THE SCIENTIFIC LEGACY OF THE SSC LINAC

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Abstract

The cancellation of the SSC project in October 1993 halted construction of a set of accelerators which would have significantly advanced the state of our art. Even though there are now strong signs that portions of the SSC Linac will be completed for use in proton therapy and radioisotope production, validation of the full range of design improvements and innovations will probably not be possible. This paper will identify the technical advances incorporated in the SSC Linac design. It will also discuss progress towards using the Linac for medical applications.

Introduction

The SSC Linac [1-3] would have accelerated H^- ions to 600 MeV for injection into the Low Energy Booster. The main technical parameters are given in Table 1. The principal technical challenges were meeting the low transverse emittance and output energy spreads, and early achievement of high availability.

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 (normalized, rms)	≤ 0.3 π mm•mrad
Output Energy Spread	≤ 100 keV
Basic Radio Frequency	427.617 MHz‡
Scheduled Availability (Collider Filling)	≥ 98.8 %

*preserve ability to upgrade to 1 GeV
†designed to handle up to 50 mA
‡9th harmonic of LEB injection rf

Ion Source and LEBT

Although the program started out assuming that the source would be a fairly conventional cesiated magnetron surface H^- source [4], poor operational reliability soon led to a reconsideration of that choice, and the pursuit of an rf-excited, uncesiated volume source [5]. The extremely compact LEBT design required for emittance preservation, combined with a beam pulse length comparable to the plasma equilibration time dictated an electrostatic LEBT, which did not work well in an environment containing substantial quantities of cesium. Combining these factors with the generally much shorter conditioning time, and equal or better emittance, of the volume source made the decision an easy one.

Several LEBT designs were considered [5], but the most thoroughly tested was a combination of two Einzel lenses [6]. Considerable effort was put into the design, construction and commissioning of a Helical ElectroStatic Quadrupole LEBT, but at the time of the project's cancellation, it had not been successfully tested.

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Radio Frequency Quadrupole

The RFQ was designed and constructed to SSC requirements by LANL [7] and delivered to Waxahachie in August 1992. It was assembled with the support stand, rf system, controls, temperature control unit, source, LEBT and diagnostics, and commissioned [8,9]. In April 1993 first beam tests were successfully completed [10]. Overall, the tests showed excellent agreement between simulation and experiment [11].

The RFQ incorporates several novel features. The rf structure is manufactured of tellurium copper, and was assembled into a complete resonator and vacuum chamber by electroforming after careful alignment. This process, pioneered in the BEAR [12] accelerator, was equally successful in this application.

The beam dynamics design is one of the few [13] that explicitly takes into account of higher order multipoles of the transverse fields. The vane-to-vane voltage is ramped from 50 kV at injection to 90 kV at the output, to minimize overall system length and emittance growth.

Instrumentation

A transverse emittance measuring system [14] was developed, based upon the standard slit-and-collector approach, using engineering resources of Allied Signal, Kansas City Division. The adjustable gap front slit was fabricated of graphite, and the 128-conductor collector was a stack of interleaved mica paper insulators and copper foils. Provisions were made for the application of a bias voltage.

Each collector foil was connected, via shielded twisted-pair, to the input of a 20 Megasample/second 10-bit digitizer [15] capable of storing 1024 discrete data values. The digitizers were provided with buffer memory and packaged, eight to a standard VXI module. The design provided significant expansion and upgrade capability by using plug-replaceable modules for the digitizer, signal processing and memory. These MIX cards have been licensed to an Austin firm, C&H Engineering, for further development and commercial exploitation.

This combination of equipment can measure the time dependence of the beam shape, or of its Twiss parameters. A full scan of the beam should be done in seconds, rather than minutes. Data analysis required development of a new code, EMAP [16]. Termination of the SSC project interrupted the completion of this activity, but several test runs had demonstrated the validity of the approach.

A very successful collaboration with the Institute for Nuclear Research, Moscow, culminated in significant advancements in the design of bunch shape monitors. Several 428 MHz units were fabricated, one of which was successfully tested with beam out of the RFQ [17]. These units used significantly less slot-length than earlier versions, fitting into a length of less than 50 mm.

In the course of preparing for the commissioning of the DTL, which was to have taken place during this past summer, a new technique for establishing the correct settings for rf phase and amplitude was developed [18]. This approach uses a least-squares fitting technique to analyze phase-amplitude scans, is based, for simplicity and accuracy, on measuring phase differences, rather than absolute phases, and requires only a single phase sensor, although more can be used if available.

DTL Input Matching Section

The matching section between the RFQ and the DTL [19, 20] was critical in minimizing emittance growth. It was also arguably the most complex 50 cm of engineering in the Linac, if not in the entire Collider complex. The IMS was equipped with four variable-gradient (30-100 T/m) permanent magnet quadrupole magnets mounted on transverse positioning stages. The quads moved in their focusing planes to provide steering.

For longitudinal matching, the IMS has a pair of 428 MHz quarter-wave stub double-gap buncher cavities [21] capable of producing the needed values of E_0TL of 136 and 146 kV, respectively, for a peak beam current of 25 mA. The overall design is simpler than that of GTA, but still allows matching in all six dimensions of phase space with minimal predicted emittance growth.

In addition, the IMS was provided with toroids and beam position monitors at input and output, and had a standard instrument pod in the center which could be used for a wire scanner, a Faraday cup, a longitudinal bunch shape monitor, or the slit of an emittance measuring system.

Drift Tube Linac

The 75% complete 428 MHz DTL was being built commercially [22] by AccSys Technologies, Inc., of Pleasanton, CA, when the project was terminated. Among its novel features are permanent magnet quadrupoles of Sm_2Co_{17}, selected for its higher radiation resistance, and a patented, improved, mounting and alignment system for drift tubes. The need for careful longitudinal matching led to cell length adjustments in the last two cells of tanks 1-3 and the first two cells of tanks 2-4 to provide additional bunching, in a way which avoided the introduction of a field tilt [23].

Coupled-Cavity Linac

The 1284 MHz side-coupled linac design incorporated a number of innovations [24, 25]. Each of its nine modules was made up of eight tanks of sixteen cells [26], connected by bridge couplers. Considerable effort was expended to make its focusing structure as smooth as possible, in the attempt to keep emittance growth to a minimum. Inter-module spaces were kept to the same electrical length as intertank spaces, so that the transverse focusing structure could be smooth. All tanks were the same electrical length, with very nearly the same gradient, to achieve smooth longitudinal focusing. Constant ß tanks were kept relatively short, so that coherent synchrotron oscillations remained small, and the emittance dilution effects on non-linear r-z coupling were minimized.

The low average power required, and the high peak power available from the klystron, encouraged us to design long modules. The number of coupled resonators in each module is substantially greater (290) than LAMPF or the FNAL linac. In spite of larger coupling constants (6 and 7%, depending on location) than are usually used (4-5%), coupled mode spacings near the $\pi/2$ mode were expected to become comparable to the synchrotron frequency in one of the modules, leading to the introduction of interesting new emittance growth mechanisms [27]. Since excitation of neighboring modes is caused by sidebands of the resonant frequency in the short drive pulse, the phenomena are not sensitive to beam current, and strategies were devised to split the affected module and drive each half separately if the effect was found to be troublesome.

The relatively high frequency used in this proton linac made the intertank gaps for quadrupole magnets and instrumentation electrically longer than was desirable, if the conventional single-cell TM_{010} bridge coupler was used. Significant tuning, mode mixing and low coupling constant problems were anticipated, and other coupling designs were investigated [28-30]. A five-cell, magnetically coupled design was ultimately chosen, as having the best combination, for this application, of coupling strength, mode purity and tunability.

Manufacturing techniques were also advanced by the construction of the CCL. This is the first side-coupled linac to be assembled with the single-braze-step approach which has become standard in the assembly of ß=1 electron linacs. The CCL was a multi-lab collaboration. Physics design was the responsibility of the SSCL. Construction was carried out, as part of an international collaboration, by the Institute for High Energy Physics, Beijing. Detailed mechanical design was carried out by LANL, under the direction of SSCL, with intensive consultation with engineers and physicists from IHEP to ensure that full advantage was taken of the manufacturing capabilities of the latter institute. One notable LANL contribution was the design of a cooling channel which passed directly through the tank segments, but entirely avoided water-to-vacuum joints.

Construction of one module has been completed, and a preliminary series of low-power measurements has been done, with satisfactory results. Negotiations are underway to ship the completed module to SSCL, as part of the contract termination arrangements, for final documentation of its performance.

Future Uses

In the long run, however, the most important legacy of the SSC Linac may not be the technical advances represented in its design. Instead, that honor may go to its role in the enhancement of health care in the southern and central United States. As early as 1991, a design study [31], sponsored by the University of Texas Southwestern Medical Center in Dallas, showed that a proton cancer therapy center could be built at the

SSC site. The center would use beam pulses from the Linac not required for its primary mission of filling the Collider rings for 20 TeV physics. In the aftermath of the SSC cancellation, the proponents of this proposal took up the challenge of convincing the State of Texas that this idea made technical and financial sense.

At the same time, a small group at the University of North Texas, in Denton, conscious of the growing importance of radioisotopes in the medical imaging field, and of the increasingly uncertain supply of isotopes from U.S. domestic sources, were working to obtain funding for a proton linac-based facility for the commercial production of medical radioisotopes. On the cancellation, this group immediately approached the State of Texas with a request that they be granted the Linac assets, if those assets should go to the state in the course of a settlement with the Department of Energy of financial claims arising out the SSC termination.

These two groups have worked with former SSCL staff members and engineers from the Lockheed Science and Engineering Company, to develop a plan for the utilization of SSC Linac assets for both proton therapy and commercial radioisotope production. That plan is now complete, and a Project Definition Study, performed by the Texas National Research Laboratory Commission under a grant from DOE, is in the final stages of preparation. The plan has been presented to both the Texas Governor's Advisory Committee on the SSC, and to DOE, and the extent to which both have been convinced of its technical and economic feasibility may best be judged from the fact that $65M funding for the project is explicitly identified in the FY95 Energy and Water Development Appropriations Bill, recently signed into law.

The plan uses all the components of the SSC Linac up to, and including, the fourth module of the CCL. Radioisotope production requires beam energies of roughly 30, 50, and 70 MeV, to use existing approved procedures. These energies correspond very well to the output energies of the final three DTL tanks: 32, 51, and 70 MeV. Commercial viability depends on high average currents: more than 1 mA. The SSC design, to meet the requirements set out in Table I, was capable of 8 μA. The major technical challenge in the proposal is to increase the average current by a factor of more than 120. Roughly a factor of 5 could be achieved simply by using all the rf pulse length available, and by increasing the peak current from its reference level of 25 mA to the design limit of 50 nA. The balance had to be obtained by increasing the overall duty factor.

Fortunately, the DTL cavity construction had not reached the point where significant assembly had taken place, and it is relatively straightforward to accommodate an increase in cavity rf duty factor from 0.09% to 3.6% by providing more cooling channels, and higher flow.

Equally fortunately, the DTL modulator construction had reached roughly the same point, and there was a great deal of commonality in the parts used for CCL and DTL modulators. This means that parts for the 6 CCL modulators now not needed can be used to upgrade the existing DTL modulators. Some new components, with higher dissipation ratings, will be required, and the cost of upgrading the rf supply is the largest element of the cost increase for providing this increased capacity.

Beam dynamics calculations have shown that it is possible to drift the 32 MeV beam through unpowered DTL tanks 3 and 4. Although space charge forces debunch the beam to some extent, and increase its momentum spread, beam losses are minimal, and the momentum spread is still within the capability of a simple bending magnet. In this way, all three of the beams destined for the radioisotope production facility can be extracted from one location in the lattice: immediately following the DTL. Beam debunching at the extraction point is predicted to result in a good approximation to a pure 428 MHz sinusoid, so that there should still be ample signal for BPMs.

The analysis of this process required a modification of the standard space charge calculation, which normally takes the center of the bunch to be at the synchronous phase. In the case of a drifting beam, the bunch center has no fixed relation to the synchronous phase of the accelerating structure.

Although DOE will make a final determination of technical feasibility of the current upgrade for radioisotope production on the basis of the Project Definition Study when it is submitted by TNRLC in mid-October, the concept has been the subject of detailed internal engineering analysis, and successfully passed a review by an international panel of accelerator experts.

Proton therapy, on the other hand, requires only very small currents (average less than 50 nA), but the energies required range from 70 to 250 MeV. The output energy of the fourth CCL module is 265 MeV, and by adjusting the strength of the quadrupoles in the CCL, beams at five discrete energies between 70 and 265 MeV can be produced (by selecting which CCL modules are energized on each pulse) and transported to the treatment area. Diversion of this current results in a reduction of radioisotope production of no more than 0.1%

The mechanism by which the proton therapy beam is diverted is of considerable importance. The main linac beam has sufficient intensity to cause injury to a patient, if the beam selection mechanism is not reliable, controllable and fail-safe. The 1992 conceptual design study developed a system which introduced a Nd:YAG laser into the first leg of a four-magnet beam bump to selectively neutralize a small fraction of the H^- beam. This component would then be separated from the main beam by the second magnet. The neutral beam destined for proton therapy would be stripped by a foil and magnetically transported to a fully rotatable gantry. The main H^- beam would be returned to the linac axis by the two remaining bump magnets, and travel to a beam absorber.

Laser selection of the treatment beam could either select a low-emittance core out of the full length of the beam pulse, or at a higher power setting could take all of the beam for a very short period of time. The latter approach offers some advantages in safety, since a failure could not result in excess beam being delivered to the treatment facility.

The two proposed users seem to be uniquely well suited to sharing the output of the linac. In addition to the complementarity of their beam requirements, having two main users allows many of the fixed operating costs to be distributed over a larger number of customers.

The plan is to construct the facility in the existing Linac buildings on what would have been the SSC West Campus. Although this location is some distance from the Medical Center, proton therapy is generally an out-patient treatment, not requiring the services of a full hospital, and the medical group sees no difficulty arising from the location.

Radioisotope production relies on an excellent transportation network for distribution of its short-lived products to the radiopharmaceutical companies who incorporate the material in medically active compounds. Fortunately, the Waxahachie site is more than close enough to major transportation hubs, such as Dallas/Fort Worth International Airport, Dallas Love Field, and Fort Worth Alliance Airport to ensure that no difficulties are encountered in this area.

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