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FEASIBILITY AND COST OF A SUPERCONDUCTING HEAVY ION LINEAR ACCELERATOR

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Design, cost, and feasibility studies for a heavy-ion linear accelerator utilizing superconducting resonant cavities are described. Comparisons are presented between this accelerator and several other conceptual designs.

1. INTRODUCTION

In recent months we have been engaged in a study of the feasibility and cost of a superconducting linear accelerator for heavy ions. This paper is a brief summary of the principal considerations and conclusions of that study.

The basic criterion for the accelerator to be discussed here is the ability to accelerate ions of arbitrary mass to an energy of at least 10 MeV/nucleon. The motivations for such a machine have been well documented[1] and will not be discussed further. The purpose of the present study was an assessment of the desirability of a serious research and development effort on the concept of a superconducting heavy ion linac as a means of achieving this goal. Thus, our work has been directed to the question of general feasibility and cost rather than to optimized solutions of every problem which could be foreseen. The question of cost is important for the following reason. In contrast to the situation which exists for electron linacs, we believe all the essential performance characteristics of a superconducting linac can be reproduced in a room temperature linac. Thus, a decision between these options would in part be based on economic considerations.

The method of the study has been to conceptually design a linac and then to study its properties and cost. Since it was beyond our resources to study all possible configurations employing a superconducting accelerator we concentrated on the particular configuration which uses a tandem accelerator as an injector for a superconducting linac. Furthermore, we did not try to optimize the tandem voltage but rather chose a 20 MV tandem of the sort described in our present heavy ion accelerator proposal.[2,3] Although restrictive, this approach does have certain advantages. Specifically, it allows a direct comparison between the present study and the cyclotron described in Refs. 2 and 3. More generally, the present study should serve as a reference point for other cryogenic linac configurations and also illuminate problems which would be common to all superconducting linacs.

The remainder of the paper will be divided into three general sections. The first is a discussion of the design and cost of the particular linac just described. The second is a discussion of the present status of rf superconducting research applicable to heavy ion linacs. The third is a summary of conclusions.

2. ASSUMPTIONS FOR A SPECIFIC DESIGN

In this section, we wish to discuss in a general way several of the choices which must be made in the formulation of a design.

A. *Basic Configuration*

As stated above, the configuration 20-MV tandem plus linac, has been chosen for detailed study. It should be understood that this is not necessarily an optimum choice. Other configurations which could be considered include no tandem at all, as in the Super Hilac,[4] UNILAC,[5] and the Los Alamos proposal,[6] smaller tandems, or injectors of other kinds.

Many properties of the tandem injector influence the performance of the final system. For the purposes of this analysis, we will assume an over-simplified model of the tandem injector in which its

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current output is limited by a maximum ion source current of 25 μA and a maximum high energy tube current for heavy ions of 4 particle μA. We will assume no beam loss and also that the accelerator is operated with a chemically complex gas as the terminal stripper and with a foil as the stripper between the tandem injector and linac. Using calculations and estimates of Stelson,[7] these assumptions yield the typical maximum beams shown in Table I. A much more complete discussion of a 20-MV tandem injector is given in Ref. 3. The results, however, are essentially the same.

TABLE I

Typical maximum beams available from the assumed tandem injector

Beam	Charge state	q/m	Energy (MeV)	MeV nucleon	Intensity (particle μA)
^{1}H	1	1	40	40	25
^{12}C	6	0.50	140	11.70	1.7
^{79}Br	25	0.32	160	2.02	1.4
^{127}I	28	0.22	160	1.26	1.00
^{180}Ta	32	0.18	180	1.00	0.70
^{208}Pb	34	0.16	190	0.913	0.70
^{238}U	36	0.15	200	0.840	0.65

Two important consequences follow from these assumptions. First, the maximum current which can be injected into the linac is about 35 μA (bromine). Second, the most difficult ion to accelerate is uranium. We shall adopt the usual strategy and design the linac to accelerate uranium.

B. *Cavity Type*

There are two fundamental constraints on the choice of cavities for our conceptual design. The first is the low velocity of the particles to be accelerated. The second is the small size dictated by the fact that the cavities must be fabricated of a superconductor. Two types of cavities satisfying these criteria have been studied. These are the re-entrant gap structures studied at Stanford[8] and the helically loaded cavities which have been studied at many laboratories.[9] For our studies, we have chosen to use the helically loaded structure. Originally, this decision was based primarily on a consideration of construction simplicity. However, it now appears that another idea reinforces this choice. This is the idea that defects in cavities may be statistically distributed and among other things may be proportional to surface area.[10] If this is true, a helically loaded cavity would be intrinsically more favourable since its effective surface area is to first order that of the helix.

In any case, our results depend in a simple way on the various cavity parameters and can be scaled to other cavity types in a straightforward way.

C. *Cavity Length*

One of the trade-offs that must be made in a design of this sort is in cavity length. In general, a large number of short cavities gives good flexibility, i.e. the ability to accommodate large differences in beam velocity profiles. This flexibility is usually purchased at the price of complexity. The alternative, long cavities, offers of course the opposite properties, simplicity and lack of flexibility.

In the present case, we have chosen a cavity structure in which the length of the coupled helix array is one meter. This choice, although somewhat arbitrary, was influenced by considerations of fabrication simplicity, electronic simplicity, and reduction of the importance of end effects.

D. *Focusing Technique*

The general problem of focusing in linear accelerators is well known. This is the idea that a particle with stable phase will tend to be radially defocused.[11] The classical solution has been to intersperse lenses between the accelerating elements. However, in the context of superconducting linacs, an old idea has been 'rediscovered'. This is the idea of alternating phase focusing. In the suggestion of Sierk, Hamer, and Tombrello[12] a typical particle undergoes substantial changes in phase within a single accelerating element so as to experience both radial focusing and defocusing. This is the so called 'sling shot' technique. In the treatment of Chambers[13] alternating groups of cavities have different phase so as to produce alternating radial and longitudinal focusing and defocusing. Either of these techniques allows one, in principle, to reduce the number of focusing elements at the price of reduced radial and longitudinal acceptance.

We have chosen not to use these techniques in our design study. Instead, we considered a conventional system with alternating cavities and lenses. We will return to this question as part of our cost analysis and consider the effect of removing the lenses in our conceptual design.

E. *Cooling Technique and Operating Temperature* The problem of cooling technique separates into four possibilities. The first is static heat transport in superfluid helium. This phenomenon has been studied extensively for helical geometries by Krafft.[14] The essential result is this: For tubes in the inside diameter range 0.5 to 1.5 cm, a maximum of about 1.7 W/cm^2 can be transported in static superfluid helium before breakdown. This is the maximum value occurring at a bath temperature of about 1.85 °K. This limit is, to first order, independent of the heating profile on the helix, For example, a helical element with inside cross-sectional area 1 cm^2 could dissipate at most $2 \times 1.7 = 3.4$ W (the factor 2 arises from the two ends).

The second possibility is dynamic heat transport in superfluid helium. By this, we mean superfluid helium which is pumped through the helix. Very little is known about heat transport in this situation and we will not consider this possibility.

The third possibility is dynamic heat transport in normal helium ($T \geqq 2.2$ °K) at pressures below the critical pressure of 2.25 atm. This mechanism has been studied by de la Harpe *et al.*[15] for a particular geometry and temperature. Good heat transfer properties were observed (better than case four to be discussed below). However, this method is subject to the criticism that bubble formation may couple to vibrational modes of the helix or cause other instabilities.

The fourth possibility is dynamic heat transport in normal supercritical helium. This general problem has been studied by Giarrantano, Arp, and Smith[16] using a helium pump described by Sixsmith and Giarrantano.[17] Jaffey[18] has used these results to calculate values for typical helix situations and the results are encouraging. For example, with a 0.48 cm i.d. tube 300 cm long, one can transport 16.7 W using helium at 4 atm with a temperature rise from 2.38 to 3.1 °K. In spite of these encouraging results, we think this approach may have disadvantages associated with its additional complexity and the possibility that a heat transport system utilizing flowing He might be a source of vibration. Therefore, our mechanical design study is based on the first possibility, static heat transport in superfluid helium.

For our cost analysis, we considered two cases. The first is static heat transport in superfluid helium for which the operating temperature would be 1.85 °K. The second is dynamic heat transport in normal supercritical helium for which we arbitrarily chose a temperature of 4.2 °K.

3. DETAILED DESIGN

As stated above, our design effort was directed towards the goal of designing a conceptually possible machine which could serve to illuminate potential problems and as a basis for a cost estimate. It was not intended to be a completely optimized design. In this section, we will very briefly describe the design, relying more on figures than text for description. In many cases, discussion of motivations and alternatives will be omitted.

Figure 1 shows a schematic layout of the accelerator. In consists of alternate cavities and quadrupole lenses all contained within a single cryostat. The number of cavities depends on the achievable surface properties of the rf superconductor and at this point is left as a variable to be used in the cost analysis. Beam dynamics studies showed that it was important for the first few cavities to be closely spaced. Since this is in other ways a disadvantage, we designed two sorts of cavity-lens junctions. These are called 'short' and 'long' sections. These are shown, respectively, in Figs. 2 and 3. They differ in two significant ways. In particular, the 'short' section has no space for in-line valves or beam monitoring and has a shorter lens.

As shown in Figs. 2 and 3, the cavities are double wall cylinders containing an array of $\lambda/2$ helices which are electrically very strongly coupled. The resultant array behaves in the π mode very much like a single helix 1 m long. The quadrupole lenses are shown throughout these drawings in outline only. They are essentially standard items which can be manufactured by several vendors. The lens parameters used in the present design are very similar to and based upon the design used for the Karlsruhe proton accelerator.[19] The current density and stored energy for these lenses are low and they should present no significant problem.

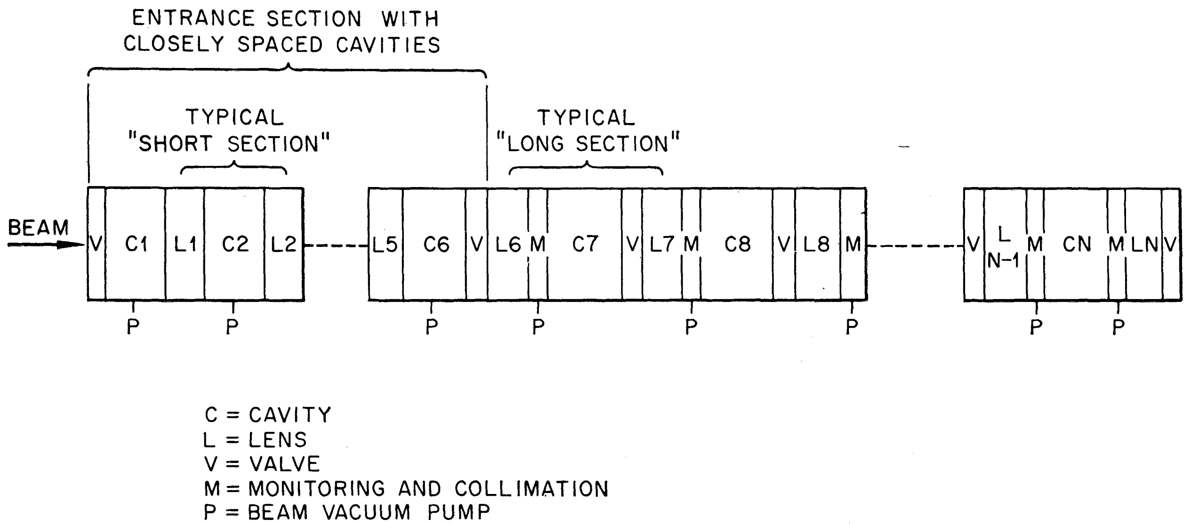

FIG. 1. Schematic arrangement of the conceptual accelerator. All of the elements are contained within a single cryostat.

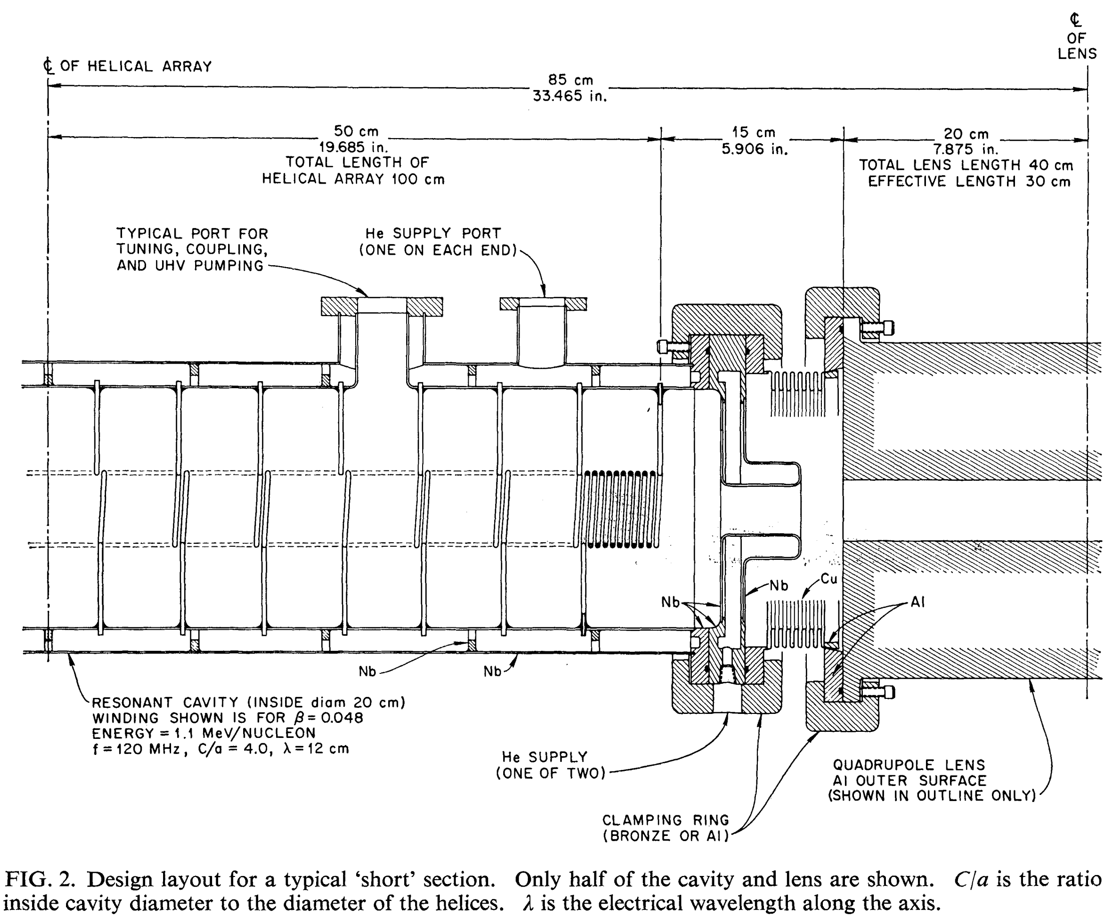

FIG. 2. Design layout for a typical 'short' section. Only half of the cavity and lens are shown. C/a is the ratio of inside cavity diameter to the diameter of the helices. λ is the electrical wavelength along the axis.

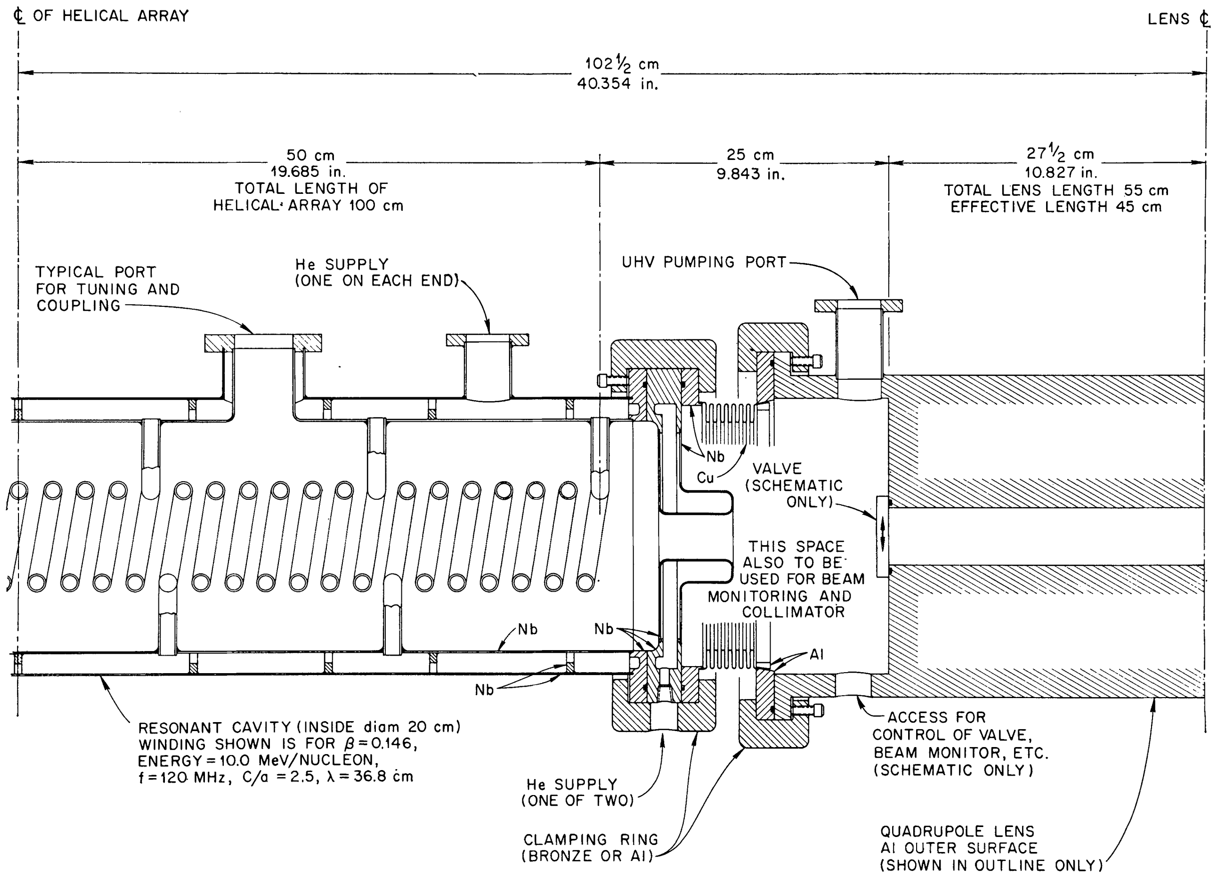

FIG. 3. Design layout for a typical 'long' section. Only half of the cavity and lens are shown. Beam monitors and collimators are not shown. Re-entrant liquid nitrogen cooling may be necessary for these elements. See Fig. 2 for a definition of symbols.

An amusing feature is that they may be used in the persistent mode with superconducting switches so that only two (primary and spare) power supplies are needed for the accelerator.

The philosophy adopted in the present design on vacuum and cryogenic systems is very similar to the Karlsruhe accelerator. Since these have been recently described by Flécher,[20] we will not repeat these ideas again. A design layout of the cryostat is shown in Fig. 4. Although a basically conventional design, our design has some features which deserve discussion.

Our most radical idea is the construction of the cryostat as a single large vessel, 8 ft in diameter. The outer vacuum tank would be constructed of mild steel cylindrical elements approximately 30 ft long which would then be bolted together to form a long cylindrical vessel. With the parameters to be developed below, the length of this vessel would be approximately 200 ft. Access to the vessel would be via 'man holes' in the two end plates. Access to the accelerator elements would then be made via the cart shown in Fig. 4. As shown in Figs. 2 and 3, the accelerator elements are designed to as to be individually replaceable and adjustable. In an effort to reduce external vibration, the vessel would be supported on H beams, perpendicular to the major axis, which in turn would be placed on pneumatic support elements (springs).

The connection between the He transport lines shown in Fig. 4 and the refrigerator would be in the midpoint of the vacuum vessel so that the use of external He transport lines would be minimized. Also, a single pump would be used to evacuate the vessel.

Two tuning functions are required for cavities of

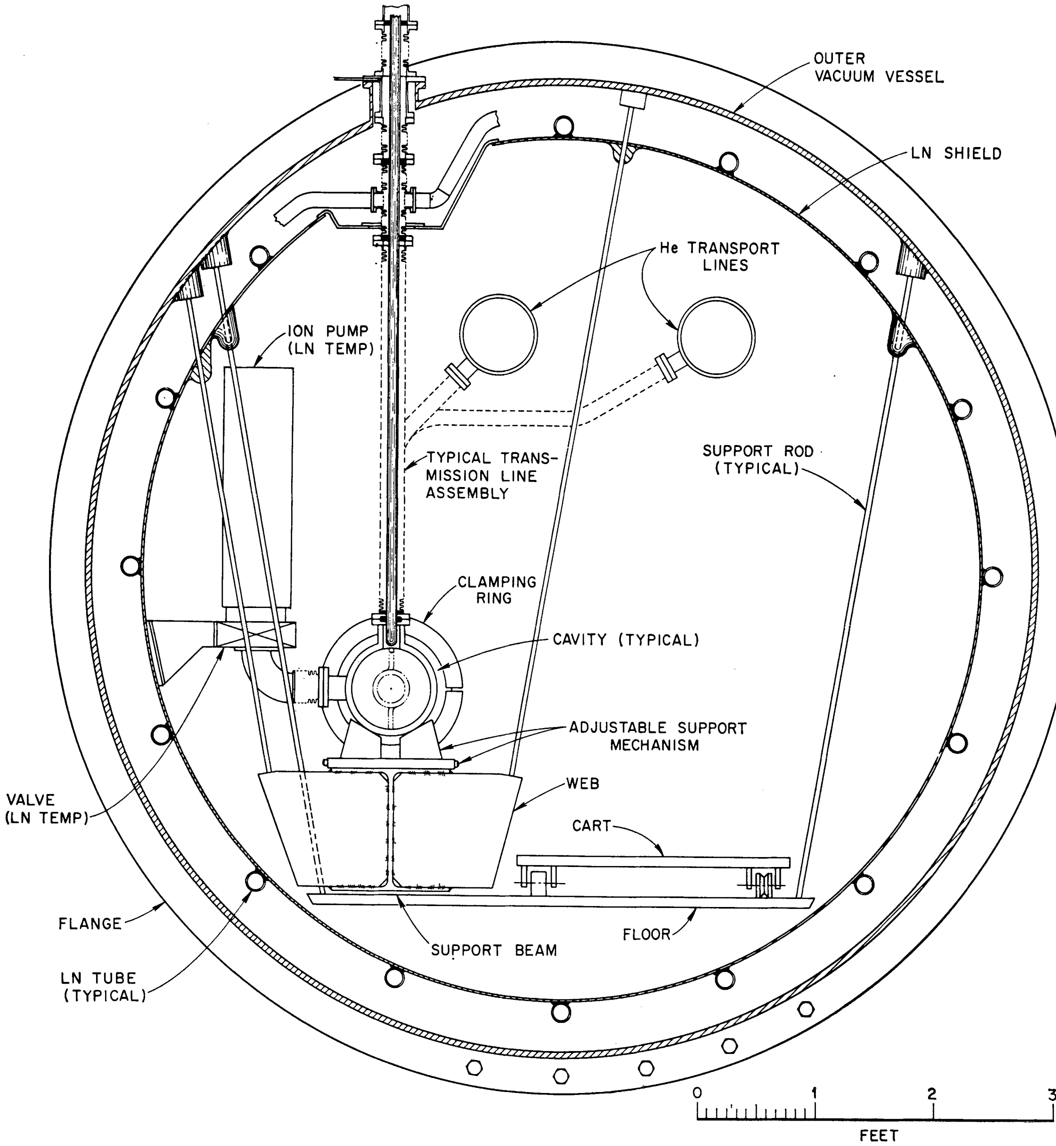

FIG. 4. Design layout for the cryostat. Many details are not shown.

the type shown here. One is called 'slow tuning'. This is the gross adjustment of cavity frequency to compensate for construction variations and radiation pressure induced frequency shifts. This would be accomplished with tuning plungers similar to that shown in Ref. 21. The other tuning function is that called 'fast tuning'.[22] This means dynamic control of the cavity frequency or really phase, so that the phase of all cavities within the accelerator is matched. The best way to do this appears to be with a variable reactance coupled to the cavity. In this case the 'reactive power' which must be transmitted to and from the reactance can be shown to be $PQ(\Delta f/f)$ where Δf is the peak-to-peak frequency modulation (driven by external vibration) present when the tuner is not operating. P is the rf power dissipated in the cavity and Q is the unloaded Q of the cavity. A simpler method uses an external load to increase the cavity bandwidth and a transmitter with modulated phase. In this case the load must dissipate a power, $P_{load} = PQ(\Delta f/f)$, and the transmitter power must be at least $2 \times P_{load}$. We have assumed that the first method is successfully employed. In either case, transmission lines and couplings are a nontrivial problem. One possible solution is that shown in Fig. 4. The suitability of this particular approach depends on parameters which are at this time unmeasured.

4. STRUCTURE PARAMETERS

In this section, we will describe the results of structure prameter calculations for the cavities described above. The problem is this: given a phase velocity profile, in this case from $E = 1$ to 10 MeV/nucleon corresponding to the acceleration of uranium, we need to calculate the various parameters, for example pitch, helix diameter, frequency, etc. of the cavities. Our calculations were based on the work of Sierk, Hamer, and Tombrello[12] and Klein.[23] In keeping with the spirit of this work, we have not attempted a complete optimization, but rather a reasonably close optimization.

Before describing the results, it will be useful to make some definitions. V will be defined as the net accelerating field, that is the voltage gain divided by the length of helical array. It includes end effects (5 per cent) and corrections for an assumed stable phase of 30°. R will be defined as the normalized surface resistivity, in this case, normalized to the theoretical value of lead at 4.2 °K and 120 MHz (2.02×10^{-8} Ω).[24]

The essential results are these:

1. For the energy range in question, 1 to 10 MeV/nucleon, a single frequency, 120 MHz, will work.
2. With $V = 2.0$ MV/m and $R = 1$, the heat generated on the helix is about $\frac{1}{2}$ of the heat transport capacity for static superfluid helium.
3. Let E_{max} and B_{max} be the maximum surface electric and magnetic fields on the helix. Then $E_{max}/V = 8.0$ and $B_{max}/V = 300$ G/MV/m over almost the entire array. The calculations attempted to minimize these ratios and these are essentially the lowest ratios possible in a structure with helical elements of circular cross section. Further improvements may be possible with non-circular helical elements.[6]
4. Conclusions (2) and (3) are violated slightly at very low particle energies, but not enough to seriously affect the basic conclusions of the study.
5. With $V = 2.0$ MV/m and $R = 1$, PQ rises from about 0.3×10^9 at the lowest energy to about 1.8×10^9 W/m at the highest energy with an average value of about 1.0×10^9 W/m.

The last result has the following significance. Arbitrarily assume that the vibration induced fm, Δf is 240 Hz (peak to peak) when $PQ = 1.0 \times 10^9$ W/m and varies in such a way that $PQ\Delta f$ is constant over the length of the accelerator. Then the reactive power required to control the fm (in a variable reactance) $= PQ(\Delta f/f) = 2000$ W. Similarly, if an external load is used to widen the bandwidth of the cavity, the load must be 2000 W and the transmitter must have a capacity of at least 4000 W. These values should be compared to a maximum beam power of about 70 W/cavity and a total power requirement of about 200 W/cavity when an external variable reactance is used.

Finally, Fig. 2 shows the actual configuration for a low energy, 1.1 MeV/nucleon, while Fig. 3 shows the configuration at 10 MeV/nucleon.

5. COST ESTIMATE

5.1. *Bare Capital Costs*

By this, we mean the basic construction cost of the accelerator. It does not include building costs, ancillary beam handling equipment, engineering, research and development, or contingencies. In general, costs quoted are in 1972 dollars and should be escalated to the year of interest. One exception is the helium refrigerator whose cost is predicted by the manufacturer[25] to remain constant due to expected technological improvements.

The analysis was based on the idea of a module consisting of one cavity and lens as depicted in Fig. 3. The number of modules was then variable, depending on V (with the one meter long cavities of the present design, the number of modules is just 60/V). Listed below is a summary of our assumptions.

Refrigeration

Based on conversations with a particular manufacturer,[25] we estimate the refrigerator capital cost to be (450 + capacity in watts at 1.8 °K)k$, plus installation, for systems larger than 150 W. This is in reasonable agreement with our conversations with other manufacturers and with the prescription of Strobridge,[26]

Cost per module	
(a) Cryostat	2.7k$
(b) Cryogenics and internal support structure	8.8k$
(c) Accelerator elements (includes 30k$/bare cavity, this item is of course very speculative)	47.0k$
(d) Electronics and control	11.0k$
Total	69.5k$
Fixed Costs	
(a) Cryostat	71.0k$
(b) Transfer lines	16.0k$
(c) Electronics and control (includes 200k$ for computer)	400.0k$
(d) Refrigerator installation	100.0k$

One goal in the cost estimate was to understand the dependence of capital and operating costs on the achievable surface parameters of the cavities, in this case, V and R. The estimate was made on the accelerator just described, with the assumption of a total acceleration of 60 MV.

The results of these assumptions are shown in the lower part of Fig. 5 where the bare capital cost described above is shown as a function of V (called 'net accelerating potential' in the figure) for different values of R. R_{max} is the largest value of R which may occur before heat transport breakdown in the superfluid helium (1.7 W/cm^2). Since losses are proportional to V^2, R_{max} is, of course, a function of V. For the 'supercritical' calculations, an extra $15,000/module was added for pumps, valves, etc. and account was taken of increased refrigerator efficiency. If the refrigerator can be used as the basic pressure source, obviating the need for individual pumps for each cavity, this estimate may be excessive.

The essential results are clear. The capital cost is quite sensitive to V and relatively insensitive to R. This effect is even more pronounced when the length of the accelerator, shown in the upper part of Fig. 5,

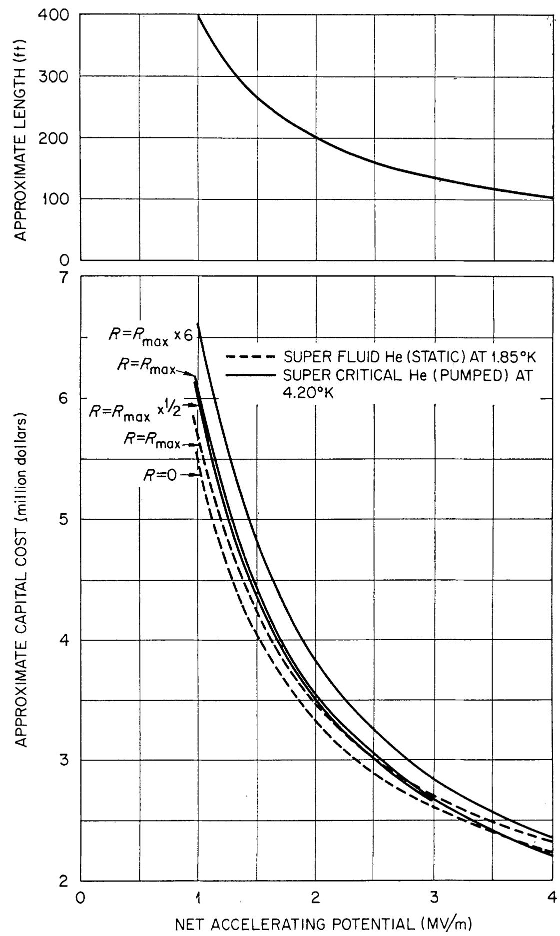

FIG. 5. Approximate capital cost and length of the conceptual superconducting linac described in the text as a function of net accelerating potential called V in the text. Different cost curves are shown for different values of R, the normalized surface resistivity defined in the text. R_{max} is the value of R at which the heat transport limit for static superfluid He is reached in the helically loaded structures discussed in the text.

is considered, since building costs will be a function of length.

What are reasonable values of R and V? Figure 6 is an attempt to answer this question. Here we have plotted R as a dependent variable and surface electric field as an independent variable. For this plot, we have arbitarily normalized the observed surface resistivity to that of Pb at 120 MHz and 4.2 °K. This assumes that the residual resistivity is frequency independent, an assumption confirmed by a single series of measurements at Karlsruhe.[27]

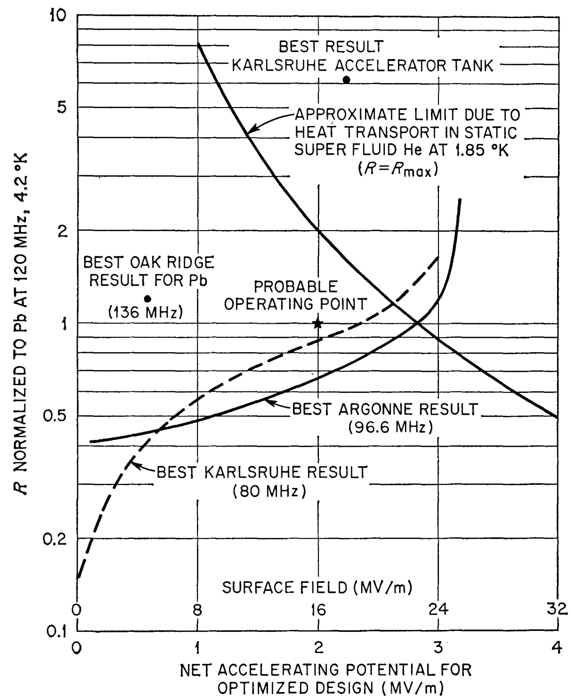

FIG. 6. The result of various measurements on helically loaded cavities. The dependent variable (vertical axis) is the observed apparent surface resistivity, as deduced from Q measurements, divided by $2.02 \times 10^{-8}\ \Omega$. The independent variable (upper horizontal axis) is the maximum surface electric field as deduced from the calculated stored energy and prior field measurements or calculations. On the lower horizontal axis are shown corresponding values of the variable V described in the text, calculated for helically loaded cavities with helical elements of circular cross section. References for the different measurements are given in the text.

The curves labeled 'Best Karlsruhe Result'[27] and 'Best Argonne Result'[28] and the point labeled 'Best Oak Ridge Result'[29] are for small $\lambda/2$ test cavities. The point labeled 'Best Result, Karlsruhe Accelerator Tank' is the best result of the first tests on the first cavity of the Karlsruhe accelerator (March and June, 1972).[30] These results represent the present 'state of the art.' Adjacent to 'surface field' on the horizontal axis we show the corresponding value of V (called 'net accelerating potential') for an optimized design of the type described above. We also show the heat transport limit ($R = R_{max}$) plotted as a function of V. In general, the experimental points go above the heat transport limit because the structures did not have optimized values of E_{max}/V, frequency differences, in the case of the Karlsruhe test cavity, convective cooling, and in the case of the Karlsruhe accelerator cavity, excessive wall losses. The conclusion is that it is reasonable to think about operation with $R = 1$ and $V = 2$ MV/m corresponding to surface fields of 16 MV/m and 600 G. The subsequent cost estimates use this assumption and the assumption of static superfluid cooling.

With these assumptions, the accelerator would have the following parameters:

Cavity parameters—$V = 2.0$ MV/m, $R = 1$
Total acceleration—60 MV
Number of modules—30
Length—195 ft

Heat Load	
Cryogenic	110 W
RF (superfluid heat transport)	78 W
Reserve capacity	100 W
Total refrigeration capacity	288 W

Bare Capital Costs (1972 dollars)	
Refrigerator (includes 100.0k$ for installation)	838.0k$
Cryostat	152.0k$
Transfer lines	16.0k$
Cryogenics and internal support	264.0k$
Accelerator elements	1410.0k$
Electronics and control	530.0k$
Computer	200.0k$
Total	3410.0k$

5.2. *Operating Costs*

Figure 7 shows electrical power costs under the assumption of 50 weeks/yr operation and a unit power cost of $0.008/kWh. For the case just considered, this works out to be 40.0k$/yr or $4.76/h. Other operating costs for the refrigerator are expected to be small, in the order of 20k$/yr. Operating costs related to cavity replacement are, of course, unknown. As an aside, we have analyzed the idea of using the refrigerator as an auxiliary He liquefier for other operations at our facility. The potential economic advantages of such a utilization are relatively small and do not significantly affect the economic considerations of this study.

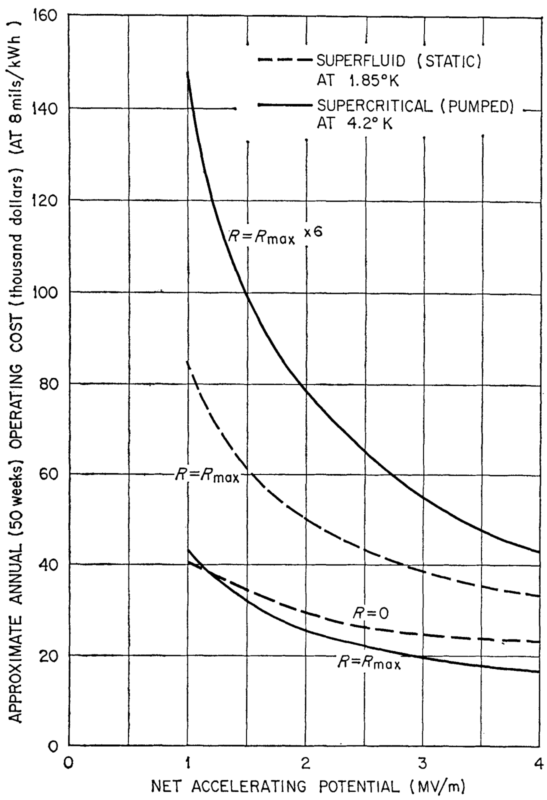

FIG. 7. Approximate annual power costs for the conceptual superconducting linac described in the text. Different curves are shown for different values of R, the normalized surface resistivity defined in the text. R_{max} is the value of R at which the heat transport limit for static superfluid He is reached in the helically loaded structures discussed in the text.

5.3. *Effects of Removing Lenses*

In an effort to understand the importance of alternating phase focusing, we estimated the effect on cost of removing the interspersed quadrupole lenses described above. Using the same parameters as before, this gives a refrigerator capacity of 267 W and a bare capital cost of 2965.5k$, that is a saving of 444.5k$. The principal reduction in cost results from savings associated with the lenses themselves (estimated cost, $5,000 each) and the fact that the number of inter-element connections is reduced.

The removal of lenses has several effects. One is trivial. The length of the accelerator is reduced from about 195 ft to about 130 ft. One is not trivial and this is the effect on beam dynamics in the accelerator. An investigation of this problem is beyond the scope of the present paper.[31] Our intuitive feeling is that removal of the lenses would seriously impair the flexibility of the accelerator as well as its transverse and longitudinal admittance. Therefore, we will assume that the lenses are not removed in our subsequent considerations. It should be understood that this decision is subject to review on the basis of careful beam dynamics calculations.

6. PERFORMANCE

As part of this study, our colleagues at the University of Frankfurt/M have performed beam dynamics studies on the linac described above. These are described in detail in Ref. 32. The calculations were made for the particular case of ^{238}U with $q/m = 0.15$ and with $V = 2.0$ MV/m. The assumed injection energy was 1.1 MeV/nucleon which gives an output energy of 10 MeV/nucleon. The essential results are these:

(1) The effective normalized[33] transverse acceptance is estimated to be 0.75 cm mrad in the *DF* plane and 1.06 cm mrad in the *FD* plane. This is very much larger than the typical tandem normalized emittances of 0.02 cm mrad estimated by Stelson.[7]

(2) Excluding misalignment effects, which have not been studied, the transverse emittance of the beam is estimated to increase by a factor of 2 while traversing the linac due to coupling between transverse and longitudinal motion.

(3) The longitudinal acceptance, that is the required distribution in phase-energy space, is comparable to that which can be achieved with the tandem injector under good conditions. Stated another way, it is not a trivial problem to chop and bunch the beam for injection. For example, the maximum longitudinal acceptance is a distribution which is about 0.7 nsec long and has an energy dispersion of about ± 1.8 per cent. A more desirable input distribution has dimensions smaller than this, for example, pulse width 0.37 nsec and energy dispersion ± 1.6 per cent.

(4) For the latter distribution described above the output energy resolution (*calculated for axial particles*) can be varied between 3×10^{-3} and 3×10^{-4} with a debuncher.

(5) The expected maximum output energy vs. charge to mass ratio (q/m) is shown in Fig. 8 which

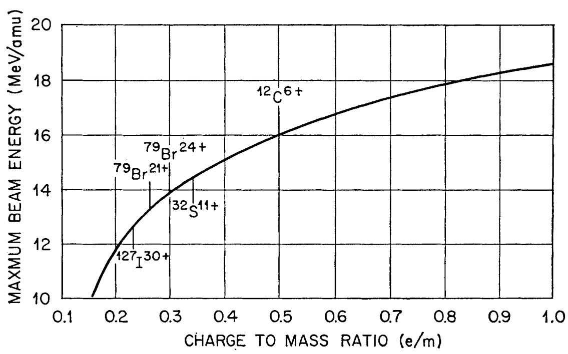

FIG. 8. Expected maximum energy for ions accelerated in the conceptual linac described in the text as a function of charge to mass ratio. The function shown is a copy of Fig. 10 of Ref. 32 and was calculated under the assumption of fixed input velocity.

is a copy of Fig. 10 of Ref. 32. The results shown in this figure are based on a fixed input velocity independent of (q/m). Increasing the input velocity does not result in a significant improvement due to reduced transit time factors.

7. COMPARISON WITH OTHER CONCEPTS

It is of interest and importance to compare the linac which we have just described to other conceptual accelerators which would perform the same function. We have chosen two such accelerators for comparison, a room temperature linac with parameters similar to those of the suprconducting linac and the cyclotron described in Refs. 2 and 3, hereafter called the 'NHL cyclotron'.

Our first comparison will be of costs. Of necessity, our comparison will be oversimplified, omitting such factors as engineering costs, contingencies, and research and development costs. These are important factors, contributing significantly to the project cost, but they are calculated at different laboratories in 'subjective' and thus different ways. We will assume a funding model in which the conceptual project is authorized for construction in the summer of 1973 corresponding to 'fiscal year 1974' of the US federal government. Also, we will assume a simplified escalation model, namely 8 per cent per year, compounded. With this introduction, we now discuss the different concepts separately.

First, the superconducting linac. In order to make a direct comparison with the NHL cyclotron, we will subtract the estimated cost of the control computer, namely 200.0k$ leaving a net capital cost of 3210.0k$ in 1972 dollars. In our opinion, the technology of superconducting linacs will not be sufficiently well developed to generate a final design in the summer of 1973. We believe that a final design will be possible only after a rather lengthy development program based on the construction of virtually exact prototypes. We estimate that such a program would probably require three years. Thus the capital cost of the accelerator must be escalated three years beyond the year of authorization. When account is taken of the fixed dollar refrigerator cost, this gives a capital cost of 4101.0k$. As stated above, the operating power cost, based on 50 weeks/yr operation and a net power cost of $0.008/kWh is 40.0k$/yr. This net power cost is typical of of Oak Ridge, Tennessee and may be higher in other locations.

Our hypothetical room temperature linac was on the one hand similar to the cryogenic one and on the other based to some extent on the TALIX proposal of Klein, Herminghaus, Junior and Klabunde.[34] We assumed a module of total length 1.62 m with a helical element 1 m long. We assumed an energy gain of 60 MV, 100 per cent duty cycle, and an effective shunt impedance, $\eta_{\text{eff}} = V^2/\text{rf}$ power per unit length, of 15.25 MΩ/m. When V was adjusted to give reasonable operating costs, we arrived at the following parameters:

$V = 1.0$ MV/m, number of modules = 60, length = 320 ft, rf power = 3.94 MW.

Bare capital costs (1972 dollars)	
Modules	1500.0k$
Rf power system	3144.0k$
Other fixed costs	550.0k$
	5194.0k$

Subtracting 200.0k$ for a computer and escalating to 1973 gives an estimated capital cost of 5393.0k$. The operating power costs based on 80 per cent 'uptime', 50 per cent conversion efficiency, $0.008/kWh, would be 440.0k$/yr.

Both the capital and operating cost of a room temperature linac are sensitive functions of the rf power consumption which in turn depends on the shunt impedance and duty cycle. The shunt impedance used for our calculation is based on helical elements of circular cross section. It should be noted that the use of noncircular helical elements may result in higher shunt impedances.[6] We have not considered duty cycles less than 100 per cent as suggested by Klein *et al.*[35] because we feel that our conceptual system will, in general, be ion source limited.[7] The implications of such a reduction are discussed in Ref. 35.

The corresponding values for the NHL cyclotron were obtained directly from the NHL proposal, Ref. 3. After escalation to 1973, we have an estimated capital cost of 5227.0k\$. The operating costs, based on a power consumption of 2.05 MW, 80 per cent uptime, and \$0.008/kWh are 115.0k\$/yr.

Although not exactly comparable, it is of interest to compare our linac cost estimates with those of Klein and Kuntze[36] who have estimated costs for designs similar to those described above. In order to convert the results of Ref. 36 into values which may be compared with the present study, we have assumed a total acceleration of 60 MV, a conversion rate of 3.15 Deutschmark/\$, an escalation factor of $(1.08)^2$ (1971→1973), an uptime of 80 per cent and a net power cost of \$0.008/kWh. The results of Table I of Ref. 36 then convert to the following values.

	Capital cost	Yearly power costs
Superconducting linac	4888.0k\$	101.0k\$/yr.
Room temperature linac	5776.0k\$	555.0k\$/yr.

These results are in good agreement with ours, especially when differences in the initial assumptions are considered.

Our second comparison will be of performance. Again, our analysis will be oversimplified and be concerned with only gross features. In this case, we will not distinguish between a room temperature and cryogenic linac, but only compare certain features of the conceptual cryogenic linac and the NHL cyclotron.

We consider first maximum energy vs. mass number. In Fig. 9 we show maximum energy vs. mass functions for the NHL cyclotron, the conceptual linac described above and an ideal linac. The ideal linac is one in which there is no loss in efficiency due to transit time factors for ions lighter than uranium. This idea is related to the following problem. The linac of our design study is optimized for the acceleration of uranium and has a phase velocity profile which matches the velocity of

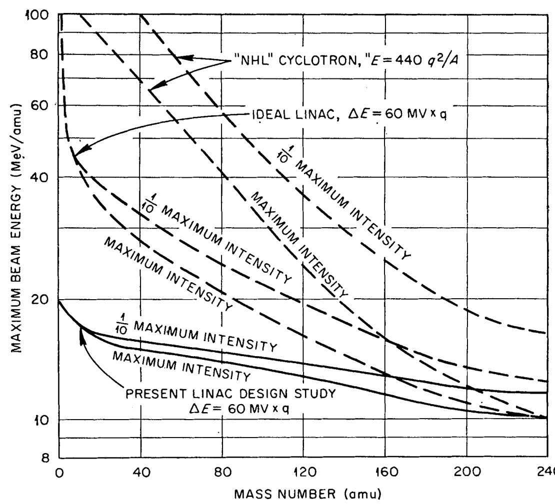

FIG. 9. Predicted maximum beam energy for different conceptual accelerators calculated with the parameters of Table I. An 'ideal linac' has no transit time losses. The 'NHL cyclotron' is the cyclotron discussed in Refs. 2 and 3. The functions labeled 'maximum intensity' were calculated for charge state combinations giving the maximum possible beam intensity. The functions labeled '$\frac{1}{10}$ maximum intensity' were calculated for charge state combinations giving 10 per cent of the maximum possible beam intensity.

ions being accelerated to their maximum possible energy. Other ions will not have this velocity profile and thus not match the phase velocity profile of the linac. This leads to losses in accelerating efficiency, an effect which is particularly severe with the 1 m long cavities of the present study. The functions labeled 'ideal linac' were calculated using transit time factors of 100 per cent independent of particle velocity. In general, this situation may be approximated by the use of very short cavities. The functions shown in Fig. 9 were calculated using the charge states shown in Table I and of course depend on those assumed charge states. Figure 9 shows graphically the more favorable maximum energy vs. mass function of the cyclotron.

It would be of considerable interest to make a careful comparison of the beam dynamical properties of the conceptual linac and the NHL cyclotron. Unfortunately, a detailed series of calculations has not been made for either machine. Therefore our observations will be qualitative rather than quantitative.

The results of preliminary studies on the linac have been described above. Similar preliminary estimates have been made for the acceleration of uranium to 10 MeV/nucleon in the NHL cyclotron.[37] Two results are of particular interest. First, the normalized transverse admittance is estimated to be 0.1 cm mrad in the radial plane and 0.4 cm mrad in the axial plane. The first value is about a factor of 10 less than that of the conceptual linac but still larger than the expected emittance of the tandem injector. Second, the input pulse shape required for an output energy resolution of 0.1 per cent has been estimated. The result is a pulse of length 3.2 nsec and energy resolution ± 0.25 per cent.

Our qualitative conclusion from the latter comparison is that although the area in longitudinal phase space is comparable, the problem of pulse formation for the cyclotron is easier since the longer pulse not only fits the tandem injector output better but implies a rather looser tolerance on pulse arrival time.

8. CURRENT STATUS OF RESEARCH AND DEVELOPMENT APPLICABLE TO SUPERCONDUCTING HEAVY ION ACCELERATORS

We wish at this point to present a brief summary of what we feel are central problem areas in the superconducting linac concept and the present status of research bearing on these problems. It should be emphasized that our remarks relate to the situation at a specific point in time, in this case November 1972, and may possibly be out of date at the time of publication. Also, in keeping with the spirit of this article, our observations will be phenomenological.

To present a broad perspective, we feel that of all the elements which must be assembled to build a superconducting linac, only the resonant cavities and their associated ancillary elements represent an area of significant uncertainty. We wish to emphasize that an actual accelerator cavity is a rather complicated device which must operate not only at high field levels, but also at a particular predetermined frequency. At the time of this writing, no laboratory has demonstrated a realistic accelerator cavity. In contrast, all but one of the measurements which have been reported to date have been on 'test cavities' which incorporate geometric features of conceptual accelerator cavities but not their complexity. The one exception is the first cavity of the Karlsruhe proton accelerator[30] which lacks only tuning capability.

We will discuss first the test cavities. Measurements on a re-entrant Nb cavity operating at 350 MHz have been reported by Ben-Zvi, Castle, and Ceperley.[38] Although surface fields as high as 26 MV/m were measured in this cavity, more typical values were 12 MV/m. This also was the typical value for the observed onset of field emission. The resonant frequency of cavities with this geometry is quite sensitive to the external helium pressure. In the measurement of Ben-Zvi, *et al.* a piezoelectric crystal array was used to compensate for pressure changes, thus stabilizing the cavity frequency.

A number of measurements on helically loaded cavities have been reported.[27–29,39–42] We will not describe the details of these measurements since the most promising results from Argonne and Karlsruhe have just been summarized in Refs. 28 and 39. There are, however, two basic points that we wish to make.

First, the best results from Argonne and Karlsruhe, as shown in Fig. 6, suggest that operation at a surface electric field 16 MV/m and an average resistivity of $2 \times 10^{-8}\,\Omega$ is a reasonable thing to think about. Both of these results were obtained with anodized niobium cavities.

Second, there remain three serious questions concerning the properties of these cavities. First, reproducibility. The Argonne results (Ref. 28) are essentially based on one cavity, so that reproducibility has not been tested. The Karlsruhe results (Refs. 27 and 39) show a good bit of fluctuation. This is not a fair test since the object of these measurements has been to study different techniques. Nevertheless, it has not been demonstrated that one can reliably build low frequency cavities with reproducible properties. Second, degradation of Q with field. Although this is an effect that can be 'lived with', the unexplained degradation of Q with field observed in the Karlsruhe measurements is disturbing. Third, radiation damage. To date no radiation damage measurements on low frequency cavities have been reported. The preliminary measurements of Halama[43] on the effect of high energy protons on a niobium pill-box cavity operating at frequencies between 2.3 and 3.9 GHz suggest that charged particle radiation damage may be a very important effect, especially for anodized surfaces. Clearly, radiation damage effects are of great importance to a practical accelerator.

The performance of the first cavity of the Karlsruhe proton accelerator has also been recently summarized.[30,44] These results are compatible with the test cavity measurements and will not be discussed. As noted previously, this cavity was not equipped with fast or slow tuning devices.

For helically loaded cavities, two other problem areas also remain. These are the fast and slow tuning functions discussed above. The slow tuning problem has a deceptively simple solution. This is the idea of using the radiation pressure induced frequency shift as a slow tuning device. For example, the first cavity of the Karlsruhe proton accelerator has a static frequency shift of about 700 kHz at its design field levels.[30] In contrast, the uncertainty in the initial frequency is thought to be in the order of ± 50 kHz.[45] Since the static frequency shift is proportional to the square of the field level, this uncertainty can be accommodated with changes in the field level of ± 3.5 per cent. This solution has the advantage of trivial simplicity and will be used in the demonstration experiments now planned at Karlsruhe and Argonne.[46] However, for a heavy ion accelerator, where flexibility is important, this is probably not a good solution since a given cavity must always operate at a particular field level. To our knowledge, only one concept for a slow tuner has been carefully studied.[21] Although we see no conceptual problems with this device, it should be understood that it has not been built and demonstrated to work on an actual cavity.

The problem of fast tuning has been the subject of intensive study at several laboratories.[22,41,46] The most striking success has been the demonstration of a working system by Dick and Shepard[41] based on loops utilizing radiation pressure induced frequency shift and a room temperature variable reactance coupled to the cavity by a transmission line. In assessing schemes for fast tuning, three ideas should be kept in mind. First, the frequency response of loops based on the radiation pressure effect is limited by the mechanical response time of the helical elements. Practically, this requires an additional variable reactance. Second, the 'reactive power' coupled to this variable reactance in practical situations will probably be rather large, in the order of kilowatts. Third, this large reactive power is the source of a number of difficulties, not only in the variable reactance but also in the transmission line and couplings.[47] The Karlsruhe group is now studying these problems for a realistic situation but it should be understood that the solutions have not actually been demonstrated at this time.

9. CONCLUSIONS

We will now try to summarize in a succinct way the conclusions of our study.

First, a superconducting heavy ion linac is a reasonable thing to think about. So far as we can see, no laws of nature are violated and conceptual solutions exist for all problems which can be foreseen at this time. However, the technology of low phase velocity superconducting linacs is not sufficiently well understood at this time to justify construction proposals. There are three principal areas of uncertainty; cavity fabrication, radiation damage, and in the case of helically loaded cavities, fast and slow tuning. Substantial development, including the construction of virtually exact prototype cavities, would in our opinion be necessary before the construction of an accelerator

Second, the basic performance characteristics of a superconducting heavy ion linac can be reproduced in room temperature accelerators. Stated another way, the potential advantages of a superconducting linac are aesthetic rather than fundamental. We will consider briefly some of the relative advantages and disadvantages of the three accelerator concepts described above. We will assume that the technological questions raised above have been solved in a satisfactory way.

Capital Cost: Here, the superconducting linac may have an advantage. However, we feel that it is important to understand that the accelerator is only one of many elements in an accelerator facility and that it is the facility cost which is important. In the case of a 'national' heavy ion laboratory, as now being proposed in the United States, [2,3,46] the differences in capital cost of the accelerator are small fractions of the proposed facility cost and even smaller fractions of the integrated 10 to 20 years costs. There are other situations, where a reduced capital accelerator cost could be more important; especially if the capital cost of a superconducting linac were further reduced by future technological developments.

Operating Cost: The electrical power costs for the room temperature linac are substantially larger than for either the superconducting linac or the cyclotron, the latter two being roughly comparable. This difference would be economically important, especially at sites with high power costs.

Performance: We have not made a definitive study of performance in this work. However, two characteristics seem reasonably clear. (1) A cyclotron will have a more favorable maximum energy vs. mass function than will a comparable linac. (2) The input pulse formation problem is easier with the cyclotron, basically because of its lower rf frequency.

Future Changes: To an unusual extent, the capital investment in a cryogenic linac is in elements other than the accelerating structure. For example, in our estimate, the accelerating cavities represent 27 per cent of the total capital investment. This has two implications: (1) It may be possible to upgrade the linac performance in the future without large capital expenditures as cavity technology improves. (2) It is conceptually possible to change the character of the linac without large capital expenditures.

Implications of a New Technology: This is a difficult and, to some extent, philosophical question.[48] On one hand, a superconducting linac represents an exploration into an almost unknown technology, an exploration which may have exciting and as yet unforeseen consequences. On the other hand, the probability of success for such a venture is almost certainly less than for a 'conventional' design. The potential builder should consider carefully his goals, making a careful distinction between the research for which the accelerator is intended and the possible and probable implications of the new technology.

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REFERENCES

1. Scientific motivations and a summary of current proposals have for example, been given recently by Blann, M. Blann, *Nucl. Instr. and Methods*, **97**, 1 (1971).
2. J. A. Martin, E. D. Hudson, R. S. Lord, M. L. Mallory, W. T. Milner, S. W. Mosko, and P. H. Stelson, 'A Proposed National Heavy-Ion Accelerator at Oak Ridge', presented at the Sixth International Cyclotron Conference, Vancouver, B.C., July 18–21, 1972.
3. 'National Heavy-Ion Laboratory', a proposal by the Oak Ridge National Laboratory, Oct. 1972, unpublished.
4. R. M. Main, *Nucl. Instr. and Methods*, **97**, 51 (1971).
5. K. Blasche, D. Böhne, Ch. Schmelzer, and B. Stadler, *Proc. Conf. on Nuclear Reactions Induced by Heavy Ions, Heidelberg, 1970*, p. 518.
6. R. H. Stokes, private communication.
7. P. H. Stelson, private communication.
8. H. F. Glavish, *IEEE Trans. Nucl. Sci.*, **NS-19**, No. 2, 307 (1972).
9. See, for example, H. Klein, N. Merz, and O. Siart, *Particle Accelerators*, **3**, 235 (1972) and the references cited therein.
10. P. B. Wilson, *Proc. 1972 Proton Linear Accelerator Conference, Los Alamos, N.M.* (LA-5115), p. 82.
11. E. M. McMillan, *Phys. Rev.*, **80**, 493 (1950).
12. A. J. Sierk, C. J. Hamer, and T. A. Tombrello, *Particle Accelerators*, **2**, 149 (1971).
13. E. E. Chambers, HEPL 653, High Energy Physics Laboratory, Stanford University, unpublished report, 1971.
14. G. Krafft, private communication and Internal Notice No. 184, Institut für Experimentelle Kernphysik, Kernforschungszentrum Karlsruhe, May 1972, unpublished.
15. A. de La Harpe, S. Lehongre, J. Mollard, and C. Johannés, *Advances in Cryogenic Engineering*, **14**, 170 (1969).
16. P. J. Giarratano, V. D. Arp, and R. V. Smith, *Cryogenics*, **11**, 385 (1971).
17. H. Sixsmith and Patricia Giarratano, *Rev. Sci. Instr.*, **41**, 1570 (1970).

18. A. H. Jaffey, private communication.
19. A. Citron, *Proc. 1970 Proton Linear Accelerator Conference, National Accelerator Laboratory, Batavia, Ill.*, Vol. 1, p. 239.
20. P. Flécher, *J. Vac. Sci. Technol.*, **9**, 46 (1972).
21. C. M. Jones, J. L. Fricke, B. Piosczyk, and J. E. Vetter, *Proc. 1972 Proton Linear Accelerator Conference, Los Alamos, N.M.*, p. 163.
22. See, for example, D. Schulze *et al.*, *Proc. 1972 Proton Linear Accelerator Conference, Los Alamos, N.M.*, p. 156, and the references cited therein, and P. Z. Peebles, Jr., Oak Ridge National Laboratory Report ORNL-TM-3654, 1972, unpublished.
23. H. Klein, Habilitationsschrift, Univ. Frankfurt/M., 1968, unpublished.
24. J. Halbritter, *Z. Physik*, **238**, 466 (1970).
25. G. P. Coombs, Cryogenic Technology Inc., private communication.
26. T. R. Strobridge, *IEEE Trans. Nucl. Sci.*, **NS-16**, No. 3, 1104 (1969).
27. J. L. Fricke, B. John, N. Münch, B. Piosczyk, J. E. Vetter, G. Westenfelder, and C. M. Jones, Notiz Nr. 183, Institut für Experimentelle Kernphysik, Kernforschungszentrum, Karlsruhe, May 1972, unpublished.
28. R. Benaroya, A. H. Jaffey, K. Johnson, T. Khoe, J. J. Livingood, J. M. Nixon, G. W. Parker, W. J. Ramler, J. Aron, and W. A. Wesolowski, *Appl. Phys. Letters*, **21**, 235 (1972).
29. C. M. Jones, J. P. Judish, R. F. King, F. K. McGowan, W. T. Milner, and P. Z. Peebles, Jr., *Particle Accelerators*, **3**, 103 (1972).
30. J. L Fricke, B. Piosczyk, and J. E. Vetter, *Proc. 1972 Proton Linear Accelerator Conference, Los Alamos, N.M.*, p. 151.
31. A similar calculation has been described by Junior *et al.*, H. P. Junior, J. Klabunde, H. Deitinghoff, and H. Klein, *Proc. 1970 Proton Linear Accelerator Conference, National Accelerator Laboratory, Batavia, Ill.*, Vol. 2, p. 759.
32. J. Klabunde, H. Deitinghoff, H. Klein, and P. Junior, Institut für Angewandte Physik, University of Frankfurt/M., Internal Report No. 72/6, June 1972, unpublished.
33. By 'normalized' emmittance we mean the following. Let x be a transverse coordinate and z the longitudinal coordinate. Let A be the area which results when the volume in phase space occupied by the beam is projected onto the $x-\mathrm{d}x/\mathrm{d}z$ plane. The normalized emittance is then $A/\pi \times \beta$ where $\beta = v/c$.
34. H. Klein, H. Herminghaus, P. Junior, and J. Klabunde, *Nucl. Instr. and Methods*, **97**, 41 (1971), and H. Klein, private communication.
35. H. Klein, P. Junior, A. Schempp, P. Finke, H. Herminghaus, J. Klabunde, and L. Lehr, *Proc. 1972 Proton Linear Accelerator Conference, Los Alamos, N.M.*, p. 265.
36. H. Klein and M. Kuntze, *IEEE Trans. Nucl. Sci.*, **NS-19**, No. 2, 304 (1972). Additional comments are given by M. Kuntze in Notiz Nr. 170, Institut für Experimentelle Kernphysik, Kernforschungszentrum, Karlsruhe, November 1971, unpublished.
37. J. A. Martin, private communication.
38. I. Ben-Zvi, J. G. Castle, Jr., and P. H. Ceperley, *IEEE Trans. Nucl. Sci.*, **NS-19**, No. 2, 226 (1972).
39. J. E. Vetter, B. Piosczyk, and J. L. Fricke, *Proc. 1972 Proton Linear Accelerator Conference, Los Alamos, N.M.*, p. 145.
40. G. J. Dick, K. W. Shepard, M. L. Yu, and F. W. Wright, *Bull. Am. Phys. Soc.*, **16**, 843 (1971).
41. G. J. Dick and K. W. Shepard, *Proc. 1972 Applied Superconductivity Conference, Annapolis, Md.*, p. 649.
42. P. H. Ceperley, *IEEE Trans. Nucl. Sci.*, **NS-19**, No. 2, 217 (1972).
43. H. J. Halama, *Proc. 8th Int. Conf. on High-Energy Accelerators, CERN, Geneva, 1971*, p. 242.
44. A. Citron *et al.*, *Proc. 1972 Proton Linear Accelerator Conference, Los Alamos, N.M.*, p. 93.
45. J. L. Fricke, private communication.
46. R. Benaroya *et al.*, *Proc. 1972 Proton Linear Accelerator Conference, Los Alamos, N.M.*, p. 168.
47. J. E. Vetter, private communication.
48. A similar argument has been presented by Sierk and Tombrello, A. J. Sierk and T. A. Tombrello, *IEEE Trans. Nucl. Sci.*, **NS-19**, No. 2, 309 (1972).

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