THE ARGONNE SUPERCONDUCTING HEAVY-ION LINAC*

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The paper summarizes the status of a project to develop and build a small superconducting linac to boost the energy of heavy ions from an existing tandem electrostatic accelerator. The design of the system is well advanced, and construction of major components is expected to start in late 1976. The linac will consist of independently-phased resonators of the split-ring type made of niobium and operating at a temperature of 4.2 K. The resonance frequency is 97 MHz. Tests on full-scale resonators lead one to expect accelerating fields of ∿ 4 MV/m within the resonators. The linac will be long enough to provide a voltage gain of at least 13.5 MV, which will allow ions with A $\lesssim$ 80 to be accelerated above the Coulomb barrier of any target. The modular nature of the system will make future additions to the length relatively easy. A major design objective is to preserve the good quality of the tandem beam. This requires an exceedingly narrow beam pulse, which is achieved by bunching both before and after the tandem. Focusing by means of superconducting solenoids within the linac limits the radial size of the beam. An accelerating structure some 15 meters downstream from the linac will manipulate the longitudinal phase ellipse so as to provide the experimenter with either very good energy resolution ($\Delta E/E \approx 2 \times 10^{-4}$) or very good time resolution ($\Delta t \approx 30$ psec). The planned linac is viewed as the prototype of an energy booster that can effectively upgrade the performance of tandem electrostatic accelerators generally.

I. INTRODUCTION

This paper outlines the status and plans of a project, now in progress, to build a small superconducting linac to serve as an energy booster for heavy ions from the FN Tandem electrostatic accelerator at Argonne. The main components of the planned accelerator system are shown in Fig. 1, and the physical layout is given in Fig. 2. The injector tandem will be used in its present location, and the linac will be located in an existing target room. As in all such systems being discussed at several laboratories, the linac will consist of an array of independently-phased resonators, thus providing a range of flexibility and performance that has not been available heretofore.

The main justification for our linac project is the development of superconducting RF accelerator technology. At the same time, every effort is being made to produce a useful accelerator system. From both points of view it has seemed worthwhile to take on the task of developing an accelerating structure with a low resonance frequency (97 MHz), even though the technology is easier at higher frequencies.

In terms of performance, there are three main objectives: (1) to provide ion beams that are well above the Coulomb barrier for ions with A $\lesssim$ 80, (2) to provide easy energy variability, and (3) to provide a beam with tandem-like quality. In short, we view the tandem-linac system as the natural way to extend the capabilities and to preserve the unique advantages of the tandem itself.

Because of the project's emphasis on accelerator development and because of limitations in funding, the maximum beam energy of the planned accelerator system will be less than some users want. Also, it is unlikely that the existing tandem injector will be able to provide ions with A > 100 even if the linac could accelerate them. Our response to these limitations is to design a modular system that can easily be expanded and/or modified to take care of future developments.

The status of the project (in early September 1976) is as follows. The conceptual design, which has evolved during the past several years, is complete and questions of performance and beam dynamics have been carefully examined. Testing of prototype components is well advanced. Construction of the small building addition shown in Fig. 2 is nearing completion. The detailed design of an accelerator system is in progress. The construction of some major components (such as resonators) will start in October 1976 and grow to a peak of

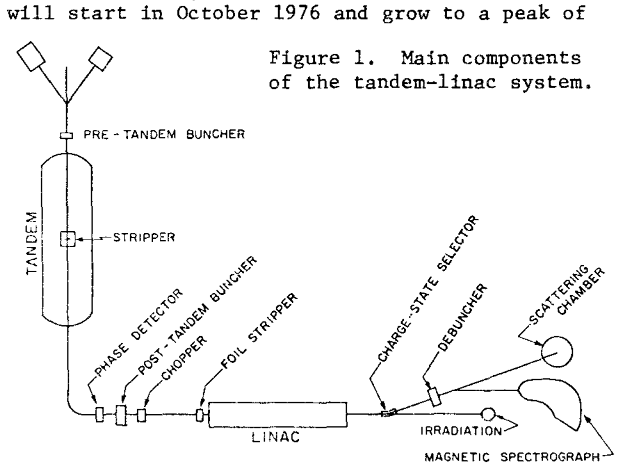

Figure 1. Main components of the tandem-linac system.

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activity in 1977. The aim is to have a first useful beam by April 1978. However, because of the developmental nature of the work, it is expected that there will then be a relatively long period during which the beam is not routinely available to users.

The plans outlined in this paper are necessarily tentative, since many design problems have not yet been worked out in detail and since experience with superconducting resonators is not very extensive. Also, it is advantageous to delay some decisions as long as possible. Fortunately, the flexibility that is inherent in a modular system of independently-phased resonators makes it feasible to proceed efficiently with the work in spite of these uncertainties.

The linac construction is planned as a multiphase process. In the initial phase, for which funding is authorized, the linac will be designed to provide ∿ 13.5 MV of voltage gain, the level of performance originally proposed. However, all aspects of the design are being worked out so that the system can easily be expanded to provide ∿ 20 MV of voltage gain, the level of performance that appears feasible for a linac about 10 meters long.

II. DESCRIPTION OF THE LINAC

A schematic representation of the planned linac is shown in Fig. 3. The system consists of an array of independently-phased resonators of the split-ring type. These resonators, in which the superconductor is niobium, operate at 4.2 K and at an RF frequency of ∿ 97 MHz. A superconducting solenoid after each second resonator is used to confine the beam radially.

The outer wall of the resonator is cooled to liquid-helium temperature in a way that does not require a helium bath. The helium-cooled components are surrounded by a nitrogen-cooled heat shield. A vacuum wall encloses the whole assembly. The vacuum space within the resonator is not separated from the insulation vacuum outside of the resonators; cryopumping on the outer surfaces of the resonators maintains an ultrahigh vacuum within the resonators.

Sets of six resonators and three solenoids are housed within individual vacuum tanks that can be isolated from the remainder of the linac. These assemblies form the complete accelerator sections B, C, and D that can readily be removed from the beam line without warming up adjacent sections. Because all resonators are independently phased, the system can be made to operate usefully even when a complete section is missing.

Sections A of Fig. 3 has the dual functions of accelerating and of matching the longitudinal phase ellipse of the incident beam to the remainder of the linac.

Other integral parts of the RF accelerator system are a refined bunching system before the linac and a debuncher after the linac (see Fig. 1).

Split-Ring Resonator

Figure 4 gives an assembled view of the prototype structure that has been tested for use in the Argonne superconducting linac. In order to reduce the diameter of the housing, the original CalTech design[1] has been modified by bending the loading tube so that the drift tubes are coaxial with the housing. The result is a structure that has an RF frequency of 96.7 MHz for a housing that is 40.6 cm in diameter (inside). The inner components of the structure are welded to the housing. In the first prototype, one end plate is attached to the housing by means of a demountable joint, and the other end is welded into place. In a second resonator nearing completion, both end plates are attached by means of demountable joints.

Only two sizes (lengths) of resonators will be used in the linac. The unit illustrated in the figure is 35.5 cm long (inside dimension) and has a maximum transit-time factor for a projectile with $\beta = 0.105$. A unit of this size will be used in accelerator section D of Fig. 3. The units to be used in sections A and B will be of the same diameter and ∿ 20 cm long. The composition of section C has not been decided yet, but Figs. 3, 5, and 6 were drawn under the assumption that high-β units will be used.

The electrodynamic properties of the high-β unit have been studied in copper models and in the superconducting prototype. Since the results of

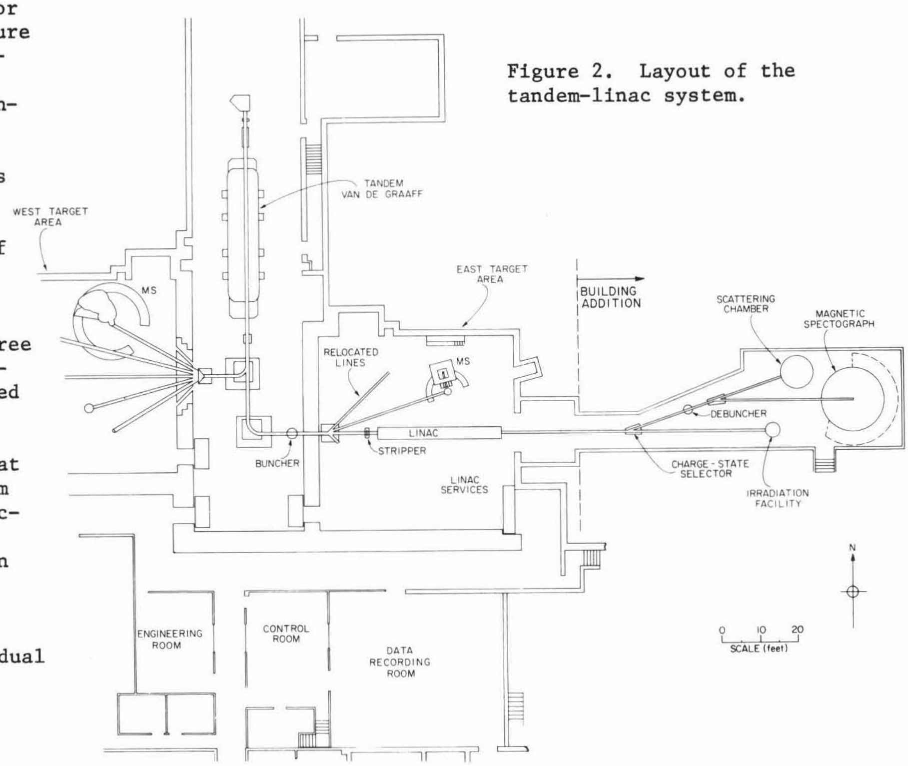
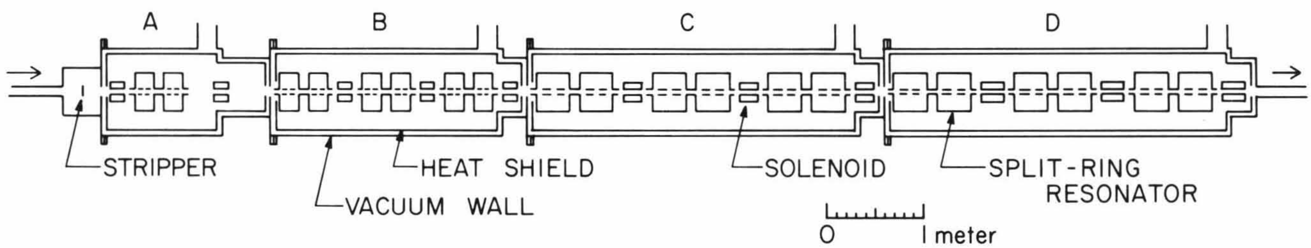


Figure 2. Layout of the tandem-linac system.

Figure 3. Schematic of the ANL superconducting linac.



these tests have been reported[2] recently, they need only to be summarized here. The initial motivation for considering the use of the split-ring structure was the expectation that it would be mechanically stable. It has turned out to be very stable indeed. The eigenfrequency shift induced by radiation pressure is only 620 Hz at an accelerating field E_a = 2 MV/m, which is small enough to effectively eliminate the problem of electromechanical coupling. Similarly, the vibration-induced frequency shift can be made as small as ± 60 Hz, which is small enough that the resulting phase changes can be controlled with a relatively simple form of voltage-controlled reactance (VCX).

The split-ring structure is also attractive from the point of view of energy gain per unit length. Let the axial accelerating field E_a be defined as energy gain per unit charge divided by resonator length (inside dimension) for a synchronous particle. Then, in the high-β unit, E_{max} = 4.8 E_a, B_{max} = 176 E_a, and $W = 0.17\ E_a^2$, where E_a is in MV/m, E_{max} is the maximum surface electric field in MV/m, B_{max} is the maximum surface magnetic field in Gauss, and W is the RF energy content in Joules. Since all of the 92-MHz helix resonators

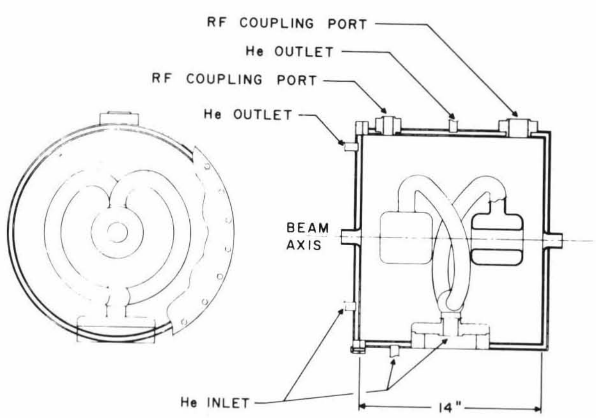


Figure 4. Assembled views of the first prototype split-ring resonator.

tested[3,4] at Argonne have operated with E ≥ 20 MV/m and B_{max} ≥ 750 Gauss, it is reasonable to expect such performance for the split ring also. If so, the accelerating field will be E_a ≥ 4.2 MV/m.

In the best performance achieved to date, the prototype resonator was operated continuously at 3.6 MV/m and was operated intermittently at 4.0 MV/m. It is probable that the field for continuous operation was limited by inadequate cooling of the ring and/or by power loss in the demountable joint that connects the end plate to the main part of the housing. Since both of these problems can be corrected, we are optimistic that the field will be pushed considerably higher. In any case, even the demonstrated level of performance is very attractive for an accelerator since it corresponds to an energy gain of about 1.3 MeV per charge in a single resonator.

In order to avoid the need for a helium bath in the linac, the housing of the first prototype was formed as a double-walled vessel (all of niobium) within which the cooling liquid helium is confined. Liquid helium also fills the hollow drift tubes and the loading tube. This arrangement greatly simplifies the mechanical design of the linac, but the specific mode of fabrication used for the housing turned out to be undesirably expensive. Consequently, we have turned to an alternative approach that is expected to be both better and less expensive. This new approach for the housing makes use of a composite material in which niobium sheet is explosively bonded to copper plate. The niobium provides the superconducting surface and the copper provides thermal conductivity and mechanical rigidity. Extensive tests on samples of the bonded material indicate that it will satisfy all requirements, and a complete resonator of the new kind is scheduled for completion in October 1976. An important aspect of our optimism concerning the bonded material is that both the electric and magnetic fields on the surface of the housing are very much lower than they are on the ring and drift tubes, which will continue to be made of pure niobium. Unless tests on the new resonator reveal unexpected problems, the composite material will be used in the resonators of our linac.

Phase Control

One of the primary problems in the design of a superconducting linac is the control of the RF phase variations induced by mechanical vibration. The magnitude of this problem increases rapidly as the RF frequency decreases because the stored energy increases with increasing resonator size.

In spite of the large size of our resonator, the rigidity of the structure makes it feasible to control vibration-induced frequency variations with a comparatively simple VCX that consists of a $\lambda/8$ transmission line with a PIN-diode switch at its end. The basic ideas involved were described earlier.[5] Recent tests on greatly improved equipment have shown that one can reliably switch, at a frequency of 25 kHz, a 20-Ohm line that has a reactive power of about ± 3.0 kvar. Such a VCX is capable of controlling the phase of our split-ring to $\leq \pm 0.32^{\circ}$ if $E_a \leq 4.2$ MV/m and if the vibration-induced frequency variation is $\Delta f \leq \pm 88$ Hz.

Solenoids

The design of the superconducting solenoids used to confine the beam radially is discussed in detail in another paper[6] submitted to this conference. As shown there, such a solenoid is adequate for our application because of the high magnetic fields available and is preferable to a quadrupole on the basis of both cost and ease of control. The results of field measurements on a prototype superconducting solenoid are in good agreement with calculations.

Cryostat

The cryostat for each section of the linac consists of a 3-foot diameter vacuum tank inside of which is attached a liquid-nitrogen-cooled heat shield. All components inside of the heat shield (the array of resonators, etc.) are mounted on a framework, and the whole assembly is slid into the cryostat from one end. The supporting framework is maintained at liquid-helium temperature so as to minimize alignment problems and heat leaks.

Since the resonator-support structure is removable from the cryostat, assembly and alignment of the resonators and solenoids is expected to be relatively simple. Also, partly because the resonators are independently phased and partly because there are not many of them, alignment tolerances are not very demanding - a radial accuracy of 0.2 mm is desired but random errors as large as 0.5 mm are tolerable.

To maintain beam quality, it is desirable to minimize the dead space between cryostats, whereas for ease of maintenance and operational flexibility, one wishes to be able to isolate and remove individual sections. By building beam-line vacuum valves into the end flanges of each section, the dead space has been kept to < 10 cm, which does not appreciably affect beam quality.

Refrigeration

The prototype resonator was tested at both 1.8 K and 4.2 K. Since the performance was similar at the two temperatures, we plan to use the higher temperature.

The refrigeration system will consist of a helium refrigerator from which liquid helium at ∿ 4.2 K is pumped in parallel to the six resonators in each acceleration section. The inner components of each resonator are cooled by boiling liquid helium flowing up the loading tube into the drift tubes, from which the liquid-gas mixture is exhausted by means of teflon tubes inserted for that purpose. The niobium-copper housing is cooled by heat conduction to the base of the resonator, where liquid helium is introduced into the inner components.

The present plan is to acquire a refrigerator with a total capacity of about 100 Watts. This rather low capacity is judged to be the best balance, in a limited budget, between the costs for refrigeration and for other components. An implication of the 100-Watt capacity is that the cool-down time of the whole linac will be several days.

III. BEAM BUNCHING

An important property of the tandem electrostatic accelerator is that it has a beam of excellent quality both with respect to emittance and energy resolution. This beam quality can be preserved in the linac if all non-linear effects are minimized, which requires the beam to be matched to the linac in both longitudinal and transverse phase space. The matching must be achieved without much loss of beam intensity, since the intensity from a tandem is small for most ions.

The matching requirement makes it desirable to be able to compress a large fraction of the beam from the ion source into pulses that may be as narrow as 50 psec. As shown in Fig. 1, we plan to achieve this by bunching the beam both before and after the tandem. The pre-tandem buncher is a gridded gap (room temperature) driven by a saw-tooth-like voltage that is formed by the superposition of four harmonic components--about 50, 100, 150, and 200 MHz. Calculations that take into account all known debunching effects indicate that this system should bunch about 80% of the DC beam from the source into pulses that are about 1 nsec wide at the output of the tandem with a repetition rate of about 50 MHz. These relatively wide pulses are then linearly compressed to a very narrow width (typically 20 psec) by a single superconducting split-ring resonator. The feasibility of post-tandem bunching has been demonstrated experimentally.[7]

Since there are expected to be serious variations in the time of flight of ions through the tandem, the pre-tandem buncher is dynamically linked to the post-tandem RF system by means of a detector that is resonantly excited by ion bunches from the tandem. This system is designed to detect a flight-time variation of 0.1 nsec in 10 msec if the beam current is 3 nA.

A complete bunching system to be used for experiments with the beam from the tandem alone is under construction and is expected to be operational by early 1977.

In order to minimize the influence of energy straggling in the stripper in front of the linac, one needs a time focus at the stripper. This upright phase ellipse then needs to be transformed into the shape and orientation required for optimum acceleration through the linac. This function is carried out by means of the two resonators in section A, and the additional drift spaces provided in that section are used for that purpose.

IV. PERFORMANCE

Characteristic features of a heavy-ion linac with independently-phased resonators are the flexibility of the system and the wide range of useful operating conditions. Thus, the uncertainty about the level of accelerating field that will be achieved ultimately in the split-ring resonator and the uncertainty about the number of resonators that can be built with available funds does not interact much with the design of the system.

In this section we give examples of the performance for several sets of assumptions.

Maximum Energy of Beam

In Phase I of the project, we expect to construct a linac consisting of sections A, B, and D or, alternately, sections A, C, and D, depending on the needs of prospective users. Since sections A and D will be built first, the decision of whether to build B or C next can be deferred somewhat. In Phase II, the fourth section will be built.

Figure 5 gives the maximum beam energy as a function of ion mass A for several assumptions. The curve labelled 5λ/2 helix gives the performance projected originally when it was assumed that the accelerating structure would be a 5λ/2 helix and that the overall length of the linac would be ∿ 10 m. Comparison of this with the other curves shows how the improved characteristics of the split-ring resonator allow one to reach somewhat higher energies for all masses with the smaller linacs ABC and ACD. All of the curves in Fig. 5 and 6 were calculated for the same assumption that the maximum accelerating fields are those corresponding to a maximum surface electric field of 20 MV/m.

An important consequence of independent phasing is that, for a wide range of projectiles, the achievable energy does not depend sensitively on the characteristics of the injector. This is illustrated in Fig. 6 for a particular linac and several sets of assumptions about the tandem injector. If desired, the high-mass performance could be improved without much loss at low masses by modifying the velocity profile of the linac.

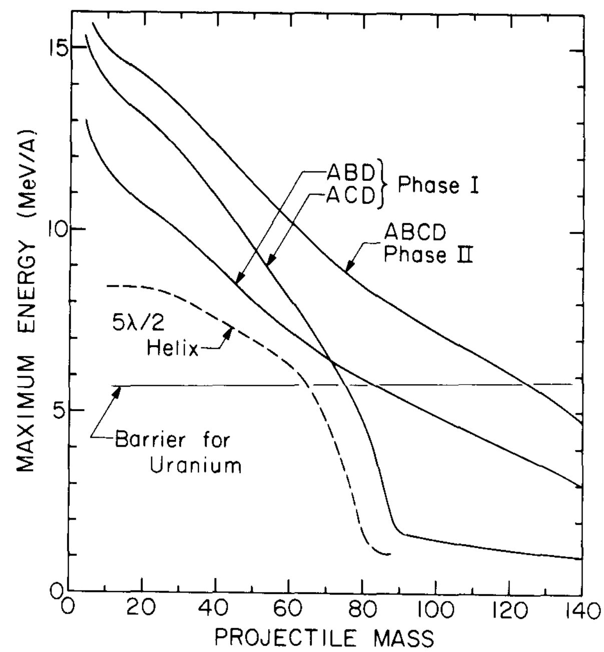


Figure 5. Maximum achievable beam energy for several linacs. For all cases, the injector is a 10-MV tandem with a foil stripper.

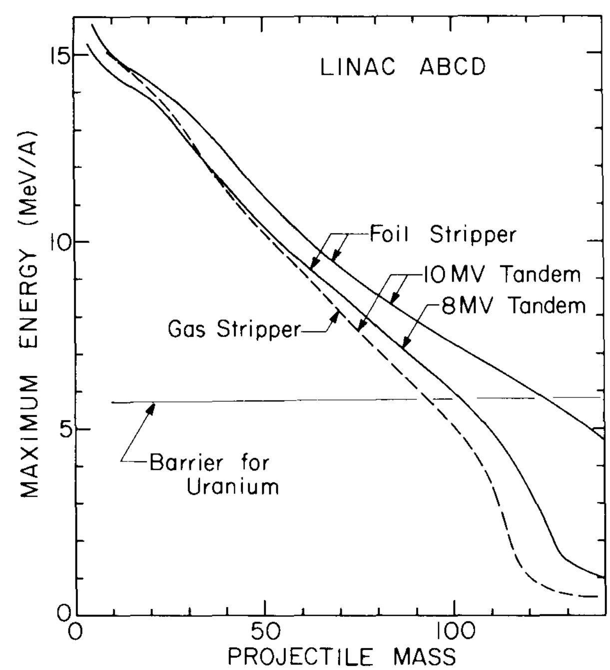


Figure 6. Maximum achievable beam energy of linac ABCD for several injectors. For all cases, E_a = 4.2 MV/m.

Energy Variability

A major advantage of the planned tandem-linac system is that the output energy can easily be varied. When continuous variation over a range of energies is required, the easiest procedure is to keep fixed all operating conditions prior to the last resonator and to vary the phase of this last resonator over its linear range of acceleration. In this way, the output phase ellipse remains almost unchanged while the energy is swept over a range of about 30 MV for a typical ion. When a wider range is required, resonators are turned off.

Beam Intensity

For all except rather light ions, it is necessary to use two strippers during the acceleration process, one in the tandem terminal and another between the tandem and the linac. Thus, even though the linac is expected to accelerate most of the incident beam, the output from the linac will be only about 2% as intense as the beam injected into the tandem. Typically, then the output-beam current is expected to be about 10^{11} particles per second for favorable ions and lower for others. In view of the good quality of the beam, this is enough for most nuclear-structure experiments.

Beam Quality

As mentioned earlier, a major design objective in our project is to preserve the quality of the beam from the tandem by controlling all non-linear effects in bunching and in the linac. A careful examination of all such effects indicates that this is best done by minimizing the radial size of the beam and by matching its longitudinal phase ellipse to the acceptance ellipses of the linac. If such matching is feasible, then none of the non-linear effects need to be large enough to cause an important loss of beam quality for most projectiles. The only exception is the extreme situation in which, because one is straining for the ultimate in energy, acceleration takes place too close to $\phi = 0$, the peak of the acceleration curve.

A solution of the equations for linear acceleration shows[8] that longitudinal matching is achieved when, throughout the linac, the energy spread ΔU (in MeV) is related to the time spread Δt (in sec) by the relationship

$$\frac{\Delta U}{A} = 1.32 \times 10^4 \left[\frac{q}{A} E_o f \sin \phi_s\right]^{1/2} \left(\frac{U}{A}\right)^{3/4} \Delta t, \qquad (1)$$

where A is the nucleon number, q is the ion charge, ϕ_s is the synchronous phase for a convention in which $\phi = 0$ yields maximum acceleration, E_o is the peak accelerating field in MV/m, and f is the RF frequency in Hz.

Equation (1) can be cast in several forms, of which one of the most useful is

$$\frac{\Delta U}{U} = 115 \left[\frac{q}{A} E_o f \sin \phi_s\right]^{1/4} A^{1/8}\, U^{-5/8} (\Delta U \Delta t)^{1/2}. \qquad (2)$$

Since the product $\Delta U \Delta t$ is a constant (a parameter of the incident beam), Eq. (2) may conveniently be used to determine the relative energy spread of a matched beam at the output of the linac.

An important implication of Eq. (1) and (2) is that, for a beam of very good quality (small $\Delta U \Delta t$), the time spread must be exceptionally small. For example, if a 100-MeV beam of ^{40}Ca from a 10-MV tandem has $\Delta U \Delta t$ = 5 keV nsec (where both ΔU and Δt are half widths at half maximum) and has q = 17 as it enters the linac, then the matched phase ellipse for our structure has $\Delta t = \pm$ 25 psec. The need for such narrow pulses is the justification for the emphasis on a refined bunching system. Of course, if the beam from the tandem has poor quality, then Δt should be much larger.

Although the product $\Delta U \Delta t$ can be largely preserved by using a matched beam, the energy resolution $\Delta U/U$ of the output beam may not be exceptionally good. Calculations based on Eq. (2) show that for a typical beam of good quality the output beam may be expected to have $\Delta U/U \approx \pm 5 \times 10^{-4}$ and $\Delta t \approx \pm$ 25 psec. A debuncher located $\sim$ 15 meters downstream from the linac (see Fig. 2) will allow the energy spread to be made about 5 times smaller, if needed.

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DISCUSSION

R. Sundelin, Cornell: I didn't see any inner tube inside the loop of the spiral in your drawing. Does this mean that you are using super fluid cooling rather than helium at 4.2 K?

Bollinger: No, there is a tube there which was not shown because of the complexity of the drawing. We use 4.2 K helium.

M. Kuntze, Karlsruhe: Could you comment on the cooling of the drift tubes of the split ring resonator?

Bollinger: The boiling helium at a temperature of 4.2 K flows up the loading tube into the drift tube. The gas-liquid mixture that results from this is exhausted from the highest point of each arm of the loading tube through a teflon tube.

J. Klabunde, GSI: How do you get the correct frequency of each cell of your structure?

Bollinger: There are three levels of tuning. The first level is to permanently deform one of the end plates. Secondly, the other end plate is deformed on demand by a remotely controlled mechanism and thirdly, we use a voltage controlled reactance for the fast tuning.

E. Jaeschke, Heidelburg: What kind of a phase detector will you use to synchronize your tandem pulsing with the linac?

Bollinger: It's a room temperature helix with a Q of about a thousand excited by the bunched beam. The signal from the helix is fed to a phase-locked amplifier which integrates the signal until it is well above noise level. The system is designed to sense the bunch phase in about 1 ms, which implies that the ion flight time changes rather slowly.