THE SUPERCONDUCTING HEAVY-ION LINAC AT ARGONNE*

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Abstract

The design, status, and performance of the first operating superconducting heavy-ion accelerator, a linac used to boost the energies of beams from a 9-MV tandem, is summarized. When completed in 1981, the linac will consist of 24 independently-phased split-ring niobium resonators operating at 97 MHz. This linac is designed to provide 29 MV of acceleration. Because of the modular character of the system, the linac has been operable and useful since mid-1978, when a beam was accelerated through 2 units and the first nuclear-physics experiments were performed. Now, 16 resonators are in use, and a beam has been accelerated for ∿ 6000 hr. Resonator performance has been remarkably stable, in spite of vacuum accidents, and the linac as a whole operates reliably without operators in attendance during nights and weekends. The ease and speed with which the beam energy can be changed is proving to be unexpectedly valuable to users.

I. Introduction

The Superconducting Linac Project at Argonne was undertaken with three major objectives in mind: (1) to develop a new technology, (2) to build a prototype accelerator that can serve as a guide for others, and (3) to build a heavy-ion accelerator that is immediatedly useful as a research tool. This paper is concerned largely with objectives (2) and (3).

For our needs at Argonne, the linac must be an energy booster for heavy ions from an existing tandem electrostatic accelerator, and the compound system must provide, at minimum cost, the beams required for precision nuclear-structure research. That is, it must have easy energy variability, excellent beam quality, and overall flexibility. In short, it should have tandem-like characteristics, but provide a much higher beam energy than is obtainable from most tandems.

II. The Accelerator System

Figure 1 shows the tandem-linac accelerator system[1] that has been developed both to test the accelerator concept and to meet our research requirements. The 9-MV tandem has been used since 1962 as a stand-alone machine. The superconducting linac is located in a former target room, and the beam from the linac is used in a small new target area. The helium refrigeration system, rf controls, an assembly area, and a resonator-test cryostat are in the linac room.

The tandem operates in the conventional way, with a negative ion (sputter) source and a foil stripper in the terminal. Beams from the tandem may be injected into the linac without additional stripping or pass through a second stripper (at ground potential), if the maximum energy is required. Before injection into the linac, the beam is bunched into narrow pulses by means of a refined two-stage bunching system.[2]

The linac, when completed in late 1981, will consist of an array of 24 independently-phased split-ring resonators made of niobium. As shown in Fig. 2, these resonators are housed in four cryostats, three of which are of the same length (∿ 4 m). Each cryostat can be isolated from the others both with respect to vacuum and cryogenics. Three of the four linac sections (A, C and D) are now in operation.

The heart of the linac is the split-ring resonator,[3-5] a three-gap structure operating at 97 MHz. Two classes of resonators are used. One type is 35.6 cm long and is optimized for a projectile velocity $\beta \equiv v/c = 0.105$ (linac sections C and D). A second type is 20.3 cm long and is optimized for $\beta \equiv 0.060$ (sections A and B).

Each resonator consists of an inner drift-tube assembly made of pure niobium and a housing made of sheet niobium that is explosively bonded to copper.[4] The rf power dissipation into liquid helium is typically 4 watts per resonator. The inner assembly is cooled by 4.8°K liquid helium within the hollow loading tube and drift tubes, and heat generated in the housing is conducted to a helium-cooled heat sink through the copper backing of the bonded niobium.

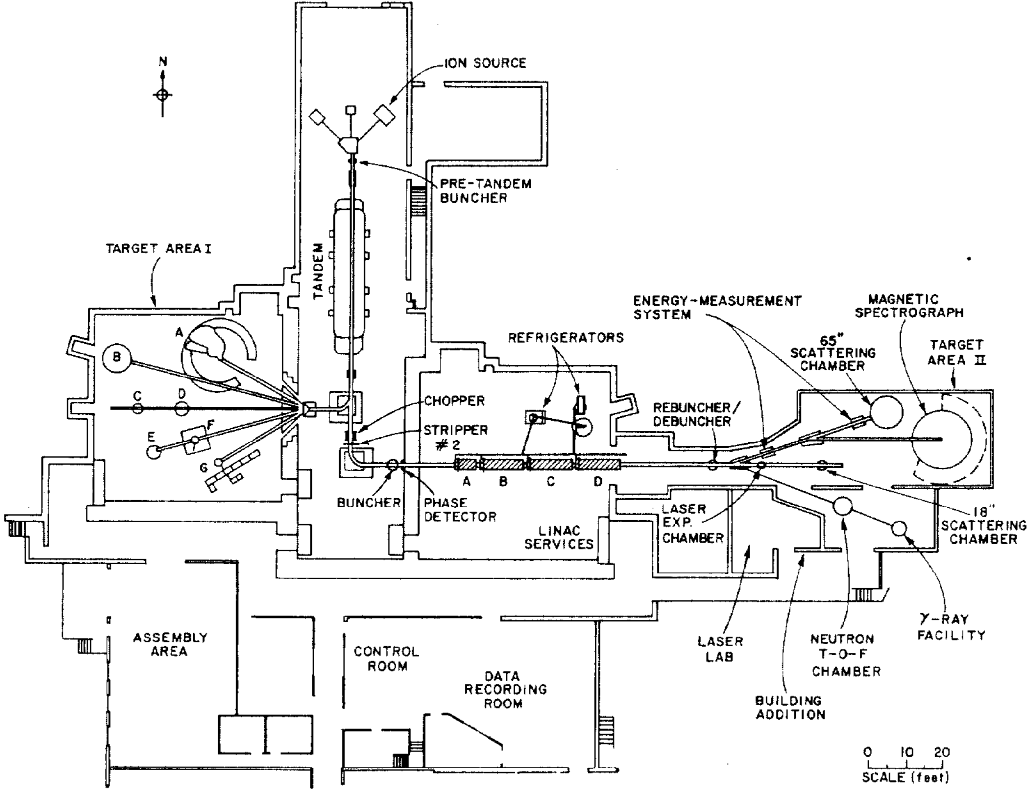

Fig. 1. Layout of the tandem-linac system at Argonne.

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RF power is fed to each resonating drift-tube assembly from a 150-watt solid-state rf amplifier by means of capacitive coupling from a 3/8-in diameter superconducting probe. Fast tuning is achieved by means of a high-power voltage-controlled reactance (VCX) developed for the purpose. This device is used to lock the rf phase of a resonator to the phase of a master oscillator.

The design aim for the resonators is an average accelerating field of 4.25 MV/m, which implies a voltage gain of 0.80 MV for a low-β unit and 1.5 MV for a high-β unit.

The resonators are cooled to a temperature of about 4.8°K by means of flowing two-phase helium (8 g/s) in a closed circulating system.[6] The total heat load of about 180 watts can be handled easily by the parallel operation of two refrigerators, a CTI-1400 (95 watts) and a CTI-2800 (300 watts). The driving pressure for the helium flow is provided by the compressors of the smaller refrigerator.

Superconducting solenoids are used to limit the transverse excursions of the beam. These hybrid magnets consist of a superconducting coil and a soft-iron return yoke and shield. The measured peak field is 7.6 Tesla; and the length of the coil is chosen to give a focussing power that is strong enough not only to counterbalance the defocusing action of the resonators but also is strong enough to allow the average beam size to be minimized through most of the booster for most ions. The solenoids are cooled by flowing liquid helium in the same way as are the resonators.

All of the cryostats for the booster are end-loading units and, except for section A, all are of the same size. In each unit, the array of resonators is surrounded by a nitrogen-cooled heat shield and, outside of that, a vacuum wall (see Fig. 2). Even though the interior of the resonators is open to the outer vacuum region, including the warm outer vacuum wall, the pressure inside the resonators is extremely low ($<< 10^{-9}$ Torr) during operation because of cryopumping on the outer surfaces of the resonators.

Each cryostat can be isolated from the others and removed from the beam line without disturbing the cooling or vacuum of the tanks remaining on-line. Once off line, the whole inner assembly of an accelerator section can be rolled out of the end of the cryostat, and all disassembly is then done in the open. When a section is ready to be put into service, it can be cooled down off line, completely tested, and finally moved on line while still cold. While the maintenance of a section is being carried out off line, the sections remaining on line can be used for acceleration.

Both the booster and the bunching system are controlled with the assistance of a model-11/34 PDP computer, which interacts with CAMAC crates by means of serial instructions. In general terms, hard-wired feedback circuitry is used to control resonator phase and amplitude on a fast time scale, whereas the computer sets the reference values, and monitors and controls phase and amplitude on a slow time scale. Often, the beam energy can be changed very rapidly by calculating resonator parameters.

A primary design objective has been to optimize beam quality so as to provide the experimenter with exceptional energy resolution and/or time resolution. This is achieved by forming the tandem beam into bunches that are narrow enough to minimize non-linear distortion in the linac and by using a debuncher/rebuncher to manipulate the output beam to meet experimental requirements.

III. Operating Experience

The partially completed booster is now operated about 50% of the total time. Almost all of this running time is devoted to nuclear-physics research with less than 10% used for accelerator development. The remaining time is used to install new hardware.

Table I gives a summary of booster operation since the first run in June 1978. Note that the number of useful resonators has increased steadily with time, and by now the linac provides a very respectable energy increase. A matter of special satisfaction is the fact that, although only 2/3 of the planned resonators have been installed to date, the demonstrated accelerating voltage is already greater than the 13.5 MV that was projected when the booster was first proposed in 1974.

Table I also shows that the accumulated operating experience is by now quite large - a total of ∿ 6,000 hours of beam-acceleration time. This experience gives realistic guidance on what to expect for future operating characteristics and has revealed the numerous practical problems that limit operational efficiency. The extensive operational experience has also shown that certain possible fundamental problems do not exist to a significant extent: problems such as serious radiation damage of the superconducting surfaces and the "thing you haven't thought of" that was formerly mentioned so frequently by those who were skeptical about the practicality of a superconducting linac.

Most of the beams used to date for research are listed in Table II. As shown by the q values, both single stripping (terminal only) and double stripping are used, depending on the beam energy required. The beam current on target is typically in the range 10 to 20 nA when double stripping is required and can be > 100 nA when single stripping is used.

The accelerating power of the tandem-booster system may be summarized in terms of an equivalent tandem with two strippers. The past and future performance of our system is shown in Fig. 3 in comparison with the largest tandems in the United States. For the Argonne system, the vertical steps in the figure represent the performance changes associated with the installation of additional resonators. Here, the indicated future steps are on the assumption that the average accelerating field remains what it is now; whereas, the gradual improvement in performance during 1982-83 is on the assumption that the average on-line accelerating voltage is gradually pushed up to the design objective. Whether or not this expected improvement is realized, the impressive accelerating power of the tandem-booster system is clear from the figure, especially in view of its relatively low cost.

The range of projectiles that can be accelerated by the tandem-booster system is gradually being expanded. Until October 1980, the upper limit for useful beams (i.e., beams with energies above the Coulomb barrier) was about A = 40 because only high-β resonators were in use. The installation of four low-β resonators then extended the upper limit to about A = 66. When

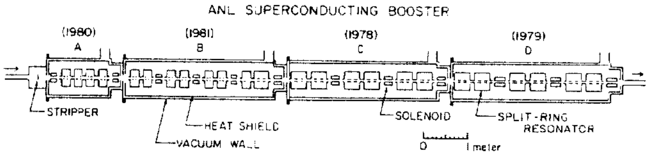

Fig. 2. Schematic of the superconducting linac.

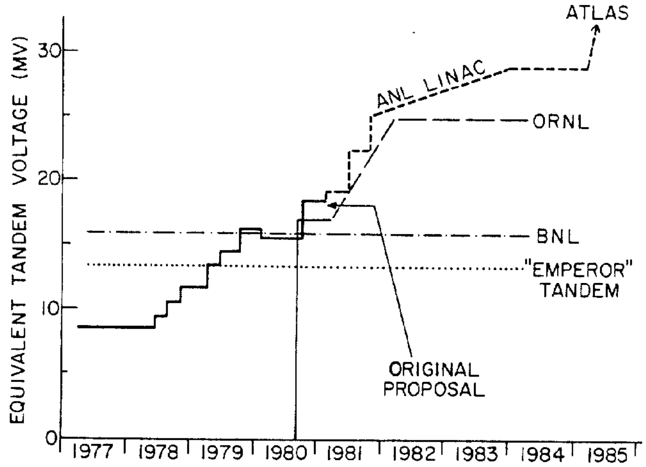

Fig. 3. Summary of accelerator performance in terms of an equivalent stand-alone tandem with two strippers (in the terminal and 30% down the high-energy tube).

section B has been installed (∿ May 1981), the mass limit will be extended very much higher, in so far as the booster is concerned, but then the ion mass may be limited by other factors such as the lifetime of stripper foils, the need for a lens in the tandem terminal, and the limited bending powers of several magnetic elements between the ion source and the linac.

One of the most valuable attributes of the booster is the exceptional ease with which the beam energy can be changed. Under many circumstances, once the resonators have been calibrated for a particular ion, the experimenter simply instructs the control computer what new energy is required, and it is rapidly done. This capability is proving to be unexpectedly valuable for measuring excitation functions with a level of detail that has rarely been undertaken heretofore.

Since the beginning of the booster project, one of the main goals has been to provide a new level of refinement for fast-timing measurements by delivering to the experimenter a beam pulse that is extremely short - say, less than 50 ps. This objective has not yet been fully realized because, although the linac itself yields such narrow pulses, they cannot be delivered to the experimental apparatus for long periods of time without drift and jitter. Rather, the effective pulse width for long runs is now in the range 100 to 150 ps when the rebuncher is used. The various causes of time broadening are not fully understood yet, but we expect to obtain better timing soon by implementing a new pulse-arrival-time detector.

Table I. Summary of booster operation

Period	Weeks of Operation	Number of Resonators	Max. Accel. Voltage (mV)
Experience			
June 1978	0.7	2	1.6
Sept 1978	1.2	5	4.1
Dec 1978	2.5	6	5.4
Mar-Apr 1979	6	7	7.6
June 1979	5	8	9.3
Oct-Dec 1979	8	11	11.3
Feb-Apr 1980	6	10	10.5
June-July 1980	7	11	10.5
Nov-Dec 1980	7	15	14
Feb-Mar 1981	3	15	14
Planned			
Apr 1981		16	15
June 1981		20	19
Final Booster		24	>25

Total Operating Time to Date
Resonators ∿ 8000 hr
Useful Beam ∿ 6000 hr

There has not yet been a need to use debunching to improve the beam-energy resolution, nor do we now have a detector that could directly observe the good resolution that should be obtainable. This capability must await the completion of a magnetic spectrograph in the experimental area.

The linac is run without operators in the area except during the normal 40-hour work week. Once a run has started, the experimenters monitor the operational functions such as changing the beam energy. The linac-development staff are on call to fix serious malfunctions. The time between significant problems is typically 12 hours, and these can usually be corrected in < 1/2 hour by an experienced person.

Operational experience has shown that the use of independently-phased resonators is one of the most advantageous features of the superconducting linac. In contrast to most accelerators, almost any component can fail, and the linac can still be operated in a useful way. This capability, more than anything else, is responsible for the apparent ease and speed with which the booster has become a good research tool.

Table II. Typical beams accelerated by the booster for use in the experimental program, as of March 1981. The output energies are not necessarily the highest energies obtainable.

Ion	Ion Charge q_1	q_2	Tandem Beam Energy (MeV)	Linac Beam Energy (Mev)	(MeV/A)
^{12}C	5	6	51	106	8.8
^{16}O	6	8	60	158	9.9
^{18}O	6	8	60	142	7.9
^{24}Mg	7	7	68	133	5.5
^{28}Si	9	9	85	182	6.5
^{32}S	8	13	77	220	6.9
^{34}S	8	13	77	189	5.6
^{37}Cl	9	14	85	272	7.4
^{40}Ca	10	16	96	170	4.3
^{56}Fe	10	10	94	127	2.3
^{58}Ni	19	19	94	319	5.5
^{59}Co	19	19	94	322	5.5
^{64}Ni	19	19	94	294	4.6

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