SLAC-Report-526

Symposium on Electron Linear Accelerators

In Honor of Richard B. Neal's 80th Birthday

Held at the Stanford Linear Accelerator Center
Stanford University, Stanford, California
on September 5, 1997

Prepared for the U.S. Department of Energy
under contract number DE-AC03-76SF00515

SLAC-Report-526
CONF-970957
UC-414
July 1998

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Editor: Robert H. Siemann

Prepared for the U.S. Department of Energy under contract number DE-AC03-76SF00515.
Printed in the United States of America. Available from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161


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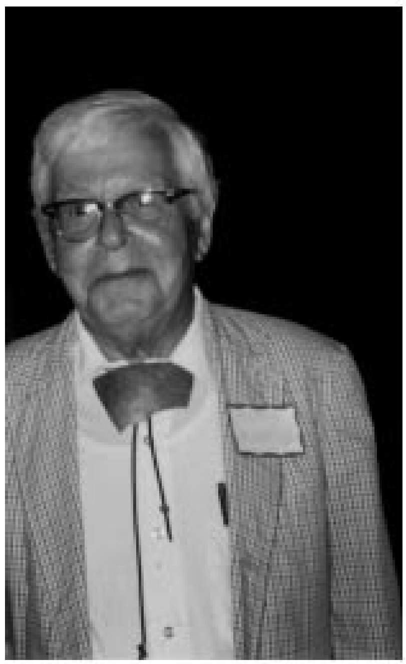


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Welcome and Introduction

Burton Richter*

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Welcome to the Symposium celebrating the 80th Birthday of Dick Neal who played such an important role in the development of this laboratory. I see in the audience many old friends who have not visited here in a while, and I look forward to talking to you all at the breaks and at dinner tonight.

I would like to begin this brief introduction with a story that, as the lawyers say, "I will connect up later." In 1966 I made my first trip to Europe with my wife Laurose. At one of the many physics parties that we attended during that trip, we met Rolf Wideröe who wrote the first paper on RF linear accelerators (way back in the 1920's, I believe). Laurose, who knows a great deal about the history of our field, uncharacteristically rushed up to him and gushed, "I'm so glad to meet you — YOU are a great man". Wideröe beamed.

I want to start this Symposium with the same phrase — "Dick Neal, YOU are a great man". Much of the success of the laboratory and the linear accelerator is due to your efforts.

Most of you know Dick because of his work here at SLAC. That is the topic of Pief Panofsky's talk and I will leave almost all of it to him and, if I don't, well there were all those years from 1963-1984 when I usually followed the Director in various presentations, and found much of what I wanted to say had been scooped by the first speaker. Turn about is fair play Pief.

Dick Neal has done much more in his career than his work at SLAC. He came to Stanford in 1947 from the Sperry Gyroscope Corporation where he had been during World War II. Sperry was the place that many Stanford faculty went to during that War because of Stanford's role in developing high-power microwave devices and Sperry's responsibility for producing those sorts of things for the War effort. At Stanford Dick first worked with W.W. Hansen who was the original driving force behind the development of linear accelerators at the University.

For his Ph.D., Dick worked with Ed Ginzton on the MARK III linear accelerator and received his degree in 1953. Bob Hofstadter began his Nobel Prize work on that machine, and a paper by Neal and Panofsky in 1955 describes the completion of the machine up to an energy of 600 MeV.

After that, Dick worked on the MARK IV accelerator at the Microwave Laboratory. This machine incorporated much new technology and was used for the first clinical trials using high-energy gamma rays for cancer therapy. There are now thousands of 6-20 MeV linear accelerators around the world which have treated many millions of malignancies and saved many lives. Dr. Richard Levy of Varian Associates will discuss what came from those first clinical trials.

In 1957 Dick was one of the small group that met at Panofsky's house to begin the plot that hatched as Project M (M for monster) and is now the Stanford Linear Accelerator Center. After many trials and tribulations, construction on the machine began in 1963 and first beam was achieved in late 1966.

Dick Neal was the Associate Director of the laboratory responsible for the technical facilities and in effect was the Project Manager for the accelerator. To get some idea of the importance of Dick Neal's contribution one has only to look at the first organization chart for Project M (Figure 1) dated December 19, 1960. In that chart, Ginzton is the Director, Panofsky is the Deputy Director, and Dick is the Associate Director for the Technical Division. But, not only was he Associate Director for the Technical Division, he was the Manager of the Microwave Engineering Department, the Manager of the Electronics Engineering Department, the Manager of the Accelerator Design Department, and the Manager of the Accelerator Structure Department. This last role may have been his most difficult one for, in it, he was the boss of Arnold Eldredge and all of us who knew Arnold knew how much skill was required for that particular job.

Dick Neal was Mr. Everything. While the number of "hats" Dick wore diminished over time, he remained responsible for the technical part of the construction and, later, for the operation and maintenance of the machine. I did not really appreciate how complex Dick's job was until, by quirk of fate, I succeeded him in 1982 as Head of the Technical Division.

Dick with his calm and quiet manner made the very complex SLAC project work. It was a huge advance over the MARK III accelerator on the Stanford Campus for, if the components of the SLAC machine had had the reliability of those of the MARK III machine, there would have been no on-time at all for the accelerator complex. Dick's work was of critical importance in making the SLAC linac a productive research tool.

We at the laboratory are going to attempt again an advance over the SLAC linac that must be as big as the advance of the SLAC linac was over the MARK III linac. We are at work on the R&D that we hope will lead to the construction of a thirty-kilometer long linac complex (the Next Linear Collider program), and it will be a very tall order indeed to match with that facility what Dick did in the SLAC facility. David Burke will discuss that program later today.

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

I will end here with my personal appreciation of all that Dick did to provide the tools for scientific research of many many people including me. I am privileged to welcome him back to the laboratory on this occasion, his 80th Birthday.

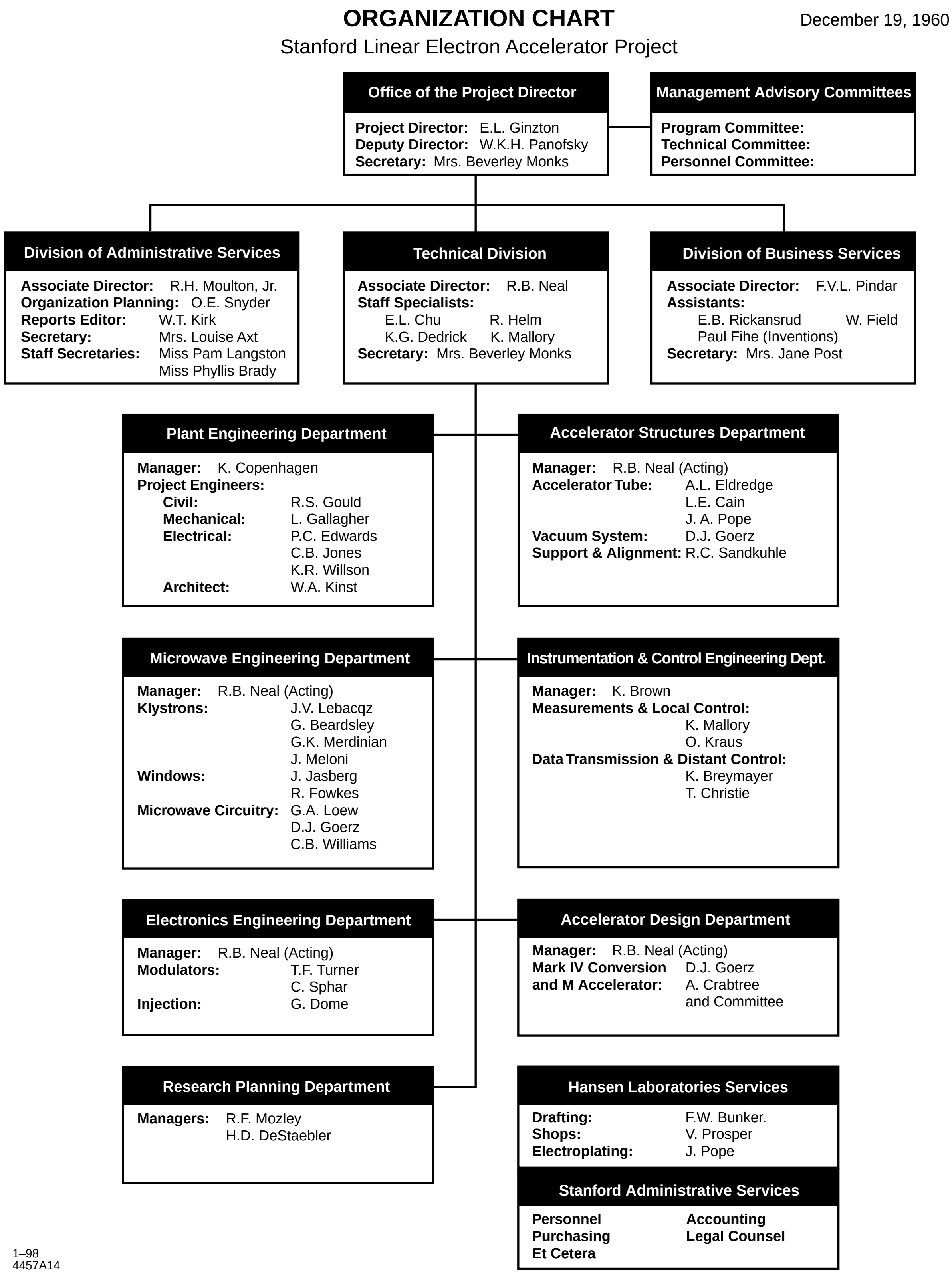

Figure 1: The first organization chart for Project M.

The Construction of SLAC and the Role of R. B. Neal

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The first beam passing through the entire three kilometer length of SLAC was obtained on May 21, 1966, although getting the beam through led to some surprises. Fig. 1 illustrates the reaction of the SLAC participants when difficulties during commissioning arose. SLAC has now operated for over 30 years, thanks to the efforts of many people, above all to those of Richard B. Neal; in today's jargon he was the Project Manager of the Construction of SLAC. I doubt that this is a record for an accelerator but it is a very long time. Usually when an individual of great age is being asked to what primary factor he attributes his longevity, the normal answer is "virtue and clean living," and most of the time he is lying. I hope that after this talk trying to describe some of the reasons for SLAC's long life I will not be accused of the same.

Ever since the original proposal to build SLAC, dated April 1957, was submitted, as illustrated in Fig. 2, I have been asked how long SLAC is apt to endure. My answer has always been: "10-15 years unless somebody has a good idea." Indeed the longevity of SLAC is due to the quality of its original construction combined with a plethora of good ideas, none of which were anticipated at the time when the machine was originally proposed.

Although SLAC was the result of a long line of development in the linear accelerator field, the actual proposal to build a machine of this magnitude was a major departure from the customs then prevalent among the practitioners of accelerator construction and the users of accelerators for research in nuclear and particle physics.

Indeed SLAC was a direct outgrowth from a series of electron accelerators pioneered by the great physicist William W. Hansen. Hansen's first machine, the MARK I accelerator at Stanford, produced a 6 MeV electron beam, and it is famous for having generated the shortest report ever written for a government agency; it read in its entirety: "We have accelerated electrons." Then followed the MARK II and MARK III accelerators, the former used for nuclear physics and the latter, 100 meters in length, supporting a very successful particle physics as well as nuclear physics program. In parallel there had been the development of hadron linear accelerators, pioneered by the work of Sloan and Lawrence before the war and then converted to practical use incorporating the drift tube design developed by Alvarez and collaborators.

Dick Neal was a major contributor both to the MARK II and MARK III accelerators. He worked on the design of both machines and managed the operation of the MARK II for nuclear physics research. His deep participation in the MARK III accelerator is documented in his 1953 thesis, entitled "A High Energy Linear Accelerator." It is published as a Microwave Laboratory report and gives a full description of the theory of the microwave structure and orbit dynamics of that machine as well as the practice of manufacturing and assembling its components.

While SLAC, in terms of its fundamental radiofrequency design, was a simple but large extrapolation of the disk loaded accelerator concept pioneered by Bill Hansen, it incorporated many concepts that were unprecedented at the time. But it should also be recognized that the more than 30 years of operation of SLAC covered an installation which underwent many changes. Table I indicates the sequence of "reincarnations" of the machine which I shall discuss further. Fig. 3 shows the initially

Figure 1: Stuck Beam

Figure 2: Proposal

+ Cartoons by Robert Gould

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

Table I: SLAC Major Milestones and Upgrades

1970	SPEAR construction started
1970	First polarized electron gun
1972	SPEAR operation started
1975-80	SLED installation
1976	PEP construction started
1980 (April)	PEP operation started
1973	SSRL started parasitic research
1979	SSRL started 50-50 SPEAR operation
1988	SSRL started 100% SPEAR operation
1984	SLC construction started
1987	SLC full operation
1992	First polarized photocathode at SLAC
1995	Polarization >80% obtained
1992	B-Factory proposed to Government
1994	B-Factory construction started
1998	B-Factory completion anticipated

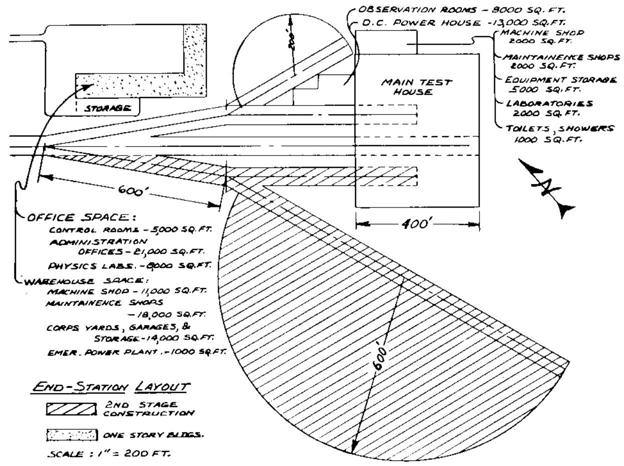

Figure 3: Initially Proposed Target Area Layout

proposed target area layout and Fig. 4 shows today's reality. There is little similarity! The initial proposal provided for two beams, one to study primary interactions of the electron beam, notably elastic scattering from protons and neutrons. The second beam was to be a producer of secondary beams to be used for research similar to that then prevalent at hadron accelerators. Indeed this became the minimum mission of SLAC, but the facility was amplified by a succession of colliding beam storage rings, and by the linear collider. In addition, the basic performance of the machine was upgraded by the SLAC energy development project, called SLED, and by a battery of higher power microwave sources, and by polarized electrons. In 1969 SLAC carried out an extensive conceptual design study to convert the room temperature structure to a superconducting accelerator - a highly premature undertaking. In addition, the SLAC proposal - the Recirculating Linear Accelerator (RLA), using the three kilometer structure repeatedly using two loops of recirculating magnets, was not accepted by the sponsoring agency. The RLA was to be both an energy doubler and a duty cycle multiplier at fixed energy. While the RLA was never built it was the conceptual forerunner of what is now the Thomas Jefferson National Accelerator Facility in Virginia.

Many factors in the building of SLAC were unprecedented. SLAC was probably the first major accelerator whose use was what I called "facility centered." That term described a machine where the research applications were centered on a group of large and generally multipurpose detectors. Prior to SLAC, most particle experiments carried out at proton accelerators were what I might call "building block" experiments, that is experiments where families of small particle detectors were clustered around the target surrounded by a variety of absorbers and analyzing magnets and where time coincidences provided the major signature for understanding the events produced. This approach was infeasible at SLAC due to the small cross-sections of events of interest, the low duty cycle of the machine which made coincidence observations precarious, and due to the large "soft" background which is generated as a result of the electromagnetic cascade induced by high energy electrons. As a result the construction of the SLAC accelerator proper, which is documented in the famous "Bluebook" edited by

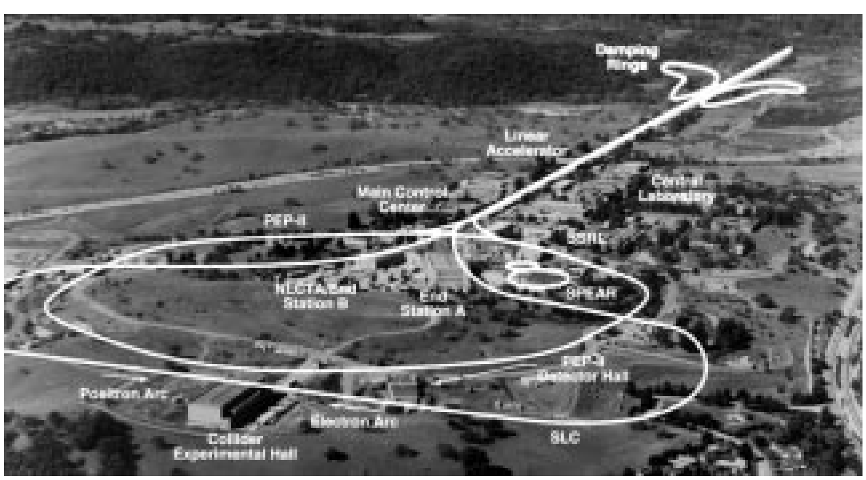

Figure 4: Aerial View of SLAC

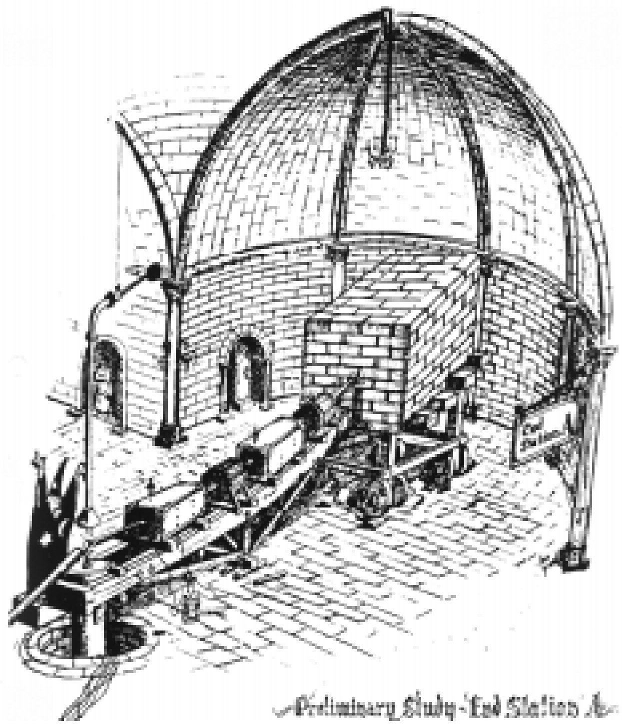

Figure 5: Architectural detail of one of the SLAC spectrometers

Figure 6: The rings and disks that are brazed together to form the SLAC accelerator structure

Richard Neal and published in 1968, was paralleled by the construction of a family of large detectors, shown in Table II, that became available at the time of initial operation of SLAC. Fig. 5 shows one of the spectrometers in "architectural detail." Today in the age of large, almost 4π steradian detectors surrounding interaction points of colliding beam machines, this mode of operation has become commonplace, but it was a rarity in its day.

In the past the construction of large accelerators has been very poorly documented in the scientific literature. People were simply "too busy" to simultaneously build great accelerators and do a proper job of documenting what they did. No proper published account exists of the series of cyclotrons built by Lawrence. Good publications document the construction of the first accelerators at CERN and the first linear proton accelerator of Alvarez, but there is no question that Dick Neal's Bluebook set a new standard for describing not only the engineering features of a new accelerator, in this case SLAC, but also accounting for the management of the construction and the organization of the laboratory. Unfortunately the Bluebook is now out of print and copies are difficult to obtain, but those who are interested in the process of SLAC's creation are well advised to get hold of a copy and read it.

The second exceptional circumstance accompanying the operation of SLAC was its very high peak, and also very high average power of the beam exceeding one megawatt. Thus stopping the beam safely and in a manner not generating excessive backgrounds and providing for high power beam collimation resulted in design requirements not hitherto encountered in particle accelerators to a significant extent. If the beam strikes a block of copper, a "melt-out" occurs at the maximum of the electron-positron shower in a few seconds. A tungsten block shatters almost instantaneously and concrete disintegrates.

The third innovation was the needed emphasis on rapid learning from past performance and on operational reliability. The SLAC linac in essence is composed of 240 sequential radiofrequency linear accelerators each properly phased to high precision and timed by its pulsing system. While a failure of one of these sequential units does not necessarily lead to loss of beam, the requirement for the simultaneous reliable operation of many subsystems was unprecedented. Let me give you one historical example of how the requirement on reliability, and, equally important, the requirement to be able to learn rapidly from failures, affected a key design choice. We considered to manufacture the disk loaded microwave structure by two alternative technologies: (1) brazing of rings and disks, which were separately machined, shown in Fig. 6; and (2) electroforming, that is machining a mandrel comprising the space inside the accelerator structure and then electroplating the structure on to this mandrel followed by dissolving the mandrel chemically. A third method, shrink-fitting the disks to a cylinder of uniform internal diameter was rejected. That method, used in the successful MARK III accelerator, developed difficulties after several years of operation due to cold flow of the copper components. The second system was eventually rejected also, not because it would not work -- it did. The reason was that if any errors were made during the manufacture, or if future difficulties would become manifest during operation, then the feedback for corrective action would be too long -- the electroforming of one section required one to two months. However, the technique chosen, joining the links and disks together, required the brazing of 200,000 joints. It speaks well for the quality control of that brazing operation, carried out largely by part-time employees, that over more than 30 years of operations, none of these 200,000 joints has ever leaked. A complex system of fast acting valves, vacion pumps and microwave windows maintained the vacuum with only five vacuum losses in 30 years.

Precision both in the manufacture of accelerator sections and the alignment were unprecedented in

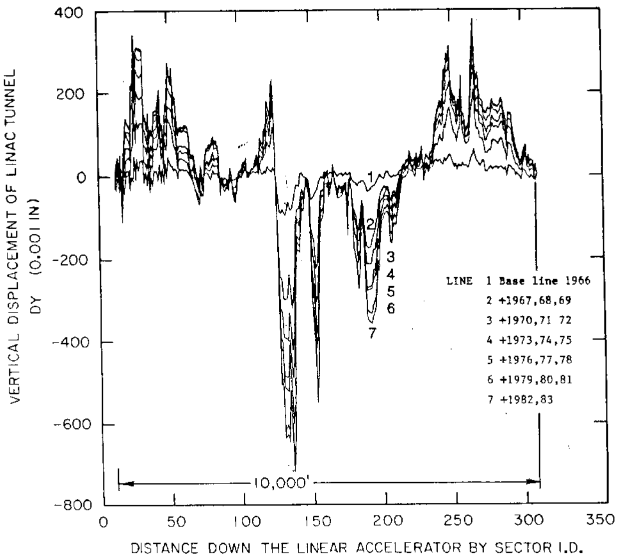

Figure 7: Ground motion along the accelerator

accelerator practice. Machining tolerances in manufacture of accelerator parts were +0.2 mils and -0.0 mils and were further improved by individual trimming of sections using radiofrequency measurements. Alignment was provided through a laser beam diffracted by a series of Fresnel lenses that were inserted into the large vacuum pipe supporting the accelerator structure. This system proved very valuable in view of the frequent ground-motions, depicted in Fig. 7. Ground motion along the accelerator length continued to move in the same direction, similar to CERN experience. The system saved months of realignment after the big earthquake on October 17, 1989.

SLAC faced a dilemma regarding its control system at the time the laboratory was created: are computers here to stay? As a result, the control system was designed using the then computerized systems still in their infancy but with backup systems permitting operation from a multiplicity of manned control points. The backup system was used until suitable computers could be obtained, but was never used thereafter.

Finally there was the transition of operation of linear accelerators from past proprietary machines, run for the benefit of the faculty and staff of a single institution, to a national facility available to any proponent on the basis of merit of a proposed experiment measured by technical feasibility and promise of results. This method of operation is now standard in all the great high energy physics laboratories of the world, in particular those operated by consortia of universities, or consortia of nations such as CERN. This, however, was the exception in 1957, in particular for laboratories operated by a single university, in this case Stanford.

SLAC was unique in technology relevant to the major accelerators then operating at the frontier of energy. There was very little experience in industry on most of the specific technologies required for creating SLAC. We adopted the policy that while we relied on industry to supply many essential components, it was necessary to maintain a limited production capacity in-house to make what SLAC needed. As a result, industry did relatively little development but only manufacture in support of SLAC's needs, and SLAC generally could fill in even for production in case difficulties were encountered when industry either failed to make satisfactory initial proposals or ran into difficulties in producing items of sufficient quality or on an adequate schedule.

Construction of SLAC was approved in 1961 and duly celebrated as shown in Fig. 8. SLAC was built on schedule, on budget and exceeding the advertised performance. This record is hardly unique in the world of high energy accelerators, but it contrasted most favorably with the record of most high technology projects in the United States, particularly in nuclear reactors, major military systems, and space ventures; a record not unnoticed by the government agencies supporting SLAC. Construction proceeded as illustrated in Fig. 9 and was monitored by the U.S. government agencies evolving from the Atomic Energy Commission (Fig. 10).

Figure 8: Approval

Figure 9: Construction

Because of the facility-centered nature of SLAC, we felt it necessary and desirable to build up a very strong in-house engineering and scientific team in order to support the construction, operation, and upgrading of the accelerator itself, as well as to support the experimenters. Nevertheless, this capable staff would have been much less effective had it not been for the creative and patient management which Dick Neal conducted on a day-to-day basis. Figure 11 shows the organization chart of SLAC during the initial construction period.

Officially Dick Neal was Associate Director for the Technical Division. The work of that division comprised two major functions. The first constituted the various engineering divisions: mechanical, electrical and civil, which supported not only the construction of the accelerator and its surroundings, but also supported the budding efforts of the Research Division in creating the scientific instrumentation for the future utilization of SLAC. The second function was responsibility for the construction of the accelerator itself. By combining these two functions under Dick Neal's leadership, it was possible to avoid the complexities in the modern "matrix organization" of conducting large construction projects. Under such an arrangement the responsibility for constructing the accelerating facilities and their environs are generally separated from the responsibility for the various engineering functions; therefore providing for a constructive interaction between these two branches constitutes a major challenge.

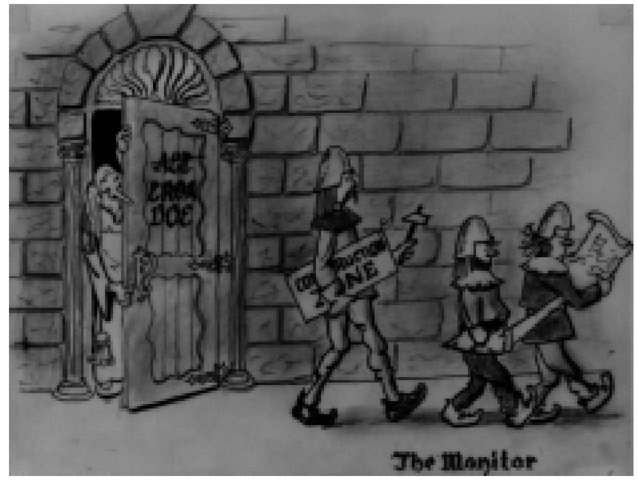

Figure 10: The Monitor

The Technical Division had responsibility both for "conventional," i.e. architecture and civil engineering, construction as well as for the technical components. This integration stemmed from the conviction that a large number of interfaces between the technical components and their civil environment had to be optimized during design. While the execution of civil design and construction was carried out by a separate entity, the joint venture firm of Aetron, Blume, and Atkinson, Dick Neal had to integrate the civil and technical elements of the project and he did so earning the highest respect of both communities. Fig. 12 shows a typical compromise between architectural and technical demands.

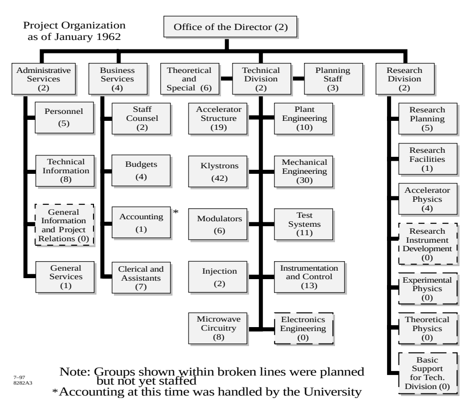

Figure 11: Organization chart during the initial construction period

Figure 12: Typical tunnel cross section

Dick Neal was able to keep the management of this broad range of responsibility directly in his own hands through a systematic approach. He created a Technical Planning Department which in the pre-computer age maintained a hand-drawn critical path network which displayed the flow of functions and responsibilities of the entire project. In addition, that department created sub-charts of the comprehensive critical path network which described the tasks and key dates required for each department and charted the actual accomplishments. Dick Neal set up a cycle of meetings, usually at the ungodly hour of 8 a.m., with each department head and the staff of the Technical Planning Department in which at each meeting the critical path network relating to one department was brought up-to-date. Fig. 13 shows one of these meetings in process. He arranged those meetings that during a two-week cycle the progress of the entire undertaking was brought fully up-to-date. This systematic approach was a large factor in achieving the success of SLAC, and it avoided the types of unhappy surprises when deficiencies are discovered too late. This continuous updating of the critical path network department-by-department at the same time served as a mechanism of detailed direction of the activities of each department. In addition, Neal conducted a weekly meeting in which each department head gave a brief status report to all other key managers of the project. I recall many of these meetings; in particular the fact that each one of them began and concluded exactly on time has left an indelible memory.

Needless to say, this cycle of systematic up-dates and meetings was only a small fraction of Dick Neal's management and engineering-physics activities. Many design decisions had to be made, and ad hoc meetings had to be organized to deal with particular problems. In addition, I was continuously impressed by the patience and skill with which Dick Neal dealt with the unavoidable personnel problems which are inherent in the construction of such an intricate interlocking enterprise as the construction of SLAC. Dick Neal spent hours mediating such conflicts with apparent inexhaustible patience. As a result of all these great efforts the construction of SLAC was what, with the benefit of hindsight and by comparison with many other high technology enterprises, can be considered to be an unqualified success.

The experimental physics community was generally unfamiliar with the design, construction and management of the large experimental facilities required to exploit the SLAC beam. Therefore the in-house group had to carry a substantially larger part of the burden of experimental facility construction than is the case today with its monster scientific collaborations. This placed an additional major burden on Richard Neal in providing technical support for the generation of these large experimental devices.

The performance of the SLAC complex is difficult to describe by simple parameters, and the figures of merit for performance shifted during the various phases of operation.

In the original proposal SLAC's energy was proposed to be 10-20 GeV. Shortly after turn-on its energy gradually improved, as shown in Table III. The only surprise on turn-on was the discovery of multi-section, multi-bunch beam break-up (BBU). This phenomenon was understood almost immediately and remedial measures were taken. Since SLAC is a constant gradient rather than a constant impedance structure, the BBU was less severe since the variable impedance of the structure also implies a gradient

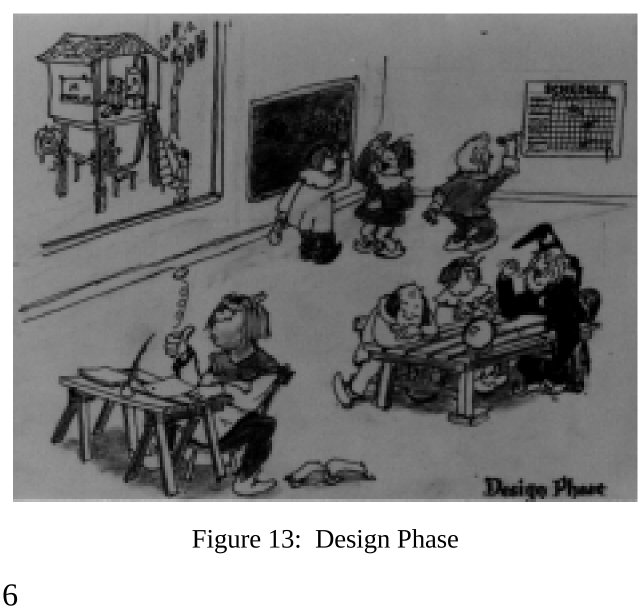

Figure 13: Design Phase

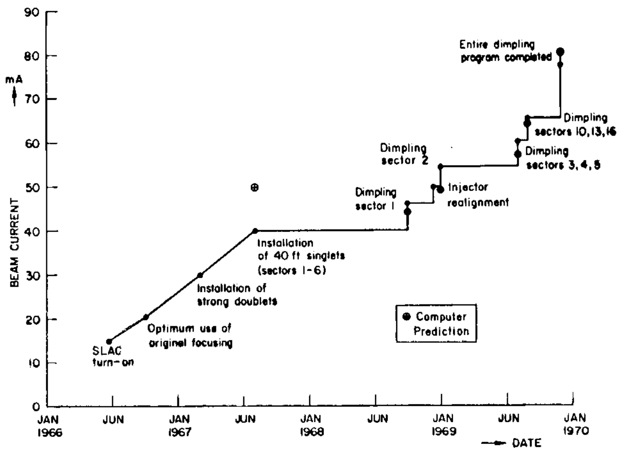

Figure 14: History of SLAC peak beam current

in the frequencies of the higher order modes relevant to the beam break-up. Remedies consisted of dispersing the frequency of higher order modes among successive sections by small deformation of the structure and by strengthening the magnetic focusing system. Fig. 14 shows the gain in peak beam current made possible by these measures.

The energy of the machine has been continually increased over the last 30 years. This increase was achieved by improvements in klystron performance, introduction of the SLAC energy development scheme (SLED), and by replacement of the klystrons with three generations of higher power tubes. Peak powers attained by these successive families of klystrons were 24, 36 and 64 megawatts respectively. Electrical breakdown has not been a factor limiting the attainable energy of the machine.

During its early phases SLAC served only a series of fixed target experiments and the pulse repetition rate was divided among different target areas through a pulsed beam transfer arrangement at the head of the magnetic beam distribution system, called the beam switchyard. This shared pulsed beam delivery system proved very efficient because some experiments were not suited for receiving the full pulse repetition rate. In particular two major bubble chamber facilities were created under the leadership of Joseph Ballam. These were used during the first two decades of SLAC operation and were suited for a pulse rate of up to 2 per second and up to 15 per second respectively, and thus could receive beams without significant impact on other uses. Each beam could be individually tailored to the experimenters' need in respect to repetition rate, energy and intensity. Energy variability on a pulse by pulse basis was achieved by triggering each klystron pulse on a programmed basis.

Because of this complex pattern of operation, beam delivery is difficult to quantify in a consistent manner, and I will not bore you with the usual statistical information. Sufficient to say, beam delivery during the first decade was made roughly at the rate of 10^{13} electrons per second and beam availability tended to be near 90 percent. One might guess that by now we have delivered between 10^{21} to 10^{22} electrons to fixed target experiments. This corresponds to a number between 1-10 millimoles of electrons or a relativistic mass of between 20-200 milligrams of electrons.

SLAC has been an excellent laboratory for extending the life of high power klystrons. Judging from the experience of earlier machines, lifetimes of only a few thousand hours were anticipated during the proposal to construct SLAC. Actual experience has led to mean times between failure (MTBF) now exceeding 50,000 hours. The good news about this favorable development has been that costs and lost beam time due to klystron failure were sharply reduced. The bad news is that even with as large a complement as 240 klystrons at SLAC, the failure rate has been so consistently low that maintenance of industrial production lines for replacement proved impossible to justify. Thus, while originally SLAC klystrons were procured from four sources, SLAC handled all klystron replacements through its internal shops after a few years.

The increase in energy due to SLED operation was accompanied by a decrease in average beam due to the shortened pulse length inherent in SLED operations. Moreover, average beam delivery tended to shrink during recent times, partially due to budget limits which forced operations to lower pulse repetition rates and induced shortened operating periods.

After the initial operating period solely dedicated to fixed target physics, operation became even more complex with the advent of storage rings in 1972. Construction of SPEAR was started in 1970. SPEAR was never formally authorized as a construction project, but was built in a housing of portable shielding blocks, and its hardware was constructed as an internally funded equipment project. SPEAR was possibly the most cost-effective high energy collider ever built leading to extremely important physics with a relatively modest construction effort and only a minor impact on the "pulse economy" of the accelerator. SPEAR was followed by PEP which was a formal construction project housed in an excavated tunnel and which provided six interaction halls for experiments. Fig. 4 has already shown the layout of the accelerator with the target area, the two storage rings, and the SLAC Linear Collider, which was to follow.

Again the beam delivery record of the storage rings is difficult to quantify. SPEAR generally delivered on the order of 100 inverse nanobarns (10^{35} cm^{-2}) per day, and PEP delivered a luminosity almost an order of magnitude higher per interaction region. After SPEAR was initiated, its usefulness for synchrotron radiation became manifest and a separate Synchrotron Radiation Laboratory was organized to utilize both x-ray beams from the bending magnets as well as to generate higher brightness beams from insertion devices. The use of synchrotron radiation increased sharply and produced extremely valuable results. In consequence it was decided eventually to construct a separate electron synchrotron injector into SPEAR since injection from the

Table IV: SLAC SLC/SLD Performance for 1992 - 1995

	SLD 1992	SLD 1993	SLD 1994
Experiment Logging	51%	63%	56%
Machine Development	9%	6%	4%
Alternate Program	1%	1%	1%
Tuning	19%	11%	10%
Unscheduled Down	18%	17%	23%
Scheduled Off	2%	2%	3%
Total Hours	2616	4079	5065
Total Z's	10,000	55,700	100,000
Average Luminosity (Z/hr)	7.5	21.7	35.3
Approx. Polarization	21%	65%	79%

main accelerator, which by that time became a 50 GeV linear accelerator, into a 2 GeV storage ring was both inefficient and constituted an undue load on the main machine. SSRL has been a very successful separate operation which is now managed as a division of SLAC but no longer interacts technically with the beam delivery of the linear accelerator and its associated storage rings and linear collider.

In 1984 SLAC decided to go beyond the energy region of the two storage rings at SLAC by starting construction of a linear collider (SLC). I will not here describe the technical characteristics of that device. It was designed from the beginning to provide collisions between electrons and positrons of 50 GeV each in order to bring the intermediate boson Z^o under direct investigation. The introduction of the SLC generated a crisis into the continuity of SLAC operations. While the soundness of the fundamental principle of the SLC was never in doubt, commissioning the SLC was considerably more difficult than envisaged. The SLC requires a quality of operation of the SLAC two-mile linear accelerator much higher than that incorporated in its basic design. Required emittance volumes of the beam for successful SLC operation are considerably smaller than those needed for fixed target experiments and also for storage ring injection. The various causes of emitance growth had to be mitigated in steps. Causes of beam jitter had to be investigated and had to be remediated by improvements of power supplies and by the introduction of active feedback systems reducing beam fluctuations. The beam optics of the arc bending magnet system required correction, and the final focus system with its large demagnification was improved. Overall, reliability standards of components had to be improved by a large factor relative to those required for an operation of the linear accelerator in its previous mode. As a result, beam delivery of the SLC operating at the Z^o peak has improved; Table IV shows the record.

A major addition to SLAC's basic utility was the use of polarized electron beams. This was introduced first in 1970 when a polarized gun was introduced. This device was

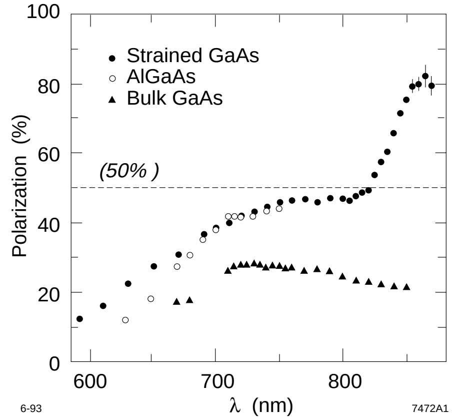

Figure 15: Polarization vs wavelength for three different cathodes that have run on the SLAC accelerator

based on the principle of ionizing electrons from an atomic lithium beam which had been spin-aligned and separated in an inhomogeneous magnetic field. Since 1992 the SLAC linear accelerator and the SLC have been operated almost exclusively with polarized electrons using electrons emitted by a gallium arsenide cathode illuminated by laser light of circular polarization. The amount of polarization attainable from such cathodes has recently been improved to exceed 80 percent by the use of strained gallium arsenide material in which the structure of valence band electrons of the cathode material is no longer degenerate due to the external strain. The availability of a high polarization electron beam has been of enormous value to the SLC experiments and has also revitalized the fixed target program by making it possible to isolate spin dependent form factors of the nucleons. Polarized targets are also generally used in such experiments. The performance summary of the SLAC polarized electron source is given in Fig. 15.

Current operation of SLAC is therefore divided between fixed target experiments, whose energy has now been extended to 50 GeV, and continued use of the SLC with the SLAC large detector. Because of the availability of polarization, results obtained in the SLC-SLD combination have been competitive with the experiments using LEP at CERN, notwithstanding the significantly larger available luminosities at the much larger LEP machine. In addition the SLC, together with specialized test facilities, constitute a basic laboratory to determine the design of the Next Linear Collider (NLC).

SLAC is currently engaged in converting PEP into a B-factory consisting of a high energy ring storing electrons of 9 GeV and a low energy ring storing positrons of 3 GeV. Stored currents are unusually high, being 0.99 amperes and 2.1 amperes for the high energy ring and low energy ring respectively. The goal is to obtain a luminosity of at least $3x10^{33}cm^{-2}sec^{-1}$. While the B-factory is a construction project, it does not require any modification to the civil engineering environment at SLAC. The B-factory will add

Figure 16: Research

a new tool to be available for physics before the end of the century, which hopefully will give another "lease on life" to the laboratory.

The above has been a brief outline of the different phases of operation of SLAC which provided the basis of its longevity. Let me conclude with a brief overview of the experimental results. The research process is illustrated in Fig. 16. SLAC has been an unusually productive laboratory both in terms of genuinely new revelations and the accumulation of archival data.

It was only natural that when SLAC was proposed emphasis was given to continuing the work on elastic electron scattering on protons and neutrons, for which Robert Hofstadter had received the Nobel Prize on SLAC's predecessor machine, the MARK III accelerator. As it turned out, elastic scattering using SLAC's facilities worked fine but did not provide any genuinely new insights. Instead, the focus of attention shifted to deep inelastic scattering where cross-sections at high momentum transfers were observed to be very much larger than anyone had surmised. This work, using three magnetic spectrometers which incorporated the new principle of line to point focusing horizontally, provided data which established "beyond reasonable doubt" evidence for a point-like sub-structure in the nucleons.

The quality and quantity of high energy secondary beams enabled SLAC to become the leading "factory" for bubble chamber pictures for a considerable period of time. The main reason for this preeminence was the high repetition rate of SLAC relative to that provided by the slower cycle of proton synchrotrons. During the peak production period SLAC produced somewhere around six million bubble chamber pictures per year, which tended to saturate the pictorial data analysis capacity of collaborators throughout the world. The 82" chamber at SLAC, using a polarized γ-ray beam generated by Compton backscattering of laser photons from the electron beam, demonstrated, in addition to many other results, helicity conservation in the photoproduction of vector mesons. The 40" operated in a mode in which photographic picture taking was triggered by an array of counters so that images from only one in 20 to 40 expansions were recorded. The chamber operated for an unprecedented 100 million expansions during its useful life.

One of the surprises from SLAC, but not so surprising to the theorists who predicted the phenomenon, was the large forward intensity of secondary beams. These were exploited for Kaon spectroscopy in a Large Aperture Solenoidal Spectrometer (LASS) and in a streamer chamber. A precision experiment on the muon asymmetry from K-decay was performed and various searches for new particles were made in vertical shafts beyond the beam stoppers.

Then came the results from SPEAR, leading to the November Revolution of 1974 when the J/ψ was co-discovered with the Brookhaven fixed target proton experiments. The unusually clean conditions at SPEAR with the MARK I, and then the MARK II detector, permitted thorough examination of the spectrometry of charmonium and the complete level structure of the psi family was constructed. An important by-product of that work was the discovery of the τ lepton, which was carried out by one of the collaborating groups in the SPEAR experiment. The group "mined the tapes" from that experiment to look for an excess of electron-positron coincidences which were interpreted to be the decay product from heavy lepton pairs, each decaying independently.

Work on the linear collider has also been extremely productive, principally since the use of polarized electrons greatly increases the sensitivity of analysis of the Z^0 decay into various channels. At the same time SLAC has now returned to the original deep inelastic scattering experiments. As a result of the energy increase of the accelerator to 50 GeV, and the availability of more than 80 percent polarized electron beams, a new series of electron scattering experiments is in progress which has greatly extended the range of the earlier experiments. While this work is not able to reach the range of momentum transfers and energies of the hadron system attainable at HERA and through the use of high energy muon beams from proton machines, the precision of these experiments makes it possible to generate form factors which exceed in accuracy measurements using the higher energy methods in those kinematic regions where such form factors overlap.

SLAC has been a maverick in high energy physics by pursuing the use of lepton beams as primary sources and using the low duty cycle high intensity linear accelerator generated beams. It is now over 30 years and 3 Nobel prizes later than when the first beam was produced in the spring of 1966. Today, with the SLAC Linear Collider, plans for the Next Linear Collider and the construction of the B-factory as well as the rejuvenated fixed target program going strong, I still answer the old question: How long will SLAC continue? with the old reply, "10 to 15 years unless somebody has a good idea." But the high standards set by Richard Neal in the construction of all aspects of the SLAC facilities and in managing SLAC's initial operations remain the principal basis of SLAC's longevity. Those high standards have made it possible to operate the SLAC linac for purposes well above its initial design goals. Thus Richard Neal deserves much of the credit for having made possible SLAC operation above 50 GeV, as a successful injector into a family of storage rings, and as a component of the world's first linear collider.

Symposium Speech

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I. OPENING REMARKS

I would like to thank Burt Richter and Pief Panofsky for their kind remarks. After these fine endorsements from the Director and Director Emeritus, this may be a good time for me to send in an application for a job at SLAC. I will add the following note to Burt and Pief: "Remember age discrimination is now illegal!" Actually, considering the many advances in accelerator technology since my retirement and the superior quality of the present staff members at SLAC, I doubt if I could qualify for a position here even if I were 50 years younger.

The famous British ballerina, Margot Fonteyn, during the later years of her life, made a similar deprecative statement about her own skills as a young dancer. Her fans responded defensively saying that it might be true that her purely technical skills were surpassed by others, but it was the <u>lyrical</u> qualities of her dancing that made her so outstanding. This prompts another note to Burt: "Don't you think that my lyrical qualities compensate for my other deficiencies?"

A tour of the Next Linear Collider Test Accelerator (NLCTA) facility yesterday convinced me that it is a physics and engineering marvel, and at the same time a work of art. For me, it was both an inspiring and a humbling experience. It showed me how far accelerator science and technology have progressed since my day in the field.

I am glad that my parents arranged that my birthday would occur on the same date as this symposium. Thanks to the SLAC Faculty and the Organizing Committee, Pief Panofsky, Greg Loew, and Bob Siemann, for assuring that these dates <u>do</u> actually match so that they are exactly 80 years apart, no more and no less!

II. COLLEAGUES, FRIENDS & ACQUAINTANCES

How does one summarize the experiences and do justice to the colleagues, friends, and acquaintances of a career of 38 years in a time allotment of a few minutes? The 38 years is the time between 1947 when I started as a graduate student at Stanford and 1985, when I retired from SLAC. To bask in reflected glory, I could mention the famous people that I crossed paths with, such as Bill Hansen, the person who was the founder of the accelerator program at Stanford that still thrives at SLAC today. I could talk about the three eminent Laboratory Directors that I served under: Ed Ginzton, Pief Panofsky and Burt Richter. I could mention the four brilliant people who became Nobel Laureates at the Hansen Laboratories and SLAC while I was at these institutions: Bob Hofstadter, Burt Richter, Dick Taylor, and Martin Perl. I could give due praise to my fellow Associate and Deputy Directors at SLAC: Matt Sands, Sid Drell, Joe Ballam, John Rees, Bob Moulton, Fred Pindar, and Gene Rickansrud. I could talk about my warm relations with my close associates who were Department Heads in the Technical Division at SLAC: Greg Loew, Larry Kral, Jean Lebacqz, Arnold Eldredge, Herm Zaiss, Fred Hall, Bill Lusebrink, Ken Copenhagen, Carl Olson, John Voss, Al Lisin, Vern Price, Ed Seppi, Lew Keller, and Pat Kilpatrick. Now that I have named these key people there isn't time to say more about them. And there are hundreds of other prominent people that I haven't even listed who made major contributions to Stanford and SLAC and certainly deserve special recognition. To do even moderate justice to them, I will have to generalize.

Being a member of the team of physicists, engineers, and technicians that designed and built SLAC in the 1960s has in itself always provided me a great feeling of satisfaction. The further recognition given to me this day as a SLAC contributor is an unexpected but much appreciated honor. I want to share this recognition with those other SLAC team members who so richly deserve these tributes.

Without diminishing the credit due to individual members of this team, it should be acknowledged that the team's success was amplified by the <u>synergism</u> that sometimes occurs in efforts of this type whereby the accomplishments of the entire group exceed the sum of the achievements of its separate members.

However, this synergism could not have occurred without the inspired leadership of Pief Panofsky who, even today, 36 years after the inception of SLAC, continues his illustrious career as physicist, as science advisor to institutions and governments and as SLAC Director Emeritus.

III. SCIENCE, TECHNOLOGY & THE FUTURE OF SLAC

Perhaps you have heard the story about Pief escorting the skeptical Professor Felix Bloch around 1961 on a tour of the Sand Hill site where the SLAC accelerator would later be built. Felix said: "Pief, I'm in favor of building the accelerator here that you call the 'Monster'. But just be sure it's a 'good Monster'!" If Felix were alive today, I believe he would add: "Yes, Pief, results have proven that you built a 'good Monster' and it still seems to have a <u>great deal of fire left in its belly!"</u>

This raises a critical question: "What about the future of SLAC?" Those of us who were here at the beginning and those who arrived later would all like to see the fiery but friendly "Monster" that we created and nourished survive well into the next century and continue to serve as a creature that supports outstanding particle physics research.

What factors affect the probability of SLAC's survival? There is a well-established strong coupling between science and technology on the one hand and potential military strength on the other. The cold war with the Soviet Union was obviously an important factor in this equation from the late 1940s until the early 1990s when the USSR collapsed. There are now emerging signs that a cold war between the U.S. and China may erupt. Some pundits say it already has. There is also a significant number of "rogue" countries such as North Korea, Iran, Iraq, and Libya which, although small, could touch off a regional or world conflagration. Thus, for those who do not believe that science is worth supporting for purely intrinsic reasons, there is continuing justification to sanction such support because science is an essential adjunct to effective national defense and our international power and prestige.

Industrial prowess and scientific strength also go hand in hand. Support of basic science is a key factor in our country's continuing pre-eminence among the industrial nations of the world.

The success and recognition that SLAC has already received among national and international physics institutions greatly enhance the likelihood that its support will be extended into the future. No other laboratory of its kind has been the home institution of the recipients of three Nobel awards during the last 20 years.

What are the stumbling blocks in the path of continuing political and financial support for SLAC? First and foremost, there are the major national problems relating to the enormous 5 1/2 trillion dollar public debt and the critical need to balance the federal budget. There is tremendous pressure upon the administration and the Congress to slash the cost of many ongoing programs or to eliminate them entirely. Some of those programs including high energy physics, that cannot demonstrate an immediate public benefit, are at a distinct disadvantage in this contest for funds. Certain other important programs, for example those involving biotechnology, inherently have a more discernible benefit and a faster pay-back. Many of us have a family member or friend whose life span or future physical well-being would be improved immensely by the success of one or more of the medical and pharmaceutical studies now in the pipeline. For good reasons, the organizations backing these programs have tremendous public support and great clout with the administration and the Congress. This support is implicit in an excerpt from a recent commencement address by President Clinton: "... if the last 50 years were the age of physics, the next 50 years will be the age of biology. We are now embarking on our most daring explorations, unraveling the mysteries of our inner world and charting new routes to the conquest of disease."

What steps can be taken by SLAC to compete with these other favored programs? First, all feasible measures must be taken to extend the stream of scientific successes into the future. This requires a top group of physicists, and outstanding staff of engineers and technicians, a judicious selection of research ventures, astute planning, and expert execution. These are resources and capabilities of which SLAC has a plentiful supply.

But in the current political environment, those decision-making people now occupying executive positions in government more often than not are members of the impatient, baby-boomer generation who from childhood have demanded immediate satisfaction for any and all of their needs and whims. Typically, they want quick results and short-term pay-backs from any research initiatives that come to them for endorsement or approval. Such quick payoffs are not usually compatible with particle physics research as we have discussed.

A possible mitigation of this dilemma consists of placing greater emphasis upon the "spin-off" benefits arising from basic physics research. Since physics research is a "cutting-edge" activity, it frequently requires the development of "cutting-edge" technology that may be relatively easy to transfer quickly to industry and to society at large.

Placing greater emphasis on such spin-offs might include having them displayed more effectively in the approval processes of research proposals than in the past, and having them occupy special sections of support documentation. Another method of capitalizing on spin-offs would be to develop collaborations with industrial companies that could potentially benefit from marketing spin-off products from basic research. With these modifications, both the long-term basic science potential and the short-term technological potential of the proposal would be high-lighted for those officials who support one potential or the other or both.

This is not to suggest that SLAC-related science and technology should be placed into competition with each other. Rather, their complementarity should be stressed. The advancement of basic science must remain the dominant objective. That's why the accelerator was authorized and built in the first place. But the associated technology should be elevated to a position nearer parity than it has been in the past.

However, it is not sufficient just to present these spin-off accomplishments to an audience of physicists and engineers who are already knowledgeable about most of them. Ways must be found to bring real and potential spin-offs strategically to the attention of the "movers and shakers" in society and government.

A quixotic example of a "quick" pay-back from basic research is a study carried out recently by a British physicist at Aston University. His findings were published in the EUROPEAN JOURNAL OF PHYSICS. They showed with impeccable logic that a piece of toast falling from a breakfast table will land, more often then not, butter side down. This is now known as the First Law of Toast: Butter

Meets Rug! This study confirms what most breakfast eaters have known for centuries or, at least, since the invention of toast.

This discussion has related mainly to ways of enhancing the likelihood of continued support of SLAC's particle physics program. But what about major new construction programs such as the Next Linear Collider, a TeV-scale machine, whose cost is likely to be measured, not in millions, but in billions of dollars? Here, the best approach appears to be to extend the presently existing Interlaboratory Collaboration for R&D on such a machine to the eventual construction program itself. I understand that such extension is being considered by the participating members of this Collaboration. The principal advantage of this approach is, obviously, that the financial burden of each participating nation will be greatly reduced compared to the cost of "going it alone". The principal concerns are: How will a nation be selected as the site of the Linear Collider, and how can this selection be made without losing the support of those nations not selected? It is likely that the collaborators in the R&D program have already considered and made preliminary judgments regarding these key questions.

IV. CLOSING REMARKS

One final brief story about the beneficial coupling of science and technology. A physicist dies and reports to the Pearly Gates. St. Peter checks his dossier and says: "Ah, you're a physicist------you are in the wrong place." So the physicist reports to the gates of hell and is let in. Pretty soon, the physicist gets dissatisfied with the level of comfort in hell, and starts researching, designing and building improvements. After a while, they've got a fusion reactor powering an air conditioning system, they have escalators and flush toilets and the physicist is a pretty popular guy. One day, God calls up Satan on the telephone and says with a sneer": "So, how's the weather down there in hell?" Satan replies: "Hey, things are going great! We've got air conditioning and escalators and flush toilets, and there's no telling what this physicist is going to come up with next!" God responds: "What's that? You've got a physicist? That's a mistake----------he should never have gotten down there in the first place; send him up here". Satan says: "No way! I like having a physicist on the staff, and I'm keeping him!" God angrily says: "Send him back here or I'll sue!" Satan laughs uproariously and answers: " Yeah, right, and just where are YOU going to get a lawyer?"

Again, I want to thank the SLAC Faculty and the Organizing Committee for sponsoring and planning this meeting and the speakers who have or will present papers today.

Lessons Learned from the SLC

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ABSTRACT

The SLAC Linear Collider (SLC) is the first example of an entirely new type of lepton collider. Many years of effort were required to develop the understanding and techniques needed to approach design luminosity. This paper discusses some of the key issues and problems encountered in producing a working linear collider. These include the polarized source, techniques for emittance preservation, extensive feedback systems, and refinements in beam optimization in the final focus. The SLC experience has been invaluable for testing concepts and developing designs for a future linear collider.

I. INTRODUCTION

As accelerators have become the main tool for exploring elementary particle physics over the last forty years, electron and proton machines have developed in parallel as complementary techniques for revealing the fundamental forces and particles of nature. The first major electron accelerator was the SLAC linac which began operation in the mid-1960s. This was followed by successive generations of electron-positron storage rings, from the early small ADONE and SPEAR rings at Frascati and SLAC with 1-2 GeV per beam, to the large LEP collider at CERN, now at nearly 100 GeV per beam. The concept of an electron-positron linear collider was proposed in the late 1970's as a way of reaching higher energy than was feasible with conventional storage ring technology. To limit energy loss due to synchrotron radiation, the bending radius of an electron storage ring must increase approximately linearly with energy and thus the size and cost increase as the energy squared. The LEP tunnel is already 27 km long so a storage ring of even twice the energy would require 100 km, making it impractical. The size and cost of a linear collider should scale only linearly with energy.

The SLAC Linear Collider (SLC), built upon the existing linac, was proposed as an inexpensive way to explore the physics of the Z^0 boson while demonstrating that this bold new technology could work [1]. Both goals turned out to be much more difficult to achieve than anticipated, with the SLC only now reaching near design luminosity. By the 1980s, storage ring technology was well understood and few surprises were encountered even with an enormous project such as LEP. As the first of an entirely new type of accelerator, the SLC required a long and continuing effort to develop the understanding and techniques required to produce a working linear collider. At the same time, there has been a parallel international collaborative effort to design an electron-positron linear collider to reach an energy of 1 TeV [2]. Both projects have benefited from a close interaction. The SLC has drawn on the ideas and knowledge

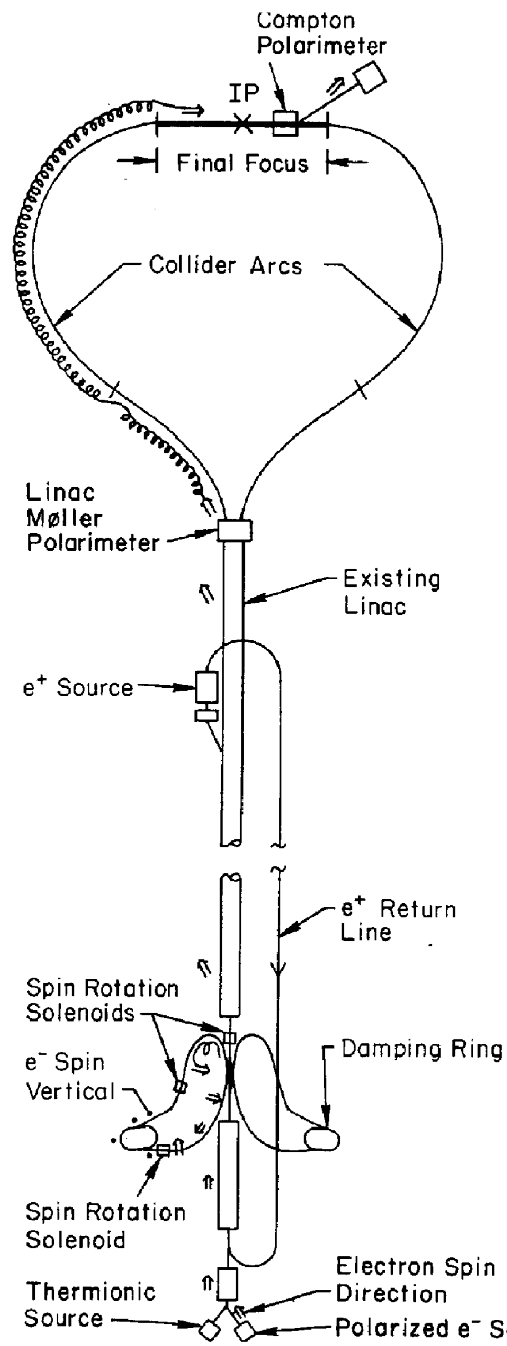

Figure 1: Schematic of the SLC showing the upgraded SLAC linac with the SLC damping rings, positron source, collider arcs and final focus. The double arrows indicate the orientation of the electron polarization as it travels through the accelerator.

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

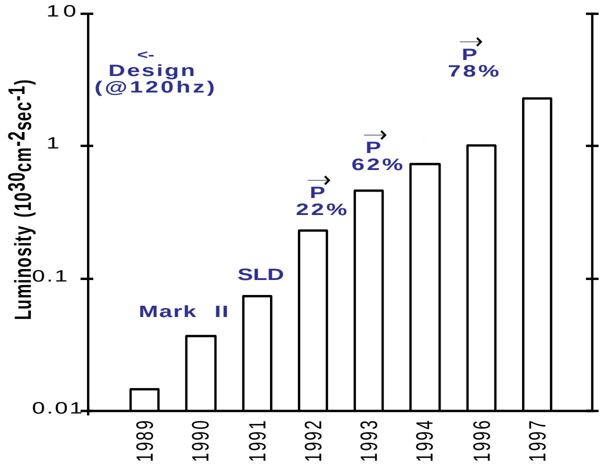

Figure 2: SLC luminosity history from 1989 to 1997 plotted on a log scale. The design luminosity was $6.0\times10^{30}cm^{-2}sec^{-1}$.

developed for the future machine while the collider design has been heavily influenced by the experience gained with the SLC.

II. BRIEF HISTORY

Design studies and test projects for the SLC were begun in 1980. Construction began in October, 1983 and was completed in mid-1987, with many upgrades in succeeding years. After two difficult years of commissioning, the first Z^0 event was seen by the MARK II detector on April 11, 1989. The SLD detector was brought on line in 1991 with a brief engineering run. SLD physics data taking began the next year with a polarized electron beam. More than 10,000 Z^0s were recorded with an average polarization of 22%. In 1993, the SLC began to run with ‘flat beam’ optics with the vertical beam size much smaller than the horizontal, unlike the original design where the beam sizes were nearly equal [3]. This provided a significant increase in luminosity and SLD logged over 50,000 Z^0s. The polarized source had been upgraded to use a ‘strained lattice’ cathode which provided polarization of about 62% [4]. For the 1994-95 run, a new vacuum chamber was built for the damping rings to support higher beam intensity and the final focus optics was modified to produce smaller beams at the Interaction Point (IP) [5]. A thinner strained lattice cathode brought the polarization up to nearly 80%. Over 100,000 Z^0s were delivered in this long run. For the next runs, the SLD experiment was upgraded with an improved vertex detector with better resolution and larger acceptance. In 1996, operations were limited by scheduling constraints and 50,000 Z^0s were delivered. The major physics run with the upgraded SLD detector began in 1997 and will continue through mid-1998. Improvements have led to a significant increase in luminosity, currently 2-3 times higher than achieved in previous years (Figure 2). More than a quarter million additional Z^0 events are expected by the end of the run.

III. OVERVIEW

Built on the existing SLAC Linac, the SLC is a ‘folded’ version of a linear collider where both electron and positron bunches are accelerated in the same beam pipe to about 50 GeV [6]. The SLC cycle begins with two electron bunches stored in the north damping ring and two positron bunches stored in the south damping ring. On each pulse, one positron bunch followed by both electron bunches are accelerated in the linac. The second positron bunch remains in the damping ring for an additional damping cycle to reduce the large incoming emittance. Two thirds of the way along the Linac, the second electron bunch is extracted onto a target to produce a new pulse of positrons. The leading positron and electron bunches are separated by a bend magnet at the end of the Linac, bent around two roughly circular transport lines, the Arcs, and brought into collision at the Interaction Point (IP). In the last 150 meters of beam line, the Final Focus, the beams are focused to micron size for collision. They then travel back through the opposite Final Focus and are extracted onto high power beam dumps. At the same time, two new bunches of electrons are produced by the polarized source and accelerated to 1.19 GeV into the north damping ring. The new positrons are transported back to the beginning of the linac where they are coaccelerated with the electrons and injected into the south damping ring, joining the positron bunch from the previous pulse. This cycle repeats 120 times a second.

IV. POLARIZATION

The SLC polarized electron source produces two bunches of $4.5\text{-}5.0\times10^{10}$ particles per pulse into the damping ring with a polarization of about 80% (Figure 3). Circularly polarized light from two YAG pumped Ti:Sapphire lasers strikes the photocathode producing a longitudinally polarized beam [7]. The polarization is rotated into the horizontal direction in the bending magnets of the linac-to-

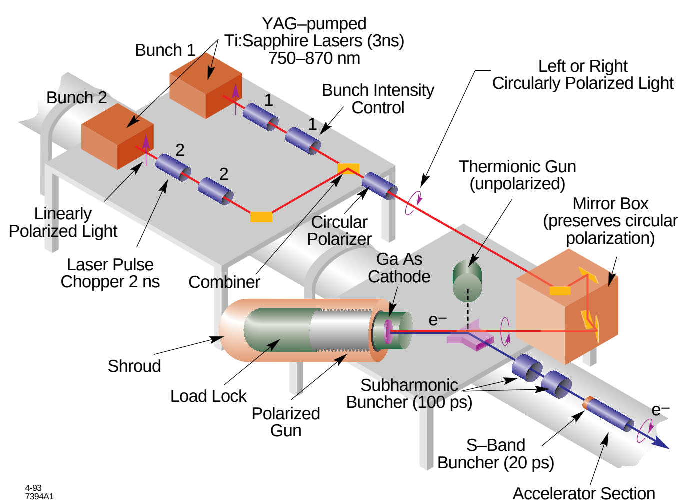

Figure 3: Schematic of the SLC polarized source with two YAG-pumped Ti:Sapphire lasers.

ring transfer line and then into the vertical by means of a solenoid spin rotator. The vertical spin is then preserved in the damping ring. Two additional spin rotators are installed in the ring-to-linac transfer line and at the entrance to the linac. These, coupled with the rotation of the transfer line, allow the spin to be oriented in an arbitrary direction in the linac. The spin is preserved in the linac, and then precesses through the bending magnets of the arcs to arrive longitudinally polarized at the IP. In 1992, tests with the first polarized electron beams revealed that the spin orientation was extremely sensitive to minor orbit changes through the arcs, due to a spin-betatron tune resonance. This problem was quickly turned into a ‘feature’, and since 1993, closed vertical bumps in the arc orbit have been used to orient the spin direction [8]. This allows operation with the additional two spin rotators off which was necessary to run ‘flat beams’, as the solenoids would couple the horizontal and vertical emittances. The polarization is measured continuously by a Compton polarimeter just downstream of the IP [9] (Figure 4).

Many years of development were required to overcome the technical challenges and produce a robust, reliable, high polarization electron source. A critical component is the strained lattice cathode development. In a conventional bulk GaAs photocathode, the laser light excites electrons from two degenerate energy levels. The electrons from these two levels have different polarizations which partially cancel, giving a maximum achievable polarization of 50%. For the strained lattice, a 100-300 nm layer of GaAs is grown on a GaAsP substrate. Because the GaAs layer is thin, its lattice distorts to match the GaAsP lattice. With long wavelength laser light (typically 865 nm), only one of the two energy levels is excited and polarization up to 90% is possible. The first strained lattice cathode used at the SLC had a 300 nm layer of GaAs and produced 60% polarization. In 1994, this was replaced with a thin 100 nm layer cathode with polarization up to 80% (Figure 5). To prevent contamination of these fragile cathodes and preserve high quantum efficiency, an ultra high vacuum load-lock and cathode transfer system were developed to permit the processing and changing of cathodes under vacuum. For 120 Hz operation, the system requires two YAG lasers running at 60 Hz each, which pump two high power Ti:Sapphire lasers to produce the two electron bunches. Numerous feedback systems are used to stabilize the beam intensity and laser steering, and for performance monitoring. The polarized source has proven very reliable with over 95% availability during several years of operation.

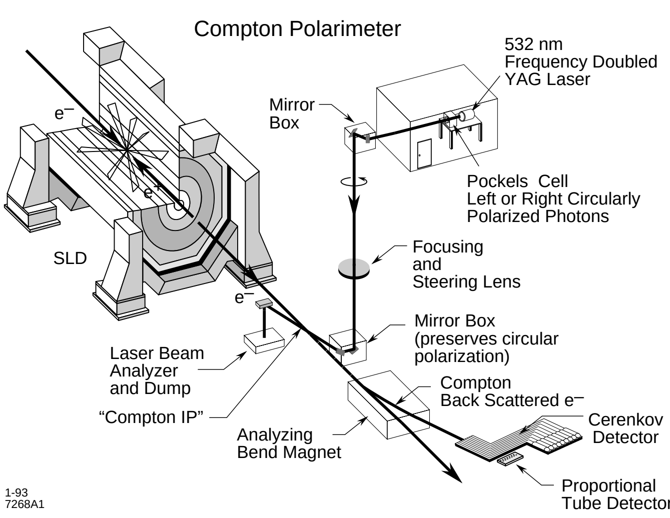

Figure 4: Schematic of the Compton polarimeter located near the SLC IP.

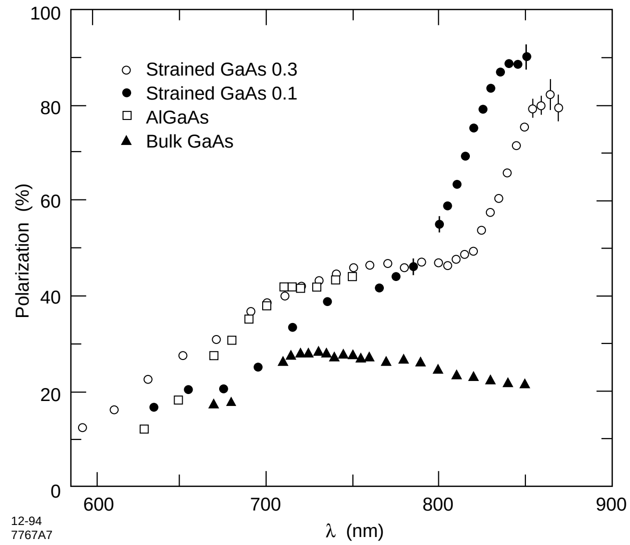

Figure 5: Polarization as a function of wavelength for different cathode materials. The SLC polarized source first used bulk GaAs, then 0.3 µm strained GaAs/GaAsP, and finally 0.1 µm GaAs/GaAsP with polarization of about 80%.

V. LUMINOSITY

In a linear collider, the luminosity depends on the beam intensities, transverse beam size, and repetition rate.

$$L \propto \frac{f\, N^+ N^-}{\Sigma_x \Sigma_y} H_d \qquad (1)$$

where L is the luminosity
f is the repetition rate
$N^{+/-}$ is the number of positrons/electrons per bunch
$\Sigma_{x/y}$ is the horizontal/vertical beam overlap size
H_d is the disruption enhancement

For small, intense, oppositely charged beams, there is an additional enhancement due to their attractive force which causes each beam to be focused by the field of the other. This phenomenon, called disruption or pinch effect, has been seen to increase the luminosity by more than 50%. To produce physics results, the collider must deliver high integrated luminosity. Operating efficiency depends not only on hardware availability but also on the speed and effectiveness of tuning techniques and on control of detector backgrounds. Improvements in SLC operating efficiency required development of precision diagnostics, robust tuning algorithms, and extensive feedback systems throughout the machine.

At the SLC, the repetition rate is 120 pulses per second. Only a single electron and positron bunch are accelerated each pulse. To increase the luminosity, one must either increase the beam intensity or decrease the beam size. The SLC designers assumed that the easiest path to higher luminosity was simply higher beam intensity. The SLC experience is exactly the opposite. Almost all of the luminosity gains in ten years of operation have come from progress in reducing the beam size. Each attempt to increase the beam intensity has uncovered numerous problems with stability and with emittance dilution due to wakefields. Even today, typical operating intensities are 3.5-4.0$\times10^{10}$, about half of the design value of 7.2$\times10^{10}$ This lesson was incorporated early on into the design of future e+/e- linear colliders all of which specify bunch intensities of about 10^{10}.

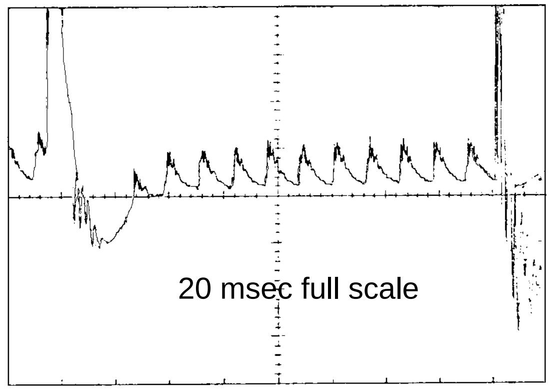

Figure 6: Illustration showing the evolution of bunch length during a damping ring cycle. The bunch damps after injection until the instability threshold is reached where it rapidly blows up. The longer bunch is then over threshold and begins to damp again.

VI. BEAM INTENSITY

The most significant limitation on the stable operating intensity of the SLC has been instabilities in the damping rings. In 1991, the intensity was limited by a •-mode instability which caused the two bunches to undergo synchrotron oscillations out of phase [10]. This was cured the next year by the installation of idling cavities, allowing the next problem, a microwave bunch lengthening instability, to receive full attention. This particular instability took several years to identify and diagnose and provides an illustrative example of the process of learning about a new type of accelerator. As early as 1989, during the Mark-II experiment, attempts were made to raise the intensity from 2.5 to 3.0$\times10^{10}$. This proved unsuccessful because occasional errant pulses, then called ‘flyer’ pulses, would be produced with such an abnormal energy or orbit that they would flood the detector with backgrounds and trip off the sensitive subsystems, requiring several minutes to recover. By 1991, in an effort to track down what caused these pulses at high intensity, it was observed that the phase of the beam on injection into the linac was correlated with its energy error. If one plotted phase versus energy for a large number of pulses, the points lay on a circle with the center completely depopulated. This was promptly nicknamed the ‘doughnut‘ effect and generated much theoretical speculation.

Finally in 1992, a new diagnostic allowed a measurement of the peak current in the bunch on each turn while the beam was stored in the damping rings. This signal, which is inversely proportional to the bunch length, quickly revealed the source of the problem. During the cycle, the bunch length decreases as the beam damps until a critical threshold is reached where an instability causes the bunch length to suddenly increase. The instability is self-limiting because once the bunch length is long enough, it becomes stable and begins to a damp again. This cycle would typically repeat several times before the beam was extracted, giving a ‘sawtooth’ profile to the bunch length signal [11] (Figure 6). The exact number of cycles is a sensitive function of the beam intensity so small fluctuations in intensity could cause the beam to be extracted just at the peak of the instability. These pulses would then enter the linac with the wrong phase with respect to the accelerating RF. The severe energy mismatch produced the infamous ‘flyer’ pulses. The instability is caused by the interaction of the intense bunch current with the wakefields generated by abrupt changes in the chamber diameter. To raise the instability threshold, new vacuum chambers were constructed for both damping rings with smooth transitions between different diameter pipes. These were installed in most of the rings for the 1994 run and the last few segments completed for 1996. The SLC now operates routinely with about 4.0$\times10^{10}$ per bunch, with the maximum beam intensity now limited by other wakefield and stability problems

VII. EMITTANCE

Emittance preservation is the key to high luminosity in a linear collider. To understand the issues, it is useful to identify three different mechanisms causing growth in the effective emittance of the beams. These can be characterized as phase space dilution, pulse-to-pulse instability, and phase space distortion. While the three categories necessarily overlap, somewhat different techniques are required to control each type of growth mechanism. With phase space dilution, the inherent emittance of the beam is increased irrecoverably, so these must be attacked at the source. Pulse-to-pulse or rapid fluctuations in the transverse or longitudinal properties of the beam can increase the effective emittance when integrated over an interval of time and must be minimized. Phase space distortion describes mechanisms which increase the projected emittance but in a correlated way which can potentially be canceled if the appropriate correction can be identified and applied. At the SLC, progress in controlling or eliminating the various sources of emittance growth has required the development of precision diagnostics to clearly characterize each problem along with appropriate correction techniques.

A. Phase Space Dilution

The most important sources of phase space distortion in the SLC occur early in the accelerator if there is a mismatch between the incoming beam and the optics of the beam line lattice. The low energy beam has a significant internal energy spread, and the lower energy particles will undergo betatron oscillations faster than the higher energy particles. If the beam is mismatched to the lattice, the slices of different energy filament resulting in a larger final emittance. This is important for injection into the electron damping ring and into the linac. The electron damping cycle is sufficiently short that a beam which filaments at injection will not have time to fully damp before extraction. At injection into the linac, it is necessary not only to beta-match the beam but also to cancel dispersion and chromaticity, including second order correlations.

The key to correctly matching the beam was the development of wire scanners which allowed a precise, rapid, non-invasive measurement of the beam profile. The first scanners were installed at the beginning and end of the linac in 1990 [12]. Four scanners separated in betatron phase provide a measurement of the beam emittance in a few seconds. The wires scan across the beam during a sequence of pulses scattering a small fraction of the particles on each pulse. Downstream detectors measure the number of scattered particles at each step to map out the beam profile. Wire scanners were absolutely essential for matching the positron beam into the SLC linac since invasive monitors like fluorescent screens would interrupt the electrons needed to produce more positrons. Today over 60 wire scanners are distributed throughout the SLC from the injector to the final focus to characterize the beam transverse size and energy distribution. Many of these are scanned routinely by completely automated procedures to provide real-time monitoring and long term histories of the beam properties.

To maintain the optical matching to high precision required not only the development of the measurement devices themselves but many iterations of refinements in the data processing algorithms. Typically four wires are used to provide a redundant measurement of the phase space. Non-Gaussian distributions require different fitting algorithms to parametrize the beam shape. Since a single measurement requires many beam pulses, it is essential to filter out errant data. Beam position monitors near the scanners are used to fit the trajectory on each pulse and correct the expected position of the beam with respect to the wire. Automated procedures require robust fitting algorithms with careful error analysis. Lastly, appropriate correction methods must be developed [13]. At the SLC, additional skew quadrupole, sextupole or octupole magnets were required in many places to provide the necessary correction tools. Future linear colliders have included precision diagnostics and correction elements in the design.

Another source of phase space dilution occurs when the beam passes off axis through the magnets of the lattice. Dispersive or chromatic correlations in the beam can filament like an initial mismatch. A variety of beam-based alignment techniques needed to be developed to find the magnetic centers to the required precision, typically tens to hundreds of microns. In general, these procedures are invasive and are used at the beginning of a run to set up the beam lines. Particularly challenging is the optical matching and alignment of the beam through the 1.2 km long collider arcs which transport the beam from the linac to the final focus. Due to physical constraints, the arcs are terrain-following (non-planar), making coupling a significant problem. Novel techniques for measuring and matching this complicated system were first developed in 1990 and continue to be refined. In addition to matching the optics and dispersion at the end of the arcs, a critical issue is the emittance growth due to synchrotron radiation, which only in 1997 has been reduced to near design values [14].

B. Stability

Pulse-to-pulse or short time scale fluctuations in the beam also cause growth in the effective beam emittance. Linear colliders are inherently less stable than storage rings and a variety of sources can cause variation in the beam properties on short time scales. Feedback systems are used extensively throughout the SLC to stabilize the beam, but they do not have the bandwidth to damp high-frequency or pulse-to-pulse changes. These variations can be caused by different sources such as collective instabilities in the damping rings, mechanical vibration, power supply regulation or wakefields. A technique suggested by Balakin, Novokhatsky and Smirnov, called BNS damping or autophasing, has been used successfully to reduce the sensitivity to these fluctuations at the SLC [15]. A correlated energy spread is introduced into the beam at the beginning of the linac such that the tail of the bunch has lower energy than the head and is overfocused by the lattice. Without BNS damping, the wakefield from the head of an off-axis bunch produces a kick on the tail which amplifies an incoming oscillation. Even with BNS damping, pulse-to-pulse jitter remains a problem.

Techniques were developed for correlating pulse-to-pulse fluctuations throughout the machine and tracking them back to their source. Collective effects such as Pi-mode or microwave instabilities in the damping rings cause pulse-to-pulse jitter in the beam and must be eliminated in the rings. Orbit oscillations in the 8-10 Hz range were caused by mechanical vibration of the quadrupole magnets in the SLC linac, and improved supports were required [16]. The pumps used for cooling water can induce vibrations near 59 Hz if not properly balanced and isolated. Poorly performing

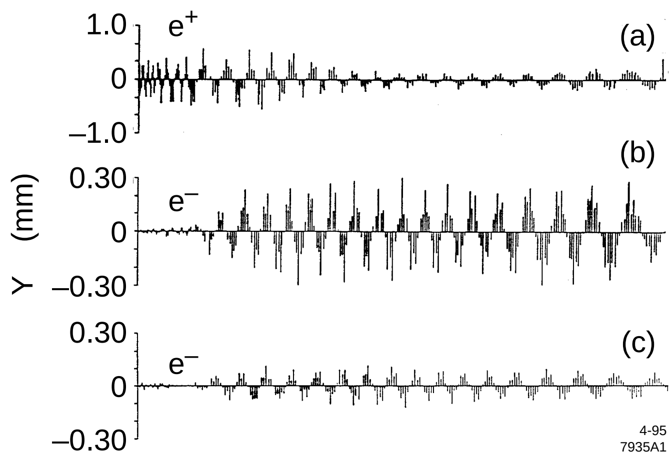

Figure 7: Trajectory oscillations showing the effect of long range transverse wakefields. An incoming oscillation of the positron beam (a) decreases in amplitude due to BNS damping but induces a large oscillation in the trailing electron beam due to the sum of wakefield kicks. (b) For the design lattice, the electron and positron tunes were equal and the kicks add in phase. (c) By splitting the tunes, the oscillation amplitude is reduced.

feedback systems have been seen to oscillate in the range of 1-2 Hz.

A particularly interesting problem was seen in 1995 when the rebuilt damping rings allowed higher beam intensity. Pulse-to-pulse trajectory jitter nearly equal to the beam size was seen on the electron beam by the end of the linac. Many possible mechanisms were considered including long range wakefields from the leading positron bunch. Calculations had predicted that this should not be a problem for the SLC parameters so the idea was initially rejected. However, measurements showed that the linac amplified incoming jitter by a factor of six, that the positron and electron jitter were correlated, and that the electron jitter decreased by a factor of two if the positrons were not present. These observations led to an experiment to actually measure the long range wakefields by observing the effect on the electron trajectory caused by an induced oscillation in the positrons. The result was dramatic (Figure 7). A 1 mm positron trajectory oscillation was reduced to 0.3 mm by the end of the linac due to BNS damping but caused an equal size oscillation in the electrons. New calculations quickly confirmed the observed effect. A partial solution was to modify the lattice so that the horizontal and vertical phase advance were not equal. Since these are interchanged for opposite sign beams, the electron and positron phase advance were no longer resonant, reducing the coupling by 30-50% [17]. This emphasizes the value of experience on an operating accelerator to complement theoretical simulations.

Another important lesson from the SLC experience is the crucial importance of feedback to reduce the inherent instabilities of a linear collider. Several generations of development were required to produce the flexible feedback systems used throughout the SLC [18]. Feedbacks control the beam energy and trajectory, stabilize the polarized source, and maintain and optimize collisions. The SLC has more than 50 feedback systems controlling over 250 beam parameters. These systems are essential for reliable operation of the accelerator and provide several less obvious benefits. Feedbacks compensate for slow environmental changes such as diurnal temperature drifts or decreasing laser intensity and provide a fast response to changes such as klystrons cycling. They facilitate smooth recovery from any interruption to operation. Feedbacks improve operating efficiency by providing uniform performance independent of the attention or proficiency of a particular operations crew. They also free the machine operators from routine tasks so they can concentrate on more subtle problems. An important benefit is that the feedbacks decouple different systems so that tuning can proceed non-invasively in different parts of the machine while delivering luminosity. Because they run continuously, they also provide a very powerful monitor of many aspects of the machine performance. Much of the SLC progress has come from using feedback to automate as many routine tuning operations as possible.

C. Phase Space Distortion

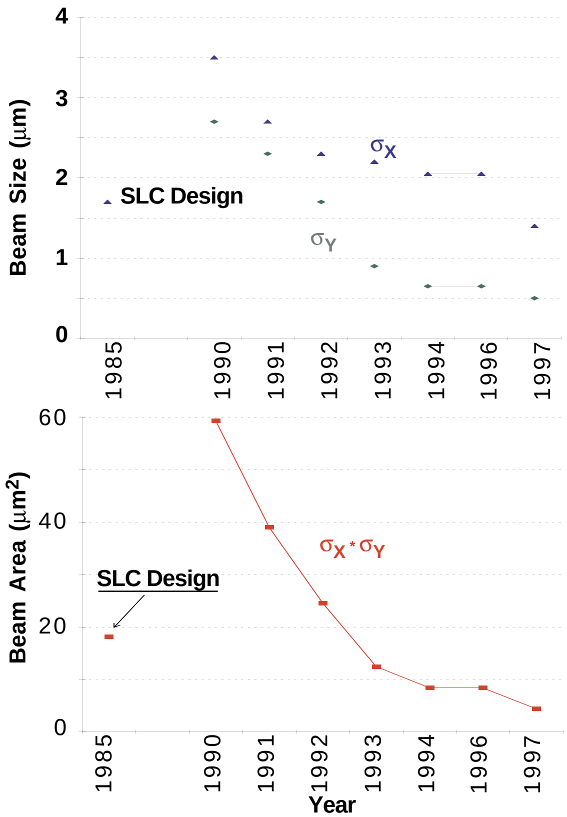

Figure 8: History of minimum beam size achieved at the SLC IP. The upper plot shows individual horizontal and vertical sizes. The lower plot shows the beam area, now less than one third of design. The decrease in 1993 came from 'flat beam' optics, in 1994 from the final focus upgrade, and in 1997 from stronger demagnification optics.

Perhaps the most interesting class of emittance growth can be described as phase space distortion where a correlation in the transverse or longitudinal phase space of the beam increases the projected emittance. Such correlations can, in principle, be corrected. The technique is to introduce an error which produces an opposite correlation, thus canceling the first error. A similar method of using an error to correct a residual error is also used for precision matching of the beam into the linac or rings. For a linear collider, one important mechanism for phase space distortion is wakefields. If the beam passes off-axis through the accelerating structure, the asymmetric wakefields from the leading particles cause a deflection in the trajectory of the later particles. BNS damping reduces the amplitude of the oscillation, but there is a residual correlation of transverse position along the length of the bunch. Simulations indicate that even when the beam is centered on the position monitor readings, wakefields from typical structure misalignments will increase the projected emittance by 100-600% if uncorrected [19].

The technique used at the SLC is to introduce a deliberate betatron oscillation to generate wakefield tails which compensate for those due to alignment errors [20]. Wire scanner measurements of the beam profile are used to characterize the wakefield tails, and then an oscillation is created by one of the linac trajectory feedbacks which is closed by the next feedback. Since 1991, this method has been applied with reasonable success using wires in the middle and near the end of the linac. One problem is that careful tuning is required to find the optimal phase and amplitude for the oscillation. The cancellation is also very sensitive to the phase advance between the source of the wakefield and the compensation so any change in the optics requires retuning. Simulations also showed that significant emittance growth could occur in the 200 m of linac downstream of the last wires. For the 1997 run, a different strategy was adopted. Wire scanners at the entrance to the final focus are used for tuning out wakefield tails to ensure that the entire linac is compensated. In addition, the induced oscillations are now made nearer the end of the linac where the higher energy beam is less sensitive to optics changes, making the tuning more stable.

VIII. OPTIMIZATION AT THE INTERACTION POINT

Another example of canceling phase space distortion is the final tuning of the beams at the interaction point (IP). At the IP, the tool for measuring the convolution or overlap of the two beam sizes is the beam-beam deflection scan [21] (Figure 9). Individual beam sizes can be measured by carbon wires located near the IP. They are used for initial tuneup with very low intensity beams, but they are too large to measure the submicron vertical beam size and too fragile to sustain full intensity. In a deflection scan, one beam is scanned across the other much as a wire is scanned across the beam. When the beams pass near each other, the attractive force between them causes a change in their trajectories which is proportional to the separation. Precision beam position monitors located near the IP measure the incoming beam position and angle and the deflection angle. A fit to the deflection angle as a function of separation gives an estimate of the overlap size of the two beams together, but not the individual beam sizes. Many iterations were required to refine the fitting algorithms, improve rejection of errant data, and devise a technique for correcting the effect of beam jitter on the measurement. For very small beams, the disruption, which is the focusing of one beam by the other, changes the deflection angle and must be taken into account. A simple fit assuming rigid beams would overestimate the beam size by 10-20%.

The beam-beam deflection angle is an extremely sensitive function of the distance between the beams and can also be used to keep the beams in collision. For typical beam sizes, the deflection angle changes by almost a milliradian per micron of beam separation. This provides a measurement of the inter-beam distance to a precision of tens of nanometers. It was anticipated that bringing the beams into collision and keeping them colliding would be one of the most difficult challenges of the SLC, but the resolution of the beam-beam

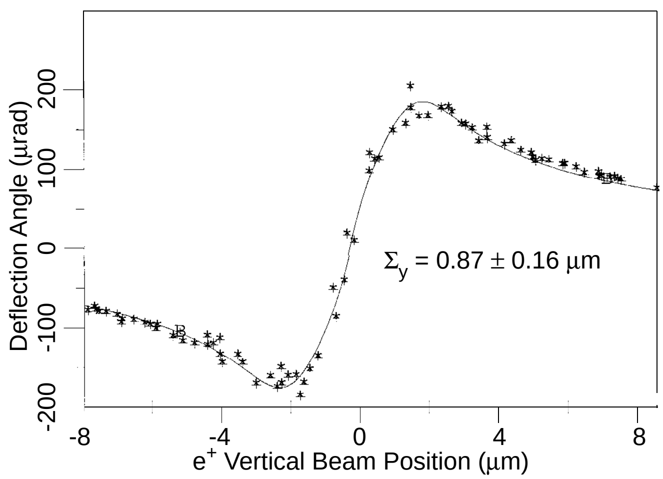

Figure 9: Beam-beam deflection scan measurement of less than 1 micron vertical beam overlap size. Individual beam sizes are 0.6 microns.

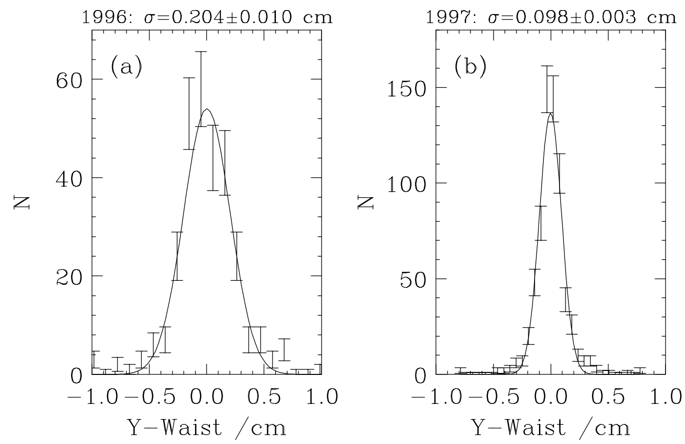

Figure 10: Distribution of incremental changes in the vertical waist position over a three month period (a) during the 1996 SLC run; (b) in the fall of 1997 with optimization feedback.

deflection made the problem easy. Feedback measures the deflections on every pulse and maintains collisions. The signal is strong enough that the feedback can reestablish collisions even if the beams are separated by more than 100 microns. Typically, operator intervention is needed only after a significant hardware modification or extended downtime.

To achieve the smallest possible beam size in collision, all longitudinal and transverse correlations must be removed. Parameters to be optimized include the position of the focal point or waist, coupling, dispersion and chromaticity. A total of ten parameters, five for each beam, are scanned routinely. It is essential that the optimization of these parameters be orthogonal for the procedure to converge. The correction schemes have evolved over the years with the addition of new devices to help ensure this orthogonality. Since the earliest SLC collisions, an automated procedure has been used to minimize the beam size as a function of each of the possible corrections [22]. This was adequate for many years, but it is slow and not sufficiently precise for optimizing very small beams. For the 1997 run, a new optimization feedback algorithm was developed which varies each parameter over a small range and then measures a large number of beam pulses, maximizing a signal proportional to the luminosity. Because of the better statistical sampling, the resolution has improved by more than a factor of two [23] (Figure 10).

One shortcoming of the beam-beam deflection as a diagnostic is that it measures only the overlap size of the two beams, making it difficult to identify which beam is too large. It is possible to estimate the individual beam sizes by fitting the distribution of the energy loss of both beams during a deflection scan [24]. To provide a more direct measurement of micron-size beams at nominal intensity, a laser wire beam size monitor was installed in 1996 [25]. This device places an optical scattering center inside the beam pipe 29 cm from the SLC IP. Light from a high power pulsed laser is brought to a focus of 400-500 nm on an optical bench at the laser IP. The e^+ or e^- beam is scanned across the laser spot and its shape reconstructed from the number of scattered particles at each step. The project was particularly challenging because of the inaccessible location inside the SLD detector. With no possibility of repair, great care was needed to prevent optical damage from the high power laser. In addition, the transport line and IP are in extremely cramped regions near and inside the detector, complicating design and construction. Early tests of the laser wire achieved a focus of 0.5-1.0 micron, but laser and beam jitter degraded the precision of the measurements. It is difficult to keep the sub-micron laser and beam colliding without the resolution of the beam-beam deflection, and more work is needed. The laser wire is a prototype beam size monitor which could be used for the micron-size beams in the main linacs of a future linear collider.

In the 1997-8 run, a significant luminosity enhancement due to disruption has been demonstrated for the first time (Figure 11). Some evidence for disruption was seen in earlier runs, but the results were inconclusive. As the beams collide, each beam is focused by the field of the other beam, causing the transverse size to shrink. If the focal length is shorter than the bunch length, the average transverse size seen by the other beam decreases, thereby increasing the luminosity. The magnitude of the disruption enhancement depends very sensitively on the bunch length as well as on the beam intensity and initial transverse size. Care must be taken to establish the optimum bunch length in the linac and to avoid energy correlations which cause the bunch length to be compressed in the arcs. There was evidence that poor control of the bunch length in 1996 resulted in a positron beam which was too short for optimal disruption. An additional bunch length diagnostic installed near the IP has allowed tighter control of this critical parameter, and a luminosity enhancement of 50-100% has been observed.

IX. SUMMARY

More than ten years of SLC operation has produced much valuable experience for future linear colliders. Because it lacks the inherent stability of a storage ring, a linear collider is a much more difficult machine, at least for this generation of control systems. Significant progress has been made on precision diagnostics for beam characterization and on flexible, intelligent feedback systems. New techniques for optical matching, beam-based alignment, and wakefield control have been developed and refined. The beam-beam deflection has become a powerful tool for stabilizing and optimizing collisions. Important lessons have also been learned on background control and collimation and on many other issues not discussed in this paper. Both the SLC and future collider designs have been enhanced by the intense exchange of ideas and experiments. The dramatic increase in luminosity during the last year demonstrates that the SLC remains on a steep learning curve and has not yet exhausted its potential.

The most enduring lesson from the SLC is undoubtedly that any new accelerator technology will present unanticipated challenges and require considerable hard work to master. Once a technology becomes routine, it is easy to forget the initial effort that was required. At the SLC as elsewhere, the most difficult problems were almost always those which were not expected. It is also clear that the experience gained on an operating accelerator is complementary to that from demonstration projects. The discipline of trying to produce physics forces one to confront and solve problems which are not relevant otherwise. The SLC now operates at near design luminosity due to the creativity and dedication of a large number of people over many years who deserve the credit for this success.

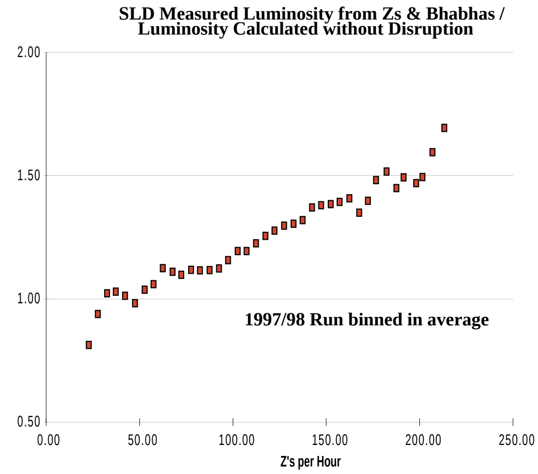

Figure 11: The ratio of luminosity measured by the SLD to the luminosity calculated from beam sizes and intensity alone, assuming no disruption

X. REFERENCES

[1] B. Richter, The SLAC Linear Collider, Geneva Accel. Conf. 1980:168.

[2] Zeroth order design report for the Next Linear Collider, SLAC pub, 1996, 2 vol..

[3] C. Adolphsen et al., Flat beams in the SLC, IEEE PAC 1993:2019-2021.

[4] T. Maruyama et al., Electron spin polarization in photoemission from strained GaAs grown on GaAsP, Phys.Rev.B46:4261-4264,1992.

[5] F. Zimmermann et al., Performance of the 1994/1995 SLC final focus system, IEEE PAC 1995:656-658.

[6] R. Erickson, (Ed.), SLC Design Handbook, SLAC pub 1994.

[7] H. Tang et al., The SLAC polarized electron source, IEEE KOELN 1995, Proc.

[8] T. Limberg et al., The North arc of the SLC as a spin rotator, IEEE PAC 1993:429-431.

[9] SLD Collaboration, The scanning Compton polarimeter for the SLD experiment, SPIN96:843-845.

[10] Y-C. Chao et al., Damping the • mode instability in the SLC damping rings with a passive cavity, Int. J. Mod. Phys. A, Proc. Suppl. 2B, 1993:1118-1120.

[11] K. Bane et al., High intensity single bunch instability behaviour in the new SLC damping rings, IEEE PAC 1995:3109-3111.

[12] M. Ross et al.., Wire scanners for beam size and emittance measurements at the SLC, IEEE PAC 1991:1201-1203.

[13] C. Adolphsen et al., Chromatic correction in the SLC bunch compressors, IEEE PAC 1991:503-505.

[14] N. Walker et al., Correction of the first order beam transport of the SLC Arcs, IEEE PAC 1991:2500-2502.

[15] V. Balakin et al., VLEPP: Transverse beam dynamics, Batavia Proc. High Energy. Accel., 1993.

[16] J. Seeman et al., Induced beam oscillations from quadrupole vibrations in the SLC linac, IEEE PAC 1993:3564-3566.

[17] F.J. Decker et al., Long Range Wakefields and split tune lattice at the SLC, LINAC 1996:140-142.

[18] T. Himel et al., Adaptive cascaded beam based feedback at the SLC, IEEE PAC 1993:2106-2108.

[19] R. Assmann et al., LIAR: A computer program for the modeling and simulation of high performance linacs, SLAC pub, 1993.

[20] J. Seeman et al., The introduction of trajectory oscillations to reduce emittance growth in the SLC Linac, HEACC92 Proc. vol. 2 879-881

[21] P. Bambade et al., Observation of beam-beam deflections at the interaction point of the SLAC linear collider, Phys. Rev. Lett. 62:2949, 1989.

[22] W. Koska et al., Beam-beam deflection as a beam tuning tool at the SLAC linear collider, Nucl. Instrum. Meth. A286:32, 1990.

[23] P. Emma et al., Limitations of interaction point spot size tuning at the SLC, IEEE PAC 1997.

[24] P. Raimondi et al., Individual beam size and length measurements at the SLC interaction point derived from the beam energy loss during a beam-beam deflection scan, IEEE PAC 1997.

[25] T. Kotseroglou et al, A laser heterodyne bunch length monitor for the SLC interaction point, IEEE PAC 1997.

Alternate Approaches To Future Electron-Positron Linear Colliders

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I. INTRODUCTION

The purpose of this article is two-fold: to review the current international status of various design approaches to the next generation of e^+e^- linear colliders, and on the occasion of his 80th birthday, to celebrate Richard B. Neal's many contributions to the field of linear accelerators. As it turns out, combining these two tasks is a rather natural enterprise because of Neal's long professional involvement and insight into many of the problems and options which the international e^+e^- linear collider community is currently studying to achieve a practical design for a future machine.

The specific challenge before today's accelerator physicists and engineers is to produce a robust design for an affordable e^+e^- linear collider with a center-of-mass energy starting at 500 GeV and a luminosity of at least $5\mathrm{x}10^{33}$ cm^{-2} s^{-1}, later expandable to energies of 1 TeV and possibly beyond.[1] The particle physics community has been greatly interested in such a collider for some years, and this interest has grown with the decision to proceed with the LHC at CERN. Indeed, these two machines are highly complementary in what they can contribute to the field. The linear collider will be a precision tool to study $t\bar{t}$ production at threshold and above. If the Higgs and/or supersymmetric particles exist, the linear collider will be instrumental in discovering and/or studying them. If none of these particles exist, the machine will make it possible to explore other mechanisms to explain electroweak symmetry breaking. These are some of the most burning issues to be elucidated in the next few years. The e^+e^- linear collider also has the potential of producing exciting physics from e^-e^-, $e^-\gamma$ and $\gamma\gamma$ collisions, and of involving other applications such as FEL's and other technologies.

II. DESIGN REQUIREMENTS AND CONSTRAINTS

The design of e^+e^- linear colliders is complex because it involves a large number of interacting parameters and requires that many of the technologies necessary to build the machine be stretched beyond their current state-of-the-art. Despite this complexity, only a few mathematical expressions are really needed to spell out the design requirements. The first one is the formula which gives the luminosity L as

$$L = f_{rep}\, n_b \frac{\mathrm{N}^2}{4\pi\sigma_\mathrm{x}^*\sigma_\mathrm{y}^*} H_D \tag{1}$$

in terms of the linac repetition rate f_{rep}, the number n_b of bunches per rf pulse, the number N of particles per bunch, the horizontal and vertical beam dimensions σ_x^* and σ_y^* at the final focus, and the pinch enhancement factor H_D which depends on the disruption D. The above expression can be rewritten as a function of three terms:

$$L = \frac{N}{\bar{\sigma}_x^*}\, \frac{1}{4\pi E}\, \frac{f_{rep}\, n_b N E}{\bar{\sigma}_y^*} \tag{2}$$

where E is the single beam energy, and the $\bar{\sigma}_x^*$ and $\bar{\sigma}_y^*$ include the dimensional averaging due to all final focus effects, namely pinch, hour-glass effect and crossing angle. For flat beams, which are the most likely to meet the ultimate specifications, the first term is more or less fixed because it is a measure of the magnetic field around the bunch and it is directly proportional to the number of synchrotron radiation gammas generated in the beam-beam interaction, which in turn can produce deleterious background $e^\pm$ pairs. The second term is simply inversely proportional to E. The third term is the ratio of single beam power P_B to beam height at the final focus. From the previous speaker[2], we have learned that the SLC beam power is roughly 40 kW/beam for a luminosity approximately 5,000 times smaller than that of the future collider. Since its energy must be at least five times greater, this means that the ratio $P_B / \bar{\sigma}_y^*$ must be made about 25,000 times greater. Hence, for example, for a value of P_B 125 times greater (~5 MW), a value of $\bar{\sigma}_y^*$ 200 times smaller (~4 nm), must be obtained. As we shall see, this choice is very close to that made by some of the designers. Unlike the SLC which produces only one bunch per rf pulse, the larger beam power will be achieved with about 100 bunches/pulse. This choice, as we shall see, brings with it a number of complications.

The second fundamental expression is simply the formula which gives the required beam energy (or voltage) V as

$$V = \left(\bar{E}_o - ki\right)L \tag{3}$$

where $\bar{E}_o$ is the average unloaded gradient in the linac, i is the steady-state beam current, k is a constant, and L is the active length of the machine. $\bar{E}_o$ in turn can be written as

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

$$\overline{E}_o \sim \sqrt{\frac{nP_0\bar{r}}{L}} \tag{4}$$

where n is the number of rf feeds, P_0 is the peak power per feed and $\bar{r}$ is the average shunt impedance per unit length. As it turns out, the detailed derivation of Equations (3) and (4), and how to use them optimally in a practical linac, were the subject of many of Neal's seminal publications.[3-18] To attain gradients on the order of 20-100 MV/m over 5-30 km lengths typically requires a total of approximately half a million peak megawatts to be supplied to room temperature linac structures.

The third and last expression of importance is the formula relating the rms beam size at the final focus to the emittance $\varepsilon_{x,y}$:

$$\sigma_{x,y} = \sqrt{\beta^*_{x,y}\varepsilon_{x,y}} \tag{5}$$

where $\beta^*_{x,y}$ denotes the betatron functions at the interaction point. Because of the hour-glass effect, the bunch length must not be greater than β^*_y (for flat beams, it is assumed that $\sigma_y << \sigma_x$). From what has been learned at the SLC[2], creating small emittances at the beginning of the machine by means of damping rings, and then preserving or limiting the growth of these emittances throughout the linacs and beam delivery systems is one of the essential challenges for all designs described below. Three major factors cause emittance growth beyond the point of low emittance production: single-bunch wakefields, multibunch wakefields, and filamentation due to dispersion. Single-bunch wakefields scale roughly as a^{-3} where a is the disk aperture radius of the structure. They favor low frequency linacs and can be controlled by good alignment and BNS damping[2]. Multibunch wakefields are caused by the same cumulative higher-order mode kicks which produced the beam-breakup effect[9,10,11,16] discovered at SLAC in 1966 when the 3 km-long accelerator was turned on and the bunches ultimately hit the disk irises. This effect can now be controlled by designing structures which both detune the higher-order modes and damp them by letting them dissipate outside of the structure, via four manifolds and/or loads [19,20]. The wakefields can also be controlled by tightening all alignment tolerances on structures and quadrupoles. The third effect, filamentation due to dispersion, is caused by the fact that particles with different energies undergo different focusing forces (i.e., the quadrupoles have different focal lengths) and result in different rates of rotation of the transverse phase space ellipses along the linac. This third effect, as well as the second, have received great attention during the past four years and their phenomenology and control are discussed in Ref. 21.

A. Choice of Linac RF Frequency

A few years ago [22], it was thought that more efficient new technologies would emerge which might supplant conventional rf linacs. This, however, has not happened. All the projects currently under design use rf for acceleration, and all except one use conventional power sources. If perhaps somewhat disappointing, this speaks well for the fifty-year vitality of the rf approach. The next fundamental question that must be answered is: "What should this rf frequency be?" Interestingly enough, this question is one that Neal posed for the SLAC accelerator forty years ago, and it is summarized in his discussion in the SLAC Blue Book [Ref. 3, pages 96-99], reproduced here because many of the same issues are still valid today (see quote below and Table I).

"Since r_0 varies as $f^{1/2}$, the rf power required to produce a given final energy in a fixed length is proportional to $f^{-1/2}$. Thus, considerations of power economy indicated that the operating frequency should be as high as possible. Other advantages of the higher frequencies are the reduced filling time, which varies as $f^{-3/2}$, and reduced energy storage, which varies as f^{-2}. A shorter filling time is advantageous since electrons can be accelerated during a larger fraction of the available rf pulse length. The use of the higher frequencies also results in greater maximum field strength (as limited by breakdown) and larger relative frequency and dimensional tolerances.

From Table I it can be seen that the maximum frequency which can be used is limited by the diameter of the aperture available for the beam and by the reduced beam current capability. Another factor against the use of very high frequencies is the increased number of power sources and feeds required. The increased cost of additional rf systems, modulators, and controls, and the increased operational difficulties which are encountered tend to offset the advantages arising from decreased power consumption at high frequencies.

An important consideration not taken into account in Table I was the degree of conservatism involved in the choice of frequency band. Although linear accelerators had been constructed and operated at L-, S-, and X-bands, the largest amount of experience was available at S-band. In fact, to this date all accelerators of this type having energies about 100 MeV have operated at S-band."

Indeed, had rf technology not progressed at all in the last 30 years, the S-band approach would still be the most if not the only logical one today. Three important developments, however, have taken place in the meantime: 1) rf superconductivity has made great strides, as a result of which 25 MV/ m gradients are now thinkable, 2) high power klystrons up to X-band have been developed, and 3) two-beam accelerator concepts and very sophisticated alignment techniques have made very high rf frequency machines with thousands of feeds and only two drive-beams (rather than many thousands of klystrons) more plausible. As we shall see below, each of these developments has opened a new niche which one of the alternate design approaches has now occupied.

Table I. Frequency Dependence of Principal Machine Parameters

Parameter	Frequency Dependence	Frequency Preference High	Frequency Preference Low	Notes
Shunt Impedance per unit length (*r*)	$f^{1/2}$	X		a
RF loss factor (*Q*)	$f^{-1/2}$		X	a
Filling time (t_F)	$f^{-3/2}$	X		a, b
Total rf peak power	$f^{-1/2}$	X		a, b, c
RF feed interval (*l*)	$f^{-3/2}$		X	a, b
No. of rf feeds	$f^{3/2}$		X	a, b, d
RF peak power per feed	f^{-2}	X		a, b, c
RF energy stored in accelerator	f^{-2}	X		a, b, c
Beam loading (*-dV/di*)	$f^{1/2}$		X	a, b, d
Peak beam current at maximum conversion efficiency	$f^{-1/2}$		X	a, b, c, f
Diameter at beam aperture	f^{-1}		X	a
Maximum rf power available from single source	f^{-2}		X	e
Maximum permissible electric field strength	$f^{1/2}$	X		g
Relative frequency and dimensional tolerances	$f^{1/2}$	X		a, b
Absolute wavelength and dimensional tolerances	$f^{-1/2}$		X	a, b
Power dissipation capability of accelerator structure	f^{-1}		X	a, b, d

Notes:

a. For direct scaling of modular dimensions of accelerator structure.

b. For same rf attenuation in accelerator section between feeds.

c. For fixed electron energy and total length.

d. For fixed total length.

e. When limited by cathode emission.

f. When limited by beam loading.

g. Approximate; empirical.

B. Machine Parameters and Designs

Generically, an e^+e^- linear collider consists of electron and positron sources, pre-linacs, damping rings, main linacs, beam delivery systems (transport magnets, collimators and demagnifying optics) and interaction regions where the physics detectors are to be located (see Fig. 1). For much of the material presented below, the author is indebted to over fifty of his colleagues who co-authored the International Technical Review Committee (ILC-TRC) report (Ref. 1), and many other colleagues who work in the field to advance their respective collider designs. As their work evolves, essential information is updated and can be found on the Web at (http://www.slac.stanford.edu/xorg/ilc-trc/ilc-trchome.html).

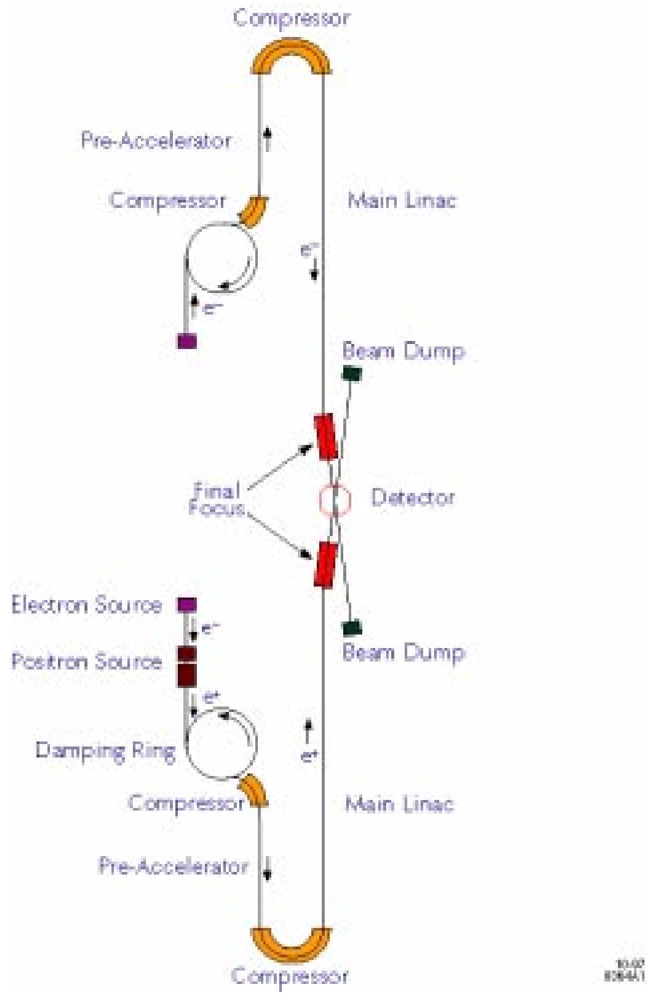

Figure 1. Layout of a Generic e^+e^- Linear Collider

The machines described below and listed in Table II with their corresponding test facilities are divided into four groups in order of ascending main linac rf frequency: 1) TESLA, 2) SBLC, JLC(C), 3) JLC(X), NLC(X) (with its future TBNLC option), VLEPP, and 4) CLIC. The main specifications of these machines are outlined in Table III for the initial 500 GeV c.m. energy stage. The building blocks of the main linac "power units" for these projects are shown in Fig. 2. Because of the large quantities of identical components involved, the design, engineering, mass production, cost and reliability of operation of these "power units" are crucial to the success of whichever linear collider ultimately gets selected and built.

C. TESLA (Group 1)

This machine is in a category by itself because it is the only one that uses superconducting accelerator sections for the main linacs. The rf frequency is the lowest (1.3 GHz) and the beam aperture is the largest (2a = 7 cm). All the characteristics of TESLA result from these basic features. The advantages are that the rf pulse is long, the bunch spacing is wide (708 ns), the transverse wakefields are weakest, and corresponding alignment tolerances are loosest (by at least a factor of 5 for multibunches). As a result,

Table II. Linear Collider World Picture

LINEAR COLLIDER DESIGN STUDIES	"HUB" LABORATORIES	CORRESPONDING TEST FACILITIES
TESLA	DESY	TESLA Test Facility
SBLC	DESY	S-Band Test Facility
JLC(C)	KEK	RF SYSTEMS
JLC(X)	KEK	Accelerator Test Facility
NLC(X)	SLAC	SLC, FFTB, NLC Test Accelerator
	LBNL, LLNL	Relativistic Two-Accelerator Test Facility
VLEPP(J)	BINP	VLEPP Test Facility
CLIC	CERN	CLIC Test Facility

Table III. Overall Linear Collider Parameters Starting at a Center-of-Mass Energy of 500 GeV

	TESLA	SBLC	JLC(C)	JLC(X)	NLC	VLEPP	CLIC
f_{rf} (GHz)	1.3	3	5.6	11.4	11.4	14	30
$L(cm^{-2}\,s^{-1})\times 10^{33}$	6	5.3	7.2	6.1	5.3	9.7	4.9
f_{rep} (Hz)	5	50	100	150	120	300	500
n_b	1130	333	72	85	81	1	60
Bunch Spacing(nsec)	708	6	2.8	1.4	2.8	-	.67
$N(10^{10})$	3.63	1.1	1.1	.7	.9	20	.4
P_B/beam (MW)	8.2	7.25	3.1	3.6	3.5	2.4	4.9
σ_x^* (nm)	845	335	318	260	303	2000	206
σ_y^* (nm)	19	15.1	4.3	3.1	6.1	4	5.4
σ_z^* (μm)	700	300	200	90	125	750	50
Active L (km) 2 Linacs	20.4	30	15	8.7	8.2	5.8	5.1
Loaded Gradient(MV/m)	25	17	33	56	55	78	100
Number of Klystrons	616	2517	4184	4400	3030	1400	2 drive linacs

emittance growth is easiest to control. Ground motion effects may be compensated by fast feedback controls and by bunch-to-bunch steering at the end of each linac. At a repetition rate of 5 Hz, σ_y^* must be 19 nm to achieve the desired luminosity. The biggest challenge for TESLA is to perfect the rf superconducting technology to the point where accelerating gradients of 25 MV/m can be attained reliably with Q_0 's of at least 5×10^9, and where costs can be made affordable. As this article is being prepared, the TESLA superconducting cavities are undergoing a shape-redesign[23] which is expected to greatly enhance their performance and lower their cost. The main linacs consist of 616 power units (see Fig. 2), each involving a pulsed modulator supplying an 8 MW peak power klystron which in turn drives 32 one-meter long superconducting structures in four long cryostats, incorporating higher-order modes couplers and quadrupoles. Related requirements are the compensation of the mechanical cavity detuning due to the Lorentz force, the absolute need to suppress field emission to avoid heat losses and captured dark current, the construction of the rf coupler, and alignment of components within the cryostats. The electron bunch train can be produced from a laser-driven gun but the positron bunch train is too intense for a conventional target to survive. Hence, the intent is to shoot the spent e^- beam after the IP through an undulator to produce γ's which then produce positrons in a thin rotating target. The 32 km damping rings (often called dog-bones because of their elongated shape with bulges at the ends) must be designed to accept and damp each long train of bunches (240 km) in a "compressed" circumference (17 km). Finally, since the main linacs are already very long (32 km total), the expandability to 1 TeV c.m. energy will preferably be achieved, at least in part, by an increase in gradient (say 40 MV/m). Such a gradient will require an additional 25% increase in length to 40 km. The desired luminosity at 1 TeV can be reached with a σ_y^* of 6.5 nm and a beamstrahlung parameter, δ_B , of 2.5%.

D. SBLC and JLC(C) (Group 2)

SBLC, much like the original SLAC linac, benefits from the most widespread and proven technology developed at Stanford and elsewhere for many years. Roughly speaking, its main linacs are together equivalent to 10 SLAC linacs. SBLC has the next-to-largest σ_y^* (15 nm) after TESLA and gets its luminosity at 50 Hz repetition rate with 333 bunches per pulse spaced 6 ns apart, and 1.1×10^{10} particles per bunch. The corresponding power unit is shown in Fig. 2. Because of multibunch operation, the accelerator structures are designed to detune and damp transverse wakefields. These structures have been tested in 6 m-long sections with two sets of higher-order mode couplers along their length, which can also be used as pick-ups to align the sections by minimizing beam induced fields. Sputtering of a 20 μm-thick low conductivity material onto the disk edges is also being used to differentially reduce the Q of undesirable modes by a factor of 5 without affecting the Q of the fundamental mode by more than 5%. Initial alignment tolerances are on the order of 100 μm and sections must be mounted on girders to within a tolerance of about 30 μm

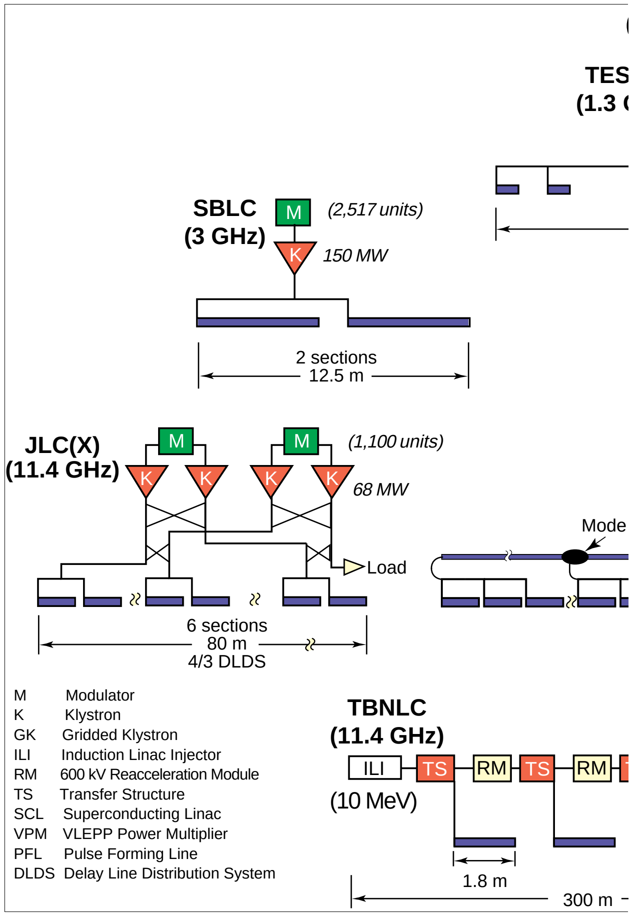

Figure 2. Main linac power units for 500 GeV c.m. energy.

rms. The electron and positron sources for SBLC are similar to TESLA's. The energy of the damping rings is 3.15 GeV. Extension to 1 TeV for SBLC is envisaged by doubling the number of klystrons and adding rf pulse compressors to double the gradient within the original machine length.

JLC(C) was not considered in any detail in the original TRC report because experimental work at C-band had not yet started at KEK at the time. Since then, an active R&D program has been launched on the rf components, including a 50 MW peak power klystron, a choke-mode type, 1.8 m-long accelerator structure and a multicell coupled cavity system for a short so-called SLED III pulse compressor.[20] The choke-mode structure eliminates the multibunch wakefield problem and has an alignment tolerance of 30 µm. The beam characteristics are similar to those of the X-band designs below, except for a longer bunch length. Extension to 1 TeV c.m. energy would be obtained by doubling the klystron output power to 100 MW and increasing the length of the main linacs by 40%.

E. JLC(X), NLC and VLEPP (Group 3)

Although VLEPP is designed for 14 GHz while JLC(X) and NLC use 11.4 GHz for their main linacs, these three machines can be described in a single group because of their technological similarities. JLC(X) and NLC have similar luminosities, repetition rates, numbers of bunches per pulse and charges per bunch. The σ_y^* at the IP for JLC(X) is 3 nm whereas that for NLC is about 6 nm, but this difference does not arise from any fundamental differences in design. There is also a slight difference in σ_z^*, and the proposed crab-crossing angle at the IP is greater for NLC than for JLC(X). It is now proposed that both machines use the delay line distribution system (DLDS) suggested by KEK to enhance peak rf power.

The difference between the two rf layouts shown in Fig. 2 is likely to disappear in the near future when the designs of the two laboratories become unified through mutual collaboration. The NLC klystron is planned to be a 75 MW tube with periodic permanent magnet (PPM) focusing, which is currently being tested successfully at SLAC. The JLC klystron will probably be similar. R&D toward efficient and simplified modulators is crucial for eventual economy of electric power and manufacturing costs. For accelerator structures, NLC will use sections in which transverse deflecting modes are both detuned (within a Gaussian distribution) and damped to a Q of about 1000 (by coupling to four external parallel rectangular matched manifolds and loads)[19]. First tests of this so-called DDS structure indicate that its fabrication can be achieved successfully by diffusion bonding of cups with cell-to-cell alignment better than

4 μm. The electron bunch trains for both machines will be produced by laser-driven photocathode guns, and the positrons by improved SLC-type sources, in combination with various L–band and/or S-band pre-accelerators. The pre-damping and damping ring energies are all at about 2 GeV.

VLEPP, which unfortunately is currently an unfunded R&D project, is based on a design with a single bunch per rf pulse which does away with the multibunch wakefield problem. This design must get its luminosity from a much greater charge per bunch (2 x 10^{11} particles) which unfortunately leads to very high backgrounds. The VLEPP rf power unit can also be seen in Fig. 2. In theory, it leads to a loaded gradient of 78 MV/m.

For extension to 1 TeV c.m. energy, JLC(X), VLEPP and NLC would all achieve this goal by doubling their number of klystrons and active length. Alternatively, if the TBNLC (two-beam) technology to be developed at LBNL and LLNL and based on drive beams accelerated by induction linacs, were to become successful in the future, the NLC could have its array of klystrons, modulators and rf pulse compressors replaced by 64 sequential drivers, each 300 meters long (see Fig. 2) with reacceleration modules to keep them at 10 MeV energy, and transfer structures to supply the individual linac structures with the desired rf pulses.

F. CLIC (Group 4)

CLIC occupies a unique position in parameter space. The IP spots are similar to those in Group 3. The machine is characterized by the highest linac rf frequency, highest dark current capture field and potentially highest gradient. It requires many innovations, has the strongest wakefields, and therefore the tightest fabrication and alignment tolerances. The rf power is generated by an intense drive beam, accelerated by LEP-type superconducting structures, which induces the power in special transfer structures. The challenge of producing thousands of klystrons, modulators and rf pulse compressors is replaced by having to create two 3 GeV high-current drive beams with a bunch time structure capable of generating rectangular rf pulses at 30 GHz. The problem of producing these very high average power (~ 40MW) drive beams and then conserving their phase space qualities along the length of the linacs is a major challenge. (A recent proposal suggests that each drive beam be subdivided into 4 or 8 sequential beams to decrease their average power.)

An advantage of the CLIC two-beam scheme is that it allows most of the components to be housed in one tunnel. The front-end of the main e^+e^- beam generation is analogous to the front-end of the SLC. A number of design features of these drive and main beams remain to be elucidated, particularly for 60 bunches/pulse operation, which has been chosen to bring the luminosity up within the range of the other machines. For 1 TeV c.m. energy, both the drive and main linacs would be doubled in length.

III. CONCLUSIONS

Because of time and space constraints, there are many topics that cannot be reviewed in this paper. Worldwide investment in this field is spawning a vast amount of new knowledge and technologies. The SLC and the FFTB at SLAC, and the new test facilities at DESY, KEK, SLAC, CERN and LBNL are contributing to an explosion of R&D. New laser-driven photocathode electron sources with 80% polarization have become a reality, and new positron sources and pre-linacs are undergoing design. The very small emittances that must be created by the damping rings and preserved through the bunch compressors, main linacs, beam delivery systems and final foci are giving rise to new ideas about instrumentation, alignment, stability, collimation and beam containment. New insights are being gained into beam dynamics (dispersion-free and wakefield-free steering, transient beam loading) and into the important field of ground vibrations over a wide range of frequencies (10^{-2} to 10^{+2} Hz) and coherence lengths. Huge progress is being made through the availability of numerous beam and microwave simulation codes and practical feedback systems. Finally, a whole new approach towards design for manufacturing (DFM) to decrease mass production costs while preserving tolerances, cleanliness to avoid field emission and dark current, high vacuum conditions, and above all, reliability of operation, is being introduced into the field of accelerator fabrication and pricing. Highlights of how the accelerator physicists and engineers who have adopted the X-band approach at KEK and SLAC are coping with all these problems is described in the next article.[24]

Just like in 1957, forty years ago when the first proposal for SLAC was being published [25], it will be fascinating to see if, how and when the international accelerator community converges on a practical design for an e^+e^- linear collider and manages to implement its construction, hopefully in an optimized, harmonious and adequately-funded manner.

REFERENCES

1 **International Linear Collider Technical Review Committee Report**, SLAC–R–95–471, ed., G.A. Loew. Stanford: Stanford Linear Accelerator Center, 1995.

2 **Lessons Learned from the SLC**, N. Phinney. Talk given at the R.B. Neal Symposium. Stanford: Stanford Linear Accelerator Center, September 1997.

3 **A High Energy Linear Electron Accelerator, M.L. Report No. 185,** R.B. Neal. Stanford University: Microwave Laboratory, 1953.

4 **Stanford High-Energy Linear Electron Accelerator (MARK-III)**, W.K.H. Panofsky, R.B. Neal, et al. *Review of Scientific Instruments*, 26:134, 1955.

5 **Design of Linear Electron Accelerators with Beam Loading, M.L. Report No. 379**, R.B. Neal. Stanford University: Microwave Laboratory, 1957.

[6] **Transient Beam Loading in Linear Electron Accelerators, M.L. Report No. 388**, R.B. Neal. Stanford University: Microwave Laboratory, 1957.

[7] **Theory of the Constant Gradient Linear Electron Accelerator, M.L. Report No. 513**, R.B. Neal. Stanford University: Microwave Laboratory, 1958.

[8] **Comparison of the Constant Gradient and Uniform Accelerator Structures, M Report No. 259**, R.B. Neal. Stanford University: W.W. Hansen Laboratories of Physics, 1961.

[9] **The SLAC Accelerator: First Year of Operation**, SLAC-PUB-0351, G.A. Loew, R.B. Neal, E.J. Seppi. Stanford: Stanford Linear Accelerator Center, 1967. Presented at the Sixth International Conference on High Energy Accelerator, September 1967.

[10] **Completion of Construction and Initial Operation of the SLAC Accelerator**, R.B. Neal. Published in *IEEE Transactions on Nuclear Science*, 14:705-719, 1967.

[11] **The Stanford Two-Mile Linear Accelerator**, R.B. Neal, et. al. New York: W.A. Benjamin, 1968.

[12] **Sample Parameters of a 2-Mile Superconducting Accelerator**, SLAC-PUB-0438, R.B. Neal. Stanford: Stanford Linear Accelerator Center, 1968. Presented at the 1968 Summer Study on Superconducting Devices and Accelerators at BNL, June-July 1968.

[13] **Consideration of the Use of Feedback in a Traveling Wave Superconducting Accelerator**, TN-68-1, R.B. Neal. Stanford: Stanford Linear Accelerator Center, 1968.

[14] **Feasibility Study of a 2-Mile Superconducting Linac**, SLAC-PUB-0560, W.B. Herrmannsfeldt, G.A. Loew, R.B. Neal, et al. Stanford: Stanford Linear Accelerator Center, 1969. Published in *IEEE Transactions on Nuclear Science*, 16:1004-1008, 1969.

[15] **SLAC: Status, Recent Progress, and Future Plans**, SLAC-PUB-0624, R.B. Neal. Stanford: Stanford Linear Accelerator Center, 1969. Invited paper at the Seventh International Conference on High Energy Accelerators, Yerevan, USSR, August 1969.

[16] **Linear Accelerators,** ed., A. Septier and P.M. Lapostolle. Amsterdam: North-Holland Publishing Company, 1970.

[17] **The SLAC Recirculating Linear Accelerator (RLA)**, SLAC-PUB-1129, R.H. Helm, G.A. Loew, R.B. Neal, et al. Stanford: Stanford Linear Accelerator Center, 1972. Presented at the 3rd All Union Conference for Scientific Problems of Charged Particle Accelerators, Moscow, USSR, October 1972.

[18] **Accelerator Parameters for an e^+e^- Super Linear Collider**, SLAC/AP-7, R.B. Neal. Stanford: Stanford Linear Accelerator Center, 1983.

[19] **1996 Linear Accelerator Conference Proceedings,** "A Damped Detuned Structure for the Next Linear Collider," R.H. Miller, et. al. Geneva: CERN, 1996

[20] **JLC Design Report**, Chapter 12, T. Shintake, H. Matsumoto, et al. Tsukuba: Japan National Laboratory for High Energy Physics, April 1997.

[21] **The Preservation of Low Emittance Flat Beams**, SLAC-PUB-6117, T.O. Raubenheimer. Stanford: Stanford Linear Accelerator Center, 1993. Presented at the Particle Accelerator Conference (PAC 93), Washington D.C., May 1993.

[22] **Future e^+e^- Colliders**, G. Loew. Presented at the 1986 International Conference on High Energy Physics at the Novosibirsk Institute, Novosibirsk, USSR, August 1986.

[23] **Note on the SC Linear Collider TESLA Cavity Design**, TESLA-97-06, J. Sekutowicz, D. Proch, C. Tang. Hamburg: Deutsches Elektronen-Synchrotron DESY, 1997.

[24] **NLC Technical Program**, D. Burke. Talk given at the R.B. Neal Symposium, Stanford: Stanford Linear Accelerator Center, September 1997.

[25] **Proposal for a Two-Mile Linear Electron Accelerator**. Stanford: Stanford University, April 1957

The NLC Technical Program

Symposium on Electron Linear Accelerators in Honor of Richard B. Neal's 80th Birthday

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ABSTRACT

There are important goals in particle physics to be addressed by a TeV-scale electron-positron linear collider. Recent developments in accelerator physics and technologies aimed for the realization of such a collider are discussed in this paper.

1. THE ENERGY FRONTIER IN PARTICLE PHYSICS

For the past 25 years accelerator facilities with colliding beams have been the forefront instruments used to study elementary particle physics at high energies. Both hadron-hadron and electron-positron colliders have been used to make important observations and discoveries. Hadron accelerators can create high collision energies, and therefore significant discovery reach. Direct observations of the $W^{\pm}$ and Z^0 bosons at CERN, and investigations of the top quark at Fermilab are examples of physics done at hadron colliders. Electron-positron colliders provide well controlled and understood experimental environments in which new phenomena stand out and precise measurements can be made. Discoveries of the charm quark and τ lepton at SPEAR, discovery of the gluon and establishment of QCD at PETRA and PEP, and precision exploration of electroweak phenomena at the SLC and LEP are highlights of the body of results produced by experiments at electron-positron colliders. The ability to view nature from these two distinct vantage points has proven essential to the advancement of our understanding of particle physics, and will remain so as the field moves forward along the energy frontier.

The present generation of colliding-beam accelerators was built to find and study the massive carriers of the weak force, the $W^{\pm}$ and Z^0 gauge bosons. The next generation of colliders must open the frontier from multi-hundred GeV to TeV energies — ten times that of the present generation. The (Main Injector) upgrade of the luminosity of the TEVATRON hadron collider at Fermilab, and the (LEP II) increase of the energy of the Large Electron Positron collider at CERN will provide first glimpses at the next thresholds of the energy frontier, but more powerful collider facilities will be required to fully explore this new territory. The Large Hadron Collider (LHC) is the descendant of the Tevatron and earlier proton colliders at CERN that will come into operation in the next decade, and will provide unique opportunities for the world-wide community of particle physicists for decades beyond that.

Studies of physics goals and requirements for the next generation electron-positron collider began formally in 1987-1988 with workshops held regionally in the United States (Ahn, *et al*., 1988; Snowmass 88; Snowmass 90), Europe (LaThuile, 1987; DESY, 1990), and Japan (JLC I, 1989; JLC II, 1990). These have become a series of internationally organized workshops (Finland, 1991; Hawaii, 1993; Morioka, 1995) from which has emerged a broad picture (Figure 1) of a collider with initial center of mass energy approximately 500 GeV and luminosity in excess of 10^{33} cm^{-2}sec^{-1}, built to be *expandable* to 1 TeV and beyond with luminosity in excess of 10^{34} cm^{-2}sec^{-1}. Expandability is an important requirement for a future collider. It must be able to eventually address energies of 1-1.5 TeV. Experiments performed at this collider will have unique windows to discovery and opportunities for study that will extend and complement experiments done at the LHC.

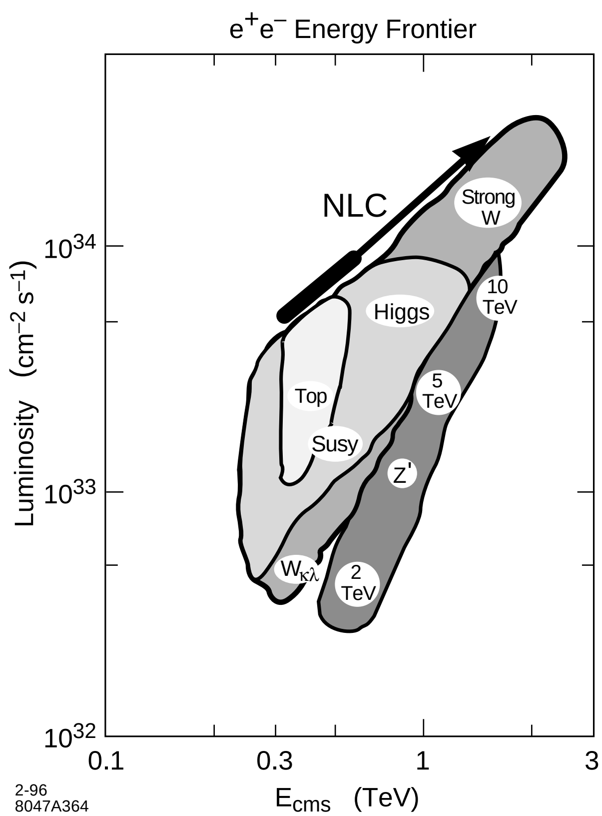

Figure 1. Physics goals for a TeV-scale e^+e^- collider.

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

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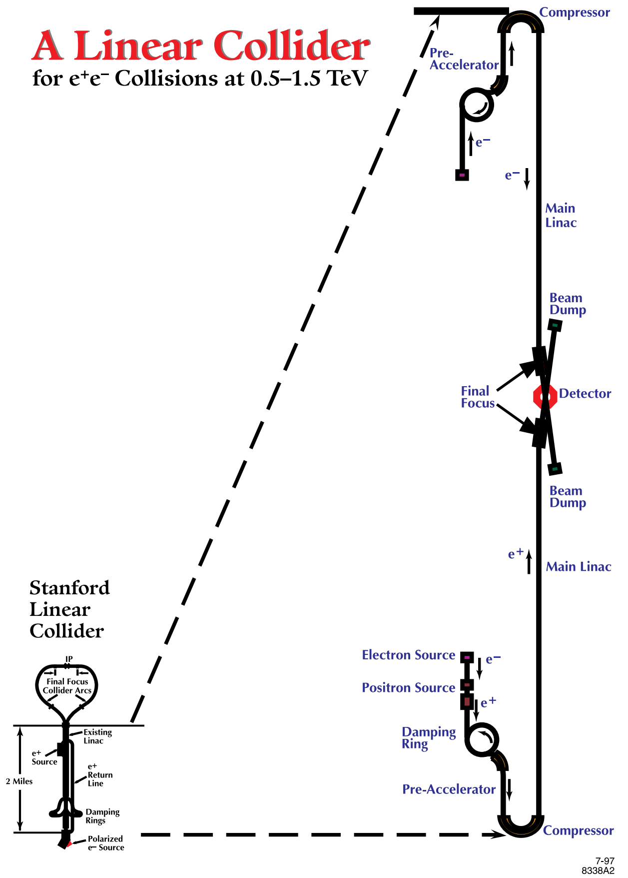

Figure 2. The pioneering Stanford Linear Collider and the Next Linear Collider.

2. THE STANFORD LINEAR COLLIDER AND THE NEXT LINEAR COLLIDER

The Stanford Linear Collider (SLC) was conceived and built to study particle physics at the 100 GeV energy scale and to develop the accelerator physics and technology necessary for the realization of future high-energy colliders. The SLC was completed in 1987 and provided a first look at the Z^0 in 1989. In time, the luminosity provided by this machine has grown steadily and is now reaching toward its design goal (N. Phinney, this Symposium). A wealth of accelerator physics has emerged from this pioneering facility, and it has been used to carry out important particle physics studies.

The Next Linear Collider (NLC) is being developed to meet the demands of particle physics research at the TeV energy scale. Shown in Figure 2, this facility will be a factor ten larger than the SLC and poses challenges that require the development of new technologies and place stringent demands on the performance and reliability of existing technologies. This paper will discuss the research and development program being carried out at SLAC and elsewhere to address this new frontier in linear accelerators.

3. COLLIDER ACCELERATOR TECHNOLOGIES AND THE CHOICE OF X-BAND

The basic components of any linear collider are those already incorporated in the SLC. Trains of bunches of electrons and positrons are created, condensed in damping rings, accelerated to high energy, focused to small spots, and collided to produce a brightness given by,

$$L = \frac{nN^2Hf}{4\pi\sigma_x^*\sigma_y^*} \tag{1}$$

where n = number of bunches per rf pulse
N = number of particles per bunch
H = enhancement factor due to beam disruption
f = machine repetition rate,

and σ_x^* and σ_y^* are the horizontal and vertical beam dimensions at the collision point. Equation (1) can be written as

$$L = \frac{1}{4\pi E} \bullet \frac{NH}{\sigma_x^*} \bullet \frac{P}{\sigma_y^*} \tag{2}$$

where P is the average power in each beam. The energy E is specified by particle physics goals. The factor, NH/σ_x^*, determines the number of beamstrahlung photons emitted during the beam-beam interaction, and since these photons can create backgrounds in experimental detectors, this factor is highly constrained. It is only the last ratio that can be addressed by accelerator technology; *high luminosity corresponds to high beam powers or small beam spots.* These two parameters pose different, and in many cases contrary, challenges to the accelerator physicist, and several technologies are presently being pursued that represent differing degrees of compromise between beam power and spot size. Table I summarizes the mainstream design choices (G. Loew, this Symposium).

The need to study particle physics at energies of 1 - 1.5 TeV and our experience with the SLC guide our choices of technologies for the NLC. Construction and operation of the main linac are the major factors in the cost of the collider complex, so the accelerator technology and design must be chosen to minimize the length of the accelerator while still meeting the demands for particle physics research. A natural match to the TeV energy region is made with a choice of X-Band microwave components at a frequency (11.4 GHz) four times that used in the existing SLAC linear accelerator. This approach requires the development of 50-100 MW klystrons and advanced rf pulse compression systems, but offers the possibility to use accelerating gradients of 50 - 85 MV/m. The requirement (Table I) that beam spots of several nanometers be created and collided is a most significant challenge. The main

Table I. Linear Collider Design Parameters (E_{cm} = 500 GeV)

	RF Freq (GHz)	RF Grad (MV/m)	Total Length (km)	Beam Power (MW)	σ_y (nm)	Luminosity (10^{33} cm^{-2} s^{-1})
SuperC	1.3	25	30	8.2	19	6
S-Band	3.0	21	30	7.3	15	5
X-Band	11.4	50	16	4.2	5.5	6
2-Beam	30.0	80	9	2.7	7.5	5

linac of the NLC must accelerate trains of bunches to high energy without diluting the beam emittance and must control the energy spectrum of the particles within each bunch and the energy difference between bunches. The technical risk of a machine built with X-Band technology will be greater than that incurred at S-Band, but the capital costs of initial installation at 500 GeV and the cost to upgrade the machine will be lower. The use of a more complex technology, such as a two-beam accelerator, is not warranted for this energy range.

4. THE X-BAND ACCELERATOR FOR THE NLC

The accelerating structures of conventional room-temperature linacs are disk-loaded cylindrical waveguides typically several meters in length. Microwave rf power is generated in klystrons and transported to the structure through a series of waveguides. A technique of pulse compression to transform the klystron rf output into a shorter pulse of higher peak power is used in the rf system of the SLAC linac, and a similar technique will be used at higher energy. A conceptual picture of an X-Band rf system with pulse compression is shown in Figure 3. The duration of the compressed rf pulse, the peak rf power, the efficiency with which ac power is converted from the AC power grid into beam power, and the capital cost of the system are the simplest figures of merit. Goals for rf systems are summarized in Table II (G. Loew, this Symposium).

4.1 Rf Power Systems and Beam Acceleration

Progress in development of X-band rf power sources has been impressive in recent years (G. Caryotakis, 1993 and R. Phillips, 1997). Solenoid-focused klystrons (Figure 4) that produce 50 MW pulses of 1.5 μsec duration are now in routine operation and tubes have reached power outputs as high as 90 MW in test runs. This meets the initial requirements for the NLC and provides good confidence that robust klystrons that generate still higher powers can be developed. A significant step has been made to reduce costs to construct and operate high-power klystrons by the introduction of periodic permanent magnet (PPM) focusing to the tube design (Figure 5). This technique, previously used in lower-power CW klystrons but never before in pulsed high-power tubes, replaces the costly solenoid focusing coil with a stack of permanent magnets that require no power for operation. A first prototype PPM X-band klystron has recently been built and tested with spectacular success. The performance of the PPM tube replicates to 50 MW that of the XL-4 design and fabrication of a second-generation PPM tube, designed to reach 75 MW output power, will soon be completed.

Structures are characterized in Table II by the gradient expected to be used, and by the size of the aperture through which the beam passes. The accelerating gradient that can be utilized is limited by high-voltage breakdown and the

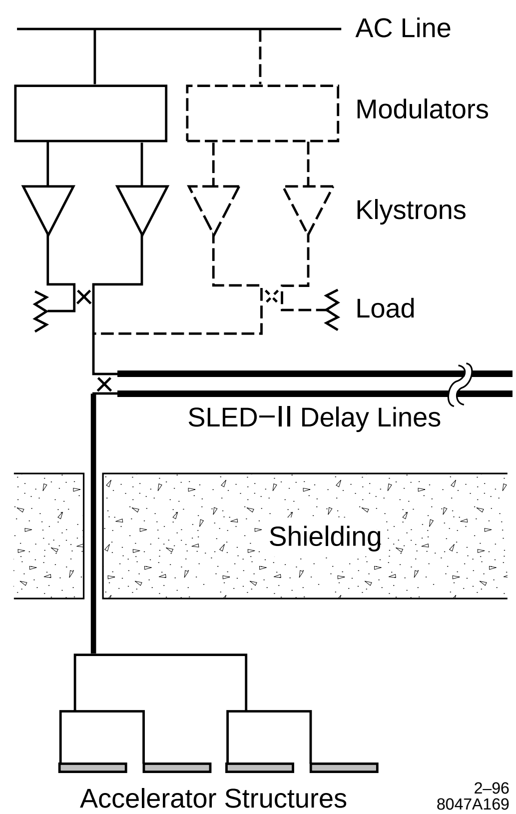

Figure 3. Microwave system for a collider based on X-Band rf power.

Table II. Goals for RF Systems (E_{cm} = 500 GeV)

	Klystrons		Compression	Efficiency	Structure	
Technology	Peak Power (MW)	Pulse Length (μs)	Power Gain	P_b/P_{ac} (%)	a (cm)	Gradient* (MV/m)
SuperC	7.1	1300	None	21	3.5	25
S-Band	150	2.8	None	10	1.0-1.5	21
X-Band	50	1.5	3.6	6	0.4-0.5	50
2-Beam	NA	NA	None	1.6	0.2	80

* Unloaded gradient.

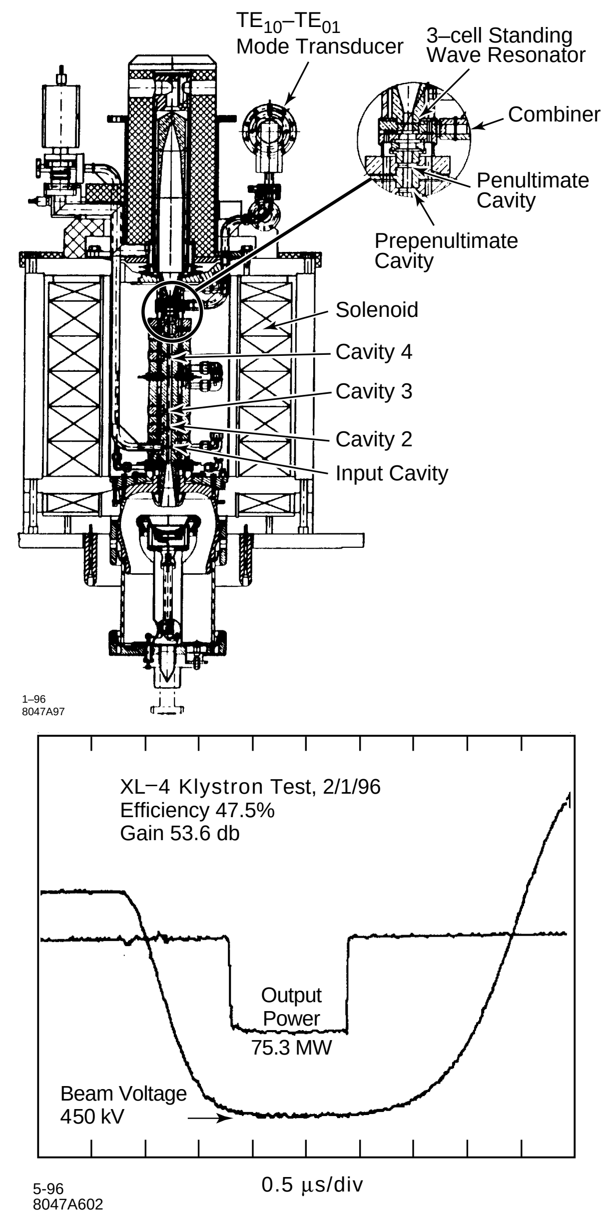

Figure 4. (a) Schematic of the XL-4 solenoid-focused X-Band klystron, and (b) pulse characteristics of XL-4 tubes.

"dark current" created when electrons are drawn from the surfaces of the linac structures and become captured on the accelerating rf wave. To become captured an electron emitted (generally at rest) from an iris in the structure must be sufficiently accelerated so as to pass into the neighboring cell before the rf voltage reverses sign. For a given rf frequency, there is a well-defined gradient beyond which electrons emitted at rest will always be captured and accelerated to relativistic velocities. The capture gradient at S-Band is about 16 MV/m, and scales to 64 MV/m at X-Band. These are not the actual limits to gradients that can be utilized in an accelerator since much of the charge is swept aside by the focusing quadrupoles of the machine lattice, but the dark current will grow rapidly above these values, and beam loading, radiation, and wake fields caused by this current will quickly reach unacceptable levels. Gradients somewhat above the capture field are likely to be useful in practice, but the operational limits are not well known. Expected thresholds of dark currents in S-Band and X-Band structures have been confirmed (Figure 6, J. Wang, 1994). A very pretty set of

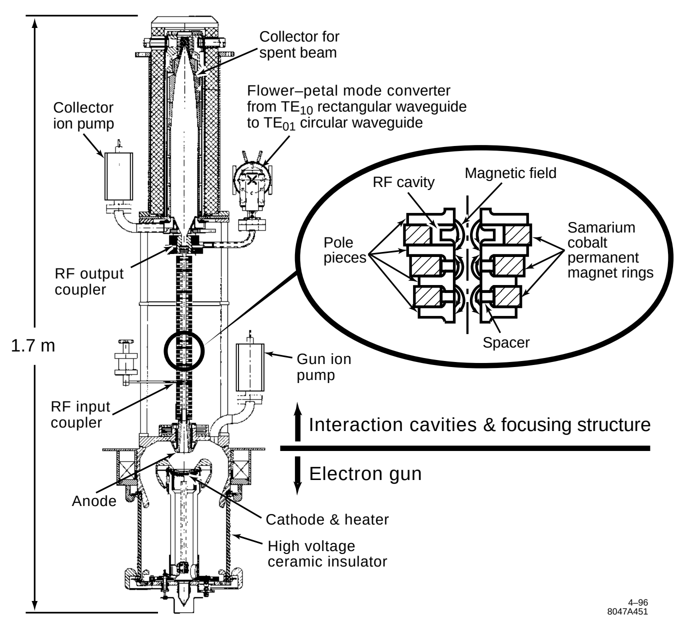

Figure 5. Schematic of a periodic permanent magnet (PPM) focused klystron.

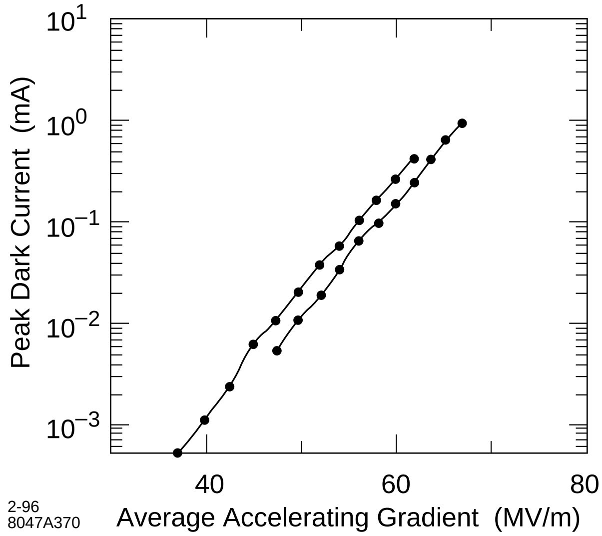

Figure 6. Processing of X-Band accelerator structures to high voltage.

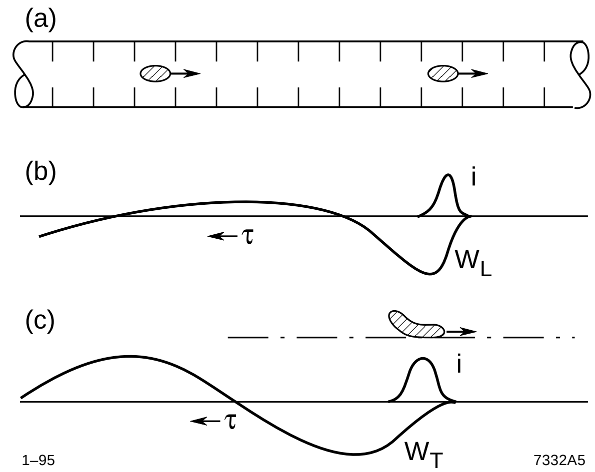

Figure 7. Longitudinal and transverse wakefields (retarded electromagnetic fields) in a linear accelerator.

studies (Matsumoto et al., 1995) have shown that dark current is predominantly caused by impurities left on and in the surfaces of the accelerator structure during manufacture and that significant reductions in dark current can be made by using pressure treated copper and maintaining modest clean-room practices during the fabrication process.

4.2 Beam Dynamics and the Design of Accelerator Structures.

A charged particle generates an electromagnetic wakefield as it passes through the structures of an accelerator (Figure 7). There is a longitudinal component of this field, and if the particle is not centered in the axially symmetric structure, then a component of the field is generated transversely to the beam axis as well. A particle traversing the structure will experience the force created by the sum of the externally applied microwave accelerating field and the wakefield generated by all particles that precede it through the structure. The presence of a longitudinal wakefield will result in a net acceleration which is not the same for each particle. This creates a finite spread in the energies of the beam particles. Transverse components of the field in the accelerating structures will deflect particles from the desired trajectory, and since the amount of the deflection is not the same for all particles, such wakefields will result in a dilution of the phase space occupied by the beam. It is necessary to control the effect of the unavoidable longitudinal wakefields, and it is imperative that transverse wakes be minimized and their effects mitigated.

Control of the dilution of the beam phase space (emittance) by transverse wake forces is a difficult task. The phenomenon of "bunch breakup" was observed early as the SLAC S-Band linac was brought into operation, and more detailed studies of the effects of transverse wakefields have been carried out with the recently available low-emittance beams from the SLC damping rings (Figure 8). It has proven necessary to not only align the physical structures of the accelerator with good precision and control the trajectory of the beam with great care, but also to "detune" the individual cells of the accelerator to prevent coherent build up of the wakefield forces. The detuning process was accomplished in the SLAC linac by dimpling the radial dimensions of each cell so that the frequencies of the lowest dipole components of the wakefields vary slightly from cell to cell. This "delicate" correction was applied to the as-build accelerator with hand-held hammers!

The electro-mechanical design of the X-Band structures for the NLC are chosen to minimize both short-range and long-range wakefields (R. Miller, *et al.*, 1993). Short-range transverse wakes are controlled by deliberately detuning the

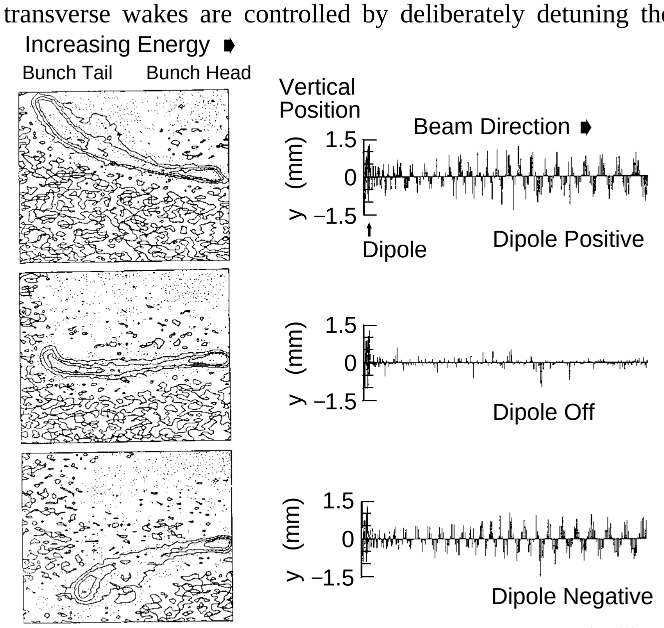

Figure 8. Distortion in the shape of an intense bunch of particles that passes through the length of the SLAC linac. The bunch shape is shown on the left for three different trajectories through the accelerator. The middle case is for a well-steered trajectory, and the upper and lower cases are the result of deliberately launching the beam into the linac onto orbits with large betatron amplitudes.

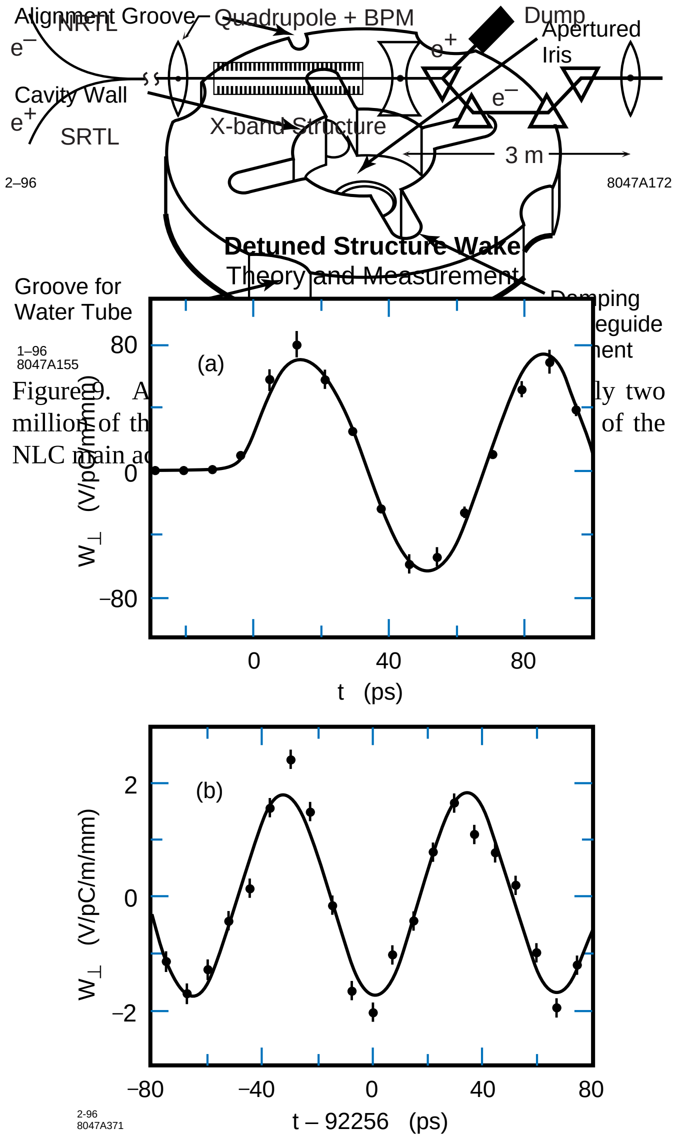

Figure 10. Measurement of transverse wakefields excited in a damped and detuned X-Band accelerator structure. (a) The ASSET Facility in the SLAC linac. (b) Comparison of measured data and theoretical prediction.

dipole frequencies - it is not planned to repeat the *in-situ* operation used to detune the SLAC linac. Long-range transverse wakes are eliminated by the use of "damped" structures that suppress the amplitude of wakefields by coupling nonaccelerating rf modes through waveguide slots to external lossy loads. The damping slots are readily apparent in the photograph of a single damped X-Band accelerator cell shown in Figure 9. Two hundred of these cells are bonded into a single 1.8 meter long accelerator structure. Small variations in the radial dimensions of each of the cells in a structure provide the detuning of dipole modes needed to suppress short-range components of the wakefields. Direct measurements have been made of the transverse wakefields left by particles as they pass through a structure fabricated with damped and detuned cells (C. Adolphsen, 1995). These have shown excellent agreement with the theoretical expectations (Figure 10) and provide good confidence that low-emittance beams can be accelerated to high energy in the NLC X-Band accelerator.

4.3 The Next Linear Collider Test Accelerator

Much work remains to be done on X-Band technologies, but with prototype rf components now in hand, tests of completely integrated systems have begun. A prototype test accelerator (the Next Linear Collider Test Accelerator NLCTA) has been constructed at SLAC to allow optimization of rf systems and provide experience with beam operations at X-Band frequencies (R. Ruth, *et al.*, LC95, 1995). The NLCTA is a 40-meter long section of six 1.8-meter X-Band structures powered by 50 MW klystrons to an accelerating gradient of 50 MV/m. It is designed so that further upgrades will allow operation to gradients of 80-90 MV/m with a doubling of the number of klystrons and future increases in the power delivered by each. This is a pattern that is also planned for the implementation of the NLC itself.

An important goal of the NLCTA is to demonstrate not only high-gradient acceleration, but also the ability to control the spread in energies of the accelerated particles. The energy spread of the particles must be maintained to within several tenths of a percent to minimize chromatic dilutions in the final focus system. (See below.) The single-bunch energy spread caused by the intrabunch longitudinal wakefield can be compensated by timing the injection of each bunch into the accelerator with respect to the peak of the externally applied rf field. This is done routinely in the SLAC S-Band linac, but will require a more precise control of the rf phase of each klystron in the higher frequency NLC X-Band linac. The problem is made more difficult by the fact that, to improve the overall energy efficiency of the collider and deliver the high luminosity demanded by the particle physics goals, the NLC is designed to accelerate nearly 100 bunches during each pulse of the rf system. The bunch-to-bunch energy variation must also be maintained to within a few tenths percent even though each bunch is removing a fraction of a percent of the applied rf power. Compensation for this beam loading is done by carefully shaping in time the applied microwave power through control of the phasing of the source klystrons. This technique has been successfully used in the NLCTA to produce a bunch train with full energy spread within 0.3% (Figure 12).

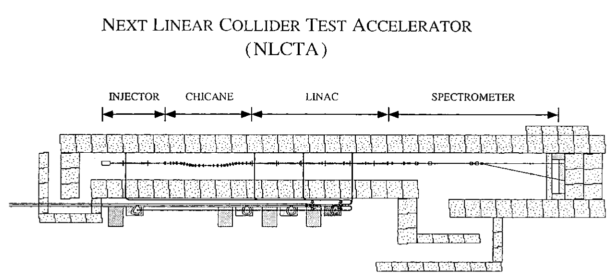

Figure 11. The Next Linear Collider Test Accelerator.

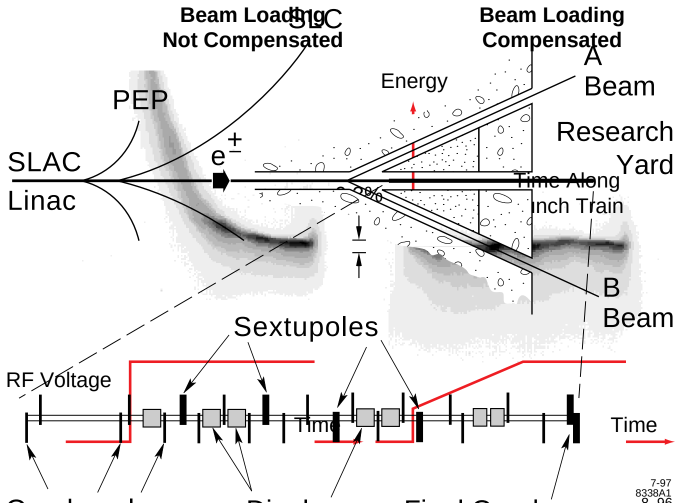

Figure 12. Beam loading compensation of the bunch train in the NLCTA.

Figure 13. Layout of the Final Focus Test Beam at the end of the SLAC linac. The FFTB is a prototype final focus for a future collider suitable for use with any accelerator technology.

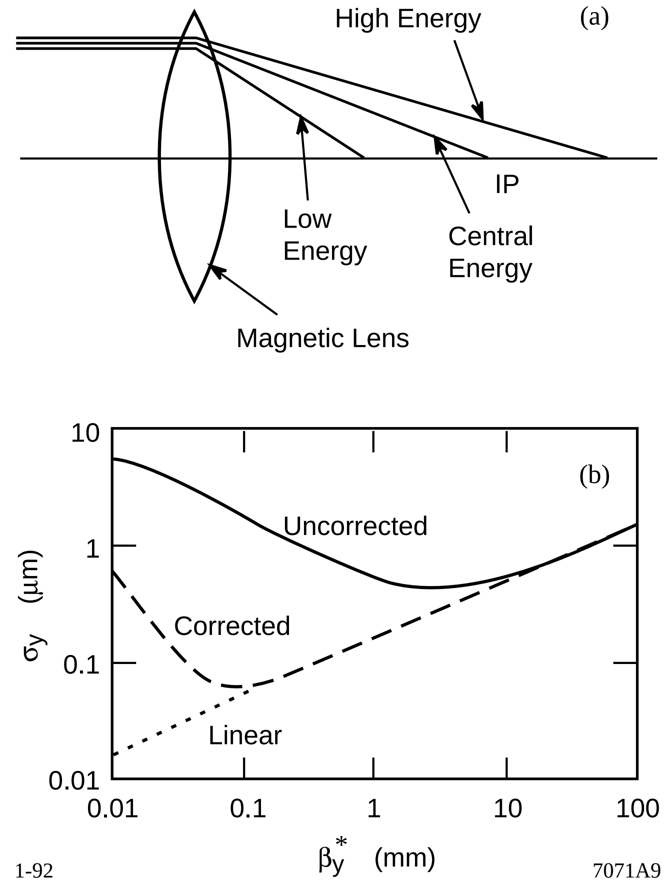

Figure 14. The chromatic correction of the FFTB optical system.

5. Final Focus and Interaction Region

Spot sizes listed in Table I all represent significant extrapolations from those achieved at the SLC. An experiment has been performed by the Final Focus Test Beam Collaboration[i] to demonstrate that such systems can be built and operated (D. L. Burke, 1994). The Final Focus Test Beam (FFTB) is a prototype beamline installed in a channel located at the end of the SLAC linac at zero degrees extraction angle (Figure 13). The FFTB lattice (K. Oide, 1989) produces a focal point at which the beam height is demagnified by a factor of 380, so that the low-emittance ($\gamma\varepsilon_y = 2 \times 10^{-6}$ rad•m) SLC beam is reduced to a size smaller than 100 nm. The demagnification factor of the FFTB beamline is in excess of that needed for the NLC.

The FFTB optics are chromatically corrected to third-order in the beam energy spread (Figure 14), and careful attention was given to alignment and stabilization of beamline components. New laser-referenced alignment techniques were used to position components with accuracies of 60 microns or better, and all magnetic elements mounted on precision stages that can be remotely positioned with step size of • 0.3 micron. Hardware systems and beam-based techniques were used to monitor changes as small as 1 micron in component alignments that occur over short time intervals (hours). New state-of-the-art instruments were developed and used to measure the FFTB beam positions and spot sizes (J. Buon, *et al.*, 1991; T. Shintake, 1992)

Following a brief shake-down run in August of 1993, data were taken with the FFTB during a three-week period in April and May of 1994. Beam demagnifications of 320 and spot sizes of 70 nm were controllably produced during this period (V. Balakin *et al.*, 1995). Measurement of these beams is shown in Figure 15. Continued experimentation with the FFTB has demonstrated that the detailed chromatic and geometric properties of the beamline are well understood, and new techniques have been developed to streamline and improve the accuracy of the tuning of the system. These include refinement of beam-based lattice diagnostics and alignment strategies, as well as development of robust microwave monitors able to measure beam motions with resolutions of a few tens of nanometers. These will all be important in the implementation of the final focus system for the NLC.

6. PROSPECTS FOR THE NLC

The SLC is successfully reaching toward its design luminosity and prototype X-Band technical components are now meeting performance specifications for the NLC. Major test facilities, the FFTB and NLCTA at SLAC and the ATF Injector Complex at KEK (J. Urakawa and L. Yoshioka, *ed.*, 1992), are providing hands-on experience with the subsystems that make up the NLC design. First comprehensive studies, the "Zeroth-Order Design Report for the Next Linear Collider" (T. Raubenheimer, *ed.*, 1996) and the "JLC Design Study" (N. Toge, *ed.*, 1997), of X-Band accelerator designs have been completed. These all provide confidence in the choice of the

[i] The FFTB Collaboration consists of scientists and engineers from BINP(Protvino), DESY, Fermilab, KEK, LAL(Orsay), MPI(Munich), and SLAC.

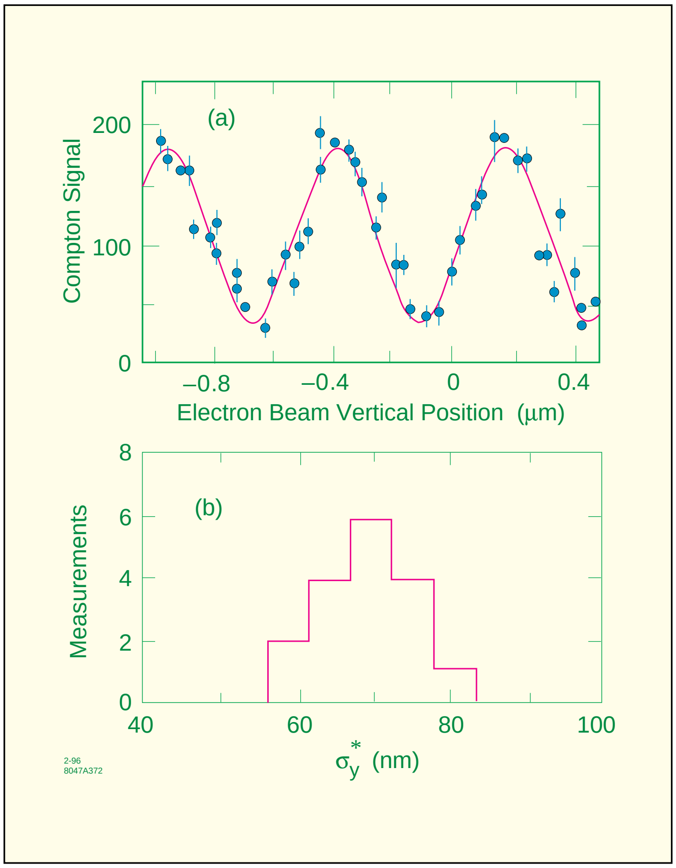

Figure 15. Measurement of 70 nm beam spots with a laser-Compton beam size monitor in the FFTB. (a) The rate of Compton scatters from a laser interference pattern is used to determine the beam size. In this case 73 nm. (b) Repeatability of spot measurement over periods of several hours.

X-Band technology and in the feasibility of the NLC design to provide the energy and luminosity requirements set forth by the physics of the TeV energy scale.

The technical R&D program for the NLC is now being directed toward opportunities to optimize performance, reduce costs, and increase the reliability of accelerator components and subsystems. Efforts made now will have the greatest leverage on the quality and cost of the final project. Klystron and power handling equipment is being redesigned to reduce complexity and simplify manufacture, new electrical designs are being examined that promise to increase the shunt impedance of the accelerator structure with little tightening of manufacturing tolerances, options for remote placement of intelligent control systems are being developed that may substantially reduce the volume of control cables needed for the complex, and the overall topology and infrastructure of the collider design is being reviewed with a critical eye to cost and reliability.

The NLC is ready for the next step - the so-called Conceptual Design - the creation of a baseline design and cost estimate for a possible construction project.

It has been recognized from the beginning that the construction and utilization of a TeV-scale electron-positron collider will be an international effort similar in scope to the LHC in Europe. The linear collider R&D program has been formulated as an international one from the outset and we are working to build and prepare for international involvement in the final design of the collider. Final discussions over siting and construction responsibilities for a facility will be difficult, but with appropriate patience and understanding, such things are possible.

REFERENCES

C.Ahn, *et al*., SLAC-Report-329, 1988.

Proceedings of the 1988 DPF Summer Study: Snowmass '88, High Energy Physics in the 1990's, E. L. Berger, ed., Snowmass, CO, 1988.

Proceedings of the 1990 DPF Summer Study on High Energy Physics: Research Directions for the Decade, F. Gilman, ed., Snowmass, CO, 1990.

Proceedings of the Workshop on Physics at Future Accelerators (La Thuile), CERN, Geneva, 1987.

Workshop on Electron-Positron Collisions at 500 GeV: The Physics Potential, DESY, 1990.

Proceedings of the First Workshop on Japan Linear Collider (JLC I), S.Kawabata, ed., KEK, 1989.

Proceedings of the Second Workshop on Japan Linear Collider (JLC II), KEK, 1990.

Proceedings of the First International Workshop on Physics and Experiments with Linear Colliders, R. Orava, ed., Saariselka, Finland, 1991.

Proceedings of the Second International Workshop on Physics and Experiments with Linear Colliders, F. Harris, *et al.*, eds., Waikoloa, Hawaii, 1993.

G. Caryotakis, "High-Power Microwave Tubes: in the Laboratory and On-Line", 5th Special Issue on High Power Microwaves, IEEE Transactions on Plasma Science; and SLAC-PUB-6361 (1993).

R. Phillips, in *Proceedings of the 7th International Workshop on Linear Colliders,* Zvenigorod, Russia, 1997.

J. Wang, *et al.*, "High Gradient Tests of SLAC Linear Collider Accelerator Strucutres", *17th Int. Linear Accelerator Conference (LINAC94)*, Tsukuba, Japan; and SLAC-PUB-6617 (1994).

H. Matsumoto, et al., KEK Preprint 91-47, 1991; private communication, 1995.

R. H. Miller, *et al.,* "Accelerator Structure Work for the NLC", *Proceedings of the XV Int.Conf. on High Energy Accelerators (HEACC),* Hamburg, Germany, J. Rossbach, ed. (1993) ; and SLAC-PUB-6624 (1994).

C. Adolphsen, *et al*., Phys. Rev. Lett. 74, 2475, 1995.

R. D. Ruth, *et al.,* "A Test Accelerator for the Next Linear Collider", *Proceedings of the ECFA Workshop on Linear Colliders (LC92)*, Garmisch Partenkirchen, p. 157, SLAC-PUB-6293, (1992); also *Proceedings of the 6th International Workshop on Linear Colliders*, KEK 95-5, 1995.

Results from the Final Focus Test Beam, The FFTB Collaboration, presented by D. Burke, *Fourth European Particle Accelerator Conference*, London, England, 1994.

K. Oide, SLAC-PUB-4953, 1989.

J. Buon, *et al*., Nucl. Instrum. Methods Phys. Res., Sect. A 306, 93, 1991.

T. Shintake, Nucl. Instrum. Methods Phys. Res., Sect. A 311, 453, 1992.

V. Balakin, *et al*., The FFTB Collaboration, Phys. Rev. Lett. 74, 2479, 1995.

Proceedings of the *SLAC/KEK Linear Collider Workshop on Damping Ring*, KEK 92-6, J. Urakawa and M. Yoshioka, eds. (1992).

“Zeroth-Order Design Report for the Next Linear Collider”, The NLC Design Group, T. Raubenheimer, *ed*., LBNL-PUB-5424, SLAC Report 474, UCRL-ID-124161, 1996.

“JLC Design Study”, JLC Design Study Group, N. Toge, *ed*,. KEK Report 97-1, 1997.

Advanced Electron Linacs

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ABSTRACT

The research into advanced acceleration concepts for electron linear accelerators being pursued at SLAC is reviewed. This research includes experiments in laser acceleration, plasma wakefield acceleration, and mm-wavelength RF driven accelerators.

I. INTRODUCTION

The frontier of particle physics is determined by the highest achievable center-of-mass energy. There has been exponential growth in center-of-mass energy because of *i)* conceptual breakthroughs in acceleration (for example, strong focusing and colliding beams); *ii)* inventions such as the klystron; *iii)* application of technologies like superconductivity to particle acceleration; and *iv)* consolidation of high energy physics research at fewer and larger facilities.

The latter is a trend that cannot go much farther for reasons that include, but go even beyond, the political vulnerability of large accelerator complexes. High energy physics experiments performed by a thousand or more scientists at remote sites are not in a strong competitive position for university positions and for the ambitious young people who want to tackle and solve important problems. Already one sees talented particle physicists performing research that is on the fringes of traditional high energy physics. Particle physics evolving as it is now will be addressing some of the most fundamental questions posed by mankind, but in a manner and at a cost that possibly cannot be sustained.

Such extrapolations into the future ignore the possibility of revolutionary developments. These could be particle physics discoveries or accelerator inventions that dramatically reduce costs and increase capabilities. The accelerator research described in this paper is one attempt to pose and answer questions that could lead to inventions and dramatic changes in electron linear accelerators.

At the present time this research is concentrated on three questions:

- Lasers are capable of terawatts of peak power. What is the potential of lasers as an accelerator power source?
- Laser driven, plasma based accelerators have demonstrated gradients of 100 GV/m. What is the next step in the development of plasma based accelerators?
- RF driven accelerators can have an acceleration gradient that is roughly proportional to frequency. What are the limits of high frequency accelerators?

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

II. LASER ACCELERATION

Laser irradiance as high 10^{19} W/cm^2 corresponding to electric fields of 10 GV/m has been achieved on existing multi-terawatt systems.[1] Solid state diode pumped lasers have good efficiency, the promise of high average power, and market forces driving development. With these attributes the laser is natural for acceleration, but the electric field is transverse to the direction of propagation. There are a number of possible ways to remove this restriction:

- The electron beam in an Inverse Free Electron Laser has a wiggle component of motion transverse to the average propagation direction, but synchrotron radiation in the wiggler magnets limits the energy.
- Laser excited plasma space charge waves have reached gradients of 100 GV/m. There is more on plasma acceleration in section III below.
- A structure with feature sizes the order of a wavelength, as in RF accelerators, would have enormous wakefields and small accelerated charge. A structure with features much larger than the wavelength does not have as severe wakefields and could accelerate higher charge.

This is the underpinning of the crossed laser beam accelerator illustrated in Figure 1.[2] Two laser beams, formed by splitting a single beam, are crossed at an angle θ. The beams are polarized in the crossing plane, and the optical path lengths are such that the transverse components of electric

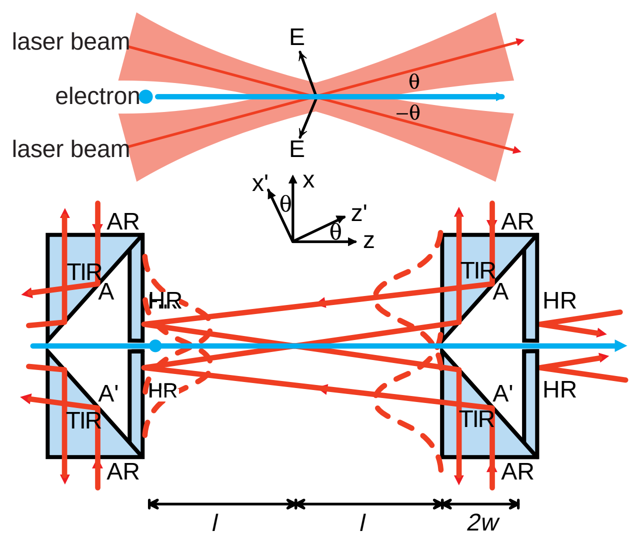

Figure 1: Schematic of a crossed laser beam accelerator.[2] The beams are focused to a waist in the middle of the structure. AR, HR, and TIR denote anti-reflection coating, high reflectively coating, and total internal reflection, respectively. Acceleration takes place over the length 2l between slits.

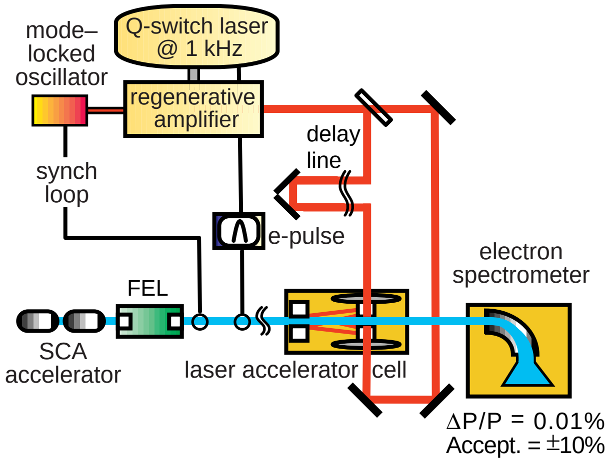

Figure 2: Schematic of structure based laser acceleration experiment.

field interfere destructively and the longitudinal components add constructively.

Treating the laser beams as focused, free space Gaussian beams,[3] the on-axis, longitudinal electric field in terms of the laser power, P, the wave impedance of free space η_v, the waist size, w_0, and the Rayleigh range, $z_r = \pi w_0^2/\lambda$, is

$$E_z = -\sqrt{\frac{\eta_v P}{\pi}}\,\frac{4\theta}{w_0\left(1+(z/z_r)^2\right)}\exp\left(-\frac{z^2\theta^2}{w^2}\right)$$
$$\times\exp\left(i\left[2\varphi_g+\varphi_r+\varphi_p\right]\right) \tag{1}$$

where

$$w^2 = w_0^2\left(1+\frac{z^2}{z_r^2}\right). \tag{2}$$

The three phases are: the Guoy phase advance that occurs passing through the focus of a beam where the wavefronts change from incoming to outgoing spherical waves (there is a factor of two from summing transverse and longitudinal field components),

$$\tan\varphi_g = z/z_r\ ; \tag{3}$$

the radial phase that accounts for wavefront curvature,

$$\varphi_r = -\frac{z}{z_r}\frac{z^2\theta^2}{w^2}; \tag{4}$$

and the relative phase of a charged particle with respect to the accelerating field

$$\varphi_p = \frac{\pi z}{\lambda}\left(\theta^2-\frac{1}{\gamma^2}\right). \tag{5}$$

For an infinite range of integration, there is no net acceleration due to the phase slip between particles and accelerating field. The field must be terminated with slits at $|z| < z_r$ by a structure for net acceleration. The maximum energy gain of an on-axis electron is

Table 1: Laser Acceleration Experiment Parameters

Ti-Saphire Laser Parameters	
Mode lock pulse rate	82 MHz
Regenerative amplifier rate	1 kHz
Energy per pulse	1 mJ
Pulse width	0.1 - 3 psec
Wavelength	0.8 - 1 μm
Superconducting Accelerator (SCA) Parameters	
Micropulse length	2 psec
Electrons per micropulse	10^8
Micropulse rate	11.8 MHz
Macropulse length	2 msec
Macropulse rate	10 Hz
Normalized emittance	8 mm-mrad
RMS energy spread	0.1%
Energy	35 MeV
Laser Acceleration Cell Parameters	
Acceptance	3 mm-mrad
Laser energy per stage	0.1 mJ
Electrons captured	10^7/sec
Energy gain per stage	330 keV

$$\Delta W_{max}\,(\mathrm{MeV}) = 30\sqrt{P(\mathrm{TW})} \tag{6}$$

with a crossing angle $\theta = 1.37 w_0/z_r$ and an interaction length $2l = 0.92\ z_r$.[2] Average gradients of almost 1 GeV/m are possible without exceeding laser damage thresholds.

The field terminating slits can be at most a few times the laser wavelength in width to avoid substantial loss of acceleration, and, with a bunch length that is a small fraction of the laser wavelength, the longitudinal wakefield in these slits severely limits the accelerated charge. Estimates are that the wakefield energy loss per stage equals the energy gain for ~10^5 electrons. Two solutions of this severe problem have been proposed. First, cylindrical optics and a line charge can be used,[4] and, second, the laser light can be recycled to accelerate multiple beams.[5]

A collaboration between the Ginzton and Hansen Laboratories (HEPL) on the Stanford campus and SLAC are building an experiment to study structure based laser acceleration.[6] The experiment, illustrated in Figure 2 and with parameters given in Table 1, will use a 35 MeV beam from the HEPL superconducting accelerator. A Ti-Sapphire laser and regenerative amplifier will provide the laser light. The electron beam will traverse a Free Electron Laser (FEL) upstream of the laser accelerator, and the Ti-Sapphire laser will be mode locked to the FEL to give picosecond level timing between the laser and beam. A pulsed kicker in the electron beamline downstream of the FEL, triggered in synchronism with the laser Q-switch, will provide low rate beam to the laser accelerator. Emittance filters between the kicker and laser accelerator will control incoming beam intensity and emittance, and the outgoing beam will be diagnosed with a high resolution spectrometer. Energy gain of

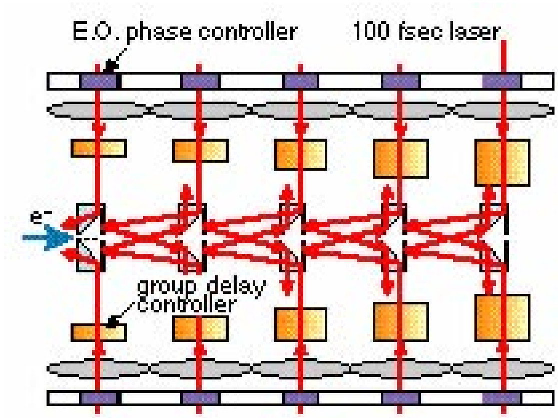

Figure 3: Multi-stage laser acceleration.[7]

330 keV (~1%) is possible without damaging the laser accelerator optics.

The first experimental run will be in November, 1997 and will be devoted to setting up the laser and electron beam lines and establishing the timing between the two beams. Observation of laser acceleration and measurement of accelerating gradient and beam loading for different accelerator configurations is expected in early 1998. These experiments should establish the viability of this approach to laser acceleration.

Building a high energy linac will require multiple stages for high energy and recycling of the laser light for acceleration of significant charge. One multi-stage concept is illustrated in Figure 3.[7] Light from a multi-terawatt laser is split and drives many cells. There is an overall electro-optical phase control and group delay elements compensate for electron beam transit time. A large accelerator would require many such sections and mode-locking of multiple multi-terawatt lasers. This is still to be accomplished.

The accelerator in Figure 3 has a single electron beam, and longitudinal wakefields could limit the accelerated charge to an unacceptably low value. The "matrix accelerator", proposed by D. Whittum for mm-wave acceleration,[8] recycles the output power that would normally be dumped into a load to accelerate multiple beams that are combined at the end of the accelerator. This seems natural for laser accelerators also. Rather than throwing away the output light in Figure 3 it could be transported to another beamline to accelerate particles there. T. Plettner and J. Spencer have devised appropriate optics for this and are studying the wavefronts of the light recycled through multiple stages.[5]

III. PLASMA WAKEFIELD ACCELERATION

Laser or particle beams can excite relativistic plasma waves that have a longitudinal, accelerating component of electric field. Gradients of 100 GV/m have been reached over short distances in laser driven plasma wakefield accelerators, and up to 100 MeV energy gain has been measured.[9,10] These are impressive accomplishments with the potential of revolutionary changes in particle accelerators.

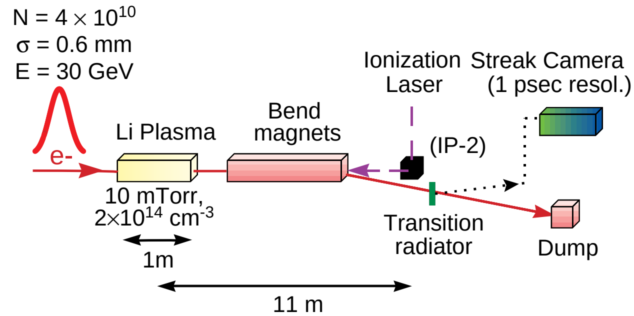

Figure 4: Schematic of E-157, the plasma wakefield acceleration experiment, to be performed in the SLAC Final Focus Test Beam (FFTB).

They have led to controversy also. Some plasma researchers have boldly extrapolated these successes into visions of small, inexpensive colliders capable of doing the particle physics research of larger, conventional accelerators. This is a vision that has attracted attention in the popular press and natural skepticism in the scientific community. That skepticism is based on *i)* the present limited experience and *ii)* the many facets of a high energy collider: beam quality and control and stability, staging of multiple acceleration sections, power source efficiency, etc., that are yet to be considered. Plasma acceleration could be a revolutionary development or it could be as difficult and distant as fusion production of energy has proven to be.

However despite skepticism, the promise and potential of plasma accelerators challenges one to test and explore them in new ways with different implications for possible future applications. SLAC experiment E-157 is such an exploration. The objective is measurement of the behavior of a well-characterized beam in a long plasma with the immediate goal of achieving up to 1 GeV energy gain with a gradient of 1 GeV/m.

The experiment, to be performed by a collaboration of physicists from LBNL, UCLA, USC and SLAC,[11] is illustrated schematically in Figure 4. The plasma is "underdense", the beam density is greater than the plasma density, and plasma electrons along the beam path are expelled by the beam as it passes. The ions are stationary. This creates a high-gradient accelerating structure with a wavelength, λ_p, set by the plasma density, n_0,

$$\lambda_p(\mathrm{mm}) \approx \sqrt{\frac{1}{n_0(10^{15}\ \mathrm{cm}^{-3})}}. \tag{7}$$

A large accelerating voltage

$$E_z(\mathrm{GV/m}) \approx 3.2\sqrt{n_0(10^{15}\ \mathrm{cm}^{-3})} \tag{8}$$

is produced after the beam passage as the space charge force from the ions draws the expelled electrons back. Energy extracted from the head of the beam has created a wakefield that accelerates the tail. The resultant peak accelerating field is ~ 1 GeV/m for the E-157 parameters. Shortening the bunch and increasing the plasma density would dramatically increase

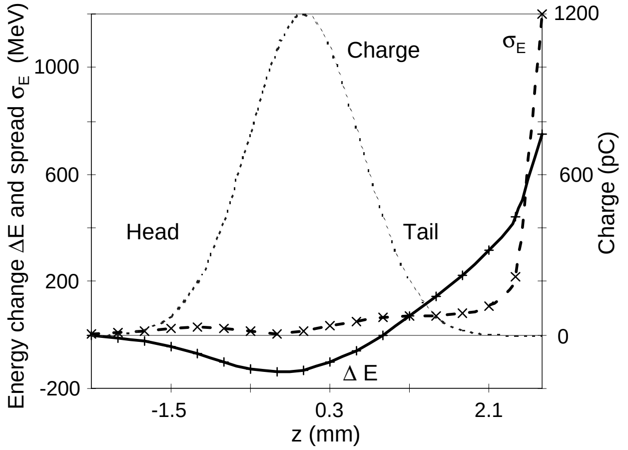

Figure 5: The expected experimental signature; mean change in energy (solid line) and energy spread (dashed line) in 1 psec slices along the beam.

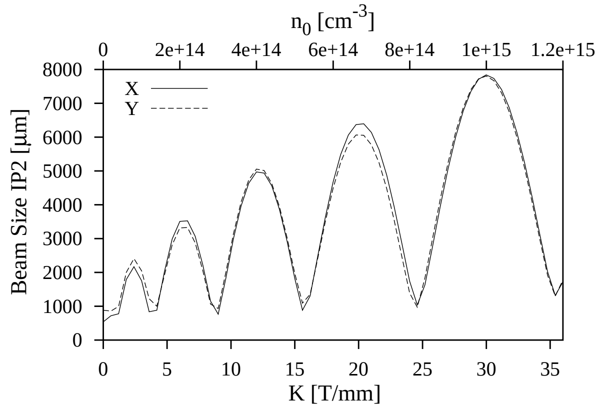

Figure 6: Betatron beam sizes at the diagnostic point (IP2) for different plasma densities.

the gradient. For example, σ = 0.4 mm and $n_0 = 10^{15}$ cm^{-3} would increase the peak accelerating gradient to ~ 2.5 GeV/m.

The primary diagnostic will be a streak camera with 1 psec resolution in the conditions of this experiment. Acceleration will be measured by measuring the beam deflection in a dispersive region of the FFTB. Figure 5 shows the expected signal; the tail of the beam will have a mean energy increase of ΔE ~ 750 MeV and an RMS energy spread of over 1 GeV.

Not only is the combination of accelerating gradient and length unprecedented, but the focusing fields are also. Once the electrons have been expelled, the remaining ion column forms a uniform focusing field with a gradient of 6000 T/m. It won't be possible to match the beam into this strong lens for two reasons: *one of principle* - the ion column is formed as the head of the beam expels electrons, and the head and tail experience different focusing gradients; and *a practical one* - the matched β and spot size are 12 cm and 4 µm, respectively, and they cannot be achieved with the FFTB magnets. The solution will be to have an integral number of betatron oscillations in the plasma as shown in Figure 6.

The beam plasma interaction has been extensively simulated for the E-157 conditions, but the accelerating and focusing field strengths and the transient nature of the plasma phenomena make unanticipated effects likely. Important advantages for understanding these effects will be the knowledge of the SLC beam and the FFTB optics together with the extensive diagnostics for measuring beam properties including trajectory, β-functions, and emittances. The incoming beam will be well-characterized. Measuring and explaining the properties of the outgoing beam promise to give new insights into the beam-plasma interaction, insights into fundamentals of particle acceleration and the viability of plasma accelerators.

IV. MM-WAVE ACCELERATORS

The predominant experience with RF linacs has been at S-band, but efficiency and gradient limitations argue for shorter wavelengths as the energy increases. The NLC is optimized for E_{CM} ~ 1 TeV and is at X-band. While some aspects of the NLC are scaled from S-band, designing a TeV energy collider has required significant innovations. Still shorter wavelengths and more innovations are going to be necessary for multi-TeV energies.

Our research in short wavelength, high gradient, RF driven acceleration has concentrated on 90 GHz which is in the middle of W-band.[12] It involves understanding of gradient limitations, developing collider concepts consistent with those limitations, application of new technologies to accelerator fabrication, and some preliminary work on W-band power sources. All of this is being done with a short range goal of building a 1 m long, 1 GeV accelerator.

A. Gradient Limitations

P. Wilson has developed convenient parametrizations for gradient limits from trapping of field emitted electrons and from RF breakdown.[13] Field emitted electrons can be accelerated to relativistic energies in a RF cycle and trapped by a traveling RF wave when the gradient exceeds

$$G_{trap} = \frac{\pi mc^2}{\lambda} = \frac{1.6\text{ MeV}}{\lambda}. \tag{9}$$

This is not a rigorous bound, but possible deleterious effects from trapped dark current include beam loading, random deflecting wakefields, radiation damage, and backgrounds in diagnostics and, possibly, the high energy physics experiment.

The RF breakdown limit is empirical and is based on experiments of breakdown at fixed pulse length and different frequencies[14] and experiments at different pulse lengths and the same frequency, f = 8.568 GHz.[15] Combining these assuming the same fractional fill time gives[13]

$$G_{break} = \frac{1.1\text{ GeV / m}}{[\lambda(\text{cm})]^{7/8}}. \tag{10}$$

This result should be taken as rough guidance only because it is based on only two experiments and because there is little understanding of the underlying causes of RF breakdown.

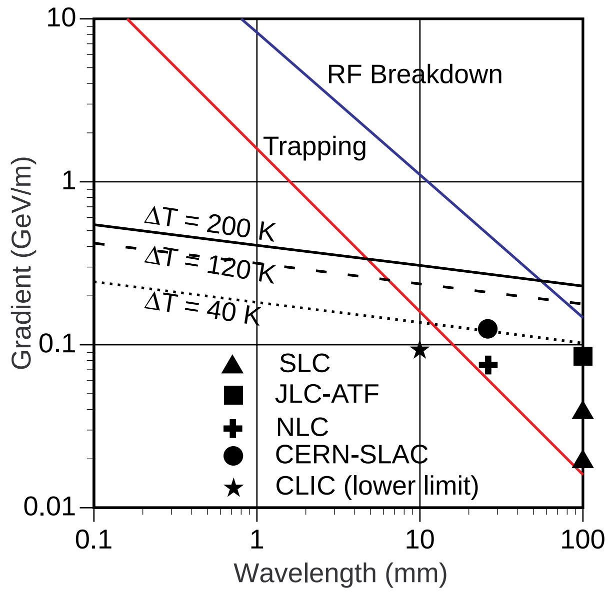

Figure 7: Gradient limits due to dark current trapping, RF breakdown, and pulsed heating. The data points are achieved gradients at different frequencies. Pulsed heating is scaled from NLC as described in text. Data are from SLC, NLC,[16] CERN-SLAC,[17] CLIC,[18] JLC-ATF[19]; they represent gradient achieved with reasonable dark current.

These two expressions are shown in Figure 7 together with gradients measured at different frequencies. The data and limits are consistent, and trapping is the more restrictive at long wavelengths. Based on considerations of trapping and breakdown only, the wavelength must be in the mm range to reach gradients of ~ 1 GeV/m. However, at that wavelength pulsed heating appears to be more important. This phenomenon needs to be understood, and accommodated in the accelerator design.

B. Pulsed Heating

RF surface currents flow within a few skin depths of the surface. The skin depth of copper at W-band is δ ♠ 0.2 µm. The resulting heat diffuses away from the surface with a diffusion depth proportional to the square root of time. For a square pulse of length T_p and gradient G the maximum surface temperature is[13]

$$\Delta T = \frac{G^2\sqrt{T_p}}{Z_H^2}\frac{R_s}{\sqrt{\pi\rho c_\varepsilon k}} \tag{11}$$

where R_s is the surface resistance, ρ is the density, c_ε is the specific heat, and k is the thermal conductivity. The impedance Z_H is the ratio

$$Z_H = \frac{G}{H_{max}} \tag{12}$$

where H_{max} is the maximum surface magnetic field. Using NLC values, Z_H = 300 Ω and T_p = 360 nsec, and scaling pulse length with filling time, $T_p \sim \lambda^{3/2}$, gives the pulsed heating curves in Figure 7.

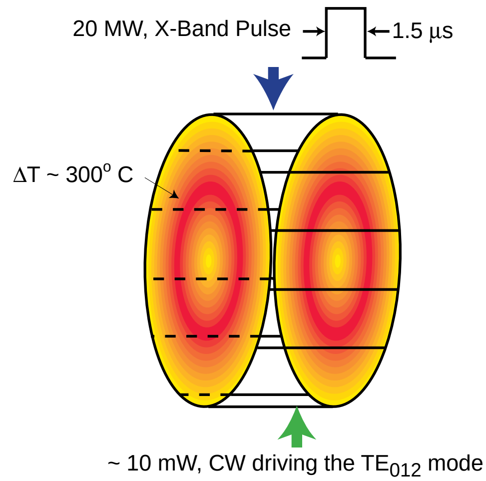

Figure 8: Schematic of pulsed heating experiment.

Surface pulsed heating can lead to fatigue and failure of metals. As the surface heats it expands in the unconstrained direction normal to the surface and goes into compression in the tangential direction where it is constrained. Plastic deformation occurs when the compression exceeds the yield strength. This corresponds to a temperature rise

$$\Delta T_y = \frac{(1-\nu)Y}{E\alpha} \tag{13}$$

where ν is Poisson's ratio, Y is the yield strength, E is Young's modulus, and α is the coefficient of linear expansion.

Repeated cycling results in the formation of slip bands and fatigue cracks, but the temperature rise that causes this damage is a factor above ΔT_y. There is disagreement over both the numerical value of this factor and the physical origin of it. For copper ΔT_y = 22K,[20] and estimates for the damage threshold include ΔT = 40K[21] and ΔT = 110K.[22] Once the threshold is exceeded, the lifetime of the metal, N_τ measured in cycles, is exponential in the stress amplitude, σ, with a scale factor σ_S[22,23]

$$N_\tau \propto \exp(-\sigma / \sigma_S). \tag{14}$$

The tolerable pulsed temperature rise in RF systems is critical for determining the achievable gradient at short wavelengths, and a series of experiments designed to measure it has begun. The experimental goals are:

- To measure the damage threshold for copper and other materials including composites and materials with surface coatings. For example, dispersion strengthened copper, Glidcop AL-15, has ΔT_y = 120K.[24]
- To verify the exponential relationship between lifetime and stress amplitude.
- To establish the scale factor σ_S in eq. (14). Kovalenko has developed a model where σ_S depends on the evaporation energy and on ambient temperature.[22]

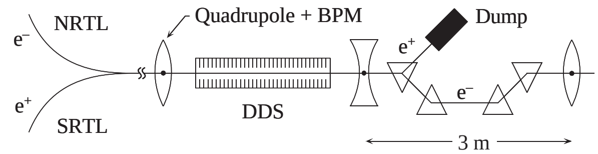

Figure 9: The ASSET facility.[28]

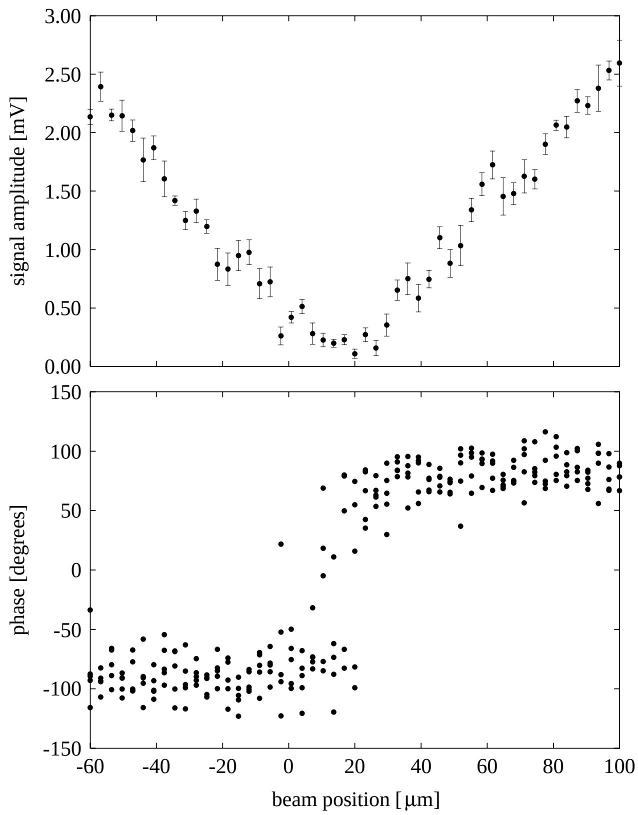

Figure 10: Amplitude and phase of the dipole mode signal at f = 14.9675 GHz.[30]

The experiment is illustrated in Figure 8. A TE_{011} mode in an X-band pill-box cavity is driven by a 20 MW, 1.5 μsec long, 60 Hz repetition rate RF pulse.[25] The surface current on the endcaps follows a J_1 Bessel function, and the pulsed temperature rise at the center of the endcaps can be up to $\Delta T \sim 300K$. Temperature rise is measured by changes in reflection of the TE_{012} mode that is excited with low power CW RF. The endcaps can be removed for metallurgical examination after an exposure.

The first round of this experiment has been performed with over 10^7 pulses on copper endcaps with $\Delta T > 100K$. There was no degradation of the Q's of the TE_{011} or TE_{012} modes, but there was some evidence of changes in crystal structure at the RF surface.[26] The experiment is currently being redesigned to eliminate problems with RF breakdown and the diagnostic RF signal, and it is expected to be running again with higher temperature rises in Spring, 1998.

C. Wakefields

Wakefields depend strongly on wavelength, for example

$$W_{\perp,\text{effective}} \propto \frac{1}{\lambda^3}, \tag{15}$$

and wakefield effects in a mm-wave accelerator must managed with a combination of reducing the accelerated charge and precise alignment. The next section deals with the former and this section with the latter.

Recent experiments have demonstrated high precision, beam based alignment using accelerator structures themselves as beam position detectors.[27] The experiments were performed at the ASSET facility located in the SLAC linac after the SLC damping rings and shown in Figure 9.[28] Electron and positron beams from the damping rings are launched on parallel trajectories The positron intensity is substantially higher, and the positron beam transverse wakefields are measured by means of the trajectory of the weaker electron beam. Both short- and long-range wakefields can be measured by varying the time between the beams.

The transverse wakefields of a 1.8 m long, X-band damped-detuned structure (DDS)[29] were measured. The DDS has RF manifolds for damping the lowest frequency deflecting mode in a band centered at 15.1 GHz. These manifolds have windows for either attaching external loads or measuring the beam induced signal. The amplitude and phase of one dipole mode is shown in Figure 10. The amplitude has a minimum and the phase changes by 180° in a region that is ± 10 μm wide which was comparable to the beam jitter.

The beam was centered at both ends of the DDS structure using these single mode signals, and then the short-range wakefield, which depends on many modes, was measured with the electron beam. This second measurement showed that the beam was centered to ± 25 μm. Understanding and improving this resolution will require further experiments.

The central feature tested in this experiment was that deflecting mode signals can be used to directly measure the relative alignment of beam and accelerator. This technique could be generalized to using deflecting mode signals in feedback loops that would move structures to maintain alignment. Such ideas will be critical for wakefield control in a mm-wave accelerator.

D. Collider Configurations

The relationship between luminosity, L, single beam power, P_B, center-of-mass energy, E_{CM}, vertical spot size, σ_y, and experimental backgrounds measured by the number of beamstrahlung photons per incident particle, n_γ, is

$$L = \frac{1}{4\pi\alpha r_e}\frac{n_\gamma}{E_{CM}}\frac{P_B}{\sigma_y}. \tag{16}$$

High luminosity requires a small beam spot and large beam power, and these require small emittance and good acceleration efficiency, respectively. This is accomplished in the NLC design with relatively low charge per bunch and multiple bunches per RF pulse.

This multiple bunch strategy cannot be followed to $\lambda \sim 1$ mm. Wakefields and emittance preservation favor small

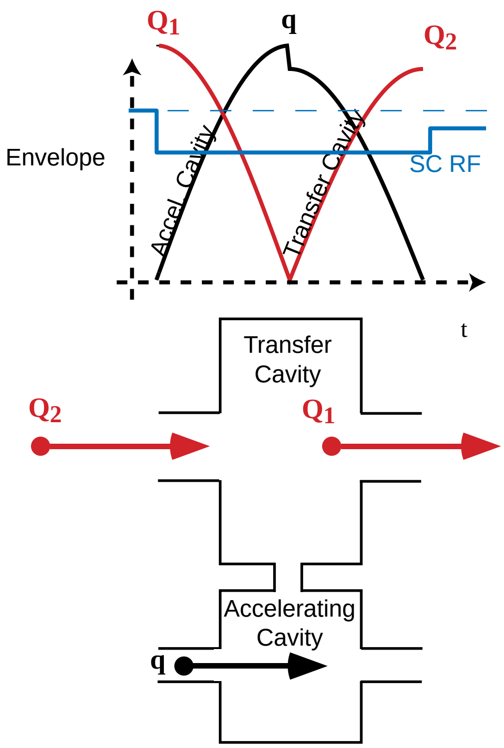

Figure 11: The field envelopes and accelerator configuration of the cavity beat-wave accelerator concept.

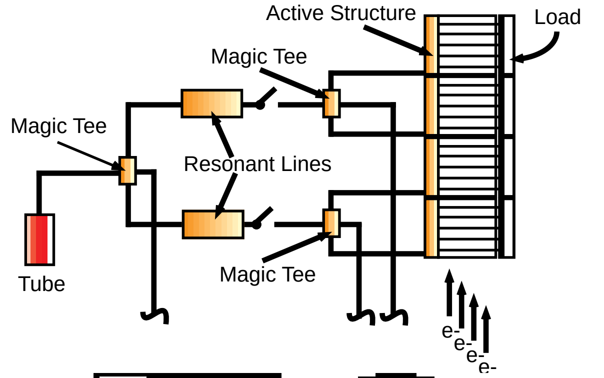

Figure 12: The matrix accelerator.

Figure 13: Sketch of the first SLAC mm-wave accelerator structure. The top and bottom layers provide mechanical strength and taper from WR10 waveguide. The thin intermediate layers contain the coupling irises. The middle layer, one piece split in two in this picture for purposes of illustration, contains the beam and vacuum pipes and the seven cells.

charge per bunch and a large number of bunches, but pulsed heating argues for a short RF pulse. Pulsed temperature rise ΔT = 200 K might be possible, but even in that case the gradient limit would be G < 0.5 GeV/m if the pulse length scaled as assumed in Figure 7. Higher gradient requires a shorter RF pulse. Satisfying the constraints of a high energy collider will need qualitative changes in accelerator configuration.

There are two ideas that have been considered. The first is the "cavity beat-wave accelerator"[31] which is a two-beam accelerator with energy recovery illustrated in Figure 11. High charge bunches Q_1 and Q_2 pass through a mm-wave cavity, the transfer cavity. The first bunch, Q_1, excites the fundamental mode of the transfer cavity. The accelerating cavity fundamental frequency is close to that of the transfer cavity, and energy beats between the transfer and accelerating cavities. The high energy beam, q, is accelerated during the first of these beats. Drive bunch Q_2 passes through the transfer cavity the first time the energy reappears there, and it is phased such that energy is extracted from the cavity fields. The drive beam is accelerated by a superconducting RF cavity. The bunches are spaced appropriately such that Q1 extracts energy from the superconducting cavity and Q2 restores energy. The net energy loss from the superconducting RF is the energy transferred to bunch q and due to inefficiencies.

The cavity beat wave accelerator has been analyzed for mm-waves and 1 GeV/m gradient.[32] The drive beam charge was 110 nC, and transverse stability of the drive beam would require strong focusing that could possibly be obtained with exotic techniques like ion-channel guiding.[33] The key to further development is solving the drive beam transverse dynamics.

The "switched matrix accelerator", illustrated in Figure 12, is a more radical idea.[8] The RF and beams travel in perpendicular rather than parallel directions. The gradient part of the structure is exposed to RF for a short time, thereby limiting the pulsed heating, and yet the RF efficiency is high because multiple beams are accelerated.

The first element is an RF power source with a relatively long pulse that is compressed to approximately 200 MW, 10 ns long pulses. This power is distributed to the primary transmission lines of the accelerator which are then discharged in sub-nanosecond pulses into secondary lines where the beams are accelerated. The beams must be combined after acceleration most likely through a non-isochronous beam transport.

At the present time D. Whittum is calculating properties of matrix accelerator with concentration on the primary and secondary transmission lines such that there is good energy efficiency and low dispersion of pulses in the secondary lines. There are important technological issues in addition to these considerations. They are the mm-wave power source, the

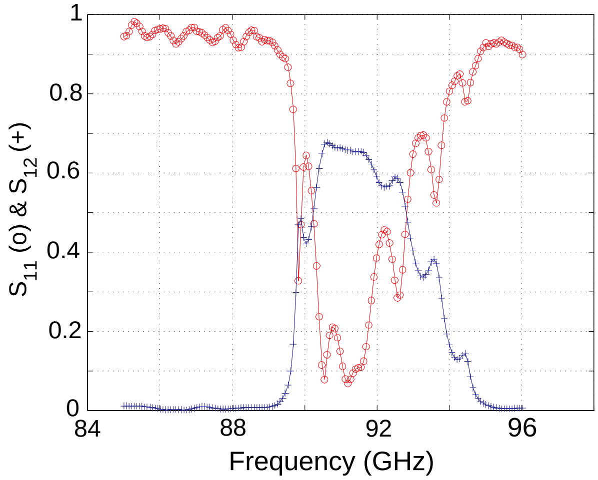

Figure 14: Reflection (S_{11}) and transmission (S_{12}) measurements.

pulse compressor, and the switches that discharge the primary into the secondary transmission lines. There are ideas and/or the beginnings of work in all these areas:

- A multi-hundred kW klystron array is being designed that is based on permanent magnet focusing, quasi-optical combining of power, and the fabrication methods discussed in the next section.[34] While not adequate for a collider RF power source, this klystron would produce record power at W-band and be the beginning of high power mm-wave production at SLAC.
- The klystron is serving as an introduction to quasi-optical techniques which are certain to be necessary for high power W-band RF manipulations.
- There has been a first test of an optically triggered silicon RF switch, and active pulse compression has been demonstrated at moderate power.[35]

The underlying idea of the matrix accelerator, orthogonal propagation of beam and RF power, has the potential for the efficient use of short, high power pulses. It appeared in the laser driven accelerator for the same reason The idea's merit for mm-waves depends on the calculations described above, and it depends on recombining wavefronts in the laser accelerator case. In both cases there is the need for successful development of the required technologies also.

E. MM-Wave Accelerator Fabrication

MM-wave accelerators have mm feature sizes, and scaling from S- and X-band accelerators and from numerical models the dimensional tolerances are 2 - 5 µm on critical features. These feature sizes and tolerances suggest fabrication by LIGA where a plastic mold is made by exposure to high energy X-rays.[36] This is followed by chemical removal of radiation damaged plastic and electrodeposition of metal into the mold to produce the final part.

We have not pursued LIGA because: *i)* reducing the consequences of pulsed heating could require materials such as Glidcop that cannot be electrodeposited, and *ii*) the large initial investment to gain proficiency with LIGA. Wire EDM (ElectroDischarge Machining) routinely reaches better than 5 µm level of precision,[37,38] and EDM machines with sub-micron precision are being manufactured although they are not readily available.

A planar,[39] seven-cell, $2\pi/3$ traveling wave structure, illustrated in Figure 13, was designed, machined using wire EDM by Ron Witherspoon, Inc., and measured.[37,40] The reflection and transmission were measured and are shown in Figure 14. These results had both encouraging and discouraging aspects. The encouraging ones were that a structure could be fabricated with wire EDM techniques and the mode pattern was close to that expected.

The discouraging aspect was that the peak transmission was less than 70% when roughly 95% was expected. The possible contribution of surface finish to losses was measured in a separate experiment using two-inch long WR10 waveguides machined with wire EDM. It was found that with the 0.2 µm rms finish of the seven-cell structure the effective conductivity was $\sigma = 2.5\infty10^{7}$ Ω/m as compared to $\sigma = 6.0\infty10^{7}$ Ω/m for OFE copper.[41] This is not enough to account for the low transmission. Other experiments eliminated energy propagation out of the beam or vacuum ports. This leaves the contact between the layers, which were just clamped together, as the most likely explanation. The next structure will be diffusion bonded to eliminate this cause of energy loss.

This next structure will have twenty-five cells and will also include a number of design innovations including compatibility with vacuum pumping and water cooling and having all of the machining including waveguide tapers and coupling irises in a single layer.[37] Machining is expected to be complete in early 1998, and we are looking forward to measuring its properties.

Once that is completed there are plans to place it or a similar structure in the NLC Test Accelerator beam and use that beam to generate RF power in a test of a high power mm-wave accelerator. This will be the first opportunity to see if the extrapolation of gradient limit from RF breakdown (Figure 7) has some validity.

V. CONCLUDING REMARKS

The SLAC advanced accelerator program described in this paper is an attempt to pose and answer questions that could lead to inventions or dramatic changes in electron linear accelerators. All of the work described is speculative, but, hopefully, well motivated and focused on significant problems.

SLAC ARDB (Accelerator Research Department B) is at the center of this work and has been fortunate to have strong support from the laboratory and enthusiastic collaboration within SLAC, other academic institutions, and industry.

VI. FOOTNOTES & REFERENCES

1. M. D. Perry, AIP Conf. Proc. 335, 75 (1995).
2. Y. C. Huang *et al*, Applied Physics Letters **68**, 753 (1996).

3. L. W. Davis, Physical Review A **19**, 1177 (1979).

4. Y. C. Huang and R. L. Byer, Applied Physics Letters **69**, 2175 (1996).

5. T. Plettner & J. Spencer, private communication.

6. Laser Acceleration Collaboration: R. L. Byer, R. H. Pantell, T. Plettner, Y. C. Huang (Ginzton Laboratory); R. L. Swent, T. I. Smith (Hansen Laboratory); J. E. Spencer, R. H. Siemann, H. Wiedemann (SLAC).

7. R. L. Byer, private communication.

8. D. H. Whittum, SLAC technical note ARDB-086.

9. A. Modena et al, Nature **337**, 606 (1995).

10. K. Nakajima et al, AIP Conf Proc **398**, 83 (1997).

11. E-157 Collaboration: S. Chattopadhyay, W. Leemans (LBNL); C. Clayton, C. Joshi, K. Marsh, W. Mori, G. Wang (UCLA); T. Katsouleas, S. Lee (USC); R. Assmann, P. Chen, F. J. Decker, R. Iverson, P. Raimondi, T. Raubenheimer, S. Rokni, R. Siemann, D. Walz, D. Whittum (SLAC).

12. This W-band research is a collaboration of SLAC Accelerator Research Department B (ARDB), other SLAC departments, and collaborators from other institutions: T. Chen, P. J. Chou, M. Hill, T. Knight, X. Lin, A. Menegat, D. Palmer, B. Podobedov, D. Pritzkau, M. Seidel, A. Seymour, R. Siemann, J. Spencer, D. Whittum, X. Xu (SLAC ARDB); C. Adolphsen, G. Bowden, R. Carr, G. Caryotakis, M. Copeland, A. Farvid, R. Folkes, R. Kirby, K. Ko, N. Kroll, R. Loewen, E. Lundahl, R. Miller, C.-K. Ng, A. Odian, C. Pearson, M. Petelin, R. Phillips, R. Pitthan, G. Scheitrum, Y.-Y. Sung, A. Vleiks, C. Yoneda, P. Wilson (other SLAC departments); W. Bruns, H. Henke, R. Merte (Tech. Univ. Berlin); T. Lee, D. Yu (DULY Research); D. Miller (EMT); S. Schultz (Univ. of Cal, San Diego): S. Schwartzkopf, R. Witherspoon (Ron Witherspoon, Inc.).

13. P. B. Wilson, AIP Conf Proc **397**, 191 (1997).

14. G. A. Loew and J. Wang, SLAC-PUB-4647.

15. A. Vlieks *et al*, SLAC-PUB-4546.

16. J. W. Wang *et al*, Proc of 17th Int. Linac Conf, 305 (1994).

17. J. W. Wang *et al*, Proc of 18th Int. Linac Conf, (Geneva, 1996).

18. R. Bossart *et al*, Proc of 1994 European Accel Conf., 680 (1994).

19. H. Matsumoto, Proc of 18th Int. Linac Conf, (Geneva, 1996).

20. Based on $Y = 6.9\infty10^7$ N/m^2, $E = 1.17\infty10^{11}$ N/m^2, $\alpha = 1.73\infty10^{-5}$, and $\nu = 0.345$.

21. H. M. Musal, Jr, Laser Induced Damage in Optical Materials 1979, Nat Bureau Standards Spec Pub 568, 159 (1980).

22. V. F. Kovalenko, Physics of Heat Transfer and Electro-Vacuum Devices, Sovetskoe Radio (1975).

23. A. Weronski and T. Hejwowski, Thermal Fatigue of Metals, Marcel Dekker, Inc. (New York, 1991).

24. SCM Metal products, Inc., Cleveland, Ohio. ΔT_y based on $Y = 35\infty10^7$ N/m^2, $E = 1.15\infty10^{11}$ N/m^2, $\alpha = 1.66\infty10^{-5}$, and $\nu = 0.35$.

25. D. Pritzkau *et al*, presented at 1997 Part. Accel. Conf.

26. D. Pritzkau, private communication.

27. M. Seidel *et al*, submitted to Nucl. Inst. & Methods.

28. C. Adolphsen *et al*, Phys Rev Lett **74**, 2475 (1994).

29. N. Kroll *et al*, presented at the 1997 Part. Accel. Conf.

30. M. Seidel, presented at the 1997 Part. Accel. Conf.

31. H. Henke, CERN-LEP-RF/88-55.

32. D. H. Whittum *et al*, submitted to 1997 Part Accel Conf.

33. D. H. Whittum *et al*, Phys. Rev. **A** 6684 (1992).

34. G. Caryotakis *et al*, SLAC-PUB-7624 (1997).

35. S. Tantawi *et al*, SLAC-PUB-7368 (1996).

36. E. W. Becker *et al*, Microelectronic Engineering **4**, 35 (1986). LIGA is an acronym for Lithografie, Galvanoformung and Abformung.

37. P. J. Chou *et al*, SLAC-PUB-7498, submitted to 1997 Part Accel Conf.

38. In a seven-cell test performed on an Agiecut 150 HSS deviation of nominal centers of cavities was within 1 µm, and the variation in sizes was less than 2.7 mm. Ref [37].

39. LIGA and wire EDM favor a planar structures, and, in addition, the matrix accelerator is most natural planar geometry.

40. P. J. Chou *et al*, SLAC-PUB-7499, submitted to 1997 Part Accel Conf.

41. For comparison, 1.5 µm rms surface finish had an effective conductivity of $\sigma = 6.3\infty 10^{6}$ Ω/m, and when chemically etched this could be increased to $\sigma = 4\infty 10^{7}$ Ω/m

Medical Uses of Linear Accelerators

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Cancer is the second leading cause of death in the United States. Approximately 1 out of 3.5 people will be treated for cancer at sometime in their lifetime and over half of these people will be treated by radiation oncology machines most of which are linear accelerators. Since the advent of linear accelerators for cancer treatment about 40 years ago, five year survival rates have improved from 39% to 54%. Much of this improvement can be directly attributable to the capabilities provided by linear accelerators.

The treatment of cancer using radiation began in the early 1900's with kilovoltage x-ray machines which operated at 150 to 350 kilovolts (Figure 1). These machines had the disadvantage of a very low depth of penetration and excessive dose to and burning of the skin (Figure 2).

Through the 1930's and 1940's several other types of equipment were used to treat cancer with external beam radiation. These included 1 and 2 MeV Van de Graaff accelerators (Figure 3), 18 to 45 MeV Betatrons (Figure 4), and isotope machines using Cobalt 60 (Figure 5). The particle accelerators had the disadvantage of low dose rates and excessive maintenance costs. The Cobalt units had the disadvantage of a declining dose rate and low

Figure 1: Kilovoltage treatment unit

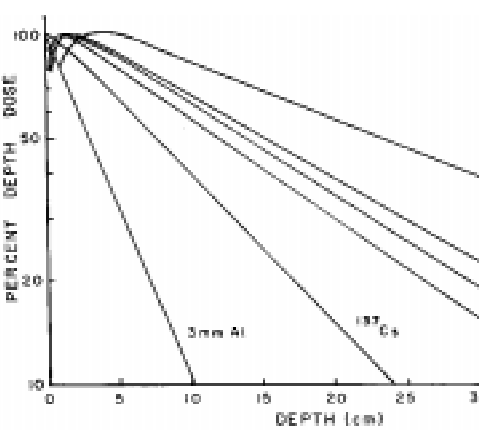

Figure 2: Depth of penetration for various energy photons. Kilovoltage x-ray machine is labelled 3 mm Al

Figure 3: Van de Graaff accelerator

Figure 4: Betatron

Figure 5: Cobalt therapy unit

energy as well as difficulty in precise location of the beam because of the penumbra effect (Figure 6).

In the mid-1950's with the earlier advent of microwave power tubes such as the klystron (Figure 7) and the invention of electron linear accelerators (Figure 8), accelerators appeared simultaneously in the United Kingdom and the United States. Such machines were in the range of 4-8 MeV in energy and limited by their inability to rotate totally around the patient (Figures 9 - 11). In 1960, the first 360º fully isocentric linear accelerator was developed at Varian and shipped to UCLA (Figures 12 - 13). In the 1960's approximately 40 of these machines were shipped to medical centers throughout the world. Satisfying the requirements for energy and flexibility, they still had the disadvantage of a high cost and the need for sophisticated physics support.

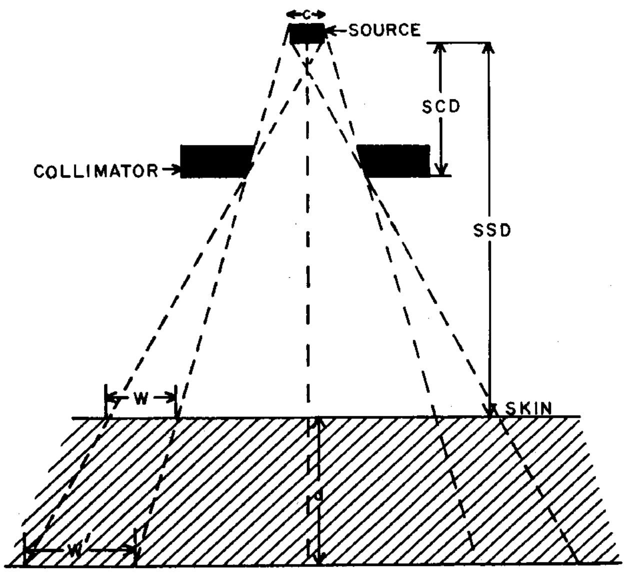

Figure 6: Cobalt penumbra effect. Sources are typically 1 cm in diameter.


Figure 7: Early klystron

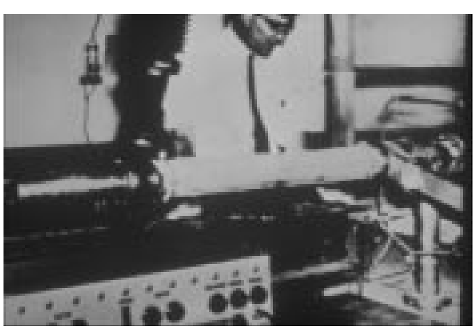
Figure 8: Research electron accelerator


Figure 9: Early linear accelerator: Vickers

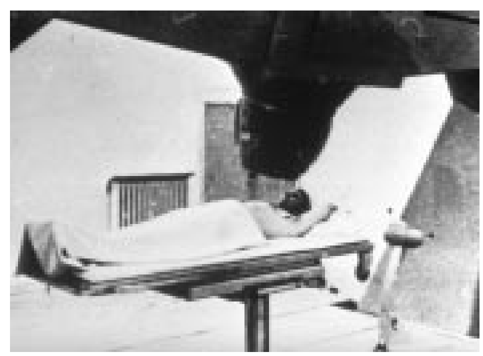
Figure 10: Early linear accelerator: Mullard

In 1968 with the adoption of standing wave accelerator technology (Figure 14) it became possible to reduce the complexity of accelerators by positioning the accelerator guide collinear with the direction of treatment and eliminate the bending magnet and all the sensitive adjustments associated with it (Figure 15). This technology brought the cost of linear accelerators to within a similar range as that of Cobalt and because of the simplicity rendered this a practical product for community hospitals without a high degree of technical support (Figure 16). Accelerators were quickly adopted and over the next 20 years became the recognized standard for external beam radiation oncology.

Additional enabling technologies have occurred to broaden the sophistication and capability of linear accelerators. These include the energy switch which has made possible high dose rates over a broad range of photon energies; the achromatic bending magnet (Figure 17) which has simplified and stabilized high energy accelerators to the point that they could also be utilized

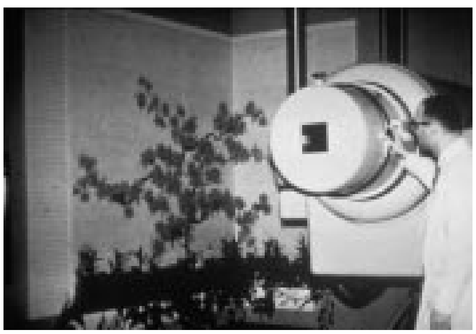

Figure 11: Early linear accelerator: Stanford/Varian

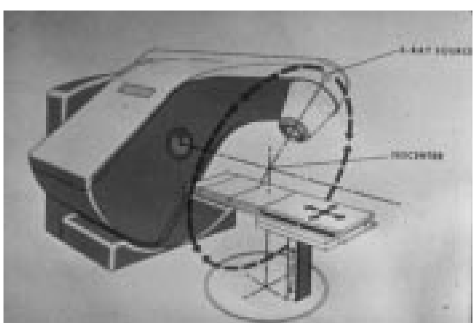

Figure 12: Concept of 360º isocentric rotation

Figure 13: First commercial 360º isocentric accelerator: the Varian Clinac 6 (ca 1960).

Figure 14: Standing wave accelerator

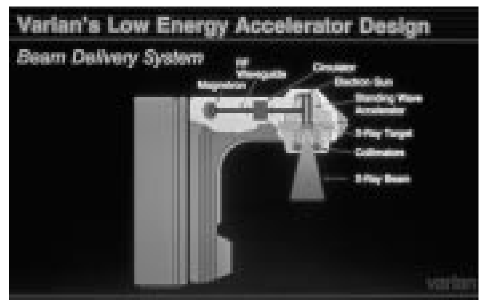

Figure 15: The first low cost rotational commercial accelerator: the Clinac 4

Figure 16: Simple Clinac 4 control console

readily in community hospitals (Figure 18); and the multi-leaf collimator (Figure 19), which has allowed precise shaping of the photon beam to match the irregular shape of most tumors (Figure 20).

The future of this technology will continue to evolve. Dynamic motion of the multi-leaf collimator during treatment will allow shaping of the photon beam in three dimensions to match the shape and density of the tumor (Figure 21). This in turn will lead to the ability to deliver higher doses to the tumor and lower doses and less complication for the healthy tissue. Further in the future, it is highly probable that the combination of conformally shaped radiation beams with radiation activated biological molecules will further enhance the effectiveness of radiation in the treatment of cancer (Figure 22).

All of this would not have been possible without the original technology developed at Stanford and at SLAC by William Hansen, the Varian brothers, and many others, and the visionary outlook of pioneers such as Ed Ginzton, Marvin Chodorow, and others who played an instrumental role in the commercialization of this technology despite the high financial risk.

The history of linear accelerators in medical technology represents a significant chapter in the humanitarian contributions of high energy and microwave physics.

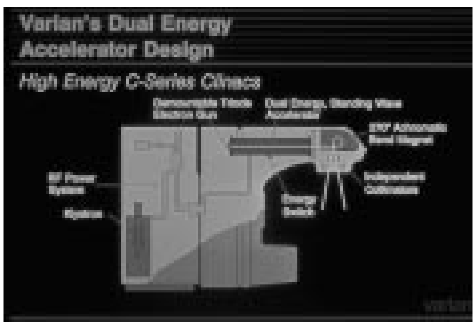

Figure 17: Enabling technologies: the energy switch and achromatic bending magnet

Figure 18: Community hospital based high energy accelerator: Clinac 2100c

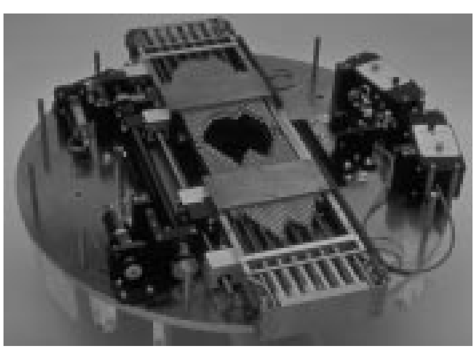

Figure 19: Multi-leaf collimator

Figure 20: Multileaf collimator shaped field

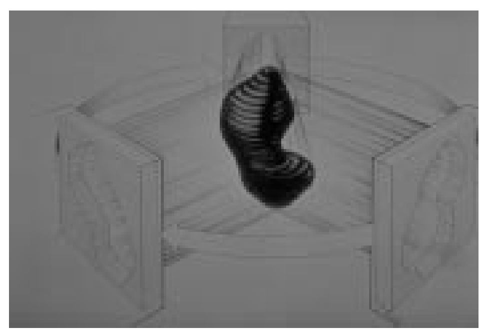

Figure 21: Three-dimensional tumor treatment with dynamic multi-leaf collimator

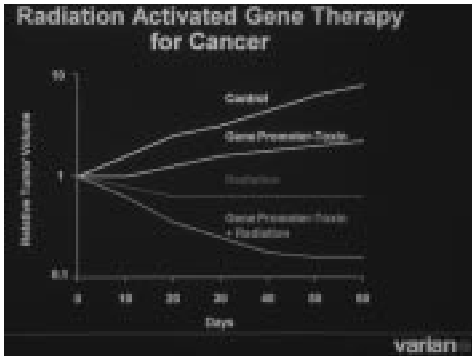

Figure 22: The potential of radiation-activated gene therapy
(From Univ. of Chicago data)

Linac-Based, Intense, Coherent X-Ray Source Using Self-Amplified Spontaneous Emission*

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ABSTRACT

We discuss the principles and properties of SASE radiation, and the reason why the SLAC linac is uniquely suited for the SASE generation of x-rays.

I. INTRODUCTION

The SLAC linac, built some thirty plus years ago by R. B. Neal, W. K. H. Panofsky, and others, is still young and vigorous. It will last another ten to fifteen years, and more if there are good ideas [1]. There is a good idea from the traditional high energy front: The SLAC linac is an important test bed for the Next Linear Collider [2]. This paper describes another good idea from a different perspective, namely its use for the Linear Coherent Light Source (LCLS) at the frontier of photon science [3]. The LCLS is an intense, coherent source of x-ray beams, which is a kind of free-electron laser (FEL) but operating in a special mode called the self-amplified spontaneous emission (SASE).

II. UNDULATOR RADIATION FROM THIRD-GENERATION SYNCHROTRON RADIATION FACILITIES

Undulator radiation is the radiation emitted by a relativistic beam of particles as it passes a periodic magnetic structure (called undulators) [4]. See Fig. (1). Undulators placed in straight section of low emittance, high current electron storage rings are the basis for the so-called third generation light source facilities. The radiation brightness—photon flux per unit phase space area—from undulators in the third generation light sources is typically about 10^{20} photons/(sec)(mm)^2(mrad)^2, which is about five to six orders of magnitude higher than the synchrotron radiation from bending magnets, which in turn is higher by another six orders of magnitude from the brightness of the x-ray tubes. The recognition of the power of the undulator radiation in studying the structure of atoms and molecules, and their arrangements in organic and inorganic materials, with far-reaching implications in the basic sciences and industries, has led to competition in recent years among countries around the world to construct third generation synchrotron radiation facilities.

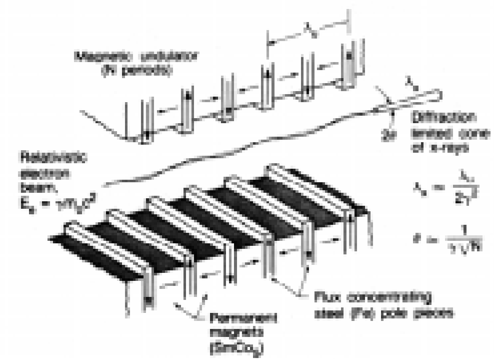

Figure 1. Schematic of a periodic magnetic structure (an undulator) of period λ_u and with a number of periods, N. The structure is based on permanent magnets.

The undulator radiation from an electron beam is an incoherent sum of radiation from individual electrons. The total radiation phase space is therefore given by a convolution of the coherent radiation phase space of individual electrons and the electron beam phase space. Since the electron beam phase space area is characterized by the rms emittance ε_x, and the corresponding quantity for coherent radiation is $\lambda / 4\pi$, where λ is the radiation wavelength, undulator radiation becomes maximally bright when $\varepsilon_x \le \lambda / 4\pi$ [5]. In this case the undulator radiation becomes transversely coherent, thus permitting interference techniques such as holography. For a typical third generation light source, the horizontal (vertical) rms emittance $\varepsilon_x(\varepsilon_y)$ is about $10^{-9}(10^{-11})$ m-rad. Therefore, the coherence condition is satisfied for UV radiation with the wavelength ≥ 100Å. Even for wavelengths down to tens of Å or shorter, the coherent fraction is substantial. These values of emittances, together with hundreds of milliamps of the ring current, and undulators with about 100 periods, are the reason why the brightness of the third generation synchrotron radiation source is so high.

* This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the Department of Energy under Contract No. DE-AC 03-76SF00098

III. FREE-ELECTRON LASERS

Imagine now that the undulator radiation generated by an electron bunch is trapped between two mirrors at both ends of the undulator. If the distance between the mirror pair, which forms an optical resonator, is properly chosen, then the radiation pulse generated from the one electron pulse can be made to return and travel together with the next electron bunch in the undulator. In that case, the interaction between the radiation pulse and electron beam is such that it causes periodic density modulation of the electron beam, with the period equal to the radiation wavelength. A density modulated electron beam radiates more strongly than an electron beam with random electron distribution. The stronger radiation pulse in turn leads to higher density modulation. This process, which is essentially the same as in conventional laser oscillators, continues until the intracavity radiation intensity reaches a saturation level. Such an arrangement, referred to as the free-electron laser (FEL), produces highly coherent radiation beams of spectral brightness many orders of magnitude higher than that of the undulator radiation [6].

The advantage of the FELs over the conventional lasers is that the wavelength can be chosen arbitrarily if electron beams of suitable energy and beam brightness, and high reflectivity mirrors, were available. To date, the shortest wavelength record of free-electron lasers has been 2400Å from a storage-ring-based free-electron laser in Novosibirsk [7]. The wavelength limit here was due to the mirror availability.

IV. SELF-AMPLIFIED SPONTANEOUS EMISSION

In the above, we have described the FEL oscillators based on use of a mirror pair. As in conventional lasers, FELs can also be used as an amplifier if seed lasers are available. An amplifier has the advantage that it does not require mirrors. For a sufficiently high electron beam brightness, and for a sufficiently long undulator, the gain in a single pass could be so high that the spontaneous undulator radiation emitted in the beginning part of the undulator could be amplified to an intense, quasi-coherent radiation, the so-called self-amplified spontaneous emission (SASE) [8]. Seed lasers are not necessary in this case. The reason why SASE has been attracting much attention recently as the basis for the “fourth generation” light source is the fact that it is currently the only known approach for obtaining tunable, coherent radiation down to the x-ray wavelength region, with brightness significantly higher than that available from current generation synchrotron radiation facilities.

A. Exponential Growth and Saturation

Various performance characteristics of SASE can be expressed by a single dimensionless parameter ρ: the power e-folding length (gain length) is about $1/4\pi\rho$ undulator periods; the SASE saturates in about $1/\rho$ undulator periods; and the saturation power is about ρ times the electron beam power. In order to limit the number of periods to less than 1000, the ρ parameter should be less than 10^{-3}. For the x-ray wavelengths in the range 10 to 1 Å, this requires the peak current of several kiloamps, the invariant emittance $\gamma\varepsilon_x \le 10^{-6}$ m-rad, where γ is the Lorentz factor, $\gamma \approx 2-3 \text{ x } 10^4$, and the energy spread $\Delta\gamma/\gamma \le 10^{-3}$.

B. Temporal Coherence

The temporal coherence of SASE radiation at saturation is very similar to that of an undulator radiation of periods $N = 1/\rho$; the SASE consists of random superposition of N_e wavetrains, where N_e = total number of electrons, each wavetrain being of about $1/\rho$ cycles. In the frequency domain, the radiation has a spectral width $\Delta\omega/\omega \sim \rho$, which specifies the first order coherence. The radiation intensity at a given frequency or time fluctuates 100%; i.e., the SASE belongs to the class of light referred to as “chaotic light.” The fluctuation can be reduced if the detector has a finite resolution so that the intensity is averaged over a finite resolution either in frequency domain or in time domain. In the case of the usual undulator radiation, the reduction factor is large, due to the long electron bunch and short radiation wavetrains. Therefore, the fluctuation is hardly observable. In case of SASE, the electron bunches are shorter and the radiation wavetrains longer, so that the intensity fluctuation could be 10-20%.

C. Transverse Coherence

In contrast to temporal coherence, SASE is quite different from undulators as far as the transverse coherence is concerned: the latter is partially coherent, while the former is fully coherent. The transverse coherence of SASE arises mathematically from the dominance of a single growing mode as a solution of the coupled Vlasov-Maxwell equation describing the high-gain FEL system [9]. Intuitively, it may be understood as follows: The angular divergence of undulator radiation is an incoherent sum of the angular divergence of individual undulator radiation, which is coherent, and the electron beam angular divergence. On the other hand, the electron beam develops density modulation in the case of SASE. The radiation angular divergence from each slice of the electron beam in which the electrons are bunched is the diffraction limited angular divergence determined by the transverse size of the electron beam, implying that the radiation is fully coherent transversely [5].

The bunching in SASE is not complete because the temporal coherence is chaotic. Nevertheless, the SASE is dominated by the bunched part, and the radiation from that part is transversely coherent.

V. STORAGE RING OR LINAC?

Let us now go back to the accelerators. The third generation synchrotron radiation facilities, the capabilities of which we already have emphasized, are all based on storage rings. However, we will see that linacs are better suited than storage rings for driving an SASE FEL for x-rays.

Storage rings provide high brightness electron beams, the brightest electron beams until recently. This is due to the inherent radiation damping taking place in storage ring bending magnets. By taking the maximum advantage of the damping, and at the same time minimizing the emittance dilution due to quantum excitation by a proper magnetic lattice, it was possible to design the high brightness storage rings for the third generation light sources. By the same token, however, the brightness achievable in storage rings is limited by the inherent beam dynamics phenomena of storage rings; quantum excitation, Touschek scattering, microwave instabilities, etc. With the impedance control and the size of storage rings that appear reasonable and feasible at present, the electron beam emittance is limited to about 10^{-9} m-rad, a bunch length of about 10 ps, with a charge of about 1 nC.

For a linac, however, the beam parameters are more or less determined by the gun. With the recent development of the RF photocathode gun [10] with the emittance correction technique [11], linacs became a very promising option for driving for SASE at x-ray wavelengths: the state-of-the-art RF gun technology could produce 1 nC electron bunches of invariance emittance $\gamma\varepsilon_x \approx 10^{-6}\mathrm{m-rad}$ in a pulse length of about 10 ps. After acceleration, pulse compression, and further acceleration, electron beams with 15 GeV of energy, pulse length of 200 fs, peak current of 5 kA, emittance $\varepsilon_x \approx 0.3\times10^{-10}\ \mathrm{m-rad}$ can be prepared, which are adequate for producing SASE radiation at ≥ 1 Å in a 200 fs pulse length. The SLAC linac is uniquely suited for this purpose, as was first emphasized by C. Pellegrini [12].

VI. FACTORS ENABLING LINAC-BASED SASE

There are basically three factors that enable the realization of 1Å SASE based on linacs. The first is the development of the RF photocathode gun as was already mentioned in the previous section. The second is the preservation of beam qualities through bunch compression and acceleration processes. The third is the development of precision undulator magnets.

A. RF Photocathode Gun

For SASE at x-ray wavelength, it is important that the already low emittance from an RF photocathode be further reduced by an emittance compensation scheme [11]. The emittance from an RF photocathode gun is due mainly to the space charge effect [13], causing the beam to expand with a different rate along the axial length of the bunch, stronger at the beam center and weaker at the ends. In the phase space picture, the emittance ellipses at different longitudinal positions "rotate" with different rates, causing an increase in overall emittance compared to the slice emittance. The emittance compensation scheme consists of reversing the beam expansion in a solenoidal focusing element, and realigning different slice ellipses in the drift section. The phenomenon here is very much analogous to the spin echo.

B. Bunch Compression and Acceleration

The beam from the RF photocathode gun is normally about ten picoseconds long. It needs to be compressed by a factor of 100 to increase the peak current to the level of a few kA, and accelerated to 10-20 GeV to achieve the required gain in a reasonable length (about 100 m) of an SASE undulator for x-ray wavelength. Avoiding the emittance dilution due to the single particle effects (focusing mismatch, dispersive and chromatic effect, etc.), and due to the beam instabilities, is a non-trivial problem due to the small emittance, high current beam under consideration. The R&D on this topic was studied extensively both numerically as well as experimentally in connection with the linear collider design efforts. Experimentally, the increase in the invariant, vertical emittance, which is about 1.5 mm-mrad, in the SLAC linac can be controlled to less than 50% through the 3 km-long linac in which the beam is accelerated to 50 GeV [14]. This is the level of control necessary for an x-ray SASE.

C. Long Undulator

The x-ray SASE requires a long undulator, typically about 100 m long with about 1000 periods. The undulator can be divided into several segments with an interruption between the adjacent segments, without degrading the exponential gain in the undulator [15]. The magnetic field tolerance of each segment is tight, but within the current state-of-the-art, due to the recent development in undulator construction spurred by the need of the third generation synchrotron radiation facilities. The interruptions between the segments can be used for focusing the electron beam and for installing diagnostic equipment. All segments must be aligned to within a few microns of accuracy.

VII. SASE PROJECTS

A. Overview

Several experimental projects are either in progress or being planned in several laboratories around the world, some of which are listed in Fig. 2. As indicated in the figure, the proof-of-principle experiments for wavelengths longer than 1μ have already achieved a significant level of single pass gain. The experiments at APS [16] and DESY [17], at wavelength around 1000 Å, will be carried out within one to two years. Eventually the goal is to achieve SASE at x-ray wavelength, for which the only linac available to date is the SLAC linac.

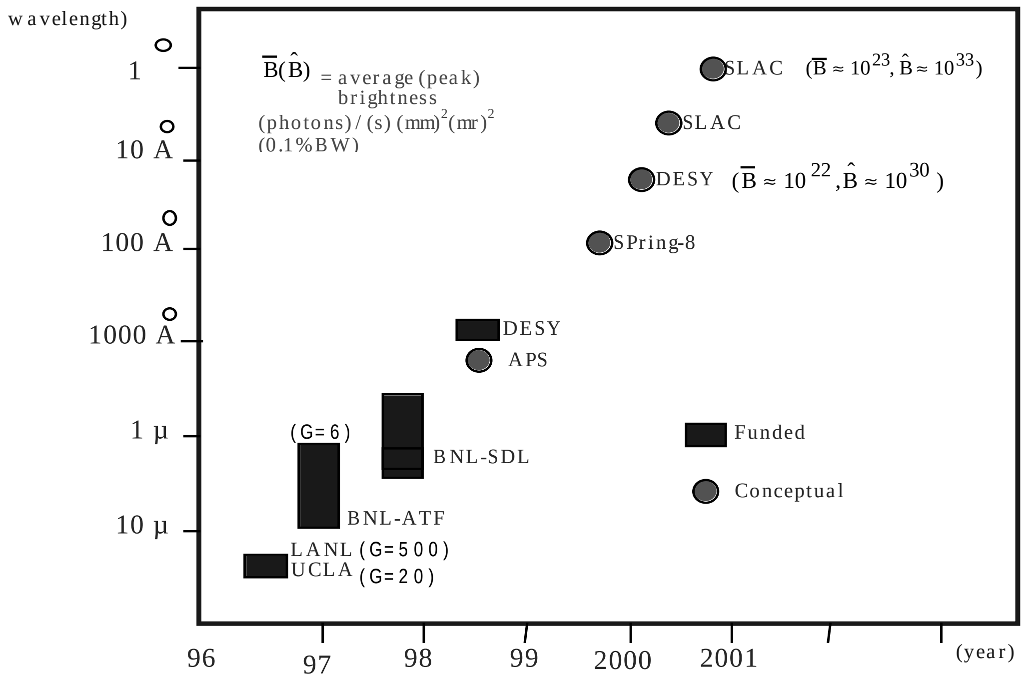

Figure 2. SASE projects around the world. The numbers within round brackets (G=) indicate the experimental gain observed recently.

B. LCLS

Fig. 3 shows the layout of the x-ray SASE project using the SLAC linac, called the Linear Coherent Light Source (Fig. 3) [3]. It uses about one third of the existing SLAC linac, but the beam will be generated by a new RF photocathode gun. The evolution of the e-beam parameters from the gun to the entrance of the undulator is indicated in the figure.

The performance in the peak (during the 100 fs pulse length) spectral brightness of the LCLS is compared with other synchrotron radiation and FEL sources in Fig. 4, and that of the time averaged brightness of Fig. 5. Note that the peak spectral brightness of the LCLS is more than ten orders of magnitude higher than the undulator radiation from third generation synchrotron radiation sources. In addition, the pulse length is about a hundred times shorter, thereby improving the time resolution by the same factor. The enhancement of the average brightness is less, due to the smaller repetition rate of the linac. However, the average spectral brightness of LCLS is still 3-4 orders of magnitude higher than the undulator sources. The average brightness can be increased further by increasing the bunch repetition rate if a superconducting linac is used, as planned at DESY [18].

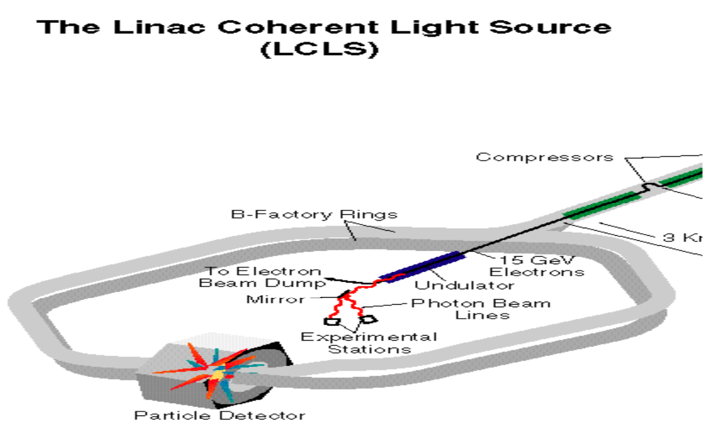

Figure 3. Layout of the LCLS

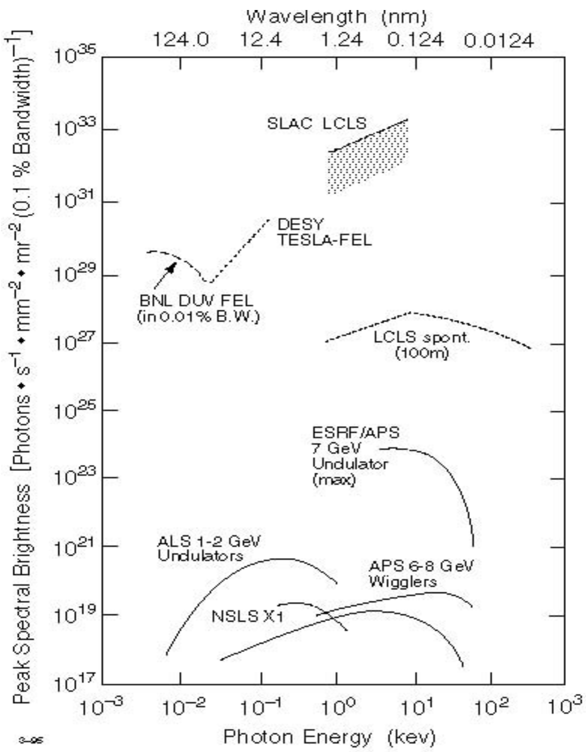

Figure 4. Peak spectral brightness

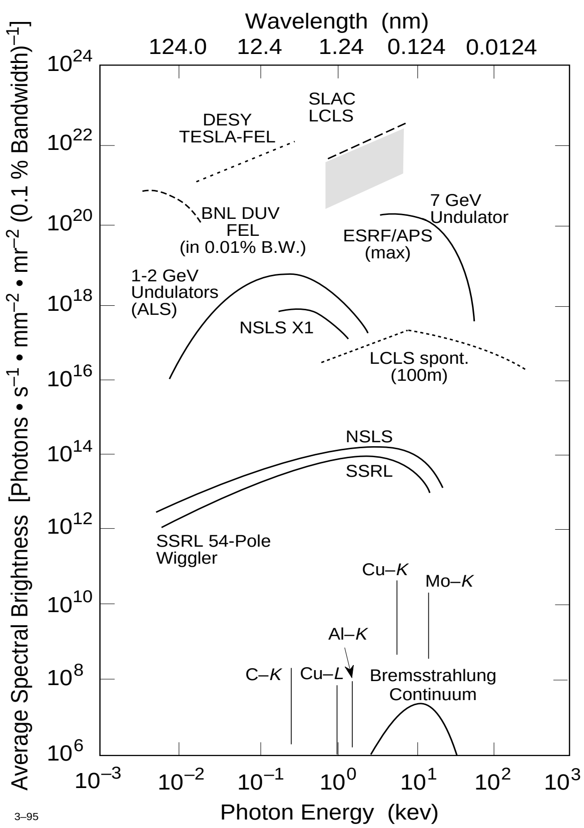

Figure 5. Average spectral brightness

VIII. SUMMARY AND CONCLUSION

In this article, we have discussed the principles of SASE, how SASE could be the basis of next generation light sources exceeding the current performance—by many orders of magnitude in spectral brightness, and by a factor of a hundred in time resolution. We have also discussed how the SLAC linac, due to its high energy and its precision control, is ideally suited for the x-ray SASE. Therefore, using the SLAC linac for generation of x-ray SASE for the frontier of the photon sciences will ensure that the SLAC linac remain scientifically vigorous for a long time.

IX. REFERENCES

[1] W.K.H. Panofsky, these Proceedings

[2] G. Loew, these Proceedings

[3] M. Cornacchia, et al., *SPIE Proc.*, edited by P.G. O'Shea and H.E. Bennett, **2998**, 2 (1997).

[4] For a review, see K.-J. Kim, "Physics of Particle Accelerators," *AIP Conf. Proc*. **184**, edited by M. Month and M. Dienes (AIP, 1989), page 565.

[5] K.-J. Kim, "Emittance in Particle and Radiation Beam Techniques," *AIP Conf. Proc.* **398**, 243 (1996).

[6] J.M.J. Madey, *J. Appl. Phys.* **42**, 1906 (1971).

[7] I.B. Drobyazko, *et al.*, *Nucl. Instrum. Methods A* **282**, 424 (1989).

[8] R. Bonifacio, C. Pellegrini, L.M. Narducci, *Opt. Commun.* **50**, 6 (1985); K.-J. Kim, *Phys. Rev. Lett.* **57**, 1871 (1986); J.-M. Wang and L.-H. Yu, *Nucl. Instr. Methods A* **250**, 396 (1986).

[9] M. Xie, to be published.

[10] R.L. Sheffield, in: *Physics of Particle Accelerators*, AIP **184**, edited by M. Month and M. Dienes, 1500 (1989).

[11] B. Carlsten, *Nucl. Instrum. Methods A* **285**, 313 (1989).

[12] C. Pellegrini, in *Proc. of Workshop on 4th Generation Light Sources*, edited by M. Cornacchia and H. Winick, SSRL Report 92/02 (1992).

[13] K.-J. Kim, *Nucl. Instrum. Methods A* **239**, 127 (1985).

[14] T.O. Raubenheimer, *Nucl. Instrum. Methods A* **358**, 40 (1995).

[15] K.-J. Kim, "Undulator Interruption in High-Gain Free Electron Lasers," to be published in *Proc. of FEL'97*, (Beijing, China, August 1997).

[16] S.V. Milton, "Advanced Photon Source Low-Energy Undulator Test Line," APS Preprint (1997).

[17] DESY Report TESLA-FEL 95-03 (June 1995).

[18] R. Brinkman, G. Materlik, J. Rossbach, J. Schneider, B.-H. Wiik, *Proc. of FEL'96*.

Banquet Speech

Herb Kinney
United States Department of Energy, Retired

How wonderful to be here for this Symposium honoring Dick Neal on the occasion of his reaching Four-Score. Most of you know Dick far more intimately than I since you worked with him on a daily basis for many years. How fortunate for you and for SLAC! I, on the other hand, had the great good luck to be identified with SLAC from the moment the Federal responsibility for the project was assigned to the AEC in May, 1959, to its successful completion in 1966 and beyond.

The project had a difficult birth for a number of reasons. It was first endorsed by Mr. Eisenhower in May 1959 at an AAAS meeting in New York at a time when science and technology were the buzz words following the shock of SPUTNIK. Stanford had a long-standing excellent relationship with the Office of Naval Research, and assignment of the project to the AEC was a bit of a shock to the Navy, to Stanford, to Dick Neal and even to the AEC. And a Democratic Congress was not wildly enthusiastic about presenting the White House with full authorization and construction of a project of such magnitude at a private education and research institution-- albeit one as highly regarded as Stanford.

Two full days of Hearings before the Joint Committee were held in mid-July 1959, but several subsequent questions arose and no action was taken by the Committee. It would be the fall of 1961 before the project would be fully authorized, and even then in Congressional legalese so obscure that only two or three of us in the Senate Gallery knew what it meant. In just two minutes the long wait was over!

On April 30, 1962 a memo from the Director to all SLAC employees read as follows: "I am happy to inform you that this morning we have signed the contract and lease which will govern the relations between the Government and Stanford University. This means that the construction of the accelerator and the creation of a new research laboratory have now become our formal obligation. I thought you all would be interested to know that there are now no more barriers toward accomplishing our work other than our ability to perform."

Little did we know that a couple of years later a slight problem called the SLAC powerline controversy would arise.

But let's get back to Richard Barr Neal and a bit of biographical information -- at least as much as he was willing to divulge. To speak ill of Dick Neal is as foreign as saying "no" to Pief! He was indeed born on September 5, 1917 in the small town of Lawrenceburg, Tennessee, quite some distance south of Nashville. His father was a doctor and Dick on occasion would accompany his father on his rounds in a horse and buggy. In those days doctors made house calls at all hours of the day and night with remuneration some orders of magnitude less then today's. A good country ham was sometimes offered as payment.

After education in the local schools, he was appointed in 1935 to the U.S. Naval Academy at Annapolis, Maryland from which he graduated in 1939. He served 2 years on the Battleship U.S.S. PENNSYLVANIA which was at the time the flagship of the U.S. Pacific Fleet under Admiral Husband Kimmel, later called "the scapegoat of Pearl Harbor." Because of physical disability (defective vision), Neal received an honorable discharge from the Navy in 1941. He accepted a position with the Sperry Gyroscope Company in Brooklyn, New York as an engineer. During the World War II years, he was a Field Service Engineering Supervisor for a large variety of Sperry instruments and products produced for the U.S. Armed Forces. At the end of the War, he participated in design studies of control systems for some of the earliest U.S. rockets built during the post-war period. He resigned from Sperry in 1947 to attend graduate school at Stanford University.

In his college days at Annapolis, Neal could be found on the football field, on the track team and on the tennis court. His hobbies include music, reading, spectator sports, ballroom dancing, ice-skating, bicycling, hiking, and flying (small planes). He holds a private pilot's license with an instrument rating. He is a Fellow of the American Physical Society, and a member of the National Academy of Engineering.

At Stanford, under the tutelage of Ed Ginzton, Dick Neal blossomed. He became a Research Assistant with an assignment to develop a method for assembly of the 300-400 KV transformers that supplied pulsed power to the first high power klystrons.

Dick went on to receive his Ph.D. in Physics from Stanford in 1953 and, as Pief indicated this morning, was a major contributor to the design of both the Mark II and Mark III machines. Ed Ginzton became his advisor, mentor and friend.

Beginning in 1956, Dick was one of about a dozen Stanford scientists who proposed the construction of the Two-Mile Linear Accelerator on a site west of the Campus -- the Page Mill site. His intimate involvement in this proposal was the beginning of what would become his life's work for the next 38 years.

Somewhat earlier and harking back to Dick's Sperry Gyroscope days in 1944, he embarked on another provident course. Richard Barr Neal and Gail Annette Nesbitt were married at Forest Hills Gardens, Long Island, New York, and resided there for three years before moving to California in 1947. The gayety, laughter, spice, and support for Dick's work that Gail was to bring to their marriage were of enormous importance as Dick's workload -- never light -- increased immeasurably in the critical days of SLAC's construction phase. For 53 years she has continued to bring gayety, laughter and spice into their marriage.

I was fortunate enough to receive a communication from Norene McCarthy, Dick's secretary during the ten year span of the busiest and most exciting period in SLAC history. She writes --

"Dick Neal's life was one meeting after another all day, every day. These meetings were with the Heads of Divisions, Departments and Projects who had been chosen because they were tops in their fields. Design, cost, contracts and government relations -- he was on top of them all. Plus, he ran the Technical Division, the largest of them all. Some of these people were wonderfully cool and collected, some the complete opposite, but I never saw Dick lose his temper or his calm control; sometimes it must have been difficult. He was there when I arrived in the morning and there long after everyone had left at night.

"His major problem (I hope) with me was spelling. I thought I was a good speller but found that my British education left Dick forever finding unusual words. Most technical people are not the best at spelling and I never believed him. I wore out the dictionary proving him wrong -- He never was!

"One thing I remember was when Gail got them started taking dance lessons. The school used diagrams of the foot positions for the different steps. Every few weeks Gail hosted a practice session at their home and I was often included. Dick would close his eyes with the girl in his arms and picture the diagram. This required silence from his partner, no conversation, no remarks or you started over at the beginning of the diagram. It took an amazingly short time for him to get the technical part down pat and he became a graceful, natural, and innovative dancer. Much better than I am and I started at 12 years old.

"Only once, just before the Thanksgiving or Christmas holidays, I served the last coffee at the last meeting for the day and spiked Dick's coffee with an airline mini bottle of brandy. He took a sip, stared at me for a moment, then finished the meeting and the drink.

"Dick's expertise in everything he did was phenomenal. My experience many years ago with the Electronic Industries attempt to train their Technical people in order to upgrade them into management made Dick's complete ease in both fields unequaled. And, he did it all with a great sense of humor (or is it humour)!" (End of Norene's note.)

There are a couple of items that occurred on Dick's watch that I recall. During the hectic period when Arnold Eldredge was delivering a 40 foot accelerator section daily for machine installation, a visit by the Bureau of the Budget Senior Analyst for the AEC occurred. Fred Schuldt was very much like Dick Neal -- thorough, dedicated, a workaholic, quiet, reserved and very much the gentleman. We happened to go over the Arnold's Assembly Area where there were untold accelerator disks and rings, thousands, maybe millions, awaiting assembly. Just prior to our arrival in examining a just completed ten-foot section, it was apparent that one disk was not in the proper sequence. Further examination indicated that the disc had been incorrectly numbered. Everything stopped. How many had been mis-numbered? What to do ?? A complete inventory and examination was ordered which took many valuable hours. Arnold confessed details of the problem to Fred Schuldt and Fred, speaking in a fatherly tone, said -- "You know you really ought to develop procedures to prevent this sort of thing." Arnold nearly collapsed from pain and I from mirth.

And, on a night shortly before a Joint Committee Hearing, I called Pief and suggested that he run SLAC flat out and see what peak energy could be obtained. As I recall the TWX the next day indicated an energy somewhat in excess of 20 GeV. Paul McDaniel instantly TWXed back -- "Congratulations -- obviously you over-designed." That TWX, addressed to Panofsky, should have been addressed Dick Neal.

Dick, who must have had some exposure to Fred Pindar, developed a penchant for conserving money. He would squirrel it away whenever he could and then use it toward the end of the FY for the most urgent needs that were then pounding on his door.

Dick was very loyal to his staff and quick to recognize their respective contributions to the task at hand. He was a friend willing to assist anyone with personal problems or otherwise. Although he appeared to be strait-laced beneath that exterior was another Dick Neal.

PLAY IT AGAIN, SAM! -- "Instrumentalists at the Console in the Central Control Room During the Initial Turn-on of the SLAC Accelerator -- May, 1966.
(1. Pief Panofsky, 2. Gary Warren, 3. Donn Robbins, 4. Dick Neal, 5. Jan Madsen (CERN), 6. Ken Crook, 7. Dieter Walz, 8. Greg Loew, 9. Matt Sands)

By finishing SLAC on time, within budget and at the design energy, Dick left an enormous legacy to the next large high energy accelerator project -- Fermilab and R. R. Wilson. Please remember in 1959- 1960- 1961 the Cambridge Electron Accelerator and the Princeton-Penn Accelerator were both indicating overruns, the AGS at

Brookhaven had risen from $20 million to $26 million, the ZGS at Argonne -- estimated albeit by an AEC Commissioner at $15 million changed in 4 months to $27 million, and so on. SLAC finished in 1966, left a report card of all A's. It made the authorization and appropriation processes for Fermilab easier and gentler tasks with the exception of perhaps the civil rights issues that arose.

A few months back there was a wonderful cartoon in the *New Yorker* depicting the Gates of Heaven, St. Peter and a small sign that read Population 3. Some years from now when Dick Neal becomes eligible for consideration they will have to change that to read 4 -- and Gail's arrival there will require another change to 5.

In closing let's go back to Earth for a moment. Stanley Walker, one of the great *NY Herald* city editors once wrote about the glories of his trade which I have taken the liberty to modify slightly.

"An accelerator physicist knows everything. He is aware not only of what goes on in the world today, but his brain is a repository of the accumulated wisdom of the ages. He is not only handsome, but he has the physical strength which enables him to perform great feats of energy. He can go for nights without sleep. He dresses well and he talks with charm. Men admire him, women adore him. He hates lies and meanness and sham, but he keeps his temper." Sounds like Dick Neal, doesn't it?

How long will SLAC endure? About 10-15 years unless somebody has a good idea!