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The Development of Modern Particle Accelerators at the Stanford Linear Accelerator Center

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Abstract

The development of high-energy accelerators at the Stanford Linear Accelerator Center has closely paralleled the advances in high-energy physics over the last fifty years. From its original conception as the world's largest linear accelerator for fixed target experiments, the facility evolved over the years with various colliding beam configurations in the quest for higher collision energies. An offshoot of the high-energy physics program was the synchrotron radiation from accelerators that proved a useful tool for x-ray studies. Photon science has since become the major thrust of the laboratory with the construction of LCLS, the world's first free electron x-ray laser.

Introduction

Particle accelerator technology had already developed to a sophisticated level by the time the Stanford Linear Accelerator was proposed in the late 1950's and early sixties. The origins of the particle accelerator and the desire of physicists to study the behaviour of fundamental particles beyond that revealed in cosmic rays and the emissions from natural radioactivity have been extensively chronicled in the past. This review focuses on those developments that took place at the Stanford Linear Accelerator Center (SLAC) and how they have led to the rise of *The Standard Model*, the birth of new accelerator technologies and the burgeoning of synchrotron radiation physics that followed.

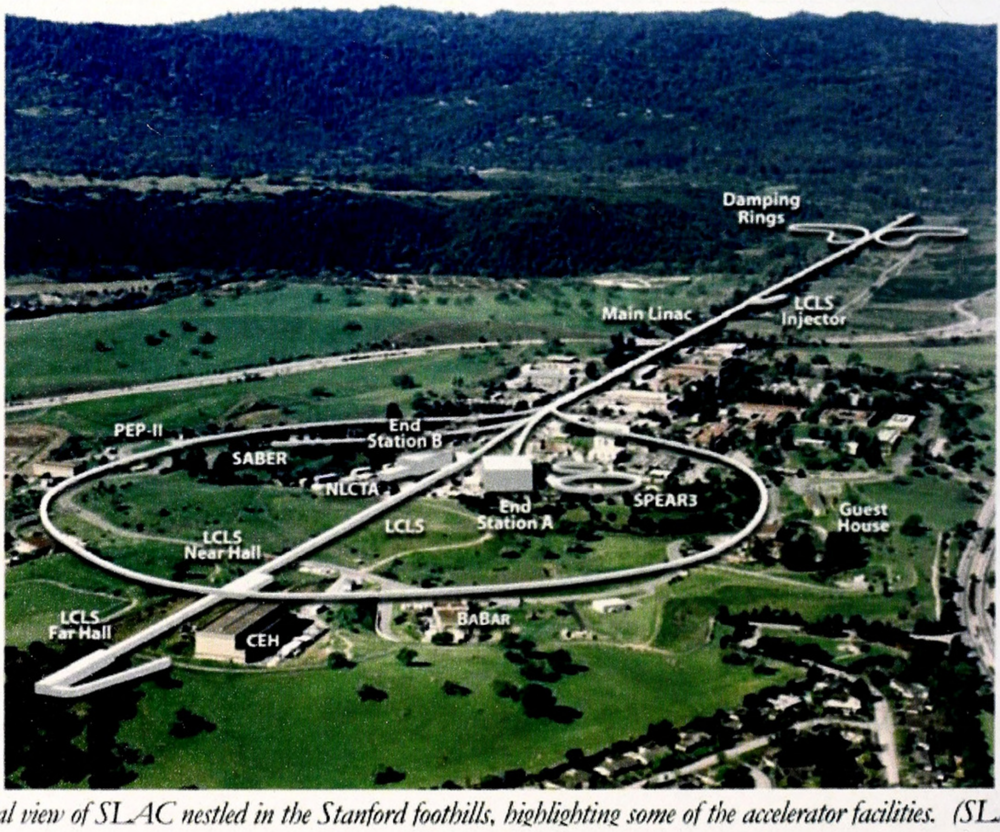

Figure 1: Aerial view of SLAC nestled in the Stanford foothills, highlighting some of the accelerator facilities. (SLAC photo)

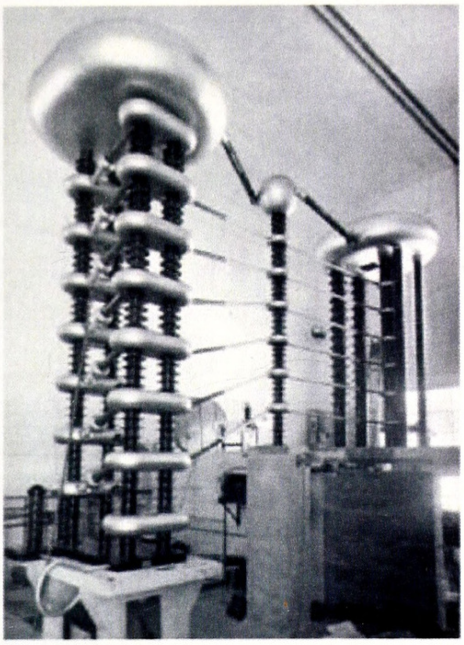

Figure 2: The Cockcroft-Walton accelerator that was moved from the Australian National University to the Physics Department at the University of New South Wales where it was used by Jak Kelly. It is an example of an early high-voltage accelerator. (ANU photo)

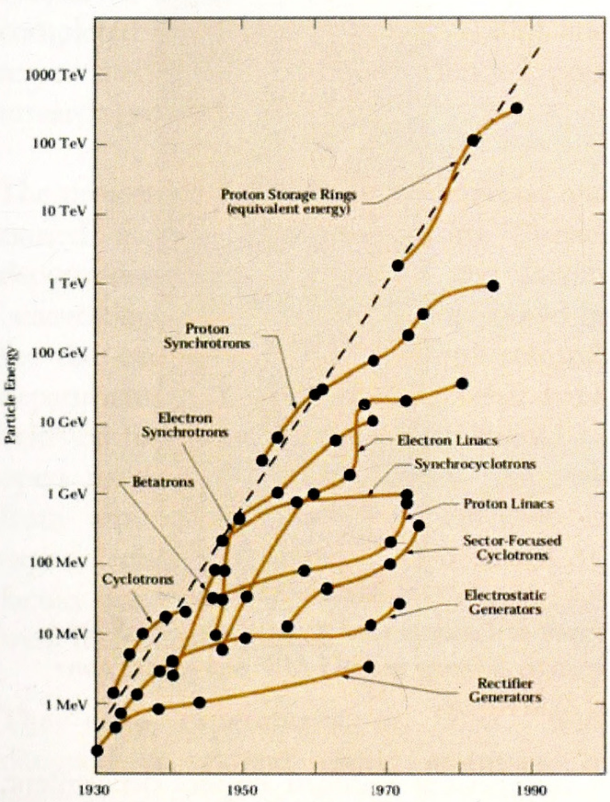

Figure3: A plot, styled after Livingston of the change in accelerator technology that allowed accelerators to increase in energy.

The machines at SLAC, shown in Figure 1, have always been used to accelerate electrons, or their antimatter counterparts, positrons. The dogged adherence to lepton machines is based on the premise that leptons are a point-like particle, with no constituent parts and therefore the study of collisions with leptons should be the least ambiguous to interpret. While other high-energy physics laboratories delved into the complexities of protons and the structure of even heavier nuclei in ion beams, SLAC made the first of its Nobel Prize winning discoveries to support its original premise: the discovery, described in more detail in the following sections, demonstrating that protons and neutrons were indeed made of smaller, constituent parts, quarks, and that only an electron beam could reveal that fine detail.

Figure 4: A view inside the two-mile SLAC accelerator tunnel showing the linac mounted above the alignment light pipe.

The driving technology behind the SLAC accelerators is the use of very high power radio frequency (RF) fields. The earliest accelerators used dc voltages to accelerate a particle just once across a fixed potential, as in Figure 2, but the energy is limited to a few MeV before high voltage breakdown becomes a problem. High energies can only be achieved by repeated application of a time-varying electric field. The successful confluence of high power microwave technology in the development of klystrons at SLAC together with particle accelerator design put SLAC at the forefront of high energy physics.

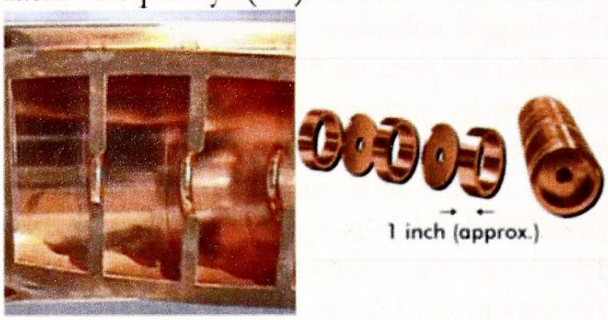

Figure 5: The SLAC linac structure is shown in a cutaway view and comprises roughly 80,000 copper cells.

The quest for higher energy accelerators is driven by both the need to resolve smaller detail and to be able to create exotic new particles of heavier mass out of the collision energy. In the wave-particle duality view of nature a higher energy particle beam has shorter wavelength and therefore can probe smaller detail in scattering experiments. The mass-energy equivalence tells us that the mass of any new particle created in a collision is limited by the centre-of-mass energy available in the collision.

The early high voltage acceleration technique would only ever be used at SLAC to power the electron gun used to inject electrons into the main linear accelerator (or linac, as it is commonly abbreviated). The electrons in the SLAC linac, Figures 4 and 5, are accelerated instead by high frequency waves using a technique pioneered by William W. Hansen at Stanford. The microwave power is delivered by klystron tubes, Figure 6, also developed at Stanford by the brothers Russell and Sigurd Varian.

The Early SLAC Linac

The physics motivation for building a 20 GeV electron linac was born out of the success of Robert Hofstadter's experiments on the elastic scattering of 188 MeV electrons. The experiments were performed on the main Stanford campus in the Hansen Experimental Physics Laboratory using the University's 220-foot long Mark III electron accelerator. These Nobel Prize winning experiments determined the precise size of the proton and the neutron and provided the first reasonably consistent picture of the atomic nucleus.

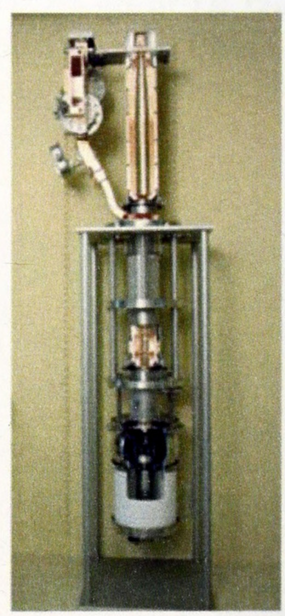

Figure 6: Cutaway view of one of the 240 S-band klystrons delivering up to 65 MW each of peak power at 2856 MHz.

A team in the Stanford Physics department, led by Wolfgang "Pief" Panofsky envisaged a machine 100 times larger that was destined to reveal not just the structure of the nucleus,

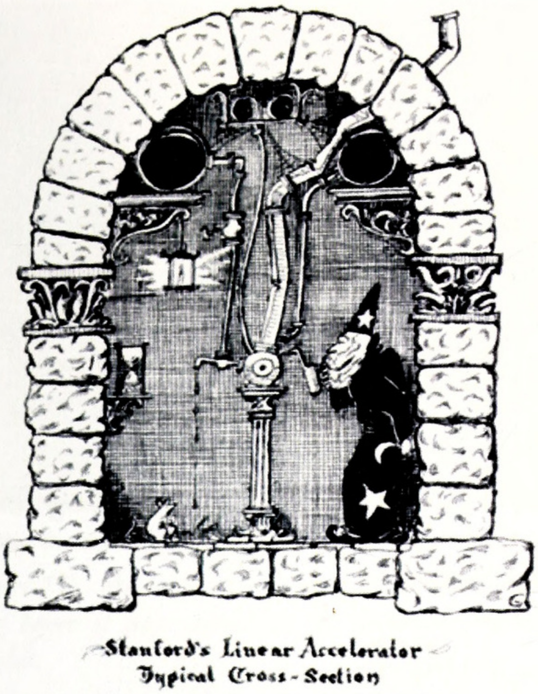

Figure 7 Whimsical view of the SLAC linac as depicted by Bob Gould the chief civil engineer during the construction phase.

but of the nucleons themselves. Dubbed Project M, where M stood for monster, it was completed in 1966 at a cost of \$120M and represented the largest publicly funded, pure research project of its time.

The project was not without controversy and caused a split in the Stanford Physics department because some of the faculty believed that the accelerator facility should be for the exclusive use of Stanford research departments. Panofsky, on the other hand believed that such a large facility should be open to the public, and invited proposals from around the world to participate in experiments at SLAC. A separate SLAC faculty was created and the two Departments went their separate ways.

The early experiments at SLAC were designed to extend elastic scattering of electrons from the proton and the neutron (in the deuteron) to higher energies, and then to extend this work to inelastic scattering, leading to the known "resonances" or excited

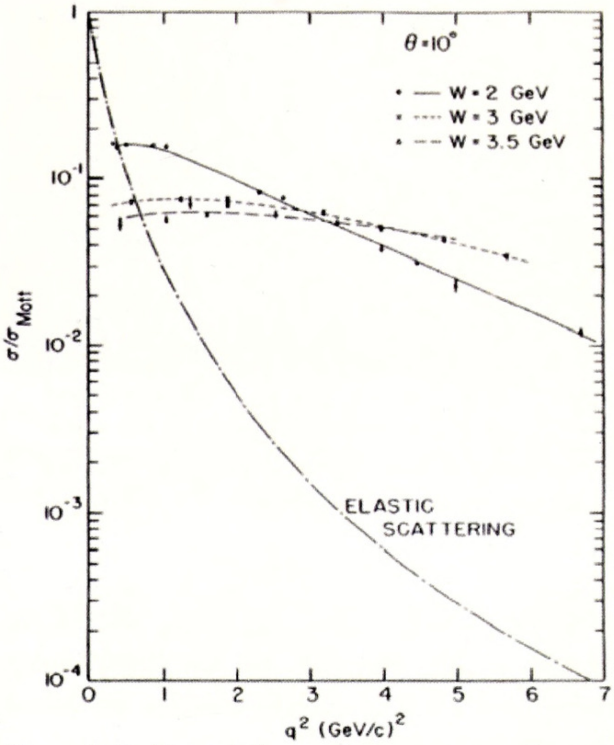

Figure 8: Evidence of the quark structure came from the ratio of deep inelastic scattering (DIS) cross-section of electron scattering in hydrogen to the theoretical Mott scattering cross-section from a point charge, plotted as a function of the square of the four-momentum transfer. The elastic scattering cross-section is plotted for comparison. (From Hoddeson et al., Fig 32.2.)

states of the nucleons, essentially extending the previous work of Robert Hofstadter to much higher momentum transfers. However, there was a growing interest in explaining the "strange" behaviour of new particles discovered at other laboratories and the conjecture by Gell-Mann and Zweig that nucleons were combinations of "quarks" of charge ± 1/3 or ± 2/3. The new research groups began examining "deep inelastic scattering" (DIS) which left the nucleons fragmented in a continuous set of energy states. The results had tremendous implications since the DIS cross-section turned out to be much larger than previously believed. The ratio of DIS, as a function of the momentum transfer to the nucleons, to scattering from a charged point particle,

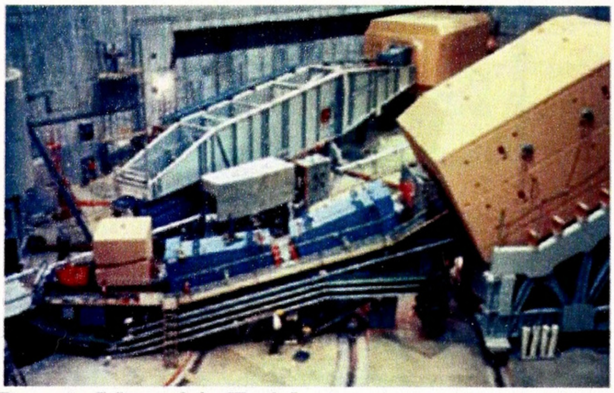

Figure 9: View of the End Station A spectrometer and detectors used to measure scattering from quarks within the proton and neutron. The scale is apparent from the human figure in the centre foreground.

exhibits a very slow variation, shown in Figure 8, in contrast to the very steep decrease with momentum transfer exhibited by elastic scattering.

The scattering experiments required the detectors to be moved through large angles to observe both the forward and back-scattered electrons. For 20 GeV electrons the spectrometer magnets are formidable and resembled locomotives on tracks, as seen in Figure 9.

Richard Taylor, Henry Kendall, and Jerome Friedman received the 1990 Nobel Prize in Physics for this work, which established the foundation of the physical reality of the quark components of the Standard Model.

Colliding Beams at SLAC

In striving for higher energies to extend the reach of scattering experiments, one must realize that the centre of mass collision energy, E_{cm}, is reduced by the recoil of the target atom of mass m_t.

$$E_{cm} = \sqrt{2m_t E_1}$$

whereas much higher centre-of-mass energies can be attained by colliding two beams of energy E_1 and E_2.

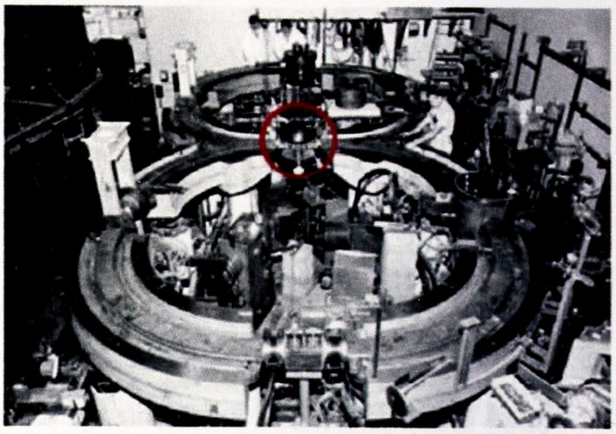

Figure 10: The Princeton-Stanford Colliding Beam Experiment used a figure eight configuration to collide 500MeV electrons.

$$E_{cm} = \sqrt{4E_1 E_2}$$

The colliding beam concept was first envisaged for hadron machines but was soon taken over by the lepton community. Unlike protons, an electron will radiate away its energy if made to follow a circular path, and this dissipative process causes the electrons to naturally converge to the axis of the beam pipe. This makes the injection process into an electron storage ring much easier.

Several design proposals were made around the world using counter rotating beams of oppositely charged particles that could economically make use of one vacuum chamber in a single ring. The availability of an electron linac to inject the beams made Stanford an obvious choice for a demonstration experiment. An electron storage ring was proposed at Princeton by Gerry O'Neil in 1956 and the Colliding Beam Experiment (CBX) began construction in 1959 at Stanford. The figure-eight ring, shown in Figure 10, collided 500 MeV electrons with currents up to 50 mA in each beam.

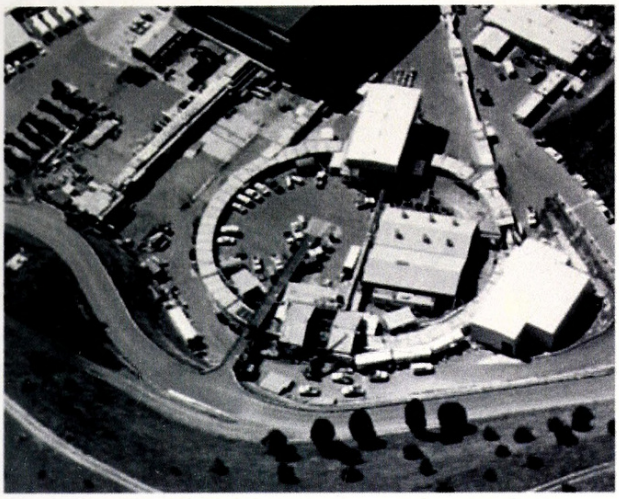

Figure 11: An early photograph of the SPEAR storage ring before it was surrounded by synchrotron radiation hutches.

The CBX revealed three major limitations that would prove essential in future storage ring design. In spite of being the largest ultra-high vacuum system constructed for an experiment, with a base pressure of 10^{-9} Torr in the 2 m^3 volume, the pressure would rise by a factor 300 when higher beam currents were stored. Desorption from synchrotron light impinging on the chamber walls caused a pressure spike that severely limited the stored beam lifetime. The synchrotron light power scales as the 4th power of beam energy and required a re-evaluation of the vacuum system design.

The second limitation observed during operation was a transverse resonant instability caused by the image charge wall currents causing wakefields in the vacuum chamber. Resonant coupling could be suppressed by separating the betatron tune of the two rings, and further damping was observed due to rest gas ionization effects.

The fundamental limit affecting all future storage rings was found in the beam-beam tune shift, $\Delta\upsilon$. This is the transverse focusing of one beam upon the other and increases as the interaction density, or luminosity, increases according to

$$\Delta\upsilon_y = \left(\frac{Nr_e}{2\pi\gamma}\right)\frac{\beta_y^*}{\sigma_y(\sigma_x + \sigma_y)}$$

for N electrons at an energy $E=\gamma m_e c^2$, with transverse beam sizes $\sigma_{x,y} = \sqrt{\beta_{x,y}\varepsilon_{x,y}}$, where $\beta_{x,y}$ are the lattice functions, $\varepsilon_{x,y}$ the beam emittances and r_e the classical electron radius. Tune shifts above 0.025 typically caused beam degradation and loss of luminosity due to resonance induced by the beam-beam interaction.

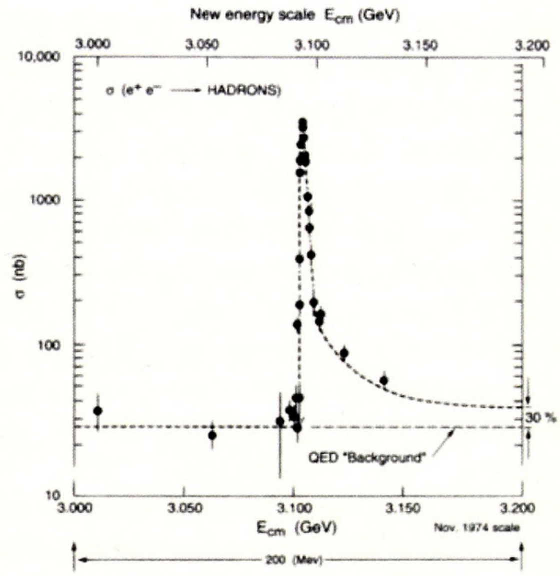

Figure 12: A historic plot marking the discovery of the J/Ψ particle at SPEAR.

The lessons learned proved invaluable for future storage ring designers, particularly one collaboration member, Burton Richter who went on to lead the effort to design the Stanford Positron Electron Asymmetric Rings (SPEAR). This collider began operation in 1972 and proved to be the most prolific of all the SLAC accelerators in providing physics results per dollar spent on their construction.

At the time of its inception, the SPEAR project was competing with more conservative upgrade projects that would raise the main linac energy by at most a factor two. These projects eventually also proved successful and led to the success of the linear collider described in the next section. However, the physics motivation of being able to raise the centre-of-mass energy by an order of magnitude over the CBX machine was enough to spur the laboratory management to fund the SPEAR construction out of operating funds without obtaining direct government funding agency approval.

Funding was not available for a new building to house the new machine so it was literally constructed on the parking lot adjacent to End Station A and covered over with concrete radiation shielding blocks, as seen in Figure 11. The design was simplified to a single ring with counter rotating electron and positron beams of 3 GeV energy. Unlike the electron-electron collisions in CBX, the e^+ and e^- can annihilate each other producing an intermediate state with enough energy, and according to conservation laws, to spontaneously produce massive new particles. Studying how these particles are produced proves to be the ideal tool for learning about their structure.

The gamble paid off handsomely with the observation of a resonance in the event rate at a centre-of-mass energy of approximately 3.1 GeV, shown in Figure 12. This was attributed to the production of a new particle the J/Ψ which could only be explained as a tightly bound pair of charmed quarks. The laboratory director announced the discovery to the Atomic Energy Commission with the statement: "I would like to report the discovery of an unauthorized particle on an unauthorized colliding beam facility". In 1974 it heralded what is now referred to at SLAC as the November Revolution. The

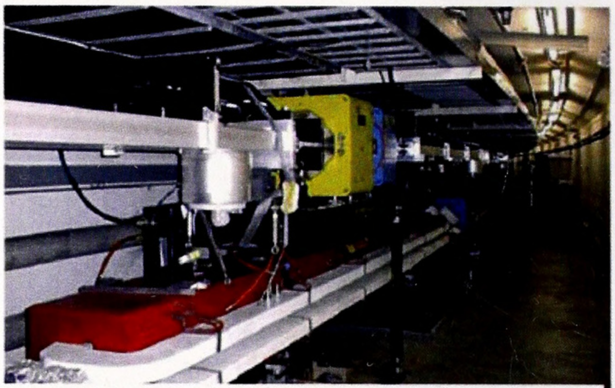

Figure 13: A view inside the PEP tunnel showing two rings stacked on top of each other for the PEP-II asymmetric B Factory.

discovery resulted in a Nobel Prize for Burton Richter and Samuel C. C. Ting, and was followed by a rich study of charmonium physics revealing the spectroscopy of various bound states of charm-anticharm quarks.

The SPEAR ring yielded yet another Nobel Prize to Martin Perl for his discovery of the tau lepton, the third of the three families of leptons, the electron, the muon and the tau.

At this point in SLAC's history funding became available to build upon this success and construct an even larger collider, the Positron Electron Project (PEP) able to attain 15 GeV with a ring 1.4 miles (2.2 km) in circumference. This was the largest ring that would comfortably fit on the SLAC site. A large ring is necessary at high energies because the energy loss per turn due to synchrotron radiation increases as the 4th power of the energy while it only decreases linearly with machine radius.

During the PEP era at SLAC Burton Richter spent a sabbatical period at CERN in Switzerland where he entertained the idea of designing the maximum energy storage ring feasible on an unlimited site. CERN went on to build the Large Electron Positron project (LEP), a 27 km circumference ring capable of attaining 50 GeV beam energies.

Three Families of Matter		I	II	III	H Higgs boson	
Quarks	+2/3	*u* Up	*c* Charm	*t* Top	*γ* photon	Force Carriers
Quarks	-1/3	*d* Down	*s* Strange	*b* Bottom	*g* gluon	Force Carriers
Leptons		*e* electron	*μ* muon	*τ* tau	*Z* Z boson	Force Carriers
Leptons		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	*W* W boson	Force Carriers

Table 1: The Standard Model can be thought of as a type of Periodic Table from which all the known sub-atomic particles can be constructed.

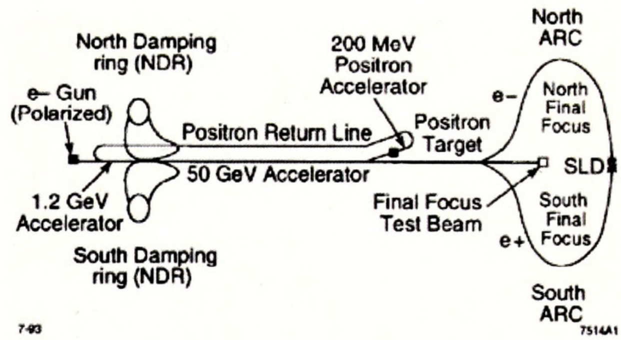

Figure 14: The SLAC Linear Collider accelerated bunches of electrons and positrons to 50 GeV which were deflected in opposite directions around an arc to collide at the detector.

Richter, on the other hand, returned to SLAC proclaiming that we must return to linear accelerator technology for colliding beams in order to overcome the energy limitations of storage rings.

Before turning our attention to the linear collider project at SLAC we should jump ahead to SLAC's final endeavour with storage rings, and the construction of an asymmetric collider known as the PEP-II B-Factory. Two rings were constructed inside the PEP tunnel, stacked one on top of the other, as shown in Figure 13, to store 9 GeV electrons in the high-energy ring and 3.1 GeV positrons in the low-energy ring, with one intersection point where the beams would be allowed to collide. The rings began operation in 1999 and eventually reached a luminosity of around 10^{35} cm^{-2} s^{-1} at astonishing beam currents of approximately 1.5 A of electrons and 2.5 A of positrons.

The centre-of-mass collision energy was tuned to the Upsilon 4S resonance to produce a flavourless meson formed from a bottom quark and its antiparticle that then decays into a pair of B mesons. It allowed the first observation of charge-parity violation outside of the kaon system and helps explain the mechanism, at the instant of the Big Bang, by which there is more matter than antimatter in the universe. A key factor in these observations was to make the collisions asymmetric in energy so that the centre-of-mass frame would be moving during the collision and allow the lifetime of the different decay channels to be identified by virtue of the distance of the new particle vertices from the collision point.

The SLAC Linear Collider

The discoveries at SLAC gave strong support to the quark model, and the "eight fold way" was enhanced to become "The Standard Model" and is summarized in Table 1.

The quarks and the leptons appeared to be divided into three families of matter and all the particles that had been discovered at SLAC and elsewhere could be accounted for in this framework. The vector bosons in the Standard Model, or force carriers had also been observed. The next step was to confirm that there were indeed only three families of matter, not more, and this could be confirmed by measuring the resonance width of the Z boson, the carrier of the weak force. Both CERN and SLAC proposed the construction of an e^+e^- collider with a roughly 100 GeV centre-of-mass energy at the Z_0

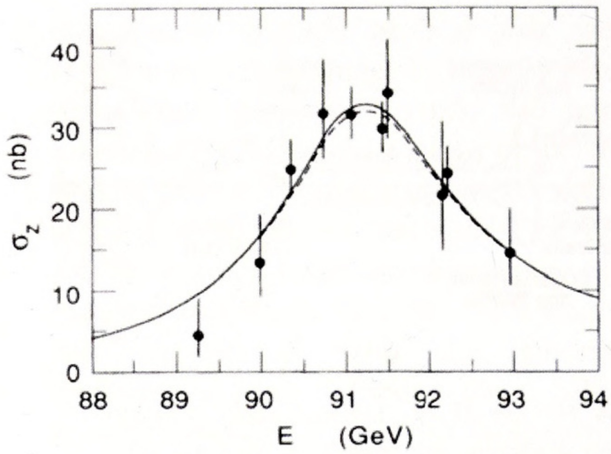

Figure 15: The SLAC measurement of the width of the Z_0 resonance at 91.4 GeV confirmed the Standard Model prediction that there were only three families of matter.

resonance to make this precision measurement. CERN proposed the 27 km LEP ring, and SLAC proposed using the 3 km long linac to reach the same energy. SLAC was able to raise the energy of the linac from its original 20 GeV to 50 GeV through the invention of the SLED device (SLAC Linac Energy Doubler). It uses RF pulse compression to deliver four times the peak RF power in a shorter pulse to the linac structure thereby increasing the accelerating field gradient.

SLAC would have to perform an extra trick of accelerating consecutive bunches of electrons and positrons and deflecting them around two opposite arcs, as shown in Figure 14, to bring them into collision in the centre of the SLD detector.

The LEP storage ring would collide the bunches ten thousand times per second as they went round and round, so the SLAC Linear Collider (SLC) would have to focus the beams to micron size diameters in order to get the same luminosity in the detector. This was possible at SLC by making very small emittance beams in the damping rings and then keeping the emittance under control as the beam was accelerated in the linac.

The storage ring was a more conservative approach and ultimately reached a higher luminosity, but the linear collider was also a test experiment for future colliders. Clearly, the next generation of colliders operating at 10^{12} or Terra electron volt (TeV) energies would be impractically large if built as rings, so it was important to test the linear collider concept whose size would still be manageable when scaled to a TeV.

The SLAC measurement of the Z_0 resonance, shown in Figure 15, was still sufficient to prove beyond a doubt that the Standard Model held true and that only three generations of matter could exist.

Synchrotron Light Sources

Already during the heyday of particle physics at the SPEAR machine another group of Stanford physicists was lobbying for access to the photon radiation generated by the beam circulating in the ring. Synchrotron radiation was regarded with disdain by the machine builders because it limited the energy of a storage ring and it produced unwanted heating and outgassing of the vacuum chamber. The photon users persisted with their claims that the synchrotron light was the brightest source of x-rays in the world, by orders of magnitude, and would allow revolutionary new science to be done.

The director of SLAC reluctantly allowed one photon beam line to be added to the SPEAR ring, worried that it would take away precious beam time from the high-energy physics program. The rest is history, as they say, and the number of synchrotron radiation beam lines grew rapidly. When SPEAR reached the end of its useful life as a high-energy physics machine it became the world's first dedicated

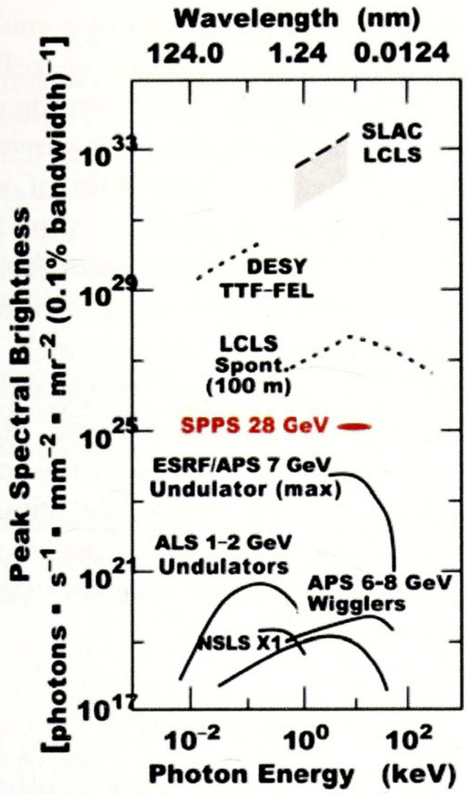

Figure 16: The peak brightness from linac-based light sources exceeds storage rings by many orders of magnitude over a range of wavelengths.

synchrotron light source. It has been upgraded several times and still operates today as a 3rd generation light source, SPEAR3.

Many dedicated synchrotron light source laboratories have now been built around the world, numbering more than sixty, including the Australian Synchrotron built in 2007 in Melbourne. These modern storage rings use *insertion devices* to wiggle the beam in an undulator section to produce extremely bright x-ray beams. The brightness of the x-rays is ultimately limited, though, by the equilibrium electron bunch dimensions in the storage ring.

The light source designers enviously looked at the extremely small electron bunches that the linear collider was producing and calculated they could create a free electron laser (FEL) at x-ray wavelengths using a very long undulator

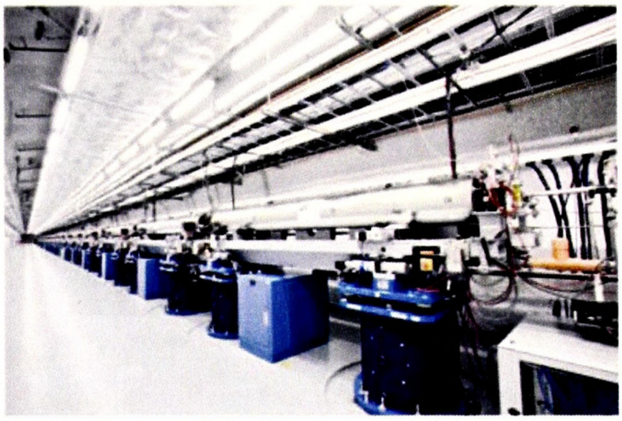

Figure 17: view of the 100 m long undulator of the Linac Coherent Light Source.

at the end of the linac. The linear collider project was not about to give up any of its precious beam time to the light source users, but we were able to do a proof-of-principal experiment to demonstrate the feasibility of x-ray production with the linac.

An electron bunch compressor chicane was installed in the linac in 2002 which would compress the bunches to a pulse as short as 80 femtoseconds duration. The bunch compressor chicane worked by putting an energy *chirp* on the electron bunch, giving the head of the bunch a higher energy, and then sweeping the bunch around a chicane so that the low energy tail would catch up with the head of the bunch.

A 2.4 m long undulator borrowed from the Argonne Advanced Photon Source was installed on a beam line at the end of the linac and the compressed 28 GeV electron bunch produced a blinding flash of x-rays at 1.5 A wavelength.

At this time the linac was primarily being used as an injector for the PEP-II collider, but it was possible to parasitically deliver 10 Hz repetition rate beams to this new photon facility, the Sub-Picosecond Photon Source (SPPS). Numerous experimental techniques

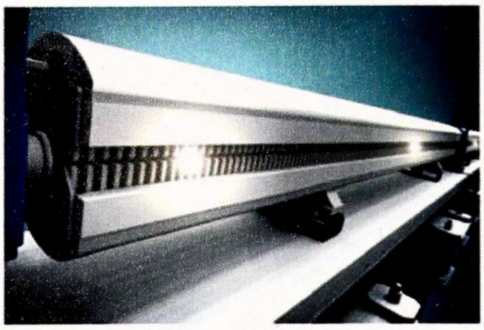

Figure 18: The LCLS undulator is made up of thousands of permanent magnet wiggler magnets.

for linac-based light sources were able to be tested with the ultra-fast pulses at this facility.

For a time the SPPS held the record for peak brightness for any x-ray source, as seen in Figure 16. The radiation, however, was still incoherent, as it is in storage ring light sources. The bigger prize was yet to come with the installation of a linac-driven FEL.

The Linac Coherent Light Source LCLS

The LCLS produced its first x-ray beam in 2009, and uses a 100 m long undulator, shown in Figure 17, at the end of the linac to produce Self Amplified Stimulated Emission (SASE) at x-ray wavelengths. The undulator is assembled in 3 m long modules made up of hundreds of permanent magnet dipoles, as shown in Figure 18. The incoherent synchrotron radiation generated as the beam wiggles back will amplify in one selected mode and produce fully coherent x-rays that are 10 orders of magnitude brighter than a storage ring light source.

Such an increase in brightness over existing machines has required the invention of a whole new science in analysing x-ray diffraction. It is now possible, for example, to image a single molecule in a single shot. It will no longer be necessary to crystallize complex organic molecules such as proteins in order to image their structure. Enough photons can impinge on a single molecule that the diffraction image can be collected from a single molecule. The downside is that of course the molecule does not survive the onslaught of such a bright beam of x-rays. However, the pulse duration from the LCLS can be as short as a few femtoseconds so it is possible to capture the image before the molecule flies apart. The extremely short duration of the pulse also allows ultra-fast phenomena to be captured in the strobed images. A technique referred to as pump-probe allows the molecule to be stimulated and then observed with the x-ray strobe at sub-picosecond intervals after the stimulus has been applied.

Conclusion

SLAC has had a rich history, playing a significant role in the development of accelerator technology and the understanding of modern particle physics. SLAC continues to play a role in the development of new technology for future colliders and participates in international collaborations to build a Linear Collider and Higgs factory. The SLAC campus, however, may become more recognized in the future for its role as the world's leading photon science laboratory with its unique facilities for x-ray laser production.

Acknowledgements

This article is written in fond memory of my mentor and thesis advisor, Professor Jak Kelly, who instilled in me a suitable awe for large accelerators and high-energy physics. I am happy to say that this fascination with accelerators has stuck with me at SLAC. In preparing this article I am also grateful to the SLAC Archive Office for their extensive collection of photographs and articles chronicling the history of SLAC.

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Patrick Krejcik graduated from the University of New South Wales with a PhD in 1980, where his supervisor was Professor Jak C. Kelly at the High Voltage Accelerator Laboratory in the School of Physics. Jak instilled in his students not only an awe for physics, and that it could be good fun, but also that it was part of a bigger adventure that was going on in laboratories around the world. Patrick pursued accelerator research at the German heavy-ion laboratory, GSI, then at the proton-antiproton collider at CERN in Switzerland, before finally moving to SLAC in California, where he now resides.

In later years, Jak wryly observed that there was an alarming trend in Patrick's career moving from heavy ions at GSI to smaller protons at CERN, then to tiny electrons at SLAC and finally to massless photons in the FEL laser, suggesting that there may only be the vacuum energy of virtual particles left to speculate on. Jak's energy and wit remains with us.