REVIEW OF SUPERCONDUCTING ION LINACS*

Lowell M. Bollinger
Argonne National Laboratory
Argonne, IL 60439

Abstract

This paper summarizes the status of the technology of superconducting (SC) linacs designed for the acceleration of ions. The emphasis is on the technical issues involved, with only brief descriptions of the numerous linacs now in operation or under construction. Recent developments of special interest are treated in more detail, and remaining technical challenges are outlined. The technology required for the acceleration of ions with velocity $\beta \simeq 1$ is not discussed because it is almost the same as for relativistic electrons. That is, this paper is mainly about SC linacs for low-velocity heavy ions.

Introduction

The development of SC technology for heavy-ion acceleration started in the late 1960's and early 1970's, stimulated by the pioneering effort at Stanford on a SC linac for electrons. A few of the milestones in the early work on heavy-ion acceleration are listed in Table 1. The main thrust of the work in the period 1969-1973 was the development of helix accelerating structures, with niobium being used as the superconductor at Karlsruhe and Argonne, and lead plated on copper at Cal Tech. This was a period when the basics of the technology were learned: techniques for fabrication, heat treatment, and surface treatment, the importance of material purity and surface cleanliness, and the difficulty of achieving phase stability. By 1974 the field had matured to the extent that new types of accelerating structures were being developed, ion beams were accelerated, and the technology of heavy-ion beam bunching was established. See [1] for more detail.

TABLE 1
Milestones in Early History

1965	1st Superconducting Linac (for Electrons)	Stanford
1969	Low-β Niobium Structure (Helix)	Karlsruhe
1970	Low-β Lead-Plated Structure (Helix)	Cal Tech
1974	High Surface Electric Field (37 MV/m)	Argonne
1974	First Phase-Locked Acceleration of Ions	Argonne
1974	Development of Split-ring Resonator	Cal Tech
1974	100-ps Heavy-ion Bunches	Argonne
1975	Funding, Heavy-ion Linac	Argonne

Table 2 summarizes some of the lessons learned during the early work on low-β SC accelerating structures, some of which were rediscovered half a decade later by those working on high-β structures. Major technical challenges continue to be (1) how to obtain clean, defect-free SC surfaces and (2) how to control the phase of low-frequency structures.

Most of the work outlined above was aimed at the development of individual accelerator components, especially accelerating structures, but in 1974 the work entered a new phase when Argonne obtained funding to build a real SC accelerator, a small prototype linac to serve as an energy booster for heavy ions from a tandem electrostatic accelerator. By 1978 this tandem-linac system was accelerating heavy-ion beams for research, and other tandem-linac systems were being constructed [3] or planned. A series of review papers [1, 4-6] provide an overview of applications of RF superconductivity to heavy-ion acceleration as the technology developed. References to most publications prior to mid 1985 are in [1].

TABLE 2
Lessons Learned from Early Experience

- High Surface Fields are Possible
- Field Levels are Limited by Electron Field Emission
- Superconducting Surfaces are not Fragile
- Several Kinds of Low-β Structures are Effective
- Fabrication of Niobium Structures is Straight Forward
- Surface Defects can be Located and Removed
- Major Technical Challenges are:
  (1) Clean, defect-free Surfaces
  (2) Phase Control

General Features of Tandem-Linac Systems

The initial use of SC linacs for heavy-ion acceleration was helped immensely by the availability of tandems as injectors since their beams (for which β is usually > 0.05) removed the need to solve the problems associated with RF acceleration of very slow-moving particles. To be effective, a linac coupled to a tandem must satisfy certain conditions: variable q/A ratio and incident velocity, CW operation, easy energy variability, and acceleration without much deterioration in either transverse or longitudinal emittance. To satisfy these requirements the accelerating structures of the linac must have few accelerating gaps (2 to 4) and be independently phased. The transit-time factor for such structures are illustrated in Fig. 1. Although 2- and 3-gap structures accelerate effectively over a rather wide range of velocity, more than one class (β) of structures is often acquired. The RF frequencies are usually in the range 90 to 150 MHz.

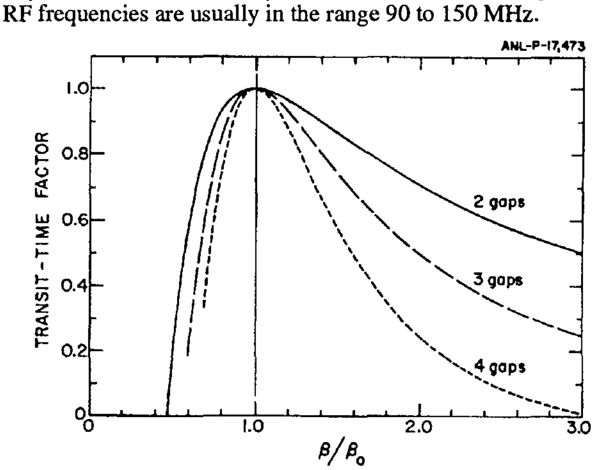

Fig. 1 Transit-time curves for accelerating structures.

*Work supported by the U.S. Department of Energy, Nuclear Physics Division, Contract W-31-109-ENG-38.

The main features of a tandem-linac system are shown in Fig. 2. The negative ion beam from the source is bunched at the tandem input, accelerated to the high-voltage terminal, pasted through a thin (< $5\mu g/cm^2$) stripped foil to form highly-charged ions, accelerated to ground potential, chopped to remove unbunched ions, pasted through a second stripper, analyzed, and rebunched to form beam pulses that are matched in longitudinal phase space to the linac. The phase of the pre-tandem buncher is controlled by the bunch-arrival time at the "phase detector" because of drifts in the ion transit time through the tandem.

The SC linac consists of an array of short independently-phased accelerating structures and transverse-focussing elements. In the illustration (ATLAS), transverse focussing is provided by SC solenoids, whereas other linacs use quadrupoles at room temperature. The accelerating structures operate at a temperature of ~4.5 K and, because of mechanical-design considerations, the interior of the unit and the insulation vacuum are interconnected.

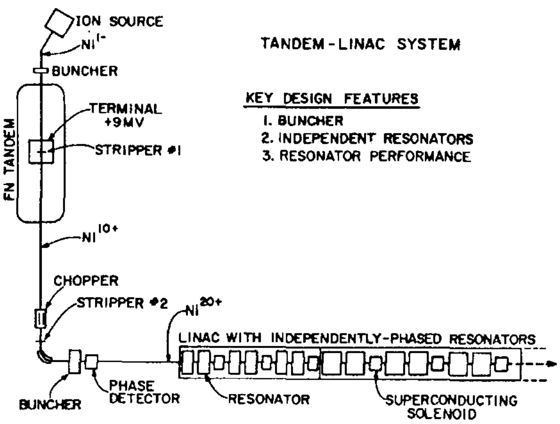

Fig. 2 Main components of a tandem-linac system.

As is discussed later, all but one of the SC heavy-ion linacs maximize the fraction of the linac devoted to active acceleration and avoid large gaps in acceleration. Consequently, the behavior of the beam in longitudinal phase space can be described approximately by conventional linac theory in which the bunch rotates around the synchronous velocity and phase. In most SC heavy-ion linacs the acceptance in both longitudinal and transverse phase space is very much larger than the corresponding phase-space area (emittance) of the beam. This condition is highly desirable so as to avoid the need for careful tuning after each change of ion species, which typically occurs one or two times weekly.

Accelerating Structures

The heart of a SC linac is the accelerating structure. When designing the structure, three main choices are involved: the kind of superconductor, the type of structure, and the RF frequency. These choices are dependent on a large number of interacting considerations. Because of the complexity of these considerations, the wide range of beam velocities, and the differing user requirements, there is no type of structure that is optimum for all applications, unlike the situation for electron acceleration. The many possibilities for low-β structures is still a challenge for the designer.

The helix structure that was explored initially for heavy-ion acceleration has been abandoned (with one exception) because of its high ratio of surface electric field E_{sur} to accelerating field E_a and especially because of its mechanical instability, which makes phase control very difficult. For a time the helix was replaced as the design of choice by the 3-gap "split ring" resonator. The Argonne version [7] and the Cal Tech-Stony Brook version [8,3] are still in use. More recently, structures consisting of drift tubes driven by a straight quarter-wave line [9] are being widely used. Fig. 3 shows three examples: a 2-gap lead-plated structure [10] used in the U. of Washington linac, a 2-gap niobium structure with outstanding performance characteristics developed at JAERI [11], and a 4-gap structure developed at Argonne [12] for use in the injector described later. The most recent development is a half-wave structure [13] for the acceleration of light ions. Because of its length, this half-wave design may not be practical at the low RF frequencies needed for low-β particles but it has excellent characteristics at higher frequencies.

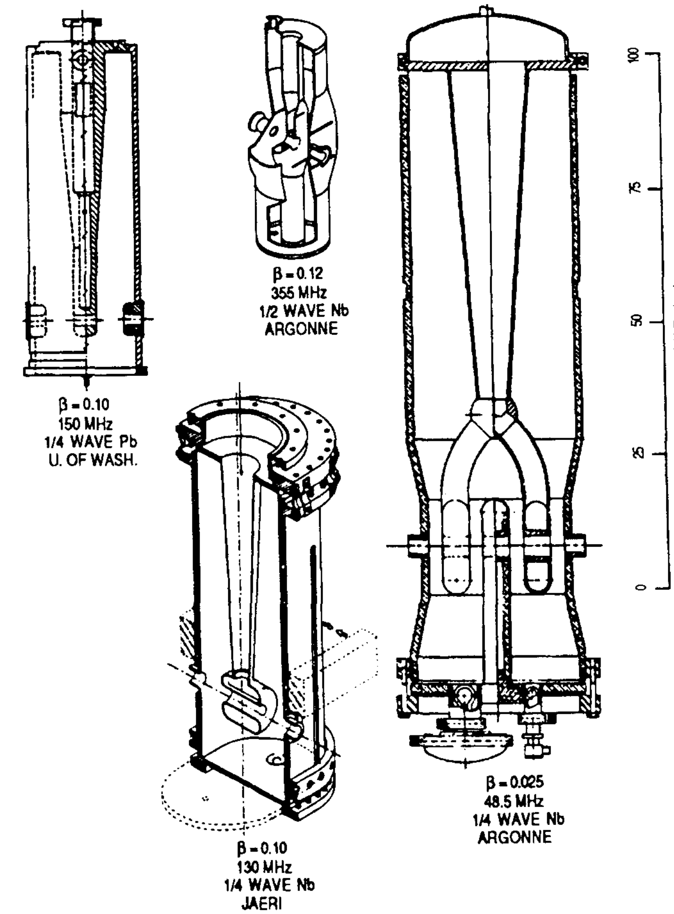

Fig. 3 Examples of recent accelerating structures.

The best performance [11-14] achieved by various kinds of accelerating structures are summarized in Table 3. In all units the superconductor is niobium, and the limiting fields are high enough that electron-loading is the dominant power-loss mechanism. It must be emphasized that Table 3 gives maximum achievable fields, and experience shows that the average performance for online operation of many units is only 50 to 60% of these values.

Table 3 also gives information about various design parameters of the resonators. In particular, note the wide range of β and the substantial accelerating voltages provided by individual units. Also, note that the ratio E_{sur}/E_a is typically ~5 whereas for β=1 structures it is ~2. Thus, although the effective accelerating fields reported for the β=1 structures are considerably greater than for the low-β structures, the maximum surface fields are similar.

TABLE 3
Best Performance of Low-β SC Resonators

STRUCTURE TYPE	β (%)	NO. OF GAPS	RF FREQ. (MHz)	MAX. ACCEL. FIELD (MV/m)	MAX. ACCEL. VOLTAGE (MV)	E_{sur}/E_a	REF
1. INTERDIGITAL (I_1)	1.0	4	48.5	8.5	0.86	6.0	[14, 12]
2. INTERDIGITAL (I_2)	2.5	4	48.5	6.1	1.55	5.5	[14, 12]
3. SPLIT RING (L)	6.5	3	97	8.1	1.64	4.7	[14, 7]
4. SPLIT RING (H)	10.5	3	97	6.5	2.31	4.7	[14, 7]
5. QUARTER WAVE	10.0	2	130	12.6	1.89	4.6	[11]
6. HALF WAVE	12.0	2	355	18.0	1.20	3.2	[13]

When preparing Table 3, I was struck by the large spread in maximum accelerating field for the various structures. Since these units are similar in material quality, fabrication technique, heat treatment, and surface treatment, it seems likely that the differences in performance result from differences in the designs. This idea was explored by trying to find some correlation between the maximum surface field E_{sur}^{max} and various design parameters, under the assumption that the limiting performance is established by electron field emission. As shown in Fig. 4, it was found that there is a remarkably good correlation between E_{sur}^{max} and the quantity AV/P, where A is the area of the surface for which the field is near its maximum value, V is the voltage through which electrons emitted from this area are accelerated, and P is the RF power dissipated at maximum CW performance. Since complete information was not available concerning the distribution of electric fields within the structures, the high-field surface area was assumed to be A=0.5 πrL, where r is the radius of curvature

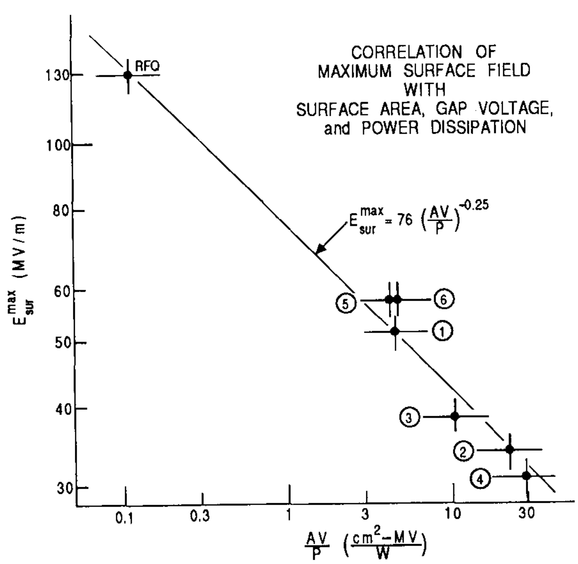

Fig. 4 Dependence of E_{sur}^{max} on AV/P. The numbers attached to data points refer to the structures in Table 3.

of the high-field region and L is the length of this region. In addition to the data of Table 3, Fig. 4 includes the results for a maximum-voltage test with a small unmodulated-rod RFQ structure.[15]

Before too much is read into the relationship between E_{sur}^{max} and AV/P, it should be recognized that the result is preliminary and has obvious limitations. In particular, the uncertainties in the data are large (especially in A), there is no supportable theoretical basis for the correlation, it is not clear whether the field limit is established by the electron-emitting surface or by the electron-receiving surface, and the relationship of the area A to the commonly held concept of electron emission by a few small points is not clear. The initial motivation for comparing E_{sur}^{max} to AV/P was the fact that the power P dissipated by electron emission is equal to the emitting area A times the voltage drop V for the electron time some functions of E_{sur}, but this relationship does not give any guidance concerning the limiting values of P, V, and E_{sur}. Nevertheless, it is believed that the qualitative features of the correlation given by Fig. 5 are real and should be considered in the design of future SC accelerating structures.

Existing and Planned Tandem-Linac Systems

Accelerating structures of the kind discussed in the proceeding section have been or are being used in the construction of the linacs for a large number of tandem-linac systems. Some general characteristics of these linacs are summarized in Table 4. Both Nb and Pb are used as the superconductor, and

TABLE 4
Superconducting Linacs of Tandem-Linac systems

SYSTEM	SC	STRUCTURE GAP NUMBER	RF FREQ. (MHz)	NO. OF ACCEL. STRUCT.	ACTIVE LENGTH (m)
OPERATING					
ARGONNE	Nb	3	97, 145.5	42	13.3
STONY BROOK	Pb	2	150	40	7.5
FLORIDA STATE U.	Nb	3	97	13	4.5
U. WASHINGTON	Pb	2	150	36	8.6
SACLAY	Nb	Helix	135	50	12.5
KANSAS STATE U.	Nb	3	97	16	3.5
CONSTRUCTION					
LEGNARO (Italy)					
PHASE I	Pb	2	160	48	~7
PHASE II	Pb	2	80, 160	93	~14
JAERI (Japan)	Nb	2	130	40	6.0
TATA INST. (Bombay)	Pb	2	150		
SAO PAULO	Nb	3	97	13	4.2
DELHI	Nb	2	~100	32	~5

all of the linacs have a large number of independently phased resonators. The total active lengths of the accelerating structures are small compared to the SC electron linacs now under construction but are large enough to enhance immensely the research capabilities of the tandem injectors. To convert the active lengths to accelerating voltages, multiply by ~3.0 MV/m for Nb structures and by ~2.7 MV/m for Pb. More detail about the operating systems are given in [1, 4-6].

Fig. 5 gives the layout of ATLAS, which is the largest of the existing SC heavy-ion linacs and is representative of the scope of a tandem-linac facility. As at other tandem-linac systems, the beam from ATLAS is used mainly for research in nuclear physics and to a lesser extent in atomic physics. A wide variety of beams are accelerated, with a change in beam type approximately weekly and a change in beam energy more frequently. Emphasis is placed on good beam quality, especially on small longitudinal emittance, which is needed to be able to deliver to the user the narrow (~100 ps) beam pulses required for time-of-flight measurements on nuclear-reaction products. The size of the facility has evolved gradually over a period of years, with the positive-ion injector discussed later the most recent addition.

Most SC heavy-ion linacs are designed to be as compact as possible so that during acceleration the phase space of the beam behaves approximately as in a conventional linac and beam tuning is simple. In these linacs the "packing fraction" (the ratio of active accelerating length to total length) is ~50%. In contrast, for the large SC linac being built at Legnaro [16] it has been decided to include within the beam path diagnostic stations at 4.3m intervals and to use large quadrupole triplets for transverse focussing. This design reduces the packing fraction to ~25% and requires the beam to be matched in 6-dimensional phase space at each of the 19 diagnostic stations. It will be interesting to see how this unusual approach to beam optics works out in practice.

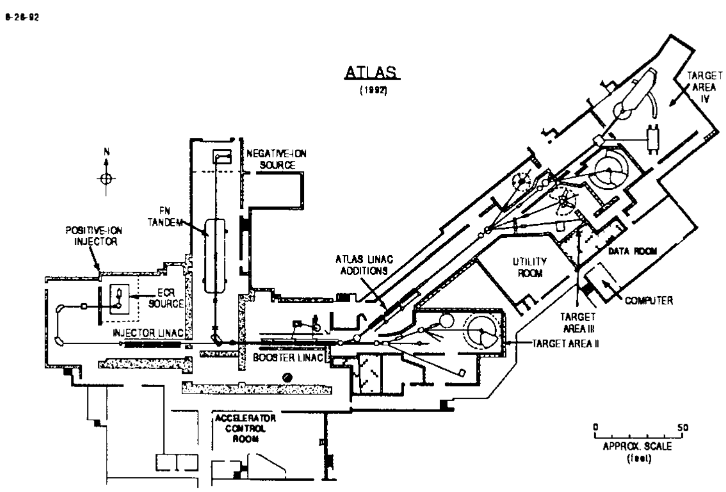

Fig. 5 Layout of ATLAS.

New Kinds of Heavy-Ion Injectors

Although the tandem-linac systems have proven to be valuable research tools, providing a total of ~100,000 hr of beam for research, by now it is widely recognized that the tandem injector is not optimum, especially for very heavy ions. Two kinds of injectors to replace the tandem are being actively developed. One is the ATLAS positive-ion injector (PII), which consists of an ECR source on a 350-kW voltage platform followed by a CW 12-MV drift-tube injector linac. A refined beam-preparation system matches the beam into the linac in 6-dimensional phase space. The layout of PII is shown in Fig. 5 and in more detail in [17]. All aspects of PII are treated in [18]. First discussed in 1984 [19], this injector system was completed in March 1992 and is now being used for research.

The main challenge for the injector linac is to boost the ion velocity from β=0.008 to >0.045 without much loss of beam quality. This is achieved by using four different types of 4-gap resonators [12], one of which is pictured in Fig. 3. Data for 2 of the four types are given in Table 3. Powerful liquid-nitrogen-cooled voltage-controlled reactances are used to control RF phase [20]. The configuration of PII is shown in Fig. 6. At the input end, where beam defocussing is a serious problem, a superconducting solenoid is placed after each resonator. A high-resolution (200 ps) fast Faraday cup [21] behind the first resonator is used to guide beam matching in longitudinal phase space.

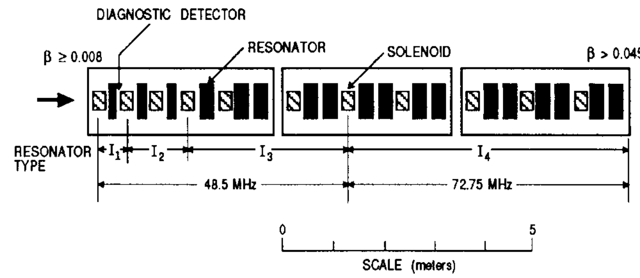

Fig. 6 Configuration of the injector linac of PII.

Operating experience [17] with ions from throughout the periodic table (including ^{238}U) demonstrates that all design goals for PII have been met. The accelerating fields are greater than was planned, transmission is ~100%, the transverse emittance growth in the linac is small, and the longitudinal emittance sets a new standards of excellence for heavy-ion beams [17].

A second possibility for an injector to replace the tandem is a low-frequency RFQ. A SC injector is desirable because a CW beam is needed for many applications, but an RFQ operated in the usual mode may not be satisfactory for some applications because of its large longitudinal emittance. A potential solution to this problem is described in Ref. [22]. The proposed injector linac, which covers approximately the same velocity range as PII, consists of 6 short independently-phase RFQ structures, each with only a small number of cells (typically 4) and each with a different β. Since beam currents are assumed to be weak, the modulations in the RFQ electrodes are designed to emphasize acceleration rather than transverse focussing. Growth in longitudinal emittance is largely eliminated by injecting into the first RFQ structure a bunched beam matched to that structure. That is, in many basic respects this proposed injector is similar to PII; the main difference is the way in which transverse focussing is provided.

The RFQ approach of [22] is being seriously pursued as a future injector for the superconducting linac [16] at Legnaro. In a collaborative effort carried out at Stony Brook, a prototype of one of the 6 proposed RFQ sections has been built and tested [23]. This 40-cm-long unit uses a Pb-Sn alloy on Cu as the superconductor, has 4 cells, and operates at 57 MHz. The maximum accelerating field achieved to date is ~1.3 MV/m, but those involved believe that, with further effort, the field could be pushed to its design value of 2 MV/m. Phase control was not attempted, and this may be difficult because of the large stored energy (4J at 2 MV/m) of the device and its relatively large RF-frequency jitter (~50 Hz) under mechanically-quiet conditions [24].

Present and Future Technical Challenges

The present and near-term future challenges for SC linacs are: (1) optimize the technology for tandem boosters in the velocity range β=0.04 to 0.2, (2) optimize replacement of the tandem, β=0.005 to 0.04, (3) develop high-current CW linacs for light ions, and (4) develop technology for the front end of a radioactive-beam accelerator, β=0.001 to 0.05. Substantial effort aimed at the first three of these tasks is underway, as reported at this conference [25-29] and as summarized in Table 5. This effort is likely to result in important advances before the next (1994) Linac Conference, especially for the superconducting RFQ and the structures designed to accelerate intense light-ion beams.

The one technical challenge that has not yet received any serious attention is the investigation of the role of superconductivity at the front end of a radioactive-beam accelerator, a subject is of intense interest now in the nuclear-physics community. Although the requirements for such an accelerator have not yet been fully specified, it is probable that they will be very demanding: very small charge-to-mass ratio (~10^{-2}), very small input β (~10^{-3}), large transverse input emittance (~150 mm-mrad), and the need for ~100% transmission and small emittance growth in 6- dimensional phase space

TABLE 5
Developmental Activities now Underway

PLACE	SC	β (%)	RF f (MHz)	STRUCTURE TYPE	APPLICATION	REF.
ARGONNE	Nb	08	100	(a) 1/4 WAVE (b) 2 COUPLED 1/4 WAVE	TANDEM-LINAC SYSTEM	[25]
LEGNARO	Nb	5.5 11	80 160	1/4 WAVE	TANDEM-LINAC SYSTEM	[26]
LEGNARO	Nb-Sn		160	1/4 WAVE	TANDEM-LINAC	[27]
STONY BROOK	Pb	3	57	RFQ	HEAVY IONS	[23]
ARGONNE (with ACCSYS)	Nb	2	196	RFQ	HEAVY IONS	[14]
LOS ALAMOS	Nb		800	RFQ	LIGHT IONS	[28]
ARGONNE	Nb	12 to 21	300 to 800	(a) 1/4 WAVE (b) 1/2 WAVE	HIGH CURRENT LIGHT IONS	[29] [13]

Whereas a SC drift-tube linac such as the one in the positive-ion injector of ATLAS may turn out to be adequate and optimum for β>0.005, it is not obvious that this technology is useful for β<0.005. The main problem is that a very low RF frequency is needed for beams of such low velocity and large emittance, and hence phase control may be impractical for SC devices. Clearly, the limits of usefulness of known SC structures need to be examined quantitatively. Better yet would be to have someone advance new ideas on how to handle the radioactive-beam requirements.

Acknowledgment

The author is indebted to K. W. Shepard for many useful discussions of SC accelerating structures, including discussion of the data for Fig. 4.

References

[1] L. M. Bollinger, Ann. Rev. Nucl. Part. Sci. 36, 375 (1986).
[2] L. M. Bollinger et al., Proc. 1976 Proton Linear Accel. Conf., Chalk River, AECL-5677, p. 95, 1976.
[3] J. W. Noe et al., IEEE Trans. Nucl. Sci. **NS-24**(3), 1144 (1977).
[4] I. Ben-Zvi, Nucl. Instr. Methods, **A220**, 177 (1984).
[5] I. Ben-Zvi, Nucl. Instr. Methods, **A287**, 216 (1990).
[6] D. W. Storm, Proc. 6th Intl. Conf. on Electrostatic Accel. and Associated Boosters, Montegrotto Terme, to be published in Nucl. Instr. Meth. (1992).
[7] K. W. Shepard et al., IEEE Trans. Nucl. Sci. **NS-24**(3), 1147 (1977).
[8] K. W. Shepard, J. E. Mercereau, and G. J. Dick, IEEE Trans. Nucl. Sci., **NS-22**(3), 1179 (1975).
[9] I. Ben-Zvi and J. M. Brennan, Nucl. Instr. Methods **212**, 73 (1983).
[10] D. W. Storm et al., IEEE Trans. Nucl. Sci. **NS-32**(3), 3607 (1985).
[11] S. Takeuchi et al., Nucl. Instr. Meth. **A287**, 257 (1990). Also, S. Takeuchi in Proc. 5th Workshop on RF Superconductivity, 1991, DESY Report M-92-01, p. 76 (1992).
[12] K. W. Shepard et al., in Proc. 1989 IEEE Part. Accel. Conf., Chicago, IEEE Cat. No. 89CH2669-0, p. 976 (1989).
[13] J. R. Delayen et al., Nucl. Instr. Meth. **B56/57**, 1025 (1991). Also, Paper TH4-37 of this conference (1992).
[14] K. W. Shepard, private communication (1992).
[15] J. R. Delayen and K. W. Shepard, Appl. Phys. Lett. **57**(5), 514 (1990).
[16] G. Fortuna et al., Nucl. Instr. Methods **A287**, 253 (1990).
[17] R. C. Pardo et al., Paper M04-12 of this conference (1992).
[18] L. M. Bollinger, R. C. Pardo, K. W. Shepard et al., in Proc. of 6th Intl. Conf. on Electrostatic Accel. and Associated Boosters, to be published in Nucl. Instr. Methods (1992).
[19] L. M. Bollinger and K. W. Shepard, in Proc. 1984 Linear Accel. Conf., Seeheim, GSI Report GSI-84-11, p. 217 (1984).
[20] N. Added, B. E. Clifft, and K. W. Shepard, Paper MO4-55 of this conference.
[21] J. M. Bogaty et al., in Proc. 1990 Linear Accel. Conf., Albuquerque, LASL Report LA-12004-L, p. 465 (1990).
[22] I. Ben-Zvi, A. Lombardi, and P. Paul, Particle Accelerators **35**, 177 (1991).
[23] A. Jain et al., in Proc. 6th Intl. Conf. on Electrostatic Acclerators and Associated Boosters, to be published in Nucl. Instr. Methods (1992).
[24] J. Noe, private communication (1992).
[25] K. W. Shepard and A. Roy, Paper TU4-50 of this conference (1992).
[26] A. Facco et al., in Proc. 6th Intl. Conf. on Electrostatic Accel. and Associated Booster, to be published in Nucl. Instr. Methods (1992).
[27] V. Palmieri et al., in Proc. 6th Intl. Conf. on Electrostatic Accel. and Associated Booster, to be published in Nucl. Instr. Methods (1992).
[28] T. P. Wangler et al., Paper TH4-9 this Conf. (1992).
[29] J. R. Delayen et al., Nucl. Instr. Meth. **A295**, 1 (1990). Also, Paper TH4-37 this Conf. (1992).