PRESENT AND FUTURE SUPERCONDUCTING LINACS

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Abstract

This paper is a survey of superconducting linacs designed for heavy-ion acceleration and a brief discussion of future prospects. Eight such machines are in operation or under construciton, and others are being planned. Most of these linacs function as energy boosters for ions from tandem electrostatic accelerators and are designed to provide output beams of relatively low energy but very good quality. The short independently-phased accelerating structures of the linacs involved in these tandem-linac systems cover the velocity range $0.04 \lesssim \beta \lesssim 0.3$. In a recent development, the technology is being extended down to ions with $\beta < 0.01$ in order to eliminate the need for the tandem injector. The main design features of the various heavy-ion linacs are summarized, and differences from superconducting linacs for electron acceleration are noted.

I. Introduction

In view of the interest at this conference in superconducting electron linacs, it seems worth while to start with a brief statement concerning the differences between the roles of superconductivity in heavy-ion and in electron acceleration. The substantial differences between the two technologies result mainly from the difference in projectile velocity: the range 0.01 c to 0.30 c for heavy ions and 1.0 c for electrons. Because of the lower velocities involved, the RF frequency needs to be lower for heavy-ion structures, and consequently the power dissipation on the superconducting surface is much smaller. This implies that the properties of the superconductor are less important for heavy-ion accelerating structures than for electron structures. Moveover, because low RF frequencies are most easily obtained by means of lumped-parameter resonators that involve long inductive elements, mechanical stability is a much bigger issue for heavy-ion structures. Finally, because of the wide range of velocities of interest, many kinds of heavy-ion structures are useful, whereas for electrons just one kind of multiple-cell cavity is dominant.

Although the development of the superconductivity technology for electron acceleration started well before that for heavy ions, by now the heavy-ion technology is a more mature subject in the sense that it has been thoroughly tested in superconducting linacs that have been extensively used to accelerate beams for nuclear physics research. The two heavy-ion systems now in full operation (Argonne and Stony Brook) have delivered a total of about 40,000 hours of beam on target.

II. Tandem-Linac Systems

All superconducting heavy-ion linacs[1] now in use serve as energy boosters for ions from tandem electrostatic accelerators. An illustration of a tandem-linac system is given in Fig. 1. The tandem is operated in a conventional way, with a negative-ion source and a stripping foil in the positive

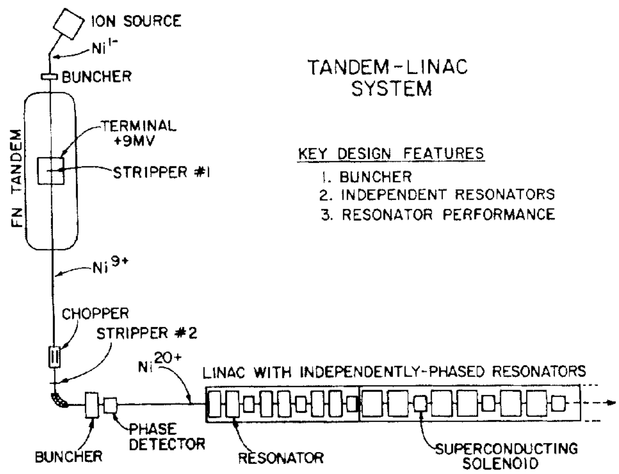

Fig. 1 Schematic of the main elements of a tandem-linac heavy-ion accelerator system.

terminal. The ion beam is bunched and analyzed before injection into the linac, which consists of an array of short independently-phased RF resonators with focussing elements interspersed at relatively short intervals.

The tandem-linac systems have been developed mainly for precision high-resolution nuclear-physics research, for which the machine must have the following characteristics: (1) overall flexibility with regard to ion species, incident velocity, and q/A, which is obtained by using short independently phased resonators, (2) easy energy variability, which is obtained by varying the amplitude of the last resonator in use, (3) good beam quality, which is obtained by preserving in the linac the excellent beam quality incident from the tandem, (4) CW operation, which comes without effort for superconducting structures, and (5) low cost, which can result from accelerating structures with high gradients and from minimal costs for RF equipment. Fortunately, in view of the low-cost requirement, modest beam energy and beam current is tolerable for much of the research for which the tandem-linac system was developed.

III. Superconducting Accelerating Structure

When designing a superconducting resonator for heavy-ion acceleration, three primary choices must be made: the superconductor (niobium or lead), the type of structure, and the RF frequency. As shown in Fig. 2, these choices have an impact on a large number of performance characteristics, and through these linkages the primary choices are somewhat interdependent. Because of the multiplicity of interactions involved, the optimum set of primary choices depends strongly on the special circumstances faced by the linac designer.

The development of superconducting structures for ions started in 1969 and is still being intensively

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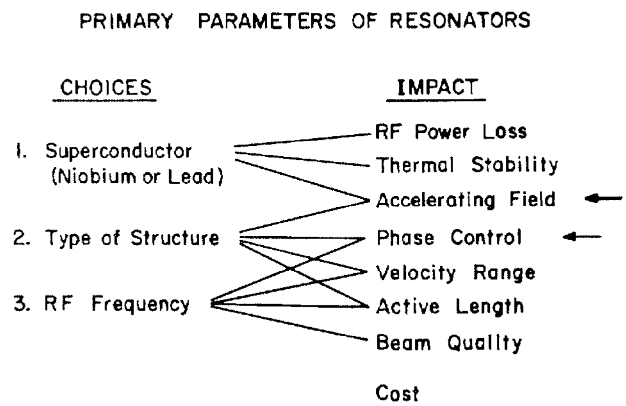

Fig. 2 Design choices for a superconducting heavy-ion accelerating structure.

pursued. The history of this work is summarized by Table I (see Ref. 1 for references). Of the eight structures shown here, three are of most interest now: the split ring (in use in the two operating linacs), the simple quarter-wave line with a single drift tube, and the interdigital structure (discussed later).

The simplest kind of superconducting accelerating structure is a straight quarter-wave line with a single drift tube, which was first developed[2] into a useful device at Stony Brook and is now being used elsewhere (see Fig. 3). This geometry has the immense advantage that the line can be tapered and massive enough to be quite rigid, thus minimizing the amplitude of RF-freqency variations induced by mechanical motion. Since this geometry is so obvious, simple, and beneficial, why was it not used much earlier? I am aware of three answers to this question, two of which are no longer valid. One is that when a quarter-wave line was considered briefly at Argonne in the early 1970s, we thought that a very low RF frequency ($<$ 90 MHz) was essential, and the considerable length of such a line appeared to pose a severe cryogenic problem; it is clear now that we had too little courage. Second, several untapered coaxial lines were tried in the early days, but low-level multipactoring seemed to impose an insuperable barrier.[3] Recent experience with tapered lines shows that multipactoring is still a problem, but it can be overcome by strenuous RF conditioning. Finally, since the quarter-wave resonator has only two gaps, its active length is smaller than that of a multi-gap structure. In my opinion, this is still a drawback for structures for $\beta < 0.10$.

Table I. Development of low-β superconducting resonators. The code for institutions is: Ka = Karlsruhe, Ar = Argonne, CT = Cal Tech, St = Stanford, SB = Stony Brook, Sa = Saclay, We = Weizmann Inst., Wa = U. of Washington.

Resonator Type	Development Period	Institutions	Super-conductor	Range of Parameters f (MHz)	β
Helix	1969-77	Ka, Ar	Nb	62-108	0.04
	1970-73	CT	Pb	40-150	0.04
Re-entrant C.	1973-77	St	Nb	430	
Spiral	1973	CT	Pb	150	0.04
Split Ring	1974-85	CT, SB	Pb	150	0.05-0.10
	1975-85	Ar	Nb	97-145	0.06-0.16
Mod. Helix	1977-86	Ka, Sa	Nb	108-135	0.04-0.08
Quarter Wave	1982-	SB, We, Wa	Pb	150-173	0.06-0.21
	1984	Ar	Nb	140	0.14
Interdigital	1985	Ar	Nb	48-73	0.008-0.037
Half Wave	1985	CT	Pb	150	0.06

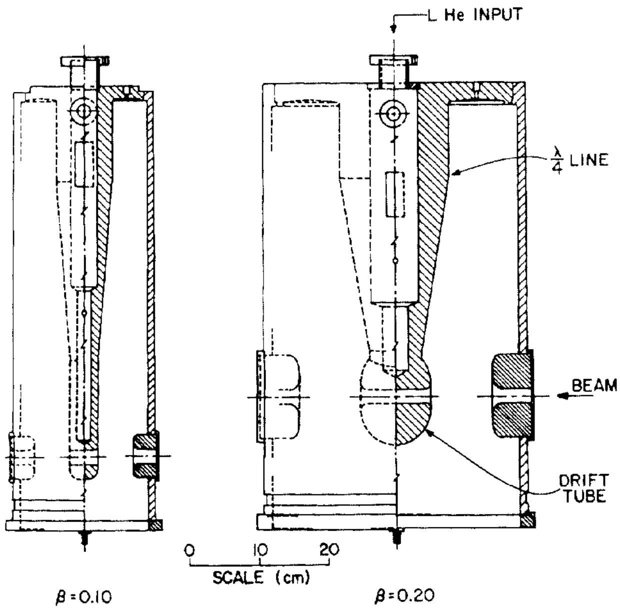

Fig. 3. Quarter-wave resonators for use in the superconducting linac at the Univ. of Washington.[10] The superconductor is Pb plated on Cu, and the RF frequency is 150 MHz.

The split-ring resonator, which was invented[4] at Cal Tech fairly early in the history of the subject, is in effect two tightly-coupled quarter-wave lines. One of the split-ring resonators developed at Argonne[5] for use in the ATLAS linac is shown in Fig. 4. The coiled-up lines form a device that is conveniently compact, and the two drift tubes provide three accelerating gaps, both advantageous features. However, the coiled-line geometry makes it difficult to achieve mechanical stability, and the 97 MHz used in the Argonne units is about as low an RF frequency as is practical for the split-ring geometry. In my opinion, the split-ring structure is still a good choice for an intermediate range of velocity: say, for β = 0.06 to 0.12.

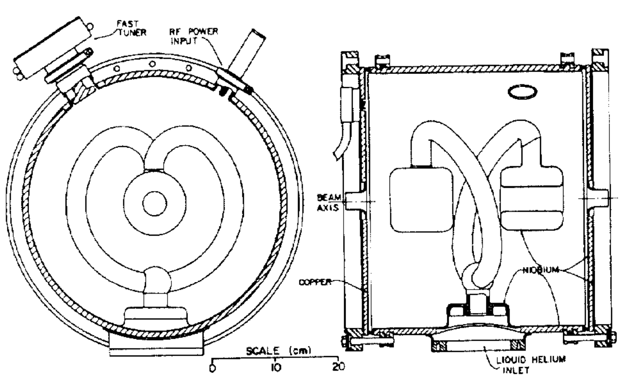

Fig. 4. One of several types of split-ring resonators[5] used in ATLAS. The superconductor is niobium, the outer housing is niobium bonded to copper, and the RF frequency is 97 MHz.

A representative performance curve for a superconducting structure is given in Fig. 5, which is a plot of quality factor Q as a function of effective accelerating field E_a. Note that Q is a high value and roughly independent of E_a for low fields and then falls off rapidly at high fields. This high-field phenomenon results from electron loading caused by the acceleration of electrons that are emitted from high-field surfaces. The various curves in the figure show how electron loading can be greatly diminished by "helium conditioning" the resonator, i.e., operating it when filled with helium gas. Presumably, this procedure works by removing absorbed gas from high-field surfaces and letting it diffuse to low-field surfaces where it does no harm.

IV. Superconducting Booster Linacs

The layouts of the two tandem-linac systems[6,7] now in operation are shown in Figs. 6 and 8. Both use FN-model tandems as injectors and both use split-ring resonators in their linacs. However, many features of the two linacs are quite different since the linac at Argonne (ATLAS)[6] uses niobium as the superconductor whereas the linac at Stony Brook[7] uses lead.

One of the attractive features of a linac with independently phased resonators is that the system can be modified and expanded with relative ease. This is well illustarted by ATLAS: it started as a stand-alone-tandem in 1962, the prototype booster linac was added during the period 1978-82, and then another major piece of linac was added in 1985. The 40° bend between the two sections of linac was introduced so that the research program started in 1978 in Area II (see Fig. 6) with the beam from the booster linac could be continued while the second section of linac and a large new experimental area were added. The whole system was completed in 1985 and since then has been used steadily for research. The total beam time provided by some part of the ATLAS linac since 1978 is 28,000 hrs. The region of projectile mass and energy now accessible to ATLAS is shown in Fig. 7.

The Stony Brook tandem-linac system is similar conceptually to the initial system at Argonne but was, of course, subjected to rather different geometrical constraints. A major requirement was to have beams from both the tandem and the linac be directed into an

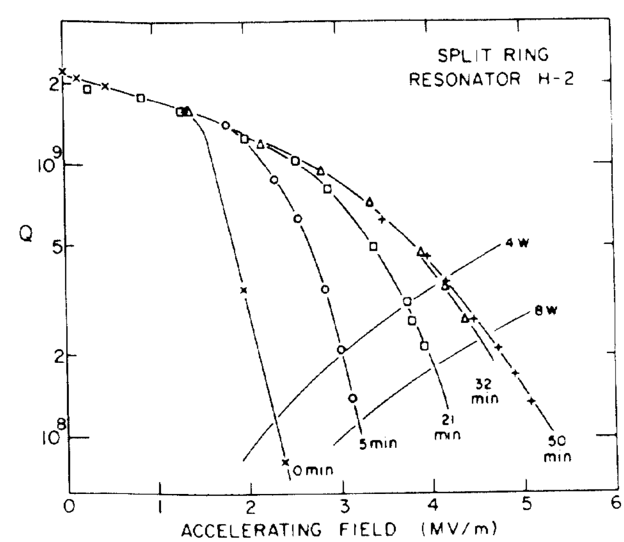

Fig. 5 Performance of a niobium split-ring resonator[5] with f = 97 MHz and β = 0.105. The time associated with each curve is the time spent on helium conditioning.

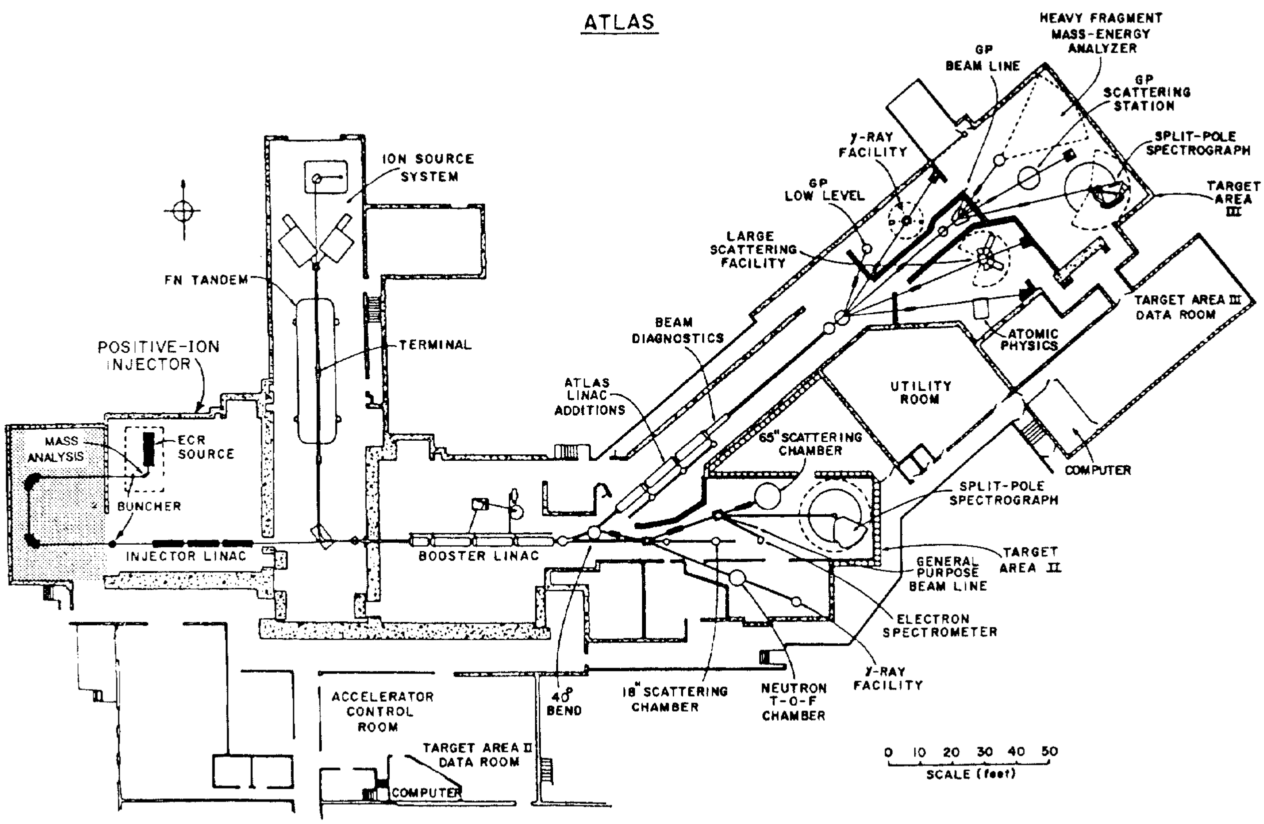

Fig. 6. Layout of ATLAS, the Argonne Tandem-Linac Accelerator System. The planned positive-ion injector now under construction is included on the left.

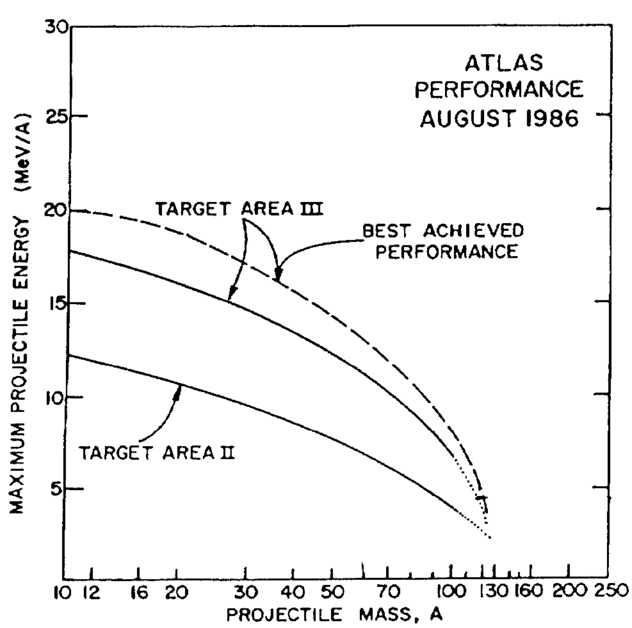

Fig. 7 Projectile mass and energy region accessible to ATLAS at this time.

existing experimental area. This was achieved rather neatly in the way shown in Fig. 8. The lead-plated 150-MHz split-ring resonators used in the linac were developed in a collaboration between groups at Cal Tech[8] and Stony Brook. The Stony Brook tandem-linac system has been used regularly for research since 1983. Some recent improvements in the system are discussed in Ref. 9.

A rather large tandem-linac system[10] is now under construction at the University of Washington. Again, it was necessary to have the linac fit within existing space and to have the beam end up at an existing target area. Since this linac must accelerate both protons and heavy ions, a quarter-wave line with a single drift tube (see Fig. 3) was chosen as the accelerating structure. The University of Washington linac is expected to be operating[11] by the end of 1987.

Table II summarizes a few important parameters for tandem-linac systems that are operating or are under construction (see Ref. 1 for references). Also, other institutions that appear to be seriously interested in building superconducting linacs are listed. The size of each linac is given in terms of the total active length of its resonators. From this active length, one can infer an approximate total length of the cryostats by multiplying by a number in the range 2 to 2.5, and one can infer the accelerating voltage by multiplying by 2.5 to 3. Thus, one sees that all of these superconducting linacs are rather small. Nevertheless, they greatly enhance the research capabilities of the tandems that serve as injectors.

Three of the superconducting linacs now under construction will come into operation in 1987: those at Florida State University, the University of Washington, and Saclay. Indeed, the machine at Florida State is being dedicated[12] this week (March 20, 1987). The linac at Kansas State is unique in that it will be used primarily to decelerate ions from a tandem for research in atomic physics.

Table II. Heavy-ion booster linacs. Under resonator type, S. R. means split ring and Q.W. means quarter wave. See Ref. 1 for references.

Institution	Super-conductor	Resonator Type	Active Length (m)	No. of Reson-ators
Operation:				
Argonne	Nb	S.R.	13.3	42
Stony Brook	Pb	S.R.	7.5	40
Weizmann I.	Pb	Q.W.	0.7	4
Construction:				
Florida State	Nb	S.R.	4.3	12
Saclay	Nb	Helix	12.5	50
U. of Wash.	Pb	Q.W.	8.6	36
Kansas State	Nb	S.R.	3.5	16
Daresbury	Pb	S.R.		
Planning				
Canberra	Pb	Q.W.		
Sao Paulo	Nb			
Tata Inst.	Pb	Q.W.		
Legnaro	Pb	Q.W.		

By now we have enough operating experience with the tandem-linac systems to know realistically what to expect from them. For ATLAS we have the following:

(1) good reliability - only 5 to 10% of unscheduled down time;
(2) exceptional resistance to component failure because of the use of independently phased resonators;
(3) good long-term stability of resonators, which can be restored to their original performance by rinsing;
(4) quick energy change (~ 2 min.);
(5) excellent beam quality in both transverse and longitudinal phase space;
(6) very narrow beam pulses: Δt = 100 to 250 psec; and
(7) total power usage ~ 20% of an equivalent room-temperature linac.

It is interesting to note that only items (3) and (7) are associated with superconductivity; the others are associated with independently phasing.

IV. Superconducting Injector Linac

Although the tandem-linac system is proving to be very successful as a research tool, it has three substantial drawbacks: (1) the beam intensity available from the negative-ion source and tandem is weak for most ions, (2) the tandem has difficulty in accelerating very heavy ions, especially because of the short lifetime of the stripping foil in the terminal, and (3) the accelerator operators need to master two difficult technologies. Consequently, we at Argonne have undertaken a project aimed at replacing the tandem with a positive-ion source and its superconducting injector linac. The objectives of this work are to (a) extend the mass range up to uranium, (b) to increase the beam intensities of all ions by a factor of 100, and (c) at the same time, to preserve the good qualities of the tandem, especially the CW operation, the easy energy variability, and the excellent beam quality.

The planned positive-ion injector system[13,14] consists of an ECR ion source on a voltage platform from which ions enter directly into the injector linac. (see Fig. 6) For ions with A > 125, the charge states of the ions from the source are expected to be in the range 20 to 30. The linac will consist

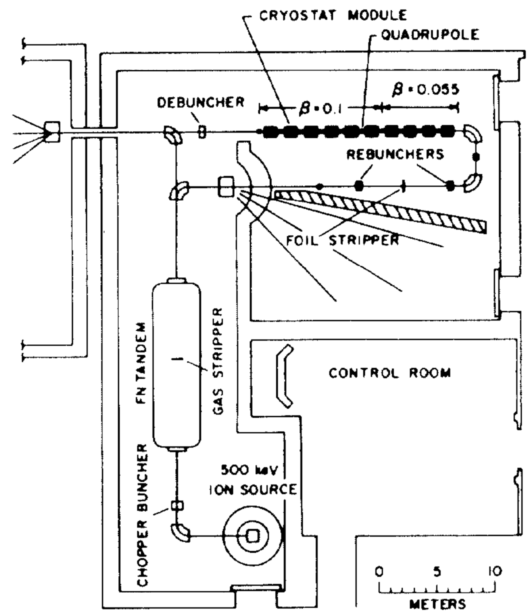

Fig. 8 Layout of the tandem-linac system at Stony Brook.

of four classes of superconducting 4-gap accelerating structures of a new kind.[15] Because of the high charge states from the source, the linac can be rather small.

The technology of the ECR source is by now well developed, and the main challenge is to operate it on a high-voltage platform, which has not been done previously. For the linac, the main challenge is to accelerate the very low velocity beams from the source without a serious loss of beam quality in either transverse or longitudinal phase space. To solve this problem, the linac will consist of very short independently-phased resonators operating at the low frequency (for a superconducting structure) of 48.5 MHz. At the front end of the machine, a short superconducting solenoid will be used after each resonator to refocus the beam, thus preserving beam quality in transverse phase space. Six-dimensional ray tracing calculations show that, with appropriate bunching and matching of the incident beam, this arrangement also permits longitudinal phase space to be preserved (see Ref. 15). Thus, overall, the quality of the beam from the injector linac is expected to be at least as good as that from an equivalent tandem. A primary reason for this perhaps surprising result is that, unlike a tandem, the linac does not have to contend with beam degradation caused by foil stripping at a location where the beam is not well bunched.

The new accelerating structures being developed for the positive-ion injector are discussed in Ref. 16. The first of the structures (which has an active length of 10 cm and a nominal β of 0.009) operated stably at an accelerating field of 10 Mv/m. This remarkably high field gradient suggests that the limiting field of a superconducting RF resonator may depend not only on the maximum surface electric field (as is often assumed) but also on the spacing between electrodes. Good progress is also being made in developing the other three classes of resonators needed for the injector linac.[16]

The positive-ion injector for ATLAS will be constructed in three phases. In Phase I, the goal is to develop the technology, build the ECR source, and build a 5-resonator 3-MV linac that is just large enough to compete favorably with the tandem as an injector; this Phase I injector will be operational by early 1989. Then, in Phase II and III the injector linac will be enlarged to 12 MV, enough to allow ATLAS to accelerate uranium ions well above the Coulomb barrier. The Phase III system is expected to be in operation by late 1990.

The calculated performance of ATLAS for several injectors is illustrated in Fig. 9. The immense superiority of the positive-ion injector relative to an 8.5-MV tandem is apparent.

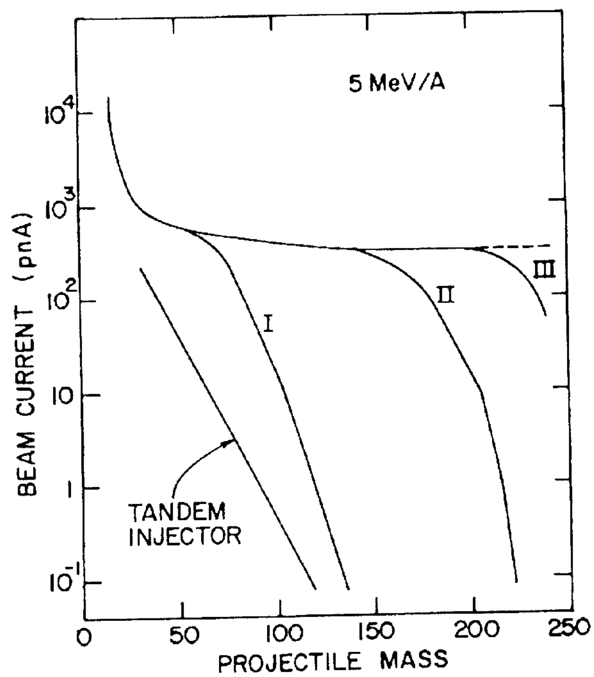

Fig. 9 Calculated beam current from ATLAS for an 8.5-MV tandem injector and for Phase I (3 MV), Phase II (8 MV), and Phase III (12 MV) linac injectors.

V. Future Prospects

The success of the two operating superconducting heavy-ion booster linacs and the obvious potential of the superconducting injector linac described in the preceding section suggest that this technology has a bright future. Let us conclude by mentioning several probably developments.

It seems to me highly probable that the positive-ion superconducting injector linac will soon be generally accepted as the injector of choice for a general-purpose heavy-ion linac. Thus, some of the tandems now in use for this function will be retired, and few if any large new tandems will be built for heavy-ion acceleration.

The role of the superconducting linac for high-current applications is not yet clear. However, the technology discussed in section IV looks encouraging enough that it seems well worth while to try to determine experimentally how far the technology can be pushed, with a view to applying the technology to injection into pulsed circular machines. Also, someone should try to build a superconducting RFQ.

In the long run, perhaps the most wide-spread application of the superconducting heavy-ion linac will be for small stand-alone machines for use in materials research and ultimately for industrial processes. The superconducting RF technology is most obviously attractive relative to electrostatic technology when the required ion is not too light and is too energetic to be provided by a small (1.5-MV) tandem, that is, for mass A > 9 and energy E > A/2 MeV.

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