CONCEPT OF A SUPERCONDUCTING LINAC FOR LOW-VELOCITY IONS*

L. M. Bollinger and K. W. Shepard
Argonne National Laboratory, Argonne, IL 60439 USA

Summary

A very low velocity superconducting heavy-ion linac is proposed which, at least for applications requiring modest beam current, seems to have substantial cost and performance advantages over existing low-velocity room-temperature structures. The proposed linac, together with a 350 kV positive ion source, would replace an FN tandem Van de Graaff accelerator as the injector of the Argonne superconducting heavy-ion linac.

Introduction

The heavy-ion accelerator ATLAS[1] is an evolving tandem-linac system being formed by enlarging the superconducting-linac part of an existing and operating tandem-linac accelerator. The tandem part of this system is a modified FN-model HVEC machine that uses a foil stripper in the 9-MV terminal, and the linac, which now has 24 resonators, will by 1985 consist of an array of 42 independently-phased superconducting niobium resonators of the split-ring type.

Now that ATLAS is nearing completion, we have been investigating how its capabilities could and should be enhanced. From the point of view of the users, ATLAS will have two important defects: (1) relatively weak beam currents and (2) an inability to accelerate ions in the upper half of the periodic table. Both of these deficiencies are caused by the tandem part of the system. After considering several possible ways to remove these limitations, we decided to focus on a concept in which a positive-ion source on an open-air voltage platform provides low-velocity ions to a linac that serves as an injector for the existing ATLAS linac.

Both room-temperature and superconducting linacs were seriously considered for this application. It was concluded that, for our needs, the optimum solution is a superconducting linac, which appears to be substantially less expensive and also to have better performance characteristics than the low-velocity room-temperature structures that have been built heretofore. However, because of the very low velocity of the ions involved, the proposed superconducting linac poses some new technical challenges.

Accelerator Concept

The general features of the positive-ion injection system chosen for ATLAS are shown by Fig. 1. The optimum ion source for our needs is, we believe, an electron cyclotron resonance (ECR) source, which will be mounted on an insulated platform at a positive potential of 350 kV. The highly charged ions from the source are accelerated to ground potential, magnetically analyzed, bunched, and fed into the proposed superconducting injector linac.

An extrapolation of published data[2,3] for ECR sources suggests that the heaviest ions can have good intensity for charge states as high as 16 to 20. In numerical examples throughout this paper we use the value q = 20, but it should be understood that the accelerator concept discussed here would not be invalid for a smaller value. We assume that the available beam currents will at most be a few tens of μA and hence that space charge or any form of beam loading will not be an important problem.

For the source system outlined above, an ion with q = 20 has a velocity β = 0.0079, which is a factor of 4 lower than can be accelerated with existing superconducting structures. Consequently, the difficult part of the injector linac is the front end, where the low velocity of the heaviest ions requires an accelerating structure with an exceptionally low frequency (for a superconducting device) and a careful choice of other parameters. This special low-velocity structure is used to boost the beam velocity to β = 0.03, after which further acceleration can be accomplished efficiently by means of the well-understood niobium split-ring technology. As shown in Fig. 1, we first use β = 0.04 resonators, and then we use the thoroughly proven β = 0.06 unit.[4]

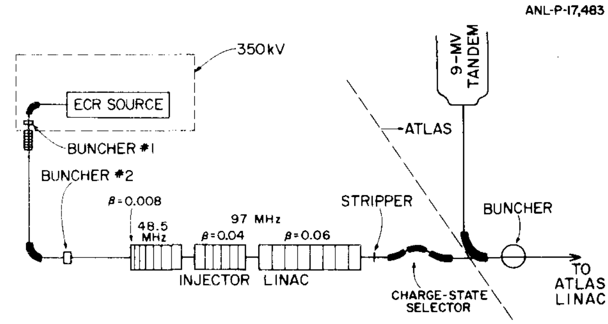

Figure 1. Schematic representation of the proposed heavy-ion injector for the ATLAS linac.

Returning to the front end of the linac, three primary questions must be answered: (1) how to overcome radial defocusing; (2) how to obtain a satisfactory accelerating field; and (3) how to preserve longitudinal beam quality? A solution of these problems is shown schematically in Fig. 2 and is discussed below.

Radial Defocusing

The most important feature of our concept is to use accelerating structures that are so short that the beam does not have a chance to grow much in size before it emerges from the structure and is refocused by a short, strongly-focusing superconducting solenoid.[5] This simple idea is reinforced by several effects that may not be evident. Transverse defocusing occurs because, under normal phase-focusing operation, the time-dependent converging forces experienced by an ion passing through the first half of an accelerating gap are weaker than the diverging forces experienced in the second half. For simplicity, let us assume that these forces are exerted at two effective locations Z_1 and Z_2 which are displaced by a distance ± d/2 from the mid-plane. Then, the change in angle brought about by the defocusing forces acting on an ion traversing a short gap is

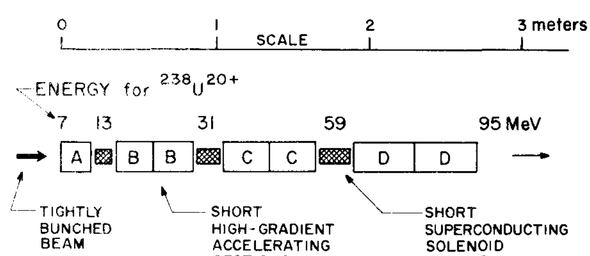

Figure 2. Elements of the very low-velocity superconducting linac. An accelerating gradient of 3 MV/m is assumed.

$$\Delta\theta \approx crqE_z d \left\{ \frac{\cos \phi_1}{U_1} - \frac{\cos \phi_2}{U_2} \right\} \qquad (1)$$

$$= cr\Delta U \left\{ \frac{\cos (\phi_s - \Delta\phi)}{U_o - \Delta U/2} - \frac{\cos (\phi_s + \Delta\phi)}{U_o + \Delta U/2} \right\} \qquad (2)$$

where c is a constant, E_z is the accelerating field in the gap, the subscripts 1 and 2 refer to Z_1 and Z_2, U is the beam energy, ΔU is the energy gain between Z_1 and Z_2, ϕ_s is the synchronous phase, and $\Delta\phi = 1/2(\phi_2 - \phi_1)$. Here the sign conventions are that a positive value of $\Delta\theta$ implies radial focusing and that ϕ_s is negative for phase-focusing operation.

First consider the influence of the factor $qE_z d$ in the numerator of Eq. (1). If one has a series of structures, of different lengths L but all providing the same energy gain, then the defocusing angle (more accurately, the resonator focal length) is the same for all structures. Consequently, the transverse admittance increases with decreasing length L. That is, the large energy gradient resulting from the large values of q provided by the ECR source and the large voltage gradient obtainable from superconducting structures are both significant assets.

Second, consider the denominator. Normally, in the treatment of defocusing, the influence of the energy change within an accelerating gap is ignored. However, because of the large value of qE_z in our concept, the change of energy within a gap may cause a substantial reduction in defocusing; indeed, it can even cause focusing under extreme conditions.

Finally, Eq. (2) shows that radial defocusing can be diminished by operating near the peak of the accelerating curve, i.e., with a small value of $|\phi_s|$. The extent to which this approach can be used depends on the time spread of the beam pulse and on the RF frequency. In a discussion that follows, we conclude that the $\phi_s = -15°$ is a satisfactory value from all points of view if the RF frequency is 48.5 MHz.

Examples of the influence of beam-energy change in a gap are shown in Fig. 3. Notice that, for the parameters chosen, the effect causes a worthwhile (but not dramatic) reduction in radial defocusing for the front end of the injector linac.

For the incident 7-MeV uranium beam, the emittance[2,3] is expected to be ~ 75 πmm-mrad. The transmission of this beam through a multigap accelerating structure formed by conventional drift tubes has been calculated, taking into account the effects listed above and assuming the following values of parameter: $\phi_s = -15°$, RF frequency f = 48.5 MHz,

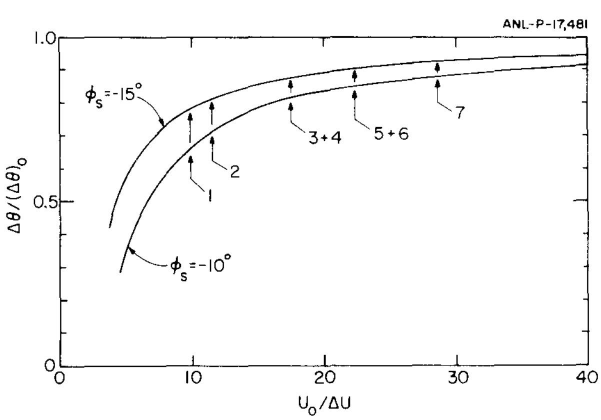

Figure 3. Effects of beam-energy change on radial defocusing angle $\Delta\theta$. Values of $U_o/\Delta U$ for the first seven accelerating resonators are indicated.

mean accelerating field E_a = 3.0 MV/m, drift tube aperture diameter d = 10 mm. It is found that the beam is fully transmitted through a structure 22 cm long. This result suggests that, for reliable operation, the diameter of the aperture should be > 15 mm and the length of the structure should be < 15 cm.

Effective Accelerating Field and RF Frequency

In the typical linac, the length ℓ of the drift tube is about 0.3 $\beta c/f$. Also, in order to obtain a reasonably large effective accelerating field, one needs $\ell/d \gtrsim 1$. As was shown in the preceeding paragraph, at the input end of the machine we should have d $\gtrsim$ 15 mm. Consequently, after imposing all of these conditions, we obtain f $\lesssim$ 48 MHz. This result leads us to choose a frequency of 48.5 MHz, half of the 97 MHz used for most of the ATLAS linac.

Details of resonator design are discussed below.

Longitudinal Beam Quality

It is desirable for the longitudinal beam quality of the injector linac to be as good as that from a tandem with a foil stripper in the terminal. For uranium ions, this means roughly $\Delta U \Delta t$ < 100 keV-ns. The limit on what is theoretically possible is $\Delta U_s \times T_b$, where ΔU_s is the energy spread of ions from the source and T_b is the bunching period. For an ECR source, we expect[2,3] $\Delta U_s \approx$ 10 eV, and T_b is typically 80 ns. Thus, $(\Delta U \Delta t)_{min} \approx$ 0.8 keV-ns, which is probably much smaller than is achievable for the output beam.

Three factors are likely to be of primary importance for output-beam quality: (1) the refinement of bunching, (2) non-linear effects during acceleration, and (3) the stability of accelerating voltages and resonator phases. This subject is too complex to be treated here, but we have considered the matter and it appears relatively easy to achieve the desired output-beam quality.

Low-Velocity Accelerating Structure

It was shown above that the front end of the injector linac requires an accelerating structure with f $\lesssim$ 48 MHz and a length L $\lesssim$ 15 cm along the beam direction. We choose to use f = 48.5 MHz, the first sub-harmonic of the fundamental ATLAS frequency 97 MHz, rather than a lower sub-harmonic, because of the cryogenic expense caused by a large structure and especially because of the need for mechanical stability.

For a given f and β, the length of the structure and also its voltage gain are determined by the number of acceleration gaps. Tentatively, we have concluded that a favorable design is a 4-gap structure formed by 3 drift tubes, with two of the drift tubes being driven by a coaxial quarter-wave niobium line, as shown schematically in Fig. 4. The first such unit of the linac (unit A of Fig. 2) would have an active length of about 10.5 cm, and the following units would be progressively longer.

Calculations of the transit-time factor of a 4-gap structure show that it can effectively accelerate projectiles whose incident energies vary by more than a factor of two. There are three major areas of concern about the 4-gap structure: (1) fabrication procedures, (2) mechanical stability, and (3) accelerating field. The good experience with single-drift-tube quarter-wave resonators indicates that no severe problems should be encountered in any of these areas.[6,7]

The 90-cm length of a 48.5 MHz quarter-wave line might make phase control difficult because of low-frequency mechanical vibrations. However, this potential problem can be controlled by making the diameter of the tapered line as large as it needs to be for adequate mechanical stability.

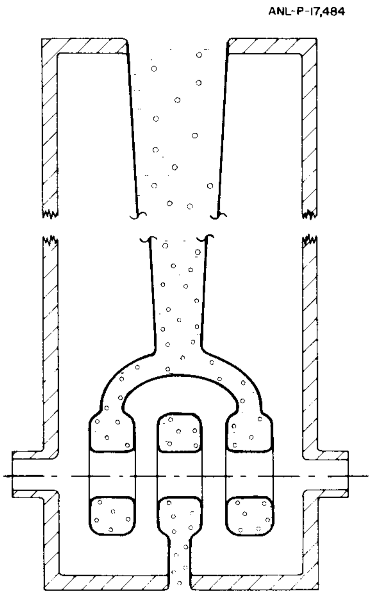

Figure 4. Cross-section of the proposed superconducting niobium resonator. The inductive center-post and forked drift-tube structure are hollow and cooled by boiling of liquid helium.

Experience with our present superconducting linac has shown that a surface electric field of 15 MV/m can be maintained reliably for a very long time (years). This value implies that an effective accelerating field of 3.0 MV/m is a conservative objective, and the extraordinary performance of some of our β = 0.06 structures[4] suggests that 3 MV/m may be unnecessarily conservative.

Injector Performance and Plans

The output energy of an injector linac depends on its size, of course. Figure 5 gives results for two possible machines, one about 8 m long with a total accelerating voltage of 10 MV, and a second about 17 m long with a total voltage of 24 MV. The immense capabilities of these relatively small systems are apparent. It is believed that the linacs can be built (including everything except prototype development and building space) at a cost of about $250,000 per MV.

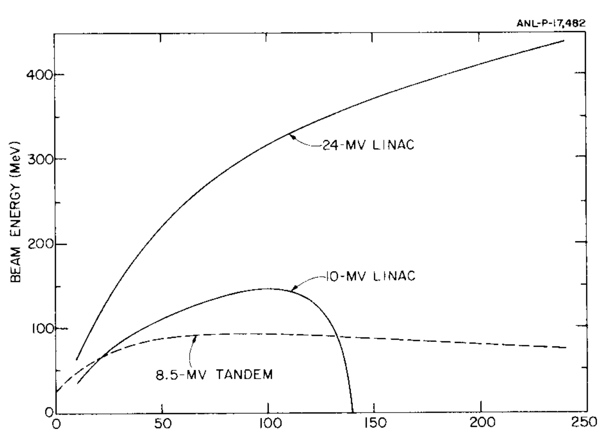

Figure 5. Output beam energy vs mass number for two different configurations of the low-velocity linac.

This relatively low cost, the large beam currents, and the probability that the beam quality can be excellent suggest that such a linac can be competitive with a tandem as a stand-alone machine.

Earlier we assumed that uranium ions from an ECR source have q = 20 with adequate intensity. If this assumption turns out to be overly optimistic and a lower charge state is more realistic, then it might be advantageous to replace the first 4-gap resonator by a simple 2-gap quarter-wave structure, which could more easily handle the lower velocity.

Implementation of the ideas summarized in this paper is expected to proceed in three stages. (1) The design and development of resonators for the front end have started, including the construction and testing of a 2-gap quarter-wave line made of niobium and operating at 140 MHz; the performance[7] is excellent. (2) Beginning in 1986, it is probable (but not certain) that funds will be available to extend the developmental activity to the construction of a prototype source-linac system with performance characteristics similar to the smaller machine in Fig. 5. Finally (3), when the main developmental questions have been settled, we will seek funding with which to expand the injector enough to allow it to accelerate all ions. The 24-MV injector of Fig. 5 would enable ATLAS to accelerate uranium ions to 10 MeV/A and lighter ions to substantially higher energy.

The authors are indebted to T. K. Khoe for helpful discussions of several aspects of this investigation.

Footnotes and References

* This research was supported by the U. S. Dept. of Energy under Contract W-31-109-Eng-38.

1. L. M. Bollinger, IEEE Trans. Nucl. Sci. NS-30, 2065 (1983).
2. J. Avianer and Richard Geller, Ann. Rev. Nucl. Part. Sci. 1981.31, pp 35-46 (1981).
3. Y. Jongen and G. Ryckewaert, IEEE Trans. Nucl. Sci. NS-30, 2685 (1983).
4. K. W. Shepard, IEEE Trans. Nucl. Sci. NS-28, 3249 (1981).
5. A. H. Jaffey, R. Benaroya and T. K. Khoe, Proc. of the 1976 Proton Linear Accelerator Conf., AECL-5677, 102 (1976).
6. J. M. Brennan and Ilan Ben-Zvi (to be published).
7. K. W. Shepard, S. Takeuchi and G. P. Zinkann, Proc. of the 1984 Applied Superconductivity Conference (to be published).