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TANDEM ELECTROSTATIC ACCELERATORS

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In this type of accelerator a constant potential is applied to the acceleration of the ion beam, however, not as conventionally with just one voltage application, but instead with a number of applications made in succession by means of a tandem arrangement of high voltage tubes. This number of voltage applications, which is the number of the so-called "stages" of a tandem accelerator, may be two, three, or four, depending on the design chosen. The principles of this type of accelerator are described, and a brief account is given of the design and performance tests of a two-stage accelerator for an output rating of 10 MeV and one-half microampere of protons. Some possibilities for future development are discussed for reaching greater energies by means of three and four-stage tandem arrangements. Preliminary experimental results show the feasibility of operating these by means of the injection of a beam of neutral particles, thus retaining the use of an external ion source at ground potential, as in the present two-stage tandem accelerators.

1. Introduction

In the case of the usual type of electrostatic accelerator, positive ions are produced inside a high-voltage terminal and then accelerated to ground in one stage of acceleration. In the case of the present type of tandem accelerator, negative ions are produced at ground, and then accelerated to a high-voltage positive terminal. Within the terminal the swiftly moving negative ions are stripped of electrons, thus becoming positive ions, which then receive an additional acceleration from the terminal to ground. Thus the particle beam receives two stages of acceleration instead of one.

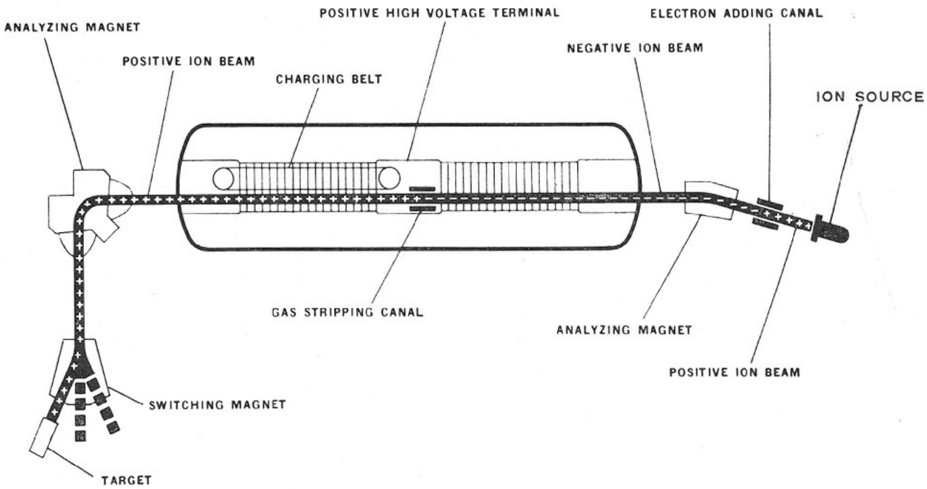

Fig. 1. Two-stage tandem accelerator.

The principles and techniques used in tandem accelerators have been originated and developed over many years and in various laboratories. It is regretted that lack of space prevents full acknowledgements here. However, reference should at least be made to the following names:

Dempster, Bennett[1]), Kaufman, Alvarez[2]), Marshall, Woodyard, Herb, and Stier.

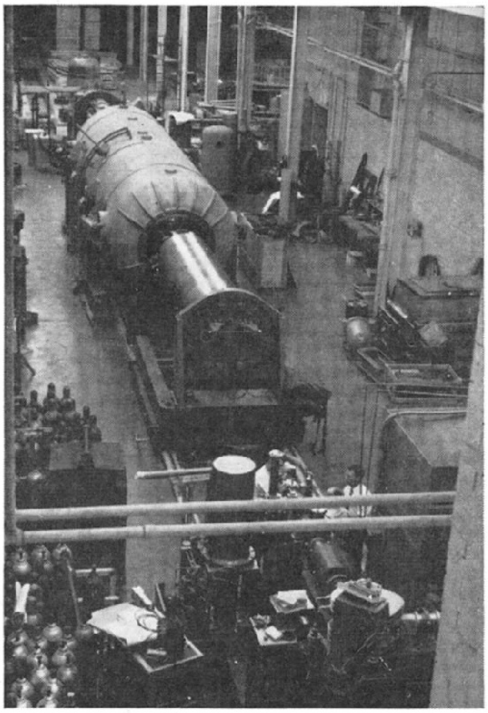

Fig. 2

The principles of operation of a two-stage tandem accelerator may be seen in more detail from the diagram in fig. 1. The positive-ion beam from the ion source at the right passes into the electron adding canal. A flow of hydrogen in this canal causes the successive attachment of two electrons to some of the positive ions, thus transforming these into negative ions. The negative-ion beam is then deflected slightly by an analyzing magnet, so that negative ions of the correct mass and energy are caused to proceed along the axis of the main vacuum tubes, and thus to be accelerated to the terminal which is at a high positive voltage. There the negative-ion beam passes into a second canal, where the presence of gas causes it to be stripped of its electrons, so that it emerges as a positive-ion beam and is then given its second acceleration which brings it back to ground. The positive-ion beam is then deflected through a 90° analyzing magnet before proceeding through a switching magnet, where it can be directed to any one of three targets.

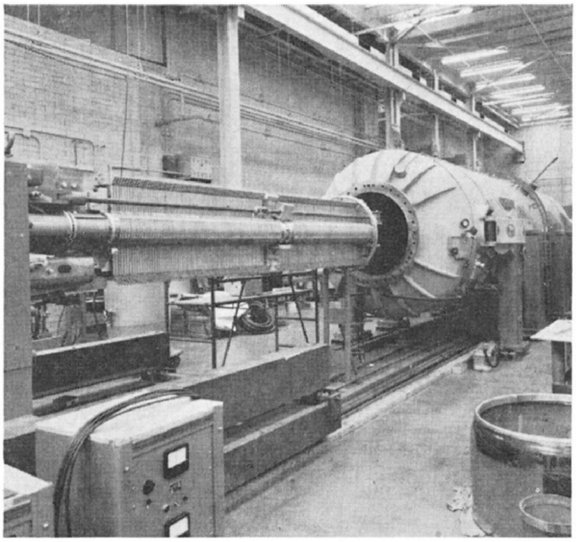

Fig. 3

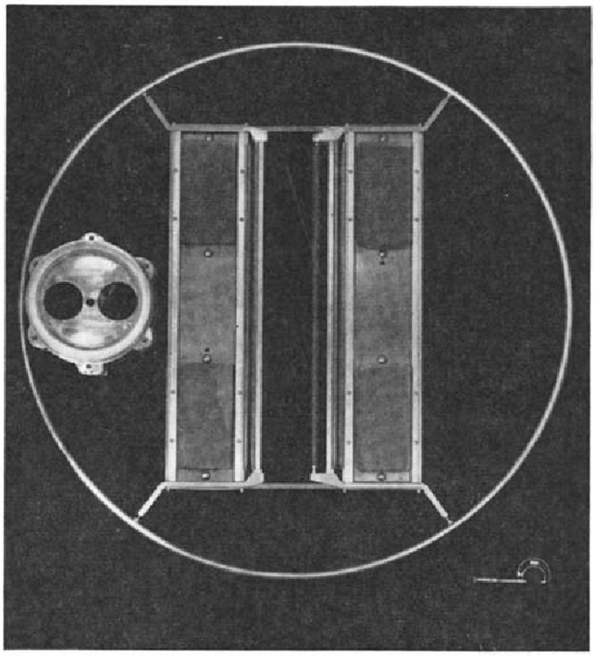

Fig. 4

[1]) W. H. Bennett and P. F. Darby, Phys. Rev. **49** (1936) 97, 422, 881;
W. H. Bennett, U. S. Patent No. 2, 206, 558 (1937);
W. H. Bennett, Rev. Sci. Instr. **24** (1952) 915.

[2]) L. W. Alvarez, Rev. Sci. Instr. **22** (1951) 705.

2. Tandem Accelerator for Chalk River

A two-stage tandem accelerator has been designed and constructed by the High Voltage Engineering Corporation for the Chalk River Laboratory of Atomic Energy of Canada, Limited. After tests in Burlington, it is now in use at Chalk River†. The next three figures are photographs showing the construction of this accelerator.

Fig. 2 shows one column rolled back from its operating position within the tank. Each column has an insulating length of 12 feet, and the tank is 8 feet in diameter and 35 feet long. Fig. 3 is a similar view, but with the equipotential rings removed, so that the acceleration tube and compression members of the column can be seen. Fig. 4 is a photograph of a "cross-section like" assembly of equipotential column parts. The outside ring is 39 inches in diameter. The four glass-block insulators can be seen at

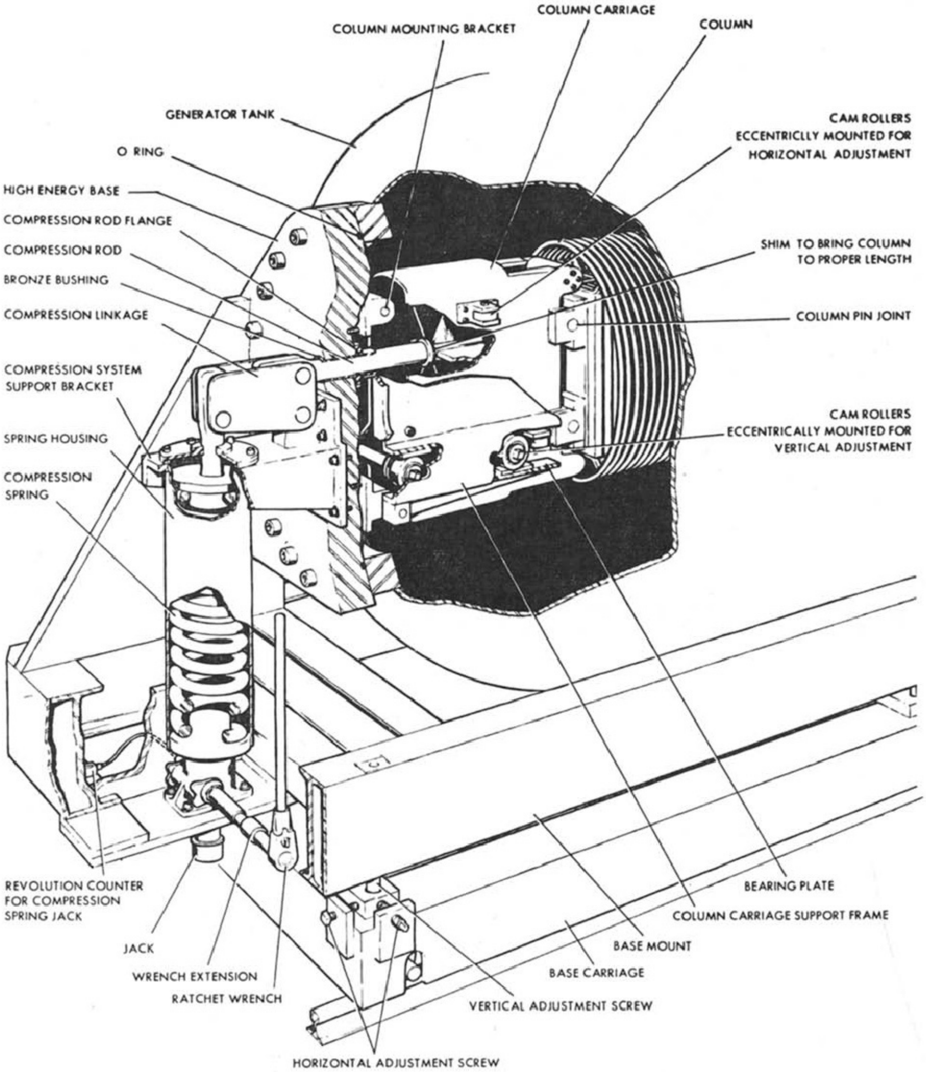

Fig. 5. Column tension adjusting mechanism.

† For additional information regarding this accelerator, reference is made to the following papers: (1) Ten MeV particle accelerator will aid nuclear research at Chalk River, by H. E. Gove, Canadian Electronics Engineering (July 1958). (2) New design makes ten MeV particle accelerator possible, by John L. Danforth, Canadian Electronics Engineering (July 1958).

Fig. 6. Tandem accelerator of University of Wisconsin, fully installed. (Reprinted with the kind permission of the University of Wisconsin.)

the corners of the large rectangle. Space for the belt is provided in the vertical region between the four glass insulators. An acceleration-tube electrode is visible at the left.

The drawing in the next figure shows how the column is mounted on the loose plate at the end of the tank. The spring mechanism maintains a compressive force of 40 000 pounds on the ends of the column, which is sufficient to hold all of the glass insulators firmly in compression in spite of the weight of the column.

The low-energy end of the accelerator is shown in fig. 2. The ion source with its radio-frequency power supply can be seen in the mid-foreground, while a high-speed vacuum pumping system appears at the left.

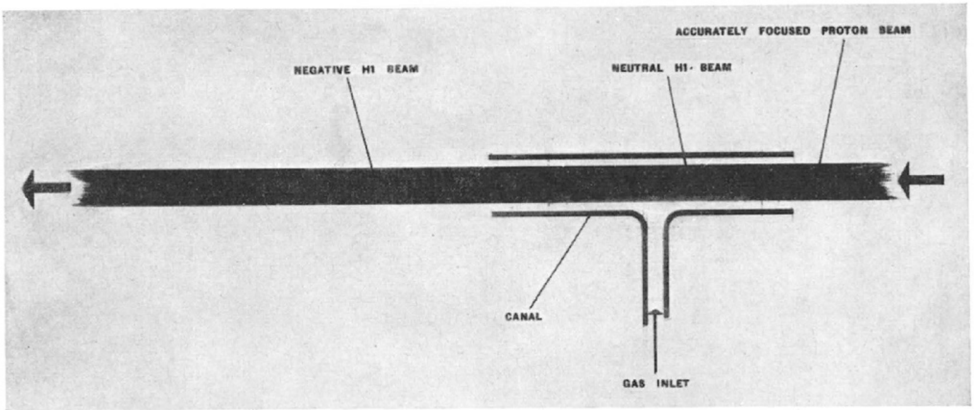

Fig. 7. Present arrangement.

TABLE 1

Neutron threshold measurements using Tandem Van De Graaff Accelerator

Reaction	Threshold energy E (MeV)	Proton resonance frequency f(Mc/sec)	$k \times 10^5$
Li^7(p,n)	1.8813 ± 0.0005	9.690 ± 0.010	†2021 ± 3
B^{11}(p,n)	3.015 ± 0.003	12.322 ± 0.003	2004 ± 3
Na^{23}(p,n)	5.061 ± 0.007	15.950 ± 0.020	2010 ± 4
Al^{27}(p,n)	5.798 ± 0.005	17.080 ± 0.010	2009 ± 4
$H^2(0^{16} + 5$,n)	14.572 ± 0.030	21.555 ± 0.020	2008 ± 5
$H^2(0^{16} + 4$,n)	— 14.572 ± 0.030	26.940 ± 0.020	2008 ± 6
	$E\,(1 + E/2Mc^2) = kf^2q^2/M$	Average of 5	2008 ± 2
Ni^{60}(p,n)	7.028 ± 0.020	18.814 ± 0.010	$k =$ (2008 ± 4) × 10^{-5} (assumed)
Ni^{58}(p,n)	9.459 ± 0.070	21.840 ± 0.080	

† Corona Stabilizer inoperative for this run.

Fig. 7 shows the ion source, and initial accelerating electrodes, together with the electron-adding canal. A flow of hydrogen maintains this canal at sufficient pressure for charge transfer, so that about 1% of the protons in the beam emerge as negative atomic hydrogen ions.

The stripping canal is located in the terminal between the acceleration tubes. Its diameter is only 0.18 inch, which requires quite accurate beam focussing and alignment.

In the tests of the accelerator, proton beams up to 13.4 MeV were obtained, corresponding to a terminal potential of 6.7 megavolts. After 90-degree analysis, a proton beam of 1.5 microamperes was focussed on the target over a wide range of voltages. These outputs considerably exceeded the specified requirements of 10 MeV and 0.5 microampere. Measurements on the proton beam after deflection by the 90° magnet showed that it was homogeneous in energy to $\pm$ 0.02%.

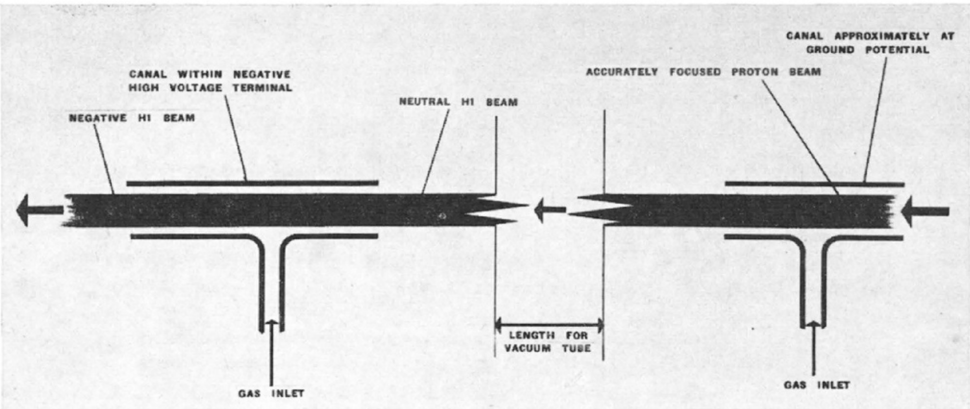

Fig. 8. Proposed arrangement,

In some of the tests, negative oxygen ions were injected into the accelerator when the terminal was at four megavolts. Observations at the target showed that some of these negative ions were completely stripped in passing through the terminal, thus reaching an energy of 36 MeV.

While the accelerator was still in Burlington, various tests were made in collaboration with a number of physicists from Chalk River. A number of neutron thresholds were studied and calibration measurements were made for a considerable range of particle energies. Figs. 9 and 10 have been taken from a recent paper† describing this work.

3. Some Possibilities for Future Development

An important feature of the tandem design is that the ion source and initial accelerating and focussing arrangements are situated outside the pressure tank, rather than inside the terminal and tank, as in the usual type of electrostatic accelerator. This external location will greatly facilitate the future development of improved ion sources and injection. It also affords ample space and accessibility for the possible introduction of various new injection devices, such as multiple-ion sources, apparatus for the polarization of particle beams, and equipment for beam pulsing.

Let us now turn to the consideration of future possibilities for the attainment of higher particle energies by tandem acceleration. Obviously, one method is by the use of higher

† Neutron threshold measurements in the proton energy range from 1.8 to 10.5 MeV using the Chalk River Tandem Van de Graaff Accelerator. This paper was read by A. J. Gale at the Vancouver Meeting (August, 1958) of the American Physical Society. Its authors were: E. Almqvist, D. A. Bromley, A. J. Ferguson, H. E. Gove, J. A. Kuehner and A. E. Litherland (Chalk River) and R. Bastide, N. Brooks, R. J. Connor, P. H. Rose (HVEC). Reprints can be obtained from High Voltage Engineering Corporation.

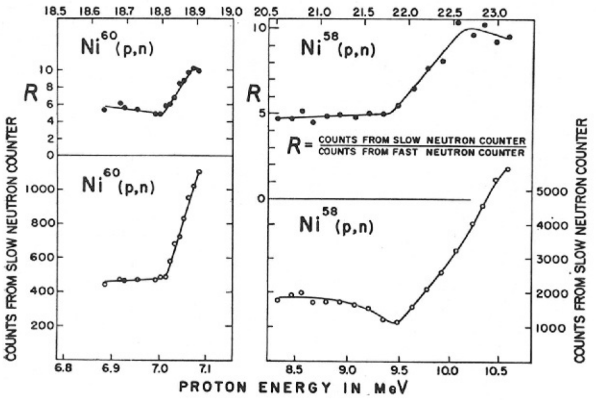

Fig. 9
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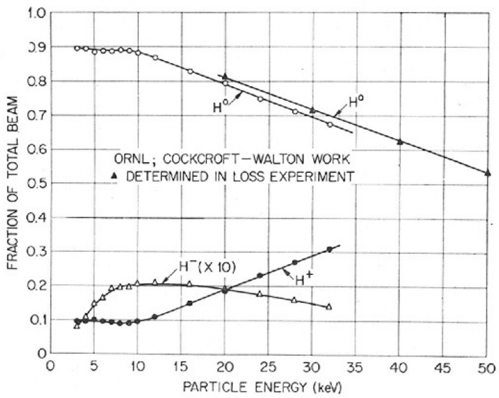

Fig. 10. Fraction of H beam in + 1.0–1 Charge states after passage through "thick" target. H in hydrogen.

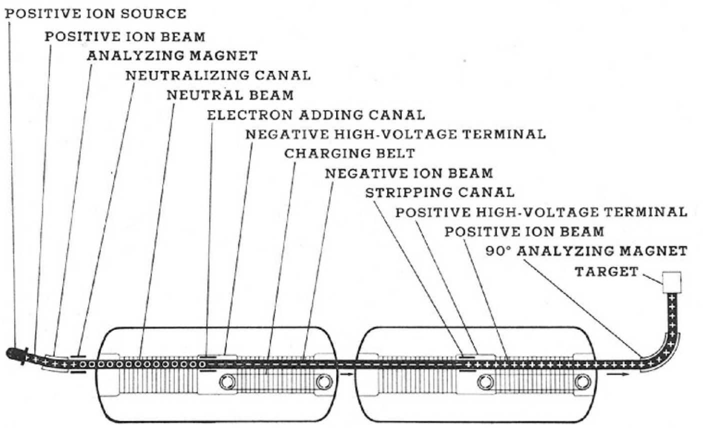

Fig. 11. Three-stage tandem accelerator.

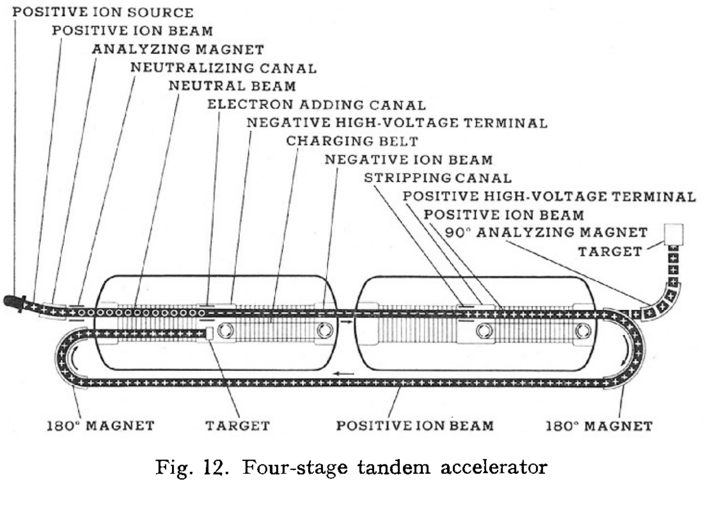

Fig. 12. Four-stage tandem accelerator

terminal potentials. At present the ceiling in this direction is represented by the ONR accelerator at M.I.T., built by J. G. Trump, and used since 1951 by W. W. Buechner for nuclear research at terminal potentials up to 10 megavolts. It is to be expected that in future accelerators there will be continuing increases in the terminal potentials attainable, due not only to growth in the size of accelerators but also to continued progress in high-voltage techniques which will make possible the insulation of still higher voltages in a given size of accelerator.

A more radical method of seeking higher tandem particle energies is by the use of more than two stages of acceleration. Fig. 11 shows a diagram of a possible arrangement for a three-stage tandem accelerator. The positive-ion beam from the ion source at the right is deflected by an analyzing magnet so that the desired positive ions are directed along the axis of the acceleration tubes. In the neutralizing canal, these positive ions encounter an amount of hydrogen which, though relatively small, is nevertheless sufficient to cause the attachment of a single electron to most of the positive ions, thus producing a beam of neutral particles which proceeds to the negative high-voltage terminal. In passing through the electron-adding canal situated in this terminal, some of the neutral particles capture and additional electron and become negative ions. These receive their first main stage of acceleration in passing from the negative terminal to ground, where they are injected into the second pressure tank as a negative-ion beam of considerable energy. In this tank, the beam receives its second and third stages of acceleration.

The operation in this tank is quite similar to that shown in the tank in fig. 1, except that in fig. 11 the injected negative ions are about 100 times more energetic and are correspondingly more homogeneous in energy, so that they can be focussed with great accuracy through the stripping canal in the positive terminal.

It is evident that an alternative arrangement for a three-stage tandem accelerator would be to have the complete apparatus for producing the negative ions installed within the negative high-voltage terminal. However, the use of a neutral particle beam, as indicated in fig. 11, appears more promising, as it would make it possible for the particle injector to be external and at ground, a situation having enormous long-run advantages, some of which have been already mentioned. Obviously such use of a neutral particle beam is practical only if the associated particle scattering is quite small. Some encouraging experimental observations in regard to the scattering effect have been made at HVEC and M.I.T.†.

TABLE 2

Positive-ion energies in MeV for certain possible arrangements of Tandem Accelerators

$V + nV$	(for two-stage tandem)
$2V + nV$	(for three-stage tandem)
$2V + 2nV$	(for four-stage tandem)

Here $V =$ terminal potential in megavolts and $n =$ number of electrons stripped from neutral atom.

TABLE 3

Positive-ion energies in MeV for two different arrangements of Tandem Accelerators

Positive ion	Two-stage	Three-stage
Hydrogen	13.4	20.1
Helium	20.1	26.8
Oxygen	60.3	67.0

Assumptions: Terminal potential = 6.7 megavolts. Complete stripping of positive ions.

It is hoped that some preliminary tests of actual three-stage tandem operation can be made by using the pair of two-stage tandem accelerators now under construction at HVEC.

Fig. 12 shows how a four-stage tandem accelerator could be made by the addition of two 180° deflecting magnets and an additional section of acceleration tube, the target being located inside the negative high-voltage terminal.

Table 2 gives some simple formulas for the positive-ion energies in MeV obtainable with the

† S. F. Philp, Doctorate thesis, 1958.

three different tandem arrangements which have been discussed.

The values for positive-ion energies shown in table 3 were obtained by substitution in the formulas of table 2 for hydrogen, helium and oxygen ions.

In the case of the four-stage tandem it is obvious that the inaccessibility of the target is a serious disadvantage. However, the effect of this difficulty could be much reduced by the development of special techniques and devices. It thus appears possible that four-stage tandems may later find usefulness for certain special types of research needing monoenergetic positive ions in an energy range somewhat higher than otherwise available.