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THE CYCLORATOR: A DEVICE FOR THE SEPARATION OF ISOTOPES BY TIME-OF-FLIGHT IN A MAGNETIC FIELD

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ABSTRACT

When the time-of-flight principle is applied to isotope separation in a magnetic field, a separation-in-time is obtained which depends directly upon the difference in isotopic masses. Modulation of the ion beam is necessary for collection of separated isotopes. The relative merits of intensity, direction, and energy modulation are discussed. Separation of uranium isotopes, with low enrichment, was achieved by energy modulation. The cyclorator is found to have the same fundamental limitations as the calutron, the most significant being loss of resolution with increased throughput.

INTRODUCTION

The early attempts to separate uranium isotopes by electromagnetic means were based upon both separation-in-space and separation-in-time principles. The former principle, as applied in the mass spectrograph, was used by Nier[1] in preparing the first enriched isotopes of uranium. From the mass spectrograph, Lawrence[2] then developed the larger instrument, the calutron, used in the Electromagnetic Plant (Y-12) for production of the first usable quantities of the fissionable isotope U 235. The separation of uranium isotopes by means of a linear time-of-flight machine, the isotron, had been achieved by Smythe[3] but, due to the early success of the calutron, development of the isotron was discontinued.

In the calutron, a 180° mass spectrograph, isotope separation is possible because, in a magnetic field, ions of greater mass travel in orbits of greater radius; the distance separating two isotopes at the 180° position depends upon the difference in the square roots of their masses. The linear time-of-flight machine, the isotron, utilizes the fact that, when accelerated to the same energy, lighter ions travel faster; the time interval separating the arrival of two isotopes at the collector depends upon the difference in the square roots of their masses exactly as does the space separation in the calutron.

The effects of differences in orbital radius and ion velocity are combined in a new way when the principle of time-of-flight is applied to ions moving in a uniform magnetic field. If ions traverse a 360° orbit all isotopes return to their common origin but the lighter ions travel faster and follow a shorter path.

1. Nier, A. O., et al., "Nuclear Fission of Separated Uranium Isotopes," Phys Rev 57, p. 546, March 15, 1940.
2. Smythe, H. D., Atomic Energy for Military Purposes, Princeton Univ. Press, 1948.
3. Ibid.

Under these conditions the separation in time between two isotopes depends directly upon the difference in their isotopic masses, rather than upon the difference in the square roots of their masses. This 360° time-of-flight separator is called a "cyclorator." Isotope separation is obtained by modulating both the ion source and the collector and then adjusting the phase relationship in such a manner as to collect the desired isotope and to reject those undesired.

A preliminary examination of the cyclorator suggested that it possessed several other possible advantages over the calutron:

1. The quality of beam focus at 360° for the cyclorator should not be affected by the angular width of the beam at the source. For a calutron beam well-focused at the 180° point the angular width of the beam at the source must be limited.

2. In the cyclorator the ions are decelerated before they are collected thus less power from the high voltage supply should be required.

3. The time-of-flight of ions of a given mass arriving at a 360° collector of the cyclorator is independent of energy; the stability requirements for the ion source then should be greatly relaxed.

In continuation of a policy of investigating alternate electromagnetic methods for the separation of heavy isotopes, a program of experimental development and evaluation of the cyclorator was undertaken.

The proposal that this method be investigated originated at the Radiation Laboratory of the University of California and preliminary experimental work was conducted there for approximately a year.[4] Late in 1948 work on this project was undertaken at Y-12 where actual performance tests were completed during the following year.[5,6,7,8] Early in 1950, it was brought to the

4. UCRL-167
5. Y-378
6. Y-445
7. Y-495
8. Y-548

attention of the Oak Ridge group that the time-of-flight principle used in the cyclorator had been described as early as 1942 in a patent application by Cyril E. McClellan, No. 469847, December 22, 1942. It should be emphasized that the work in Oak Ridge was completed without knowledge of the McClellan application and, insofar as physical implementation of the principle is concerned, bears no resemblance to the device described therein.

The purpose in preparing this report is to bring together information to support the conclusion that the cyclorator can be used for the separation of heavy isotopes but that it is subject to the same basic limitations as the calutron.

BASIC PRINCIPLES

The theory and physical principles of isotope separation by the time-of-flight method are reviewed in this section. In addition to presenting illustrative numerical examples, the concepts of modulation and collection of ion beams are discussed.

The radius of circular motion of an ion in a region of uniform field intensity is given by

$$r = \frac{c}{H} \sqrt{\frac{2mV}{e}}$$

where e and m are the charge and mass of the particle, V is the potential difference through which the ion has been accelerated, c is the velocity of light, and H is the magnetic field intensity. This fundamental equation of the mass spectrograph and the calutron demonstrates that ions of common energy but having masses m_1 and m_2 are separated in space by a distance

$$\Delta d \sim (\sqrt{m_2} - \sqrt{m_1})$$

at the 180° point of their circular orbit. If the ions are allowed to complete the circular path they arrive at their source with no separation in space.

A working equation applicable also to the time-of-flight method gives the beam radius, r, in inches, V in kilovolts, e in electronic charges, m in atomic mass units, and H in kilo-oersteds:

$$r = \frac{1}{H} \sqrt{\frac{3.22\ mV}{e}}$$

The transit time or period of the circular motion, however, depends on the mass. Generally, the time required for an ion to go through θ radians is:

$$t = \frac{\theta}{\omega}$$

where $\omega = \frac{eH}{mc}$ is the ionic angular velocity. In the special case of a complete circle, $\theta = 2\pi$ and

$$T = \frac{2\pi c}{eH} m$$

The difference in time for ions of masses m_1 and m_2 to return to the point (or line) of projection is thus

$$\Delta T = \frac{2\pi c}{eH} \Delta m$$

a quantity independent of the ion energy.

The time-of-flight method of isotope separation is based upon this time interval which depends upon the mass difference between the isotopes rather than the difference between the square roots of their masses. If it is assumed that spatial and time effects can be equally well resolved, there should be an advantage in the 360° time-of-flight method of approximately a factor of two for the separation of uranium isotopes, as compared with the calutron.

A convenient working formula for the cyclorator giving the transit time for a 360° orbit is

$$T = 652 \frac{m}{H} \text{ microseconds}$$

for a singly-charged ion of m atomic mass units in a field intensity H oersteds. A similar relation obtains ΔT in terms of Δm. For example, the period of a U 238 ion in a field of 6600 oersteds is 23.5 microseconds and the difference in period for the U 235 and U 238 isotopes is 0.296 microseconds. This time difference implies a displacement in position near the 360° point for two ions leaving a source at the same instant, approximated by:

$$\Delta S = 2\pi r(\Delta T/T)$$

For example, if the ions considered above were accelerated through 18 kv, the radius would be 17.8 inches, and the space separation

$$\Delta S = 2\pi(17.8)(0.296/23.5) = 1.4 \text{ inches}$$

A physical mechanism must be applied in order to take advantage of this separation in space and time. Basically this may consist of a periodic variation of some characteristic of the ion beam leaving the source, such as the intensity, the initial direction, or the energy. A corresponding analysis of

the beam incident on the 360° collector must be provided. The simplest analysis technique, modulation of intensity, is used here to compute the proper frequency for variations of this type.

Suppose that a periodic potential is applied to an accelerating electrode of the ion source to create a simple half-wave rectification effect. After traversing their circular paths, the light ions in the original pulse are ahead of the heavy ions in space. If the modulation frequency is chosen correctly, light and heavy ions will be completely separated from each other. Figure 1A shows these relations schematically. The necessary relation between the modulation angular velocity (ω_s) and the ionic angular velocity (ω) is easily derived from the condition that the peaks of intensity in time of the two isotopic beams are shifted in phase an amount equal to 180° of the modulation cycle in the transit through 360° of angular motion.

$$\omega_s \Delta T = \pi$$

In terms of frequency (for the case of a 6600 oersted field),

$$f_s = \frac{1}{2\Delta T} = 1.69 \text{ megacycles}$$

The ratio of the angular velocities, using the condition $\omega T = 2\pi$ is

$$\frac{\omega_s}{\omega} = \frac{T}{2\Delta T} = \frac{m}{2\Delta m} = 39.667$$

If one of the ions, for example U 238, is to be periodically reflected by the same rf potential that modulates the source, an integral number of rf cycles have elapsed by the time the ion executes 360° of motion; thus an independent relation incompatible with the frequencies ratio above must be met:

$$\frac{\omega_s}{\omega} = n \text{ (an integer)}$$

Satisfying the latter with n = 40, the nearest integer to 39.667, leads to a very slight mixing of isotopes due to an error in ion phase shift of 1.5°. Strict adherence to the ideal ratio leads, however, to an error in reflection

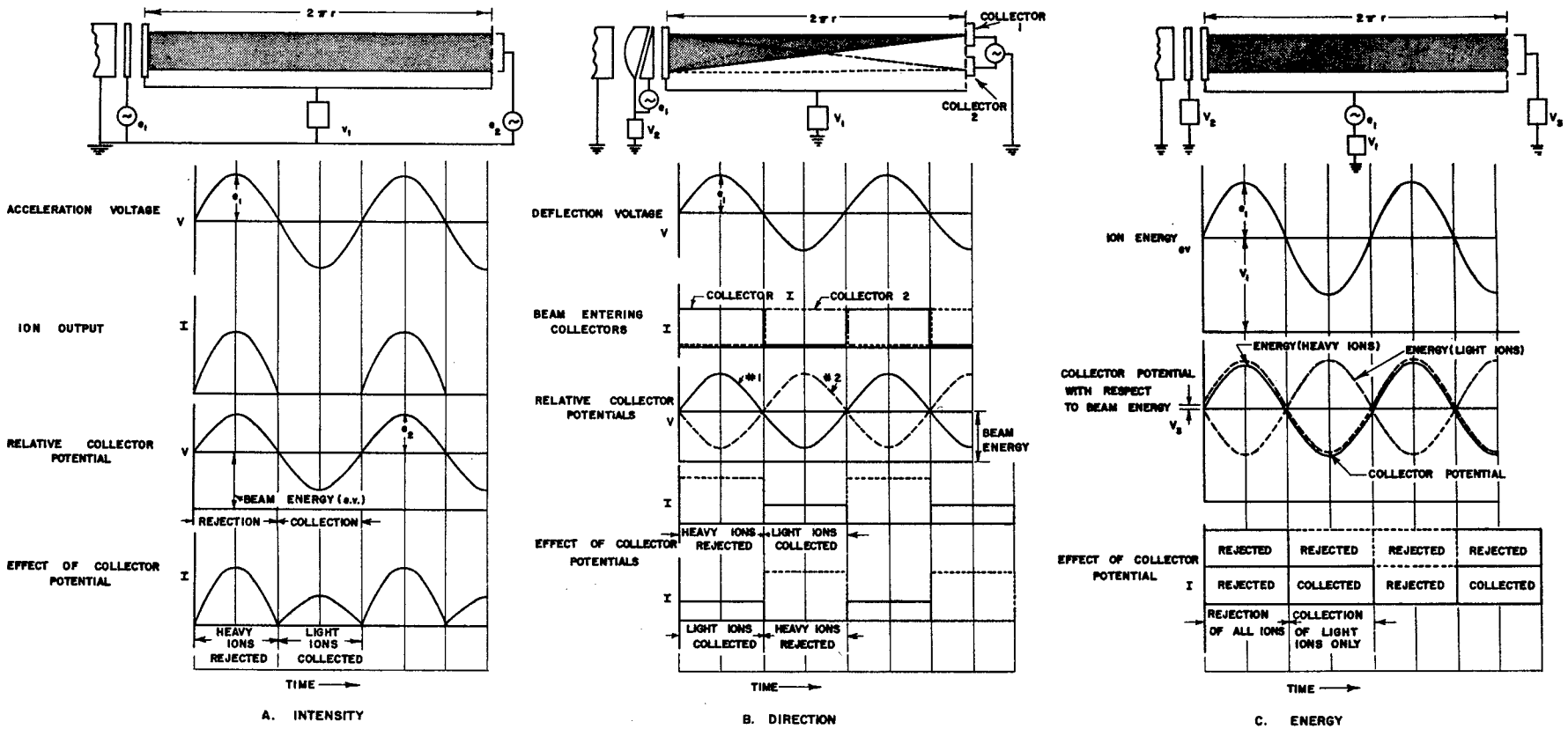


FIGURE 1 METHODS OF MODULATION

corresponding to 120° phase shift. This may be compensated for if a phase shifting circuit can be provided between the source and collector.

Direction modulation is a special case of intensity modulation. The beam is given a velocity component alternately along and opposite to the direction of the magnetic field. A split accelerating electrode may be used to give the ions this motion. The spiraling ions break into the U 235 and U 238 groups, to be collected at opposite ends of a collector. The potentials on the two portions of the collector are 180° out of phase with each other, as shown in Figure 1B.

In the energy modulation method, the accelerating potential is raised slightly during half the cycle and dropped during the other half. On arriving at the 360° point, the ion groups consist of U 235 and U 238 ions in the original isotopic proportions, but "tagged" according to energy. A properly phased potential is applied to the collector to separate the desired and undesired isotopes. Figure 1C shows the energy-phase conditions. In order to achieve the maximum efficiency of the separation process, secondary collectors must be provided to collect the rejected ions, as described in a later section.

In the beam region the magnetic field must be very uniform in order to avoid phase shifts between the ions of the same mass on arrival at the collector. If the average magnetic field around the orbit of one ion differs from that of another ion by an amount ΔH, then the difference in arrival times compared with the total transit time is given by

$$\frac{\Delta T}{T} = \frac{\Delta H}{H}$$

Since there is a phase shift of 180° for $\Delta T/T = 1/80$, the fractional deviation in field must be far less than 1% to prevent ion mixing. For example, to keep the phase shift within 15°, the average field for one orbit must be the

same as that for the other within 0.1%. Only if the beam is of small angular divergence can this requirement be eliminated. In that case, assuming the U 235 and U 238 ions follow their respective orbits at all times, a frequency adjustment can be made to counteract the effect. The requirement becomes more difficult to meet if energy modulation is used, since the orbits periodically contract and expand with time.

In the course of research on the cyclorator all three methods have been tested. A high degree of intensity modulation was found possible at Berkeley, but the utilization of a maximum of only one half of the possible ion source output by this method led to the consideration of the other two schemes at Oak Ridge. Because the direction modulation of an ion beam was found to have energy modulation inherently associated with it, the major emphasis was placed upon separation by the energy modulation method.

THE EXPERIMENTAL PROGRAM AT OAK RIDGE

The experimental program at Oak Ridge has been an extension of the work on time-of-flight separation begun at Berkeley. Of the various methods considered, it first appeared that the direction modulation method offered the greatest advantages since it allowed collection of the desired uranium isotope during both halves of the cycle with a reasonably simple collector arrangement. As experimental results were obtained and combined with the theoretical investigations it was concluded that the energy-modulated cyclorator would be superior, at least for the initial separation tests. Since the goal of the Oak Ridge program was to devise a simple separation unit that could be integrated with the existing facilities with a minimum of time and effort, the original designs made use of the basic structure of the Beta calutron, including the accelerating and beam power supplies.

Exploratory Tests of Direction Modulation

It was shown in the exploratory tests of the direction-modulated cyclorator that large uranium ion currents (50-100 ma) comparable to those from the calutron, could be measured at approximately 360° from the source. In order to obtain a high separation factor with direction modulation it is necessary to bring the beam from the long calutron arc to a spot focus at the ion collector. Under this condition sharp variations in beam intensity will be produced when the beam is modulated from side to side. This requirement is quite analogous to that for good resolution in a cathode-ray tube.

The electrode arrangement used to provide the focus and to sweep the emergent ion stream from side to side consisted of a "split accelerating slit" with a curved leading edge. The sections of the electrode differed slightly in potential, which served to give the ions a component of velocity parallel to the magnetic field. Figure 2 shows a typical set of electrodes which were used. This slit system, when driven by a time-varying potential, was found to produce the desired modulation of the position of the beam on the collector. A subtle difficulty was encountered, however, which prevented clean-cut isotope separation. It can be described in the following sequence of physical facts, for which an analysis and illustrations are given in the Appendix.

(a) The periodic deflection of the ion beam in the magnetic field direction is accompanied by a variation in the component of beam velocity that determines the radius of circular motion. This is equivalent to saying that there is an energy modulation of the beam.

(b) The principle of independence of time of flight on beam energy holds for collection at the 360° point only. If ions travel less than 360°, those of low energy travel a shorter angular path and thus require less time to reach the collector than do those on high energy.

(c) Since the time differences that allow separation are small in comparison with total ion transit times, the pattern of arrival times of ions of different masses will be distorted enough by the above effect to reduce the enrichment factor sharply. The reason that the energy modulation has a large effect is that an ion executes its complete path during 40 cycles of the impressed rf potential. A variation of angular path length of only 1/80 serves to shift the phase of arrival of ions with masses 235 and 238 by 180° in the rf cycle.

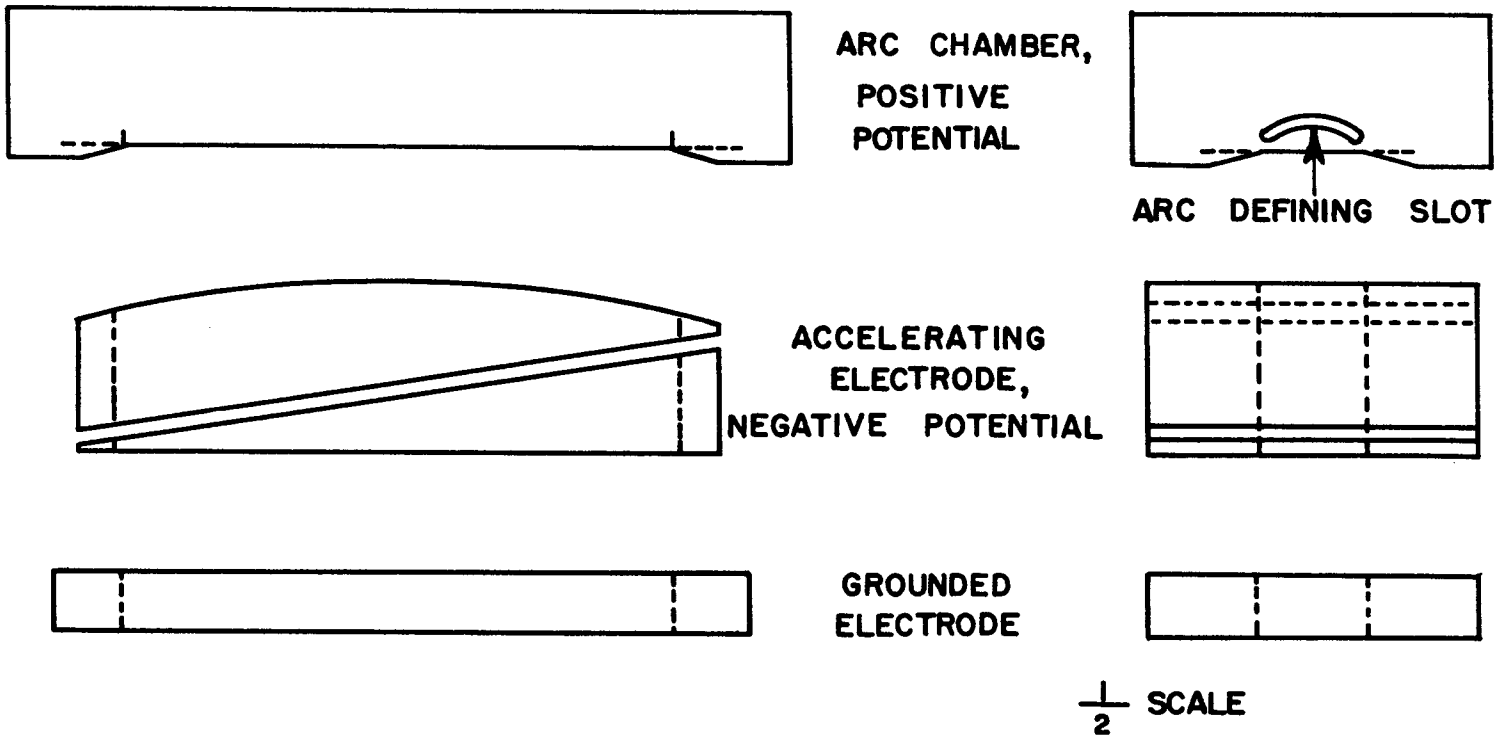


FIGURE 2. ELECTRODES FOR DIRECTION MODULATION

(d) There is a lower limit to the source electrode dimension that can still provide the needed direction modulation with a given potential variation. By this physical limitation, the collector can thus be no nearer the 360° point than the distance thus prescribed. Increasing the potential, so as to reduce the required angle of the split in the accelerating electrode introduces more energy modulation and defeats its purpose. (To a good approximation, the magnitude of direction modulation is proportional to both the electrode dimension and the modulating potential.) An approximate theoretical analysis of the effects of tapered and split accelerating slits on direction and energy modulation, and the effect of energy modulation on isotope separation is given in the Appendix.

On the basis of the above difficulty with direction modulation, it appeared that development of the separator along the lines of the energy modulation method would be preferable. Since there would no longer be a need for thick deflecting electrodes, collection very close to the 360° point could be achieved and the distortion effects caused by the varying beam radius would be minimized. Although the above studies were valuable in the design and operation of later equipment, they were not carried to the point where actual separation of isotopes was attempted.

The Energy Modulation Method

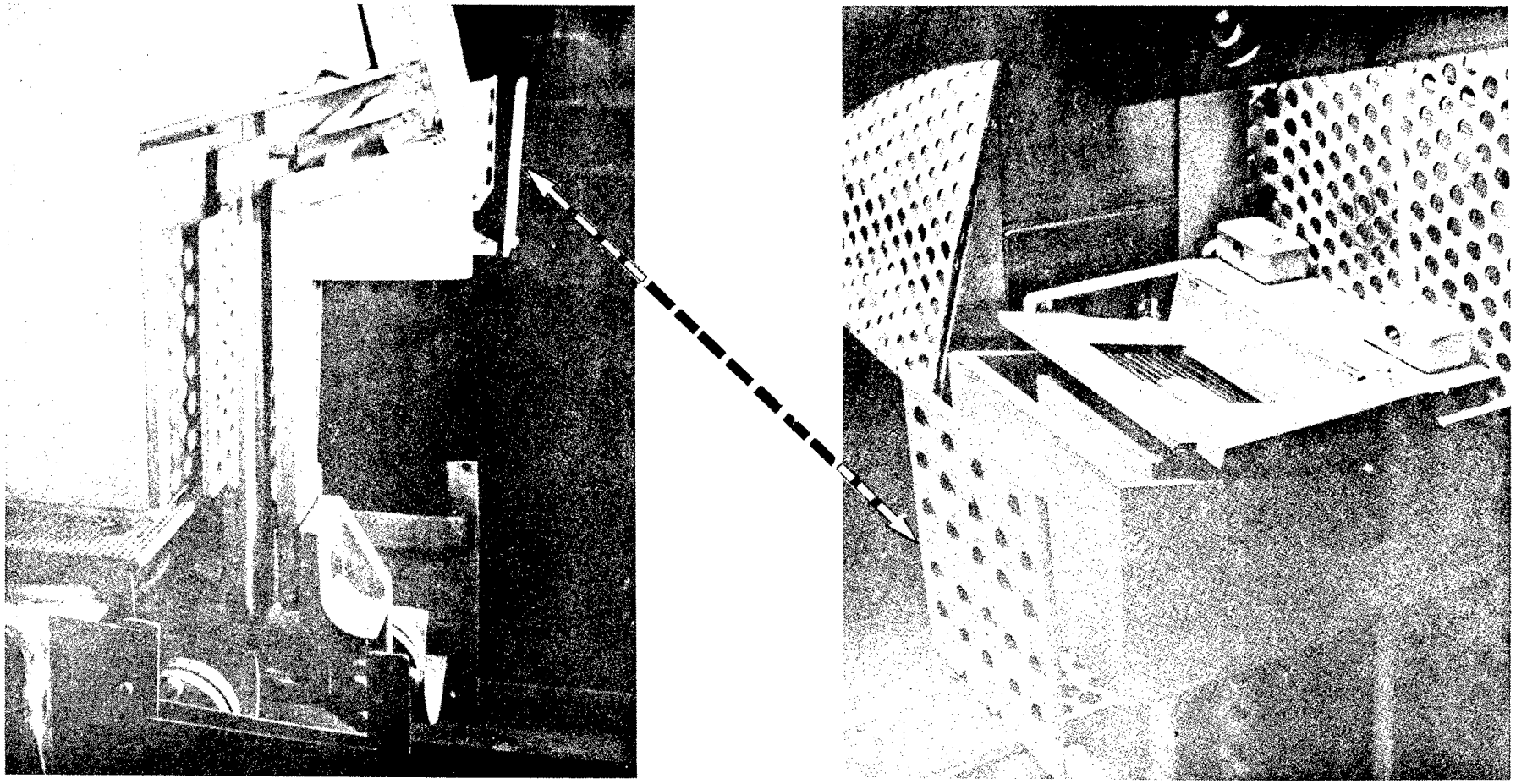
In the preceding discussion it was shown that a path essentially 360° in length is necessary to minimize the dependence of transit time on energy. A cyclorator unit was constructed which focused and spiraled the beam from a short arc to a collector mounted beside the accelerating slit in such a way that the beam traveled a full 360° path. With this improvement the cyclorator could also have been used as a direction modulated cyclorator. However, the degree of focus required would be very difficult to achieve, the

used only to study energy modulation. Photographs of this unit are shown in Figure 3.

The placement of the collector beside the source introduced serious spatial limitations and it was for this reason that many mechanical failures resulted. In particular, the coaxial lead to the collector, which was required to hold dc and rf potentials simultaneously, failed repeatedly. Several modifications of design, made in an attempt to reduce the available volume for oscillation of electrons, were only partially successful.

To provide a better apparatus for the work on energy modulation a new separation unit was designed, Figure 4. This equipment was similar to that used at Berkeley in their cyclorator experiments. In this assembly the arc and associated components were at ground potential while the accelerating slit and separation region (linear) were at high negative potential, as in Figures 5 and 6. The collector was placed so that the angle traveled by the beam was as nearly 360° as possible, actually 350°.

Referring to Figure 5, the ions are accelerated from the grounded ion source (1) by the -30 kv applied to the accelerating slit, (2) and are decelerated to the liner entrance slit (3) which is at a potential of -18 kv plus the 4 kv radio-frequency component. Thus the ions entering the liner have an energy which varies with time at the frequency of the potential applied to the liner. These ions travel through 350° orbits and return to the liner exit grid (4) where they are decelerated to the collector (5) through a voltage equal to the difference between liner potential and collector potential. This difference in potential has an rf component because the liner exit grid is at liner potential. If the frequency of the liner voltage is adjusted to give the proper phase relationships at the collector, separation will be obtained between the U 238 ions and the U 235 ions.



ION SOURCE SIDE COLLECTOR SIDE

FIGURE 3. ENERGY-MODULATED CYCLORATOR

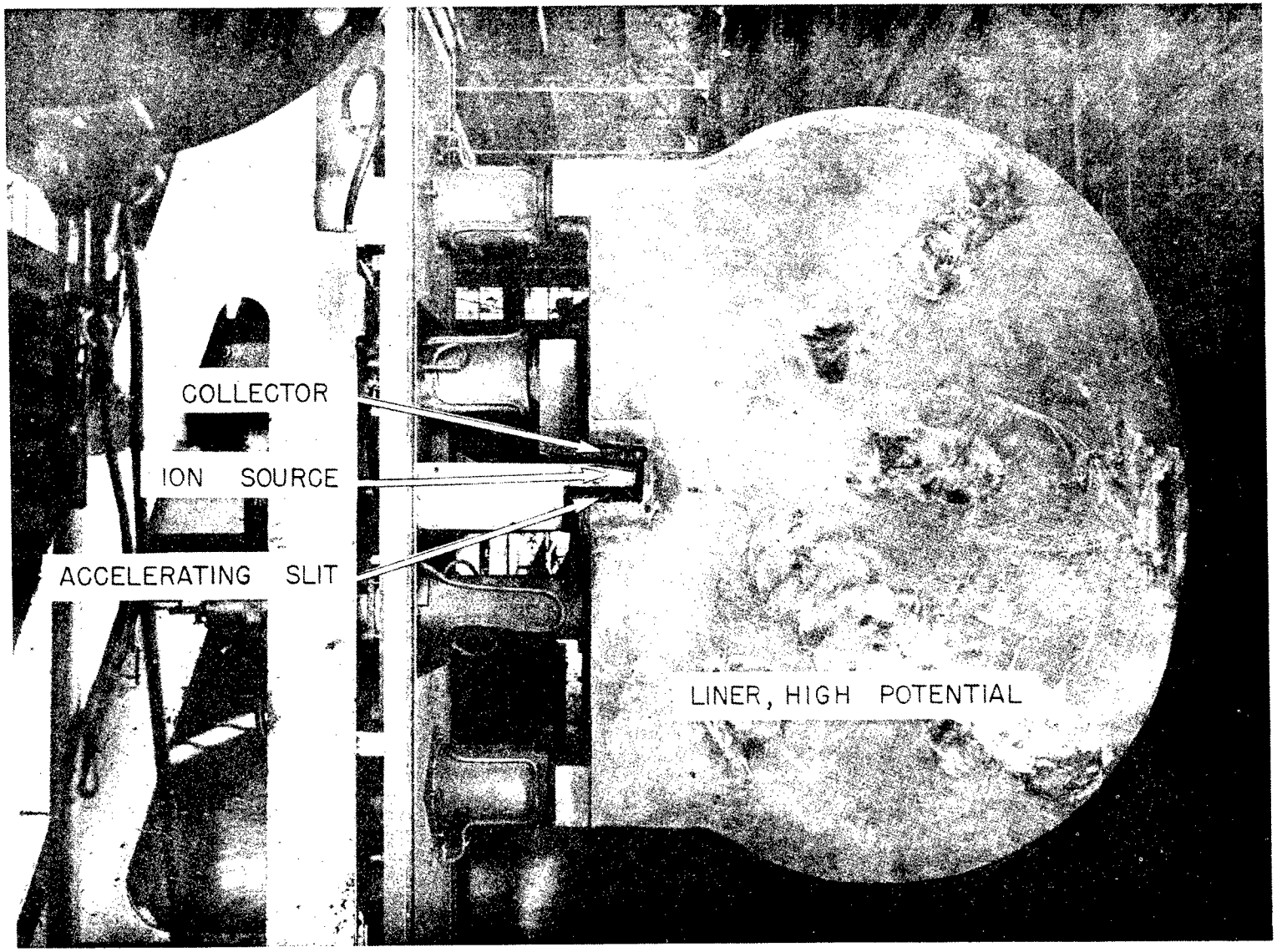


FIGURE 4. CYCLORATOR WITH GROUNDED SOURCE

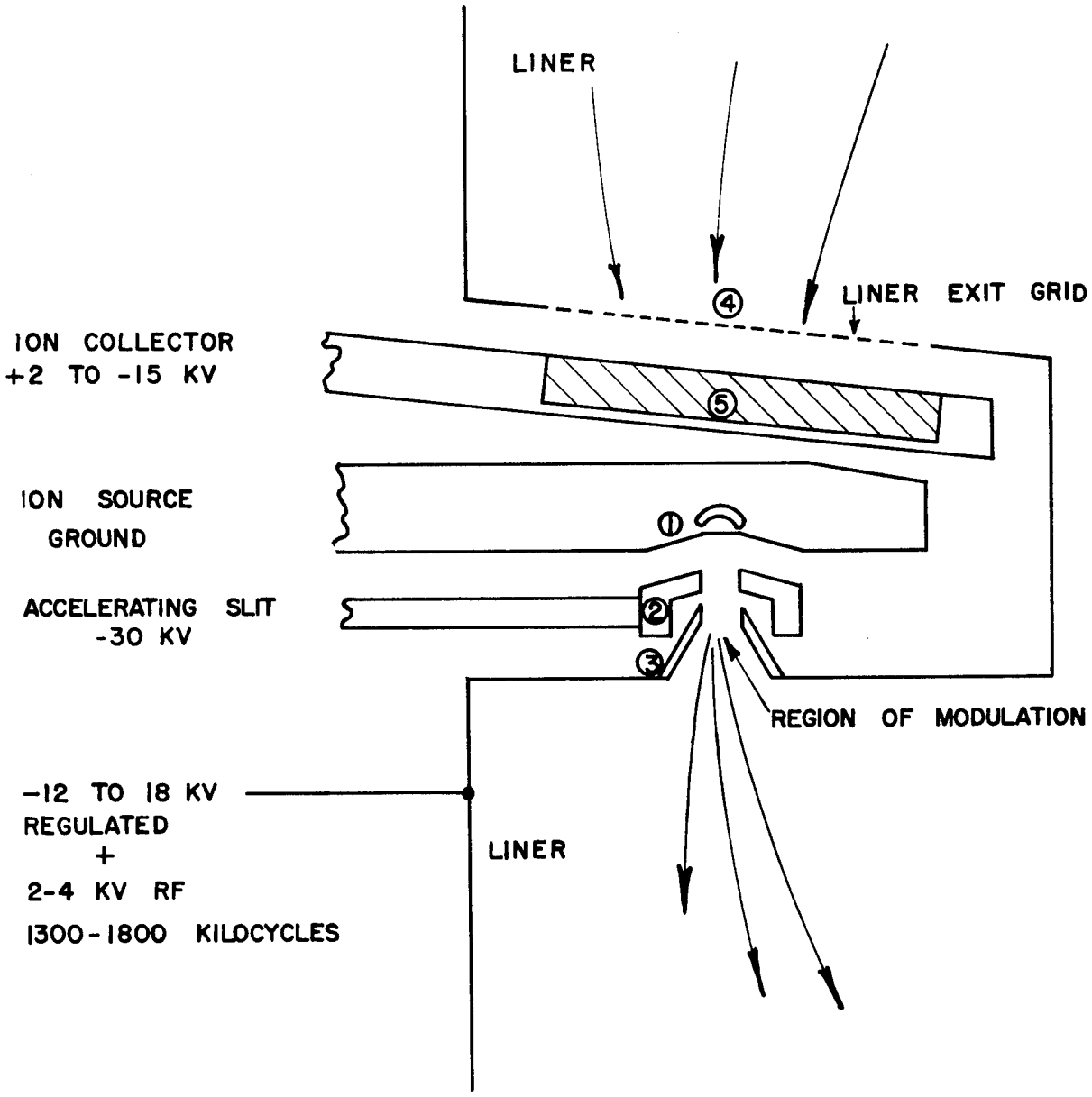


FIGURE 5. ENERGY MODULATION, SOURCE AND COLLECTOR

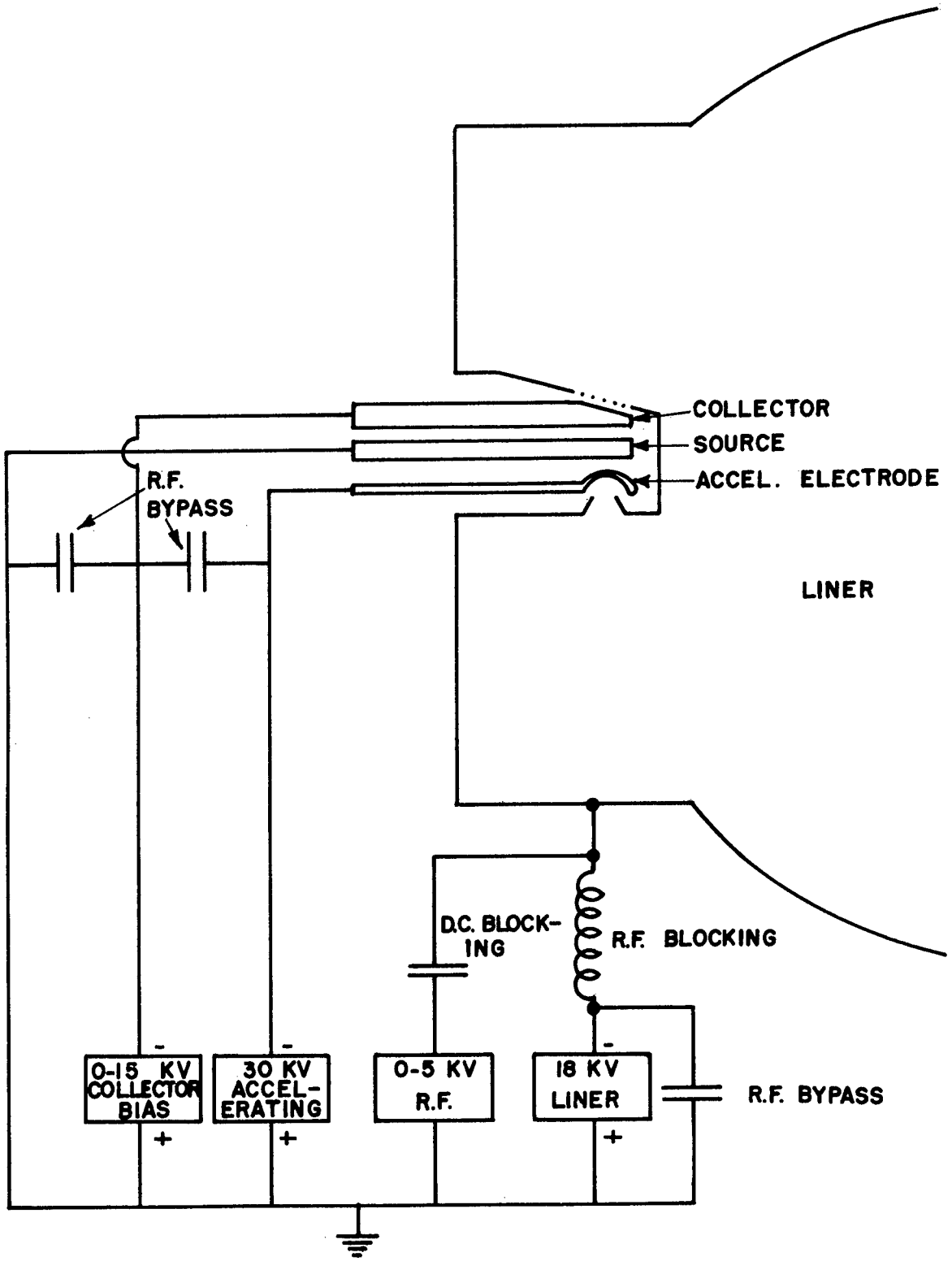


FIGURE 6. ENERGY MODULATION, POWER SUPPLIES

It should be noted that the collector arrangement used in these experiments is capable, even under conditions of ideal time resolution, of extracting no more than half of the desired isotope. Separation of the reflected remainder could be achieved by the use of two additional collectors. A possible arrangement and the relations of ion energies to collector potentials are shown in Figure 7. By inspection of the graphs, it may be seen that half of the U 235 should be taken out at collector E_1; almost all of the U 238 removed at E_2; and the rest of the U 235 collected at E_3. Since the ions make only a quarter of a revolution in space between E_1 and E_2, there would be a 45° phase shift resulting in a contamination that reduces the impoverishment factor in collector E_2 from the ideal, infinity, to a maximum of approximately 16.

Deceleration and Collection

The collector design for the cyclorator was greatly complicated by the requirement that its thickness be small while maintaining high material retentivity. The collector was 1/2" thick in the direction of the incoming beam and material retention was provided for by a series of 1/64" thick carbon plates placed to form pockets at an angle of 15° to the normal. Wear caused by sputtering was negligible both because of the very low particle energy and the low current.

The collection system used with the energy modulation requires that the beam be decelerated from its original energy to a value as low as possible and collected at this energy. It follows that large power savings are possible because of the reduction in current through the high voltage liner supply. For effective use in the cyclorator the deceleration system must possess a sharp break in the characteristic of the ion current vs collector voltage. The ideal deceleration characteristic would be that shown in Figure 8a, which

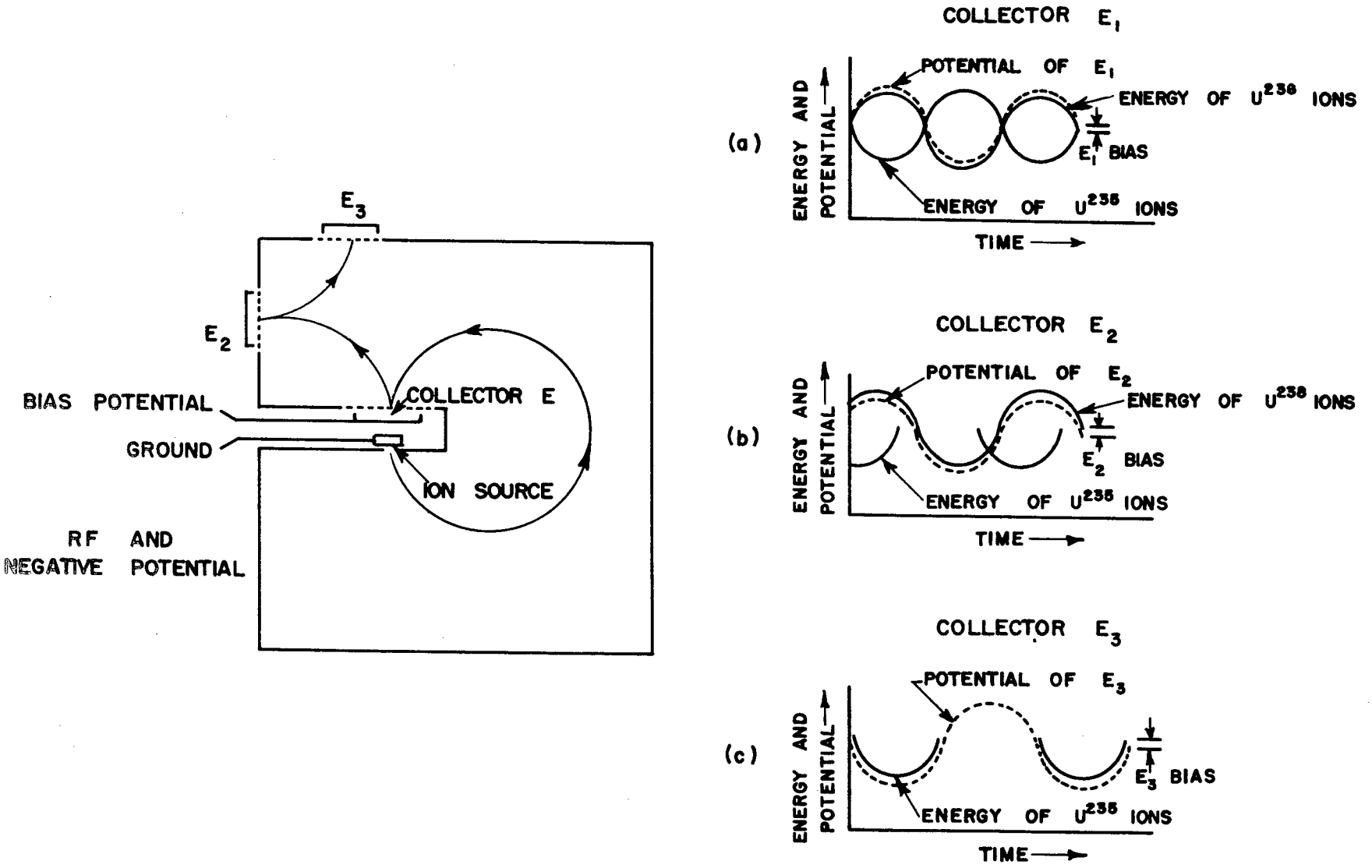
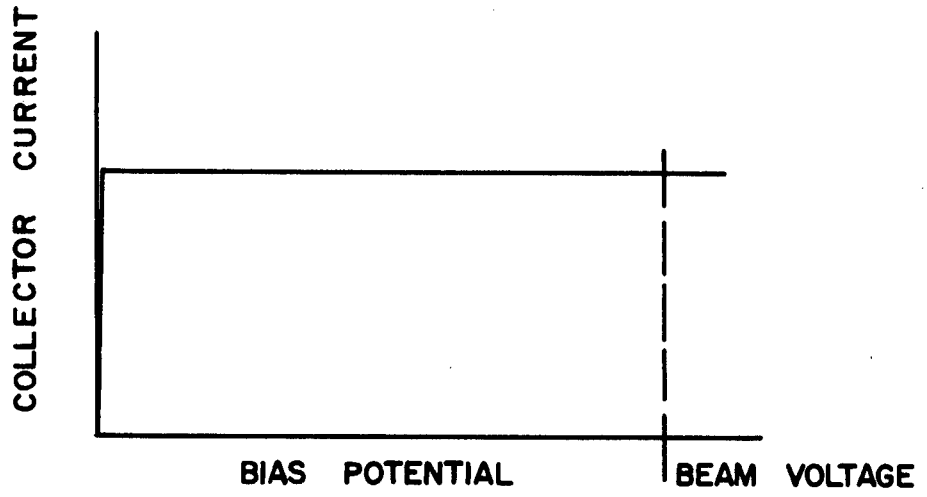
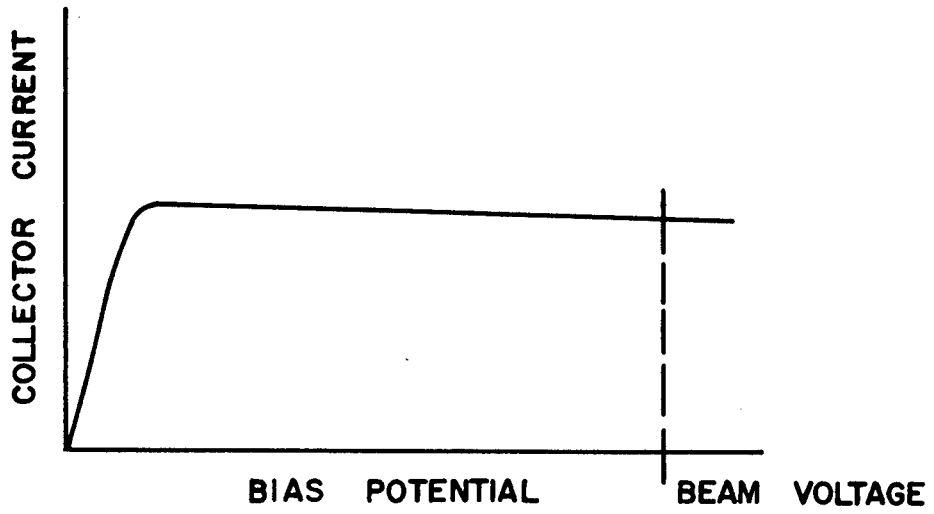


FIGURE 7. PROPOSED MULTIPLE COLLECTOR SYSTEM



(a) IDEAL



(b) WITH ANGULAR DIVERGENCE

FIGURE 8. CHARACTERISTICS OF BIASED COLLECTOR

requires that the particles enter the deceleration gap normal to the equipotential surfaces.

In the device actually used the ions have an angular distribution upon arriving at the collector and are further deflected as they pass near the grid wires. If the collector potential is varied under the above conditions the curve will be similar to that given in Figure 8b. The lack of sharpness is caused by the distribution of ion velocities in the direction of deceleration of a beam having an angular distribution and further by the non-uniformity of the electric field near the grid.

The characteristic can be much improved by curving the deceleration grid and collector so that the ions enter perpendicularly to the equipotential surfaces. The requirement that the transit time from source to collector be the same for all angles of the distribution is also better satisfied with a curved collector.

In early tests of the deceleration system with the collector nearly at ground potential, negative current was metered. This current masked, to a large extent, any variations in the positive ion beam received when the frequency was varied. In order to study this effect, the ion collector was placed within a Faraday cage in such a manner that its potential with respect to the cage could be varied. It was found that potential differences as high as 600 volts had no appreciable effect on the negative current and thus it was presumed that the particles originated near liner potential. It was proposed that this current consisted of negative ions produced in the oscillating regions where the decelerating field penetrates between the grid wires into the liner.

Two changes were made in the geometry of the decelerating system based upon the assumption that negative ions were being collected. The gradient was reduced by increasing the deceleration gap and the grid wires were arranged parallel to the magnetic field to reduce the effect of the penetrating potential. These changes resulted in a decrease of the negative current from 4 ma to 0.5 ma. Figure 9 shows collector characteristics obtained before and after the geometry was modified.

The Radio Frequency System

Radio frequency voltage was provided by a conventional tuned plate oscillator utilizing two water-cooled GL 434 A triodes in parallel. The tuned circuit consisted of a tapped inductance which paralleled the capacity of the liner to ground. Fine frequency adjustments were made by means of a 50-200 μμf variable vacuum capacitor across the inductance, while large frequency changes were made by changing taps on the inductance. A schematic diagram of the oscillator is given in Figure 10.

Operation Techniques

The techniques used in the operation of a time-of-flight separator naturally differ radically from those of the calutron. In the series of experiments, a number of observations were made that led to the most favorable monitoring of the system. During the startup period, while a stable arc is being obtained, the bias potential on the collector is raised above its normal value in order to reject all ions. Figure 11 gives a typical characteristic of U 238 collector current vs frequency. For low U 235 concentration in the feed material, 0.7%, the criterion for U 235 enrichment is that of obtaining a current minimum, and for U 235 depletion, a current maximum.

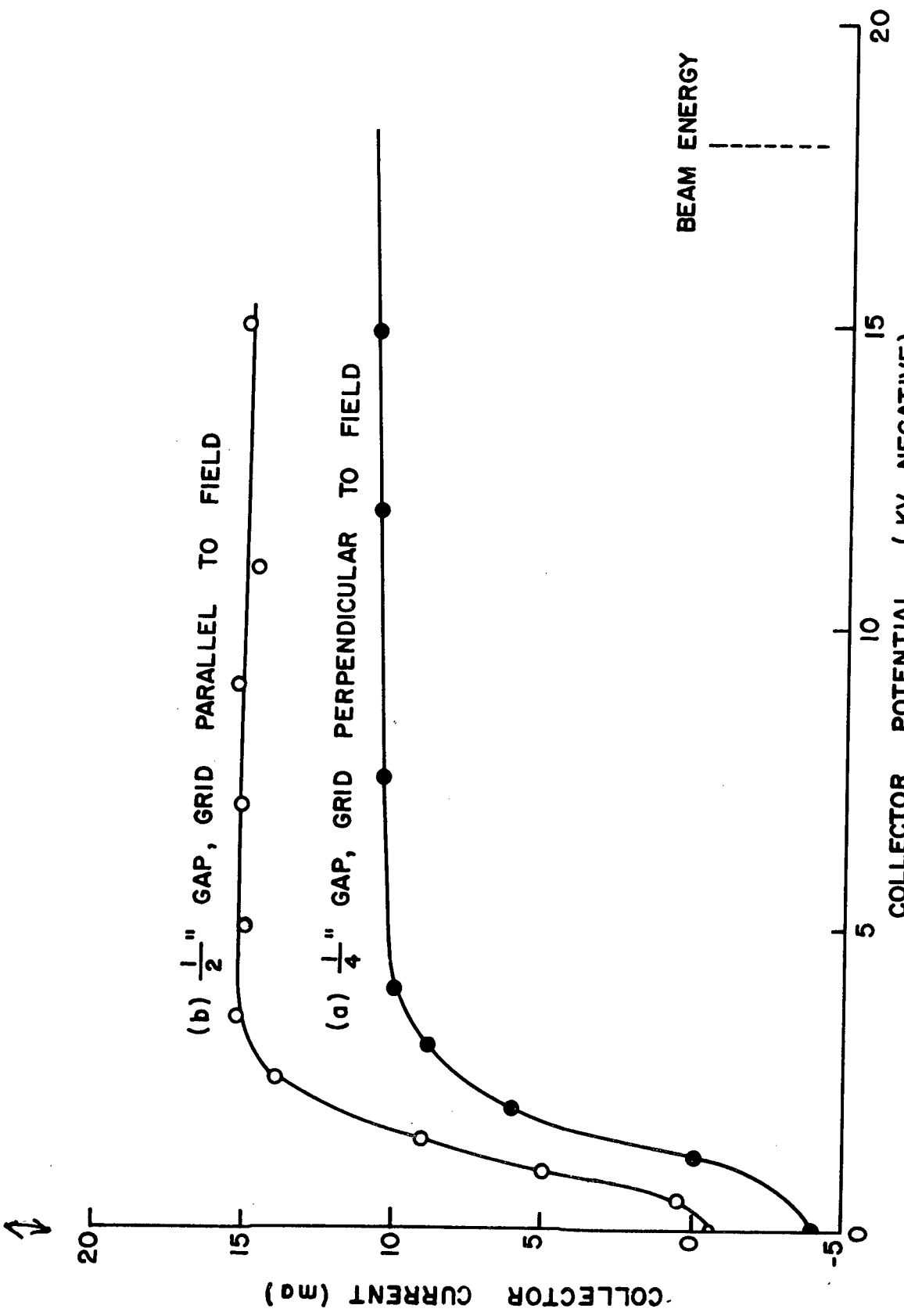


FIGURE 9. EFFECTS OF COLLECTOR MODIFICATION

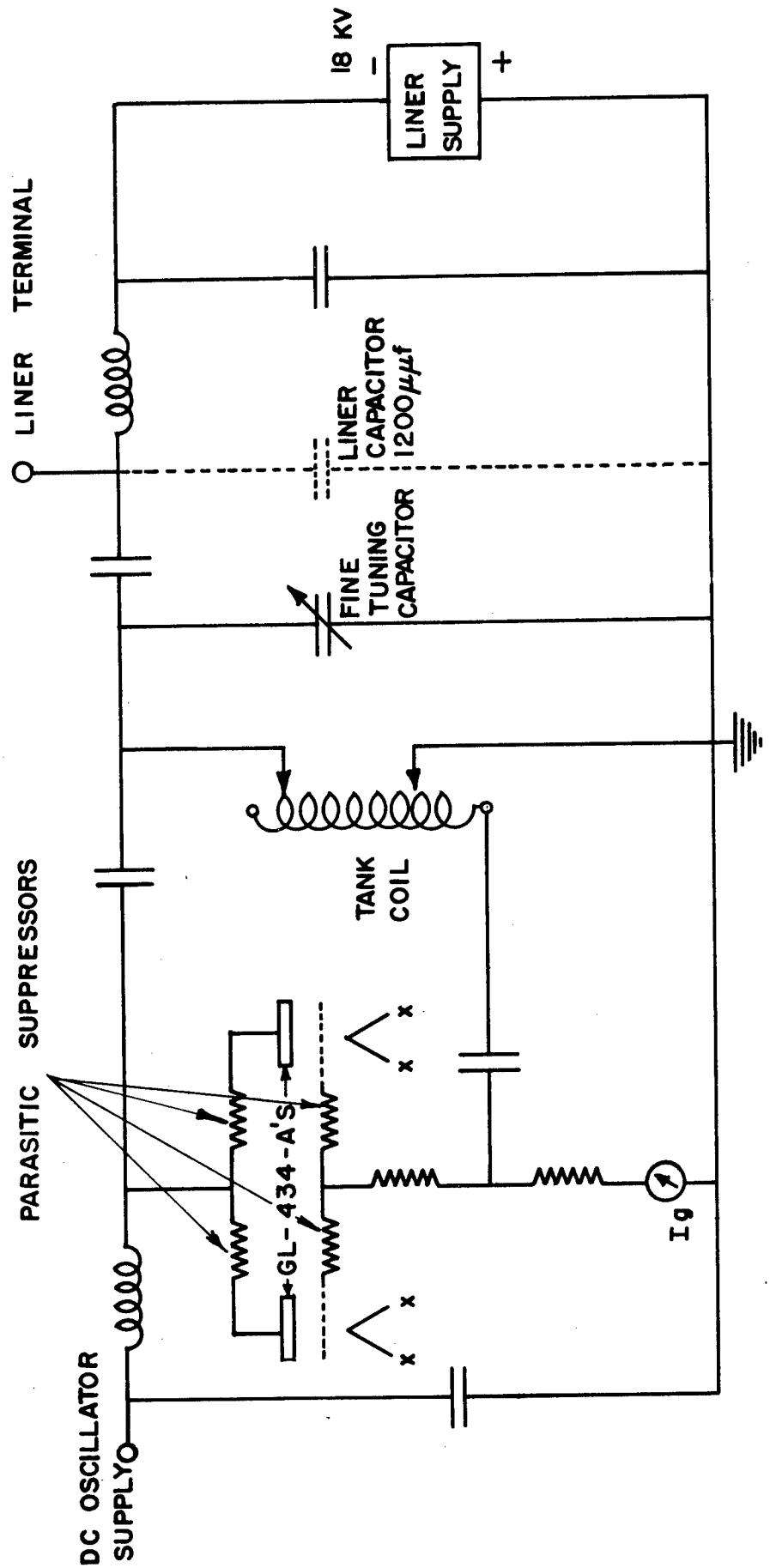


FIGURE 10. RF SYSTEM

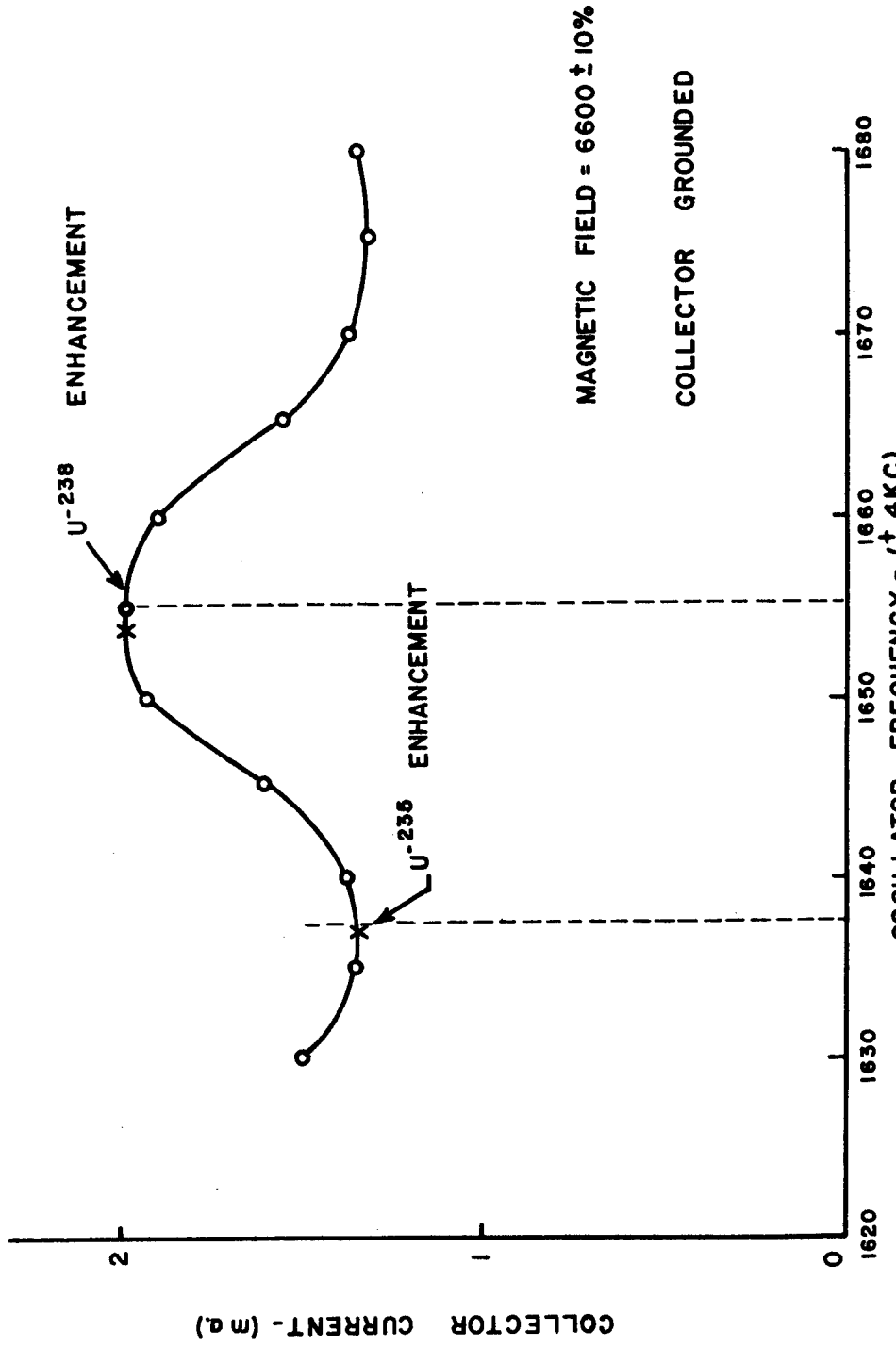


FIGURE II. EFFECT OF MODULATION

Unlike the calutron, the beam energy need not be adjusted accurately because the focus is independent of energy.

The arc conditions, as in the calutron, are critical to the extent that if the arc current is increased beyond a certain point no evidence of separation can be noted. This situation appears to be similar to that of beam "blow-up" (loss of focus) in the calutron. In the range where separation is achieved the arc conditions appear to affect only the output and not the resolution.

The bias potential is important in that it affects both the collection efficiency for the desired ions and the enrichment factor. Theoretically, a portion of the ions will be collected at any dc collector voltage less positive than twice the rf voltage. Placing the collector at a voltage more positive than ground gives more efficient rejection of the undesired isotope and reduces the time of collection of the desired isotope to less than 1/2 of each rf cycle. The result of this mode of operation is the collection of a smaller sample of more highly enriched material. The gain in enhancement is not without sacrifice, however, both because the efficiency is reduced and because it would be difficult to further separate the beam reflected from this collector.

Isotope Separation Tests

Four isotope separation tests were completed. Runs 1 and 2 were made at an average beam energy of 18 kev. It was discovered that this energy placed the beam in a region of rather severe magnetic field non-uniformity. To minimize this cause of low enrichment the beam energy was decreased to 12 kev where the magnetic field was relatively uniform over the beam path. Run 3, at the low beam energy, was very unsteady which accounted for the low enrichment. In Runs 1, 2, and 3 the enrichment of U 238 was sought. In contrast, Run 4 was operated to give a sample enriched in U 235. To provide better

rejection of the U 238, the collector bias was maintained at 2.5 kv positive rather than zero as for the previous runs. It should also be noted that the material collected during this separation was segregated to form two batches. Batch (a), consisting of material that adhered to the collector, showed an enhancement of 1.48. Batch (b), the loose material which had fallen from the liner walls and grid wires, was impoverished in U 235 as would be expected. The data from the above tests are summarized in Table I.

Suggested Improvements

A number of modifications of the cyclorator were proposed during the course of the development program. Of these, two are reported here as being of possible future interest.

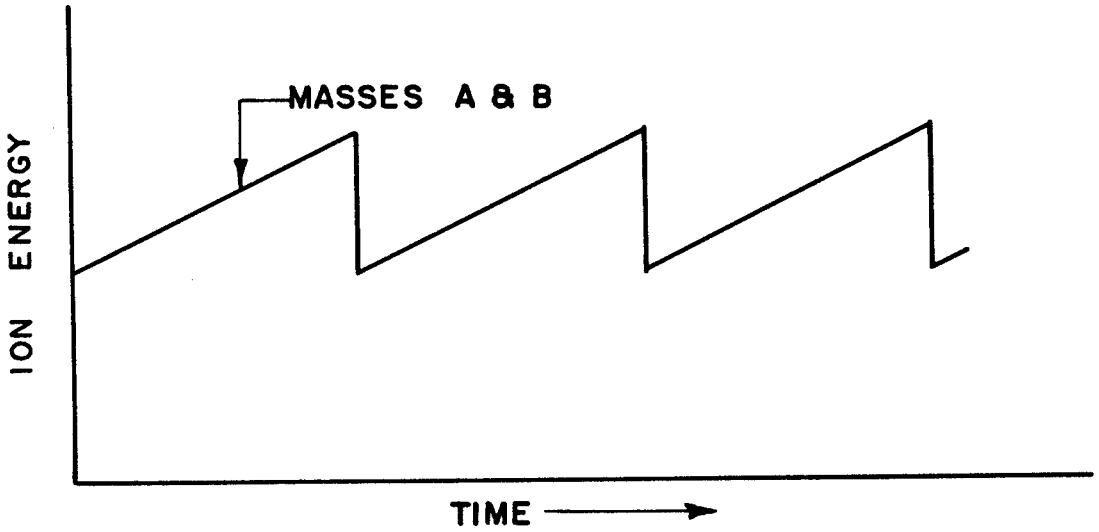
Waveforms for Energy Modulation. As has been discussed earlier, a sinusoidal modulation of energy results in a maximum of 50% collection of a desired isotope by a single collector. A type of energy modulation that obviates this difficulty is described below. Assume that the ions are

TABLE I: CYCLORATOR SEPARATION RUN DATA

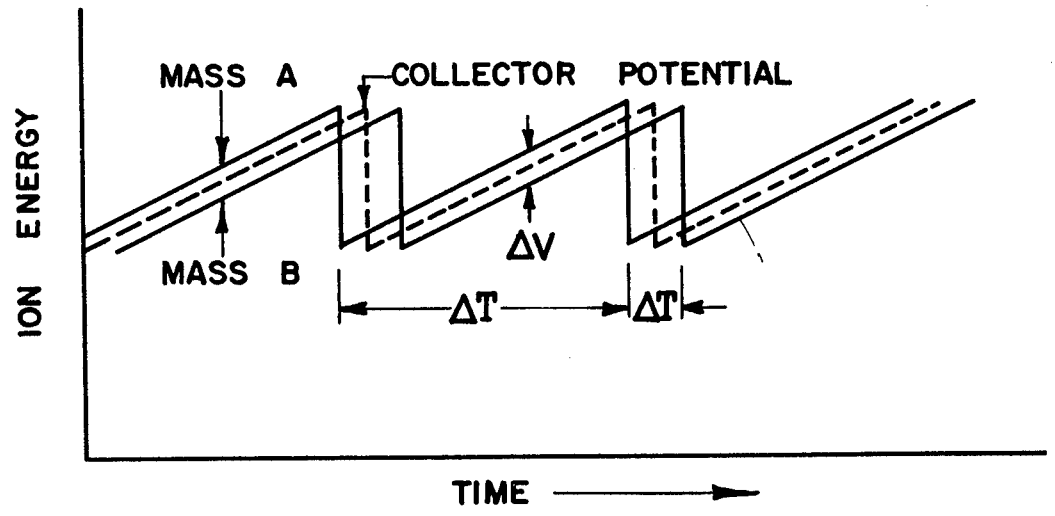
Run No.	Average Current (ma)	Source Voltage (kv)	Bias Voltage (kv)	Uranium (grams)	U 235 (%)	Enrichment (238:235)	Enrichment (235:238)
1	3.2	18	0	0.275	0.686	1.035	0.965
2	3.4	18	0	0.172	0.593	1.198	0.834
3	4.5	12	0	0.255	0.606	1.173	0.852
4	0.3	12	2.5	0.476	*a 1.04 b 0.660	a 0.675 b 1.078	a 1.480 b 0.929

* Batch a - Footscraper blades from collector pocket
Batch b - Loose material which had fallen from grid wires and liner walls

accelerated from the source by a large steady voltage on which is superposed a small sawtooth variation of potential, as shown in Figure 12. By virtue of the time-of-flight effect, ions of different mass arriving at the collector have a difference in energy ΔV, with the usual time difference ΔT. From inspection , it is evident that voltages and times are related by $\Delta V/V = \Delta T/T$, where T is the repetition time of the sawtooth. If the collector is biased with a sawtooth potential intermediate between the energies of the incident ions, nearly 100% collection of the desired isotope should be possible. By further study of the areas of the waveforms it is found that the theoretical enrichment of the method is $(T - \Delta T)/\Delta T$, and since a practical limit on $\Delta V/V$ is 0.1, a maximum enrichment of 9 might be expected.



(a) AT SOURCE



(b) AT COLLECTOR

FIGURE 12. SAWTOOTH MODULATION

LIMITATIONS OF THE CYCLORATOR

In principle, the time-of-flight method as applied in one or more of the modulation forms of the cyclorator appears to have several advantages over the calutron for isotope separation. Experimental and theoretical work reveals however that there are many physical restrictions and limitations that make separation by the cyclorator very sensitive to design and mode of operation.

The expectation that a wider angular divergence of the beam from the source could be collected is fulfilled, of course. The principal reason that large ion beams cannot be handled in either device is that time-dependent variations in potential are automatically developed in the separating region as the beam intensity is increased. At this time no means have been found to combat these fluctuating fields, which serve to distort the spatial disposition of the ions in the calutron, or the transit time of ions in the cyclorator. The fundamental fact is that an electric force has the ability to change the direction of ion motion, or to change the time required to traverse a given distance.

Aside from the above rather intangible factor, separation by the cyclorator is strongly influenced by the following effects:

(a) The enrichment drops sharply in any system in which the collector is not at the exact 360° position. This introduces the practical problems of finding available space for accelerating electrodes, or alternatively achieving a beam spiral by auxiliary deflecting potentials which are foreign to those used in the basic principle. Further, valuable process tank space is taken up by these spiral orbits.

(b) In order to obtain high purity, it is necessary to apply large bias potentials that reject the bulk of the desired isotopes. Although small essentially pure samples may be collected in this way, it is at the expense of efficiency of the process. Further electrical separation of the rejected mixture of isotopes is rendered difficult by this procedure.

(c) The complete isolation of a desired ion type from the undesired by the most favorable method, sinusoidal energy modulation, could be achieved only by multiple reflections of ions, from a sequence of three collectors, between which ion losses due to scattering reduce the intensity. In addition, this operation is effective only if the collector grid surface is perpendicular to all entering ion reflections and if the decelerating electric field behind this grid affects all ions symmetrically. These requirements are incompatible with perfect 360° focusing, even in theory. The alternative, saw-tooth energy modulation, eliminates the necessary multiplicity of collectors but still requires a 360° path length. Excluding the latter difficulty, the maximum enrichment is probably around 10, because of the inaccuracy of waveform and the sensitiveness of collected currents to collector potential.

CONCLUSIONS AND RECOMMENDATIONS

It has been shown in the study of the cyclorator principle that ion beams may be successfully direction- and energy-modulated at frequencies as high as 1.6 megacycles per second. The separation of the isotopes of uranium by the energy-modulated cyclorator has been demonstrated at low beam current. The enrichment of U 235 so obtained was 1.48. Although in principle perfect separation of isotopes in one stage is possible by this method, it has been found that resolution is extremely sensitive to deviations from ideal conditions, all of which are difficult to satisfy simultaneously in a practical design.

In the judgment of those familiar with both the cyclorator and the calutron the two devices have the same fundamental limitations: low ion output and dispersal of beam by oscillatory electric fields in the separation region.

It would appear that further investigation of the cyclorator be deferred until the fundamental nature of the second limitation, beam dispersal, becomes better understood.

It is recommended that the time-of-flight principle be considered as applicable to a precise determination of isotopic masses, where only very small currents are needed and the ideal requirements can be very closely approached.

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Source design and construction were carried out by J. S. Luce, G. F. Leichsenring, J. E. Mann, O. D. Matlock, R. G. Reinhardt, and R. W. Wright.

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APPENDIX

Ion Focusing

The physical basis for the use of a curved accelerating slit is that ions crossing an electric field which is directed at a slight angle to the usual beam are given a component of velocity parallel to the magnetic field, z-wise. They preserve this speed in the separating region; by the correct choice of the slit geometry they are displaced to a common focal point, Figure A.

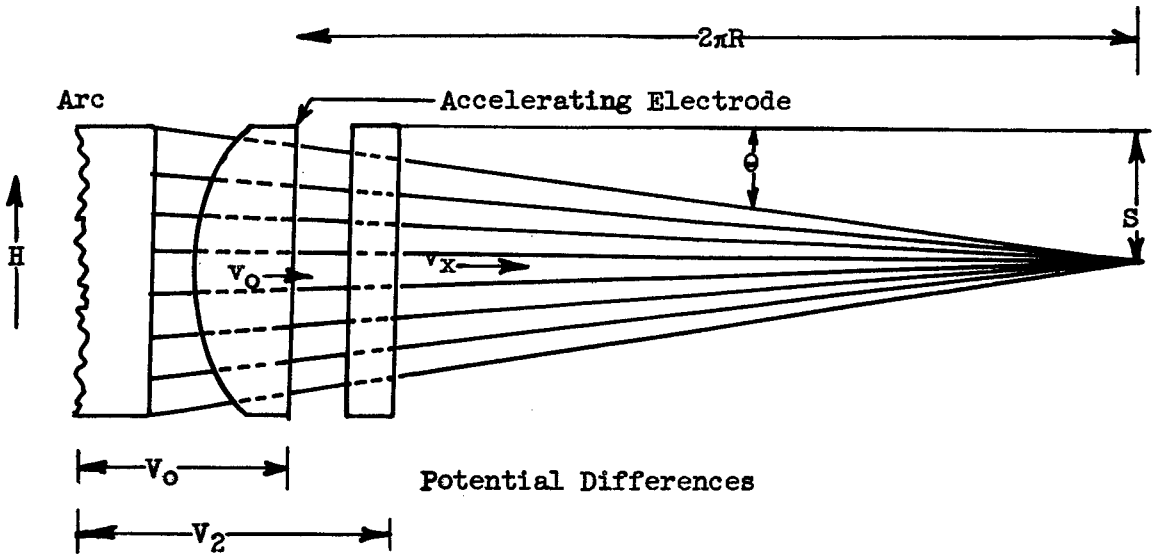

Figure A

The curvature of the accelerating slit and the necessary associated thickness is small, as shown below. In the accelerating gap the electric field direction is continually changing, but one may estimate its effect on the ion motion by assuming it is uniform and tilted at some maximum angle θ with the arc. The maximum possible z component of velocity introduced in the gap is approximately $v_z = \sqrt{\frac{2eV_o}{m}} \sin\theta$. The transit time in the orbit is $2\pi R/v_x = 2\pi R \sqrt{\frac{m}{2eV_2}}$.

The displacement is thus $S = 2\pi R \sqrt{\frac{V_o}{V_2}} \sin\theta$. For a typical case of S = 4", R = 17", V_o = 36 kv, the maximum angle of tilt is computed to be only 1.5°.

Split Accelerating Electrode

The space occupied by an accelerating electrode that periodically deflects ions in the z direction may be estimated. Consider the simplified geometry in Figure B, in which focus is ignored, and a steady potential difference V_1 is applied between the halves.

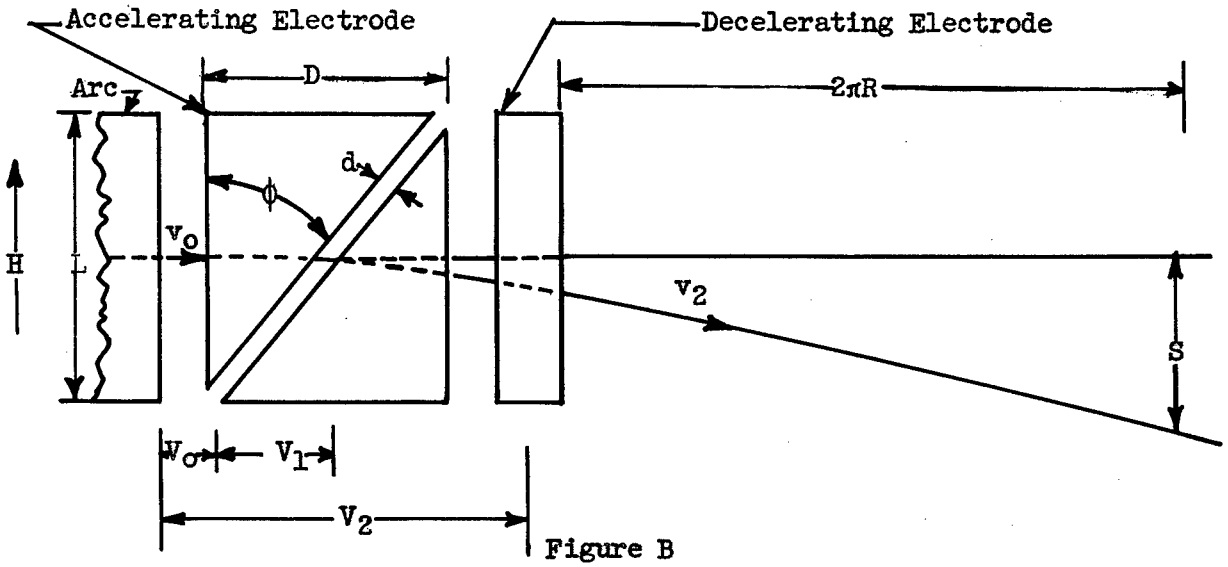

Figure B

The z component velocity produced by the electric field is $v_z = \left(\frac{eE_z}{m}\right) t$, where $t \simeq \frac{d}{v_o \cos\phi}$ is the transit time in the gap of width d, and $E_z = \left(\frac{V_1}{d}\right) \sin\phi$. The displacement in traversing the beam circumference $2\pi R$ is $S = v_z \left(\frac{2\pi R}{v_2}\right) = \pi R \frac{V_1}{\sqrt{V_o V_2}} \tan\phi$. In terms of the arc length, $\tan\phi = D/L$, or $S = \frac{\pi R}{L} \frac{V_1 D}{\sqrt{V_o V_2}}$. In order to obtain a 1" displacement from an 8" arc with say 4 kv deflecting potential (other parameters as in previous example) the required distance D is computed to be about 1.9" (4.8 cm).

Effect of Split on Beam Energy

In the cyclorator, the potential between the two halves of the accelerating electrode is periodic of the form $V_1 \sin \omega t$. Even though all the ions must traverse the final electrode, the potential of which sets the beam radius, their velocity in the plane of the circular orbit will be dependent on time of emission from the source because of the variation in acceleration during the time of transit through the system. Consider an idealized arrangement as sketched in Figure C. This slit system, in which the tilt of the slit is neglected, is applicable to the motion of an ion near the bottom of Figure B. The region of length D is taken as field-free.

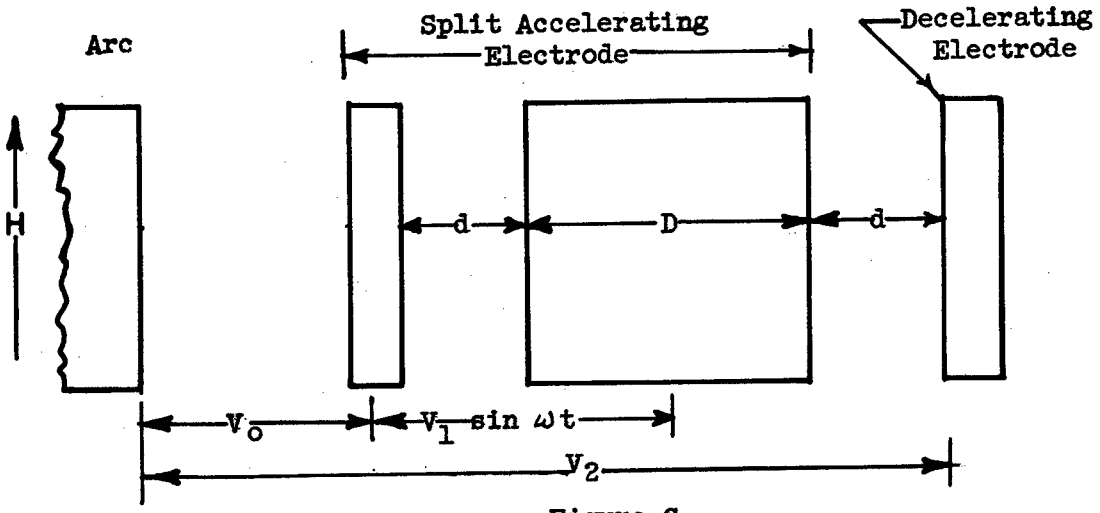

Figure C

If the gaps labeled d are much smaller than the "drift tube" length D, then the ion energy on leaving the system is the sum of the increments in the various gaps

$$E = V_o e + V_1 e \sin \omega t + \left[V_2 - V_o - V_1 \sin \omega (t + \tau) \right] e$$

where τ is the transit time through the drift tube, to a first approximation equal to $\frac{D}{V_o}$, this may be rearranged to yield the modulation of the orbit ion energy

$$Ve = E - V_2 e \simeq 2 V_1 e \sin \frac{\omega D}{2V_o} \cos \omega \left(t - \frac{D}{2V_o} \right)$$

For example, with V_1 = 4 kv, D = 4.8 cm, $\omega = 10^7$ sec^{-1}, $v_o = 1.7 \times 10^7$ cm/sec, the maximum energy modulation is computed to be 7.8 kev. A similar relation for the other extreme assumption that region D experiences a time varying electric field, may be derived. It should be pointed out that in the more precise analysis of the ion motion, evidence is found of a severe distortion of the energy-time characteristic from a sine wave into a double valued function. A corollary is that space bunching of ions would be predicted.

Effect of Energy Modulation on Mass Separation

If there is a modulation of ion energy and thus beam radius the difference in arrival times of ions of two masses at a collector located at an angle α from the ideal 360° point is shown below to be markedly different from the standard relation,

$$\Delta T = \frac{2\pi c}{eH} \Delta m \equiv \Delta T_o = \frac{2\pi}{\omega} \frac{\Delta m}{m}$$

The time of transit in general is given by

$$T = \frac{2\pi}{\omega} - \frac{x}{v}$$

where x is the distance between source and collector, as shown in Figure D or since

$$\omega = eH/mc \text{ and } v = \sqrt{\frac{2E}{m}},$$

$$T = \frac{2\pi c}{eH} m - x\sqrt{\frac{m}{2E}}$$

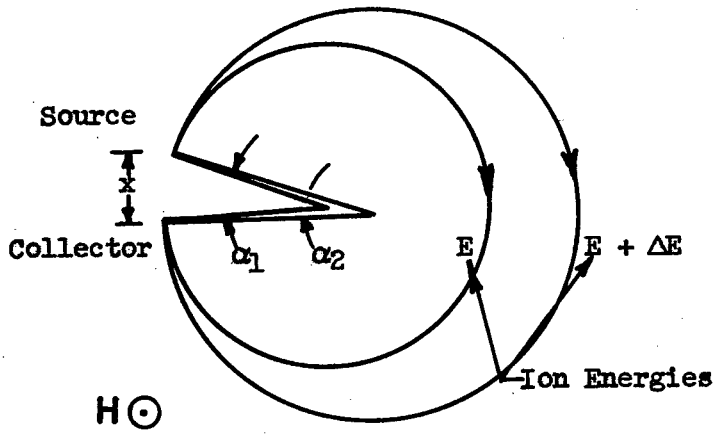

Figure D

Evaluating the differential of T, considering variations in energy and mass differences, we obtain

$$dT = \frac{\partial T}{\partial m} dm + \frac{\partial T}{\partial E} dE$$

The result is approximately

$$\Delta T \simeq \Delta T_o - \frac{x}{2v}\left(\frac{\Delta m}{m} - \frac{\Delta E}{E}\right)$$

Examination of this expression reveals the following: Even without energy modulation, i.e., $\Delta E = 0$, there is a correction to the 360° time of arrival of an amount $\frac{x\Delta m}{2vm}$. This error, however, can be compensated for by an rf frequency adjustment. The effect associated with the term involving energy, however, $\frac{x}{2v}\frac{\Delta E}{E}$, where ΔE will range from zero to the maximum beam energy difference cannot be so treated. The condition for complete ion mixing (180° phase shift) is that for which the energy term (using the peak to peak energy variation 2 Ve) is exactly equal to the basic time difference ΔT_o. The maximum angle between collector and source may for a given energy modulation fraction $\Delta E/E$ can thus be written

$$\frac{\alpha}{2\pi} = \frac{\Delta m/m}{Ve/E}$$

For the case of E = 18 kev, Ve = 7.8 kev, $\Delta m/m = 1/80$, we find $\frac{\alpha}{2\pi} = 0.029$ or R = 17", x = 1.53". This limiting dimension is already smaller than the 1.9" required to achieve the direction modulation of 1" that was assumed to be desirable. The possible compromises in dimensions and potentials are few in number because of the interrelation of variables. From the equations derived in the above paragraphs it is noted that

$$S \sim V_1 D$$

and for $\frac{\omega D}{2v_0} \ll \frac{\pi}{2}$, $Ve \sim V_1 D$. Thus the resultant energy modulation is proportional to the displacement achieved. If V_1 and/or D are reduced to the point where phase shifts do not disturb ion separation, the deflection in the z direction is so small that ions are not resolved physically.

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