SLAC – PUB – 3570
February 1985
(E)

THE SLC PROGRAM*

CHARLES Y. PRESCOTT

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

ABSTRACT

A brief report on the goals and progress of the SLAC Linear Collider program is presented. Included are the status of the machine and detectors, and an overview of the physics program.

Invited talk presented at the Aspen Winter Physics Conference
Aspen, Colorado, January 13-19, 1985

---

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

1. INTRODUCTION

The SLC proposal was conceived as a prototype of a new class of particle accelerators, the linear colliders.[1] The desires for higher energy e^+ e^- collisions were based on the highly successful e^+ e^- physics program at existing machines and the promise of exciting physics experiments at higher energies. Scaling of storage ring parameters to reach higher energies led to designs of very large machines and estimates of very costly projects. The SLAC Linear Collider proposal was an economical step to achieve the next increment in energy that seemed appropriate, namely that needed to reach the $Z°$.

To achieve economically the desired luminosity, comparable to that possible in a scaled-up storage ring, the small beam size and short duty cycle capabilities of a linac were exploited. Modifications of the existing SLAC linac were required, including damping rings to reduce beam emittance, higher power klystrons to increase the accelerating gradient, and beam transport lines to split the e^+ and e^- beams and bring them into collision. The SLC proposal was approved in stages, with final approval of construction in early 1984. This report summarizes the status as of January 1985. The first beams are scheduled for January 1987.

2. THE STATUS OF THE MACHINE

Figure 1 shows schematically the plan for the SLC. The various components include the existing linac structure upgraded for higher energy and better control of the beams, a new gun and booster, two damping rings to provide small beam emittances, a positron source, beam transport arms, a final focus section, and the experimental hall and detectors.

Tests of the injector and one of the two damping rings have been underway for over a year. The purpose of the damping rings are to reduce the beam emittance normally delivered by a linac gun and an injector to values low enough to be focussed to small spots. At design performance, the south damping ring is expected to have two bunches of 5×10^{10} electrons circulating diametrically opposed. The design of the lattice is optimized for fast damping of electron orbits through quantum fluctuations. The damping time is 3 milliseconds. After circulating in the damping rings for the linac interpulse period (nominally 5.3 milliseconds at the linac pulse rate of 180 Hz) , the two bunches are extracted and sent into the linac, along with an e^+ bunch from the other damping ring. The first e^- bunch and the e^+ bunch are sent to the experiments, while the second e^- bunch generates e^+'s for a future e^+ bunch.

In February 1984, single bunches of 1×10^{10} electrons were accelerated into the south damping ring, extracted and accelerated through 10 sectors (1/3 of the linac). Invariant emittance, momentum spread, and bunch length were all within design specifications. This demonstration of the fundamental principles represented a major step in the project and satisfied a milestone to be passed before conventional construction started.

Since February 1984, construction of the second damping ring on the north side of the linac has begun, improvements to the injection and extraction lines have been done. Beam tests in the fall of 1984 demonstrated that two electron bunches of 5×10^{10} electrons in each bunch were accelerated up to the south damping ring. Bunch charges of 4×10^{10} electrons were circulated in the damping ring, but not extracted. No emittance measurements were made on these bunches. The immediate goals for the spring 1985 running are to demonstrate two bunches can be injected and extracted from the damping ring, with 2×10^{10} electrons each bunch, and accelerated through 10 sectors. Emittance and momentum spread will be measured at that point. The north damping ring construction is well underway, and operation of that ring on e^+ beams is scheduled for March 1986.

Conventional construction for ths SLC is well along. The connections between the linac switchyard and the collider tunnels were completed last summer. The arc tunnels are close to completion, with access available in March 1985 and July 1985 for the north arc (e^- beam) and the south arc (e^+ beam), respectively. The next steps for the arc tunnels are to provide a surveyed coordinate system, install cabling and pipes for the magnets, then magnet supports followed by the magnets themselves. The magnet installation is scheduled to begin in September 1985.

The construction of the interaction hall for the experiments has begun. Preliminary excavation started last summer. The construction of the hall itself is underway, with completion expected in February 1986.

Installation of the first detector (Mark II) is presently scheduled to begin in spring 1986. Other technical components for the collider include the positron source, new klystrons, arc magnets and final focus magnets, and a polarized electron gun. The positron source includes a pulsed kicker and beam line to extract the second e^- bunch, a target, a 200 MeV booster, and a return line to bring the e^+'s back to the front of the accelerator. The kicker and beam line are expected to be tested toward the end of this year's spring running, May 1985. The return line consists of a simple vacuum pipe, mounted on the ceiling of the linac tunnel. The vacuum pipe and it's quadrupoles and steering magnets will be installed between June and October 1985. The 200 MeV booster will be tested in March 1986, and shortly thereafter, e^+'s are scheduled to be sent back to the front of the linac, accelerated through sector 1, and injected into the north damping ring. The final step, acceleration of e^+'s down the linac, is scheduled for June 1986.

Upgrading the klystrons from 38 megawatt units to 50 megawatt units is required to achieve sufficient energy for Z° production. The linac presently has a complement of 240 klystrons. The energy upgrade requires replacing approximately 180 of the klystrons with 50 megawatt tubes. Production of the 50 megawatt tubes has not been easy. SLAC must design and build them , since no supplier of these tubes exists. Early tests of these higher power units revealed a problem with vacuum windows failing due to the higher electric fields present. The problem has been solved by splitting the microwave plumbing at the output into two waveguides and two windows, then recombining into one waveguide. Fifteen such tubes have been completed at SLAC and are being installed in sectors 9 and 10 for tests under realistic accelerator conditions. Lifetimes of the cathodes, a critical parameter, will be measured during these tests.

Magnets for the collider arcs and final focus are under construction at SLAC. The magnets combine bending and quadrupole fields into one element. The basic design allows the beam to follow the local terrain so that tunnels and the experimental hall remain near to the local ground surface. Installation of the magnets begins in September 1985.

The polarized electron gun exists in prototype form. An earlier version of this device was operated successively on the linac in 1978 and 1979. It is a laser-driven photoemission source with a cathode of gallium arsenide. Polarizations of 40% have been achieved, and currents in excess of 5×10^{10} electrons in a single bunch are readily achieved with modest laser power. Plans to replace the gallium arsenide cathode with other similar materials are expected to provide considerable higher polarization. The polarized source is not scheduled to operate during the first year of the SLC operation.

Final focus and steering are essential in order to reach the SLC luminosity goals. Without focussing, the luminosity would be about $5 \times 10^{26}\ cm^{-2}\ sec^{-1}$ at full current. At this luminosity the SLC would yield 1.6 Z°'s per day, which isn't too bad by today's standards, but far below what is possible. Focussing the linac beams from elliptical spots of $250\ \mu m \times 30\ \mu m$ to round spots of 1 to 2 μm diameters can raise the luminosity to well above $1 \times 10^{30}\ cm^{-2}\ sec^{-1}$. The function of the final focus is to provide a small spot size in the presence of $\pm 1/2\%$ momentum spread. Control of the aberrations leads to a complex set of magnets, requiring 500 feet of space, six bending magnets, 25 quadrupoles, and 8 sextupoles for each of the two incoming beams. In addition extraction and dumping of used beam, and steering of beams into collision is part of the final focus section. Installation of these components is scheduled for late 1986.

Mechanical stability of the arc magnets and final focus magnets is essential. Tolerances of $\pm 0.1\ mm$ are required. Seismic noise has been shown not to be a problem, but thermal effects and floor settlement must be accommodated. Automatic alignment mechanisms are being designed for the final focus section.

Beam steering and beam finding techniques are important to bring micron-sized beams into collision. The techniques envisioned incorporate several steps to go from the millimeter scale to the micron scale. They are:

(i) for gross steering, beam position monitors, which sense the proximity of charge to an electrode, are suitable down to ±100 *μm*. Such devices are currently in use in the linac;

(ii) below the 100 *μm* level, it is proposed that momentary raster scans over approximately 100 *μm* × 100 *μm* areas in steps of 10 *μm* sizes be used. A single scan requires less than one second; and

(iii) when the two incoming beams pass within 10 *μm*, they begin to interact through the magnetic fields, causing deflections. Detectors downstream sense the presence of synchrotron radiation emanating from the beam-beam interaction. Gamma rays in the 1 *MeV* range signal the nearby passage of the other beam. The flux of soft γ's, the energy spectrum, and the angles of the γ's tell the control system the direction and amount to adjust offsets to bring the beams into full collision. The final 10 *μm* adjustments will depend on sensing the magnitude and direction of the γ's from the beam-beam interaction ("beamstrahlung"). In head-on collisions, the beamstrahlung photon energies reach 100 *MeV* and scatter outward at angles up to 2.5 *mrad*.

Luminosity of the SLC is expected to reach 6×10^{30} cm^{-2} sec^{-1} at the design intensity of 5×10^{30} e^{+}'s and e^{-}'s. The linac pulse rate is 180 *Hz*. The spot size is expected to be 1.8 *μm* diameter and 1.5 *mm* long. Divergence of the incoming beam is 0.3 *mr* and grows to 2.5 *mr* after collision with the other beam. All beamstrahlung photons lie inside the 2.5 *mr* after collision with the other beam, so detector components are mostly free of this source of backgrounds. At full luminosity of 6×10^{30} cm^{-2} $sec{-}1$, each beam is strongly focussed in passing through the other. The expected pinch effect is important to the SLC physics, and will be studied carefully because of the implications for future collider projects.

At a luminosity of 6×10^{30} cm^{-2} sec^{-1}, a production of 3×10^6 Z°'s per year is expected, based on an operation efficiency of 1/4 of the calendar year.

3. THE STATUS OF THE DETECTORS

Through a series of deliberations beginning in 1982 and extending into 1984, the SLAC Experimental Program Advisory Committee (EPAC) selected two detectors for the SLC experimental program. The first of these, the Mark II, was selected from several proposals to upgrade existing PEP detectors. The ground rules established by the EPAC were that the first detector be an upgrade, that the modifications be tested at PEP, and that the detector be ready for SLC turn-on in early 1987. The EPAC further decided that a second detector should be built from "grounds-up", optimizing it's capabilities for Z° physics. Desireability to incorporate 4π hadron calorimetry, and that the second detector should be ready for data in calendar 1988 were recommended. The single proposal for a new detector was the SLD, which was approved in the spring of 1984.

3.1 THE MARK II DETECTOR

The Mark II collaboration consists of eight institutions[2] of approximately 67 physicists, but expecting to grow to 100 by beam turn-on, plus students. The proposal is a significant upgrade of the existing Mark II. It will incorporate the following new components; a new coil, an end door retraction mechanism, an endcap electromagnetic calorimeter, a new central tracker, a time-of-flight scintillator and photomultiplier system, new FASTBUS electronics, a 6-layer trigger chamber, a luminosity monitor, and a vertex detector. The only components not changed are the iron return yoke, the liquid argon calorimeter, and the muon detector. These changes are nearing completion, with the testing at PEP to be underway in October 1985. A move to the SLC interaction region is planned in the spring or early summer of 1986. Figure 2 shows a quadrant cross section of the upgraded Mark II. The new endcap calorimeter, combined with the liquid argon modules and the luminosity monitor provide nearly 4π coverage for electromagnetic interactions. The endcap calorimeters are under construction at LBL, and are expected to be tested next month, February 1985, at SLAC. Installation of the endcaps is planned for April 1985. The endcaps are a lead-drift tube sandwich device, somewhat like the Mark III endcap design. They consist of 36 layers of aluminum tubes and $1/2\ X_\circ$ lead sheets ganged together in quasi-tower geometry, and segmented in depth three times. The first 8 layers are ganged together into $3 \times (X - Y - U - V)$ groups, followed by 12 layers ganged again in $X - Y - U - V$ geometry, followed by 16 layers of $X - Y$ geometry. The total system consists of 1300 channels; resolution with argon-ethane gas operating in a saturated avalanche mode is expected to be $\approx 17\% \sqrt{E}$. The angular coverage is 18° to 45°.

The Mark II central tracker consists of 12 layers of vector cells, each containing 6 sense wires. The inner radius of the tracker is 19 cm, the outer radius is 148 cm, and the length is 2.5 m. The magnetic field during running will be 5 kG. The system contains 5832 sense wires, processed in FASTBUS by multihit electronics. Resolution with $argon - CO_2 - CH_4$ gas is expected to be below 200 μm, with a 2 mm two-track separation.

The drift chamber will measure dE/dx to augment time-of-flight and electromagnetic calorimetry for e/π separation. Construction of this drift chamber is complete. Tests are underway, with cosmic ray tests in the detector scheduled for April 1985.

Several vertex detector schemes are being considered for Mark II; a precision drift chamber capable of 40 μm resolution at 4 atmospheres, a silicon strip detector, and CCD's. None of these will be tested at PEP, and a choice of which to use will be made in the summer of 1987.

3.2 THE SLD DETECTOR

The SLD detector will be constructed by a collaboration of 22 institutions[3] consisting of presently approximately 100 physists, but expected to grow considerably before data begins. This detector goes beyond the the Mark II capabilities in the following areas; hadron calorimetry and full hadron particle identification over nearly 4π solid angle, and tracking and muon identification over 4π solid angle. The detector was approved by the SLAC EPAC in May 1984, and achieved DOE funding approval in November 1984. The rate of funding has not yet been established. Construction will begin in the fall of 1985.

Figure 3 shows a cross section of a quadrant of the SLD. Access to the interior systems is achieved by retraction of the large doors, which withdraw the endcap calorimeters, Cerenkov ring imaging devices, and endcap tracking devices.

Tracking in the SLD consists of a vertex detector and a central and endcap drift chamber system. Resolutions for single tracks in the vertex and drift chambers are expected to be 5 μm and 100 μm, respectively, with two-track separations of 40 μm and 2 mm. Tests of prototypes have confirmed these performance values. Processing of raw data from these devices will be done in fast front-end processors in FASTBUS. Momentum resolution in the central region is expected to have the form $\Delta p/p = \sqrt{(.0092)^2 + (.0013p)^2}$, in a 6 kG field.

Particle identification in the SLD is based on Cerenkov rings in a Cerenkov ring imaging device (CRID). Full $e/\pi/k/p$ separation is expected over the full momentum range of particles. Muons are identified at the back of the iron calorimeter. The CRID system will cover nearly the full 4π solid angle. The system will achieve complete particle identification at all momenta by combining a liquid radiator (FC-72) and a gas radiator (isobutane) into a single detector. Cerenkov photons are collected in rings in a photon detector consisting of isobutane and methane and small amounts of the photosensitive compound tetrakis-dimethyl-amino-ethylene (TMAE). With suitable electric fields, photoelectrons drift toward a detector of sense wires at the ends of the CRID volume. The arrival times can be translated into drift distances from the detectors. Circles of photoelectrons can be identified; the radii serve to identify the particle types. Prototypes of the CRID system have demonstrated rings from both liquid and gas radiators for π's at 11 GeV/c. Performance from the liquid radiator has achieved theoretical expectations, and results from a gas radiator are expected in the spring of 1985.

Calorimetry in the SLD is based on a depleted uranium-lead tile-liquid argon device, followed by an iron-gas calorimeter incorporating the Iarocci streamer tube technology. The liquid argon calorimeter contains 20 $X_\circ$ in the electromagnetic section and 3.6 λ in the combined electromagnetic and hadronic sections. The liquid argon calorimeter will be inside a conventional aluminum coil of $\approx 0.5\ \lambda$, followed by the iron-gas calorimeter of $\approx 5\ \lambda$ thickness. Muon identification is incorporated in the outer two layers of the iron-gas system. The choice of the uranium and lead for the liquid argon calorimetry combines the desireable features of high density for compactness, fission compensation for better energy resolution, liquid argon for calibration stability and ease of readout segmentation, and tower geometry for simplicity in the analysis. Tower sizes are 33 × 33 *mr* in the electromagnetic section and 66 × 66 *mr* in the hadronic portion. Design goals for resolution are $\sigma(E) \approx 8\%\sqrt{E}$ (electromagnetic) and $\approx 50\%\sqrt{E}$ (hadronic). Tests of prototypes are underway, with results to be reported in the next month or two.

4. THE PHYSICS GOALS

The electroweak parts of the standard model today appear to work wherever they have been tested. The field of particle physics is facing an important branch in the progress of understanding. On the one side are predictions of grand unification which see no new physics beyond the 100 *GeV* scale. The three forces explain all phenomena out to the GUTS scale of 10^{15} *GeV*. The Higgs boson(s) remain to be found. On the other side are many models of interesting processes with mass scales below 1 *TeV*. Hints of new physics such as supersymmetry, technicolor, compositeness, or other processes, may already be seen in the collider experiments. The physics program of the SLC concentrates on production of Z°'s for study. In the decays of this object lies detailed information on weak interactions and potential new physics up to the 1 *TeV* energy scale. The large counting rates available at the peak of the Z° provides the source of data we need to probe particle interactions out to the *TeV* scale.

Table I is a long list of physics topics that has been discussed in various contexts relating to Z° physics. It is not necessarily intended to be a complete list. The purpose of this list here is to characterize the Z° program in terms of the demands on the machine, and the demands on the detectors. Not all of the listed topics will be of equal importance or interest, but that may be difficult to judge today. Table I characterizes each topic according to the luminosity required, translated into equivalent number of Z°'s produced. The design goal of 6×10^{30} cm^{-2} sec^{-1} yields an estimated 3×10^6 Z°'s in a calendar year, operating at $\approx 1/4$ efficiency. Many physics topics do not require that many Z°'s. A machine which operates at 10^{29}, for example, can provide enough data to study many of these questions. Table I is an attempt to estimate the demands placed on the machine.

The second part of Table I looks at the same topics for the detectors. Some of these topics place little demand on detector capability, while others require considerable performance from a detector. For example, processes with final state neutrinos are best studied with calorimetry which has 4π coverage. Heavy quark processes can be separated from other processes with a vertex detector and hadron particle identification. Particle identification is of significant use in studies of new mesons and baryons. The discovery potential of large detectors will be best in the detectors providing the most complete and clean particle information. Table I provides two simple one-dimensional projections of a complex set of conditions and circumstances associated with Z° physics. Surely some of these topics will lead to new physics, new experiments, and many talks and publications in the coming years.

5. CONCLUSIONS

The SLC program is an accelerator experiment and a physics experiment. The progress in the accelerator experiment has been rapid, with injector and damping ring components working, conventional construction on schedule, and technical components in production. Accelerator studies will investigate beam-linac and beam-beam interactions, with application to the design of future linear colliders. The physics experiments start in 1987 to study Z° properties and to look for new physics effects. Detectors to fully exploit the potential physics are under construction.

ACKNOWLEDGEMENTS

This report summarizes the work of a great number of people. I would like to thank the following individuals for their assistance in assembling the material: R. Stiening, R. Erickson, J. Clendenin, S. Ecklund, D. Getz, and J. Faust helped with the accelerator status and construction schedules; G. Feldman, J. Dorfan, J. Kadyk, M. Breidenbach, D. Leith, and D. Hitlin provided information on the detectors, and numerous colleagues, too many to name, have contributed to studies of the physics goals.

REFERENCES

1. B. Richter, "Large Linear Colliders," SLAC-PUB-3371 (1984).
2. California Institute of Technology, Colorado, Lawrence Berkeley Labs, Hawaii, John Hopkins, Michigan, UC Santa Cruz, and SLAC.
3. California Institute of Technology, Cincinnati, Colorado, Columbia, Frascati, Illinois, Massachusetts Institute of Technology, Northeastern, Rutherford-Appleton Labs, Perugia, Pisa, Triumf, Northridge, University of British Columbia, Ferrara, UC Santa Barbara, Tennessee, Vanderbilt, Victoria, SLAC, Wisconsin, Washington.

Table I. The Z° Physics Program Demands

Physics		Z°'s		Vertex	Tracking	EM Calor.	Particle ID	Had. Calor.	Muon ID	$4\pi\ \Omega$
Topic	10^4	10^5	10^6							
Mass	●				●	●				
Width	●				●	●				
ν Counting		●			●	●				●
Lepton Couplings		●			●	●			●	
Heavy Quark Couplings		●		●	●		●			
Jets	●			●	●	●	●	●		
Higgs Search			●	●	●	●				
Hadronic Studies			●	●	●	●	●	●	●	
Top	●			●	●	●	●	●		
Toponium			●	●	●	●				
CP Violation			●	●	●	●	●	●	●	
Polarization Studies		●		●	●	●	●	●	●	●
Rare Z° Decays			●	●	●	●	●	●	●	●
SUSY		●			●	●		●	●	●
$SU(2)_L \times SU(2)_R \times U(1)$			●		●	●			●	●
Compositeness		●			●	●			●	●
Flavor-changing N. C.'s			●	●	●	●	●	●	●	

This table characterizes the demands placed on the machine and detectors. It is a list of physics topics that may be of interest. For each topic an estimate of the required luminosity, in terms of the number of produced Z°'s, is given. Estimates of the detector capabilities that are desirable or necessary are also given. The table is intended to be an overview. The list of topics is surely incomplete, and demands of the machine and detector may change as new ideas and techniques develop.

FIGURE CAPTIONS

1. Schematic layout of the SLC main components.
2. A quadrant section of the Mark II upgraded detector.
3. A quadrant view of the SLD detector on a log scale. Traditional detector schematics give short shrift to the precision components near the collision point. This logarithmic sketch strikes a different balance.

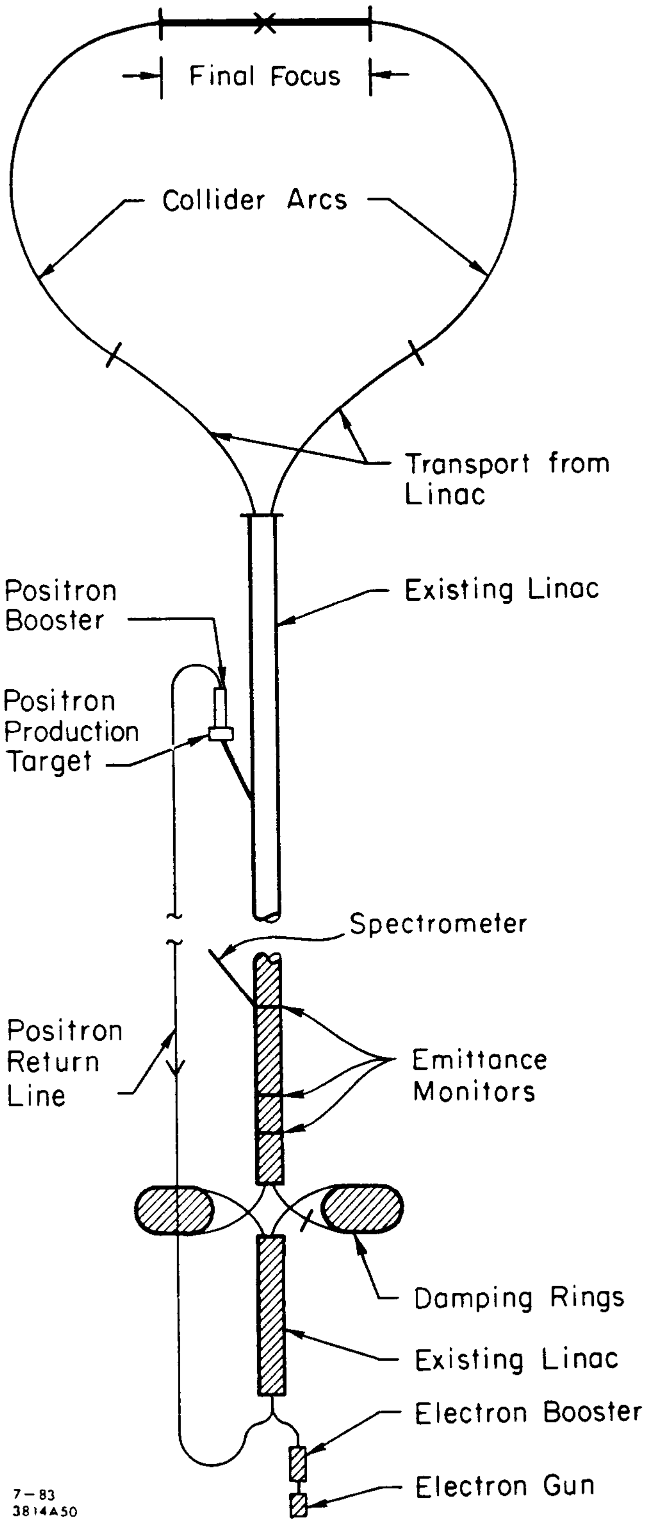
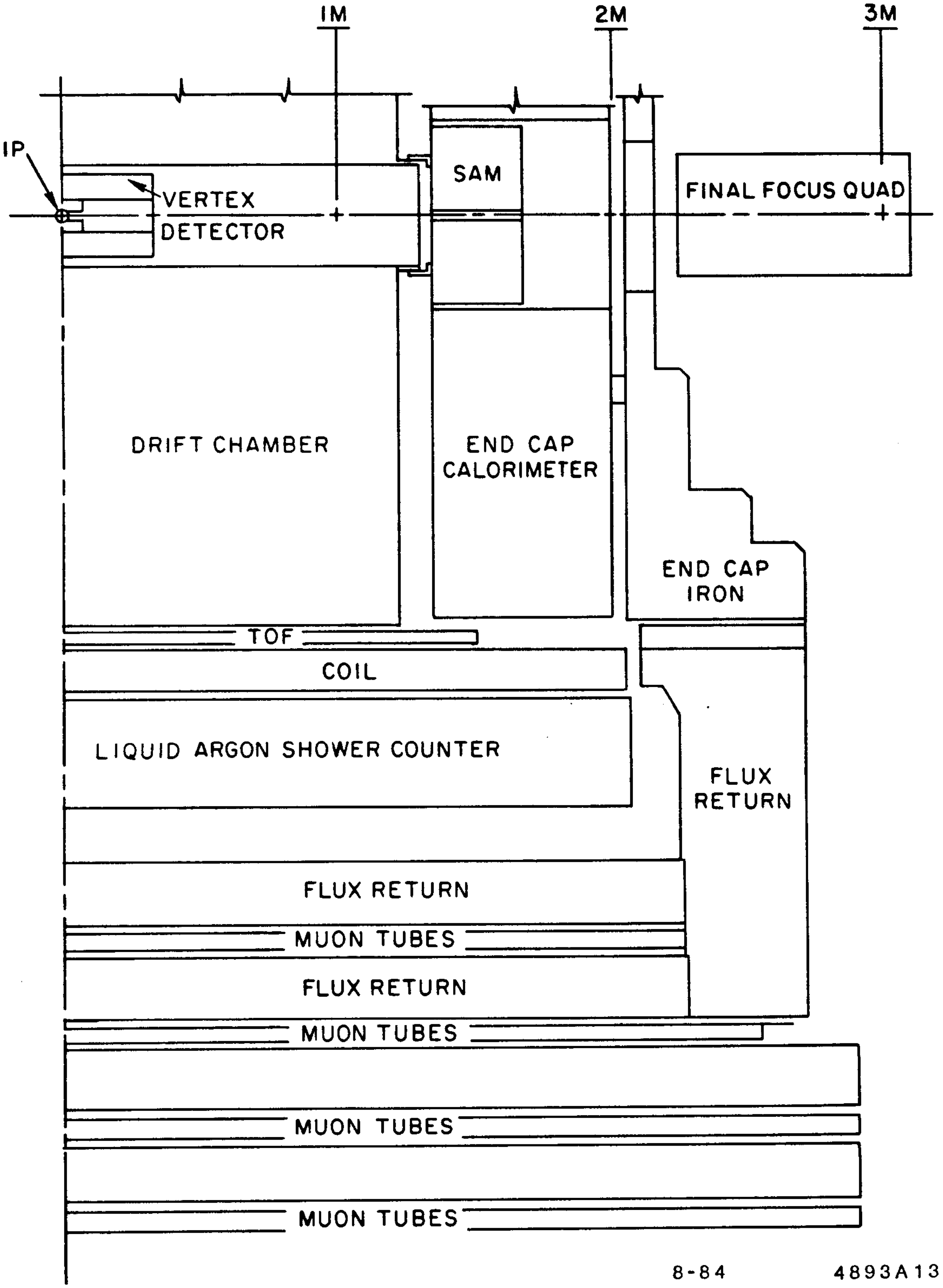

Final Focus
Collider Arcs
Transport from Linac
Existing Linac
Positron Booster
Positron Production Target
Spectrometer
Positron Return Line
Emittance Monitors
Damping Rings
Existing Linac
Electron Booster
Electron Gun
7-83
3814A50

Fig. 1



1M
2M
3M
IP
VERTEX
DETECTOR
SAM
FINAL FOCUS QUAD
DRIFT CHAMBER
END CAP
CALORIMETER
END CAP
IRON
TOF
COIL
LIQUID ARGON SHOWER COUNTER
FLUX
RETURN
FLUX RETURN
MUON TUBES
FLUX RETURN
MUON TUBES
MUON TUBES
MUON TUBES
8-84
4893A13

Fig. 2

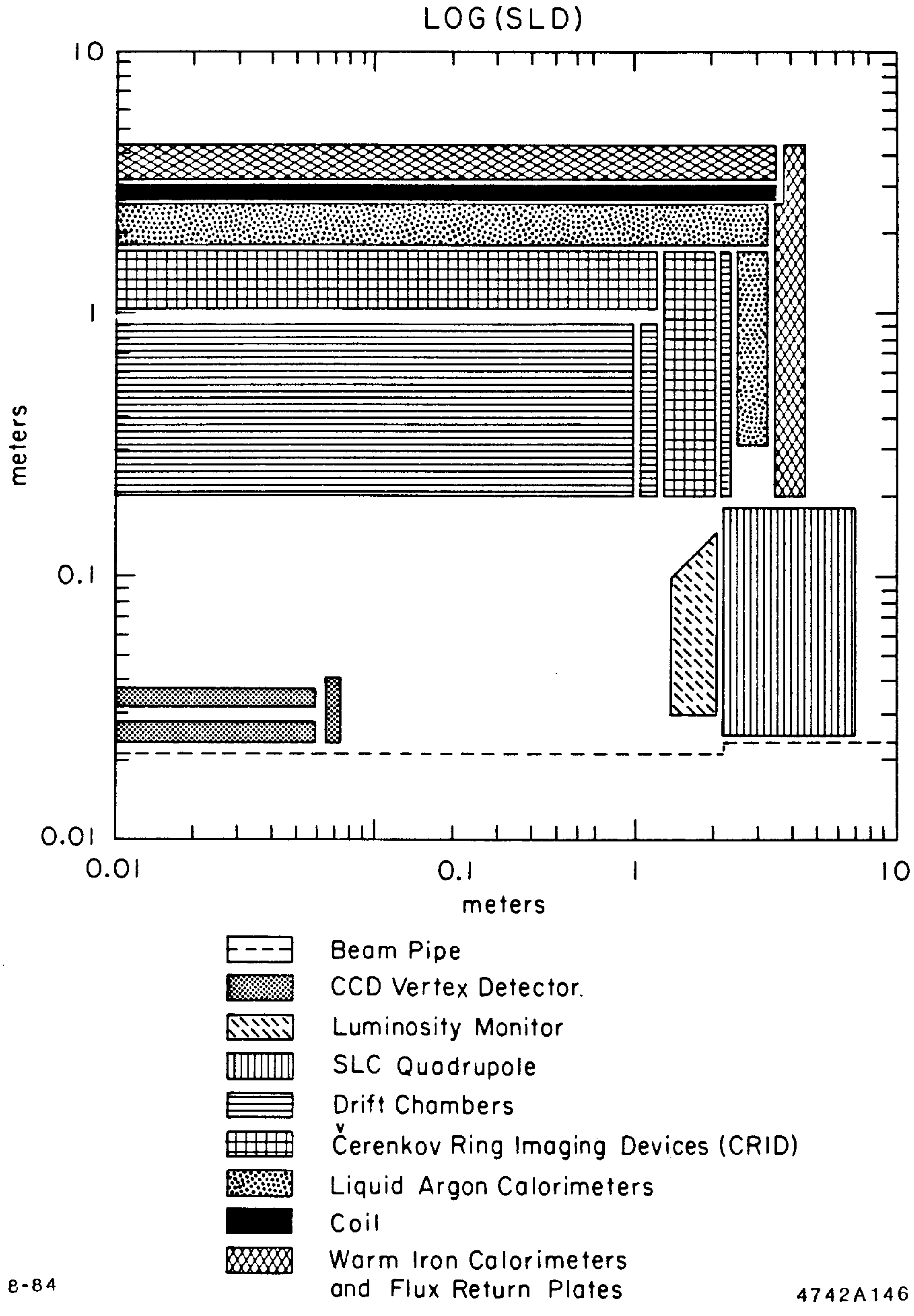

LOG(SLD)
10
1
0.1
0.01
meters
0.01
0.1
1
10
meters
Beam Pipe
CCD Vertex Detector.
Luminosity Monitor
SLC Quadrupole
Drift Chambers
Čerenkov Ring Imaging Devices (CRID)
Liquid Argon Calorimeters
Coil
Warm Iron Calorimeters
and Flux Return Plates
8-84
4742A146

Fig. 3