THE SSC LINAC

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Abstract

The preliminary design of the 600 MeV H$^-$ linac for the Superconducting Super Collider injector is described. The linac must provide a 25 mA beam during 7–35 µs macropulses at 10 Hz within injection bursts. Normalized transverse emittances of less than 0.5 π mm-mrad (rms) are required for injection into the Low Energy Booster synchrotron. Cost, ease of commissioning, and operational reliability are important considerations. The linac will consist of an H$^-$ source with electrostatic LEBT, 2.5 MeV radiofrequency quadrupole accelerator, a 70 MeV drift-tube linac, and 530 MeV of side-coupled linac. The RFQ and DTL operate at 428 MHz and the side-coupled linac operates at 1284 MHz. A modest total length of 150 m results from the tradeoff between cost optimization and reliability. The expected performance from beam dynamics simulations and the status of the project are described.

Introduction

The design of the SSC linac is determined primarily by the requirements of the Low Energy Booster (LEB). Multiturn H$^-$ injection into the LEB allows the use of a modest linac current with small emittance. The use of quasi-adiabatic capture in the LEB reduces the complexity of the linac front end and lowers the emittance for several reasons—the front end current is lower, a higher frequency RFQ is used, no choppers are required, and fewer turns will fill the LEB (fewer passes through the stripper).

The present design of the linac satisfies the LEB requirements and should have adequate design safety margins to provide for substantial flexibility, excellent reliability, and the potential for future upgrades. Although no inventions are required for this design, further development of several portions could improve reliability and lower construction costs of linac components. These development areas are described below within the appropriate linac component descriptions.

Nominal linac operation consists of the two modes listed in Table I—filling the collider rings and providing test beams. The linac satisfies the factor-of-five increase in LEB current for test beams by operating with a longer macropulse (increasing the number of injection turns). Since the other linac operating parameters remain unchanged, no linac tuning should be required in changing operating modes and no degradation in beam quality should occur. Of course, the option of lower current for as long as 35 µs is possible for both operating modes.

TABLE I
SSC Linac Requirements

- Filling collider ring
  - 25 mA H$^-$ current during macropulse
  - 6.6 µs macropulse (three-turn LEB injection)
  - 1×10^{10} / LEB bunch
  - < 0.5 π mm-mrad (t, rms, norm) emittance
  - 10 Hz repetition rate
- Test beam operation
  - 25 mA during macropulse
  - 35 µs macropulse (16-turn LEB injection)
  - 5×10^{10} / LEB bunch
  - < 4 π mm-mrad (t, rms, norm) emittance
  - 10 Hz repetition rate

Figure 1 is a block diagram of the major components of the linac with major system parameters and simulated performance shown. It consists of an H$^-$ source, an RFQ to bunch and initially accelerate the beam, a drift-tube linac to accelerate the particles to relativistic velocities, and a coupled-cavity linac for most of the energy gain. A substantial base of experience exists for linacs of this type with similar parameters. Based on past experience, actual linac performance can be expected to be close to the design simulations. By not departing too far from typical existing facilities, the availability requirement of 98% should be attainable after a reasonable commissioning period.[1] To provide adequate safety margins and allow future upgrades, the linac components are designed to handle twice the current with twice the emittance. Safety margins of this size are attainable with only a small impact on the cost of the linac. The frequencies are chosen to provide bunches on an harmonic of the LEB buckets at 600-MeV injection and for optimal accelerator operation. There are nine linac bunches per LEB bucket. The possible future transition to bunch-to-bucket LEB capture is therefore not forbidden by this design. Also, the harmonic relationship preserves the possibility of notching the beam to improve the efficiency of quasi-adiabatic capture.

The transfer line between the line and LEB has also been designed and is described in these proceedings.[2] The transfer line contains an energy analyzing section, a transverse emittance measuring section, and a buncher and focusing elements for longitudinal and transverse matching onto the stripper of the LEB injection girder.

Some aspects of the linac design will probably change during the preliminary design and engineering development stages. Accelerator changes will be incorporated where performance, reliability, or cost improvements are possible over the baseline design presented here. This baseline design is within the state-of-the-art of linac performance and is a cost-effective approach.

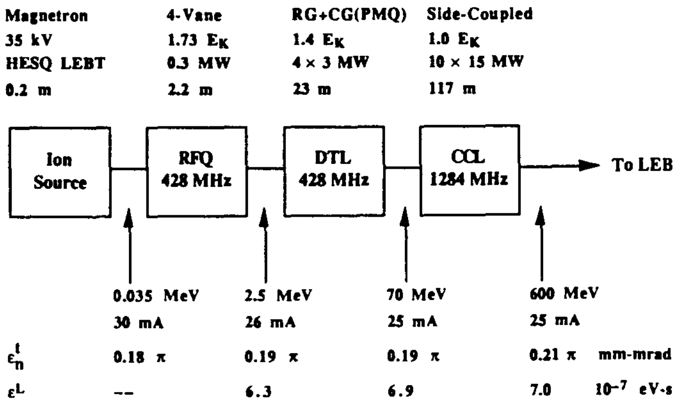

Figure 1. Linac block diagram.

Ion Source

The first component of the linac will be an H$^-$ ion source. There are three very different ion sources that should be capable of meeting the SSC beam criteria. These are the magnetron,[3] the Penning,[4] and the non-cesium volume source.[5] All three of these sources have unique advantages that must be considered. Of the three, only the magnetron has been used at large HEP facilities where long-term operation with high availability is required. If brightness becomes an issue, the Penning source is the brightest H$^-$ source available. The simplest source to maintain and operate is the rf-excited volume source, which also may have an additional advantage

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in terms of system reliability since it can be operated without filaments or cesium injection.

The magnetron has been chosen for the baseline design since it would require little effort to optimize it to the SSC beam parameters of 30 mA at 35 keV with very low duty. A prototype has been developed and delivered to the SSCL by the Texas Accelerator Center (TAC) for installation on the linac test stand. The Penning source could also easily be developed as a production source. Due to the similar electronics and vacuum systems of the magnetron and Penning sources, it is conceivable that these sources could be used interchangeably. The rf-excited volume source has the potential of being simplest and most reliable with further improvement in reducing the gas usage and the extracted electron current. SSCL is supporting this development effort at Lawrence Berkeley Laboratory.

Low Energy Beam Transport

The beam from an ion source is relatively large in radius and divergence and must be matched to the RFQ. The section of the linac that provides this match is called the low energy beam transport (LEBT). It also usually contains source diagnostics and provides the differential vacuum pumping between the source and the RFQ. The LEBT consists of lenses that focus the beam onto the entrance of the RFQ.

Most existing LEBT systems use magnetic focusing solenoids or permanent magnet quadrupoles. These LEBT systems also utilize charge neutralization in the background gas to minimize the required focusing strengths. The neutralization time should be short compared to the pulse length; otherwise, a large fraction of the beam at the front of the pulse will be lost due to inadequate focusing. As neutralization develops, the space charge forces decrease. Consequently the beam phase space ellipse rotates, constantly changing the match into the RFQ acceptance. Additional problems arise due to beam-plasma instabilities and the interface uncertainty as the beam appears charged again as it enters into the electric fields of the RFQ that has swept away the charge neutralizing ions formed in the collisions. Improper matching at such transitions and the conversion of field energy into transverse kinetic energy associated with changes in the beam profiles may cause significant emittance growth and particle loss.

The SSC linac requires a pulse length shorter than 35 μs. This is comparable to the expected neutralization time in hydrogen gas. The beam would need to be on approximately 100 μs to become fully neutralized. The neutralization time can be reduced by introducing xenon into the LEBT; however, full neutralization will always considerably increase the pulse length required from the source. The frequency of source maintenance is therefore increased and the reliability of the RFQ is decreased because of the poorer vacuum and increased cesium deposition rate. For the short-pulse operation of the SSC linac it is best to avoid neutralization if possible.

The 30-mA operating current is small enough that several concepts using electric focusing to avoid neutralization can be considered: einzel lenses, electrostatic quadrupoles, and radiofrequency quadrupole lenses. The RFQ lens can probably transport higher currents with fewer aberrations, but it is more complex and adds another rf system. The einzel lens and helical electrostatic quadrupole (HESQ) are the leading candidates for the SSC linac. The einzel lens is probably the most mature technology for this application. However, it requires voltages similar to the source voltage and is prone to aberrations. We are presently building a dual enizel lens LEBT for evaluation on the linac test stand.[6] The helical electrostatic quadrupole is somewhat more efficient than standard electrostatic quadrupoles and should be very reliable since modest voltages are required. A prototype HESQ LEBT is presently being characterized at TAC. We are starting construction of a fully engineered HESQ LEBT with nickel electroformed electrodes for evaluation on the linac test stand.[7] The HESQ LEBT parameters are summarized in Table II.

TABLE II
HESQ Simulation Parameters

Length	22.5 cm
Voltage	7 kV
Breakdown voltage	100 kV
Pitch of helix	15 cm
Electrode spacing	1.46 cm
Bore radius	1.5 cm
Input beam	
Current	30 mA
Transverse emittance (n, rms)	0.18 π mm-mrad
Output beam	
Current	30 mA
Transverse emittance (n, rms)	0.20 π mm-mrad

RFQ Accelerator

The RFQ accelerator is currently the accelerator of choice between the source and drift-tube linac instead of the Cockcroft-Walton high-voltage column used at earlier facilities. A considerable amount of RFQ design and operational experience now exists at many laboratories around the world at several frequencies and ion species.[8] Proton and H^- RFQs have been operated at 80, 200, and 425 MHz. The RFQ provides superior acceleration and matching performance in much less physical space and with greater reliability. With the RFQ operating at the same frequency as the DTL, more than 90 percent of the continuous beam from the source can be bunched, accelerated to several MeV, and captured by the DTL within a few meters with all apparatus at ground potential except for the 35-kV source. Most of the RFQ length is required for matching the beam transversely into a narrow channel and for quasi-adiabatically bunching the beam prior to acceleration. The attention to matching and gradual bunching and acceleration pays off not only in the improved capture efficiency, but in much less growth of the emittances in this section of the accelerator. The brightness requirements of the SSC and its future upgrades should be readily achievable by the linac because of the superior performance of RFQs.

With the choice of quasi-adiabatic capture in the LEB, excellent linac performance can be achieved by using an RFQ and DTL operating at the same frequency. The higher frequency improves the RFQ longitudinal emittance and the choppers and bunchers at low energies of older systems are always a source of transverse emittance growth. The beam macropulse length and, hence, the number of injection turns, is also minimized in this design since none of the beam is intentionally discarded.

The design of the RFQ is straightforward since several devices with similar requirements have been operated. The design philosophy adopted here is to make the RFQ operationally flexible and reliable. The current should be variable from 5 to 50 mA with the source emittance degraded by as much as a factor of two. The beam position tolerances should be reasonable and the maximum peak surface fields should be less than 36 MV/m (1.8 Kilpatrick). The output energy is a tradeoff between optimal matching into the DTL and keeping the length of the RFQ reasonable. The injected energy into the DTL should be high enough so that the drift-tube lengths are long enough for adequate permanent magnet quadrupoles. Two 425-MHz drift-tube linacs using permanent magnet quadrupoles have been built and successfully operated at higher currents with a starting energy of 2 MeV. A DTL injection energy of 2.5 MeV appears to perform well in our simulations with ample design margin. The mechanical structure of the RFQ could be either 4-vane or 4-rod. The 4-vane structure is chosen for this design primarily because of its much larger experience base. A design example is presented that satisfies the above requirements and can be fabricated with little further development. This RFQ is being fabricated for SSCL by Los Alamos National Laboratory. A 4-rod RFQ is being developed at TAC as a possible second injector for the SSC linac.

The RFQ design simulation parameters are listed in Table III. The input beam is 30 mA with a normalized transverse rms emittance of 0.20 π mm-mrad. The current limit for this design example is kept large so that this RFQ could work with higher beam currents. Another significant advantage of a higher current limit is that the specified tolerances for the RFQ fabrication process can be relaxed. One pays a price in terms of slightly increased length and power. Furthermore, this design example has a large acceptance that makes it possible to accelerate injected beams with transverse emittances that are larger by a factor of 2.

TABLE III
RFQ Design Parameters

Frequency	428 MHz
Injection energy	0.035 MeV
Output energy	2.5 MeV
Injection current	30 mA
Output current	27 mA
Input trans. emittance (n, rms)	0.20 π mm-mrad
Output trans. emittance (n, rms)	0.19 π mm-mrad
Output long. emittance (rms)	0.063×10^{-5} eV-s
RFQ length	222 cm (3.17 λ)
Total peak power	283 kW
Beam peak power	77 kW
Copper peak power	206 kW
Duty factor	0.05%
Copper power (average)	103 W
MPSEF	1.73 E_K

RFQ-DTL Matching Section

The RFQ-to-DTL matching section contains four quadrupoles and two 428-MHz bunchers. The quadrupole magnets are an extension upstream of the DTL FODO lattice. The permanent-magnet quadrupoles are variable with gradients varying from 131 to 140 T/m and lengths of 3.8 mm. The bunchers are located between the first and second and the third and fourth quadrupoles. The bunchers need net voltages of only 100 and 70 kV. They are operated at –90 deg for no net energy gain. By choosing a ramped gradient drift-tube linac with initial focusing strengths similar to the output of the RFQ, this matching section was designed to be independent of the beam current. This substantially eases commissioning and improves flexibility. Space will be provided in the matching section for the diagnostics required for tuneup of the source-LEBT-RFQ front end. The diagnostics also facilitate the setup of this section to provide a properly matched input beam for the DTL. The length of this section for one RFQ is approximately 75 cm. Additional RFQs approximately double the length of the section to accommodate the bending magnets, additional quadrupoles, and one additional buncher per RFQ. For the longer matching sections it is critical to keep the transverse size of the beam small to avoid transverse emittance growth.

Drift-Tube Linac

A DTL is the accelerator of choice to accept the 2.5-MeV output of the RFQ and accelerate the H^- ions to the relativistic velocities needed by the CCL. At 2.5 MeV the ions have sufficient velocity that permanent magnet quadrupoles have ample strength to control the beam. The DTL will be contained in four tanks, each powered by a single klystron. A gradient (E_o) of 4.6 MV/m (1.4 Kilpatrick peak surface field) will be used and is considered conservative in terms of operational reliability. Isolation valves, variable quadrupoles, steering magnets, and beam diagnostic stations are placed between the tanks.

The 428-MHz DTL is similar to several others that were recently built. But it is a fairly expensive structure because of the effort involved in fabricating the drift tubes. Decreasing fabrication costs will be an active area for engineering development. At this point in the design the strategy is to start the coupled-cavity linac (CCL) at the lowest reasonable energy. Below 70 MeV the performance and efficiency of the CCL falls rapidly. The present simulations indicate that 70 MeV is probably a good compromise between cost and performance.

The DTL design presented here uses conservative parameters for electric and magnetic fields and yet accommodates a wide range of current and emittance. The permanent magnet quadrupoles in the drift tubes have a gradient of 140 T/m by using a pole-tip field of 1.1 T and a bore radius of 8 mm. Recent high-current DTLs have successfully used permanent magnet pole-tip fields as large as 1.3 T. A peak surface electric field of 1.4 Kilpatrick, which is also considered to be conservative for this type of linac, has been chosen for this design. The beam size remains small transversely and longitudinally throughout the DTL with all transitions made gradually. The gentle treatment of the bunch reduces the demands on the RFQ-DTL matching section, should simplify commissioning and operation, and naturally leads to preservation of beam quality.

The DTL parameters are linearly ramped in the first tank (2.5–14 MeV) from the output parameters of the RFQ. The longitudinal and transverse focusing strengths at the start of the DTL are forced to be nearly equal to the focusing strengths at the end of the RFQ. This ensures a smooth match into the DTL and makes the operation of the matching section nearly independent of beam current. To hold the longitudinal focusing strength constant, the accelerating field (E_0T) is ramped from 1.5 to 4.0 MV/m. The particle phase is also ramped to hold the phase width of the zero-current separatrix constant in real space. Throughout the DTL the beam size is kept small relative to the bore size (< 25 %). When realistic fabrication errors are included using PARTRACE, the edge of the beam should stay within a radius of 6 mm with 95 % confidence.[9] The last three DTL tanks will each be approximately 5.8 m in length and add approximately 19 MeV per tank. The beam will be steered back onto the axis between each tank using the two variable and movable permanent-magnet quadrupoles located $1\beta\lambda$ apart between tanks. Simulations with up to twice the transverse emittance or three times the current also showed no beam loss and no transverse emittance growth. The parameters of the DTL are listed in Table IV.

TABLE IV
DTL Design Parameters

Frequency	428 MHz
Injection energy	2.5 MeV
Output energy	70 MeV
Injection current	25 mA
Output current	25 mA
Emittance (n, rms)	
Input transverse	0.19 π mm-mrad
Output transverse	0.19 π mm-mrad
Input longitudinal	0.063×10^{-5} eV-s
Output longitudinal	0.069×10^{-5} eV-s
DTL length	23 m
Number of cells	151
Number of tanks	4
Magnetic lattice	FODO
Synchronous phase (from peak)	–35 to –30 deg after 14 MeV
Accelerating field (E_0T)	1.5 to 4.0 MV/m after 14 MeV
MPSEF	1.4 E_K (28 MV/m)
Total rf power	12 MW

DTL-CCL Matching Section

Since the CCL operating frequency is the third harmonic of the DTL frequency, the beam must be bunched for longitudinal matching and transversely matched into the CCL magnetic lattice. The matching section must accomplish this with little beam loss and negligible emittance growth. The conceptual design for this section accomplishes these requirements in a space of 2.7 m using two 1284-MHz rf bunchers, one quadrupole singlet, and two quadrupole doublets. The quadrupole doublets are an upstream extension of the CCL lattice. The bunchers are positioned between the first and second and the third and fourth quadrupoles and will be powered by splitting rf from the first CCL klystron. Space is available for current, position, and energy diagnostics in this design. Analogous to the DTL matching, the first two tanks of the CCL have ramped gradients making the operating values of this matching section nearly current independent. The beam size remains nearly constant so the PARMILA simulations indicate no losses or emittance growth.

Coupled-Cavity Linac

A standing-wave CCL will be used for most of the energy gain provided by the linac. It is the simplest of the linac types used on the SSC, provides the highest gradient, and is the least expensive per meter to fabricate. Many CCLs of the side-coupled type have been built during the past twenty years since it was developed and used for the 800-MeV LAMPF linac. It has especially been exploited in recent years for electron accelerators used for a variety of applications including commercial medical diagnostic and therapy devices, free-electron lasers, and racetrack microtrons.[10] The side-coupled linac was recently adopted as the accelerator of choice for the Fermilab linac upgrade to 400 MeV.[11]

The CCL will operate on the third harmonic of the DTL—1284 MHz. The higher frequency was chosen to reduce structure and rf costs through a smaller, more efficient structure and to raise the voltage breakdown threshold. A harmonic higher than the third complicates the DTL-CCL matching section and leads to more emittance growth. An average gradient (E_0T) of 6.7 MV/m with a peak surface field of 32 MV/m (1.0 Kilpatrick) will be used. The ratio of peak surface field to average gradient is kept low by enlarging the outer radius of the nose of the accelerating cell at the expense of shunt impedance. This should provide very dependable operation with a brief commissioning period, yet keep the linac length short to minimize cost. After an initial conditioning period of a few days, the linac should lose a pulse due to a spark less than once per hour. The rf system and H^- source will probably cause lost pulses at a higher rate than linac sparks.

The coupled-cavity linac will be made up of cells that are brazed together into tanks. The tanks are separated to provide space for focusing and steering magnets and diagnostics. The number of cells per tank is determined by the minimum spacing permitted for the quadrupoles in the magnetic lattice. The tanks are then resonantly coupled together into modules with bridge couplers to minimize the number of klystron systems (these typically contribute nearly half of the construction costs of a high-gradient linac). The number of tanks that can be coupled together in a module with one rf source is limited by the gradient droop in the end tanks and the available peak rf power per klystron.

The side-coupled structure is the most efficient structure for low-current designs such as this where one klystron will drive many cells. If we allow a 3 % droop in the gradient from the center cell to the end cell, a side-coupled module with 128 accelerating cells would require a 5 % coupling constant between cells and would have a shunt impedance at 82 % of the SUPERFISH value. Similar performance for an on-axis module would require a 10 % coupling constant and would yield a shunt impedance at 67 % of the SUPERFISH value. An annular-ring-coupled structure with four coupling slots would require a coupling constant of 7.1 % and would yield a shunt impedance at 69 % of the SUPERFISH value. The high coupling constant available from the disk-and-washer structure does not outweigh the considerable engineering development still required and the complexity of tuning the structure to avoid the modes crossing the accelerating frequency.

The present design of the CCL from 70 to 600 MeV was simulated with 60 tanks of 22 cells/tank (20 cells/tank in the module end tanks). Ten klystrons are used to power these as 10 modules with six tanks/module. Multiple-cell bridge couplers (5 and 3 $\beta\lambda/2$) will be used to accommodate (>30 cm) the focusing quadrupole and beam diagnostics between tanks. The spacing between modules will be larger to accommodate the additional diagnostics and an isolation vacuum valve. Conventional magnet quadrupoles are used with 70-degree phase advance per cell. The bore of the linac starts with a radius of 1.27 cm and is reduced to 1 cm after the 6th module. With alignment errors simulated using CCLTRACE, the beam should always fill less than 60 % of the bore with 95 % confidence.[12] This bore size should be conservative for this low-duty linac.

At the end of the linac, 99 percent of the beam should be within a 1-MeV window and the bore-radius–to–beam-radius ratio is 3:1. The CCL design parameters are summarized in Table V. This section of the linac is expected to easily transport the beam with no losses and no emittance growth. In fact, if the transverse emittance of the source is improved by a factor of two, most of that improvement should survive the entire linac as presently designed.

TABLE V
CCL Design Parameters

Frequency	1284 MHz
Injection energy	70 MeV
Output energy	600 MeV
Injection current	25 mA
Output current	25 mA
Emittance (n, rms)	
Input transverse	0.19 π mm-mrad
Output transverse	0.21 π mm-mrad
Input longitudinal	0.06×10^{-5} eV-s
Output longitudinal	0.06×10^{-5} eV-s
CCL length	117 m
Number of modules	10
Number of tanks per module	6
Number of cells per tank	22 and 20
Magnetic lattice	FODO
Synchronous phase (from peak)	–30 deg
Accelerating field (E_0T)	6.7 MV/m
MPSEF	1.0 E_K (32 MV/m)
Total rf power	140 MW

The CCL was simulated to 1 GeV by continuing the same module and magnetic lattice structure. An additional length of 98 m was required. The beam continued to be well behaved, with no losses or emittance growth. The bore-radius–to–beam-radius ratio remained approximately 3:1, and the energy spread grew to only slightly above 2 MeV. A future upgrade of the SSC linac to 1 GeV will be straightforward since the additional tunnel length will be built during the original construction. Prior to upgrade, the extra length will contain a transport line consisting of a continuation of the CCL lattice.

Rf Requirements

As described above, the SSC linac is composed of three different accelerator structures (RFQ, DTL, and CCL) at two different frequencies (428 and 1284 MHz). The high-power rf requirements of the three systems are shown in Table VI.

TABLE VI
Linac Rf Power System Requirements

	RFQ	DTL	CCL
Frequency (MHz)	428	428	1284
Pulse length (μs)	50	50	50
Repetition rate (Hz)	10	10	10
Rated peak power (MW)	4	4	20
Operating peak power (MW)	0.3	3	15
Number of klystrons	0	4	10
Operating efficiency (%)	-	50	45

The power for the RFQ will be split from the klystron driving the first DTL tank. This is feasible for two reasons: first, the first DTL tank has 1 MW of excess power since it has a ramped gradient; and second, the beam loading of the RFQ and first DTL tank are similar. The tubes will actually be operated at 25 percent less power from their rated and factory tested values to improve reliability, shorten turn-on time, and provide control margin. A 50-μs rf pulse is chosen to provide a 35-μs linac beam pulse. The 15-μs differential will be used for cavity filltime and settling of the feedback controls.

Each rf amplifier consists of a charging supply, pulse-forming network (PFN), pulse transformer, and klystron. Since the duty factor is so low, efficiency is not an issue in operating costs; therefore, nominal klystron tube efficiencies are assumed. Klystron tubes at these power levels and pulse lengths are readily available. A PFN is the most straightforward and well-understood modulator scheme available and will work well at a pulse length of 50 μs. The dc power supplies are small because of the low duty factor.

The low-level rf systems will provide the feedback and feedforward required to maintain the fields in each tank to an amplitude constant to 0.5 % and a phase constant to 0.5 degrees.

Status and Schedule

The present SSC schedule calls for 200 GeV test beams to be available by the end of 1995. This requires the operation of the linac, LEB, and MEB. In support of this we are planning on starting the commissioning of the full linac by the end of 1994. The source and LEBT tests have already started. The RFQ will be added in early 1992 to the linac test stand at the Dallas offices. Installation of those components and the DTL at the SSC campus should begin by the end of 1992.

Cost Estimate and Procurement Plan

The base cost (no contingency, escalation, or R&D) of the SSC linac was estimated to be approximately $33 million in FY90 dollars. Approximately 90 % of the linac will be procured from industry. The DTL structures, CCL structures, and rf systems will be built by industrial partners. The source, LEBT, and RFQ are being built either internally or through collaborations with other laboratories.

Acknowledgments

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