THE SSC LINAC

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Abstract

The 600 MeV H- linear accelerator is the first stage of acceleration in the chain of accelerators which make up the Superconducting Super Collider. This paper will review the present status of design and construction, conventional construction and supporting research and development. More detailed technical papers are also being presented at this conference. [4-7, 9, 11, 14-27]

Introduction

The SSC linear accelerator [1-4] is designed to accelerate beams of H^- ions to 600 MeV. Macropulses of 9.6 µs duration, 21 mA peak current, are stripped, and fill each of the 114 rf buckets of the Low Energy Booster (LEB) with 10^{10} protons in 4 turns. The linac operates at 10 Hz, to support the fast-cycling, resonantly driven LEB. The linac can provide longer (35 µs) pulses at 25 mA to fill the LEB for Test Beam operation. The main parameters of the SSC Linac are given in Table 1.

TABLE 1
Linac Specifications

Particle	H-
Output Energy	600 MeV*
Nominal Output Current	25 mA†
Pulse Length	2 - 35 µs
Pulse Repetition Frequency	10 Hz
Output Transverse Emittance (n, rms)	≤ 0.3 π mm•mrad
Output Energy Spread	≤ 100 keV
Basic radio frequency	427.617 MHz ‡
Scheduled availability (Collider filling)	≥ 98.8%

* ability to upgrade to 1 GeV must be preserved
† designed to be able to handle up to 50 mA
‡ 9th harmonic of LEB injection rf - preserves bunch-to-bucket transfer option

The three main linac requirements which are notably different from those of earlier proton linacs for injection into booster synchrotrons are: low transverse emittance, high availability, and preservation of the bunch-to-bucket LEB injection option. The latter requirement determined the basic rf frequency and output energy. Since space charge forces in the LEB at injection dominate overall emittance growth in the Collider, space has been reserved in the linac tunnel and the rf gallery for additional klystrons and coupled-cavity linac (CCL) modules to boost the output energy to 1000 MeV. This is the best understood method for doubling the Collider luminosity.

A study carried out this year for the Southwestern Medical Center determined that the linac would be a suitable source of protons for a radiotherapy facility. Although a final decision has not been made, the linac has been designed to provide 70 to 250 MeV protons for this purpose. The primary impact is the need to provide a stub-out from which the transfer line to the proton radiotherapy facility can begin, and to provide for adjustable quadrupole magnets in the CCL portion of the linac.

*Operated by the Universities Research Association, Inc. for the United States Department of Energy under Contract No. DE-AC35-89ER40486.

Ion Source/LEBT/RFQ [5]

Both magnetron and rf volume sources [6, 7] have demonstrated normalized, transverse rms emittances of ≈0.1 π mm•mrad, significantly better than the design objective of 0.18 π mm•mrad. These results were obtained with an in-house analysis code, and confirmed with REANE [8]. In addition, the volume source continues to demonstrate superior operational characteristics with respect to commissioning times and stability.

Both Einzel lens and Helical ElectroStatic Quadrupole (HESQ) LEBTs will undergo detailed characterization on the recently completed computer-controlled emittance measurement system. A collaboration to investigate a conventional electrostatic quadrupole lens [9] is being set up with the low energy beam transport group at the University of Maryland .

The four-vane RFQ (Table 2) was designed [10] and built by AT Division staff at Los Alamos National Laboratory, under contract to the SSCL. A major design change in early 1991 reduced the higher multipole content of the cavity fields and significantly improved transmission. Electroforming technology restricts the design to 1.1 m long sections. Rather than increase from two to three sections, the aperture was slightly decreased and a voltage ramp created, which increased the rf power required. The design now shows essentially zero transverse emittance growth during acceleration, at the additional expense of a 30% increase in longitudinal emittance and LEBT focussing strength. Construction of the RFQ is now complete, and it is expected at SSCL in mid-September.

TABLE 2
RFQ Specifications

Frequency	427.617 MHz		
Input Energy	0.035 MeV		
Output Energy	2.5 MeV		
Input Current	30 mA		
Output Current (accelerated beam)	≈ 27 mA		
Input Transverse Emittance (n, rms)	≤ 0.20 π mm·mrad		
Output Transverse Emittance (n, rms)	≤ 0.20 π mm·mrad		
Output Longitudinal Emittance (rms)	≈ 0.8 * 10^{-6} eV·s		
Output Beam Radius (rms)	0.75 mm		
Vane Tip Radius	1.5 - 3.85 mm		
Bore Radius	2.0 - 3.5 mm		
Peak rf Field	36 MV/m (1.8 * Kilpatrick)		
Total rf power	345 kW		
Structure power	280 kW		
Length	2.1863 m		
Input Instrumentation:			
Wire Scanner	1	Toroid	1
Faraday Cup	1	Segmented Aperture	1

The RFQ end walls are specialized devices, providing vacuum isolation valves and instrumentation in a package occupying minimum length along the beam line for optimum beam handling on both input and output of the RFQ.

The rf power amplifier, low level rf controls and elements of the rf supervisory controls were obtained through a collaboration with LANL [11]. The power amplifier, based on the GTA design, has been delivered to SSCL, installed, connected to utilities and commissioned. It has achieved satisfactory performance at the 600 kW level. A new high voltage power supply has now been shipped to SSCL and is ready for installation, commissioning and acceptance testing. Amplifier supervisory controls are based on an Allen-Bradley PLC, and have also been integrated with the power amplifier and tested. The SSC standard for supervisory controls will be based on single-board computers on a VME/VXI bus, and work has begun to develop a replacement supervisory control system more representative of subsequent linac modules.

The low level rf control system is based on the I&Q system [12]. It has been commissioned at SSCL, tested with a cavity load and klystron simulator, and integrated with the power amplifier. Supervisory controls for the low level system are based upon the system developed for GTA [13].

The RFQ will be permanently equipped with beam position monitors, toroids and wire scanners. A diagnostic cart will provide longitudinal and transverse emittance measurement capability during commissioning. Voltages will be calibrated by bremsstrahlung end point measurement. First beam tests are planned for the end of calendar 1992.

All rf accelerating cavities, including the RFQ, will use temperature variation for resonance control. The RFQ has a closed loop cooling/heating system to adjust the temperature setpoint, either manually, or automatically, on the basis of a resonance error signal derived from the low level rf system.

All resonant structures have relatively long thermal time constants, so a rapid response to a request to service any linac customer will depend on how accurately the temperature control unit can hold the resonator on tune, and on the difference between the temperature distribution characteristic of an rf driven structure and one heated through the water system. This will be established by experiment, but all rf systems may have to run continuously if a rapid response is required.

RFQ/DTL Matching Section and DTL

Matching from the RFQ into the DTL [14, 15] is one of the operations most critical to preservation of beam transverse emittance. The original linac plan foresaw (for reliability) two ion source/LEBT/RFQ systems matched into the single DTL in a 120° switchyard. Shortage of internal engineering resources, the difficulty of designing a satisfactory switchyard, and a renewed emphasis on cost, led to a decision to abandon dual injectors and revert to a simpler, in-line matching section. A system of 4 bunchers, 3 dipoles and 14 permanent magnet quadrupoles was replaced with a much simpler one with 2 bunchers and 4 variable gradient permanent magnet quadrupoles (Table 3). Detailed design of subsystems and components is well advanced. Commissioning is to begin in May 1993.

The complexity and compactness of the design has required special attention to the interface to the DTL.

TABLE 3
RFQ/DTL Matching Section Technical Parameters

Length		600 mm	
Bunchers:			
Number		2	
Type		Double-gap	
Frequency		427.617 MHz	
Peak Voltage (E_0TL)		136/146 kV	
Power required		30 kW	
Quadrupoles:			
Number		4	
Type		Variable gradient PMQs	
Gradient		30 - 100 T/m	
Bore		24 mm	
Instrumentation:			
Beam Position Mon.	3	Toroids	2
Wire Scanners	2	Slit & Collector	1 set
Segmented Aperture	1	Faraday Cup	1

Drift Tube Linac

The main components of the DTL are being obtained from industry after competitive bid. The four Alvarez tanks are being manufactured by AccSys Technology, Inc. [16], the klystrons will be delivered by Thompson CSF, and the pulse modulator order has been placed with Maxwell Laboratories, Inc., Balboa Division. The first klystron is expected by the end of the calendar year, and the first modulator by mid-1993. The first DTL tank is expected in November 1993, with all components scheduled to be at SSCL by May 1994. The main technical features of the DTL are given in Table 4.

TABLE 4
DTL Technical Parameters

Number of tanks, modulators, klystrons 4
Length, Cells, Output Energy, rf Power Required:

Tank 1	4.499 m	56 cells	13.41 MeV	1.187 MW
Tank 2	5.956 m	40 cells	32.84 MeV	2.333 MW
Tank 3	6.063 m	30 cells	51.59 MeV	2.360 MW
Tank 4	6.258 m	26 cells	70.00 MeV	2.387 MW

Peak rf power available		4 MW	
Permanent Magnet Quadrupoles		156/Sm_2Co_{17}	
Quad Gradient (-0, +5%, sorted)		132.7 T/m	
Quadrupole Bore		18.5 mm	
Design Transverse Emittance (n,rms)			
Input		0.20 π mm•mrad	
Output		0.21 π mm•mrad	
Instrumentation:			
Beam Loss Monitors	3	Beam Position Mon.	6
Toroids	3	Wire Scanners	3
Absorber/Collectors	3	Diagnostic Pods	3

The gradient in tank 1 is ramped, and all tanks are post-stabilized. Rf phase in the last two cells of tanks 1-3 and the first two cells of tanks 2-4 is adjusted for extra longitudinal focussing through the intertank space. Initially achieved by moving the gap centers, this had the unintended effect of producing a field tilt. The tilt could be corrected using the post stabilizers, but an alternative solution [17, 18] restored field flatness while maintaining post stabilizer operating range.

DTL/CCL Matching Section

Frequency tripling occurs at this point in the accelerator and makes careful design of this section (Table 5) for minimum emittance growth critical. Fortunately, the beam energy is 70 MeV which provides sufficient longitudinal space and beam stiffness for solutions to be reasonably easily implemented.

TABLE 5
DTL/CCL Matching Section Technical Parameters

Length		2.9526 m	
Bunchers:			
Number		2	
Type		CCL sections	
Frequency		1282.851 MHz	
Peak voltage (E_0TL)		1.2/1.8 MV	
Power required		426/657 kW	
Quadrupoles:			
Number		9	
Type		Electromagnet	
Gradient		40 T/m	
Bore		23 mm	
Instrumentation:			
Beam Position Mon.	3	Toroids	3
Wire Scanners	3	Slit & Collector	1 set
Beam Loss Mon.	3	Bunch Shape Mon.	1
Absorber/Collector	1	Diagnostic Pods	4
Design Output Transverse Emittance		0.21 π mm•mrad	

Coupled-Cavity Linac

Changes to the CCL (Table 6) are the most significant that the Linac design has undergone in the past year [19-24].

Design for Reduced Emittance Growth

Redesign of the side-coupled linac was required by increased transverse emittance growth, associated primarily with frequency tripling and RFQ changes. The mechanism driving emittance growth was coupling between longitudinal phase and the magnitude of the rf defocussing force. The original design had a predicted emittance growth through this mechanism of approximately 30%. After the RFQ change, this grew to about 50%. This would not produce a beam within the emittance specification of Table 1.

Another motivation was the need to minimize cost, without jeopardizing performance. In the CCL this led to an attempt to reduce the number of klystrons. Originally, the CCL was sub-divided into ten 6-tank modules, each with a klystron. First and last tanks in each module had 20 cells; the remainder had 22. The shorter tanks freed beam line space for instrumentation. Bridge coupler lengths in the original design were 5/2 $\beta\lambda$ in modules 1-5, and 3/2 $\beta\lambda$ in modules 6-10. Intermodular spaces were 9/2 and 7/2 $\beta\lambda$ in the first five and four modules, respectively. Pulsed quadrupoles between each pair of tanks provided a F0D0 transport channel. For ease of manufacture, all cells in any given tank were designed for the same value of β. To make optical properties approximately independent of current, the accelerating gradient was ramped from ≈1 MV/m to the equilibrium value of 6.6 MV/m in the first two tanks of module 1.

It was observed that coherent synchrotron motion caused emittance growth, through the mechanism cited earlier. This occurred even for zero injection phase error because of the ion β variation in constant β tanks. It was further observed that the motion was made more complex by the biperiodicity in longitudinal focussing arising from two different tank lengths. The first part of the solution was, therefore, to reduce the magnitude of the oscillation by reducing the number of cells per tank, and increasing the number of tanks per module. Then, by keeping the same number of accelerating cells in each tank (16), and eliminating the longer intermodular instrumentation spaces, the number of quadrupoles was increased, and their spacing decreased. This further reduced average beam size, non-linear r-z coupling and emittance growth. This lattice, now very smooth and regular in all three phase planes, has essentially no emittance growth.

TABLE 6
CCL Technical Parameters

Frequency	1282.851 MHz
Input Energy	70 MeV
Output Energy	600 MeV
Number of modules / tanks	9 / 72
Peak Surface Field	32 MV/m (1.0*Kilpatrick)
Field Gradient (E_0T)	7.2 - 6.55 MV/m
Synchronous Phase	-25°
Amplitude Stability	± 0.5%
Phase Stability	± 0.5°
Magnet Lattice	F0D0
Length	112.41 m
Bore radius	10.0 mm
First-Neighbor Coupling Constant	6 - 7 %
Intertank & Intermodule Spaces	
Modules 1 & 2	7/2 $\beta\lambda$
Modules 3-9	5/2 $\beta\lambda$
Bridge Couplers:	Multi-cell B-coupled
Number	63
Coupling Constant	≈ 12%
Transverse Emittance (n,rms)	
Input	0.22 π mm•mrad
Output	≤ 0.25 π mm•mrad

The most serious problem arising from these changes was elimination of intermodular instrumentation space. A special effort on compact quadrupoles, diagnostic boxes and flanges, produced designs for these components which fit in available space, as set out in Table 6. The CCL diagnostic plan was refined to provide diagnostics space between tanks, rather than just between modules. Although we can neither justify nor afford permanent instruments at all these locations, the ability to concentrate diagnostics in critical locations as needed will provide the flexibility necessary to achieve our ambitious goals for beam quality. The difficulty of predicting the optimum location for a fixed set of instruments is increased by the large transverse phase advance ($60° \leq \sigma_{0t} \leq 80°$).

Design for Fewer Klystrons

First, the beam size reduction gave a reduced bore radius, even while the ratio of maximum beam size to bore radius was decreased. This allowed the basic cavity to be redesigned for improved shunt impedance. Second, other minor cavity geometry changes led to a few percent increase in efficiency, as well as a small reduction in peak surface electric field. Third, re-evaluation of the ramped gradient section in the first module showed that the penalty associated with forgoing this option was negligible.

Concern had surfaced over potential difficulties in driving such long assemblies of coupled resonators. It was concluded that the design coupling constant of 5% was certainly too low, and it was raised to 7% in modules 1 - 5, and 6% in modules 6 - 9. This change used up all the power saved, so that the only way to reduce the number of rf stations was to reduce the klystron power margin. The original designers had wisely included a power reserve of approximately 73%, over the amount required to establish cavity fields and accelerate beam. By reconfiguring the 10 modules of 6 tanks into 9 modules of 8 shorter tanks driven at slightly higher gradient, the same performance was achieved, while maintaining a margin for waveguide loss, control and klystron aging of 63%. The design improvement referred to in the preceding paragraph kept the peak surface electric field below 1.0*Kilpatrick.

Design for International Production: China

A requirement for substantial international contributions led to favorable consideration of a proposal from the Institute for High Energy Physics, Beijing, (IHEP) for a collaboration in CCL construction. This institute successfully constructed the SLAC-style linac injector for the Beijing Electron-Positron Collider (BEPC), and has subsequently provided accelerating columns of this design to institutes around the world.

A build-to-print approach has been adopted, and several Chinese scientists and engineers have visited SSCL to learn the specialized techniques of assembly, tuning and testing which must be applied to side-coupled proton linacs.

The standard TM_{010} bridge coupler design used at LAMPF and FNAL was difficult to tune, and would have been challenging in the higher β modules. This was of particular concern, since we are determined that complete modules should be assembled and tested at low power in the factory in Beijing. Several [21-23] alternative design concepts were analyzed numerically and modelled at low power. A magnetically-coupled multi-cell design was chosen for its high internal coupling co-efficient (low power flow phase shifts and high group velocities) and relative ease of fabrication and tuning. Although concern about the number of cells per module was first addressed in the context of the new design, the number of cells per module is nearly the same as in the original.

We were able to purchase engineering services from the AT Division at Los Alamos to supplement internal resources. They proposed and implemented an automated drawing scheme. It has taken some time to set up, but it will greatly speed up the process of generating the 1500 - 2000 drawings needed for the CCL.

Design for International Production: India

The design effort on compact quadrupoles, previously referred to, was carried out, to the prototype stage, using internal SSCL resources. The offer of a contribution from India led to the identification of these quadrupoles and other magnets in the Linac-LEB transport/transfer lines, as suitable items for contribution. An engineer from the Indian Center for Advanced Technology in Indore is at SSCL reviewing these magnet designs for physics and manufacturability. The first prototype magnet is expected at SSCL in February 1993. The CCL quads were originally proposed as pulsed magnets, to minimize cooling, but were changed to dc magnets to economize on power supply and control costs. The new requirement to support provision of beams to the proton therapy facility implies laminated magnets with short time constants. We must switch the field in the CCL and transport line quadrupoles between 600 MeV and 70 Mev settings between linac pulses, since the plan is to drift the lower energy beams through all or part of the CCL without acceleration. Those modules not required for a particular beam energy will receive a standard rf pulse, but it will not arrive with the beam.

Proton Radiotherapy Facility

The University of Texas Southwestern Medical Center at Dallas proposed a joint initiative towards a medical proton therapy facility at the SSCL. The proposal was that the linac could provide beams of 70 - 250 MeV protons for radiotherapy when it was not servicing either collider or test beam users. A study group was formed under the direction of SSCL, to review the options. The group included Particle Accelerator Corporation and Lawrence Berkeley Laboratory. Options considered included: direct application of linac beams; extraction of a 70 MeV beam from the linac for storage and acceleration in a small synchrotron/storage ring; and extraction of variable energy beams from the linac for injection into a storage/pulse-stretcher ring. A variety of beam application techniques, as they integrated with the basic technical options, were investigated, and the possibility of using the linac beam for generation of small quantities of radioisotopes for local PET applications was considered. The SMC group selected direct application of linac beams (with intensity reduction), with no radioisotope production capability. Efforts are underway to obtain funding, and the linac tunnel has been provided with a stub-out branch from which the medical beam transfer line may be extended, without interrupting linac operations during medical facility construction.

Conventional Construction

Design of linac conventional facilities is complete, including tunnel and rf gallery extensions for an upgrade to 1000 MeV. Contract award for conventional facilities was in May 1992, and construction is underway. Excavation for underground facilities is complete, and pouring of concrete for the source gallery and tunnel has begun. Scheduled beneficial occupancy is April 1993, with contract completion in July.

Reliability Engineering

Other proton linear accelerators have achieved the reliability levels set for the SSC Linac. Those that have done so have typically taken more than a decade of operation to achieve it. We will have to operate at these levels by 1999.

The SSCL strategy for guiding engineers in designing to achieve high levels of availability was to allocate to machines, sub-systems and components, specific levels of availability which, when rolled up with the allocations for the rest of the Super Collider, resulted in facility availability to take high energy data 80% of the time scheduled. In a facility of this size and complexity, this frequently led to a stated requirement for a water pump, for example, of 0.999999 availability.

This approach had three problems: first, the only way to reliably achieve such high levels of availability, in design, was by redundancy. Such pervasive redundancy was not part of the baseline estimate, and can not be afforded. Thus, no <u>useful</u> guidance is provided to engineers. Second, the method takes no account of actual operating profiles: e.g., the linac will be required to provide beam for collider fill, at equilibrium, for a period of 1 to 2 hours every 24 to 48 hours. The availability allocation process did not take systematic advantage of this fact. Finally, the process did not take into account preventive maintenance or availability of spares and personnel.

Under the auspices of DoE, the Linac was the subject of a pilot study on an alternate reliability assessment program. This program utilized a linac model which included:

1) a detailed description of the accelerator at the circuit board level, and as needed, even lower;
2) estimates of MTBF and Mean Time To Repair (MTTR) for components, including time for identification and diagnosis of faults, crew assembly, getting spares, making repairs and testing; and
3) the linac mission, showing the time the linac will spend in a typical operational cycle servicing each customer.

The program (TIGER) then simulated many years of operation using Monte Carlo methods. Failures were identified and classified as to the degree to which they threatened the basic mission. This approach proved capable of providing specific guidance to the engineers on components of particular concern, and the amount of improvement needed to bring the linac operation back within acceptable bounds of availability.

In summary, overall linac availability is predicted to be quite good, although it still needs improvement to achieve our goals. Specific items identified as needing attention were precisely those which experienced accelerator builders and operators might have predicted at the outset. This approach needs considerable attention to verify both the model and the data, but it does give some reason to hope that reliability can be managed effectively in design and construction.

System Engineering

The SSC is subject to a formal System Engineering discipline [25] which addresses those project management issues arising in a large organization attempting to complete a large, expensive project with tight time and cost constraints.

This involves development of specification trees and management of the process by which functional and physical requirements flow down through the various levels of specification to the lowest level. Development of Interface Control Documents attempts to ensure that communication across organizational boundaries takes place efficiently and effectively, so that no aspect of system integration "falls through the cracks". A co-ordinated series of design reviews provides essential opportunities for the physicists preparing system specifications and requirements to manage and direct the activities of the engineering divisions as they attempt to fill the requirements. Finally, preparation and documentation of test plans provides the basis for demonstration of successful completion of the project, both in total and in detail.

Commissioning Plans

A detailed commissioning plan [26, 27] is being created to satisfy the requirement for an acceptance test plan for the linac. In addition, it has played a major role in development of requirements for beam instrumentation and the control system.

Conclusion

In summary, the Superconducting Super Collider injector linac is proceeding from detailed design to construction. We are on schedule to achieve of our most significant milestone - Ready to Support LEB Commissioning - April 1995. Assuming the Proton Radiotherapy Facility is approved, it is scheduled to begin commissioning during calendar 1996.

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