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SUPERCONDUCTING LINACS - SOME RECENT DEVELOPMENTS*

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Lowell M. Bollinger

Argonne National Laboratory

Argonne, IL 60439

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Abstract

The paper is a review of superconducting linacs that are of interest for heavy-ion acceleration. Most of the paper is concerned with energy boosters for projectiles from tandem electrostatic accelerators, the only application for which superconducting linacs are now used for heavy-ion acceleration. There is also a brief discussion of the concept of a superconducting injector linac being developed as a replacement of the tandem in a multi-stage acceleration system. Throughout, the emphasis is on the technology of the superconducting linac, including some attention to the relationships between resonator design parameters and accelerator performance characteristics.

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J.S.W.

I. Introduction

This paper is concerned only with superconducting linacs for heavy-ion acceleration because of the relationship of such linacs to electrostatic accelerators. Throughout the paper, the emphasis is on recent advances in the technology, with no effort to give a balanced history of the subject or a detailed description of each of the many accelerators now under construction.

It should be understood that the focus on heavy-ion acceleration means that a major part of the technology of RF superconductivity is being ignored, since the acceleration of electrons with superconducting RF structures is also a very lively subject. An immense amount of detail about all aspects of the technology may be found in the proceedings of a recent workshop [1].

II. Some General Features of Tandem-Linac Systems

Since the only established application of the superconducting heavy-ion linac is as an energy booster in a tandem-linac system, let us start by making sure that the operation of such an accelerator system is understood. A schematic of a tandem-linac system is given in Fig. 1. The tandem operates in its conventional mode, with a negative-ion source and a terminal stripper. If a high energy out of the linac is more important than a large beam current, a second stripper is used at the output of the tandem.

The DC beam of the ion source must somehow be bunched into the narrow pulses required for acceleration in the linac. This is not an easy task, because the buncher must form pulses that are exceptionally narrow (typically, ~ 100 ps wide) and also should be very efficient ($\sim 70\%$) in order to conserve the relatively weak beams from the negative-ion source. These objectives can be achieved by means of a two-stage bunching system consisting of a room-temperature multiple-harmonic buncher at the front end of the tandem and a

high-power buncher (usually a superconducting accelerating structure) between the tandem and the linac. Because of instability in the ion transition time through the tandem, it is desirable to use some form of "phase detector" to control dynamically the RF phase of the pre-tandem buncher in such a way that the beam pulses arrive at the post-tandem buncher at the desired time.

All superconducting heavy-ion linacs now in use or under construction consist of relatively short independently-phased RF accelerating structures. This design feature, which was initially a major departure from the long multigap structures used in most room-temperature linacs, was chosen mainly on the basis of two considerations: (1) the ability to effectively accelerate ions with a wide range of velocity and charge-to-mass ratio and (2) the relative ease of fabrication of small units.

In addition to the RF accelerating structures, the active part of the linac consists of discrete focusing elements that are used to control the radial size of the ion beam. Both room-temperature quadrupoles and superconducting solenoids are used for this purpose.

Obviously, the tandem-linac system is considerably more complex than the tandem alone. What, then, is the justification for constructing such a system? Is it mainly the capability of achieving very high beam energies? This question is addressed in Fig. 2, where the design objectives of two tandem-linac systems are compared with several other kinds of accelerators. We find the following: tandem-linac systems based on small tandems are more than competitive with the largest stand-alone tandems, they are even competitive with the existing tandem-cyclotron system HHFIR, but they provide a much lower beam energy than a system of cyclotrons is expected to provide.

It is clear, then, that the tandem-linac system must be justified by something other than high beam energy. Two considerations are of primary

importance. First, the addition of a superconducting-linac energy booster is a relatively easy and inexpensive way to extend the capabilities of an existing tandem facility. Second, if properly designed, the tandem-linac system can preserve the excellent beam characteristics of the tandem, characteristics that are important for much of nuclear-physics research. In particular, one can preserve the easy energy variability and, with more effort, the excellent beam quality of the tandem. It seems to me that most designers of energy boosters have not paid enough attention to beam quality.

Perhaps one general characteristic of the linac should be mentioned before we proceed to more detailed matters. In order to preserve the area of the incident longitudinal (i.e., energy-time) phase space, the linac should be operated in a phase-focussing mode. This implies that, relative to what is customary for a tandem, the output beam has a large energy spread ΔE and a very small time spread Δt . However, if the product $\Delta E \Delta t$ of the incident beam is small and is preserved through the linac, then the energy spread of the output beam can be made very small by debunching. For various historical and practical reasons, the capability of manipulating the output phase ellipse has not yet been developed as far as it should be.

III. Existing and Planned Superconducting Linacs

In the design of a superconducting-linac energy booster, three primary choices must be made: the kind of superconductor, the RF frequency, and the type of accelerating structure. Once these choices are made, numerous other design and operating characteristics have already been established to a large degree: the helium refrigeration requirement depends mainly on the type of superconductor; the number of resonators required to provide the desired accelerating potential depends on all three independent variables; the

difficulty of achieving phase control depends on the RF frequency and the type of resonator; and the output beam quality depends on the RF frequency. Also, the cost depends in a complex way on all of the main independent variables and on many other factors as well.

Some of the design choices that have been made in practice are summarized in Table 1, which gives data for all existing or authorized superconducting-linac boosters [2-11]. Note that most of the resonators are either 3-gap (split-ring) or 2-gap (quarter-wave) structures. Also, most of the niobium resonators have RF frequencies near 100 MHz and the lead resonators have RF frequencies near 150 MHz. This difference results partly from historical factors and partly from the fact that the superior superconducting characteristics of niobium make it easier to design for the desired low frequency.

In the table, the size of each linac is specified by its total active length rather than in terms of an accelerating voltage, thus avoiding the considerable uncertainty as to what accelerating field will actually be achieved in the on-line resonators. At the present state of the technology, the total accelerating voltages may be estimated by multiplying the active lengths by 3.0 MV/m for niobium resonators (except for the helix) and 2.5 MV/m for lead resonators. The on-line performances of both kinds of resonators are expected to increase gradually with time, as various practical problems are solved.

Some insights about design issues may be obtained by a comparison of the Argonne and Stony Brook [3] boosters, the only two linacs for which there is considerable operating experience. As shown in Table 2, both systems use resonators that are optimum for $\beta \approx 0.06$ at the front end of the machine and resonators with $\beta \approx 0.10$ at the output end. However, because Argonne uses

niobium as the superconductor whereas Stony Brook uses lead, some characteristics of resonators in the two systems are quite different. In particular, the niobium resonators operate at a lower RF frequency, which is advantageous for the preservation of the incident longitudinal emittance $\Delta E \Delta t$. Also, the lower surface resistance of niobium results in a lower RF power dissipation, and its higher critical magnetic field permits design choices that tend to produce somewhat higher accelerating fields. On the other hand, the lead-plated resonator is easier and less expensive to fabricate, and the smaller size of the lead unit results in a lower stored energy, which makes it easier to achieve phase stability. Finally, the higher frequency and hence smaller size of the lead resonators implies that more units are needed to provide a given accelerating potential.

There does not seem to be any accepted convention for specifying the total accelerating potential of a booster linac in terms of a single number -- indeed, no such number can tell the whole story. In Table 2, the effective accelerating potential V_L is given in terms of $\Delta E/q$, the maximum energy gain per charge for the optimum ion species and for an RF phase of 15° (a typical value). It should be recognized, of course, that ΔE is significantly less than qV_L for ions that are far from the optimum mass (typically, $A = 55$). For both the Argonne and the Stony Brook linacs, the actual accelerating voltages listed in the table are substantially less than the original design objectives. For the Argonne linac, this is because a number of factors prevent the resonators from performing as well on line over a long period of time as they do in off-line tests. For the Stony Brook linac, performance is limited at this time mainly by mechanical instability of the low- β resonators and by a shortage of refrigeration capacity. Both systems can undoubtedly be improved.

By now, extensive operational experience with superconducting resonators has provided answers to some design questions. In particular, it has been shown that the superconducting surfaces are very rugged and, if kept clean, can function effectively for years. However, the following important design questions still remain unanswered: (a) does the maximum accelerating field of a superconducting structure depend on the total voltage at the accelerating gap or only on the surface electric field, (b) to what degree does the output beam quality depend on having a low RF frequency, (c) does operational reliability and ease of maintenance depend strongly on the number of resonators in the system, and (d) is it important, for long-term operational reliability, to have redundancy in the cryogenic system? Some systematic, objective investigations of these questions are much needed.

We do not have time to discuss individually each of the ten systems listed in Table 1. However, it should be recognized that each of these is important for the advancement of the field because each must attack difficult design and operational problems under a unique set of local conditions. Some distinctive features of work now in progress are summarized in Table 3.

The largest of the superconducting linacs is ATLAS [5], which is expected to accelerate a beam for the first time in April 1985. As shown in Fig. 3, the linac consists of the original booster linac and the new ATLAS linac located at an angle of 40° relative to the booster. The new linac tunnel and Target Area III almost enclose the original Target Area II. This configuration has permitted research with the beam from the booster linac to continue with minimal interruption throughout the course of the ATLAS construction project.

The main technical challenge of the ATLAS project was the development of a resonator [12] appropriate for the higher velocities involved. Several

possibilities were considered, and it was concluded that the cost-effect choice was a split-ring resonator in which the housing is the same as for the $\beta = 0.105$ unit and the RF frequency is $3/2$ times the 97 MHz of the booster linac. Such a design gives maximum acceleration for ions that have $\beta = 3/2 \times 0.105 \approx 0.16$, a larger value than has been used heretofore. The higher RF frequency is achieved simply by shortening the loading arm of the original $\beta = 0.105$ unit. Many of the $\beta = 0.16$ units have now been made and tested, and it is found that their maximum accelerating field is essentially the same as that of the $\beta = 0.105$ unit.

All three classes of resonators used in ATLAS are pictured in Fig. 4. In the whole ATLAS system, there are 11 units with $\beta = 0.06$, 22 units with $\beta = 0.105$, and 9 units with $\beta = 0.16$. The $3/2$ relationship between the RF frequency in the two parts of the linac means that the maximum beam-pulse rate is half of 97 MHz rather than 97 MHz. None of the users of the facility objected to this limitation.

One of the performance problems of the tandem-booster system at Argonne has been that rebunching is not as effective as is desired. This results partly from the geometrical layout of the present system, where the distance from the linac to the debuncher is about half as great as the distance from the debuncher to the target of the experimenter, an arrangement that magnifies the pulse width. In order to reduce this problem, the new building for ATLAS provides a long (~ 17 m) drift space between the linac and the rebuncher. This will allow the two drift paths to be about equal, thus providing a magnification of unity. What is needed is a separate rebuncher at the optimum location on each beam line, but this is too expensive.

A view of the new ATLAS linac when the installation was nearing completion is shown in Fig. 5. The projected performance is shown in Fig. 6,

where the maximum energy of ions with $A < 80$ is determined by resonator performance whereas the maximum mass is determined by other factors such as the lifetime of terminal stripping foils.

Another large energy booster that has important features is the one under construction at the University of Washington [9]. This is the only tandem-linac system that is specifically designed to accelerate both the lightest ions and heavy ions, which implies a wide range of velocity. Consequently, a 2-gap structure, the straight quarter-wave resonator, was chosen. Fig. 7 shows the design of the two types of units that are being developed for this application [13]. In both, the superconductor is lead on a copper base, and the frequency is 150 MHz. A prototype unit of the $\beta = 0.10$ type has been tested at accelerating fields above 3 MV/m for a power dissipation of 3 W, which meets design specifications; consequently, the construction of many of these $\beta = 0.10$ units has started. The prototype $\beta = 0.20$ unit has not yet performed satisfactorily, probably because of a defect in a weld.

The planned layout of the linac at the University of Washington is shown in Fig. 8. As can be seen, the relationship between the existing tandem and the target room and also the small size of the linac area require the beam to undergo many bends. These bends must be accurately isochronous, since very good beam quality for protons is a primary goal of the project. It will be interesting to see how well this goal is achieved.

The projected performance of the University of Washington system is shown in Fig. 9. Here the unusual feature is the high energy for protons, deuterons, tritons, and alpha particles.

IV. Some Technological Advances

In addition to the things that have already been mentioned in connection with various linac projects, a number of technical developments are of general interest for superconducting-linac technology. Those developments that seem most significant to me are described very briefly below.

Helium Refrigeration. A wider range of refrigerators is now available commercially, including units that are designed for operation without liquid nitrogen precooling. Recently, wet expanders that substantially increase the refrigeration capacity have become commercially available. An expander of this type will be added to the existing refrigerator at Stony Brook [3].

Helium Distribution. As a result of the excessive heat losses that have been experienced at some laboratories with removable liquid-helium transfer lines, at Florida State, University of Washington, and Kansas State field-assembled joints will be used to transfer liquid helium from the main distribution system into the beam-line cryostats [14].

Beam Diagnostics. Two items need to be mentioned. First, a non-destructive time-of-flight energy-measurement system at Argonne is now working well [15]. In this system, two room-temperature resonators on the output beam line are excited by the beam. The phase difference is a function of ion time-of-flight and therefore ion energy. If the resonant detectors are 10 meters apart, the energy can be measured with an accuracy of a few parts per 10^4 .

A second new diagnostic tool is a high-resolution magnetic analyzer at Stony Brook that has been instrumented for the study of longitudinal phase space [16]. The magnet selects a narrow band of energy for which the time spectrum is measured. By sweeping the magnet current, the whole energy-time phase ellipse can be defined in about 5 minutes. It is hoped that this system will permit an apparent degradation in longitudinal phase space to be

understood.

Beam Separation. As part of the ATLAS project, a beam-separation system has been planned and partially installed [17]. If a stripper is located immediately in front of the boost linac, then several charge states can be accelerated simultaneously through the booster to approximately the same energy. At the linac output, these several beams are first bent through about 24° by a magnet, causing the beams corresponding to adjacent charge states to separate by about 2 cm. Two of the charge states are then selected for independent use by bending one of them an additional 15° with a second magnet and by allowing a second beam to go straight ahead through a field-free region produced by a "super-tube".

Resonator Development. Several important developments are in progress in addition to those mentioned earlier. A straight quarter-wave resonator made of niobium has now been built and tested at Argonne. It operates at a frequency of 140 MHz and has a β of 0.14. The excellent performance is shown in the upper curve of Fig. 10. The accelerating field easily goes to 4.7 MV/m, where it collapses because of a defect in the housing; presumably the field could be extended further by eliminating this defect. The relationship between the performance of niobium and lead [16] superconducting surfaces in resonators of similar design is well shown in Fig. 10.

Much effort has been expended during the past year in an effort to improve the superconducting characteristics of lead plated on copper. Good progress [8,18] has been made in this respect on the resonators for the new booster at Oxford [8]. The technique being used gives a thin ($1\ \mu$) smooth surface of lead that does not need to be chemically polished and that causes the Cal Tech type of split-ring resonators to have a low-field Q of 3×10^8 , a value that is about three times higher than has been obtained elsewhere for

the same type of resonator.

What may result in a significant improvement over lead is an effort at Stony Brook to develop a technique for plating a lead-tin mixture [16]. It has been found that a thin shiny surface can be laid down with relative ease and chemical polishing is unnecessary. In preliminary measurements, it has been found that a lead-tin surface on a quarter-wave resonator gives a low-field Q that is substantially greater than the Q for a similar resonator plated with pure lead, as shown in Fig. 11.

A new class of resonator [19], a so-called half-wave unit, is being developed at Cal Tech. This 3-gap structure is formed by two straight quarter-wave lines in the same housing. That is, it is like a split ring with straight loading arms. The lead-plated prototype of the new structure is ready for testing.

V. Positive-Ion Injector

Everything discussed up to this point has been concerned with the technology of superconducting linacs that are energy boosters for ion beams from tandems. As a result, all of the resonators are designed for ions with relatively high velocities (say, $\beta > 0.03$) and, although the subject has not been discussed here, at these velocities it is relatively easy to achieve good beam quality in both longitudinal and transverse phase space. That is, the tandem plays the important role of accelerating the ion through the low-velocity range that is most difficult for a linac. Consequently, the tandem-linac combination has been a very natural and rewarding system on which to develop the technology of the superconducting linac.

Looking into the future, however, one sees that the tandem has at least two serious technical drawbacks: (1) the beam currents are small and (2) it

is relatively difficult to accelerate ions in the upper part of the periodic table. Also, if one must start from the beginning, large tandems are very expensive per MV of acceleration. But is there a better way to take a heavy-ion beam through the difficult low-velocity range and end up with good beam quality? After considering several possibilities, we at Argonne have concluded that there is. It is simply to push the superconducting-linac approach down to the extremely low velocities that are involved when the input ions come from a positive-ion source on an open-air voltage platform.

Our concept [20] for a positive-ion injector to replace the tandem is summarized by Fig. 12. The source is an electron cyclotron resonance (ECR) source on a 350-kV voltage platform. Such a source produces micro-amp beams of highly charged ions for most nuclear species that have reasonable abundance. For the heaviest ions such as ^{238}U , the charge state is expected to be 20 or greater. Thus, an injector linac that is designed to accelerate all ion species must be able to accept 7-MeV uranium ions, which corresponds to $\beta \approx 0.008$.

Before entering the linac, the beam from the source is analyzed and bunched. The injector linac consists, in effect, of two distinct parts. The difficult front-end part covering the low-velocity range from $\beta = 0.008$ to say $\beta = 0.03$, and the remainder.

The problems and questions associated with the low-velocity end of the injector linac are, qualitatively, the same as those for a booster linac, but for the injector these problems are an order of magnitude more serious. At the extremely low velocities involved, how does one achieve phase control, good transverse and longitudinal beam quality, and adequate accelerating fields? There are clear-cut answers to these questions, as discussed previously [20]. One of the first questions to be answered is how to control

the radial defocussing generated by the acceleration process, an effect that can be very strong for slow-moving ions. As is shown in Fig. 13, this will be achieved by using very short accelerating structures followed by strongly focusing solenoid lenses, an arrangement that allows the beam to be transmitted through the accelerating section before it can spread out very much. Good longitudinal beam quality requires very narrow beam pulses and a low RF frequency. Both transverse and longitudinal beam quality require a small beam radius, that is, a source with a good emittance.

The superconducting resonator [21] planned for this application is a 4-gap structure formed by three drift tubes and the end plates, as shown in Fig. 14. The central drift tube is grounded and the outer pair is driven by a straight quarter-wave line that is sized to operate at 48.5 MHz. The diameter of this very long (for a superconductor) tapered line is made large enough to provide good mechanical stability. Note that the purpose of having four gaps rather than the more customary two gaps for a quarter-wave resonator is merely to increase the length of the active region.

A prototype of the first accelerating structure for an injector linac is now well along toward completion. The quarter-wave line is a hollow niobium tube, and the attached drift-tube assembly is made of solid high-thermal-conductivity niobium. The outer housing is niobium explosively bonded to copper. This cylindrical tube is deformed in the neighborhood of the drift tubes to form the 4-inch long active region of the accelerating structure.

Tests on copper models have already shown that the 48.5 MHz resonator will be stable enough mechanically to allow the phase to be easily controlled. Tests on the niobium prototype will be carried out in the summer of 1985.

One of the key questions about the concept of a positive-ion linac injector is whether its beam quality can be good enough. To answer this

question, detailed ray-tracing calculations that take into account all known phenomena in the injector linac are being carried out [21]. Although this study has not yet been completed, the results obtained to date are very encouraging. In particular, the measured emittance of an ECR heavy-ion source is good enough to permit the transverse beam quality of the linac to be about the same as for a tandem with a foil stripper in the terminal. Surprisingly, it appears that the longitudinal beam quality of the injector linac can be better than that of a tandem with a foil stripper, largely because the linac does not have to contend with the energy straggling associated with terminal stripping.

The size and layout of an injector linac depends, of course, on what it is required to do. Even for the heaviest ions, the difficult front-end section need provide only about 5 MW of acceleration; thereafter, a straightforward application of well-developed technology is satisfactory. The near-term goal at Argonne is to build an injector linac about 5 m long that provides about 7 or 8 MV of acceleration for injection into ATLAS. When linked to an ECR source, the beam energy of this small linac will be competitive with the existing FN tandem for a wide range of ions with $A > 130$, and the beam current will be at least an order of magnitude greater. A much larger machine would be required to accelerate uranium to a useful energy.

VI. Future Prospects

As a prelude to a brief look into the future, it is worthwhile to recall that the application of RF superconductivity to heavy-ion acceleration is only about a decade old. In view of all the advances in technology during that brief time and the rapid pace of change now, it seems safe to assert that superconducting linac technology will continue to be an active subject for at

least another decade. This is especially true since, for lack of time, I have had to ignore a major component of the subject, the applications to electron acceleration and the advances in technology that these applications have stimulated [1].

The design and fabrication of resonators is likely to continue to be the area of most interest in the technology of heavy-ion acceleration, with multigap structures tending to play an increasingly important role for the low-velocity range and two-gap structures being dominant for the highest velocities.

In this paper, considerable attention has been devoted to the relationship between niobium and lead as superconductors, and some of you may have gotten the impression that one of these materials will ultimately be proven best and the other abandoned. This is not my view. Rather, it seems likely that a greater variety of superconductors will become available and will be used, depending on the nature of the application. These superconductors will include niobium metal, niobium coated on a copper substrate, a niobium-tin alloy, plated lead, a plated lead-tin mixture, and perhaps others.

The number of tandem-linac projects probably will not increase as rapidly in the future as in the recent past, not because the technology is stagnating, but rather because the scientific community will conclude that there are already enough such systems. On the other hand, the existing tandem-linac systems will be steadily improved, and some will be enlarged.

For the same reason, even if the Argonne positive-ion injector turns out to be very successful, only a limited number of such injectors will be built. It is not yet clear to what extent superconducting linacs can be useful as injectors in applications that involve very large beam currents, e.g., applications such as injection into storage rings.

It could well be that the main application of RF superconductivity to heavy-ion acceleration during the next decade or two will be for the construction of small stand-alone linacs. Perhaps a few such machines will be built as the equivalent of the tandem, general-purpose machines for research. But it is more likely that they will be designed for specific applications in areas such as atomic physics and especially materials science. If ion implantation advances to the point where beams of ions with mass greater than about 40 and energy greater than about 50 MeV are needed, then the superconducting linac may be the technology of choice.

References

- [1] Proceedings of the Second Workshop on RF Superconductivity, Geneva, Switzerland, July 23-27, 1984, ed. H. Lengeler, CERN, November 1984.
- [2] J. Aron, R. Benaroya, L.M. Bollinger, B.E. Clifft, K.W. Johnson, J.M. Nixon, P. Markovich, R.C. Pardo, and K.W. Shepard, IEEE Trans. Nucl. Sci. NS-28 (1981) 3458.
- [3] J.M. Brennan, R. Coughlin, J. Hasstedt, J.W. Noe, P. Paul, R. Pillay, A. Scholldorf, J. Sikora, G.D. Sprouse, in Proc. of the 1985 Particle Accelerator Conference, May 13-16, 1985, Vancouver, British Columbia, to be published (1985).
- [4] I Ben-Zvi, B.V. Elkonin, J.S. Sokolowski, I. Tserruya, in these Proceedings (1985).
- [5] J. Aron, R. Benaroya, J.M. Bogaty, L.M. Bollinger, B.E. Clifft, P.K. DenHartog, K.W. Johnson, P. Markovich, J.M. Nixon, R. Pardo, K.W. Shepard, M. Waterson, G. Zinkann, in Proc. of the 1985 Particle Accelerator Conference, May 13-16, 1985, Vancouver, British Columbia, to be published (1985).
- [6] J.P. Fouan, private communication (1985).
- [7] J. Fox, private communication (1985).
- [8] D.McK. Hyder, private communication (1985).
- [9] D.W. Storm, J.G. Cramer, W.G. Weitkamp, H.E. Swanson, D.I. Will, J.G. Amsbaugh, T.A. Trainor, in Proc. of the 1985 Particle Accelerator Conference, May 13-16, 1985, Vancouver, British Columbia, to be published (1985).
- [10] D.C. Weissner and T.R. Opel, in these Proceedings (1985).
- [11] P. Richard and T. Gray, private communication (1985).

- [12] K.W. Shepard, S. Takeuchi, and G.P. Zinkann, IEEE Trans. MAG-21 (1985) 146.
- [13] D.W. Storm, J.M. Brennan, I. Ben-Zvi, in Proc. of the 1985 Particle Accelerator Conference, May 13-16, 1985, Vancouver, British Columbia, to be published (1985).
- [14] D.W. Storm, private communication (1985).
- [15] R.C. Pardo, R.N. Lewis, K.W. Johnson, and B.E. Clifft, IEEE Trans. Nucl. Sci. NS-30 (1983) 2237.
- [16] J.M. Brennon, private communication (1985).
- [17] R.C. Pardo, in Proc. of the 1984 Linear Accelerator Conference, Seeheim, Fed. Rep. of Germany, May 7-11, 1984, Report GSI-84-11, Conference, September 1984, p. 433.
- [18] J.R. Delayan, private communication (1985).
- [19] J.R. Delayan and J.E. Mercereau, in Proc. of the 1985 Particle Accelerator Conference, May 13-16, 1985, Vancouver, British Columbia, to be published (1985).
- [20] L.M. Bollinger and K.W. Shepard, in Proc. of the 1984 Linear Accelerator Conference, Seeheim, Fed. Rep. of Germany, May 7-11, 1984, Report GSI-84-11, Conference, September 1984, p. 217.
- [21] K.W. Shepard, in Proc. of the 1985 Particle Accelerator Conference, May 13-16, 1985, Vancouver, British Columbia, to be published (1985).

Table 1

Characteristics of superconducting-linac energy boosters in tandem-linac systems.

<u>System</u>	<u>Superconductor</u>	<u>Resonator Type</u>	<u>f_{RF} (MHz)</u>	<u>Active Length (m)</u>	<u>No. of Resonators</u>	<u>Ref.</u>
<u>Operating:</u>						
ANL Prototype Booster	Nb	split ring	97	6.5	24	[2]
SUNY Stony Brook	Pb	split ring	150	6.7	40	[3]
Weizmann Institute	Pb	quarter wave	162	0.7	4	[4]
<u>Construction:</u>						
ANL ATLAS	Nb	split ring	97	12.9	42	[5]
Saclay	Nb	helix	135	12.5	50	[6]
Florida State	Nb	split ring	97	4.5	13	[7]
Oxford	Pb	split ring	150	2.1	9	[8]
U. of Washington	Pb	quarter wave	150	8.6	(36)	[9]
<u>Development:</u>						
Canberra	Pb	quarter wave	150	0.8	4	[10]
Kansas State	Nb	split ring	97	(3.5)	(16)	[11]

Table 2

Comparison of superconducting linacs at Argonne and Stony Brook

	Argonne <u>(Booster)</u>	<u>Stony Brook</u>
Superconductor	Nb	Pb
RF Frequency (MHz)	97	150
Resonator Type	Split Ring	Split Ring
Stored Energy (J)*	2.7	0.42
No. of Resonators	24	40
Max. $\Delta E/q$ (MV)	19	12
β_1	0.06	0.055
β_2	0.105	0.10
Beam Time (hr)	26,000	3,800

*The values of stored energy are for full-power operation

Table 3

Some distinctive features in superconducting linacs

<u>System</u>	<u>Distinctive Features</u>	<u>Ref.</u>
ATLAS	Largest of the superconducting linacs	[5]
	RF frequency change within linac	[5]
	Dual-beam capability	[17]
Weizmann Inst.	First use of quarter-wave structure	[4]
Stony Brook	Operating experience with Pb	[3]
	Plan for partial change to quarter-wave structures	[3]
U. of Washington	Acceleration of both protons and heavy ions	[9]
	Very hi- β structure ($\beta = 0.20$)	[13]
Kansas State U.	Intended primarily for deceleration	[11]

Figure Captions

- Fig. 1. Schematic of the main components of a tandem-linac heavy-ion accelerator system.
- Fig. 2. Comparison of performance of several different kinds of heavy-ion accelerators. The label MSU refers to the superconducting cyclotron at Michigan State University, and HHIR refers to the tandem-cyclotron system at ORNL.
- Fig. 3. Layout of ATLAS, the Argonne Tandem-linac Accelerator System [5].
- Fig. 4. The three classes of niobium resonators in ATLAS. From left to right, the resonators have b 's of 0.105, 0.16, and 0.06 and operate at frequencies of 97, 145.5, and 97 MHz, respectively [5].
- Fig. 5. Upstream view of the ATLAS linac addition. The helium-distribution system is on the left-hand side of the machine.
- Fig. 6. Energy-mass performance of the ATLAS system [5].
- Fig. 7. Lead plated resonators for the University of Washington linac [13].
- Fig. 8. Layout of the University of Washington linac [9].
- Fig. 9. Performance of the University of Washington linac for two sets of assumptions about its resonators [9].

Fig. 10. Comparison of performance of quarter-wave resonators with niobium [12] and lead superconductors [16].

Fig. 11. Comparison of performance of quarter-wave resonators plated with lead and with a lead-tin alloy [16]. For two sets of data, the resonators had not been conditioned for high-field operation.

Fig. 12. Concept of the superconducting positive-ion injector system being developed at Argonne [20].

Fig. 13. Schematic representation of the front end of a superconducting injector linac [20] designed to accelerate $^{238}\text{U}^{20+}$.

Fig. 14. Design drawing of the $b = 0.009$ niobium resonator intended for use as the first accelerating structure of the ANL injector linac [21]. The overall length of the 48.5 MHz unit is about 1.0 m.

TANDEM-LINAC SYSTEM

KEY DESIGN FEATURES

1. BUNCHER
2. INDEPENDENT RESONATORS
3. RESONATOR PERFORMANCE

Figure 1

Figure 2

ATLAS

Figure 3

Figure 4

Figure 5

Figure 6

U. OF WASHINGTON

QUARTER WAVE RESONATORS

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

FRONT END OF POSITIVE-ION INJECTOR

Figure 13

Figure 14