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INITIAL OPERATION OF THE ARGONNE SUPERCONDUCTING HEAVY-ION LINAC*

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ABSTRACT

Initial operation and recent development of the Argonne superconducting heavy-ion linac are discussed. The linac has been developed in order to demonstrate a cost-effective means of extending the performance of electrostatic tandem accelerators. The results of beam acceleration tests which began in June '78 are described. At present 7 of a planned array of 22 resonators are operating on-line, and the linac system provides an effective accelerating potential of 7.5 MV. Although some technical problems remain, the level of performance and reliability is sufficient that appreciable beam time is becoming available to users.

INTRODUCTION

This paper reports the status of the Argonne superconducting heavy-ion linac, which has been developed to boost the energy of heavy-ion beams from an FN tandem accelerator.[1,2] The intent of the project has been both to develop superconducting rf technology for the acceleration of heavy ions, and to provide a useful accelerator for use with the Argonne FN tandem. Most of the development tasks have been completed, and are reported elsewhere. Current funding provides for a linac of four modular sections, of which two have been completed and are presently operating.

The physical layout of the accelerator system is shown in Fig. 1. The pre-tandem beam-bunching system and a post-tandem superconducting buncher are housed in the tandem vault. The linac and most of the helium refrigeration system are located in a previously existing target room, with the linac output going into a small new target area.

Preserving the good quality of the tandem beam requires an exceedingly narrow beam pulse injecting the linac. This has been accomplished with little loss in the tandem beam intensity by a two-stage bunching system.[3] The pre-tandem buncher is a gridded-gap (room temperature) driven by a sawtooth-like voltage generated by superposing four rf harmonic components. This system compresses about 80% of the dc tandem beam into 1 nsec pulses at the tandem output. The post-tandem buncher is a single superconducting split-ring resonator which linearly compresses these pulses to a width of typically 50 psec at the linac entrance.

The linac consists of an independently phased array of superconducting split-ring resonators, each of which can provide more than 1 MV of effective accelerating potential over a range of a factor of two in particle velocity.[4,5,6] Independent phasing allows the velocity profile of the linac to be varied over a

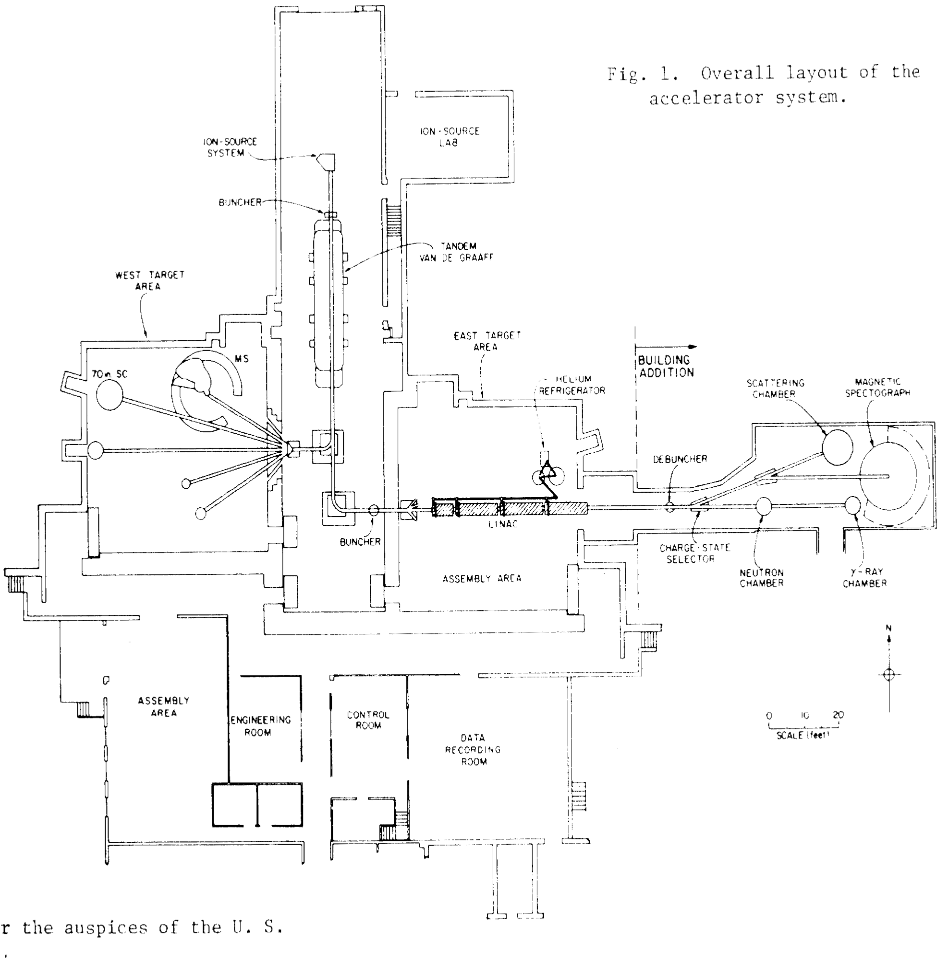

Fig. 1. Overall layout of the accelerator system.

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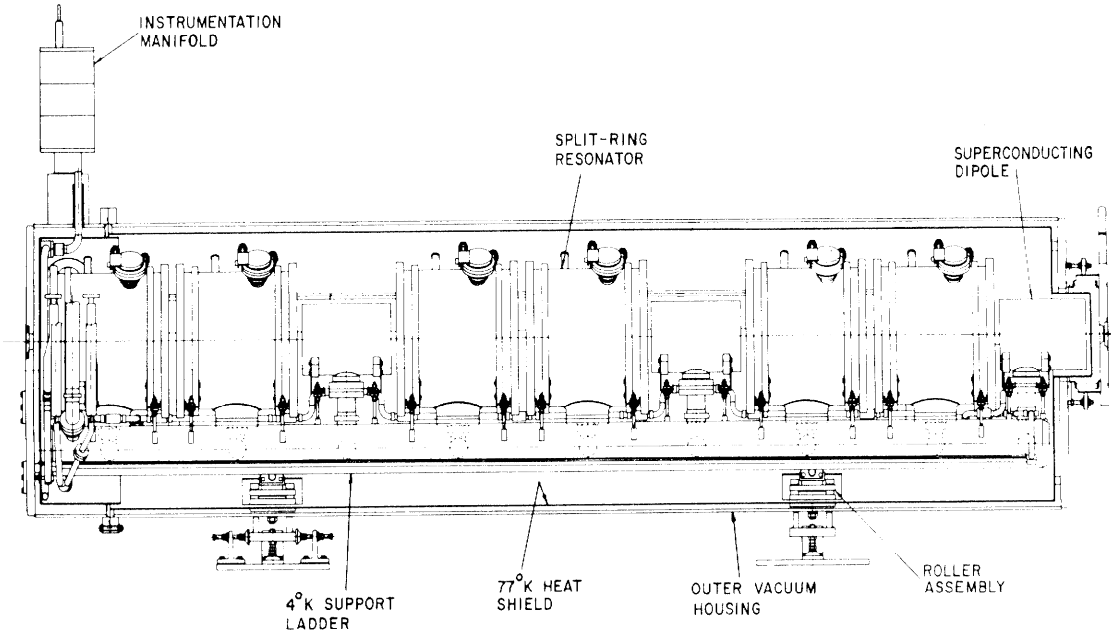

Fig. 2. Cross section of a linac cryostat module. The cryostat dissassembles by rolling the resonator array, together with all cryogenic plumbing and electrical leads, out of the vacuum housing.

wide range, and provides a high degree of operational flexibility. Focussing within the linac is accomplished with a superconducting dipole following every pair of resonators.[7] Beam diameter within the linac is typically kept smaller than 6 mm both to prevent beam impinging on the superconducting surfaces of the resonators, and also to limit the energy spread induced by radial variation of the transit-time factor within the resonators.

The linac target area was constructed in 1977, and installation of the experimental equipment shown in Fig. 1 will be completed in 1979-80. For initial operation, experiments are being performed on the zero-degree beam line. Later, with the installation of the superconducting debuncher-rebuncher and the charge selector magnet, the location of the various experimental stations will be changed to that shown in Fig. 1.

Beam acceleration tests with the linac began in June 1978 with two resonators in a single linac module, and have continued to the present array of eight resonators in two modules. As is discussed below, most, but not all, of the operational problems encountered in these tests have been overcome. However, a level of performance and reliability has been achieved that is beginning to provide significant beam time for users.

LINAC SYSTEMS

Cryostat Module

The linac is formed of modular cryostat sections any one of which can be taken off-line without disturbing operation of adjacent sections.[1] Figure 2 shows a cross section of a typical cryostat. A principal design feature is that the cryostat is end loading, i.e., the support frame for the resonator array rolls out of one end of the cryostat so that good access is provided for assembly, alignment, leak testing of nearly all vacuum seals, and general systems checkout.

The vacuum system consists of a 1500 l/sec turbomolecular pump permanently attached to the cryostat, and the cryopumping provided by the exterior surfaces of the cold resonators. The turbopump is used primarily for pumpdown of the cryostat, and is turned off during normal operation. When the cryostat is cold, pressure at the room temperature outer wall is typically less than 10^{-8} Torr.

Except for failure of a flexible metal bellows in the liquid helium system of one cryostat during the initial beam acceleration test, performance of the cryostats has been good. Turnaround time for removing a cold cryostat from on line for minor modification or repair and having it fully operational again has proven to be four to five days.

Refrigeration and Helium Distribution System

Cooling is provided by a CTI 1400 helium liquifier with three compressors, which nominally yields 95 watts of refrigeration at 4.6K. The refrigerator output is used as the source for a continuous flow of liquid helium through the cryostats. The available flow rate is not sufficient to drive the cryostats in parallel, and therefore the several cryostats are connected in series, with a heat exchanger after each cryostat to recondense any gas generated.[8] After passing through all the cryostats, the helium undergoes a Joule-Thompson expansion and is cooled by several tenths of a degree. Returning to the refrigerator, the two-phase mixture of helium passes through the secondary of the heat exchangers associated with each cryostat.

The refrigerator is also used to produce liquid helium for off-line testing of resonators.

Since May of 1978, when the refrigerator first went into operation, the refrigeration and distribution system has been in almost continuous operation. Two of the three compressors now have over 5500 hours of service. During the first months of operation there were numerous problems: plugged valves, blocked heat exchangers, etc. These problems have gradually been eliminated with the repair of minor hardware defects and by developing operational procedures. At present the system operates with negligible down-time, and with very little operator attention, averaging about an hour per day.

The most serious remaining problem with the refrigeration-distribution system is a spurious heat load, on the order of twenty watts, which appears to be due to thermo-acoustic pressure oscillations in portions of the distribution system. As it does not presently cause a performance limitation, little effort has been expended to date toward solving this problem.

Resonators

Current plans call for two types of split-ring resonator, a high-beta type, useful for particle velocities $\beta = v/c$ from .07 to .14, and a low-beta unit for $.04 < \beta < .09$

Figure 3 shows a high-beta resonator. Principal design features are the central loading structure, formed of pure niobium, which is hollow and cooled by forced flow of helium.[5] The outer housing is formed of an explosively-bonded copper-niobium composite and is cooled by conduction through the copper. The interior length of the resonator is 14 inches, and it operates at 97 MHz.

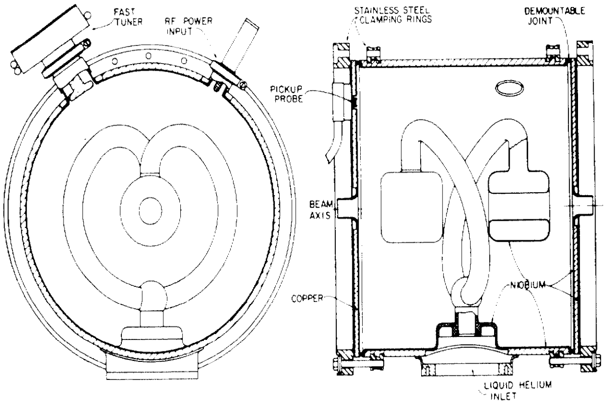

Fig. 3. 97-MHz, 14-in. length, high-beta split-ring resonator. The inner loading structure is made of Nb and is hollow to permit cooling by forced-flow of liquid helium. The outer housing is formed of an explosively-bonded Nb-Cu composite and is cooled by conduction.

Eight high-beta units have been completed and perform excellently in off-line tests.[6] Currently, the average performance level is 4.0 MV/m accelerating gradient for four watts rf input to the resonator. At this field level, each resonator provides 1.4 MV of effective accelerating potential.

The low-beta resonator is similar in design to the high-beta type, except the length is reduced by about 40%. A prototype low-beta unit has been completed and performs well in off-line tests, but has not yet been used to accelerate beam.

Off-line tests indicate that normal handling and operating procedures, e.g. cycling to room temperature, storage in dry N_2 at room temperature for at least one month, and operation at high fields with beam for at least hundreds of hours cause no appreciable degradation of resonator performance.

On-line Resonator Performance

A number of problems have been encountered in realizing the full accelerating potential of the resonators on-line. Some progress has been made, as is reflected in the available on-line accelerating potential which has increased from 4 MV in September '78 to the current value of 7.5 MV. However, several problems remain to be solved, since the present performance level, although quite useful, represents $\sim$2/3 of the intrinsic resonator capability.

During the initial beam test, in June '78, a 3-in. diam. metal bellows failed in one of the cryostats, dumping 50 liters of liquid helium into the high-vacuum space. Thus, in a time period of 1 s, the resonator environment changed from a vacuum of $6\ 10^{-9}$ Torr to helium gas at more than atmospheric pressure and a temperature approaching that of liquid nitrogen. The performance of resonators in this cryostat was severely degraded, as is shown in Fig. 4.

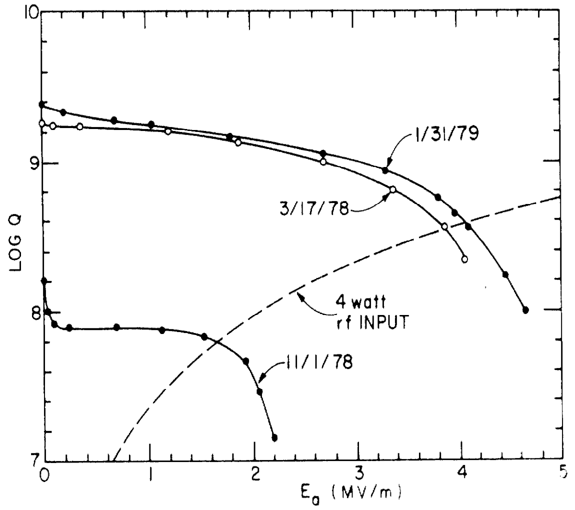

Fig. 4. Q vs accelerating field level for a typical high-beta resonator. In chronological sequence are: the initial performance, performance after a severe vacuum accident, and performance after electropolishing the resonator interior.

Performance was restored by electropolishing 40 μm from the resonator surface, a procedure which requires about two man-days of effort per resonator. In an adjacent cryostat, which was flooded to at least several Torr during this accident, resonators were degraded appreciably, but much less severely, to a performance level of 3 MV/m at 4 watts rf input. The bellows failure was due to a design error which easily was corrected. A later vacuum accident in which several liters of helium gas were released into a cryostat caused no observable performance degradation.

Difficulties have also been encountered with the parallel-flow liquid helium distribution within the cryostats. Initial problems with obtaining uniform flow to each resonator have been largely solved. Some problems remain with obtaining proper flow of liquid helium within the resonator.

As seen in Fig. 3, each arm of the split-ring assembly has a high point which will accumulate helium gas generated by the rf power loss in the resonator. A vent line in the interior of each arm exhausts the resulting two-phase mixture of helium from the resonator. In the initial design, flow through the two arms was in parallel. In this configuration, it was found that siphon effects in the vent lines could cause flow instabilities which effectively blocked flow to one of the arms. Operationally, the problem manifested as a thermal breakdown of a resonator after 5 or 10 min. of operation at high fields. A design change to series-flow of helium through the two arms has eliminated the flow instability, and considerably improved performance. Inadequate cooling of some portions of some resonators still occurs, however, and limits the average obtainable cw field to ∿3 MV/m. Some resonators seem properly cooled and will operate at gradients greater than 3.5 MV/m, while others will not operate continuously above 2.5 MV/m. This non-uniformity indicates that the problem is not fundamental, and it is being actively pursued.

A requirement of on-line operation that had not appeared in off-line tests is the periodic reconditioning of some resonators. Intrinsic to the performance shown in Fig. 4 is a process of helium conditioning, i.e. operation at high field levels in the presence of $\sim 10^{-4}$ Torr of He gas for a period of roughly an hour, which reduces electron loading. We have found that some resonators require repetition of this process after, say, 50 hours of operation at high fields.

Superconducting Dipoles

The dipole focussing elements consist of a commercially-wound Nb-Ti coil enclosed in an iron shield to limit the magnetic field at the superconducting resonator.[7] A typical dipole assembly is 8 in. in diam. and 10 in. long, with a 1 in. clear bore. Five solenoids are currently on line, all of which will operate at fields greater than 7.5 T, some 10% above design values. The solenoids are run in persistent mode, except for brief adjustment periods. No difficulties have been experienced in solenoid operation.

Resonator RF Control

The RF phase and amplitude in each resonator are controlled locally by hard-wired feedback circuitry. With one exception, discussed below, performance of this system has been generally satisfactory. Phase and amplitude errors are typically less than 1 degree and a few parts in 10^4, respectively.

The critical element of the control system is the fast tuning unit, which compensates for changes in resonator eigenfrequency caused by mechanical vibration. The fast tuner is based on a voltage-controlled reactance, PIN diodes, which must switch several kilowatts of RF reactive power. A key design decision for the linac was to mount the diode element directly to the superconducting resonator, eliminating the need for a high-power RF coupling line, but making the diodes inaccessible in case of failure.

Since June '78, six of 52 diodes have failed, always by shorting, which renders the fast tuner, and the resonator, inoperative. This problem has been solved by attaching a fuse to each diode so that a failed diode can be removed from the tuning circuit with an externally applied dc current. With this system, failure of two of the six diodes associated with each resonator can be tolerated without loss of performance. Thus, at present, diode failure does not represent an operational problem.

Computer Control System

Control of the accelerator system is based on a PDP 11/34 computer. To date, the computer has performed only rudimentary control functions, such as setting resonator phase and amplitude and solenoid currents, monitoring temperatures, etc. During the coming year, the computer will be given additional control tasks, especially with regard to tuning the linac.

LINAC OPERATION[*]

Beam Tests

Several runs with beam have provided stringent tests of all aspects of the accelerator system. In June '78, two resonators were used to accelerate a beam of $^{19}F^{6}$. Following repair of damage due to the previously-described vacuum accident, in September five resonators, in two cryostat modules, were used to accelerate a 56-MeV beam of $^{16}O^{6+}$ to 78 MeV. Although modest in scope, this test was significant in requiring the total system to function well for several days. The run was concluded by providing beam for an exploratory nuclear physics experiment for more than two days.

The system was again run in December and six resonators were used to accelerate an 85-MeV beam of $^{32}S^{14+}$ to 148 MeV. This run was quite demanding in that it extended over a two-week period, involved double stripping for the first time, and required the linac to provide a reliable beam for experiments in two sets of apparatus, for 5-1/2 days.

At this writing, a seven-resonator array has been operating for two weeks, accelerating an 85-MeV $^{32}S^{14+}$ beam to as much as 178 MeV. Three weeks of user time are scheduled, of which one is completed.

Operating Characteristics

The most outstanding feature has been the general reliability of linac operation. While accelerating beam, the linac systems typically require little or no operator intervention for periods of many hours. Linac downtime has been small, less than one in twenty-four hours, primarily to provide for re-conditioning of some of the resonators.

A remaining problem is occasional loss of phase control of a resonator due to excessive mechanical vibration. When this occurs, either the beam or data taking must be stopped, causing the loss of beam time. The fraction of time lost has declined from ∿50% in September '78 to a present value of 10 to 20% as various sources of vibration have been eliminated.

Beam quality is essentially as expected,[1] although two factors limit presently available performance. Firstly, the second stripper is temporarily located upstream of the tandem beam-analyzing magnet, rather than at the time focus at the linac entrance. Thus energy straggling in the stripper dominates the output time-energy spread. Secondly

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[*] Extensive information about the linac systems and operations is contained in two documents, "ATLAS-A Proposal for a Precision Heavy-Ion Linac..." and an addendum to this proposal.

absence of a debuncher-rebuncher downstream of the linac prevents obtaining the full time or energy resolution capability of the linac in the experimental areas.

Another technical problem is a slow drift in the output energy of the linac, typically a few parts in 10^3 per hour, the source of which has not yet been located.

Linac tuning has proven straightforward. At present this is accomplished by calibrating the RF phase of each resonator by varying the phase and observing the output beam energy. In this procedure, the first resonator is tuned, with all others off, and then one successively turns on and tunes each resonator in the chain. At present tuning is done manually, and requires several hours. Eventually, the operation will be fully computer controlled, and should go very much more rapidly.

FUTURE PLANS

Although some technical problems remain, the linac currently provides a useful capability, and a significant and increasing amount of user time is becoming available.

The developmental program planned for 1979 and 1980 is expected to upgrade the performance of the system both by installation of additional components, and by improving the performance of all components.

Planned hardware additions include a third linac module in 1979, which will add four high-beta and several low-beta resonators to the linac. IN 1980, a fourth module is planned, and a superconducting debuncher-rebuncher is to be installed downline of the linac.

ACKNOWLEDGMENTS

It seems appropriate here to identify the staff members of the linac project together with primary areas of responsibility, namely: L. M. Bollinger— project management; the author, R. Benaroya, P. Markovich, C. H. Scheibelhut— resonator and cryostat development; J. M. Nixon— refrigeration system; K. W. Johnson, B. E. Clifft— RF control; A. H. Jaffey, T. K. Khoe— beam dynamics; T. P. Wangler— beam diagnostics; and J. Aron— budget and procurement.

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