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The paper summarizes plans developed by four different groups for the construction of small superconducting linacs to boost the energy of heavy ions from existing tandem electrostatic accelerators. The projects considered are the linac under construction at Argonne and the design efforts at Karlsruhe, at Stanford, and by a Cal Tech-Stony Brook collaboration. The intended uses of the accelerator systems are stated. Beam dynamics of linacs formed of short independently-phased resonators are reviewed, and the implications for performance are discussed. The main parameters of the four linacs are compared, and a brief analysis of accelerating structures is given.

Introduction

The aim of this paper is to review four projects concerned with the design and construction of small superconducting linacs for heavy-ion acceleration. These are the projects at Argonne[1], a Cal Tech-Stony Brook collaboration[2], a proposal by a Karlsruhe[3] group to build a linac at Heidelberg, and the Stanford[4] project. Of these, only the Argonne linac is under construction; the others are all in the stage of proposals based on the results of extensive developmental efforts. This paper outlines the main features of the four design concepts.

All of the linacs considered are to serve as boosters of heavy ions from existing tandem electrostatic accelerators. The main components of a representative tandem-linac system are outlined in Fig. 1. One starts with a negative-ion source at the low-energy end of the tandem. The beam from the source is partially bunched before injection into the tandem.

After acceleration to the tandem terminal, the negative ions are stripped in either a foil or in gas, and the multiply-charged positive ions so formed are accelerated back to ground potential.

After passing through an analyzing magnet, where a single charge state is selected, the beam is further bunched by a high-field resonator in order to produce the narrow pulses required for optimum acceleration in the linac. Also, either before or after the tandem, unbunched particles are removed by means of a chopper.

Because of the long flight path, the time required for an ion to pass from the pre-tandem buncher to the post-tandem buncher is unsteady. Consequently, some means is required to detect the rf phase with which ion bunches arrive at the post-tandem buncher. This phase signal controls the phase of the pre-tandem buncher. Before being injected into the linac, the ion beam is stripped a second time. If the required charge-state selector is located after the linac, then several charge states may be accelerated through the linac.

In all projects considered, the linac itself is an array of short independently-phased resonators. Interspersed with these are focusing elements (quadrupoles or solenoids) that limit the beam size.

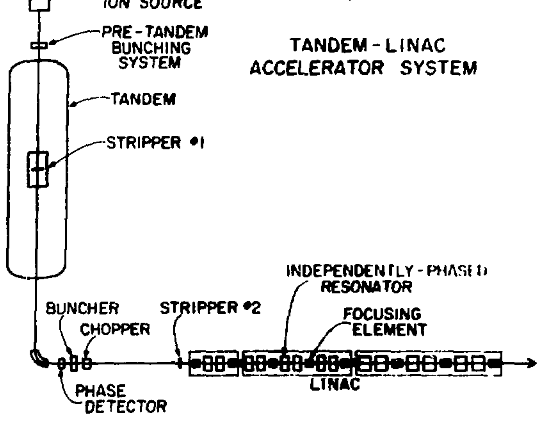
The superconducting linacs are being justified, to some extent, as a contribution to the development of a new technology. However, there is also a keen interest in using them for research. All of the accelerator systems are aimed at the needs of nuclear-structure research. The energy of most interest for such research is the region near the Coulomb barrier, that is, from a few MeV per nucleon to perhaps 15 MeV per nucleon. The accelerator systems considered here will effectively extend research into this band for ions in the lower part of the periodic table but leave untouched the high-mass region.

An accelerator for nuclear-structure research should have easy energy variability and it should provide ion beams of very good quality both with respect to transverse and longitudinal emittance. These characteristics are natural attributes of the tandem-linac system.

Beam Dynamics

An important feature of the linacs considered is that they are formed of short independently-phased resonators. The essential difference between them and a conventional linac is that the velocity profile is established by phasing rather than by the increasing lengths of successive accelerating units. Since the velocity need not be matched to the resonator length, the projectile phase may change greatly while it traverses the structure. Nevertheless, phase focusing is present in the same way as in a long structure with a well-established velocity profile. Consequently, the internal behavior of an ion

Fig. 1.



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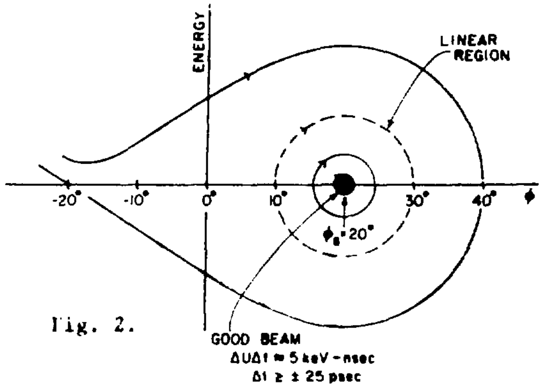

Fig. 2.

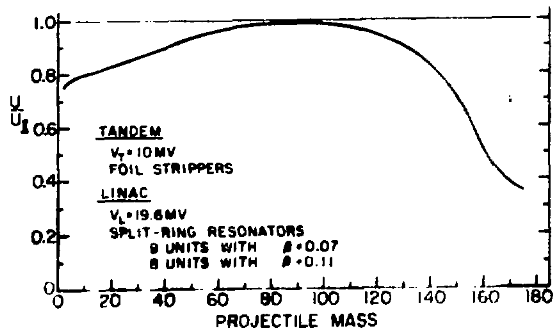

Fig. 4. Accelerating efficiency.

bunch can be described[5] in terms of an equivalent phase space, as shown in Fig. 2, where the acceleration process is treated as though the center of the bunch were synchronous with the forward-travelling wave in a conventional long structure. Here ΔU is the deviation from the average energy of the bunch, and the synchronous phase ϕ_s is the average phase of bunch in each resonator. Within the circle marked "linear region", the phase-restoring forces are accurately proportional to $\phi_s - \phi$ and, if the beam can be confined to this region, beam quality is preserved.

Sometimes it may be advantageous to shape and place the bunch in phase space so as to emphasize a specific beam characteristic at the linac output. Such flexibility requires a sophisticated bunching system.

A short independently-phased resonator can effectively accelerate a wide range of velocities. This is illustrated in Fig. 3, where the transit-time factor (defined by the equation on the figure) is given as a function of U/U_s for two structures, where U_s is the synchronous energy of the structure. A linac formed of such resonators is exceedingly flexible with regard to the mode of operation and hence is tolerant of sub-standard performance of resonators. A failure of resonators to provide the design accelerating field will reduce the maximum beam energy, but the linac can continue to function usefully.

The transit-time factor of a single resonator does not give a direct indication of how transit-time effects influence the output energy of an accelerator system. Rather, one

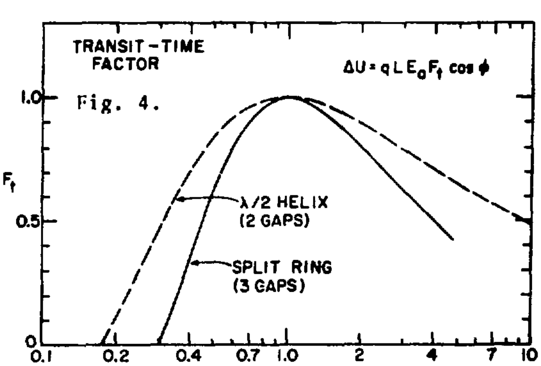

Fig. 4.

needs to know, for a particular system, the mass dependence of the ratio U/U_I, where U is the output energy and U_I is the energy of an idealized system in which the transit-time factor is unity for all resonators. An example is given in Fig. 4. Even though only two sizes of resonators are used, the linac accelerates efficiently over a wide range of mass.

Bunching

A sophisticated bunching system is required for an optimum tandem-linac accelerator. One important requirement is to match the longitudinal phase space of the beam to the linac. As indicated in Fig. 2, one may wish to have ion bunches as narrow as ± 25 psec, which is almost two order of magnitude narrower than is now standard practice. Moreover, because of low beam currents for some ions, the buncher should bunch a large fraction (say 80%) of the dc beam from the source. Calculations indicate that these requirements can be met by bunching in two stages, first before the tandem and then after the tandem. Of these, the first stage is by far the most difficult since there the ions are moving extremely slowly, and several time-spreading effects are important. Post-tandem bunching to form ultra-narrow pulses has been shown experimentally[6] to be easy.

The accelerator user may require a bunching frequency that ranges from perhaps 5 MHz up to the rf frequency. This challenge has not been accepted yet by buncher designers.

Accelerating Structures

The accelerating structures chosen for use are illustrated in Fig. 5, a scale drawing of the inner dimensions of resonators tested to date. Let us briefly consider the main features of each design.

The Argonne split ring[7,8] is a large structure (for a cryogenic system) designed for the high-energy end of the linac. A low-beta unit is under development. The rf frequency is a compromise between a desire to have as low a frequency as possible (to minimize the bunching problem and to maximize the accelerating length of an individual unit),on the one hand, and the desire to limit the radial dimensions and stored energy, on the other. The split-ring tube is shaped so as to

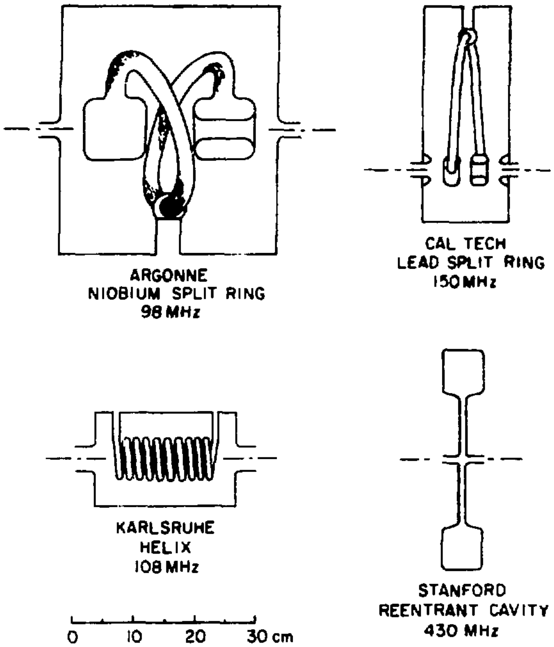

Fig. 5

make the drift tubes coaxial with the housing, thus minimizing the radial size. The structure is mechanically stiff, and hence the rf frequency is insensitive to mechanical vibrations and radiation pressure. The drift tubes are large in order to minimize surface electric fields, sensitivity to mechanical misalignments, and beam-quality deterioration. These desirable features are obtained at the cost of increased stored energy, which increases power dissipation and magnifies the phase-control problem.

The Cal Tech split ring[2,9] tested to date is designed for the low-energy end of the linac. A high-beta unit is under development. The superconductor is lead on copper, which is attractive from the point of view of ease of fabrication and cryogenic simplicity. Because of the high rf frequency (relative to the Argonne design), the radial size is acceptable even though the drift tubes are not coaxial with the housing. The Q of the structure is lower than that of most superconducting structures because the surface resistivity of lead is higher than that of niobium.

The Karlsruhe $\lambda/2$ helix[3,10] is a structure with $\beta = 0.09$ designed for use throughout the linac. A special design feature is that, to reduce fabrication costs, the resonator is formed entirely by arc welding (rather than beam welding). Also, the end plates are welded on rather than attached by means of demountable joints. Relatively large beam ports allow surface treatment to be carried out after the end plates are attached. The 1-cm diameter of the helix wire is thick enough to make the helix fairly stiff. Nevertheless, phase control is still more difficult for the helix than for the other structures. Large end effects of the helix structure limit the average energy gain per unit length achievable with $\lambda/2$ units.

The Stanford re-entry cavity[4,11] is based on the technology developed for the Stanford superconducting electron linac. The good features of the design are a) the axial symmetry, which eliminates beam-steering effects that are present to come extent in the other resonators, b) the wide velocity acceptance of a single-gap structure, and c) mechanical rigidity. These advantages are obtained at the cost of an exceptionally strong sensitivity to multipacting (because of spacial symmetries), a low average field gradient, and an uncomfortably high rf frequency.

Ref. 1-4, 7-11 give details on resonator performance. Some features common to all are outlined in Fig. 6. Here, for a representative unloaded structure, Q is plotted as a function of the maximum surface electric field E_{max}^{sur}. In the low-field region, the loss results mainly from the surface resistivity of the superconductor, whereas in the high-field region, electron field emission is dominant.

The maximum field strength that can be achieved is often determined by cooling. A second set of curves in Fig. 6 give Q vs E_{max}^{sur} for a fixed level of power dissipation. These curves are approximately valid for either a split-ring or a helix structure at 100 MHz; and a power loss in the neighborhood of 25 Watts per meter of active length is representative of the planned linacs.

The point of intersection of appropriate power-loss and resonator-performance curves gives the maximum operating field of a structure. In practice, for the low-frequency niobium structures, at least, electron field emission usually sets the operating field.

Cryogenics and Phase Control

In order to minimize costs, all groups have decided to operate the resonators at temperatures near 4.5°K. Recent experience with low-frequency structures has shown that there is no significant temperature dependence of performance for $T < 4.5$°K. Apparently, the residual resistivity caused by surface defects

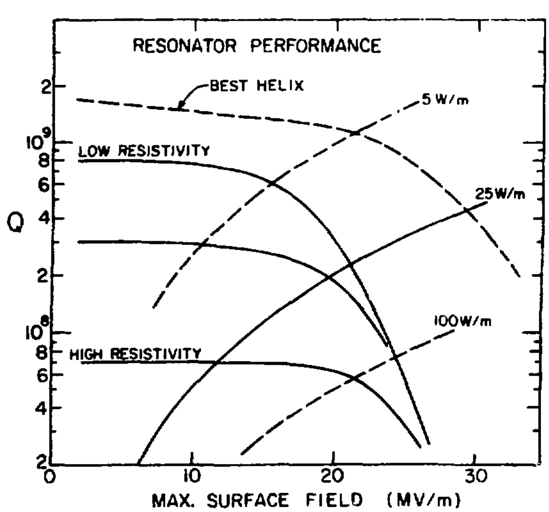

Fig. 6. Resonator performance.

in a practical superconductor are dominant and insensitive to temperature.

The extremely narrow band width of a superconducting resonator and the large size of a structure suitable for heavy ions cause frequency variations to be important and make phase control a significant problem. However, effective means of control have been found for all of the structures considered here.

There are two main elements of a practical phase-control system: 1) an accelerating structure that is rigid enough to limit mechanical motion, and 2) some form of electrical feedback. Perhaps the most elegant electrical control is that used with the Cal Tech split ring, namely, negative phase feedback. The much higher stored energy of the Argonne split ring and the larger frequency variation of the Karlsruhe helix would make phase feedback an expensive approach; instead, both are contolled by a voltage-controlled reactance (VCX) that makes use of reactive power and involves switching PIN diodes.

The Stanford approach is to use a combination of mechanical deformation of the cavity wall and negative feedback. This technique has not been tried on less rigid structures because of fear that the controlling motion may induce harmful vibration.

Summary of Linac Parameters

Important parameters of the four linacs are summarized in Table 1. The best simple measure of a linac's accelerating power is its total voltage gain V_L, which gives a rough indication of the output energy U from the relationship

$$U \le U_o + qV_L , \quad (1)$$

where U_0 is the incident energy and q is charge. Fig. 4 gives an example of the accuracy of the equation, since $U_o + qV_L \equiv U_I$. A 20-MV linac injected by a small tandem is approximately equivalent to a 25-MV tandem for ions in the lower third of the periodic table.

TABLE 1. Linac Characteristics

Linac Size	Argonne	Cal Tech-Stony Brook	Karlsruhe	Stanford
Overall length (meters)	9.6	15.5	19	34
Active length (meters)	4.7	6.8	12	9
Resonators				
Type	split ring	split ring	$\lambda/2$ helix	reentrant
Superconducting material	niobium	lead	niobium	niobium
RF frequency (MHz)	98	150	108.5	430
Number and design β:	12, β=0.105	16, β=0.055	40, β=0.095	90, $\beta \le$ 0.04
Design objectives:				
Max. surface E (MV/m)	20	18	16	12
Max. surface B (mT)	67	33	62	18
Minimum Q	4×10^8	1×10^8	5×10^7	8×10^8
Cryogenics				
Operating temperature (°K)	4.7	4.2	4.5	4.2
Total refrigeration (Watts)	97	150	200	200
Mode of helium cooling	flowing 2-ϕ	pool boiling	flowing 2-ϕ	bath
RF Power and Controls				
Total RF power (kW)	2.8	10	4	0.6
Mode of phase control	VCX	-ϕ feedback	VCX	Piezo-El.
Transverse Focussing				
Type of element	SC solenoid	RT Quad	SC solenoid	SC solenoid
Number of elements	8	12	10	9
Bunching				
Pre-tandem	yes	yes	yes	no
Post-tandem	yes	yes	yes	yes
Injector				
Type of tandem	FN-model	FN-model	MP-model	FN-model
Max. voltage (MV)	9.5	9.5	13	8.5
Performance				
Design objective:				
Max. voltage gain (MV)	20	20	10	17
Ion with U_{max} = 5 MeV/A	75	90	63	44
Worst credible performance:				
Max. voltage gain (MV)	12	13	9	14
Ion with U_{max} = 5 MeV/A	60	65	50	37
Status	under construction	advanced design	advanced design	advanced design

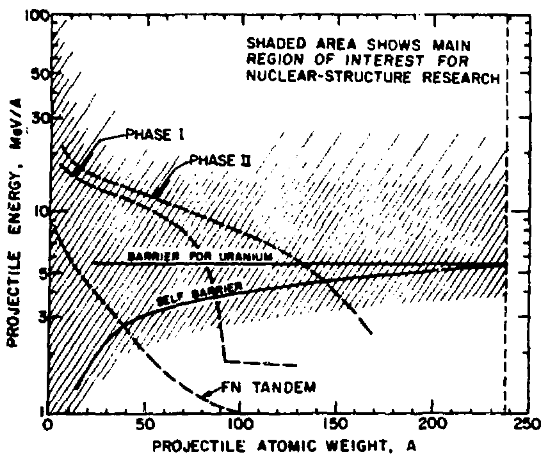

Fig. 7. Representative performance.

The inverse relationship between the effective length of an accelerating structure and the number of units required to form a linac is apparent in the table. The optimum design is a compromise between having a minimum number of resonators and having individual units that are small enough to be manageable. More experience is required before this optimum is located with certainty.

Refrigerator sizes are influenced greatly by economics. However, a larger refrigerator would not increase the operating field greatly because field emission increases so rapidly with increasing field.

The total rf power required is small for all of the linacs under discussion, and most of it is used for phase control.

Performance

Beam Energy

The accelerating powers of the systems under discussion are specified in Table 1. More detail is given in Fig. 7 for one system (Argonne), where the Phase I curve gives energy performance that is representative of a 20-MV linac formed largely of resonators of one size. The Phase II curve shows how the performance can be extended by the addition of only 6 low-β resonators.

Energy Variability

The output energy can be varied over a considerable range merely by changing the phase of the last resonator of the linac. If the phase is restricted to the almost linear part of the acceleration curve, then the output phase ellipse is almost independent of phase. A wider energy range can be covered by turning off resonators.

Beam Current

The linac is expected to accelerate almost all ions injected into it if they have the same charge. Thus, the output beam is determined almost entirely by the tandem and by stripping. If two strippers are used, the number of ions out of the linac can be about 2% of the number injected into the tandem. Typically, the output will be ~10^{11} ions per sec, which is adequate for most nuclear-structure research, especially in view of the good beam quality.

Beam Quality

If beam bunching is refined enough, the ion beam incident on the linac can be accelerated without a significant deterioration of beam quality. Thus, beam quality is established by the tandem and by bunching and stripping. Typically, the transverse emittance of the linac output is expected to range from 1 to 10 mm mrad, depending on the ion and the strippers.

The longitudinal emittance (the product $\Delta U \Delta t$) is determined primarily by pre-tandem bunching and stripping. The optimum is a system in which the post-tandem buncher forms a time focus at the second stripper so as to minimize the influence of straggling. Then $\Delta U \Delta t$ is expected to be in the range 5 to 50 keV nsec, depending on the ion and on the stripper quality. These values correspond to a convention in which both ΔU and Δt are half widths at half maximum of the distributions.

The energy and time spreads of the linac output beam depend on many operating parameters. Typically, however, an incident beam of good quality ($\Delta U \Delta t$ = 5 keV nsec) in the Argonne linac gives $\Delta U/U = \pm 0.5 \times 10^{-3}$ and $\Delta t = \pm 25$ psec.

If the experimenter requires either better energy resolution or better time resolution, then the natural way to obtain it is to debunch or rebunch the beam, respectively. Typically, a debuncher-rebuncher system requires just one conventional resonator, and a flight path about 10 meters long can improve the energy resolution by a factor of 5. The time resolution can also be improved by a comparable factor, if the beam pulse is not extremely narrow initially.

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