DESIGN OF THE SSC LINAC

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Abstract

The preliminary design of the 600 MeV H^- linac for the Superconducting Super Collider (SSC) 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 0.4 π mm-mrad (rms) are required for injection into the Low Energy Booster (LEB) synchrotron. Cost, ease of commissioning, and operational reliability are important considerations. The linac will consist of an H^- source with electrostatic low-energy beam transport (LEBT), 2.5 MeV radiofrequency quadrupole accelerator (RFQ), a 70 MeV drift-tube linac (DTL), and 530 MeV of coupled-cavity linac (CCL). The RFQ and DTL operate at 428 MHz and the CCL operates at 1284 MHz. A modest total length of 143 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 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 rf 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.

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 rings
  - 25 mA H^- current during macropulse
  - 7 μs macropulse (three-turn LEB injection)
  - 1×10^{10} / LEB bunch
  - < 0.4 π mm-mrad (t, rms, norm) emittance
  - 10 Hz repetition rate
- Test beam operation
  - 25 mA during macropulse
  - 35 μs macropulse (15-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 starts with two sets of an H^- source and RFQ to bunch and initially accelerate the beam. Only one set is operated at a time, with the other set in standby in case of source failure. The beam is then matched into a drift-tube linac to accelerate the particles to relativistic velocities, and followed by a coupled-cavity linac for most of the energy gain. Based on past experience, actual linac performance can be expected to be close to the design simulations. By not departing too far from tested designs, the overall availability requirement of 98% of scheduled operating time 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. The frequencies are chosen to provide bunches on the 9th harmonic of the LEB buckets at 600-MeV injection.

The transfer line between the linac and LEB has also been designed.[2] It 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.

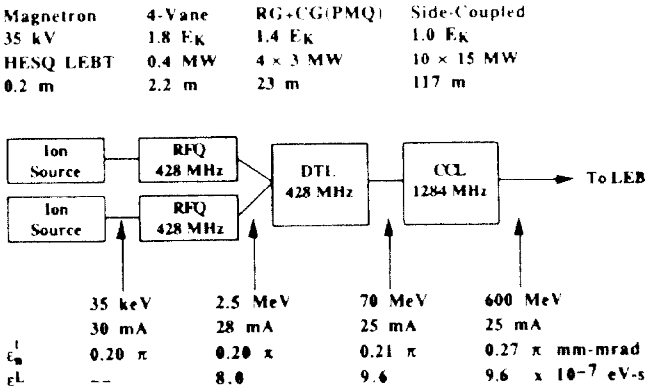

Figure 1. Linac block diagram.

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 high energy physics 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 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). It is currently operating at its design parameters on the SSCL Linac Test Stand.[6] SSCL is also supporting the development of an rf-excited volume source at Lawrence Berkeley Laboratory where preliminary tests are very promising.[7]

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The beam from an ion source is relatively large in radius and divergence and must be matched to the RFQ in the LEBT. The LEBT also contains source diagnostics and provides the differential vacuum pumping between the source and the RFQ. For the short-pulse operation of the SSC linac it is best to avoid neutralization by using electric focusing. The 30-mA operating current is small enough that several concepts using electric focusing can be considered. 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 testing a dual einzel lens LEBT on the linac test stand.[8] 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 constructing a HESQ LEBT with nickel electroformed electrodes for evaluation on the linac test stand.[9] For 30 mA operation, a 22.5-cm HESQ has an operating voltage of 7 kV. Simulations indicate that there should be no transmission losses and less than 10% transverse emittance dilution.

RFQ Accelerator

The RFQ accelerator is 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.[10] 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. More than 90% 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. 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 rf 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.

TABLE II
RFQ Design Parameters

Frequency	428 MHz
Injection energy	35 keV
Output energy	2.5 MeV
Injection current	30 mA
Output current	28 mA
Input trans. emittance (n, rms)	0.20 π mm-mrad
Output trans. emittance (n, rms)	0.20 π mm-mrad
Output long. emittance (rms)	8×10^{-7} eV-s
RFQ length	220 cm (3.2 λ)
Total peak rf power	355 kW
MPSEF	36 MV/m (1.8 E_K)

The design philosophy adopted here is to make the RFQ operationally flexible and reliable. The current should be variable from 5 to 50 mA. The beam position tolerances should be reasonable and the maximum peak surface fields should be less than 36 MV/m (1.8 Kilpatrick). The first RFQ is being fabricated for SSCL by Los Alamos National Laboratory. Its design simulation parameters are listed in Table II.

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_0) 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 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 1.2 T and a bore radius of 8 mm. 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 (2.5–13.4 MeV). 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 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 2.6 to 4.0 MV/m. When realistic fabrication errors are included using PARTRACE, the edge of the beam should stay within a radius of 6 mm with 95% confidence.[11] The last three tanks will each be approximately 6.1 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. The parameters of the DTL are listed in Table III.

TABLE III
DTL Design Parameters

Frequency	428 MHz
Injection energy	2.5 MeV
Output energy	70 MeV
Output current	25 mA
Output trans. emittance (n,rms)	0.21 π mm-mrad
Output long. emittance (rms)	9.6×10^{-7} eV-s
DTL length	23 m
Number of cells/tanks	152/4
Magnetic lattice	FODO
Synchronous phase (from peak)	–30 deg
Accelerating field (E_0T)	2.4 to 4.0 MV/m after 14 MeV
MPSEF	28 MV/m (1.4 E_K)
Total peak rf power	12 MW

Coupled-Cavity Linac

The CCL 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.[12] The side-coupled linac was recently adopted as the accelerator of choice for the Fermilab linac upgrade to 400 MeV.[13]

The CCL will operate on the third harmonic of the DTL—1284 MHz. The higher frequency reduces construction and rf costs through a smaller, more efficient structure and raises the voltage breakdown threshold. 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 dependable operation with a brief commissioning period, yet keep the linac length short to minimize cost.

The CCL 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. The number of tanks that can be coupled together in a module is limited by the gradient droop in the end tanks and the available peak rf power per klystron.

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).[14] Ten klystrons are used to power these as 10 modules with six tanks/module. Bridge couplers (5 and 3 $\beta\lambda/2$) are used to provide space (>21 cm) for the focusing quadrupole 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 1.25 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.[15] This bore size should be conservative for this low-duty linac. At the end of the linac, 99% of the beam should be within a 1-MeV window. The CCL design parameters are summarized in Table IV.

TABLE IV
CCL Design Parameters

Frequency	1284 MHz
Output energy	600 MeV
Output current	25 mA
Output trans. emittance (n,rms)	$0.27\,\pi$ mm-mrad
Output long. emittance (n,rms)	9.6×10^{-7} eV-s
CCL length	117 m
Number of tanks/modules	60/10
Number of cells per tank	22 (20 in end tanks)
Magnetic lattice	FODO
Synchronous phase (from peak)	–30 deg
Accelerating field (E_0T)	1.0 to 6.7 MV/m after 2nd tank
MPSEF	32MV/m (1.0 E_K)
Total peak rf power	140 MW

The CCL was simulated to 1 GeV with the same gradient by continuing a similar module and magnetic lattice structure. An additional length of 80 m (6 modules) 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.

Status and Schedule

The present SSC schedule calls for 200 GeV test beams to be available by the end of 1996. 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 first RFQ will be tested in mid-1992 on the linac test stand at the Central Facility. Installation of those components and the industrially-supplied DTL in the linac tunnel on the SSC campus should begin in early 1993.

Acknowledgments

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