SLAC-PUB-6735
December 1994
(A)

STATUS AND FUTURE PROSPECTS FOR UNITED STATES ACCELERATORS AND ACCELERATOR PHYSICS

R. H. SIEMANN*

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

ABSTRACT

The recent performance and future prospects of accelerators in the United States are reviewed. The next decade promises significant improvements and major new facilities. There is uncertainty beyond that because of the SSC cancellation and the new, enhanced importance of international accelerator projects.

1. Introduction

This paper is a review of the status and future prospects of accelerators in the United States. These accelerators cover a wide range: electrons and protons, circular and linear, colliders and fixed target. Each type has its own peculiarities, but much of the underlying physics and language is common. It is worthwhile beginning by summarizing this.

Particles in an accelerator are focused in the directions transverse to their motion by quadrupoles, and they are bunched into short bunches along the direction of motion by the RF system. When n_1 particles per bunch in one beam collide with n_2 particles per bunch in the other beam with a collision frequency f_c, the luminosity is

$$L = \frac{1}{2\pi}\frac{n_1 n_2 f_c}{\sqrt{\sigma_{x1}^2+\sigma_{x2}^2}\sqrt{\sigma_{y1}^2+\sigma_{y2}^2}}.$$

The parameters σ_{x1}, σ_{x2}, σ_{y1} and σ_{y2} are the rms horizontal and vertical beam sizes at the interaction point, and the denominator is the effective area of overlap of the two beams. Usually $\sigma_{x1} = \sigma_{x2} = \sigma_x$ and $\sigma_{y1} = \sigma_{y2} = \sigma_y$ giving

$$L = \frac{1}{4\pi}\frac{n_1 n_2 f_c}{\sigma_x \sigma_y}.$$

The horizontal and vertical beam envelopes vary along the accelerator. They are described by amplitude functions, usually called β-functions, that follow from solutions of two Hill's equations with driving terms based on the specific magnet configuration. The rms beam size at a location *s* along the accelerator is given by

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

Plenary Session Talk at the Meeting of the American Physical Society, Division of Particles and Fields (DPF '94) Albuquerque, NM, August 2 - 6, 1994

$$\sigma = \sqrt{\beta(s)\varepsilon_n / \gamma}$$

where $\beta(s)$ is the β-function at s, and γ is the beam energy in units of mc^2. The invariant emittance, ε_n, is a constant inversely proportional to the phase space density of the beam. The β-functions are minimized at the interaction point to maximize the luminosity, but there are limits to this. A tightly focused beam has a large angular divergence, and the bunch length, σ_L, and interaction point β-functions, β_x^* and β_y^*, must satisfy

$$\sigma_L \leq \min\left(\beta_x^*, \beta_y^*\right).$$

The bunch length itself is determined by a combination of the RF system, the magnet configuration, and the longitudinal phase space density of the beam.

Liouville's theorem states that phase space density is constant in Hamiltonian systems. Electron storage rings and $\bar{p}$ sources are not Hamiltonian because of synchrotron radiation and stochastic cooling, respectively. The phase space density and emittance of electron rings are determined by the properties of synchrotron radiation, and a wide range of emittances are possible depending on the magnet configuration. Anti-proton sources use feedback to reduce emittance. The bandwidth and power of the cooling electronics strongly influence intensity and emittance.

Proton storage rings are Hamiltonian, but nonlinearities and instabilities can lead to significant phase space distortions. The rms phase space density which is the density averaged over local distortions is the one of practical interest. This density can remain constant at best, and it is determined by the particle source and any effects that distort phase space during acceleration.

Linear colliders combine aspects of electron storage rings and proton accelerators. The particle sources are damping rings, and synchrotron radiation determines the emittance there. Once the beam is extracted from the damping rings and accelerated careful attention must be paid to minimizing instabilities and nonlinearities to preserve the rms invariant emittance.

Different factors that can limit the luminosity. These include the availability of particles, single beam instabilities, and beam-beam effects. The availability of particles applies most strongly to $p\bar{p}$ colliders where $\bar{p}$ production is the dominant performance limitation.

Single beam instabilities are caused by beam generated electromagnetic fields, called wakefields, acting back on the beam that caused them. Wakefields can impose hard limits on the number of particles with the beams being lost if those limits are exceeded, or they can impose soft limits through intensity dependent emittance or background increases. At low energies wakefields are electrostatic fields commonly called space-charge fields while at high energies they are caused by variations in vacuum chamber geometry and resonant modes in RF cavities or other structures. Short range wakefields act on a single bunch and affect the number of particles/bunch. They are difficult to control with feedback because frequencies comparable to the inverse of the bunch length are involved. In addition, the study of single bunch instabilities is at the forefront of accelerator theory and experiment, and recent experience at the SLC has taught us that we cannot be confident with calculations.

The bunches can interact with each other through long range wakefields thereby putting a limit on the total current, $I_{tot} = nef_c$. Feedback can be used to control multibunch instabilities, and, their effects are easier to estimate reliably.

The primary interaction between beams is through their electromagnetic fields at the interaction point. There is a maximum field strength, and when it is exceeded backgrounds increase and/or luminosity decreases. These effects are parametrized in storage rings by the beam-beam strength which is often called the beam-beam tune shift,

$$\xi = \frac{r}{2\pi} \frac{n\beta_y^*}{\gamma\sigma_y(\sigma_x + \sigma_y)};$$

$r = r_e = 2.82\times10^{-15}$ m for e^+e^- colliders and $r = r_p = 1.54\times10^{-18}$ m for proton colliders. Roughly speaking, e^+e^- storage rings have a limit per interaction region of $\xi < 0.03$ to 0.05, and proton storage rings have a limit summed over all interaction regions of $\Sigma\xi < 0.02$. The luminosity can be rewritten in terms of ξ when the beam-beam effect is a limit

$$L = \xi \frac{I_{tot}}{e} \frac{\gamma}{r\beta_y^*}.$$

(If the beams have unequal currents, etc., the parameters of one of the beams should be used in this equation.)

The fields at the interaction point of a linear collider can be much stronger than those of a storage ring because the beams only collide once. These fields lead to focusing during the collision (disruption), photon radiation (beamstrahlung), e^+e^- pair production, and low invariant mass hadronic events. The consequences of the beam-beam interaction in linear colliders is discussed in the section on future linear colliders, but, in contrast to experimentally established limits on ξ, there is almost no experience with the beam-beam interaction in linear colliders, and these consequences are based on theory and conjecture.

2. The AGS

The AGS (Alternating Gradient Synchrotron) at Brookhaven National Laboratory is a venerable accelerator with a long list of accomplishments in accelerator physics and in the particle physics experiments performed there. It is the only US accelerator that does not have colliding beams as the mainstay of its operation. The high energy physics research program has become dominantly the search for rare or forbidden Kaon decays, and this has required a large increase in the AGS intensity.

The central element of that intensity increase was the addition of the AGS Booster synchrotron that was completed in 1991. The Booster overcame an intensity limit caused by space-charge effects by raising the injection energy from 200 MeV to 1.5 GeV. In addition to the Booster, improvements were needed to the AGS itself to handle higher current. The performance shown in Table 1 for 1994 is the result of improvements in the RF system, implementation of a pulsed quadrupole system that speeds up the passage through the transition energy, and the damping of longitudinal and transverse instabilities. This is an ongoing effort and further improvements are expected from additional work on the RF system and the feedback systems that control instabilities and from corrections of the AGS magnetic field at low energy. When this work is completed the design intensity of

Date	Proton Intensity per Pulse ($\times 10^{13}$)	Repetition Period (sec, w/o Slow Spill)
1990 (Before Booster)	1.8	1.7
1994 Peak 8 hr Shift Avg.	4.0 3.6	2.8
1995 (Projection)	6.0	2.0

Table 1. AGS Performance.[1]

6×10^{13} protons/pulse for the Booster/AGS improvement program would have been reached. Further improvements are foreseen from increasing injection, acceleration, and transfer efficiencies and from increasing the Booster intensity.

In addition to these intensity improvements, acceleration of polarized protons is being studied in the AGS with the goals of maintaining the 80% injection polarization to high energy. Recent experiments have shown that the underlying spin dynamics are well understood, and a polarized beam at the normal AGS extraction energy is expected in 1995.

3. CESR

The CESR interaction region geometry has been modified to allow beams to collide at an angle of ±2 mrad. This makes it possible to use bunch trains, closely spaced bunches, where unwanted collisions at the interaction region are avoided by the crossing angle, and, in an extension of the "pretzel" technique developed at CESR, collisions between different bunch trains in the arcs are avoided by the use of electrostatic separation. Until recently only single bunches rather than bunch trains were being used, and people were gaining experience with this new mode of operation. Routine operation with multiple bunches per bunch train will require improvements in the interaction region apertures and superconducting RF to store higher currents. Recent CESR performance along with short term and longer term goals are presented in Table 2.

Parameter	1993	October, 1994
Peak Luminosity (10^{32}cm^{-2}s^{-1})	2.9	2.4
Best Daily Luminosity (pb^{-1})	15.2	12.8
Best Monthly Luminosity (pb^{-1})	284	
Integrated Luminosity (pb^{-1})	1362	
Current per Beam (Bunches × mA)	7×16 mA	9×11 mA
Beam-Beam Parameter (ξ)	0.04	0.04
Crossing Angle (mrad)	0	±2
Goals, Luminosity & Number of Bunches		6×10^{32}cm^{-2}s^{-1}, 27 10×10^{32}cm^{-2}s^{-1}, 45

Table 2. CESR Performance[2]

Parameter	High Energy Ring	Low Energy Ring
Luminosity (10^{33} cm^{-2}s^{-1})	3.0	
Beam Energy (GeV)	9.00	3.11
Number of Bunches	1658	
Single Bunch Current (mA)	0.60	1.29
Total Current (A)	0.98	2.14
Beam-Beam Parameter (ξ)	0.03	0.03
β_y^* (cm)	2.0	1.5
σ_x, σ_y (μm)	155, 6.2	
Bunch Length (cm)	1.0	1.0
Collision Geometry	Head-on with Magnetic Separation	
First Colliding Beams	Summer, 1998	

Table 3. PEP-II Parameters[3]

4. PEP-II

PEP-II will be a high luminosity e^+e^- collider operating at a center-of-mass energy, E_{CM} = 10.58 GeV, the mass of the Y(4S). The beam energies will be unequal to give the center-of-mass a boost that will allow measurement of B-meson decay times with vertex detectors. Parameters are given in Table 3.

The total currents must be large since $L \propto I_{tot}$, and storing these currents is the major issue for the vacuum and RF systems. The synchrotron radiation powers are 5.29 MW and 2.66 MW in the High Energy and Low Energy Rings, respectively. The vacuum chambers must absorb this power while maintaining a good vacuum and providing shielding to prevent radiation damage to equipment in the accelerator enclosure. The copper vacuum chamber technology pioneered at DESY is being used in the High Energy Ring, and the Low Energy Ring employs localized photon beam stoppers similar to those in third generation synchrotron light sources. Cleanliness during manufacturing and vacuum pump design are receiving special attention because dust particles can be trapped by a high current electron beam. This was discovered at HERA where the recent increase in luminosity came from switching from electrons to positrons to avoid this.

The RF system must make up the radiated power efficiently without causing instabilities. Wakefields are minimized by using a high accelerating gradient to reduce the number of cavities and by damping unwanted, high frequency cavity modes to decrease long range wakefields. In addition to control multibunch instabilities, PEP-II will have a feedback system that measures and corrects the positions of bunches that are only 4.2 nsec apart using Digital Signal Processing techniques. Another feedback system will control instabilities caused by the fundamental, accelerating mode.

The primary collision is head-on; the bunches are separated almost immediately after the interaction point using permanent magnet dipoles and taking advantage of the energy difference. Despite this the beams are still close enough to experience each other's fields at the parasitic crossing point. This complicates the beam-beam interaction and prevents further increasing the number of bunches.

Most of the global decisions affecting the PEP-II design, such as those described above, have been made, and construction is well underway. Collisions are expected in the summer of 1998, and studies of CP violation should start soon afterward when the BaBar detector is ready.

5. The Tevatron

In the Tevatron the horizontal and vertical β-functions at the interaction point are equal, $\beta_x = \beta_y = \beta$, the horizontal and vertical emittances of each beam are equal, $\varepsilon_{nx} = \varepsilon_{ny}$, but the p and $\bar{p}$ beams can have different emittances, $\varepsilon_{np} \neq \varepsilon_{n\bar{p}}$. The luminosity is limited by the number of $\bar{p}$'s and the $\bar{p}$ beam-beam tune shift. Writing the luminosity in terms of these $\bar{p}$ parameters

$$L = \xi_{\bar{p}} \frac{I_{tot,\bar{p}}}{e} \frac{2\gamma}{r_p \beta^* (1 + \varepsilon_{n\bar{p}} / \varepsilon_{np})}.$$

where $\xi_{\bar{p}}$ depends on the phase space density of the proton beam

$$\xi_{\bar{p}} = \frac{r_p}{4\pi} \frac{n_p}{\varepsilon_{np}}.$$

It has a maximum value $\xi_{\bar{p}} < 0.02 / N_{ip}$ where N_{ip} is the number of collision points. While these equations shouldn't be taken literally because there are subtle beam-beam effects for unequal emittance beams, they show the interplay that dominates the Tevatron luminosity. The number of protons should be increased until the beam-beam limit is reached; the number of collision points should be minimized, and, once that is done, the luminosity depends directly on the $\bar{p}$ current.

Table 4 summarizes the Tevatron performance for Run Ia in 1992/1993, Run Ib, the present run, and that expected in the era of the Main Injector. It illustrates the Tevatron improvement program that is centered on these points. Prior to Run Ia the beams collided at twelve points around the ring while they produced useful luminosity only at the CDF detector (D0 was not installed yet). The beam-beam strength parameter summed over all collision points reached the beam-beam limit and limited the luminosity. The improvement for Run Ia was operation with electrostatically separated orbits that avoided unwanted collisions and allowed the number of protons/bunch to be increased without exceeding the beam-beam limit.

The linac kinetic energy was increased from 200 MeV to 400 MeV for Run Ib to reduce the space-charge intensity limit at injection into the Booster. The Booster intensity and $\bar{p}$ production rate have increased by 1.7 and 1.5, respectively, from this improvement.

The Main Injector will significantly increase the number of protons that can be accelerated and targeted for $\bar{p}$ production. The number of $\bar{p}$'s will increase so much that the beam-beam limit would be reached for protons, and to avoid that, the number of bunches has to be increased also from 6 to 36. The Main Injector is scheduled to be commissioned in the summer of 1998, and collider operation is expected in the fall of that year.

Further Tevatron energy and luminosity upgrades are being actively considered. Parameters are still evolving, and the DiTevatron in Table 5 is a snapshot taken last summer that shows the key features of Tevatron upgrades: energy increases will require

Parameter	Run Ia 1992/1993	Run Ib 1994/1995	Main Injector
Peak Lum. (10^{30} cm^{-2} s^{-1})	5.4	16	123
Integrated Lum./Week (pb^{-1})	1.1	3	25
Beam Energy (GeV)	900	900	1000
Dipole Magnetic Field (T)	4.0	4.0	4.4
Total # of protons (10^{12})	0.8	1.2	13.7
Total # of $\bar{p}$'s (10^{12})	0.19	0.3	1.30
Total Beam-Beam Strength Parameter, $\Sigma\xi_{\bar{p}}$	0.011	0.013	0.020
$\bar{p}$ Stacking Rate (10^{10}/hr)	4	6	15
Bunches	6	6	36
Interactions/Crossing (45 mb)	1.1	3.3	3.2
Bunch Spacing (nsec)	3493	3493	395

Table 4. Tevatron Parameters.[4] The first two columns are achieved performance, and the third is a projection in the Main Injector era.

replacing the present Tevatron magnets with new ones that take advantage of developments made for the SSC and LHC, and luminosity upgrades depend on increasing the $\bar{p}$ accumulation rate and on a large number bunches to keep below the beam-beam limit and to reduce the number of interactions per crossing.

Doing that requires a new place to store $\bar{p}$'s between fills and improving the $\bar{p}$ flux from the production target. The present Accumulator can not hold the total number of $\bar{p}$'s needed, and a new accumulator would have to be constructed. A promising idea is building a fixed energy, permanent magnet ring in the Main Injector tunnel. In addition to providing storage between fills this ring offers the possibility of recovering $\bar{p}$'s from the previous store. The present Accumulator would still be used to cool the beam before injecting into the new accumulator.

There are two ways to improve the $\bar{p}$ flux from the target: increase the number of incident protons or increase the $\bar{p}$ acceptance downstream. Both approaches are being considered and both are difficult. The issue is associated with manipulations of longitudinal emittance which is proportional to the product of bunch length and momentum spread. The proton beam is tightly bunched just before hitting the $\bar{p}$ production target, and the acceptance of beamlines downstream of the target determine the momentum spread. This momentum spread is much larger than could be accommodated by the Accumulator, so the beam is "debunched", the momentum spread is decreased at the price of increasing the bunch length. The Debuncher Ring does this in the Fermilab $\bar{p}$ source.

The equivalent process must be performed in an improved source. If the entire Main Injector beam were targeted, a new, large debuncher would have to be constructed in the Main Ring tunnel because the present Debuncher has only one-seventh the circumference of the Main Injector. If only one-sixth of the Main Injector beam were targeted as is planned now, the debunching could be done with a ~ 1 GeV high gradient linac that would have a large momentum acceptance. An alternative to either of these would be replacing

Parameter	Main Injector	DiTevatron
Peak Lum. (10^{30} cm^{-2} s^{-1})	123	2000
Integrated Lum./Week (pb^{-1})	25	400
Beam Energy (GeV)	1000	2000
Dipole Magnetic Field (T)	4.4	8.8
Total # of protons (10^{12})	13.7	25.7
Total # of $\bar{p}$'s (10^{12})	1.30	9.8
Total Beam-Beam Strength Parameter, $\Sigma\xi_{\bar{p}}$	0.020	0.019
$\bar{p}$ Stacking Rate (10^{10}/hr)	15	100
Bunches	36	108
Interactions/Crossing (45 mb)	3.2	17
Bunch Spacing (nsec)	395	132

Table 5. Performance with the Main Injector is compared with DiTevatron parameters from the Hadron Collider Workshop, University of Indiana, July, 1994.

the Booster with a new, high intensity injector for the Main Injector and thereby increase the intensity of the proton beam itself. Each approach has advantages, difficulties and drawbacks, and implications for simultaneous operation of collider and fixed target programs. Whichever route is taken, a substantial accelerator, in addition in the new accumulator ring, would have to be constructed.

There are also crucial accelerator physics issues related to operating the Tevatron as a collider with a large number of bunches. Fortunately, many of these can be studied experimentally, and once that is done they should introduce relatively little uncertainty into Tevatron upgrade plans.

Of course, any Tevatron upgrade beyond the Main Injector must be justified by an outstanding particle physics program in the era of the LHC, and that is being actively discussed among high energy physicists.

6. The SLC

The SLC has been delivering luminosity to the SLD detector for several years, and it is planned to continue until PEP-II physics starts. The goal is greater than 5×10^5 polarized Z's. Two major projects were completed recently to improve on the 1993 performance (Table 6). A single bunch instability in the damping rings that limited the beam current was removed with the installation of new vacuum chambers designed specifically to reduce wakefields. (The characteristics of the instability changed in unexpected ways; this is an interesting accelerator physics problem with implications for future colliders.) The final focus was improved by removing the dominant optical aberrations and adding improved diagnostics. The result has been a reduction of the beam height from 0.8 μm in 1993 to 0.5 μm today. Commissioning these two improvements together took some time, but that is over and the SLC is well on the way to producing 10^5 Z's in the 1994/95 run.

Parameter	1993	1994
Luminosity (10^{29}cm^{-2}sec^{-1})	3	7
Polarization	62%	80%
Inter. Point Current (10^{10}/pulse)	3.0	3.5
RMS Spot Size (μm^2)	2.6×0.8	2.6×0.5
Integrated Lum. (pb^{-1}, Z's)	1.7, 50,000	Goal is 10^5 Z's

Table 6. Typical SLC Parameters.

7. Future Linear Colliders

Future linear collider development has focused on an E_{CM} = 0.5 TeV collider with the potential for being expanded to 1 TeV or more. The luminosity can be written in terms of the power of a single beam, $P_B = \gamma mc^2 nf_c$, the vertical spot size (it is assumed that $\sigma_x \gg \sigma_y$), and a factor related to detector backgrounds. Those backgrounds come from the strong electromagnetic fields at the interaction point. The number of beamstrahlung photons per incident particle serves as a measure and is given by

$$n_\gamma \approx \frac{2\alpha r_e n}{\sigma_x}.$$

The luminosity is

$$L = \frac{1}{8\pi\alpha r_e mc^2}\frac{n_\gamma}{\gamma}\frac{P_B}{\sigma_y}.$$

Roughly speaking, there are two different approaches to high energy linear collider design. In one the beam power and vertical spot size are large while in the other they are both small. Alignment and stability tolerances can be relaxed when the spot is large, and that is the attraction of that approach. The designers of colliders employing small spots agree with this but consider their tolerances reasonable.

Selected parameters from LC-93 are given in Table 7. The colliders are:

TESLA which is based on superconducting RF. All the others would use room temperature RF.

SBLC which uses 3 GHz RF where there is extensive operating experience. TESLA and SBLC are large beam power, large spot designs while the others rely on a nanometer vertical beam size for good luminosity.

NLC which uses higher frequency, 11.4 GHz, RF in configuration similar to conventional linacs.

JLC-I which has three RF frequency options. Multiple bunches are accelerated in each RF pulse as they are in TESLA, SBLC, and NLC.

VLEPP which employs a single high intensity bunch rather than multiple bunches.

CLIC which is a "two-beam" accelerator with klystrons replaced by an RF power source based on a high-current, low-energy beam traveling parallel to the high energy beam.

The two basic, interrelated issues are putting a high energy linear collider on solid technical footings and deciding between these different options. Work is going on worldwide with close coordination and frequent workshops, and in many cases that work is

Parameter	TESLA	SBLC	JLC-I (S)	JLC-I (C)	JLC-I (X)	NLC	VLEPP	CLIC
L $(10^{33} cm^{-2} s^{-1})$	7	4	4	7	6	8	15	2 - 9
RF Freq (GHz)	1.3	3.0	2.8	5.7	11.4	11.4	14	30
Loaded Gradient (MV/m)[c]	25	17	19	33	31	38	96	78 - 73
Rep Rate (Hz)	10	50	50	100	150	180	300	1700
Bunches per RF pulse	800	125	55	72	90	90	1	1 - 4
σ_{x0}/σ_{y0} (nm)	1000/64	670/28	300/3	260/3	260/3	300/3	2000/4	90/8
P_B (MW)	16.5	7.3	1.4	2.9	3.4	4.2	2.4	.4 - 1.6
n_γ	2.7	2.0	1.6	1.4	1.0	0.9	5.0	4.7
AC Power (MW)[a]	137	114	106	193	86	141	91	175
$2P_B/P_{AC}$	0.24	0.13	0.03	0.04	0.09	0.06	0.05	0.02

a) Linac power only (damping ring, detector, utility power, etc. not included)

Table 7. Selected Linear Collider Parameters for E_{CM} = 0.5 TeV.[5]

being done by collaborations similar to those that are common in experimental high energy physics.

One such collaboration, the Final Focus Test Beam (FFTB) Collaboration, has demonstrated optics with a demagnification comparable to that required for a next generation linear collider. Their goal was to focus a 47 GeV beam from the SLC to a 60 nm high spot. The beam was commissioned this spring, and during the last three hours of the first extended run they achieved a 70 nm spot that was stable and reproducible over several hours.

Other important recent developments include: a test of an accelerating structure designed specifically to reduce long range wakefields; accelerating gradients exceeding 50 - 100 MV/m in room temperature structures; gradients of 25 MV/m in superconducting cavities; and prototype klystrons reaching the performance needed for some of the colliders in Table 7. In addition, there are prototype facilities planned and under construction at several laboratories. These include linac prototypes at KEK, SLAC, DESY and Protvino, and a damping ring prototype well underway at KEK.

Energy reach and energy expandability have come to the fore recently. Ten years ago it was hoped that the next linear collider would have E_{CM} ~ 1 - 2 TeV. However, as work progressed it was realized that this would be too large a step from the SLC, and designs concentrated on E_{CM} = 0.5 TeV. While there is a strong physics program at that energy, the attractiveness of a linear collider increases significantly if the energy could be increased as a second stage.

Table 8 gives some preliminary parameters for E_{CM} = 1 TeV. The energy of the room temperature accelerators, SBLC and NLC, is increased by doubling the gradient which requires four times the RF power. The TESLA energy increase would come by increasing the length since the gradient is near that which can be obtained with superconducting RF. At 1 TeV everyone must rely on small spots, and the colliders based on large beam power must have the alignment, beam position monitor precision, vibration isolation, etc. to meet tight tolerances even if they are unneeded at 0.5 TeV.

Parameter	TESLA[6,7]		SBLC[6,7]		NLC[8]	
E_{CM}	0.5	1.0	0.5	1.0	0.5	1.0
L	7	10	4	6	8	20
Load Grad.	25	25	17	34	38	74
Linac Length	20	40	29.4	29.4	14	14
Rep Rate	10	5	50	50	180	120
Bunches/pulse	800	4180	125	50	90	75
σ_{x0}/σ_{y0}	1000/64	325/8	670/28	742/6.3	300/3	425/2
P_B	16.5	15.3	7.3	5.8	4.2	9.4
P_{AC}	137	153	114	230	141	144
$2P_B/P_{AC}$	0.24	0.20	0.13	0.05	0.06	0.13

Table 8. Comparison of Parameters for E_{CM} = 0.5, 1.0 TeV. Units are same as Table 7.

The combination of progress on individual components and the anticipated success of prototypes has lead to optimism that a technically sound proposal for a future linear collider could be completed in the next several years. The energy range of that collider should be an important part of the considerations.

8. Accelerator Physics

Continuing progress in accelerator science and in particle physics are inextricably linked. From AGS beam dynamics to the Tevatron $\bar{p}$ source to klystrons for a future linear collider, all of the accelerators in the US are at the forefront of accelerator physics and technology. The foundation for much of this work is the design, operation, and improvement of present and previous generations of accelerators.

A year ago high energy physics in the United States suffered a tremendous loss with the cancellation of the SSC, and we are still struggling to recover from that loss. International facilities appear to be part of that recovery. Roughly ten years from now the US will no longer be at the energy frontier, and the foundation of past successes will begin to erode as people and facilities age and become outdated. Future opportunities will erode along with the foundation, but this must not happen if there is to be any realism in thoughts about multi-TeV linear colliders, hadron colliders beyond the LHC, plasma accelerators, or $\mu\mu$ colliders. It is our challenge to avoid this by making accelerator science as international and collaborative as experiments have become.

References

1. W. T. Weng and T. Roser, private communication.
2. D. H. Rice, private communication.
3. J. T. Seeman, private communication.
4. D. Finley, G. P. Jackson, S. Werkema, private communication.
5. G. Loew, Proc Fifth Int Workshop on Next Generation Linear Colliders, p. 341 (1993).

6. R. Brinkmann, "Low Frequency Linear Colliders", 1994 European Particle Accel Conf.
7. B. Wiik, Proc Fifth Int Workshop on Next Generation Linear Colliders, p. 463 (1993).
8. R. Ruth, private communication.