RECENT ADVANCES IN DC ACCELERATORS

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Steady progress in the generation of higher voltages, and in ion source and acceleration tube technology has been made since the last National Accelerator Conference in 1965. Commentaries on the progress of this work will be made by Trump and other speakers during the present conference. While these advances in technology are of the most pressing importance it appears that the application of well-known physical principles to heavy ion acceleration have lead to a striking extension of the usefulness of the dc acceleration method.

The advantages of the tandem accelerator for heavy ion acceleration are well-known. They are particularly applicable for ions such as helium, lithium and beryllium now that adequate sources of negative ions of these elements are available. Mono-ergic beams with energies up to 48, 64 and 80 MeV respectively, can be produced by commercially available accelerators. For these elements the tandem accelerator is fulfilling the classic role of the dc accelerator, i.e., the production of distinct homogeneous beams of variable energy. Increased operating voltages serve to extend the range of reactions which may be studied. The tandem principle utilizing a single charge transfer can be extended to the heaviest elements in the periodic table without serious complication. Unfortunately, the energy per nucleon falls rapidly. For uranium, a 10 MV terminal only provides ions with an energy of 0.5 MeV/amu which is too low for nuclear experimentation, although adequate for most atomic or solid state investigations. A terminal potential of over 30 MV is required to overcome the coulomb barrier for uranium on uranium collisions (5.5 MeV/amu)[1]. To overcome this limitation, Van de Graaff[2] and Hortig[3] have suggested methods which offer excellent prospects for accelerating heavy ions to very high energies with the existing high voltage technology. It is the purpose of this paper to explore some of the possibilities of these new techniques.

Among the suggestions of Van de Graaff, the most direct and easily applicable is that of multiple stripping, illustrated in Figure 1. Negative ions which are injected into the first of the tandem accelerators, are stripped in the terminal and are stripped again at voltages of $3/4\,V_T$, $1/2\,V_T$, $1/4\,V_T$ as they are accelerated down the positive ion tube. The beam emerging from the first accelerator, or a component of it, is accelerated to the negative terminal of the second accelerator. It will be shown that uranium ions with energies in excess of 5.5 MeV/amu, i.e., 1.3 GeV, can be obtained in this way using available accelerators.

The negative ion after passing through a foil in the terminal, emerges as a positive ion beam having several charge components. The intensity of these components is approximately given by an expression of the form

$$N(q_i) = \frac{N(o)}{\sqrt{2\pi}\,\sigma}\, e^{-(q_i - \bar{q})^2/2\sigma^2} \qquad \text{-------(1)}$$

where $\bar{q}$ the most probable charge and σ measures the width of the curve and is identifiable as the standard deviation when $N(q)$ approximates a Gaussian distribution[4, 5]. (This is the case except where the electron shell structure has an effect on the distribution or near an extreme where $\bar{q}$ approaches either zero or Z.) Typically σ has a value ~ 1.8 so that at least ten charge states have an intensity greater than 1%. The ions leaving the terminal are accelerated by the voltage between the first and second foils and gain an additional energy $V_T/4q_i$. Each of these beams form a new charge distribution on passing through the second foil

$$N(q_j^i) = N(q_i)\,\frac{N(o)}{\sqrt{2\pi}\,\sigma}\, e^{-(q_j - \bar{q}^i)^2/2\sigma^2} \qquad \text{---(2)}$$

where $\bar{q}^i$ is the most probable charge formed at an energy $V_T + V_T/4q_i$, and q_j^i denotes the j^{th} charge state formed from the i^{th} component of the incoming beam. Thus, at this second foil, the beam fractionates further into components of different energy or charge. These beams are further fractionated after being accelerated and passing through the third foil. However, those components for which $i + j = k$, for all possible i or j for which $N(q_j) > O$, will have the same energy. This degeneracy in the energy of various components significantly narrows the final energy spectrum and enhances the intensity of the separate beams.

Betz et al[6] have shown that the most probable charge, measured in the energy region of interest, is closely represented by an expression of the form

$$\frac{\bar{q}}{Z} = 1 - C\exp - DE^{1/2} \quad \text{---------- (3)}$$

where C and D are constants depending on the ion species and the stripping material. Using expressions (1) and (3), with experimentally determined values for σ, C and D, the energy spectrum of the accelerator was calculated. Figure 2 shows a typical example for $V_T = 10$ MV and for uranium ions. The width of the spectrum changes very little with energy since the relative width depends directly upon σ, which is approximately constant. The spectrum would be somewhat changed if shell effects had been taken into account. The energy components of the spectrum are spaced $V_T/4^e$ apart and each is composed of a spectrum of charge states resulting from the summation following the fourth stripping foil. The number of different charges in a given energy component will generally be in excess of ten with a fairly even intensity distribution. The width of a component depends upon a number of factors such as the equality of voltage spacing down the accelerator column and upon variations in the thickness of the stripping foils, or of dust targets if this proves a practical alternative. The energy inhomogeneity introduced by differences in the charge of the particles entering the stripping media will produce only minor effects. Provided voltage variations along the acceleration column are kept below 50 kV, the summation of energy effects should not exceed 0.5%.

The variation of the median energy of the spectrum for I and U ions as a function of terminal potential is shown in Figure 3. Table I gives more detailed information of the rate of gain of energy for different terminal potentials. It can be seen that a terminal potential of 30 MV yields some ions with an energy of 1.5 GeV. To reach this energy with the voltages which are available it is necessary to use two accelerators. Referring again to Figure 1, particles emerging from the first accelerator are stripped again at ground potential and injected into a second accelerator having a terminal at a negative potential. To obtain a mono-ergic beam on the target located in the terminal of the second accelerator a crossed field analyzer or other device can be used to select a beam of one charge and energy from the first accelerator. Table II shows the energies reached by uranium ions when accelerated in this way.

During 1966 Van de Graaff conducted a series of experiments using an MP tandem accelerator[1,7]. The results verified the predictions of Table I at 8 and 10 MV, which gives reasonable assurance of the calculations for the higher voltages. It could be inferred from the appearance of the foils in the accelerator at the end of a run that no beam was lost from scattering by the terminal foil. Scattering after the terminal foil is insignificant because of the $1/E^2$ dependance of $\langle \theta^2 \rangle$, (see equation 6). Much practical work remains to be done, but there can be no doubt that this method even in the crude form of 1966 and given the second accelerator can provide 1 - 10 nA of uranium ions at energies above 1 GeV.

What must be regarded in comparison as a speculative but very intriguing scheme has been proposed by Hortig[3,8]. In it Hortig describes the principles of a multi-stage heavy ion dc accelerator capable in principle of reaching energies up to 10 GeV. Figure 4 shows a series of negative terminal tandem accelerators each preceded by a dust or foil target, and with gas or vapor terminal targets. Shown on the same figure is the variation of the most probable charge $\bar{q}$ of uranium ions as a function of energy for air and carbon foil stripping media. Injecting a beam of particles of energy E_A through the first foil the beam is accelerated by the tandem accelerator to an energy

$$E_B = E_A + \bar{q}_f^A V_T$$

(See point A on the upper curve of Figure 4.) On passing through the gas target the most probable charge is changed to $\bar{q}_f^B$ corresponding to the point B on the lower curve. Leaving the gas target, the beam is decelerated to ground potential ending with a net gain of energy

$$\Delta E = V_T (q_f^A - q_g^B)$$

the process is repeated in the succeeding accelerators as shown on the figure. After about twenty traversals through these 4 MV tandem accelerators the median energy exceeds 1.2 GeV. The energy gain depends directly upon the difference in the most probable charge in solids and gases. But it is important to note that the technique will work even if there are considerable errors in the curves shown in Figure 4. It does not however seem likely that $(\bar{q}_f - \bar{q}_g)$ will change by more than 10%. There is more likelihood that $(q_f - q_g)$ will be increased by a choice of more appropriate target materials. The energy gain per traversal is a function of the tandem voltage and the energy, as is illustrated in Figure 5, where the energy gain ΔE is shown as a function of the terminal potential and the starting energy. There is a sharp maximum in ΔE as the terminal potential is increased particularly at low energies. The terminal potential which gives a maximum energy gain maybe calculated from the expression derived

TABLE I The most probable energy (MeV) for uranium and iodine ions from a tandem accelerator is shown as a function of terminal potential. The ions were stripped in the terminal and again at potentials of $7/8\,V_T$ and $3/4\,V_T$, or $3/4\,V_T$, $1/2\,V_T$, and $1/4\,V_T$*.

Foil Potential	TERMINAL POTENTIAL (MV)													
	8		10		12		16		20		30		12	
	E	$\bar{q}$	E	$\bar{q}$	E	$\bar{q}$	E	$\bar{q}$	E	$\bar{q}$	E	$\bar{q}$	E	$\bar{q}$
						URANIUM								
V_T	8	6.9	10	8.8	12	9.8	16	11.6	20	13.2	30	16.4	12	9.83
$7/8\,V_T$	---	---	---	---	---	---	---	----	---	----	---	----	26.7	15.4
$3/4\,V_T$	22.0	13.9	32	16.9	41.5	19.3	63.2	23.5	85.9	27.3	153	35.0	49.9	21.1
$1/2\,V_T$	50.0	21.1	74.3	25.5	99.4	29.1	157	35.4	222	40.7	415	51.0	----	----
$1/4\,V_T$	919	28.1	138	33.6	186.8	38.0	298	45.5	426	51.5	798	62.3	----	----
Final E	148	34.6	222	40.7	301	45.6	479	54.5	683	60	1265	70.1	240	41.9
MeV/amu	0.62	----	0.93	----	1.3	----	2.0	----	2.9	----	5.3	----	1.0	----
						IODINE								
V_T	8	8.48	10	9.5	12	10.5	16	12.1	20	13.5	30	16.2	12	10.5
$7/8\,V_T$	---	----	---	---	---	----	---	----	---	----	---	----	27.7	15.7
$3/4\,V_T$	25.0	14.9	33.9	17.1	43.4	19.1	64.4	22.4	87.3	25.2	152	30.6	51.2	20.4
$1/2\,V_T$	54.8	21.0	76.7	24.0	101	26.5	154	30.7	213	34.0	381	39.6	----	----
$1/4\,V_T$	96.8	26.2	137	29.5	180	32.3	277	36.6	383	39.7	678	447	----	----
Final E	149	30.4	210	33.8	277	36.5	423	40.6	582	43.4	1013	47.5	235	34.9
MeV/amu	1.2	----	1.7	----	2.2	----	3.3	----	4.6	----	7.9	----	1.9	----

*The numbers in the table may be regarded as significant to two figures.

TABLE II The energy of uranium ions accelerated by the arrangement of tandems shown in Figure 1 for different terminal potentials. The median energy corresponding to ~ 1% of the initial beam intensity reaching the terminal target after analysis between accelerators, and a higher energy corresponding to 0.01% of the initial beam, have been calculated.

V_{T_1} (MV)	V_{T_2} (MV)	E (1%) (GeV)	E (0.01%) (GeV)
10	16	0.87	0.97
16	10	1.02	1.11
16	12	1.13	1.21
18	12	1.23	1.38
20	12	1.40	1.56

by Fiks and Vialov[9].

$$(V_T)_{max} = (\bar{q}_f - \bar{q}_g)/2\,e\,\bar{q}_f \frac{d(q_g)}{dE} \text{ -------- (4)}$$

It is clear that the terminal potential must not be too high at the beginning of the acceleration cycle if energy is to be gained. By increasing the voltage of the tandem accelerators as the energy is increased so as to stay on the optimum for maximum energy gain the number of stages can be reduced. On the other hand, with a 4 MV terminal potential, the energy gain reaches ~ 100 MeV per accelerator and this would appear to offer a much more economical system. The phasing and other such problems associated with the RF devices do not arise in this accelerator and were it not for scattering in the targets of the accelerator which increases the phase space occupied by the beam the optical problem could be regarded as a comparatively simple one.

Three loss processes have been identified which can effect the success of this accelerator:

(i) Single large-angle scattering events in the targets will cause particles to be lost if they are scattered through an angle larger than the angular aperture α of the accelerator. The probability for scattering through angles larger than α has been calculated by Fiks and Vialov. For an ion injected with an energy E_i, and assuming a constant energy gain ΔE per stage they find,

$$P(\alpha) = .04 \frac{t}{M_t} \frac{Z_t^2 Z^2}{\Delta E E_i} \frac{\cos\alpha}{\sin^2\alpha} \left(1 - \frac{M}{M_t}\sin^2\alpha\right)^{1/2} \quad ----(5)$$

where Z_t, M_t and t are the atomic number, atomic weight, and thickness of the target in gm/cm^2. Z is the atomic number of the scattered particle and M its atomic mass. It is worth noting that the maximum angle of scattering is restricted to M_t/M by center of mass considerations i.e., 0.05rdn for uranium on a carbon target. Even at low injection energies loss from this cause is small.

(ii) Multiple scattering of low velocity heavy ions is much more significant but is difficult to estimate. The mean-square multiple-scattering angle for fast light ions in a target is well-defined by the formula

$$\langle\theta^2\rangle = .04 \frac{t}{M_t} \frac{Z_t (Z_t + 1) Z^2}{E^2} \ln 2.1 \frac{(Z_t + 1)}{Z_t^{5/3}} \cdot \frac{t}{M_t} \quad ----(6)$$

$\langle\theta^2\rangle$ is the mean square scattering angle in the laboratory. For small angle collisions and for a heavy incident ion such as uranium screening will be important, reducing the effective values of Z and Z_t, so that Eq. (6) over estimates the multiple scattering. For a large number of transversals the multiple scattering becomes

$$\langle\theta^2\rangle = \frac{\text{const}}{\Delta E E_i} \quad ---------- (7)$$

The same assumptions were made as in Eq. (5). Fiks and Vialov have calculated the number of particles lost after a large number of passages through the accelerator and found that one-twentieth of the beam was lost because of scattering. The calculation was made for uranium ions injected at 25 MeV into an accelerator with an acceptance angle of 5×10^{-2} radians, and carbon foil thickness of 14 $\mu gms/cm^2$.

(iii) The most important source of loss results from the statistical nature of the acceleration process and the variation of $\bar{q}_f$ and $\bar{q}_g$ as a function of energy Figure 6. At low particle energies the charge distributions in gases and solids overlap so that some particles can loose rather than gain energy. Taking this effect into account and scattering at an injection energy of 25 MeV and a terminal potential 4 MV, Hortig estimates that the loss from both causes amounts to 30-40% in the early acceleration cycles. No further losses from this effect then occurs until very high energies are reached where the most probable charge in a gas and a solid again approach each other. In this region many cycles are required to pass a particular energy with the result that scattering in the targets or residual gas again becomes important and beam is lost. This process appears to put an upper limit of about 10 GeV on the acceleration process for uranium ions.

Hortig has shown that a means does exist for removing the transverse energy introduced by the scattering[10]. In a periodic focusing system the beam oscillates about the axis and scattering and the stochastic increase of the oscillation energy due to a charge increase away from the axis cause the beam to diverge. By restricting the solid targets to a region near the axis, the increase in transverse energy from this cause is considerably reduced. The gas target which is not restricted in extent has a damping effect which Hortig has shown to be sufficient to produce a net reduction in the transverse energy. Figure 7 shows how the scheme will work. A particle passing through the solid target is scattered and on the average will have its charge increased and hence in the restoring field of the lenses its amplitude of oscillation will be reduced. Particles missing the solid target will continue without gaining or loosing energy. Figure 8 shows a calculation of the effect of a scattering and the damping which occurs. A system has now been formed which tends to reduce the amplitude of the oscillation of wavelength L to the diameter "a" of the solid (foil) stripper. At very high energies where the difference between solid and gaseous targets is small, Hortig shows the beam size is given by the expression

$$D = \frac{L}{\pi\sqrt{2}} \langle\theta^2\rangle \left(\frac{1}{\bar{q}_g/\bar{q}_f - 1}\right)^{1/2}$$

provided $D > a$, a being the diameter of the solid target, indicating that the ion beam does not diverge even for strong multiple scattering. It is evident that the final particle energy is limited to the region where the average target in gas and in solid is large enough to support the acceleration process as well as damp the transverse oscillations.

Rather than build a long line of accelerators Hortig has suggested the scheme shown in Figure 9. The beam is injected at a low charge state, but once on the acceleration axis, is stripped and is reflected to and fro through the tandem accelerator, or series of tandem accelerators, by the reflecting magnets. Each magnetic mirror consists of three

uniform magnetic fields and excellent reflecting properties are obtained for $\beta = 0.2997$ and $H_1 = 1.5\, H_2$[8]. The change in angle as a function of the distance X from the incident central trajectory is then given by

$$\Delta = -0.98 \times 10^{-5} X + 0.53 \times 10^{-4} X^2 - 1.7 \times 10^{-2} X^3$$

if X is measured in units of the radius of curvature in H_1. It is hoped that these small aberrations can be corrected by the appropriate choice of the sense of relation in the two mirror systems, and by the damping mechanism which compensates for scattering processes.

An advantage of the mirror system is that only one or at the most a few accelerating elements are required. In addition, the damping processes which relies on having the solid stripper restricted to a small region around the axis would probably be difficult to use effectively in a linear system. It is interesting to note that because of the mean radius of curvature in the magnets increases very slowly with energy from 51 cm at 20 MeV to 73 cm at 1 GeV, (H_1 = 14 kg). The magnets which are required are consequently not large and the optical properties of any magnetic focusing elements do not change radically as the particles gain energy. It is possible that technical objections will be discovered which make this novel method of acceleration impractical, but at the time of writing this technique must be considered along side the cyclic methods for the acceleration of the very heavy elements to several GeV. In conclusion it must be pointed out that if heavy ion collisions above the coulomb barrier are required, as for example in trans-uranic research, a 16 MV tandem (design aim 20 MV) is commercially available. This machine can accelerate ions up to about the middle of the periodic table to suitable energies. For what might be regarded as an ultimate in nuclear collisions, namely uranium on two tandems are required as suggested by Van de Graaff. Suitable facilities for this experiment will exist at High Voltage Engineering Corporation, see Figure 1, and also at the Brookhaven National Laboratory.

Acknowledgments

I wish to express my deep indebtedness to the late Dr. Robert J. Van de Graaff. His genius is behind most of the ideas in this paper. I also wish to express my thanks to Dr. L. Grodzins and Dr. G. Hortig for many helpful discussions and to the latter for permission to use unpublished material. The work was supported by the High Voltage Engineering Corporation.

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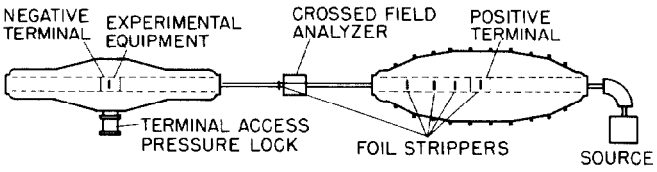

Fig. 1. An arrangement of tandem accelerators planned for the HVEC tandem facility is shown which can produce heavy ion beams with energies in excess of 1 GeV. The negative ions injected into the positive terminal machine are stripped repeatedly as they are accelerated down the high energy tube. A component of this beam is then accelerated to the terminal of the second accelerator.

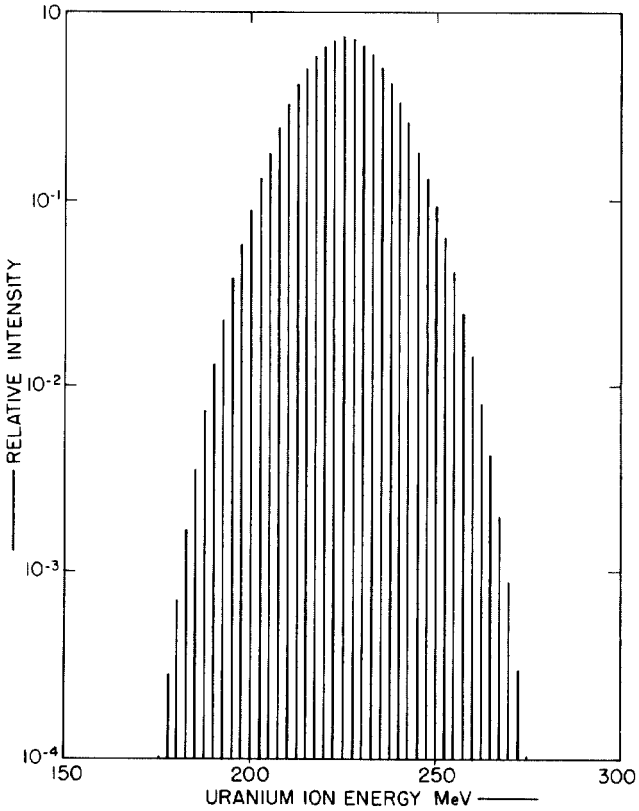

Fig. 2. The energy spectrum of uranium ions accelerated in a 10 MeV tandem accelerator.

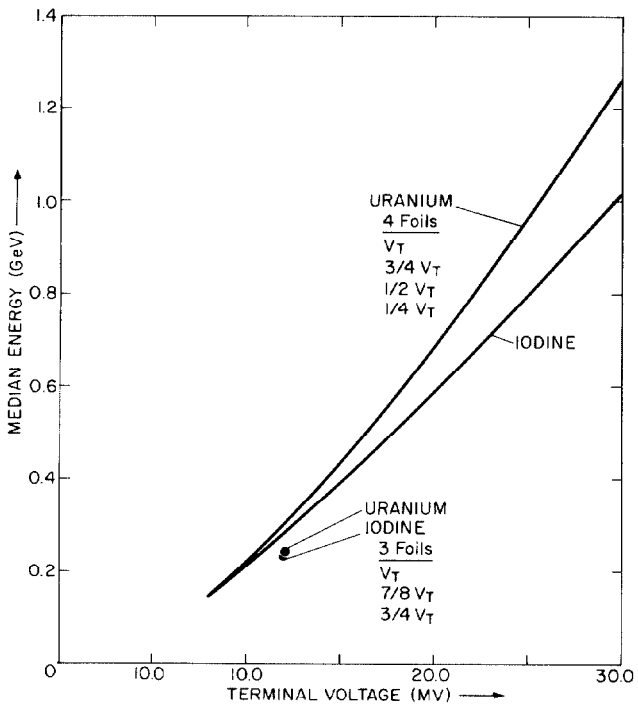

Fig. 3. The variation of the median energy, i.e., the intensity at the center of the spectrum for I and U beams as a function of terminal potential.

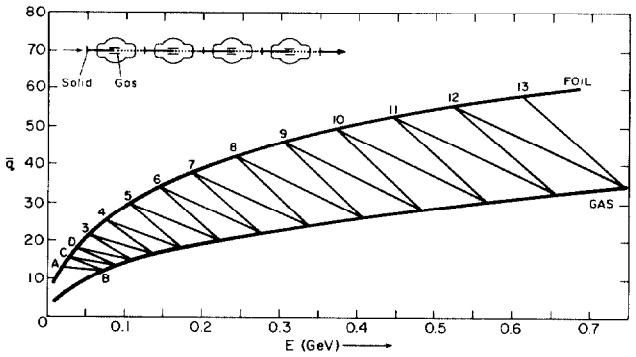

Fig. 4. A series arrangement of tandem accelerators. The curves show the most probable charge in gas and foil targets as a function of energy. Starting at 20 MeV the lines connecting the points A, B, C etc., show the energy gain and loss in each successive accelerator.

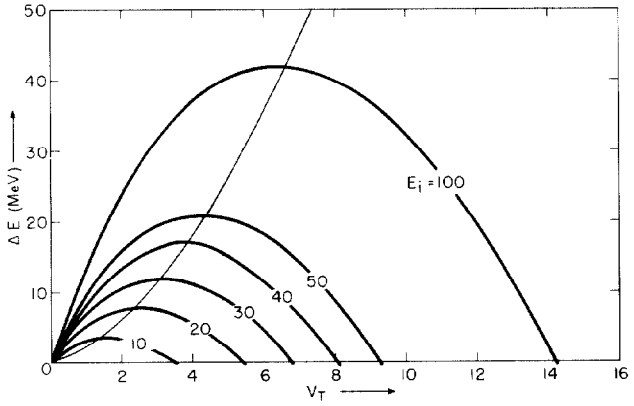

Fig. 5. The energy gain per traversal through the tandem accelerator as a function of terminal potential and injection energy.

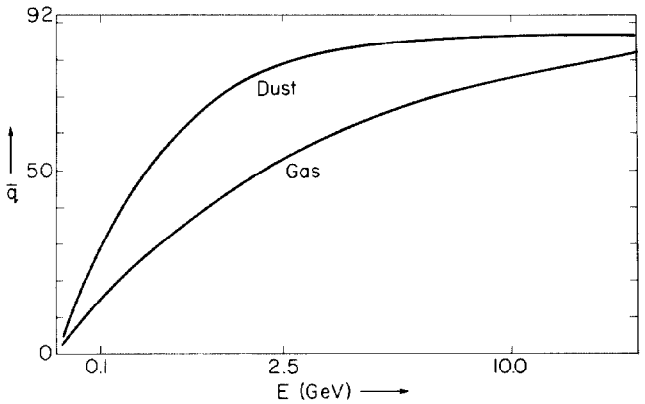

Fig. 6. The variation of the most probable charge of uranium ions in gas and solid targets as a function of energy. The curves are based on the available data at low energies and fit the data obtained with lighter elements as a function of 137 β/Z at higher energies.[11]

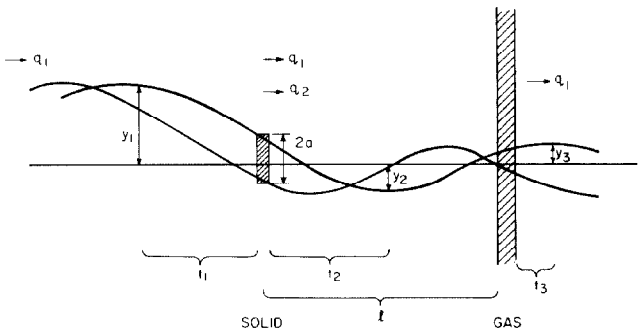

Fig. 7. Trajectories of particles passing through an axially restricted solid target and an extend gas target.

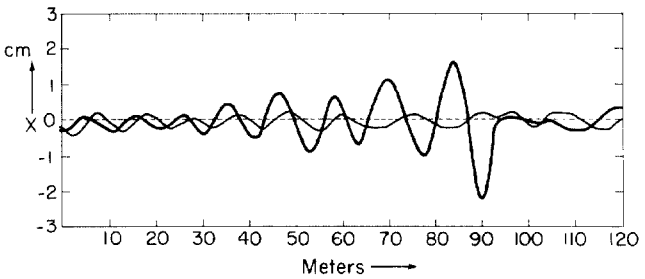

Fig. 8. Damping of a scattered particle in a periodic focusing field by the method proposed by Hortig.

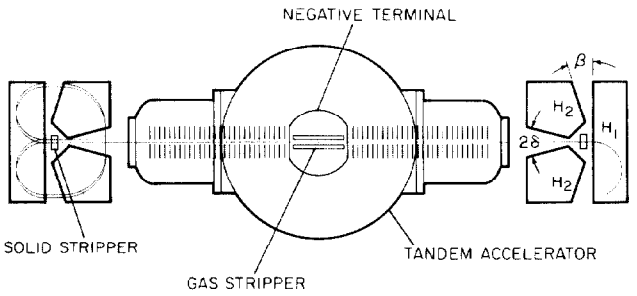

Fig. 9. An alternative scheme suggested by Hortig. Reflecting magnets and focusing elements are used to direct the beam repeatedly through a tandem accelerator or a series of tandem accelerators.