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A SUPERCONDUCTING HEAVY ION INJECTOR LINAC*

K.W. Shepard
Physics Division
Argonne National Laboratory
Argonne, IL 60439

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K.W. Shepard
Physics Division
Argonne National Laboratory
Argonne, IL 60439

Abstract

A conceptual design for a very low velocity (.007 < v/c < .07) superconducting heavy-ion linac is reviewed.[1] This type of linac may have significant cost and performance advantages over room-temperature linacs, at least for applications requiring modest beam currents. Some general features of the design of very-low velocity superconducting accelerating structures are discussed and a design for a 48.5 MHz, v/c = .009 structure, together with the status of a niobium prototype, is discussed in detail. Preliminary results of a beam dynamics study indicate that the low velocity linac may be able to produce heavy-ion beams with time-energy spreads of a few KeV-nsec.

Introduction

The recently completed Argonne Tandem-Linac Accelerating System (ATLAS) accelerator consists of a 9 MV tandem electrostatic accelerator injecting a superconducting linac that has an effective accelerating voltage of approximately 40 MV. The tandem is a modified FN-model machine, using foil stripping in the high-voltage terminal. The linac consists of an array of 42 independently phased superconducting niobium resonant cavities of the split-ring type.

Performance of the ATLAS system is limited by the characteristics of the tandem electrostatic injector in two significant ways: (a) beam currents are relatively low and (b) foil stripping and the small size of the tandem restricts useful ion species to the lighter half of the periodic table.

As was discussed in an earlier paper,[1] a cost-effective way of overcoming these limitations seems to be to replace the FN tandem with a positive-ion source and a small superconducting linac. Because the velocity of the ions involved is a factor of five lower than can be accelerated by present superconducting resonators, the proposed linac requires a substantial extension of existing superconducting RF technology.

In what follows, first the over-all conceptual design of the injector is briefly reviewed, and then the design and development of very-low-velocity superconducting resonators is discussed with emphasis on the technically difficult low end of the velocity range. Some results of a beam-dynamics study are presented, and the status of a prototype superconducting resonator is discussed.

Elements of the Injector Linac

The first element of the injector will be an electron-cyclotron resonance (ECR) positive-ion source[2] mounted on a high voltage platform. To accelerate uranium beams, a 350 KV platform will be required. The highly charged ions from the ECR source will be accelerated to ground potential, bunched, and analyzed before entering the superconducting injector linac.

The linac will consist of an array of short superconducting resonators, interspersed with superconducting solenoid focussing elements and arranged in several modular cryostats. A tentative layout for the first cryostat module is shown in Figure 1. Solenoid focussing elements are highly effective at low velocities and since superconducting solenoids have been used very successfully in ATLAS,[3] somewhat smaller solenoids of the same basic design will be used in the injector linac.

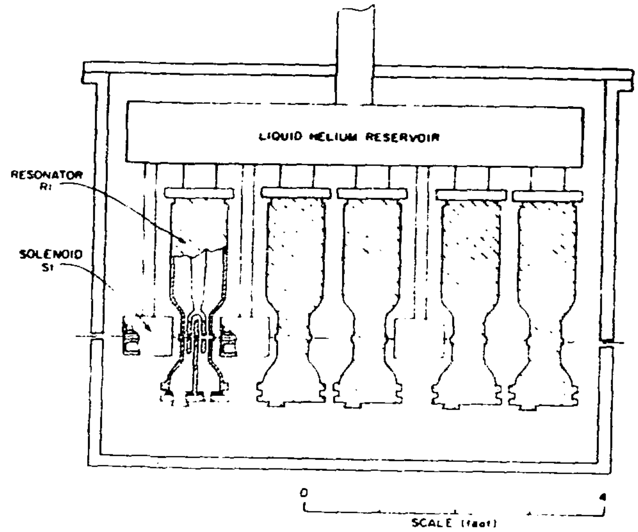

Figure 1. Schematic representation of the initial cryostat module of the proposed superconducting injector linac.

The viability of this type of linac relies on the fact that short, high-gradient superconducting accelerating structures can be closely interspersed with short, powerfully focussing superconducting solenoids. The rapid alternation of radially and longitudinally focussing elements maintains the beam in much the same way as does a Wideroe structure with quadrupoles in the drift tube, but with the simplicity and versatility of small, independently controlled modular elements. Also, the high RF efficiency of superconducting resonators is particularly advantageous at very low particle velocities.

A tentative injector linac design calls for four different resonant cavity geometries which would span a range of particle velocities from .075 c to .07 c as shown in the energy gain curves of Figure 2.

The resonant cavities would be of two basic types: for higher velocities a two drift-tube, 3-gap structure operating at 48.5 MHz will be used. An attractive geometry for this type would be a low-velocity version of a recently proposed half-wave heavy-ion accelerating structure.[4] At lower velocities a 4-gap, forked drift-tube structure shown in Figure 3, will be used.

Although a single drift tube, two-gap resonator is conceptually simpler than the proposed forked drift-tube structure, the latter will provide twice

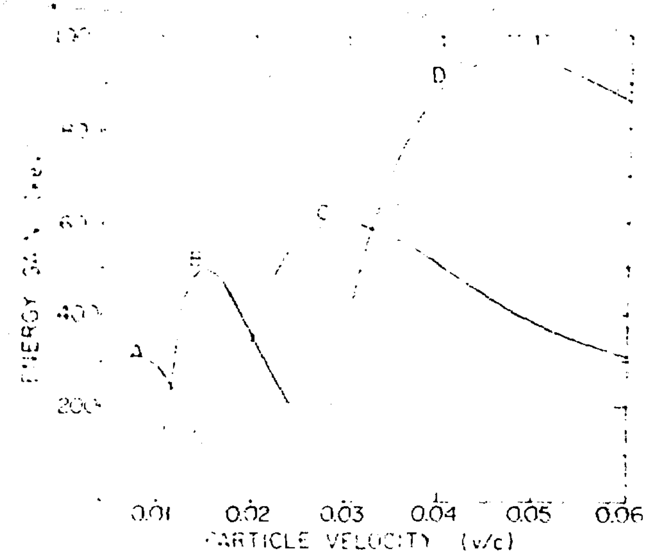

Figure 2. Energy gain as a function of particle velocity for four types of 48.5 MHz superconducting resonators which could form an injector linac. An accelerating gradient of 3 MV/m is assumed.

the accelerating gradient and require half as many resonant cavities as the former. Resonator, cryostat, and control electronics costs for a linac will all scale with the number of resonators. Thus, the small added cost of a forked drift tube will be repaid many times by the reduced number of resonators.

For the proposed injector linac, a 28 resonator linac would accelerate uranium beams sufficiently to inject into ATLAS. Only ten resonant cavities would be sufficient for mass numbers below 120.

A Very Low Velocity Accelerating Structure

Development work has been started with the forked drift tube, 4-gap resonant cavity, since the greatest technical difficulties, particularly that of mechanical stability, occur at the lowest velocities.

Virtually all of the superconducting accelerating structures currently used for the acceleration of heavy ions consist of various forms and combinations of a quarter-wave resonant transmission line terminated in the capacitive load of a drift tube which shapes the electromagnetic field near the beam axis. We propose to use this class of resonator for the proposed injector linac, but must match the resonators to particle velocities a factor of six lower than has been so far achieved. This requires either that we go to a lower frequency by lengthening the transmission line or that we reduce the beam-axis wavelength by foreshortening the drift tubes, or that we do both. Either choice conflicts with other crucial design requirements.

Foreshortening the drift tubes increases both off-axis variations of the accelerating field and also radial defocussing effects. Also, as a drift tube is shortened, the aperture must be reduced or the efficiency of the drift tube in coupling to the beam is decreased.

The other conflicting requirement is the great mechanical stability required of a superconducting resonator. For the class of superconducting resonators discussed here, ambient mechanical vibration causes RF eigenfrequency jitter $\delta\omega$ typically several factors of ten larger than the intrinsic resonator bandwidth. Phase control of the resonator then requires a fast-tuning system which must control an RF (reactive) power

$$P = 2\delta\omega U_0 E_a^2$$

where $U_0 E_a^2$ is the RF energy content in terms of the normalized energy content U_0 and the accelerating field level E_a. Existing tuning systems can supply at most a few kilowatts.[5]

For a given transverse mechanical acceleration, the displacement of a drift tube at the end of a transmission line will vary as at least the cube of the length of the line. Also, the effect of a given displacement on eigenfrequency will be inversely proportional to the capacitive gap between the drift tubes or *wavelength along the beam axis*. Thus, going to lower particle velocities by either lowering the RF frequency or by reducing the wavelength rapidly worsens the mechanical stability of a superconducting accelerating structure.

A coaxial, cylindrically symmetric geometry for the transmission line has two properties of particular advantage for the present application.[6] The simplicity of the geometry makes it feasible to construct a line with a substantial taper, providing a high degree of mechanical stiffness. Also, for a given drift-tube voltage or accelerating field, the RF energy of a coaxial line, to the extent that end effects can be ignored, depends only on the ratio of line diameter to housing diameter. Thus the diameter of the line can be increased, obtaining good mechanical stiffness without paying a penalty in terms of increasing the RF energy content.

The F-type Resonator

Figure 3 shows the cross section of a 48.5 MHz, β_0 = .009, 4-gap accelerating structure (hereafter referred to as the F-type resonator). This resonator geometry will usefully accelerate particles with velocities as low as .0075 c and would provide for the acceleration of $^{238}U^{20+}$ in the proposed injector linac.

The outer cylindrical housing has an 8" ID and an overall length of 42 inches. The tapered center conductor has a diameter of 4 inches at the shorted end and tapers to a diameter of 2 inches at the high-voltage end. The forked drift tube straddles a low-voltage counter drift tube, both of 5.5 inch diameter in the transverse plane. The drift tube diameter is larger than required to shape the field on the beam axis in order to provide a large capacitive load and shorten the transmission line, thus increasing mechanical stability.

Table I compares the electromagnetic properties of the F resonator with the split-ring structures currently in use in the ATLAS system.[7] The peak surface fields are acceptably low, and performance is expected to be limited by electron loading. On the basis of performance of resonators in the ATLAS system, accelerating gradients of 3 MV/m or higher should be obtainable in the F-type resonator. At this gradient, a single F-type resonator would provide an effective accelerating potential of 300 KV.

Table 1
Properties of Several Argonne Superconducting Resonator Geometries

Type	Optimum Velocity	Frequency	Peak Surface Fields* Electric	Magnetic	RF Energy*	Static Frequency Shift*	Length
[illegible]	[illegible]	[illegible] MHz	4.80 MV/m	260 G	0.120 [illegible]	59 Hz	35.6 cm
[illegible]	0.105	97.0	4.80	185	0.147	112	35.6
[illegible]	0.065	97.0	4.85	142	0.073	59	20.3
F	0.009	48.5	5.5	104	0.032	--	10.2

*At an accelerating gradient E_a = 1 MV/m. E_a is defined as the energy gain per unit charge per unit length for a synchronous particle.

Mechanical properties of this geometry have been measured in the linac environment at room temperature using a full-size normally conducting model. Such measurements in this laboratory in the past have given fairly accurate (within typically a factor of two) indication of vibration levels of superconducting resonators in actual cryogenic operation. A total eigenfrequency jitter of 30-60 Hz peak-peak was observed, a vibration level roughly equal to that experienced by the present ATLAS resonators. With the low RF energy content of the F resonator, a vibration level ten times as high would be within the range of the PIN diode based fast-tuning system currently used for ATLAS.

An earlier version of the F resonator employed a tapered line half the diameter of the present design, and exhibited a vibration induced RF eigenfrequency jitter of ~1000 Hz p-p.

A Prototype Superconducting Niobium Resonator

Construction of a prototype niobium superconducting resonator has been initiated and is, at this writing, approximately 80% complete.

The outer housing of the resonator and the counter drift tube are constructed of explosively-bonded niobium-copper composite which provides good thermal stability together with high mechanical strength.

The outer housing of the prototype resonator has been explosively bonded directly in cylindrical form, eliminating a difficult seam weld, and reducing construction costs.[8] The 8 inch ID tube used for the F resonator will also serve as the outer housing for the next two of the three remaining resonator types required by the injector.

The tapered line has been formed by welding two half cones of .090 inch niobium sheet.

The forked drift tube is being formed from a solid piece of niobium, with a few cooling channels drilled into the solid block. The recent availability of very high thermal conductivity niobium permits this cost-effective approach without degrading the thermal stability of this critical component.[9,10] The use of cooling channels in a solid block increases by a factor of six the distance heat must flow through the niobium when compared with the present drift tube design. The drift tubes used in the current ATLAS superconducting cavities are hollow, with 1.5 mm wall thickness and cooled by nucleate boiling of liquid He inside the drift tube. The thermal conductivity of the niobium to be used for the drift tube of the F resonator has been measured and found to be nearly ten times larger than typical values for the reactor-grade niobium currently employed. Thus the use of cooling channels will not degrade the thermal stability of the drift tube as compared with current practice.

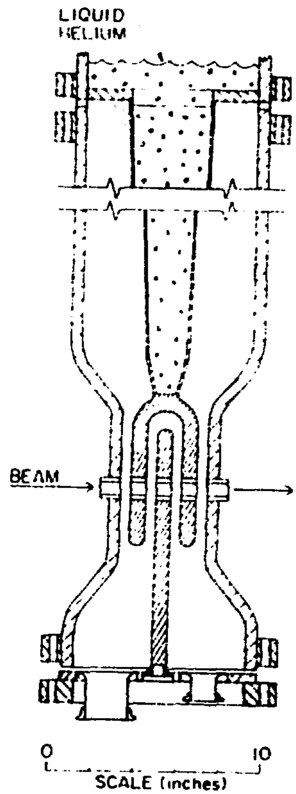

Figure 3. Cross section of the F-type resonator. The 48.5 MHz resonant cavity has four accelerating gaps, a clear aperture of 1.5 cm and an active length of 10 cm.

Some Beam Dynamics in the Resonator

The beam dynamics of the first resonator in the injector are particularly interesting because of the exceptionally large energy change of the beam within the resonator and also because of the small aperture. For the case presented here, $^{58}Ni^{13+}$ from a 200 KV platform, the beam energy more than doubles in traversing the four accelerating gaps of the first resonant cavity.

On and near the beam-axis the electromagnetic fields can be represented very accurately by a near-field electrostatic approximation with cylindrical symmetry. The electric fields have been calculated numerically, using the method of moments, from the drift tube geometry. The results presented here are for bunches of 500 particles randomly distributed over the defined incident phase space volume and numerically traced through the resonator with a 0.5 mm mesh and with radial variation of both longitudinal and transverse fields taken into account. This calculational approach is a straightforward, brute force numerical method which includes from the outset virtually all the electromagnetic forces experienced by a particle traversing the resonator.

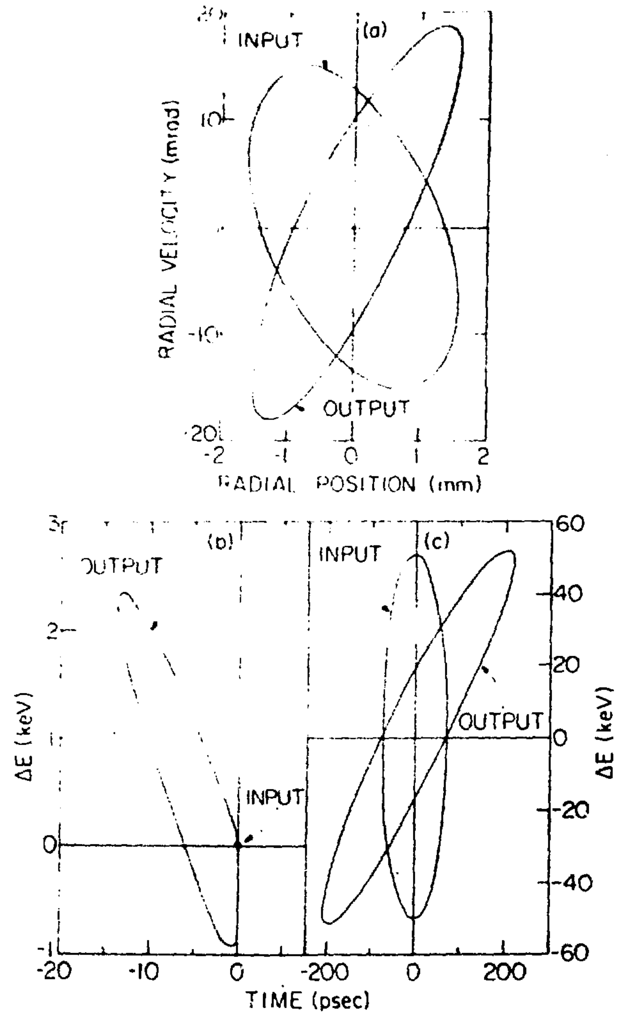

Figure 4. Calculated dynamics of a $^{58}Ni^{13+}$ beam with entrance velocity β_{in} = .0098, traversing an F-type resonator operating at E_a = 3 MV/m. Exit velocity is β_{out} = .0142 and the entrance RF phase is 26 degrees in advance of synchronous phase. Curve A - Transverse phase space. The entering bunch has a traverse emittance ϵ = 20 π mm-mrad. Curve B - Longitudinal properties of a bunch entering with zero time-energy spread to show effects of radial variation of the longitudinal accelerating field. Curve C - Longitudinal phase space assuming an injected bunch with a 150 ps time width and a 4 KeV-nsec time-energy spread.

Initial estimates[1] that radial defocussing effects would be small are born out by the detailed numerical results. Figure 4A shows the transverse phase space for a $^{58}Ni^{13+}$ beam with the expected entering emittance of 20 π mm-mrad.[11] Defocussing effects are quite mild and present no design problems.

Figure 4B shows the time-energy spread induced in a bunch with the above transverse properties, but zero initial time-energy spread, by off-axis variations of the accelerating field. The induced spread of .05 KeV-nsec is extremely small and shows clearly that finite-aperture effects in the low-velocity resonator will not be a practical limit on beam quality.

Figure 4C shows the longitudinal phase-space for a bunch with the above transverse properties and an initial time energy spread that assumes that a time width of 150 picoseconds and a time-energy spread of 4 KeV-nsec can be achieved from the source. The additional time-energy spread acquired in traversing this first resonator is less than 0.5 KeV-nsec, and is expected to be even less for subsequent resonators.

Results such as the above indicate that the linac will be intrinsically capable of very high beam quality, and the actual limits are likely to be set by extraction, bunching, and analyzing systems. The anticipated total time energy spreads of a few KeV-nsec for the case presented compares very favorably with the 50 KeV-nsec that would be typical of a high quality tandem-produced beams.

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