PRESENT STATUS AND PROBABLE FUTURE CAPABILITIES OF HEAVY-ION LINEAR ACCELERATORS*

Lowell M. Bollinger
Argonne National Laboratory, Argonne, IL 60439 USA

Abstract

The general characteristics of heavy-ion linacs are summarized, with emphasis on the similarities and differences of systems based on different technologies. The main design considerations of superconducting linacs are outlined, the many projects based on this technology are listed, and a new concept for a superconducting injector linac is described. The role of RFQ structures for heavy-ion acceleration is summarized. A concluding section lists some probable applications of heavy-ion accelerators during the next decade.

1. Introduction

This paper gives a brief summary of the present and near-term future capabilities of heavy-ion linacs of the kind that are most closely related to this conference. That is, the paper is concerned with heavy-ion physics-research linacs and not at all with numerous applications such as inertial fusion and radiation sources. In effect, this limitation on the scope of the paper means that we ignore the central design problems associated with very intense beams. Instead, the emphasis here is on beam quality, overall flexibility, and cost.

Another limitation on the scope of the paper is that no effort is made to give a catalog of detailed information about existing heavy-ion linacs, since it is assumed that this audience is not interested in such details. Rather, the objective of the paper is to illuminate some of the primary design problems and how these influence the choice of machine parameters, with emphasis on some general features that are different from those of cyclotron-based systems.

2. Some General Features of Heavy-Ion Linacs

Much of the subject matter of this paper is defined by Fig. 1, which attempts to show schematically the numerous heavy-ion linac configurations that are in use or are planned. Of these systems, the UNILAC[1] at GSI contains the most features that are prototypic. The figure shows eight main components or functions of this system. (1) It starts with a source that produces multi-charged positive ions which are accelerated by means of (2) an electrostatic injector (350 kV) to a velocity of β = 0.006. These very slow moving ions are (3) bunched and then (4) injected into a special low-velocity accelerator section, which in the UNILAC is a Wideröe structure operating at a frequency of 27 MHz. By the time the velocity of the ion reaches β = 0.05, the energy is high enough to make it worthwhile to (5) strip the beam to a higher charge state, and the Wideröe structure is no longer optimum. Instead, (6) several Alvarez structures operating at 108 MHz are used to provide the main energy gain of the system. Since both the Wideröe and Alvarez sections are multi-gap structures that require a fixed velocity profile, they cannot provide energy variability. This is achieved by means of (7) an array of 17 independently-phased single-gap structures. Finally, (8) a rebuncher/debuncher accelerating structure is used to adjust the phase ellipse of the output beam to the requirements of the experimenter.

All of the accelerator systems shown in Fig. 1 fit approximately within the framework of components and functions outlined above for UNILAC. Let us illustrate this point by considering an accelerator that depends on an entirely different technology, the tandem-linac system ATLAS[4] at Argonne. Here the source provides a singly-charged negative ion that is first accelerated by a 300-KV electrostatic injector. Next the tandem takes the beam through the difficult low-velocity range, performing much the same function as the Wideröe section of the UNILAC. The linac part of ATLAS consists of an array of 42 independently-phased superconducting 3-gap resonators which form a system that is similar in its operation to the single-gap part of UNILAC but at the same time provides the main accelerating power of the machine. Thus, although the technologies involved in UNILAC and ATLAS are quite different, the basic ideas are similar and, indeed, the performance is also similar in many ways.

The energy-mass characteristics of beams from representative heavy-ion linacs are given by Fig. 2. In many respects, the room-temperature UNILAC sets the standard; its beam is notable for its large intensity over the full mass range but has the drawback of not being CW. The Heidelberg room-temperature linac[6] has demonstrated the value of small independently-phased resonators and is unique in its ability to operate in either a CW or pulsed mode; its 13-MV tandem injector is a considerable advantage relative to the 9-MV tandems used in other tandem-linac systems. The ATLAS system is nearing completion as an expansion of an operating prototype superconducting linac; the new system will provide relatively high energies for CW beams in the lower half of the periodic table but will not attempt to compete for the heaviest ions because of the limitations of its small tandem injector. The tandem-linac system at the University of Washington,[8] recently under construction, is notable because it is intended for the acceleration of both protons and heavy ions.

Before going on to further discussion of Fig. 1, let us make sure that a few basic characteristics of linacs are understood. First consider the velocity profile of the linac. In a conventional, long, multi-gap accelerating structure, the velocity profile is established entirely by the geometry of the structure, which changes continuously to make allowance for the increasing velocity of the ion as it progresses along the linac. Ions of all types must have the same velocity profile, which makes for inflexibility in at least two respects: (1) injection energies and charge-to-mass ratios q/A that are greater than the design values cannot be used to generate a higher output velocity; and, (2) all acceleration gaps must function accurately in the prescribed way, otherwise the beam will be lost. Both of these problems can be avoided by (a) using an accelerating structure with so few gaps that it can accelerate over a range of velocity and by (b) independently phasing each structure to match the beam. For an array of such resonators, individual units may fail altogether without seriously upsetting the overall performance of the system.

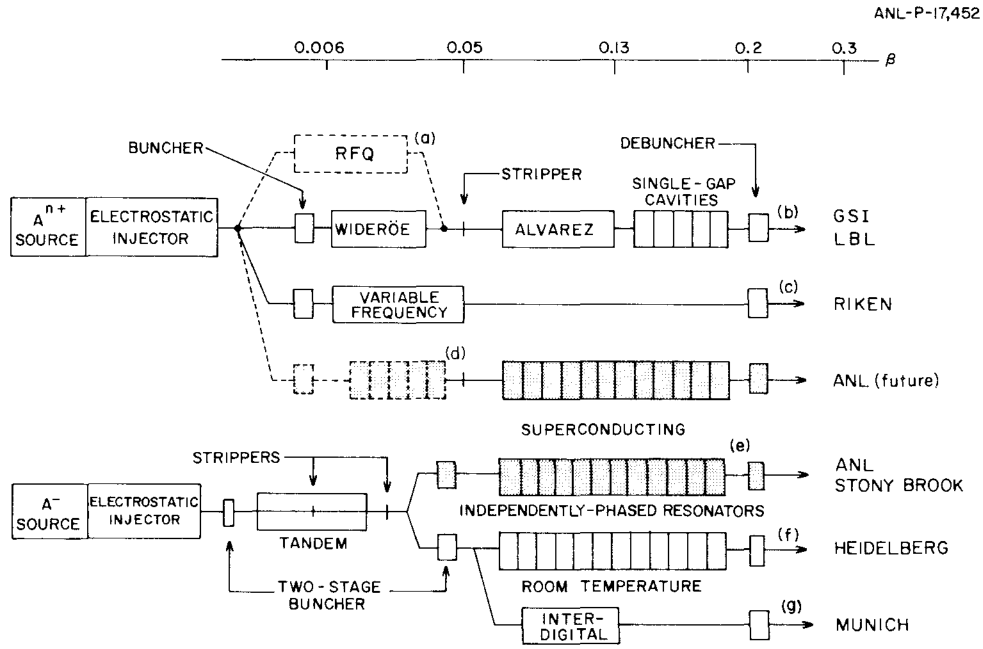

Figure 1. Configurations of heavy-ion linacs. Dashed lines mean possible future machines, and grey (dotted) components are superconducting. (a) A possible future RFQ injector. (b) UNILAC[1] and (partly) superHILAC[2]. (c) Variable-frequency linac[3] at the Riken Institute (Japan). (d) ATLAS[4] with future superconducting positive-ion injector.[10] (e) ATLAS and SUNYLAC[5] with superconducting independently-phased resonators; similar future systems are listed in Table I. (f) Heidelberg system[6] with room-temperature independently-phased resonators. (g) Munich system[7] with room-temperature interdigital booster linac.

Clearly, the extent of operational flexibility provided by independent phasing depends on the velocity range over which the structure can accelerate effectively, which in turn depends mainly on the number of gaps in the structure. Examples of the dependence of the transit-time factor (relative accelerating field) on velocity are given[9] in Fig. 3, which shows the considerable advantage of having a structure with very few gaps. However, this advantage in flexibility is counterbalanced by the fact that the total voltage gain of a resonator increases with increasing number of gaps, and consequently the optimum number of gaps depends on the application and may not be clear-cut. In practice, most independently-phased resonators used in tandem-linac systems have 2 or 3 gaps.

An important difference between the linac and the cyclotron is the fact that the linac is phase focusing. That is, the resonator phase is adjusted so that the ion bunch arrives at the accelerating gap before the voltage is at its peak value, and as a result the ions that arrive early experience less accelerating field than the ions that lag behind. Consequently, the beam is continually rebunched, which causes the energy-time phase ellipse to rotate, as shown in Fig. 4. The phase ellipse is said to be "matched" to the accelerating structure when the shape of the phase ellipse is not changed by the rotation. There are two important characteristics of matched beams: (1) the effective area of the phase ellipse is not changed by nonlinear terms in the accelerating field, and hence longitudinal beam quality is preserved, and (2) for most structures, a matched beam has a relatively large energy spread ΔE and a small time spread Δt. However, if the product $\Delta E \Delta t$ is small enough, the output beam can be debunched or rebunched in order to provide the desired energy resolution or time resolution, respectively, and these operations on the output beam should be regarded as an integral part of the acceleration process.

The subject of energy and time resolution involves too many details to be treated thoroughly in this paper. However, the essential points are that the product $\Delta E \Delta t$ is a measure of the output beam

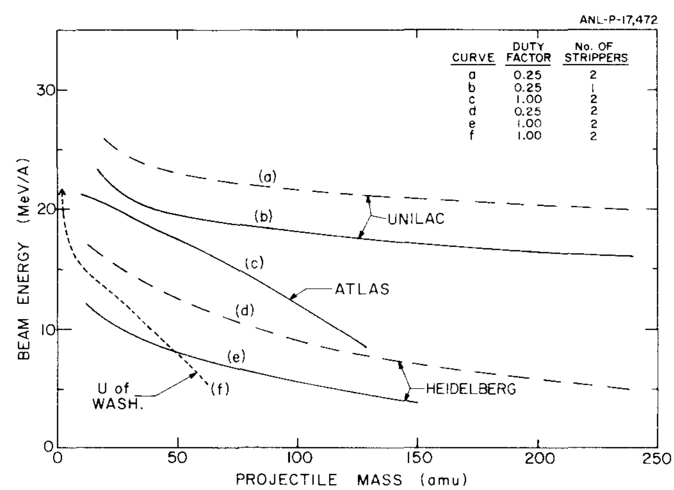

Figure 2. Maximum beam energies available from four representative heavy-ion linacs. The curve for ATLAS shows expected initial performance, about 25% lower than long term goal.[4] The design objective for the University of Washington machine[8] is 37 MeV for protons.

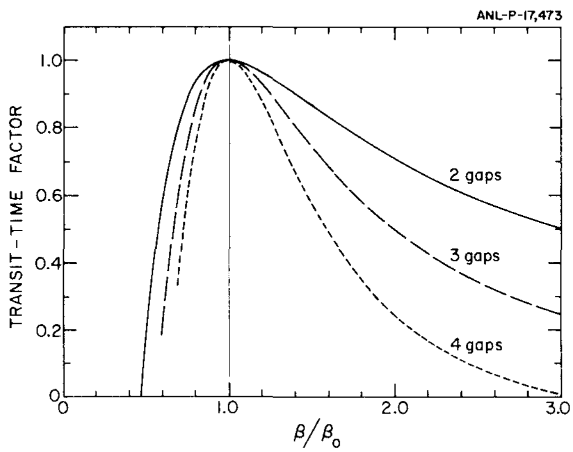

Figure 3. Curves of transit-time factor calculated[9] for realistic field profiles.

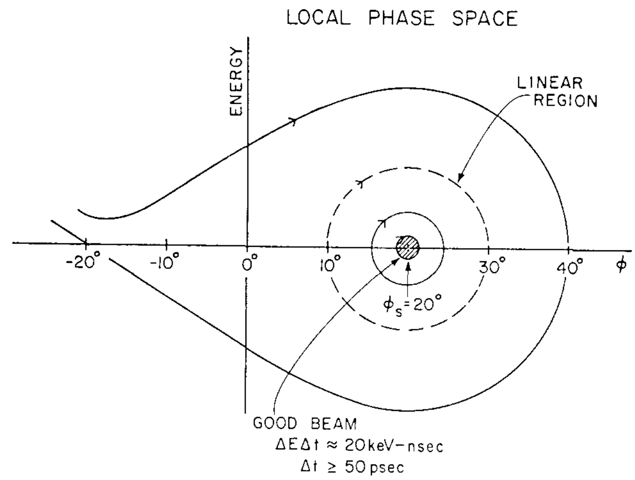

Figure 4. Idealized energy-time phase space for a matched beam.

quality and, for any given value of $\Delta E \Delta t$, debunching or rebunching can in principle be used to produce a small energy spread or a small time spread. In order to be able to carry out these operations effectively, there are two requirements: (1) the product $\Delta E \Delta t$ should be minimized and (2) the debuncher/rebuncher system should have enough accelerating power and have appropriate flight paths.

For most accelerators, the primary lower limit on the value of $\Delta E \Delta t$ is set by the characteristics of the low-velocity part of the accelerator. For example, in a tandem-linac system, this limit is set by the pulse width Δt and by energy straggling ΔE at the stripper in the tandem terminal. Typically, values of $\Delta E \Delta t$ range from 10 to 100 keV-ns, depending on the ion species involved and on the buncher and stripper characteristics.

Similarly, the transverse emittance ε of the output beam is usually established by what happens near the front of the machine. In the case of the tandem-linac system, a lower limit on ε is set by the beam size and by angular straggling in the tandem-terminal stripper. This value is quite small, being typically $\varepsilon = 20\pi$ mm mrad-MeV$^{-1/2}$.

A characteristic feature of the linac is that the acceleration process causes transverse defocusing when the synchronous phase is chosen to provide phase focusing. Thus, some form of transverse focusing must be provided throughout the linac. One implication of this need for focusing is that it requires space, and thus the average accelerating gradient is reduced, especially at the low-velocity end of the machine. This subject is treated in more detail later.

Several general features of Fig. 1 are of interest. First, notice that the range of projectile velocity covered by existing heavy-ion linacs is roughly $0.006 < \beta < 0.25$. At the high-velocity end there is no severe technological limit; rather, above some value of β the linac is no longer cost effective relative to a circular machine for a given application. At the low-velocity end, it is increasingly difficult to solve the linac-design problems, and at some point the linac is no longer competitive with the electrostatic accelerator. Consequently, unless some characteristic such as beam intensity is of overriding importance, the velocity range covered by heavy-ion linacs is not likely to expand much in the forseeable future.

Another point of general interest is the relationship between room-temperature and superconducting linacs. In fact, the nature of the conductor need not cause an essential difference in the operational performance of the linac, as is shown by the close similarities of the room-temperature linac at Heidelberg[6] and the superconducting linacs at Argonne[4] and Stony Brook,[5] all of which make use of short independently-phased accelerating structures. On the other hand, there are substantial differences between the superconducting linacs, all of which operate CW, and the room-temperature machines at GSI and LBL, which use long accelerating structures that can only be operated in a pulsed mode and that have a fixed velocity profile.

In the final analysis, the important comparisons are those having to do with costs for construction, for electric power, liquid nitrogen, and liquid helium, for operating manpower, and those associated with the level of technological difficulty. Unfortunately, there seems to be no one who has intimate experience with both room-temperature and superconductivity heavy-ion linacs, and therefore it is probably too early to expect to get a consensus of views on relative costs and technical difficulty. My own opinions are that, taking all factors into account, a superconducting linac is substantially less expensive to build and also somewhat (but not dramatically) less expensive to operate than a room-temperature machine with equivalent characteristics.

3. Superconducting Linacs

The efforts now being devoted to heavy-ion linac development and construction are concerned mainly with two technologies: (1) superconducting linacs for tandem-linac systems and (2) RFQ linacs serving as injectors of large machines. The first of these topics is summarized in this section and the second topic is mentioned again in Section 4.

All of the superconducting heavy-ion linacs now in operation or funded serve as energy boosters for beams from tandems. This limited use stems mainly from financial considerations and from the young state of the technology rather than from some inherent

TABLE I. Summary of status and characteristics of heavy-ion superconducting linac. In the column for resonator type, S.R. means split ring and QW means quarter wave.

Institution	Status	Tandem Voltage (MV)	Resonators: Super-conductor	Type	f (MHz)	β_o	Number	V_L (MV)	Ref.
Argonne	Routine Operation	8.5	Nb	S.R.	97	0.06	11	21	3
			"	"	"	0.105	13		
Argonne (ATLAS)	Construction	8.5	Nb	S.R.	97	0.06	11	40	9
			"	"	97	0.105	22		
			"	"	145.5	0.16	9		
Stony Brook	Operation	8.5	Pb	S.R.	150	0.055	16	20	4
			"	"	"	0.10	24		
Saclay	Construction	8.5	Nb	Helix	108				
Florida State	Construction	8.5	Nb	S.R.	97	0.105	12		10
Weizmann	Construction	12	Pb	QW	~ 170	0.09	4		11
Oxford	Construction	10	Pb	S.R.	150				12
Washington	Construction	8.5	Pb	QW	150	0.09	(16)		7
			"	"	"	(0.18)	(16)		
Canberra	Development	12	Pb	QW					
Kansas State	Planning	6.5	Nb	S.R.	97	0.06	(16)		12
Sao Paulo	Planning	8.0	Nb	S.R.	97				13
Tata Institute	Planning	12							

technological limitation. Also, all of the superconducting booster linacs make use of short independently-phased accelerating structures. This phenomenon results from two things: (1) the advantages of independent phasing and (2) the difficulty of making long superconducting accelerating structures.

Table I is an effort to summarize the status of the numerous superconducting-linac projects. Note that there are two machines in operation, six under construction, and at least four in the developmental or planning stages. Several features of the table require some explanation. All tandem injectors of a given type are assigned the same terminal voltage even though the operators may claim slightly different values. In any case, the exact terminal voltage usually has little impact on the linac-output energy. As used here, the linac voltage V_L is the sum of the effective voltages of individual resonators for synchronous projectiles, and hence the energy gain imparted to any particular projectile with charge q is somewhat smaller than qV_L. Unless there is considerable operating experience with resonators of the type involved, estimates of linac voltages are not given because there is still some uncertainty as to what the linac configuration and the resonator performance will turn out to be. However, all of these new systems are aiming at accelerator voltages in the range 10 to 25 MV, and all of them are intended primarily for projectiles in the lower half of the periodic table.

In designing a superconducting linac, three major choices must be made: what superconductor, what RF frequency, and what resonator type? The answers to these questions determine the number of units required to provide a given accelerating voltage, the phase stability of the resonators, the refrigeration load, the beam quality, and the cost. Clearly, a full discussion of the complex interactions between this array of design considerations is beyond the scope of this paper. However, several comments appear worthwhile. First, a low RF frequency is desirable because (1) the voltage gain per resonator increases with length and (2) a low frequency tends to improve beam quality by making bunching easier and beam matching less important. But the need to achieve phase control pushes the design toward high frequency. That is, low frequency is better but high frequency is easier. As is seen in the table, the compromise frequencies chosen for all types of resonators now in use are in the range of 97 to 175 MHz.

Second, as to the type of superconductor, there are now only two practical choices: niobium metal or lead plated on a copper backing. Niobium is by far the better superconductor, having a residual resistance that is lower by an order of magnitude and a critical magnetic field that is higher by an order of magnitude. These characteristics lead to a lower cryogenic heat load and a larger voltage gain for niobium resonators. On the other hand, niobium structures are harder to fabricate and somewhat more costly per resonator, although not necessarily per MV of acceleration.

Finally, the type of structure that is optimum depends on too many circumstances and requirements to be discussed in detail. However, of the several possible structures, two are most popular at this time: the 3-gap split-ring structure is favored because it is conveniently compact cryogenically and because it is long enough (along the beam direction) to provide a relatively large voltage gain; and the 2-gap quarter-wave resonator is favored because it is mechanically rigid and because it provides effective acceleration over a relatively large velocity range (see Fig. 3).

One sees from Table I that the resonator chosen for many of the new booster linacs is the quarter-wave structure with lead as the superconductor. There appear to be two dominant considerations in this choice: (1) the desire to minimize the difficulty of fabrication, and (2) the desire (on the part of the University of Washington, at least) to have a broad range of velocity acceptance so that both protons and heavy ions can be accelerated. The drawbacks of the choice are that the RF frequency is relatively high and a rather large number of resonators are required.

By now, the superconducting linac at Argonne (the precursor of ATLAS) has accelerated a beam for about 17,000 hours, and consequently the operating characteristics can be evaluated with confidence. Here we will mention only those properties that are characteristic of the linac technology. (1) The system is extremely rugged and can be operated usefully in spite of many kinds of equipment failure. (2) Operational reliability of the linac is high, with unscheduled maintenance time being about 5%. (3) Beam energy can be changed quickly (2 min.) by means of the control computer. (4) The value of the product $\Delta E \Delta t$ is about what is expected from the bunching and stripping process and is small enough to allow rather short beam pulses to be obtained; optimized tests have demonstrated the possibility of obtaining pulses as short as 50 ps, but the unfavorable geometrical arrangement of the rebunching system normally used limits the pulse width to the range 100 to 250 ps, depending on ion species. (5) The overall power usage for 21 MV of acceleration is about 300 kW.

It is interesting to note that only one of the above list of primary characteristics of a superconducting accelerator has anything to do with superconductivity. Rather, it is the use of short independently-phased resonators that dominates the behavior of the machine and has allowed it to operate so easily and well.

4. Some Recent Developments

It may seem strange that this paper has progressed this far with hardly a mention of the RFQ structure, since whole accelerator conferences are dominated by the subject. The excuse for this omission is that the subject matter of this paper has been limited to heavy-ion linacs designed for physics research, for which the RFQ does not yet have a proven major role, except as an injector.

The RFQ is a new kind of structure that simultaneously and continuously applies an accelerating field and an electric quadrupole focusing field.[15] Because of these properties and the fact that the accelerating field can be turned on gradually, the RFQ can accept an intense low-energy beam and continuously focus it, adiabatically bunch most of it, and accelerate it with good beam quality to velocities that are high enough to be injected into some more conventional accelerator.

In view of these remarkable characteristics, it is not surprising that dozens of RFQ linacs are being built, mainly to serve as injectors for light-ion machines. A fairly recent summary of all known applications has been given by Klein.[16] A good example of one of these is a pulsed heavy-ion injector for the Bevatron.[17] This 199-MHz injector accelerates $^{28}Si^{4+}$ from 8.4 to 200 keV/A over a distance of 2.25 m, thus having an average field gradient of about 0.7 MV/m. The device has a duty cycle of 0.2%, a high beam transmission (90%), and an excellent emittance (0.5π mm-mrad). In order to obtain these characteristics, the field-forming RF vanes were fabricated and located with exceptional precision. Overall, the new injector is said to be a considerable improvement over the Cockroft-Walton and piece of an Alvarez structure that it has replaced.

Undoubtedly, the RFQ fills many needs, especially for pulsed injectors or when extremely large beam currents are involved. However, if we restrict ourselves to the applications considered in this paper i.e., general-purpose heavy-ion linacs for nuclear-physics research - the RFQ seems to have the following significant limitations: (1) CW operation is proving to be difficult to achieve;[16] (2) the average accelerating gradient is very low; (3) long structures of the kind required for ions with small q/A have not yet been proven feasible; (4) the dimensional tolerances for long structures are extremely demanding; (5) the output beam quality is not as good as is desirable for some applications; and (6) it is likely that a structure with the precision and low RF frequency desired for slow-moving heavy ions would be quite expensive. In other words, the RFQ seems to be very attractive for some applications but not as a CW accelerator for ions with a small value of q/A.

What kind of linac should be used, then, for CW acceleration of heavy, slow-moving ions? Recently we at Argonne have become interested in the answer to this question because we want to replace the negative-ion source and the tandem injector of ATLAS with a positive-ion source and a linac injector. This major change is expected to allow two important improvements in performance: (1) the beam intensity can be increased by one or two orders of magnitude and (2) the mass range can be extended up to the heaviest ions.

The most challenging part of a positive-ion injector is the low-velocity end of the linac, where the ions will have $\beta = 0.008$, for which low velocity transverse defocusing is a major problem. In the past, the Wideröe structure has been used for this application, and an RFQ has to be considered as a possibility now. However, since each of these two approaches would be difficult and expensive for CW operation, we decided to consider seriously what could be achieved with a superconducting linac. The result of this examination is very encouraging; it appears that the technical problems have straightforward solutions and that the cost of the required superconducting linac can be less than half as much as a room-temperature linac with equivalent characteristics.

The main problem in designing a linac for very slow-moving particles is how to overcome the beam defocusing brought about by the acceleration process itself. This problem is solved in the Wideröe structure by building a magnetic quadrupole lens into each second drift tube, and it is solved in the RFQ structure by the RF electric quadrupole field that is generated by the electrodes that also form the RF accelerating field. After considering several

CH1996-3/84/0000-0508 $1.00 © 1984 IEEE

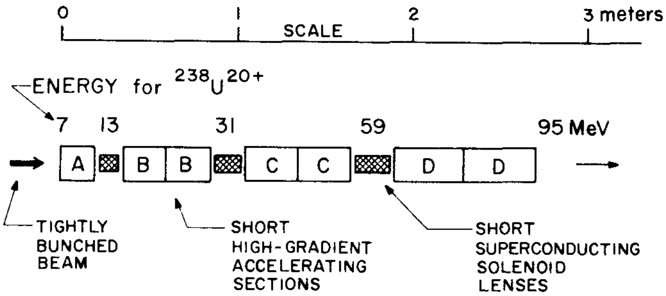

Figure 5. Schematic representation of the proposed superconducting injector linac[10] being studied at Argonne.

possible superconducting solutions, we concluded that the easiest and best approach is one in which the linac consists of short high-gradient independently-phased structures interspersed with short superconducting solenoids, as is shown in Fig. 5. That is, each accelerating structure is short enough that the beam emerges into a strong focusing lens before it has a chance to expand much. Because of their high gradients (~ 3 MV/m), even the very short accelerating structures at the front end of the linac rapidly increase the energy to the point where beam defocusing is no longer a serious problem. In other words, the proposed superconducting injector linac is conceptually the same as the present ANL linac, the only difference being that for the front end of the injector the problem of beam defocusing is the dominant consideration in the choice of machine parameters.

In order to be able to accelerate well the slow-moving ions from the source, the accelerating structure should operate at a substantially lower frequency than has been used previously for superconducting structures. For our needs, a frequency of 48.5 MHz appears optimum. The design we intend to develop is a 4-gap structure formed by three drift tubes and the resonator end plates, with two of the drift tubes being driven by a quarter-wave line. Because of the low RF frequency, this line is rather long (~ 100 cm) for a superconducting device, but the cryogenics should not be a problem, and mechanical stability of the quarter-wave line can be achieved by making its radial dimensions large enough. The resonator at the front end of the injector (the difficult end) will be only about 10 cm long in the beam direction, but this will provide about 300 kV of accelerating voltage, almost enough to double the beam energy and substantially reduce the defocusing forces.

The beam energies that ATLAS could provide if it had a positive-ion injector depend, of course, on the size of the injector. One possibility that is being considered is a 24-MV injector linac, which is about 16 m long. For the heaviest ions, this injector would enable ATLAS to provide relatively intense beams with excellent beam quality and easy energy variability up to energies of 10 MeV/A.

Since the proposed injector linac is intended as a replacement of a tandem, it is natural to ask whether this kind of linac could possibly be competitive with the tandem as a stand-along machine. The answer seems to be "yes". The linac is at least competitive with respect to cost, especially for big machines. With respect to performance, perhaps the three characteristics of a tandem that are most valued by its users are (1) easy energy variability, (2) good energy resolution, and (3) small emittance. Operating experience with our present machine has shown that a linac with independently-phased resonators has easy energy variability and can provide a beam with excellent emittance.

But what about energy resolution? This question is too complicated to be discussed here in detail. However, an examination of the acceleration process in the proposed injector linac indicates that it is realistic to expect to be able to achieve an energy resolution of $\Delta E/E = 10^{-4}$ for a debunched beam. This quality of performance would require an ion source with a small energy spread ($\Delta E \approx 10$ eV), a bunching system capable of matching the beam to the linac ($\Delta t \approx 0.3$ ns), an accelerating structure with very low frequency ($f \leq 50$ MHz), and very good stability (1 part in 10^4) for most accelerating voltages. We expect to be able to achieve all of these characteristics.

The only respect in which the linac is clearly inferior to the tandem is its inability to accelerate well over a very wide range of q/A. Thus, for all except the lightest ions, it appears that the superconducting linac could be a very attractive substitute for a stand-alone tandem, especially if the large intensity of the positive-ion source is needed.

5. Future Prospects

Let us conclude this paper by attempting to foresee what may become of heavy-ion linacs during the next decade. Such forecasting is likely to prove wrong, of course, but it is fun!

First, it seems probable that the UNILAC will turn out to be the largest general-purpose heavy-ion linac that is ever built. More generally, what this means is that future linacs will be built in order to achieve specific advantageous performance characteristics in a cost-effective way, and high beam energy is not one of these characteristics. Therefore, if very large heavy-ion linacs are built, they are likely to be for specialized purposes that requires extremely large beam currents. Obvious examples of such high-current applications are inertial fusion and injection into a large heavy-ion storage ring.

A fairly large number of relatively small heavy-ion linacs will be built as injectors of bigger machines and as energy boosters. Pulsed injectors and also injectors that must handle extremely large beam currents will use room-temperature technology. The RFQ will play an important role in these applications, especially when the required energy gain is not large.

The construction of boosters of heavy-ion beams from tandems will continue to remain active during the next decade, in part because the large and expensive tandems now going into operation are likely to feel threatened by the numerous small tandem-linac systems that will soon be operating. Most of these future boosters will probably be superconducting and will have small independently-phased resonators.

Some small stand-alone heavy-ion linacs are likely to find applications during the next decade. Two such applications come to mind. One possibility is a general-purpose machine for research in nuclear and atomic physics, in effect, the equivalent of a tandem. Linacs of this kind will employ superconducting independently-phases resonators. A second and more likely development will be aimed at the needs of materials science and technology. Such

CH1996-3/84/0000-0509 $1.00 © 1984 IEEE

machines might be used initially for research on subjects such as radiation damage and ion implantation far beneath the surface, and they would then evolve into commercial applications associated with these same subjects. The commercial applications are likely to be so specialized in nature that several linac technologies will be useful. In any case, it is probable that by 1995 there will be more heavy-ion linacs of this kind than all others combined.

Clearly, the heavy-ion linac has a future!

Footnotes and References

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

[1] N. Angert, D. Böhne, J. Klabunde and H. Trautmann, in Proc. 1979 Linear Accelerator Conf., Montauk, N.Y., Sept. 1979, BNL 51134, 17 (1979).

[2] J. Staples et al., IEEE Trans. NS-26, 3739 (1979).

[3] M. Odera, Y. Chiba and T. Kambara, in Proc. 1979 Linear Accelerator Conf., Montauk, NY, Sept. 1979, BNL 51334, 28 (1979)

[4] J. Aron, R. Benaroya, L. M. Bollinger, B. E. Clifft, K. W. Johnson, P. Markovich, J. M. Nixon, R. Pardo, K. W. Shapard and G. Zinkann, in Proc. 1981 Linear Accelerator Conf., LA-9234-C, 25 (1982); L. M. Bollinger, IEEE Trans. Nucl. Sci. NS-30, 20645 (1983).

[5] J. W. Noe, P. Paul, G. D. Sprouse, G. J. Dick and J. E. Mercerean, IEEE Trans. Nucl. Sci. NS-24, 1144 (1977).

[6] M. Grieser, R. Hammel, B. Huck, H. Ingwerson, E. Jaeschke and R. Repnow, IEEE Trans. Nucl. Sci. NS-30, 2095 (1983).

[7] E. Nolte, R. Geier, U. Ratzinger, W. Schollmeier, IEEE Trans. Nucl. Sci. NS-30, 2983 (1983).

[8] Conceptual Design Report, May 25, 1983, Dept. of Physics, Univ. of Washington (unpublished, 1983).

[9] K. W. Shepard, private communication (1984).

[10] L. M. Bollinger and K. W. Shepard, to be published in Proc. 1984 Linear Accelerator Conf. (1984).

[11] K. R. Chapman, Nucl. Instr. Methods, 220, 194 (1984).

[12] E. Ben-Zwi, private communication (1984).

[13] H. R. McHyder, private communication (1983).

[14] O. Sala, private communication (1984).

[15] K. R. Crandall, R. H. Stokes, and T. P. Wangler in Proc. 1979 Linear Accelerator Conf., Montauk, NY, Sept. 1979, BNL 51134, 205 (1979).

[16] H. Klein, IEEE Trans. NS-30, 3313 (1983).

[17] John Staples, IEEE Trans. NS-30, 3533 (1983).