LOW-β SC LINACS: PAST, PRESENT AND FUTURE*

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Abstract

This paper is a general review of superconducting low-β technology and applications from its beginning in 1969 into the near-term future. The emphasis is on studies of accelerating resonators and on SC linacs that boost the energy of heavy-ion beams from tandem electrostatic accelerators used for nuclear-physics research. Other topics are positive-ion SC injectors to replace tandems and the need for accelerating structures with β outside of the present proven range, $0.008 < \beta < 0.2$.

1 EARLY HISTORY

The development and construction of the superconducting (SC) electron linac at Stanford stimulated others to investigate SC technology needed to accelerate low-β ions [1]. This effort started (1969) at Karlsruhe, Germany. Much of this work was devoted to Nb helix resonators and related technology. Accelerating fields of 2 to 3 MV/m were achieved for β = 0.04, suggesting that it was feasible to build a useful SC low-β linac. However, it was difficult to control the RF phase of a helix because of its mechanical instability.

In 1970, a small group at Cal Tech also started studies of the helix, but later found that other geometries provided greater accelerating fields and mechanical stability. These new units included the "split ring", two curved RF arms driving two drift tubes with opposite phases. Unlike the helix, for the split ring the RF and the field-formation elements are independent, thus allowing the RF arms to be mechanically stiff. All of the low-β structures at Cal Tech used lead plated on copper as the SC.

In 1971, a group at Argonne joined the study of SC low-β technology and, from the beginning, the goal was to build a SC linac to boost the energy of heavy ions from a tandem electrostatic accelerator. Again, this work started with the single-cell helix, and two such Nb structures (β = 0.06) with independent phase control accelerated an ion beam (proton) for the first time. This and other achievements led to a proposal to build a small SC low-β linac.

A fourth effort (1973) on a low-β structure was at Stanford, where a small group studied a Nb cavity with β = 0.04 and f = 430 MHz. For these parameters, the accelerating gap was very narrow (~ 1 cm), which required the accelerating field to be exceptional large for this unit to be competitive with other structures, which had active gaps ranging from ~ 5 to 15 cm.

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2 FIRST SC ION LINAC

The demands on SC low-β studies at Argonne changed greatly in 1974 when the Atomic Energy Commission agreed to support construction of a small SC linac, i.e., we had to consider all aspects of the system: RF phase control, beam optics, cryogenics, etc. - not just the accelerating structures. Our initial plan was to use 5-cell helix resonators for a 13-MV linac to boost the energy of heavy ions from our 8.5-MV tandem. Fortunately, before our funding arrived in late 1975 we were able to replace the helix with the Cal Tech split ring, but with several changes: (1) Nb as the SC, (2) a smaller frequency (97 MHz) so as to increase the active length, and (3) an outer housing made of Nb explosively bonded to copper. Figure 1 compares our design to other structures that were available at the time.

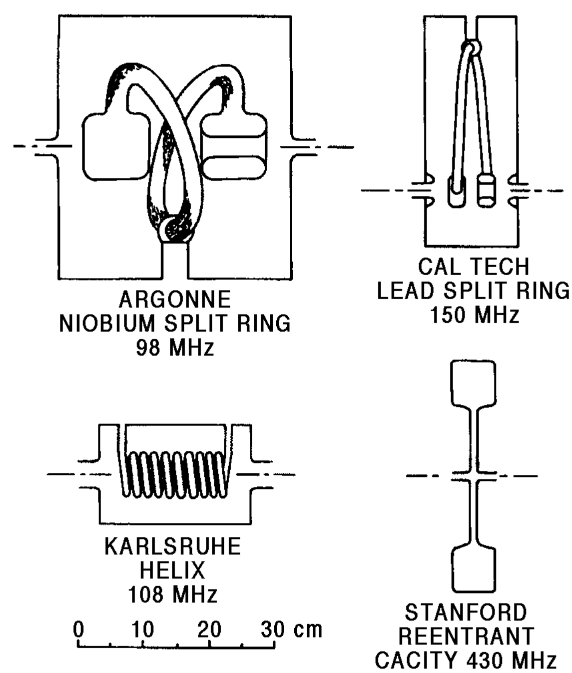

Figure 1: Heavy-ion accelerating structures in 1977.

The layout of the tandem-booster linac system [2] is shown in Fig. 2. Note the beam bunching system [3], 2 bunchers and a chopper, which converts ~ 65% of the DC beam of the tandem into narrow beam pulses (~ 200 ps). Initially the pulse rate of the beam was 97/2 = 48.5 MHz but, at the user's request, it was soon reduced to 97/8 = 12.125 MHz. Two classes of resonators are used in the booster: β = 0.065 and β = 0.105. The split rings are closely mounted in groups of 2 separated by SC beamfocusing solenoids, the first accelerator of any kind in which SC was used for both acceleration and beam optics.

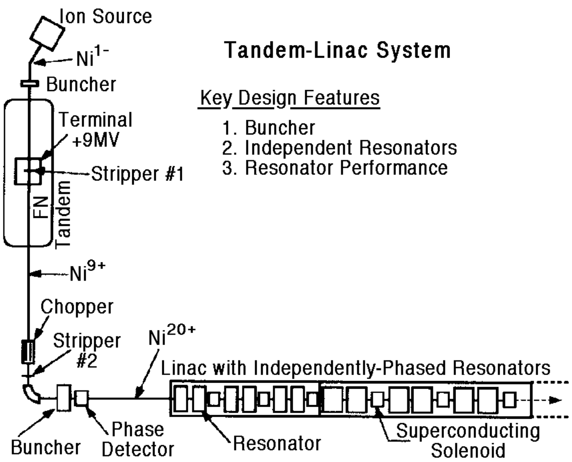

Figure 2: Main components of a tandem-linac system.

The phase control of each resonator is controlled by a VCX (voltage control reactance) but, in spite of the sturdy arms of our split rings, our initial VCR's provided only marginal control. After several major upgrades, the control problem was removed by a VCX that has a stored energy of 30 kW.

As soon as a small part of the booster was operable it was tested (June, 1978) and soon used for research (September, 1978). This step-by-step approach was continued for the next 3 years until the booster was completed. The goals of the project were more than met: an accelerating voltage of ~ 22 MV, excellent beam quality, short beam pulses, adequate acceptance of the tandem beam, easy change of beam energy, and future expandability.

In late 1983 funding was obtained to extend the booster linac and to add an adequate experimental area. The goal was to be able to accelerate ions with A ≤ 130 to energies above the Coulomb barrier (~ 5.5 MeV/A). Since the original linac was operating well, we used the same technology for the addition. After completion in 1985, the entire linac provides ~ 38 MV; and the enlarged tandem-linac system [1,4] was named ATLAS.

3 EXISTING SC LOW-β LINACS

During the twenty-year period following the initial success of the tandem-linac system at Argonne, other laboratories undertook similar projects [5-15], listed in Table 1. Their primary goals were the same as discussed in Sec. 2, but often with significant differences in technology, as indicated in Table 1 and in [1,16]. For lack of space, only a few of these tandem-linac systems are mentioned below. Accelerating structures are treated in Sec. 4.

Table 1. <u>Heavy-Ion Tandem-Linac Accelerators</u>

Location	Accelerating Structure	f (Mhz)	β
Argonne--(In USE)	Split Ring (Nb)	97	.065 → .105
Stony Brook--(In USE)	SR + 1/4 Wave (Pb)	150	.06 → .10
Florida State--(In USE)	Split Ring (Nb)	97	.105
Saclay--(Terminated)	Helix (Nb)	135	.08
U. Washington--(In USE)	1/4 Wave (Pb)	150	.10 → .20
JAERI (Japan)--(In USE)	1/4 Wave (Nb)	130	.10
Kansas State--(In USE)	Split Ring (Nb)	97	.105
Legnaro (Italy)--(In USE)	1/4 Wave (Pb, Nb, Nb/Cu)	80, 160	.055 → .11 → .15
Sao Paulo--(?)	Split Ring (Nb)	97	.105
Bombay--(?)	1/4 Wave (Pb)	?	?
Delhi--(Under Construction)	1/4 Wave (Nb)	97	.08
Canberra--(In USE)	Split Ring (Pb)	150	.10

The second SC linac was built at Stony Brook [5] with split-ring Pb/Cu resonators provided by Cal Tech. The other parts of the linac were handled by a small group of faculty members and students at Stony Brook. I was especially impressed that students, after training, did work such as welding large pipes.

The linac at U. of Washington [8] was the first to use the quarter-wave resonator (QWR), a new class of structure developed at Stony Brook [17]. Two types of units are used: β = 0.10 and β = 0.20, both with Pb/Cu as the SC. These relatively large values of β indicate that the goal was to accelerate rather light ions, including protons, as needed by the research program.

The linac at JAERI (Japan) [9] was the first to use Nb for QWR. The oval-shaped outer shell of these units are explosively-bonded Nb to Cu. These units provide an average accelerating field > 5 MV/m, much greater than other SC low-β linacs in routine use.

The most ambitious of all SC low-β projects [11-13] is at Legnaro (Italy). It's injector is a 15-MV tandem, and the linac is designed to provide 48 MV, both substantially larger than any other tandem-linac system. The initial plan was to use QWR units with Pb/Cu as the SC, and some such units were installed, tested, and used. These initial structures are now being replaced by several kinds of RFQ units in which the SC is bulk Nb metal in some and Nb sputtered on Cu in others [11,12,13,18].

An interesting aspect of the teams that have designed and built the SC low-β linacs is that very few persons who played major roles had much experience in accelerator technology before entering the SC low-β game; indeed, I can think of only one American who did have earlier experience. On the other hand, most of the leading figures were physicists who had a thorough understanding of their goals.

4 ACCELERATING RESONATORS

The SC low-β resonators available in 1977 are shown in Fig. 1. Since then, many other structures have been studied, starting with the quarter-wave resonator (QWR) developed [17] at Stony Brook in 1983. The laboratories involved in these investigations are listed in Table 2, which includes (a) work before 1983, (b) other designs that have been fully tested, and (c) work now in progress. Most of these units were designed for use in planned or existing linacs.

Table 2. Development of Accelerating Structures

Split Ring		**1974-1982**
Cal Tech -	Pb	
Argonne -	Nb	
Stony Brook -	Pb	
2-Gap Quarter Wave		**1982 →**
Stony Brook -	Pb	
Rehovot (Israel) -	Pb	
U. of Washington -	Pb	
Argonne -	Nb	
Bombay -	Pb	
JAERI (Japan) -	Nb	
Legnaro -	Pb, Nb, Sput. Nb, NsSn	
Canberra -	Sputtered Nb	
4-Gap Interdigital		**1985-1990**
Argonne -	Nb	
2-Gap Half-Wave		**1990 →**
Cal Tech + Argonne -	Nb	
Argonne + CEBAF -	Nb	
2-Gap QW with Nb Outer Jacket		**1992 →**
Legnaro -	Nb	
2-Gap QW with SS Outer Jacket		**1992 →**
Argonne + Delhi -	Nb	
RFQ		**1990-1993**
Stony Brook	Pb	

Figure 3 shows some of the resonators initiated in the 1980's; all but the half-wave unit are now in use. The units in Fig. 4 are more recent products for which an important objective is to reduce fabrication costs. Design changes and improvements in welding appear to have reduced costs by a factor of ~ 1.5.

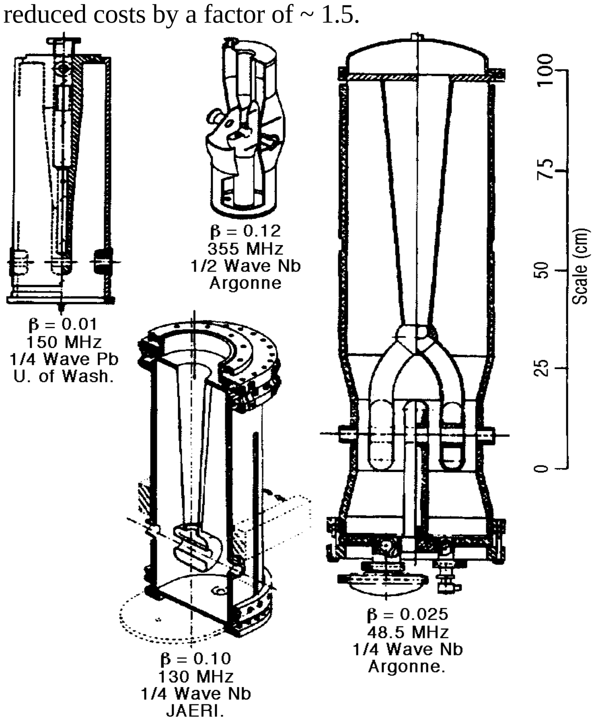

Figure 3: SC resonators from the 1980's.

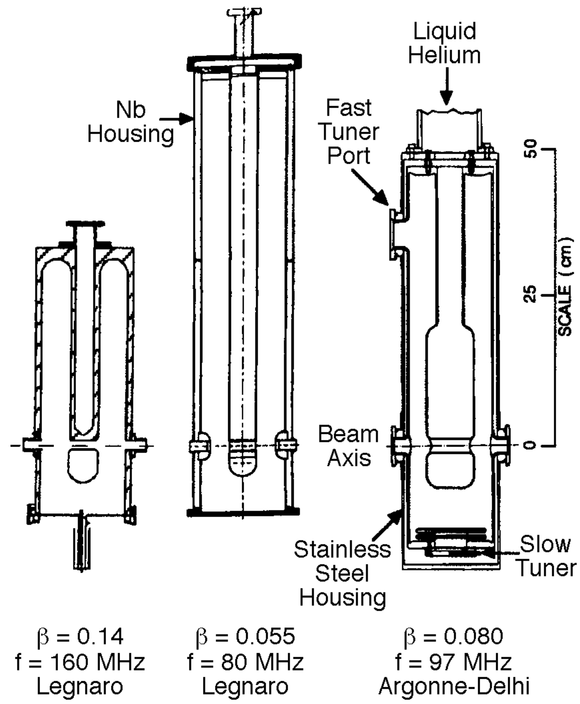

Figure 4: New resonators.

The long-term efforts at Legnaro and Canberra to use sputtered Nb on Cu as the SC surface are now being tested on the linac at Legnaro and the results are very encouraging [18,19]. It seems unlikely that sputter Nb will be superior to bulk metal, but it may reduce costs.
In SC low-β resonator design, many factors need to be considered: the SC material, RF frequency, optimum β, number of accelerating gaps, mechanical stability, the number of different resonator types needed, the ratio of accelerating field to maximum surface field, fabrication difficulties, and costs. Many of these factors interact with each other, making it impossible to determine a unique solution. For example, for resonators in routine use, the split ring in ATLAS has the greatest accelerating voltage because of its large size generated by its three gaps, low frequency, and high β. However, the higher-frequency 2-gap QWR in the JAERI linac has a greater accelerating field, is more stable mechanically, and is effective over a wider range of β. Which one is better?

5 POSITIVE ION INJECTOR

The linacs discussed above were energy boosters for tandems, an injector which requires a negative-ion source. By 1983 we at Argonne recognized that our tandem needed to be replaced because it could not produce useful beams for the upper half of the periodic table. After considering several possibilities, including a much larger tandem, we decided to build a positive-ion injector (PII) consisting of an ECR ion source on a voltage platform followed by a very-low-β SC linac [20,21].

Since ECR sources were well developed by the mid-1980's and the bunching concept used at our tandem could be used at PII, the main challenge was the linac, which had to accelerate ions from β = 0.008 up to β = 0.05 without destroying the excellent quality of beams from the ECR. The front end of the linac seemed especially difficult because of the very low velocity and the rapid change in velocity of the beam.

One of the four interdigital resonators [22] used to span the required β range is shown in Fig. 3. The housing is Nb explosively bonded to Cu, and this housing is compressed around the beam line so as to form an oval-like shape. As in the booster linacs, SC solenoids are located after one or two resonators so as to minimize the beam size within resonators. The PII linac is easily tuned and, in practice, the whole ATLAS linac (including PII) is now usually tuned to the same recorded velocity profile for many ion species, and consequently tuning is exceptionally easy and rapid [23].

A different positive ion injector [24] is planned for the SC linac at Legnaro. The ion source is an ECR, of course, and its output is injected into an array of three Nb SC RFQ's followed by a QWR section. These RFQ 80 MHz units are designed to cover the β range 0.009 to 0.05. A full-scale stainless-steel model of an RFQ has been studied and a Nb unit is under construction. Based on the experience for other SC low-β resonators, phase control for a large SC RFQ may be difficult. In the early 1990's a SC low-β RFQ was built and tested at Stony Brook [25], but phase control was not attempted.

6 OPERATIONAL EXPERIENCE AT ATLAS

ATLAS is the largest and most intensively used SC low-β linac now in operation. The overall layout of the system is shown in Fig. 5. The primary injector is PII, where a second, more powerful ECR ion source has been added recently. The tandem is still used for very light ions and for radioactive species.

The first experiment with a small part of ATLAS was 20 years ago, Sept. 1978. Since then the system has been used steadily as the linac grew, and in recent years its beam has been used for research and occasionally development for more than 5,000 hr. annually [23]. Overall, since 1978 ATLAS has provided ~ 70,000 hr. of useful beam time.

Because of its positive ion injector, ATLAS provides beams for all parts of the periodic table. This wide range is used regularly; for example, 28 different isotopes ranging from hydrogen to uranium were used in FY1997. Altogether, there were 63 separate runs ranging from 8 hr. to 8 days.

7 NEEDS FOR NEW ACCELERATING STRUCTURES

Several future applications of SC linacs come to mind: (1) small linacs for purposes other than nuclear physics, (2) accelerating structures for intermediate-β ions, and (3) radioactive ion accelerators (RIB).

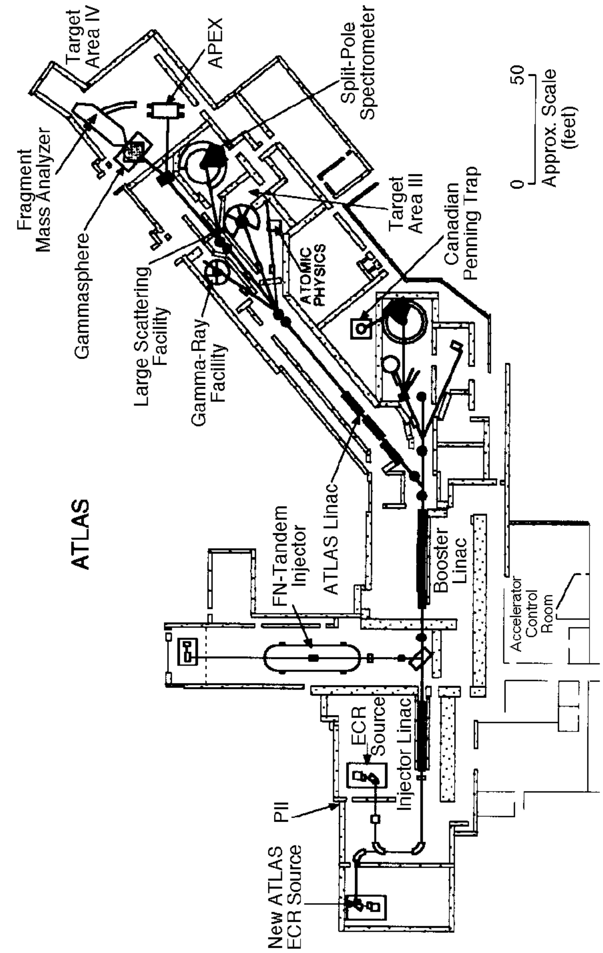

Figure 5: ATLAS in 1998.

Small linacs might be useful in materials science and industry. For example, most ion implantation is done with small electrostatic accelerators which provide limited depths of implantation and range of ion species. These limitations could be removed by a small SC low-β linac. However, it is not obvious that this approach is optimum, especially since CW operation may not be needed.

SC accelerating structures for intermediate-β ions may be attractive for a number of accelerators now being considered, of which I will mention two. One class is the high-current high-energy machines that have been studied at Los Alamos. They have tested 700 MHz SC cavities with β ≈ 0.48, 0.64, and 0.82, and have concluded that for them, room-temperature structures are better for β = 0.48, and SC is optimum for the other two [25].

Another active proposal is a radioactive ion beam accelerator (RIB) at Argonne. The driver of this system is to be a 200-MV linac that can accelerate both protons and much heavier ions. CW operation is highly desirable, which makes SC technology very attractive. In an

Argonne-CEBAF collaboration [27], a SC 1/2-wave resonator with f = 350 MHz and $\beta = 0.4$ is being built for possible use in the RIB driver. An important feature of the 1/2-wave design (see Fig. 3) is that its ratio of accelerating field to surface field is substantially greater than for all other low-β resonators and, consequently, in an earlier test [28] on a $\beta = 0.10$ unit, the maximum accelerating field was 18 MV/m, ~ 50% greater than other low-β units as shown in Table 3 of [20]. However, additional experience is needed before the optimum structure can be chosen.

The third need for resonators is in the range below $\beta = 0.008$, the present limit set for SC by the first resonator in PII at Argonne. The requirements for the Argonne RIB are extreme: to accelerate a CW beam of radioactive ions with q/A = 1/120 through the range from $\beta = 0.001$ to $\beta = 0.008$ without seriously deteriorating the beam quality. The system planned [29] has two steps: a CW room-temperature 12.125 MHz RFQ on a 300 kV platform for the β range 0.001 to 0.0025, followed by a second RFQ on an independent voltage platform for the β range 0.0025 to 0.008. The first RFQ is undergoing tests now [29] and seems likely to be an excellent solution, and the second RFQ should be less demanding than the first because of the greater velocity of the beam. Note that the very low RF frequency is an essential design feature because of its low RF-power requirements. It appears, then, that if a very low RF frequency is acceptable and if the 12.125 MHz RFQ's function as well as expected, then SC structures are not competitive below $\beta \approx 0.008$.

As has been hinted by the topics mentioned in this section, there are still many questions to be answered about SC low-β linacs. Unlike most of the past, these questions are concerned with the two fringes of the low-β spectrum, and answers are needed for small but important parts of future accelerator systems. The subject is still interesting - but, for me, not as exciting as it was in the 1970's.

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