© 1973 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

PROPOSED ACCELERATOR FOR HEAVY IONS*

RICHARD H. STOKES

Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico 87544

Summary

The design of a flexible linear accelerator for heavy ions is described. An array of short, independently phased helix resonators is used with a 4 MV injector having a positive ion source.

Introduction

In recent years the growing interest in heavy ion physics has resulted in many proposed designs for heavy ion accelerators. In early 1971, at Los Alamos, we began to search for alternatives to the tandem-cyclotron combination which was initially proposed. As a result, a new accelerator concept has emerged, and the required technology is being further developed. We will describe the proposed linear accelerator system and briefly present some of the results obtained during our development program. A part of the progress in linac resonator structures has been reported,[1] and the most recent results are reported in References 2 and 3.

In order to permit a broad and definitive experimental program, a heavy ion facility must have several basic characteristics. It should be capable of accelerating a wide variety of ion species to a suitably high energy which can be varied over a broad range. The low cross sections which are typical of many heavy ion interactions dictate a considerable emphasis on the attainment of sufficiently high beam intensities. Other factors such as energy resolution, duty factor, or pulse width, must be emphasized for certain types of experimental programs. We have attempted to choose a system of moderate size which would be capable of precision heavy ion experiments in those areas which are thought to be initially most important. Because most of the emphasis in the search for superheavy elements is in the use of ions with intermediate masses,[4] we have chosen to develop a system to accelerate all ions throughout the first half of the nuclear chart, to energies sufficient for nuclear reactions with heavy targets. The results presented are based on use of ^{124}Sn (9+) to optimize the design. Later we show that this allows the acceleration of all ions, but the energies of ions much heavier than ^{124}Sn fall below the Coulomb barrier for a uranium target.

An accelerator of this scope would have a high utility for a wide range of heavy ion experimental programs. It would achieve significant economics compared to larger accelerator proposals, and would commit available resources to an area projected to have the highest scientific productivity. If heavier ions at higher energy become necessary, it is possible to extend the accelerator by simply adding resonators and RF power systems which are identical to those used initially.

*Work performed under the auspices of the U.S. Atomic Energy Commission.

For many years the helix waveguide structure has been developed at Frankfort under the direction of Prof. H. Klein. The Frankfort group has proposed a post-accelerator for the Heidelberg MP tandem using room temperature helix resonators containing many half wavelengths. Originally we examined the possibility of using superconducting helices, in which case the use of short ($\lambda/2$) resonators is attractive, to avoid losses in the dielectric rods which are used to support the helix at voltage nodes. In the course of this work we observed that $\lambda/2$ helix resonators have highly desirable properties for use at room temperature. We have concluded that a linear accelerator using short independently phased resonators, together with an appropriate ion source and injection system, provides the intensity and the high level of flexibility required for a general purpose facility.

Independently Phased Helix Resonators

Fig. 1 shows the form of the helix we have adopted. The helix resonators operate in their lowest mode with a frequency ω, for which they have an electrical length of $\lambda/2$. Recent experimental and theoretical work[1] on this type of resonator has resulted in the ability to predict resonant frequencies and electric and magnetic field distributions. Although these resonators are analogous to a $\lambda/2$ shorted transmission line, these studies show that the axial electric field distribution predominately has a full sine wave component as shown in Fig. 2. In this figure the points show the axial electric field distribution as determined from a perturbation measurement using a sapphire bead. At a given time, the axial

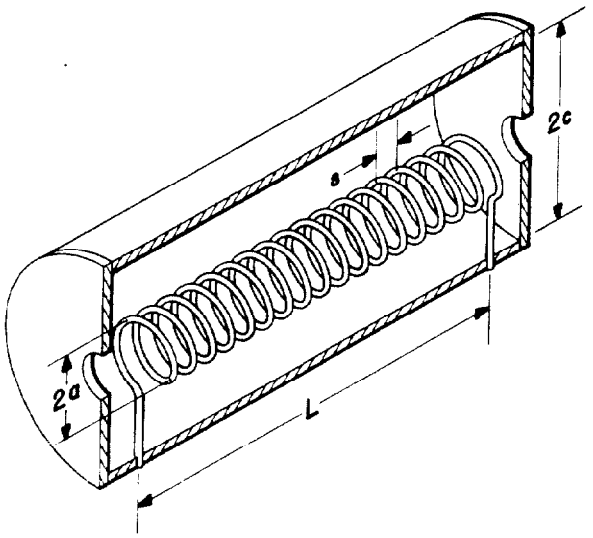


Fig. 1. Helix resonator

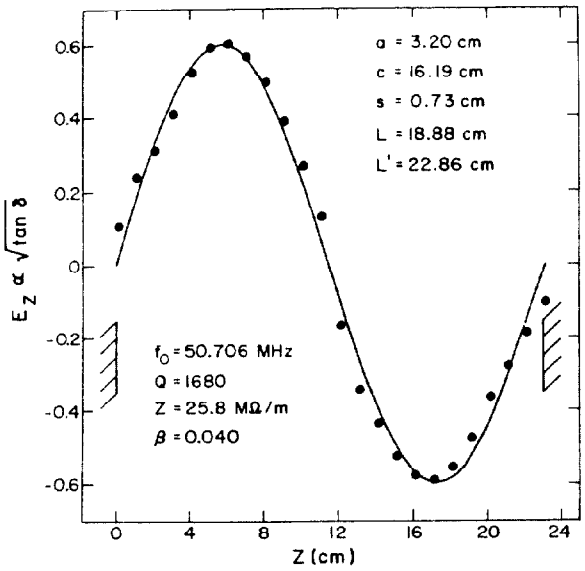


Fig. 2. Measured results from a helix resonator constructed of copper. The points are the axial electric field distribution as determined by bead perturbation measurements, and the curve is a sine wave plotted for comparison. L' is the total length between the end shorting planes.

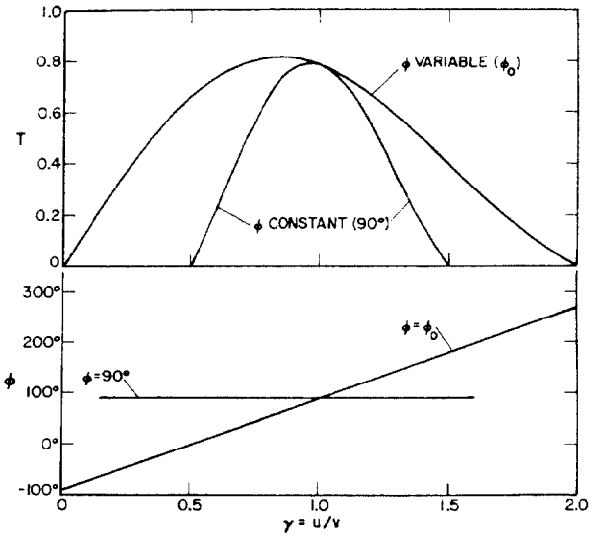


Fig. 3. Transit time factors for constant and for variable resonator phasing. The broad T curve is obtained when the phase at the time of particle entry is varied according to the line $\phi = \phi_o$ in the lower part of the figure. The variable γ is the resonator phase velocity divided by the particle velocity.

electric fields in the two halves of the resonator are oppositely directed. Since the axial field always has a predominant full sine wave shape, the sine approximation will be used to illustrate the acceleration properties. All other significant Fourier components can be easily included in a complete analysis.

For the space and time variation of the axial electric field we shall use

$$E(z,t) = E_1 \sin(2\pi z/\lambda) \cos(\omega t - \phi).$$

The particle enters the resonator at t = 0, and traverses it with velocity v. The resonator phase velocity is $u = \omega\lambda/2\pi$, and we shall use the velocity ratio $\gamma = u/v$. The axial transit time factor can be expressed in terms of γ, and in terms of φ, the phase of the electric field at the time of particle entry:

$$T(\gamma,\phi) = \frac{1}{4}\left(\frac{1}{1-\gamma^2}\right)\left[\cos\phi - \cos(2\pi\gamma - \phi)\right].$$

In order to optimize the acceleration efficiency of a given resonator for various particle velocities we set

$$\frac{\partial T(\gamma,\phi)}{\partial\phi} = 0 ,$$

which results in the relation

$$\phi = \phi_o = \pi(\gamma - 1/2) .$$

If the phase of the electric field at t = 0 is required to be ϕ_o, then the transit time factor will be maximum and given by

$$T_m = \frac{1}{2}\left(\frac{1}{1-\gamma^2}\right)\sin\pi\gamma$$

Fig. 3 shows a plot of T_m (curve labeled φ variable) compared with the T which results when φ is held constant at 90°, the value which maximizes T for γ = 1, the synchronous velocity. Both curves are broad in velocity space because the shortest possible resonator length is used. When the resonator is phased to achieve maximum T for all velocities, a further factor of two increase in breadth results. The use of such independently phased λ/2 resonators is the method by which we achieve a broad velocity capability.

The bottom part of Fig. 3 shows a plot of ϕ_o versus γ. Longitudinal focussing is obtained in a manner completely analogous to usual linac custom by adding a synchronous phase ϕ_1, so that the phase of the electric field at t = 0 for phase stable operation becomes

$$\phi = \phi_o + \phi_1 , \quad 0 < \phi_1 < \pi/2 .$$

With this choice of phase the energy gain for a particle of charge q, in a resonator of length ℓ is

$$\Delta E = q\, E_o\, T_m\, \ell \cos\phi_1 ,$$

Where E_o is the axial electric field averaged from 0 to ℓ/2.

Other properties of helix resonators can be mentioned only briefly here. For a linac operating at room temperature, the resonator efficiency is of great importance. The test resonator of Fig. 2 has a shunt impedance Z = 25.8 MΩ/m and a phase velocity $\beta = u/c = 0.04$. Other resonators with this velocity have been constructed with shunt impedances greater than 30 MΩ/m. For the velocity profile to be discussed later, a value of 22 MΩ/m appears to be a valid average over the whole accelerator. We have improved the resonator efficiency for the lowest velocity

resonators through use of a helical conductor with a non-circular cross section.[2,3] This has permitted the shunt impedance and the electric field to be maintained at acceptably high values while enabling the helix to be cooled for operation at 100 percent macroscopic duty factor.

Accelerator Design

The ion source and injection system are an important part of any heavy ion accelerator. Recognizing the limitations of tandem accelerators, instead we have chosen to use a single-ended electrostatic injector with a positive ion source. The observed properties of helix resonators have shown that they are capable of operation down to phase velocities of $\beta = 0.02$ with acceptable values of shunt impedance. In our design this is compatible with a 4 MV injector. Such a pressurized DC machine is small enough so that rapid gas cycling is possible to gain access. In addition, when constructed with a vertical column, the injector can accommodate a turret with remotely switchable sources. Our use of a positive source and a single foil stripper results in a considerable beam intensity advantage compared to the use of a tandem injector. A tandem requires use of a negative ion source and a first stripper in the high voltage terminal. For high energy and heavy ions, another stripper following the tandem is used. Estimates of the intensity advantage of the positive source with a single stripper compared to use of a tandem range between 30 and 1000. Also, by necessity, tandem injection has zero intensity for most noble gases.

As discussed above, ^{124}Sn has been used as the reference projectile to assemble the velocity profile. Only a small decrease in efficiency results when groups of identical resonators are used. We have chosen 8 groups operating at 50 MHz with resonator phase velocities from $\beta = 0.0228$ to 0.0840. After the third group a ^{124}Sn (9+) ion reaches an energy of about 110 MeV, which is close to the optimum for placing the foil stripper. Following the stripper, the maximum intensity charge component is selected for further acceleration. The velocities and the number of resonators in each group were chosen to give symmetric excursions of equal amplitude over the peak of the transit time factor. The abscissa of Fig. 4 shows the phase velocity β, and the number N, of identical resonators in each group. The bars are proportional to the total lengths of resonators in each group. There are 124 resonators with a total resonator length of 35.8 meters. In the model of Fig. 4, all resonators operate at $E_o = 1.25$ MV/m, and the total power consumption for 100 percent duty factor and $Z = 22$ MΩ/m is 2.5 MW. Depending on the results of forthcoming power tests, we expect that the final design will have each group operating at a power level which optimizes overall accelerator performance.

On an expanded scale, Fig. 4 shows the excursions of the operating point across the peak of the T curve. Above this, the required variations of ϕ_o are plotted. A value of $\phi_1 = 30°$ was used, so that the phase of the electric field at the time of particle entry into each resonator is $\phi_o + 30°$. At the top of Fig. 4 the energy gain history is plotted with the final energy equal to 696 MeV. The Coulomb barrier for ^{124}Sn bombarding a uranium target is about 654 MeV. As we shall see, the final energies of all lighter ions increasingly exceed their Coulomb barrier for a uranium target. The final energy of ^{124}Sn is attained in an efficient manner. We can compare to the case in which each resonator has a different phase velocity so that operation is always at the peak T. In contrast, the use of eight groups results in a final energy which is only 0.3 percent lower.

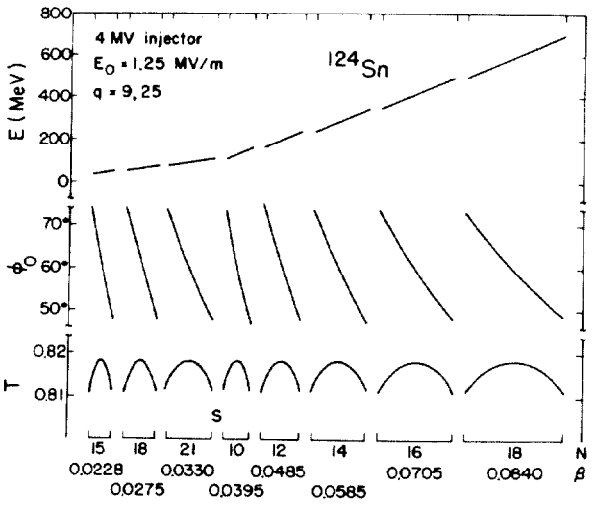


Fig. 4. Acceleration cycle for ^{124}Sn ions. Eight groups of resonators are used. In the first group there are 15 identical resonators with phase velocity $\beta = 0.0228$, etc. The excursions of the transit time factor and the required phasing of each resonator are plotted. A snychronous phase of 30° has been used so that at the time of particle entry the phase is required to be $\phi_o + 30°$. Following the third resonator group, a foil stripper is used to increase the ionic charge from 9+ to 25+.

Studies are underway of magnetic quadrupole focussing and bunchers and de-bunchers. These elements together with independent phasing provide great flexibility in the choice of beam characteristics. Many combinations of final energy, energy spread, intensity, and microstructure width can be obtained by programming ϕ_1, and the other parameters along the acceleration cycle. The beam characteristics can also be varied by changing the position of the stripper. Computer studies are now being made with the use of several beam dynamics programs developed for this type of accelerator. Initial results suggest that the effects of an input buncher and an output de-buncher can be largely accomplished within the accelerator array by proper phasing and other adjustments of the acceleration cycle. The phase of each resonator and the quadrupole focussing system would be computer controlled. We believe that all operating conditions can be met by having completely flexible phase control with each resonator either operating at full power or being turned off. Operating the resonators at fixed voltage simplifies the amplitude control system. The proposed 100 percent duty factor avoids RF modulation equipment and further simplifies the phase and amplitude feedback control.

The design of the RF system is of the highest economic importance. Most considerations suggest that each resonator have its own power amplifier driven from a phase reference line. Initial investigations show that this arrangement only slightly increases the cost for a certain total power requirement. This is partly a result of still being able to construct the DC power supply equipment in large packages. With each resonator having its own RF

supply, the failure of either would have minimal effect on accelerator operation. If a fault develops, it is possible to de-activate that resonator and, unless maximum energy is required, operation can continue by rephasing all subsequent members of the array.

Accelerator Characteristics

We will briefly summarize some of the characteristics of an accelerator with the velocity profile discussed in the last section. Figs. 5 and 6 show the acceleration cycles of ^{76}Ge and ^{48}Ca. The injector still operates at 4 MV and we assume a 7+ charge from the ion source. After the third resonator group, the ion is stripped and the maximum intensity component is further accelerated. The variations in T, ϕ_o, and the energy are plotted with $\phi_1 = 30°$. For ^{48}Ca, a comparison with the accelerator operating at peak T throughout, shows the final energy to be reduced only 6 percent by operating with a profile optimized for ^{124}Sn, with 8 velocity groups. The third column of Table I gives final energies for a number of ions accelerated by this same arrangement. The initial and final charge state is given in parentheses. For each ion the laboratory Coulomb barrier for a ^{238}U target is listed for reference.

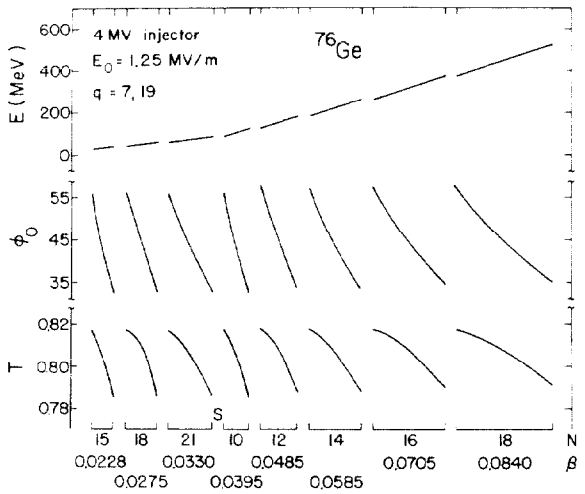


Fig. 5. Acceleration cycle for ^{76}Ge ions.

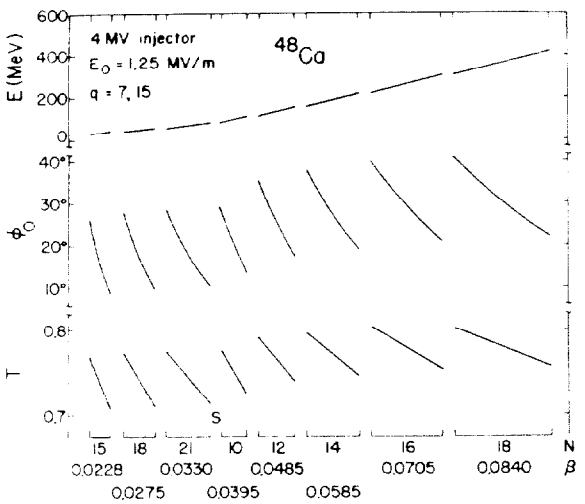


Fig. 6. Acceleration cycle for ^{48}Ca ions.

Table I. Final Energies (MeV)

Final ion energies with one stripper, E(1), and with no stripper, E(0). E(b) is the approximate lab Coulomb barrier energy for a ^{238}U target. The numbers in parentheses are the charge states used.

Ion	E(b)	E(1)	E(0)
^{1}H	13	---	23 (1)
^{4}He	24	---	56 (2)
^{18}O	90	213 (5,8)	158 (5)
^{48}Ca	231	413 (7,15)	242 (7)
^{64}Ni	331	494 (7,18)	244 (7)
^{76}Ge	386	525 (7,19)	241 (7)
^{86}Kr	442	552 (7,20)	235 (7)
^{100}Mo	527	635 (8,23)	267 (8)
^{124}Sn	654	696 (9,25)	291 (9)
^{186}W	1074	781 (10,29)	262 (10)

This array of resonators can be operated in another mode. The stripper can be removed entirely for lower energy and higher intensity beams. The fourth column of Table I lists the final energies reached and the charge state used.

Conclusions

Major design characteristics and operating capabilities have been described for a heavy ion linear accelerator which uses independently phased resonators. The linac, together with a positive ion injector, combines the intensity and the flexibility required for a broad program of heavy ion research. The accelerator design requires minimal development of new technology, and provides an attractive basis for future heavy ion facilities.

Acknowledgements

Many individuals have assisted in the development of this accelerator design. It is a special pleasure to acknowledge the contributions of: D. D. Armstrong, P. J. Bendt, B. H. Erkkila, W. S. Hall, K. S. Jancaitis, L. J. Laslett and T. A. Tombrello.

References

1. T. A. Tombrello, K. S. Jancaitis, P. J. Bendt, B. H. Erkkila, and R. H. Stokes, "Measurements and Calculations of Field Distributions in Short Helical Resonators," Proc. 1972 Proton Linear Accelerator Conference, LA-5115, (November, 1972); Particle Accelerators, to be published.

2. P. J. Bendt, B. H. Erkkila, and R. H. Stokes, "Design and Measured Characteristics of Minimum-Loss Low-Velocity Helix Resonators," 1973 Particle Accelerator Conference, San Francisco.

3. L. J. Laslett, K. S. Jancaitis, and T. A. Tombrello, "Peak Fields and RF Losses in Helical Resonators," 1973 Particle Accelerator Conference, San Francisco.

4. J. R. Nix, "Predictions for Superheavy Nuclei," Physics Today, p. 30 (April, 1972).