oscillations,
- local orbit bumps for local orbit correction,
- chopper, buncher, bunch compressors or decompresser for various applications,
- two harmonic rf cavities for flattening the bunch distribution and providing tune spread for the Landau damping, etc.

Beam scientists continue to provide innovative ideas for beam measurement and beam manipulation. In the near future, experiments with stochastic cooling in the optical regime, beam profile measurements using laser interferometry, high-energy electron cooling, corrections for beam-beam effects, local chromatic correction, global stopband correction package, etc., will continue to provide high quality beams for high-energy physics experiments as well as industrial applications. In the following, we list a table of beam measurement tools.

13.1. Wish List of Beam Measurement and Manipulation Tools

Measurement manipulation	Tools and operation methods
Beam current	DCT (PCCT) Wall gap monitor
Betatron motion optics, tunes, nonlinearity higher-order beam moments	Beam position monitor (BPM) turn-by-turn
Beam profile	 Sum signal for longitudinal beam profile flying wire for transverse beam profile residual gas monitor for transverse beam profile harp for transverse beam profile streak camera SR monitor laser interferometer
Transport matrix	
Beam transfer function	phase and amplitude modulation
Beam cooling	high bandwidth detector high power microwave amplifier Schottky signal detector wiggler, optical amplifier
Sub-ps bunch detection	(see the report of T9 group)
Banana effect (LC)	(see the report of T9 group)
Beam halo or tail distributions	(see the report of T9 group)

13.2. Talks

1. M. Minty: Beam Measurements and Manipulations
2. F. Pilat: Operational Correction of Linear and Nonlinear Errors in the RHIC Interaction Regions
3. C. Bhat: Beam Deceleration Measurements in the MI

14. Beam Polarization

Electron beam polarization has provided energy calibration for LEP, HERA, etc. High-energy spin physics experiments have provided useful information on standard model, and spin structure of quarks in nucleons. For attaining high-energy polarized beams, spin dynamics in high-energy accelerators is an important topic in accelerator physics. The current status and future development of spin dynamics of polarized beams in high-energy accelerators is listed as follows.

14.1. Polarized Ion and Electron Sources

Polarized proton sources can be obtained from ABS or OPPIS with 80% polarization and a few mA of H^- high brightness sources. Polarized deuteron sources have also made much progress in recent years.

In electron storage rings, beam polarization can be obtained by the Sokolov–Ternov effect. On the other hand, a polarized electron source is needed in a linear collider and in the CEBAF facility. At SLC, polarized electrons are produced by the strained Ga-As photocathode attaining a polarization of 80–90%. This has enabled SLC to achieve very accurate measurement of the left–right asymmetry parameter for the Z production. Polarized electron sources with a high quantum efficiency will continue to play an important role in future linear colliders. In the near future, possible polarized positron sources may be generated from the pair production of circular polarized photons. The result of this research effort can provide polarized beams for future linear colliders.

14.2. Spin Dynamics

The equation of spin motion in an accelerator obeys the Thomas-BMT equation, while the dynamics of particle motion obeys the Lorentz force law [38].

Understanding the physics of beam polarization in accelerators has produced many innovative spin manipulation methods, e.g., the spin rotator and/or Siberian snake, spin transparent insert, rf dipole kicker, tune jump, spin matching, etc.

High-energy polarized beam experiments in ZGS, AGS, SPEAR, LEP, etc. has produced many fruitful results in high-energy physics. In the near future, high-energy polarized beam experiments will be available in RHIC and HERA for polarized protons, polarized deuterons, and polarized electrons. For RHIC spin, about $N_B = 2 \times 10^{11}$ polarized protons per bunch with polarization higher than 70% are extracted from the AGS and injected into RHIC. A total of 120 bunches in two rings will be stored in two rings, accelerated, and brought to collision in RHIC. Two snakes in each ring and four spin rotators in each major detector will be needed to provide polarized beam collision up to a center of mass of 500 GeV. The RHIC polarized beam experiments will provide very important knowledge on spin dynamics for future high-energy spin colliders.

14.3. Summary

Polarized antiproton beams are difficult to come by, thus it is difficult to design a polarized proton-antiproton collider. On the other hand, a high energy polarized proton-proton collider in the VLHC can be implemented with a small initial cost adjustment. Experience in the polarized beam experiments at RHIC can be used to study spin dynamics issues such as the rf spin flip, snake resonance, spin chromaticity, spin diffusions, etc. If a polarization option is considered for the VLHC, local spin matching should be considered in the design of the accelerator.

Polarized e^+e^- collider (VLLC) in the VLHC tunnel may be difficult. The spin chromaticity has been shown to limit the polarization of polarized beams in the LEP to a maximum energy of 60 GeV. Unfortunately, the spin matching effort for the final LEP polarized beam experiment was limited only to two harmonics. Since the spin tune spread of the LEP electron beam is about 1 and the resonance strength is large at high energy, more extensive spin matching correction (with at least five harmonics) should have been applied in the final polarized beam run in LEP.

Although the feasibility of highly polarized beam in B-factories and VLLC is unlikely, more careful analysis should be carried out in the near future with the consideration of polarization wigglers and spin rotators.

Besides these efforts, topics such as polarization lifetime, dynamics of multi-snake accelerators, spin diffusion in high-energy colliders, etc., should be examined in the RHIC spin colliders. Polarized deuteron sources and acceleration of polarized deuterons can be studied in details in the near future.

14.4. Talks

1. T. Roser: RHIC Polarization
2. D. Barber: Electron Polarization in Rings
3. R. Assmann: Polarization in LEP
4. A. Chao: Polarization in PEPII
5. S. Derbenev: Polarized Deuterons in Colliders

References

[1] A. Hofmann, EPAC96, p. 143.
[2] See, for example, A. Chao *Physics of Collective Beam Instabilities in High Energy Accelerators* Wiley, 1993.
[3] Revol & Nagaoka, "Observation, Modelling and Cure of Transverse Instabilities at the ESRF," PAC 2001, to be published.
[4] F. Zimmermann, "The Electron Cloud Instability: Summary of Measurements and Understanding," PAC 2001, to be published.
[5] J. Holmes et al., Proceedings of the 1999 Particle Accelerator Conference, p. 109.
[6] 2001 Report on the Next Linear Collider, SLAC-R-571 (June, 2001).
[7] TESLA Technical Design Report, DESY 2001-011 (March, 2001).
[8] R. Brinkman, O. Napoly, and D. Schulte, "Beam-Beam Instability Driven by Wakefield Effects in Linear Colliders," to be published.
[9] S. van der Meer, *Stochastic Damping of Betatron Oscillations in the ISR*, CERN Internal Report, CERN/ISR-PO/72-31.
[10] G.I. Budker, Atomnaya Eneggiya, 22, 346 (67). For a review, see V.V. Parkhomchuk and A.N. Skrinsky, Uspekhi 43 (5) 433-452 (2000).
[11] I. Ben-Zvi et al., "Electron Cooling for RHIC," PAC01, to be published.
[12] P. Wesolowski et al., "Electron Cooling at PETRA Using a Bunched Beam," PAC01, to be published.
[13] A.C. Crawford, S. Nagaitsev, A. Sharapa, and A. Shemyakin, Nucl. Intrum. Meth., **A435**, 339 (1999).
[14] A. Burov, S. Nagaitsev, A. Shemyakin, and Ya Derbenev, PRST-AB, **3**, 094002 (2001).
[15] Ya Derbenev, Nucl. Instrum. Meth., **A441**, 223 (2000).
[16] A. Piwinski, *Touschek Effect and Intrabeam Scattering, in "Handbook of Accelerator Physics and Engineering*," p. 125, World Scientific, edited by A. Chao and M. Tigner (1999).
[17] J.D. Bjorken, S.K. Mtingwa, Particle Accelerator 13 (1983) 115.
[18] W. Fischer et al., "Beam Lifetime and Emittance Growth Measurements of Gold Beams in RHIC at Storage," PAC 2001, to be published.
[19] W. Fischer et al., "Measurements of Intra-Beam Scattering Growth Times with Gold Beam Below Transition in RHIC," PAC 2001, to be published.
[20] K. Bane et al., SLAC-AP-135, (2000).

[21] K. Bane et al., “Intrabeam Scattering Analysis of ATF Beam Measurements,” PAC 2001, to be published.
[22] M. Venturini, “Intrabeam Scattering and Wake Field Effects in Low Emittance Electron Rings,” PAC 2001, to be published.
[23] D. Neuffer, Part. Acc. 14, 75 (83).
[24] A.N. Skrinsky, Proceedings of the International Seminar on Prospects of High-Energy Physics, Morges, 1971.
[25] “A Feasibility Study of a Neutrino Source Based on a Muon Storage Ring,” edited by N. Holtkamp and D. Finley, 2000.
[26] “Feasibility Study-II of a Muon-based Neutrino Source,” edited by S. Ozaki, R.B. Palmer, M.S. Zisman, and J.C. Gallardo, 2001 (http://www.cap.bnl.gov/ mumu/studyii/final_draft/The-Report.pdf).
[27] V. Balbekov et al. “Double Field Flip Cooling Channel for the Neutrino Factory,” PAC 2001, to be published.
[28] V. Balbekov et al. “Muon Ring Cooler for the MUCOOL Experiment,” PAC 2001, to be published.
[29] C.-x. Wang and K.-J. Kim, “Dispersion in a bent-solenoid channel with symmetric focusing,” Proceeding of NuFact’01 meeting.
[30] Ya. Derbenev “Conceptual Studies on Ionization Cooling of Muon Beam,” MUCOOL Note 185 (http://www-mucool.fnal.gov/notes/notes.html).
[31] R. Fernow, Proceedings of the 1999 Particle Accelerator Conference, p. 3020 (1999).
[32] Kwang-Je Kim and Chun-xi Wang, PRL **85**(4) 760, 2000.
[33] A.J. Dragt, T.J. Stasevich, and P. Walstrom, “Computation of Charged Particle Transverse Maps for General Fields and Geometries Using Electromagnetic Boundary Value Data,” PAC2001, to be published.
[34] D.T. Abell, F. McIntosh, and F. Schmidt, “Symplectic Map Tracking for the LHC,” PAC2001 (2001), to be published.
[35] J. Shi, Nucl. Instrument Meth. A**444**, 534 (2000); J. Shi, Particle Accelerators, **63**, (2000).
[36] See P. Raimondi, invited talk at the Snowmass T5 group and Proceedings of EPAC 2000.
[37] See, e.g., C. Johnstone, invited talk at the Snowmass workshop.
[38] See, e.g., S.Y. Lee, *Spin Dynamics and Snakes in Synchrotrons*, (World Scientific Pub. Co., Singapore, 1997).