THE CREATION OF SLAC LEADING TO 30 YEARS OF OPERATION

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The first beam passing through the entire three kilometer length of SLAC was obtained on May 21, 1966. We are therefore commemorating 30 years of operation of that machine. 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 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 made, 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 a plethora of good ideas, essentially none of which were anticipated at the time when the machine was originally proposed.

Although SLAC was the outgrowth 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 using machines operating at the energy frontier. 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 which in its entirety read: "We have accelerated electrons." Then followed the MARK II and MARK III, the former used for nuclear physics, and the latter 100 meters in length, supported a very successful high energy 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 by incorporating the drift tube design developed by Alvarez and collaborators.

While SLAC, in terms of its fundamental radiofrequency design, was a simple 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 30 years of operation of SLAC covered an installation which underwent many changes. Table 1 shows the sequence of "reincarnations" of the machine which I shall discuss further. Figure 1 shows the initially proposed target area layout and Fig. 2 today's reality. 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 was to be a producer of secondary beams 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 (SLED), 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. A SLAC proposal, the Recirculating Linear Accelerator (RLA), using the three kilometer structure repeatedly two loops of with 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.

Table 1:SLAC Major Milestones and Upgrades

SLAC Major Milestones and Upgrades	
1957 (April)	SLAC proposed to U.S. Government
1961 (Sept.)	SLAC authorized by U.S Congress
1962 (July)	Groundbreaking
1966 (May)	Beam through full length
1967 (April)	Commence Research Program at SLAC
1969	Superconducting Conversion Study (not built)
1971 (June)	Recirculating Linear Accelerator proposed (not built)
1973	SLAC Energy Development (SLED) proposed
1975-80	SLED installation
1970	SPEAR construction started
1972	SPEAR operation started
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
1970	First polarized electron gun
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

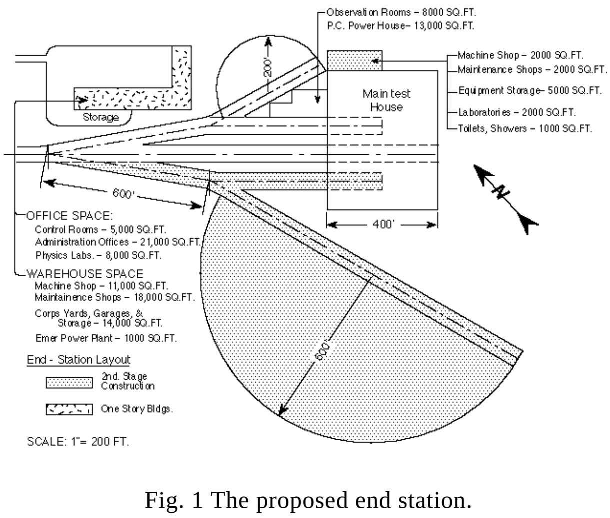

Fig. 1 The proposed end station.

But there were other factors which were unprecedented initially. 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 not feasible 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 well documented in the famous "blue book" edited by Richard Neal (1968) was paralleled by the construction of a family of large detectors, listed in Table 2, that became available at the time of initial operation of SLAC. Today in the age of large, almost 4 π steradian detectors surrounding interaction points of colliding beam machines, this mode of operation has become commonplace, but it was a rarity in its day.

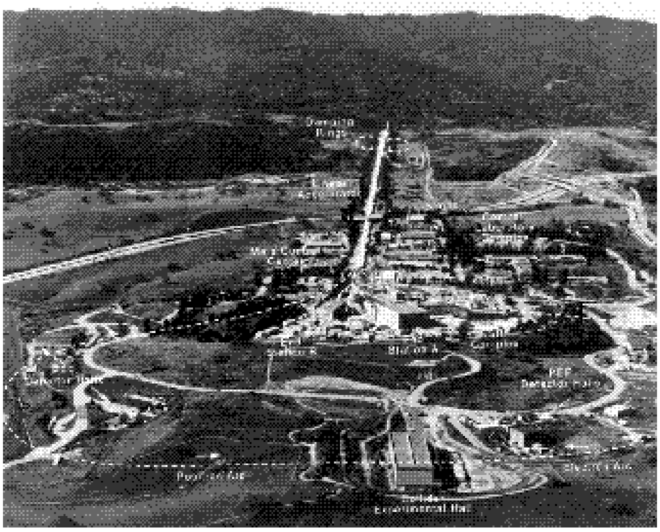

Fig. 2 The end station reality.

Table 2: Initial complement of experimental facilities at Slac

INITIAL COMPLEMENT OF EXPERIMENTAL FACILITIES AT SLAC
e-scattering spectrometers
20 GeV
8 GeV
1.6 GeV
2-meter streamer chamber
40” rapid cycling bubble chamber
General Purpose magnet as hadron spectrometer
K_L beam for lepton asymmetry observation
Beam transport for heavy lepton searches

The second exceptional circumstance accompanying the operation of SLAC was very high peak and also very high average power of the beam (exceeding one megawatt). Thus stopping the beam safely in a manner not generating excessive backgrounds and providing for high power beam collimation resulted in design requirements not hitherto encountered to a significant extent in particle accelerators. Figure 3 shows what happens in a few seconds if the beam strikes a block of copper. The "melt-out" occurs at the maximum of the electron–positron shower. A tungsten block shatters almost instantaneously and concrete disintegrates.

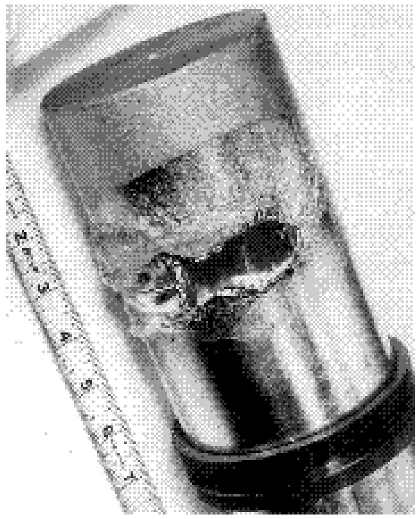

Fig. 3 Effect of beam on copper target.

The third innovation was the needed emphasis on rapid learning from poor performance and on operational reliability. SLAC 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 units does not necessarily lead to loss of beam, the requirement for the simultaneous reliable operation of many subsystems was unprecedented. Let me give one example of how the reliability, and, equally important, to be able to learn rapidly from failures, affected a key design choice. We considered the manufacture of the disk loaded microwave structure by two alternative technologies: (1) brazing of rings and disks, which were separately machined, shown in Fig. 4; 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 (used in the successful MARK III accelerator), shrink-fitting the disks to a cylinder of uniform internal diameter was rejected and 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 any errors made during the manufacture or if future difficulties became 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 the full 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 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. 5. Groundmotion 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.

Fig. 4 Structure brazing and components.

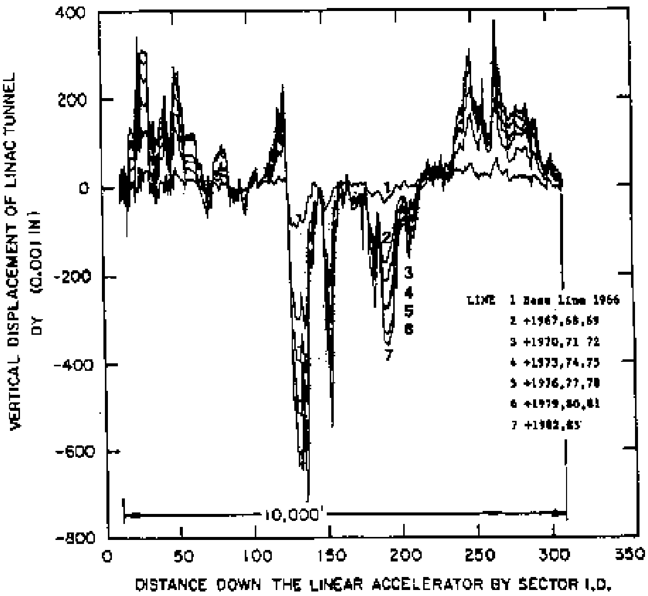

Fig. 5 Background motion.

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 laboratories of the world, in particular those operated by consortia of universities, or consortia of nations such as CERN. It 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 SLAC's needs, and SLAC 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 schedule.

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 developments in the United States, particularly in nuclear reactors, major military systems, and space ventures; a record not unnoticed by the government agencies supporting SLAC.

Because of the facility-centered nature of SLAC, we felt it necessary 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. During the early operating period of SLAC, the experimental physics community was generally unfamiliar with the design, construction and management of large experimental facilities, and therefore the inhouse 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.

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 to be 10–20 GeV. Shortly after turn-on its energy gradually improved, as shown in Table 3. 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 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. Figure 6 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 improvement 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 which were used during the first two decades of SLAC operation 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.

Table 3: Energy records

Energy (GeV)	Date
18.4	June 2, 1966
19.0	December 16, 1966
20.16	January 10, 1967
20.58	August 16, 1968
21.0	September 13, 1968
21.5	April 27, 1969
22.10	August 23, 1970
22.28	July 25, 1973
22.74	November 11, 1974
33.4	March 5, 1980
53.0	January, 1987

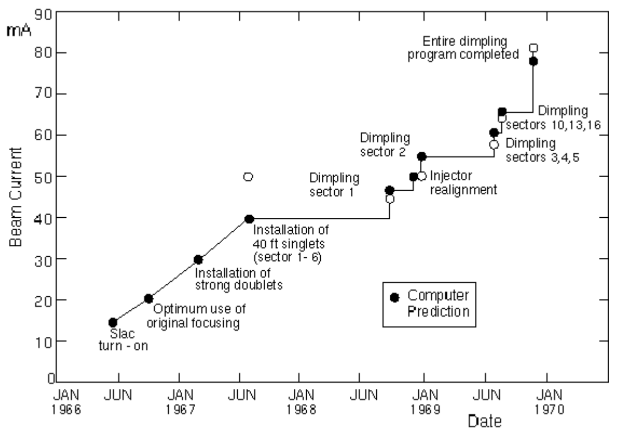

Fig. 6 Evolution of beam current.

Because of this complex pattern of operation, beam delivery is difficult to quantify in a consistent manner. 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.

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 industry's interest in maintaining a production line for replacement proved impossible to justify. Thus, while originally SLAC klystrons were procured from four sources, after a few years experience SLAC handled all klystron replacements through its internal shops.

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 has tended to shrink recently, partially due to budget limits which forced operations to lower pulse repetition rates and shortened operating periods.

After the initial operating period solely dedicated to fixed target physics until 1972, operation became even more complex with the advent of storage rings. 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 provided six interaction halls for experiments. Figure 2 shows the layout of the accelerator with the target area, the two storage rings, and the SLAC Linear Collider, which was to follow.

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 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 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 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 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 thc intermediate boson Z^0 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 the detailed difficulties in commissioning the SLC were considerably larger than envisaged. The SLC requires a quality of operation of the SLAC two-mile linear accelerator that is much higher than that incorporated into 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 emittance 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, the quality of beam delivery of the SLC operating at the Z^0 peak has improved; Table 4 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 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 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 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 Table 5 and Fig. 7.

Table 4: SLAC SLC/SLD performance for 1992–1995

	SLD 92	SLD 93	SLD 94/5
Exp't Logging	51%	63%	56%
Machine Develop.	9%	6%	4%
Alternate Program	1%	1%	4%
Tuning	19%	11%	10%
Unsched Down	18%	17%	23%
Sched. Off	2%	2%	3%
Total Hours	2616	4079	5065
Total Z (x 1000)	10	55.7	100
Ave. Lum (Z/hr)	7.5	21.7	35.3
Approx. Polarization	21%	65%	79%

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).

Table 5: Performance Summary for the SLAC Polarized Electron Source

Year	Experiment	Cathode Material	Polarization (%)	Hours*
1992	SLD	Ga-As	22	4000
1992	E142 (n)	Al-Ga-As	40	1100
1993	SLD	Strained Ga-As	63	5300
1993/1994	E143 (p/d)	Strained Ga-As	84	2200
1994/1995	SLD	Strained Ga-As	77	6000
			Total	18,600

* Availability ≥ 98%

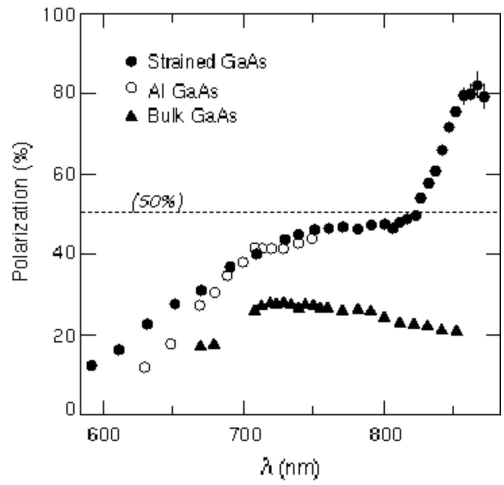

Fig. 7 The polarization versus wavelength for three different cathodes that have run on the SLAC accelerator. The bulk GaAs cathode delivered beam to the SLC in 1992. The AlGaAs cathode was used for a fixed target experiment in 1992. The strained GaAs cathode has been used for both fixed target running and SLC since 1993.

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 3×10^{33} cm^{-2} sec^{-1}. While the B-factory is being undertaken as a construction project, it does not require any modification to the civil engineering environment at SLAC. The B-factory will add 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. 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/psi 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 tau 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 because of the fact that the use of polarized electrons greatly increased the sensitivity in the study of the products of the Z^0 decay into various channels. At the same time SLAC has now closed the loop back to the original deep and 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 the 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 high 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 character of linear accelerator generated beams. It is now 30 years and three 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 will answer the old question: How long will SLAC continue? with the old reply, "10–15 years unless somebody has a good idea. "