THE ARGONNE TANDEM-LINAC ACCELERATOR SYSTEM*

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Design considerations and operational experience for the existing heavy-ion accelerator consisting of a tandem injecting into a superconducting linac are summarized, with emphasis on the general features of the system. This introduction provides the basis for a discussion of the objectives and design of ATLAS, a larger tandem-linac system being formed by expanding the existing superconducting linac.

I. Introduction

The Argonne Tandem Linac Accelerator System (ATLAS) is a heavy-ion facility being formed[1] by extending the linac part of an existing tandem-linac accelerator. From the point of view of accelerator technology, the project is of interest primarily because the linac is superconducting. To the user, however, the project is important because it will considerably extend the energy range accessible with heavy-ion beams of high quality and easy energy variability.

The ATLAS project is an outgrowth of a developmental effort that started in the early 1970's and culminated in the construction of a prototype superconducting linac which now serves as an energy booster for heavy ions from an FN-model tandem electrostatic accelerator. Throughout this long effort to form a tandem-linac system, there were two guiding objectives: (1) to develop a new technology that permits the energy of heavy-ion beams to be increased in a cost-effective way and (2) to preserve and if possible improve on all the good features of the tandem accelerator: good energy resolution and emittance, easy energy variability, versatile ion sources, and overall flexibility. The existing prototype superconducting linac and its operation in a tandem-linac system have amply demonstrated that these objectives can be met.

II. The Present Tandem-Linac System

Since ATLAS is closely linked to the existing tandem-linac system and its technology, let us review briefly the main characteristics of this existing system. The mode of acceleration is illustrated in Fig. 1. A negatively charged ion from the source is injected into the tandem and accelerated to the terminal. There the ion passes through a thin foil stripper (typically 3 $\mu g/cm^2$ thick) and many electrons are stripped off. The resulting positive ion is accelerated on back to ground potential where, in our system, its energy is usually in the range 50-100 MeV, depending on the ion species. The ion then passes through a second stripper, if a high energy is needed; but if beam intensity is more important, only terminal stripping is used. Then the beam from the tandem (which usually consists of many components with different charge states and energies) is analyzed, bunched, and injected into the linac.

The objectives of maximizing versatility and beam quality impose several requirements on a tandem-linac system that need to be understood. First, the bunching system must be both exceptionally efficient and form very short beam pulses. Efficiency is required because tandem beams are relatively weak for many ion species of interest and short pulses are required in order to provide a matched beam to the linac so that beam quality is preserved. We achieve these characteristics with a two stage bunching system[2] consisting of: (1) a pre-tandem room-temperature bunching gap driven by a saw-tooth-like wave form generated by four harmonics and (2) a post-tandem superconducting accelerating structure of the same kind as is used in the linac. This system compresses about 70% of the D.C. beam from the ion source into pulses about 100 ps wide.

The second set of requirements is on the accelerating structures. They must operate at a rather low frequency because the incident ion velocity is often low, they must have few gaps in order to be able to accelerate the wide range of velocities provided by the tandem injector, and they must be independently phased in order to be able to vary the velocity profile of the linac to what is required for the incident energy and the charge of the projectile.

Note that none of the above fundamental requirements are related to the fact that the linac is superconducting. On the other hand, the use of superconducting RF technology plays a dominant role in the technical problems that must be solved, in the determination of costs, and in the nature of the operational problems.

Since our existing prototype tandem-linac system and its technology have been described previously,[3] only its main features are summarized here. The tandem is a modified FN-model tandem Van de Graaff that has been in use in various forms since 1962. Its maximum terminal voltage is about 9 MV. The linac is located in a former target room and the beam from the linac goes into a new experimental area. The linac consists of 24 resonators distributed in four cryostats. Except for the first unit, all the cryostats are of the same size and are thus interchangeable, if necessary.

The linac accelerating structures are split-ring resonators[4] made of niobium. This structure has two drift tubes and hence three gaps. The drift-tube assembly, made of hollow, pure niobium metal, is cooled by forced-flow boiling helium at a temperature of

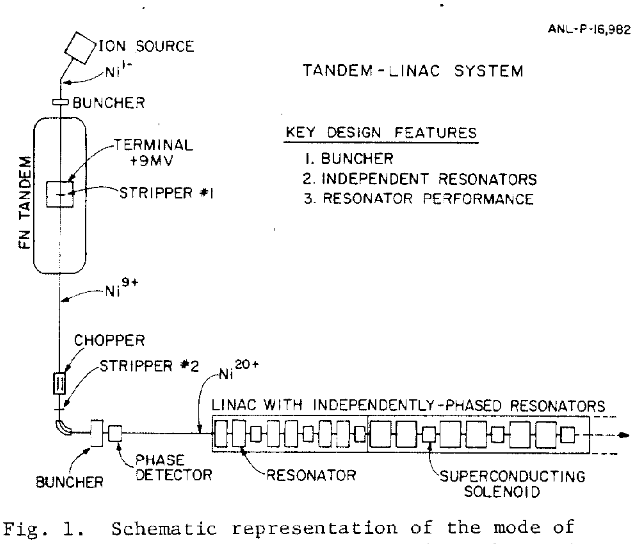

Fig. 1. Schematic representation of the mode of acceleration in the Argonne tandem-linac heavy-ion accelerator.

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about 4.7 K. The outer housing is a composite material made of niobium sheet that is explosively bonded to copper plate. The niobium (on the inside) provides the superconducting surface, whereas whatever heat is generated flows through the outer copper to the helium-cooled base.

The RF frequency chosen from the resonators, 97 MHz, is a compromise involving three main factors: (1) the RF frequency needs to be low to make it easy to preserve beam quality, (2) but a low frequency implies large size and this increases cryogenic costs, and (3) more important, a large size makes phase control more difficult because of enhanced mechanical motion. Our choice of 97 MHz still appears about optimum for a niobium split-ring resonator designed for projectiles with β in the range 0.05 - 0.12.

Two types of resonators are used in the present linac. The first eleven units in the array are 20.3 cm long and optimized for a projectile with $\beta = 0.06$, and the last thirteen units are 35.6 cm long and optimized for $\beta = 0.105$. For both sizes, the useful accelerating field is limited by electron loading rather than by resistive loss on the superconducting surface. The maximum useful accelerating field of a resonator ranges from 2.5 to 4.0 MV/m, depending on the operational history of the unit. Typically, the accelerating field of a new resonator is initially at the high end of the range but, after a long period of operation (say, two years), it is likely to have been degraded by a serious vacuum accident or some other mishap. The original performance can then be restored by simply cleaning and rinsing the superconducting surfaces. There is no evidence that exposure to air, pump oils, radiation, or any other normal form of contamination does any fundamental damage to the superconducting surfaces.

Parts of the present linac have been in operation since June 1978, and by now over 10,000 hours of beam time have been logged.[5] This long period of operation has revealed many operational problems, of course, but most of these have been eliminated. The one remaining major problem is the fact that, because of the relatively long turn-around time required to take a cryostat off line and then return it to operation ($\sim$ 10 days), the linac as a whole cannot be kept in top condition without sacrificing more running time than is acceptable for an intensively used machine. It appears to us that the best solution to this operational problem is to have a spare accelerator section that can be interchanged, when necessary, with a malfunctioning on-line section. The fact that the velocity profile of the linac may be altered by such an interchange is unimportant for a large fraction of experiments.

The initial motivation for the use of small, independently-phased resonators in the linac was the desire to be able to effectively accelerate projectiles with a wide range of incident velocity and charge/mass ratio. However, it has turned out that two other considerations are equally important. One of these is the relative ease with which a small unit can be fabricated and put into operation, in contrast to a multicell unit in which a single defect can degrade the performance of the whole array. At the present state of superconducting RF technology, this is an important advantage. A second consideration is the fact that, for an independently-phased array, one or indeed many resonators may cease to operate without destroying the usefulness of the accelerator. This operational ruggedness is well illustrated by our experience; we have rarely been able to operate all of our resonators at the same time, and yet equipment failure has never forced us to cancel a set of scheduled runs.

One of the most gratifying aspects of the superconducting linac has been its reliability in operation. Perhaps the best evidence for this is the fact that at least half of our long running time to date has been accomplished without a qualified operator being present. That is, once the linac was tuned for a particular beam, the user was responsible for the operation, including changing the beam energy. This approach (made necessary by fiscal considerations) was feasible, of course, only because the linac was computer controlled from the beginning.

As was stated earlier, a primary objective in our work has been to form a machine that has excellent beam quality, easy energy variability, and overall flexibility. These characteristics have, in fact, been achieved. The ruggedness and flexibility of the linac has already been mentioned. Similarly, the tandem can be operated at a greatly reduced terminal voltage without decreasing the linac beam energy much.

One of the most useful operational characteristics of the tandem-linac system is the ease with which the beam energy can be changed. This involves merely varying the amplitude of the last resonator required to achieve the desired energy, with all other parameters of the system being kept constant. At the present stage of development, an energy change is accomplished in about one minute by merely instructing the control computer to provide the desired beam energy.

Not much effort has been devoted to a detailed study of beam quality, but the data obtained to date are in qualitative agreement with the expectation that the transverse emittance $\Delta x \cdot \Delta x$ is determined by the emittance of the source and by angular scattering in the stripper foils, and the longitudinal emittance $\Delta E \cdot \Delta t$ is determined by the pulse width formed by the pre-tandem buncher and by energy straggling in the stripping foils. Depending on the projectile and the foil thickness involved, the numerical valves for the emittances are typically in the range 1 to 2 mm-mrad for $\Delta x \cdot \Delta x'$ and 20 to 80 keV-ns for $\Delta E \cdot \Delta t$.

There are two features of our present stripping system that are less than optimum, from the point of view of minimizing both the transverse and longitudinal emittance. One is the general problem that stripping-foil lifetime decreases rapidly with decreasing thickness, which requires us to use stripping foils in the tandem terminal that are thicker than is desirable, namely, 3 $\mu g/cm^2$ rather than say 1 $\mu g/cm^2$. Perhaps future improvements in foil technology will lessen this difficulty. A second problem is that the second stripper contributes greatly to the longitudinal emittance of the beam injected into the linac because the stripper is not located at a time focus. We expect to eliminate this problem ultimately by placing the second stripper at the entrance of the linac, where the beam pulse is very narrow.

In principle, it is feasible to tune the linac so as to minimize either the time spread or the energy spread of the output beam. However, this approach makes the beam pulse abnormally broad during some part of the acceleration process, and consequently the phase ellipse tends to be distorted and its effective area enlarged. Under most circumstances, then, a better strategy is to accelerate a matched beam (in energy-time phase space) and to use a debuncher/rebuncher in the output beam line to tailor the output phase ellipse to the users needs. This approach is used in our present operation but, unfortunately, the small size of the experimental area limits the effectiveness of both rebunching and debunching. For example, because of spacial constraints, the distance from the linac to the debuncher/rebuncher is only about 8 m, and the distance from the rebuncher to the scattering chamber is 16 m, thus making the beam pulse at the scattering chamber about twice as wide as it is at the linac output. In practice, the measured beam pulses at the scattering chamber are typically 150 ps wide, whereas pulses as short at 50 ps have been measured in demonstration experiments in which the detector was relatively close to the rebuncher. Clearly, the beam could be used much more effectively for fast-timing experiments if we did not have such severe constraints on the location of the rebuncher. These constraints result in part from our decision to use, as a cost-saving measure, a single rebuncher for all beam lines.

III. The ATLAS Project

The full ATLAS facility is being formed by extending the existing superconducting linac described above and by adding a large new experimental area. The primary objectives of the project are: (1) to increase the beam-energy range, (2) to extend, if feasible, the range of projectile mass, (3) to preserve the good beam quality, (4) to provide an adequate experimental area, and (5) to preserve the ongoing research program with the beam from the present linac.

The solution to the question of how to enlarge the facility and yet preserve the present research program is given by Fig. 2. By bending the beam from the existing linac through 40°, the ATLAS linac and its associated building can be added to the existing building with only minimal interruption of the present operation.

The actual layout of the full ATLAS facility is shown in Fig. 3, where the grey areas of the building and the fully-darkened parts of the linac are the additions being provided by the ATLAS project. Note that the beam from the existing linac (labelled "Booster Linac") can continue to go into the present experimental area while the new building and linac are under construction. The main feature of the building is a large open experimental hall (Area III) separated into quasi-independent work spaces by means of movable shielding.

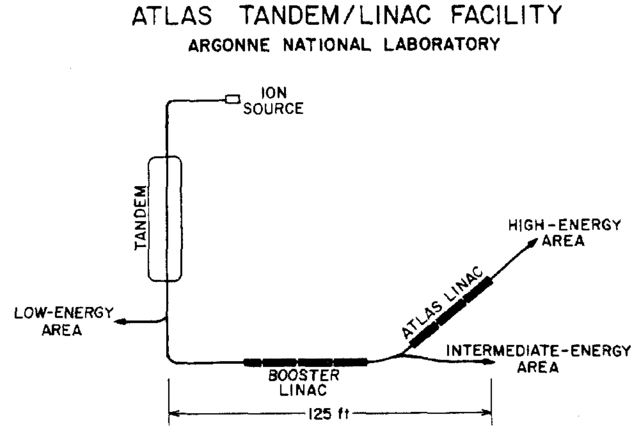

Fig. 2. Main elements of ATLAS.

The linac addition consists of three cryostats of the same size as are now in use. They will be cooled by the helium refrigerations now in operation. We have considerable flexibility as to the kind and size of resonators that can be housed in the cryostats but, as discussed below, we plan to use six resonators in each cryostat, all of the same size as the present $\beta = 0.105$ units.

The primary technical challenge of the ATLAS project is how to make an accelerating structure that is optimum for ions with velocities beyond the range of the present $\beta = 0.105$ structure. Several possibilities were studied, and it was concluded that the cost-effective solution for us is a split-ring resonator that has the same housing as the existing $\beta = 0.106$ unit and that has an RF frequency of 145.5 MHz, 3/2 times the 97 MHz of the existing units. This design has several desirable characteristics: (1) it provides maximum acceleration for projectiles with $\beta = 0.16$, a rather high value, (2) it has a stored energy that is low enough to permit the RF phase to be controlled with our developed technology, and (3) the use of a standard housing reduces fabrication costs. The RF frequency of 3/2 x 97 MHz is suitable because the

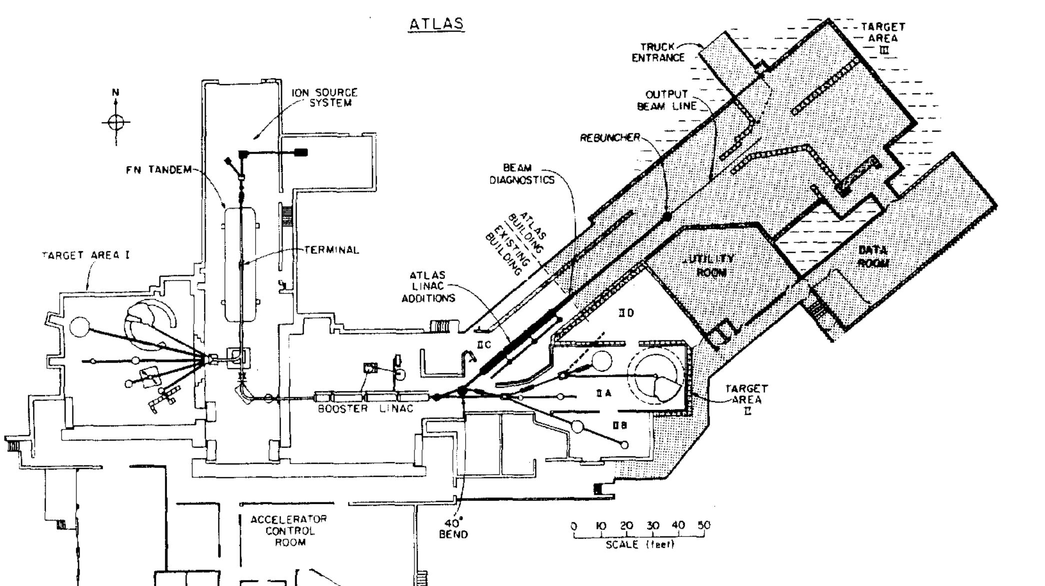

Fig. 3. Layout of the ATLAS facility.

maximum beam-pulse rate is 1/2 x 97 MHz. Additional detail about the new design is given by Shepard and Zinkann[6] in another paper at this conference.

The overall arrangement of accelerating structures planned for the ATLAS linac is summarized by Fig. 4. The system will consist of a total of 42 split-ring resonators: the first 11 units have $\beta = 0.06$, followed by 19 units with $\beta = 0.105$, and ending with 12 units with $\beta = 0.16$.

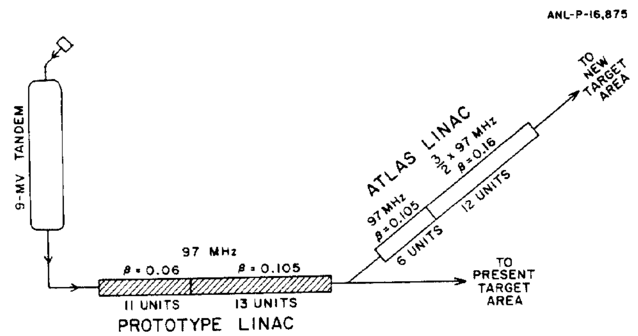

Fig. 4. Resonator types in the ATLAS linac.

A second important technical challenge of the ATLAS project is the design of the 40° bend area. There are two parts to the problem. The first is how to transmit the beam around the bend and into the new linac without degrading beam quality. The problem is made difficult by the fact that the available space is small but nevertheless the distance between linacs (∿ 6 m) is long enough for the beam pulse to broaden considerably under normal operating conditions. Initially, we believed that the phase ellipse out of the booster linac could be manipulated by the booster itself to have a weakly bunching configuration that would deliver a properly matched beam to the new ATLAS linac. Although calculations show that this is indeed feasible in principle, operating experience with the present linac convinced us that it might not be practical for routine operation, in view of the fact that the available diagnostic tools give only indirect information about the actual phase ellipse and that the time available for tuning a new beam is very short (a few hours, at most). Consequently, we have decided to add a rebuncher between the two parts of the linac. Also, the problem is made easier by using 97-MHz resonators in the first cryostat after the bend.

The main challenge in the 40°-bend region results from our plan to split the beam into two components, one going into the existing target room and the second going simultaneously into the new linac. This idea is especially attractive if the second stripper is immediately in front of the booster linac, since then several charge states can be accelerated to approximately the same energy in the booster. The design problem is how to separate these charge states cleanly without deteriorating beam quality. This problem has not yet been solved in detail, but two alternative ideas are being studied, both involving the use of magnetic fields from superconductors.

Some facets of the planned performance of ATLAS are summarized by Fig. 5. This figure emphasizes the fact that precision high-resolution heavy-ion nuclear physics is likely to be of primary interest for beam energies in the general neighborhood of the Coulomb barrier, and ATLAS is aimed squarely at this range. The maximum beam energies indicated by the figure are believed to be realistic goals that will gradually be

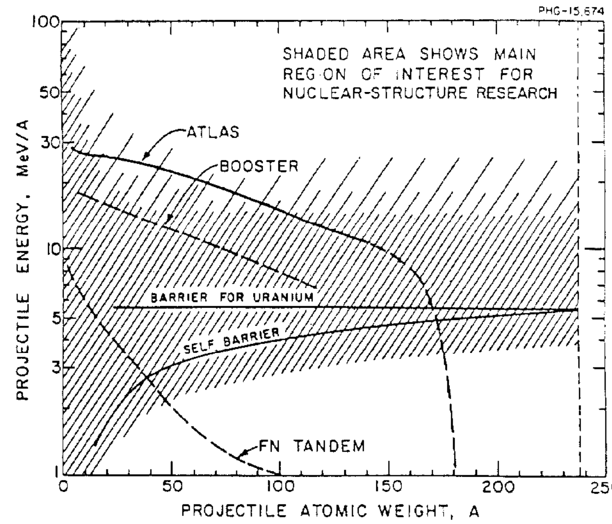

Fig. 5. Design goals for ATLAS.

achieved as various operational problems are solved. During initial operation, however, the beam energies are likely to be about 20% lower.

The practical mass range for ATLAS is likely to be determined by our FN-model tandem, which is not the ideal injector. In particular, the small size of the terminal makes it necessary to use foil strippers, and at the low voltages involved (∿ 9 MV), foil lifetime may limit most operation to A < 130.

Beam intensity is determined mainly by the characteristics of the ion source and the tandem, since the bunching system is very efficient and the linac transmits essentially 100% of the incident beam. In practice, the beam intensities out of the present linac are typically in the range 50 to 100 nA, about as much as most users need.

It is expected that the ATLAS linac will accelerate its beam without any important degradation of beam quality. The primary difference from the present situation is that the layout of the ATLAS experimental area will allow debunching and rebunching to be carried out much more effectively.

There are several features of the ATLAS system and its intended use that may be of general interest. The plan to form two independent beams has already been mentioned. Note that it is feasible, in principle, to vary the energies of these beams independently since, for the high-energy beam, the effect of a change in the parameters of the booster linac can be cancelled by the ATLAS linac.

Time-of-flight technology will be emphasized in the use of the ATLAS beam. Probably the most important aspect of this is the routine use of beam bunching and debunching. Under the good geometrical conditions that will be readily available, it seems realistic to expect to be able to provide beam pulses with widths in the range 50 to 100 ns or, if preferred, energy resolution widths of a few parts in 10^4.

Another application of time-of-flight is in the control and diagnosis of the linac and its beam. One such application is an accurate measurement of beam energy, as described by Pardo *et al.*[7] elsewhere in these Proceedings. Our requirements are that the measurement must be non-destructive, continuous, accurate to $\sim 2 \times 10^{-4}$, and usable with beams that are so weak that individual pulses cannot be detected. The solution is to measure the phase difference between two beam-excited resonators that are spaced $\sim$ 10 m apart. The resonators now in use are room-temperature helices, which provide signals with adequate strength for beams as weak as 1 nA. The main technical challenge was to obtain the required accuracy in the presence of the severe flickering of beam intensity which may be present if the linac is not operating well. This electronic problem has now been solved, and the energy-measurement system appears to satisfy all requirements.

Another interesting feature of the ATLAS system is the widespread use of superconductivity. All of the bunchers beyond the tandem (at least 5 units in the full ATLAS system) are our standard split-ring resonators. Superconducting solenoids are used to refocus the beam in the linac itself, and at least one solenoid is planned for use in the 40°-bend region. In the experimental area, it does not appear to be cost effective to use superconducting magnets for beam focussing or for small bends, but the two main switch magnets will be superconducting. These magnets are cyclotron-like devices consisting of split solenoidal coils encased in an iron yoke and magnetic shield, thus forming the broad field required to distribute the beam over a wide range of angles. The first of these magnets, now about to be tested,[8] is expected to have a maximum Bρ of about 2.8 tesla-meters.

The schedule for the construction of ATLAS is shown in Fig. 6. Throughout the development of the existing prototype linac, individual or small groups of resonators were put on line and used for research as soon as they were available. This approach was desirable at the time but it does involve a considerable extra effort and will not be used for the ATLAS addition. Rather, all new resonators will be fabricated, installed, tested on line, and finally used to accelerate a beam only when the system as a whole is functional. The first acceleration tests are planned for early 1985.

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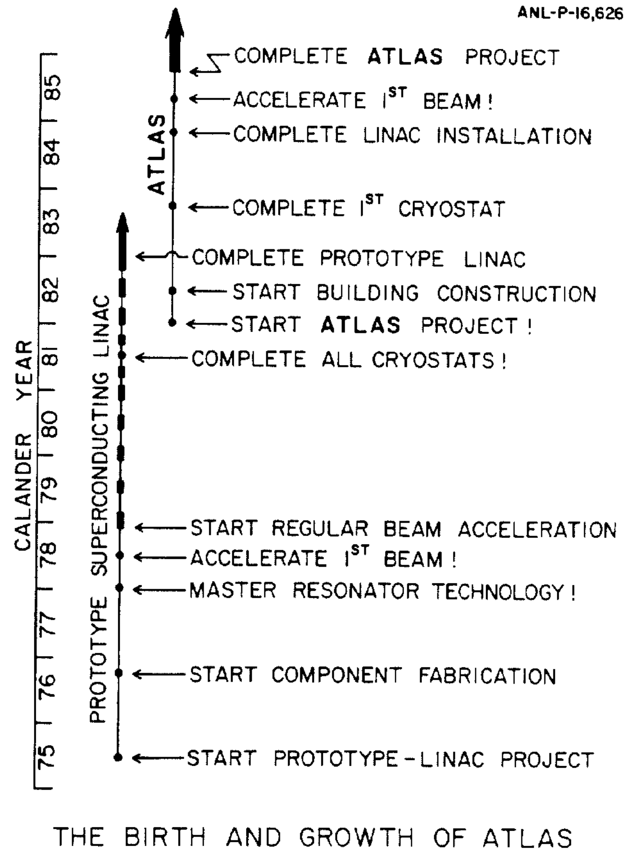

Fig. 6. Construction schedules for the Argonne superconducting linacs.

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