

Aug. 23, 1966

R. J. VAN DE GRAAFF
APPARATUS FOR PRODUCING INTENSE BUNCHED BEAMS
OF MONOENERGETIC NEUTRONS

3,268,730

Filed Feb. 28, 1963

5 Sheets-Sheet 1

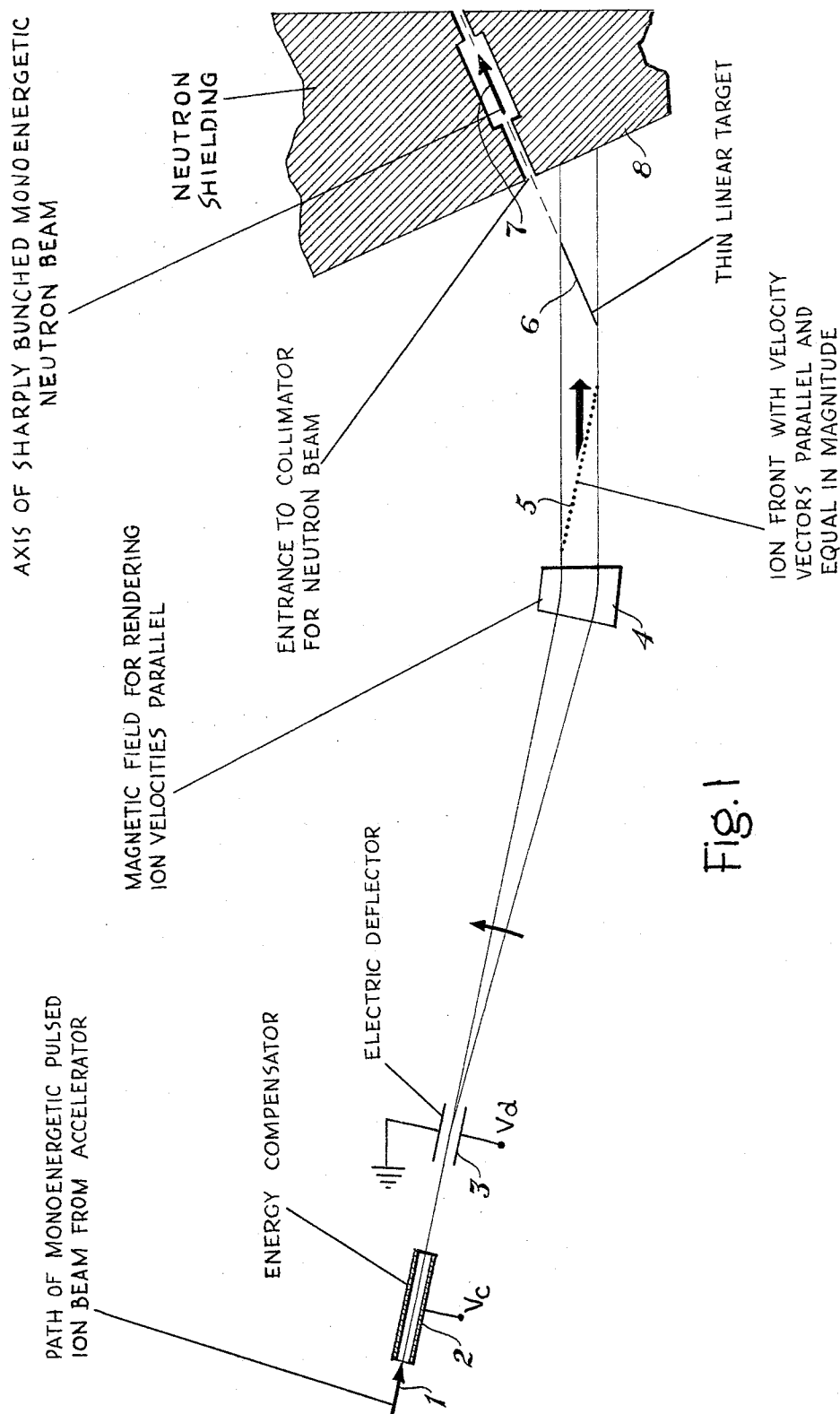


Fig. 1

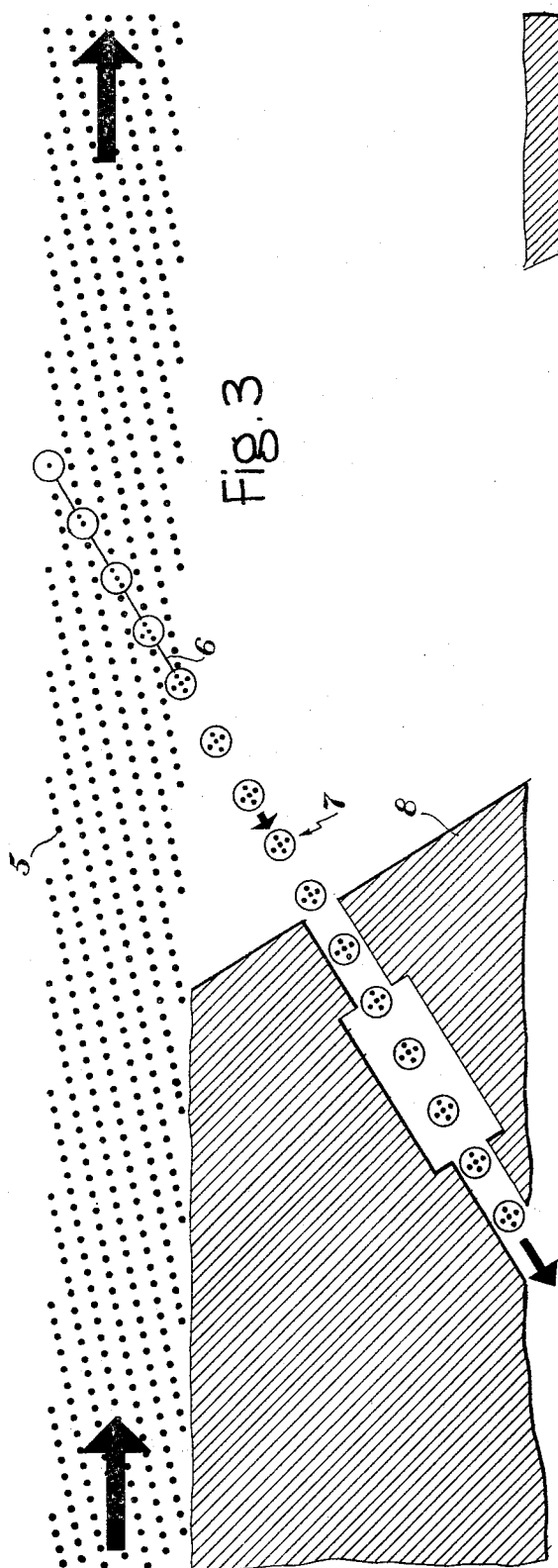
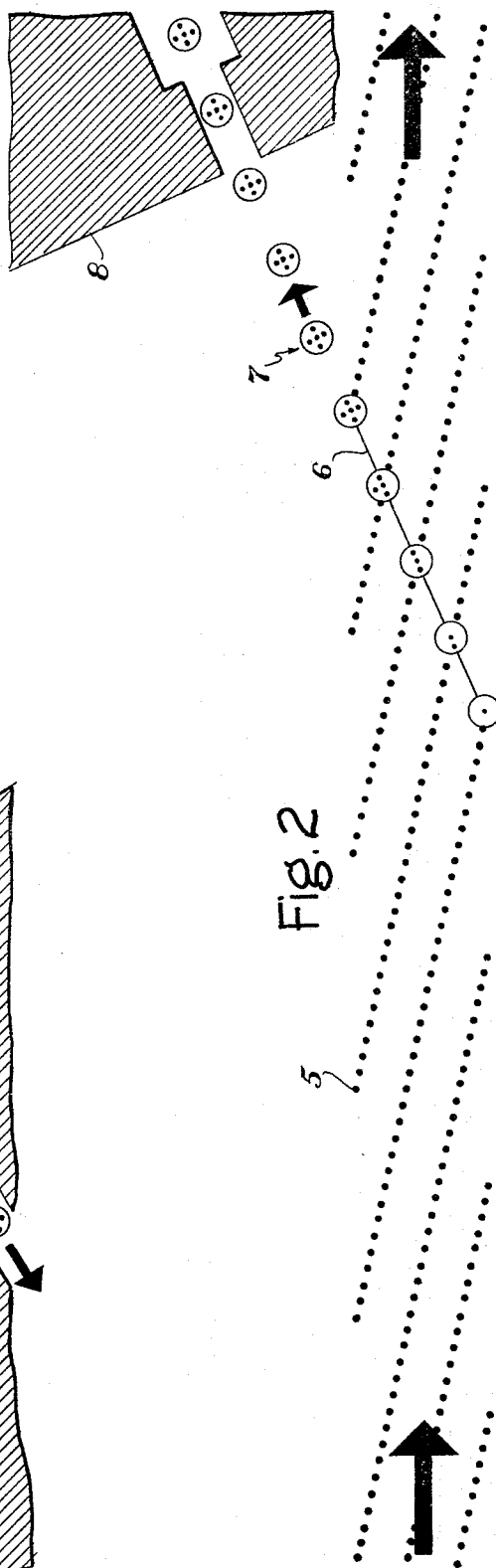
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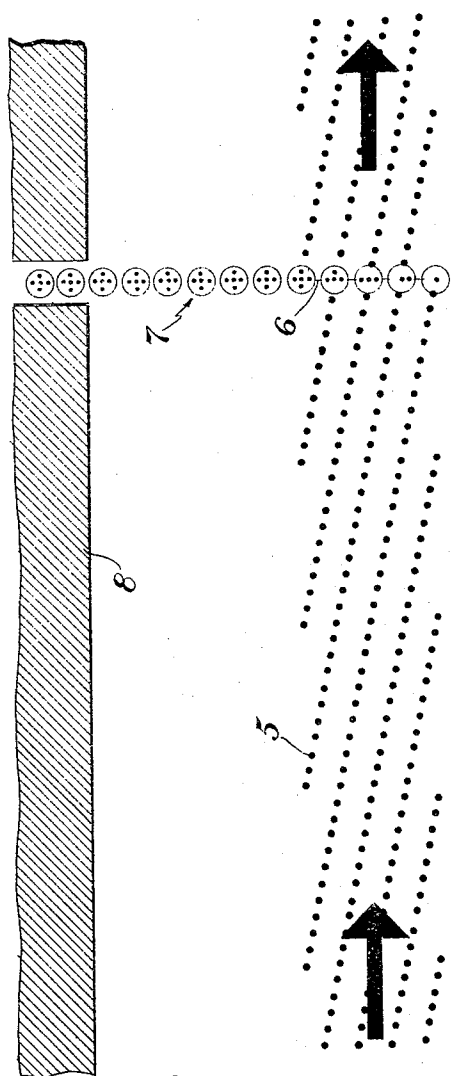


Fig. 4

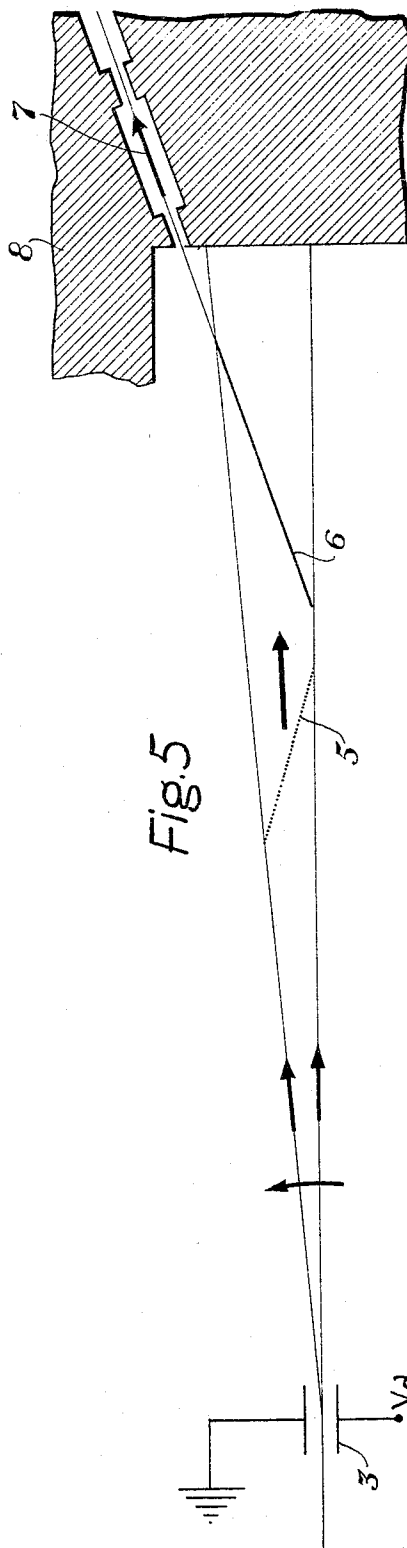


Fig. 5

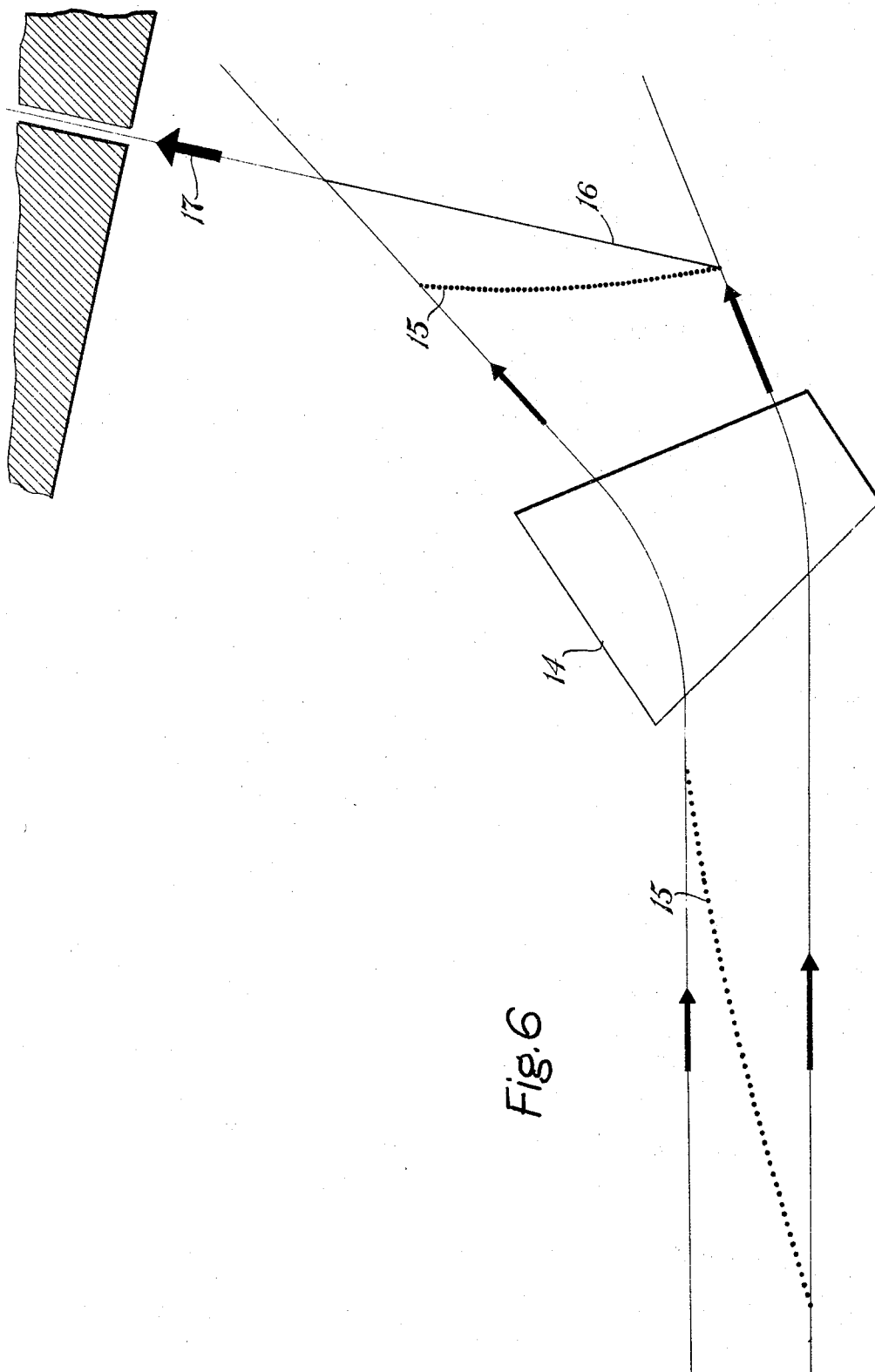
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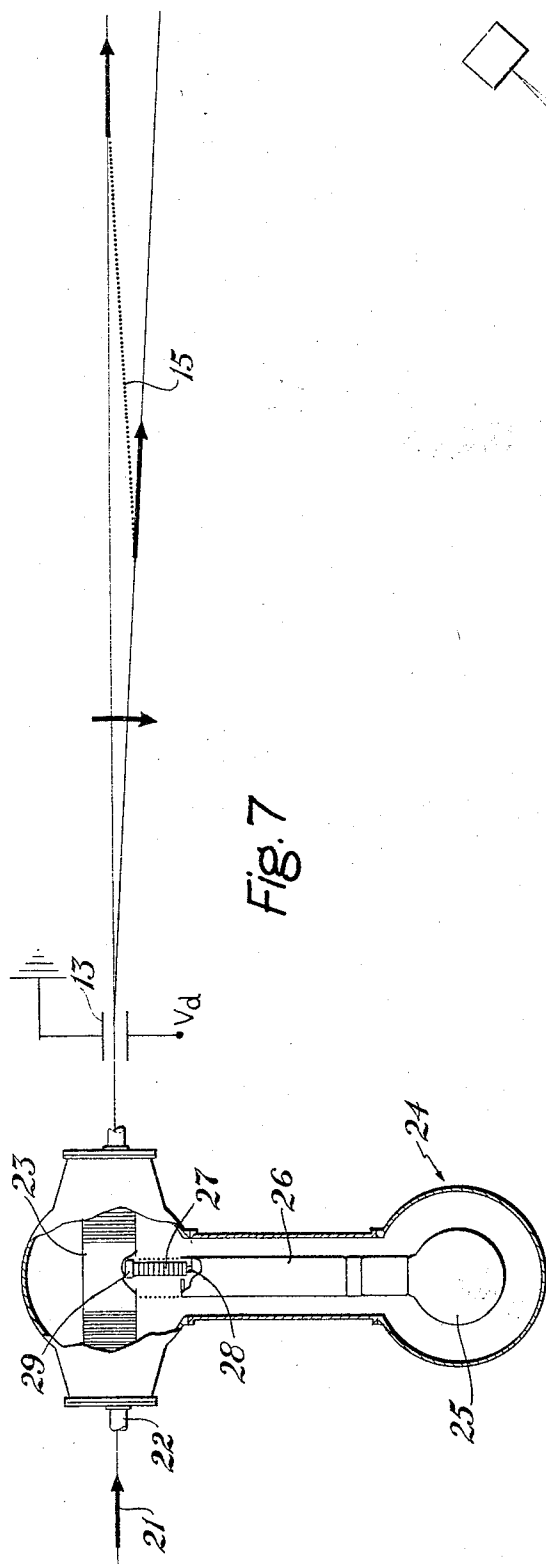
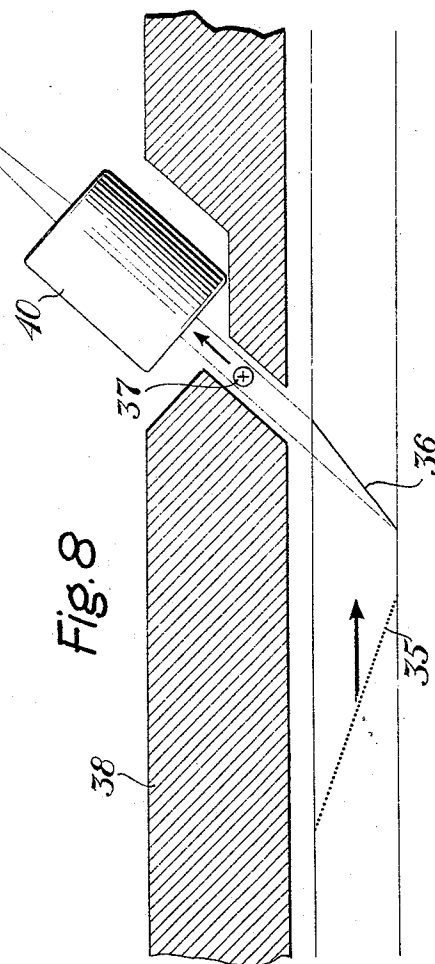
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APPARATUS FOR PRODUCING INTENSE BUNCHED BEAMS OF MONOENERGETIC NEUTRONS

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High Voltage Engineering Corporation, Burlington,
Mass., a corporation of Massachusetts
Filed Feb. 28, 1963, Ser. No. 261,608
6 Claims. (Cl. 250—84.5)

This invention relates to the production of intense bunched beams of monoenergetic neutrons. In general, the invention accomplishes the bunching of neutrons without bunching the ions which produce them. In one embodiment of the invention the ion beam is enriched prior to arriving at the target, but in another embodiment of the invention, even this concentration of the ions is not necessary.

In all embodiments of the invention, after D.C. acceleration long pulses of accurately focused ions are given a slight but increasing angular deflection so that the ions then travel in adjacent paths as an ion front onto a thin linear target which can be of considerable length. A steady magnetic field may be provided in order to control the angle and position of impact upon the target as the beam sweeps across the target. In one embodiment of the invention the ions are monoenergetic and are directed in mutually parallel paths onto a relatively long target which is placed at an angle to the ion trajectories corresponding to that at which neutrons of the desired energy will be emitted. Consequently the desired neutrons are emitted along a path which travels along the length of the thin target. The rate of deflection of the ion beam is then selected so that the last ion in each ion front strikes the target simultaneously with the arrival at the same point of all the neutrons having the desired energy which were produced by the previous ions in the ion front. The precise results of this embodiment may be approximated in a simplified version. In a second embodiment of the invention, the ion beam is velocity modulated so that the ion front is enriched (i.e. the ion density is increased) prior to arrival at the target, thereby utilizing time-of-flight both for the neutrons produced and the ions which produce them. Although such velocity modulation introduces energy variation in the ion beam, a considerable range of ion energies can be utilized by timing and guiding the ion front in such a way that the ions within each ion front strike the target at a different angle, the angular variation being adjusted so as exactly to compensate for the energy variation in the ion beam with the result that along a predetermined direction emanating from the target the neutrons produced by the ion front will have the same energy.

Research with neutrons is of fundamental interest, both in pure science and technology. In the field of pure science, the neutron is recognized as a basic particle. As is well known, atoms may be considered as structures of three basic particles, namely electrons, protons and neutrons. As basic particles, neutrons have the special interest that they have nuclear forces without the complication of coulomb force.

As is also well known, neutrons are the agency by which a chain reaction is carried on in atomic reaction by fission. As more and more refined designs are required for atomic power and many other purposes, there is a correspondingly increased demand for more precise and complete measurements of elastic and inelastic scattering of neutrons by nuclei. Two factors make such precise measurements with neutrons much more difficult than similar measurements with charged particles. In the first place, neutrons cannot be produced directly as charged particle can be produced but must be produced

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indirectly, usually as a low yield process by the use of charged particles. Thus the intensity of beams of neutrons is many orders of magnitude less than the intensity of beams of charged particles. In the second place, the energies of neutrons cannot be measured in the simple precise way as is the case with charged particles which can be deflected by electric and magnetic fields. Moreover, the detection of neutrons is more difficult than the detection of charged particles.

Since neutrons are not appreciably affected by electric or magnetic fields, one of the best ways of determining their energy is by the observation of their time of flight over a known distance. For precise and effective measurements of this type, sharply pulsed ion beams have been produced as, for example, by "klystron bunching" which is velocity modulation bunching, or by magnetic bunching as with a Mobley magnet. In these methods, the bunched neutrons are obtained by previously bunching the positive ions which produce the neutrons. In the method proposed in this application, the neutrons themselves are bunched without the need at any time for bunching the positive ions at a point, thus greatly minimizing certain difficulties associated for example with space charge and target heating. Moreover, the proposed method is in principle exact: For example, the neutron beam in a given direction can be made highly monoenergetic and very sharply pulsed in time; its imperfections in these respects depend primarily only on such practical limitations as target thickness, homogeneity of the positive ion beam, etc.

The production of monoenergetic neutrons by bombardment of thin targets with artificially accelerated ions is well known. See, for example, the article entitled, "Monoenergetic Neutrons From Charged Particle Reactions" by Hanson, Taschek and Williams in The Reviews of Modern Physics, vol. 21, page 635 (October 1949). See also the tables in "Fast Neutron Physics," Part I by Marion and Fowler, at Section 1. For low energy neutrons from about 3 k.e.v. through the kilovolt range up to a few hundred thousand electron volts, neutrons are commonly produced using the lithium pn reaction. For neutrons in the intermediate range between 1 m.e.v. and over 10 m.e.v., the deuteron on deuterium reaction is commonly used. For the production of neutrons having energies of 14 m.e.v. or higher the deuteron on tritium reaction is commonly used. See, for example, "Introduction to Neutron Physics" by Curtiss (D. Van Nostrand Company, Inc. 1959) pages 97 through 126.

The invention may best be understood from the following detailed description thereof having reference to the accompanying drawings in which:

FIGURE 1 is a diagram showing an overall plan view of apparatus for practicing the invention;

FIGURE 2 is a diagram showing in detail the portion of the apparatus of FIG. 1 in the vicinity of the target and illustrating the production of a monoenergetic neutron beam in the forward direction;

FIGURE 3 is a diagram similar to that of FIG. 2, except that the monoenergetic neutron beam is produced in the backward direction;

FIGURE 4 is a diagram similar to that of FIG. 2, except that the monoenergetic neutron beam is produced in a direction perpendicular to the direction of ion velocity;

FIGURE 5 is a diagram similar to that of FIG. 1 showing a simplified version of the apparatus of FIG. 1;

FIGURES 6 and 7 are diagrams similar to that of FIG. 1, showing an embodiment of the invention in which the ion beam is velocity modulated; and

FIGURE 8 is a diagram similar to that of FIG. 1 showing apparatus for bunching monoenergetic charge particles from nuclear reactions.

Referring to the drawings and first to FIG. 1 thereof, therein is shown in diagrammatic fashion a plan view of one embodiment of apparatus for practicing the invention. A monoenergetic pulsed ion beam 1 is produced by a particle accelerator (not shown) by any of a number of conventional means. The ions may be positive or negative but for simplicity of description, it will be assumed that the ions are positive. An electrostatic belt-type generator in combination with a suitable evacuated acceleration tube may be used to produce a monoenergetic ion beam and may be pulsed by techniques well known in the art. In general, the time interval between pulses will be longer than the pulse length, perhaps a great many times longer than the pulse length, but the invention is not limited to this type of pulsing. The monoenergetic pulsed ion beam is directed into an energy compensator 2 which comprises a metal tube, the potential of which may be controlled by a conventional voltage source providing a time-varying voltage signal V_c . The function of the energy compensator 2 will be described in detail hereinafter. After passing through the energy compensator 2, the pulsed ion beam 1 next passes through an electric deflector 3 comprising a pair of metal plates, one of which is maintained at a fixed potential such as ground, and the other of which is connected to a voltage source which applies a voltage signal V_d to this plate, thereby producing a time-varying electric field transverse to the direction of motion of the ion beam 1 so as to cause the ion beam to execute a sweeping motion in a well known manner. The swept ion beam then is permitted to travel through a long evacuated drift tube (not shown) from which it emerges into a magnetic field 4 for rendering the slightly divergent ion velocities parallel. The magnetic field 4 may be produced by conventional means such as a magnet having a pair of pole faces between which the ion beam travels. The ions emerge from the magnetic field all travelling in a parallel direction, and one pulse of ions is shown in FIGURE 1 as an ion front 5 with velocity vectors equal in magnitude and parallel. A long straight thin target 6 is positioned in the path of this ion front 5 so that all the ions strike the target 6, although different ions strike the target at different places. The various parameters are so chosen that neutrons having the desired energy are emitted in a direction along the length of the target as a sharply bunched beam 7 of monoenergetic neutrons. A collimator 8 for the elimination of neutrons not having the proper direction axial to target and neutron beam is positioned in the path of the emergent neutrons. This collimator comprises neutron shielding having an aperture or apertures therein aligned with the sharply bunched neutron beam.

The function of the electric deflector is to sweep the beam so that the target spot moves along the target with constant velocity. The function of the magnetic field is to render the ion velocities parallel so that the angle of impingement upon the target will not vary. The need for the magnetic field arises from the fact that the invention is utilizing the phenomenon that the energy of the emitted neutrons is a function of the energy of the incoming ions and the angle between the paths of the incoming ions and the outgoing neutrons. Since in the embodiment of the invention shown in FIG. 1 the incoming ion beam is monoenergetic and since it is necessary that all the neutrons in the sharply bunched beam have the same direction, it is necessary that all the ions strike the target at the same angle.

As is well known in the art, the ion beam is accelerated in an evacuated region and must travel in an evacuated region throughout its journey to the target. Because the construction of such vacuum chambers as acceleration tubes, drift tubes, and assorted vacuum plumbing is well known in the art, it is not shown in the drawings. Thus, for example, in traveling from the electric deflector 3 to

the magnetic field 4 of FIGURE 1, the ion beam travels through a drift tube (not shown) which comprises simply a hollow tube of conductive material such as metal which is evacuated and which is in most cases maintained at ground potential. In accordance with the invention, this drift tube may be made quite long. For example, it may be 600 feet in length or even longer and in general would be preferably over 100 feet in length. By using a long drift tube of this nature, the amplitude of the deflection introduced by the electric deflector 3 may be quite small thereby minimizing errors introduced by this deflection.

In particular, the use of the drift tube reduces the energy variation introduced by the electric deflector. It will be noticed from FIGURE 1 that the ion beam enters the electric deflector from a region at ground potential and upon leaving the electric deflector proceeds again to a region at ground potential. Consequently, if the electric field in the electric deflector were constant, the electric deflector would produce no net change in the kinetic energy of the ion beam. However, because of the fact that while any given ion passes through the electric deflector, the electric field through which the ions pass changes, the ions emerge from the electric deflector with a slight deviation in energy. Although as noted the use of a long drift tube reduces the energy deviation thus introduced, if desired, this small energy deviation can be precompensated by providing the energy compensator 2 shown in FIG. 1. In this compensator, each ion is given an energy deviation approximately equal in magnitude but opposite in sign from the energy deviation that it will experience in the deflector. In both cases the energy deviation is caused by the changing electric field while the particle passes through that particular device. The procedure would be to provide first a suitable changing potential on one electrode of the electric deflector as indicated at V_d for producing the desired ion front. After this is done the compensation would be made empirically by a similar time varying signal on the compensator electrode indicated at V_c which approximately precompensates for the energy deviation.

Referring now to FIG. 2 of the drawings, therein is shown an enlarged plan view of an ion front 5, the long thin target 6 and finally the adjacent end of the collimator 8. FIGURES 2, 3 and 4 are analogous to time exposure photographs made with stroboscopic light of extremely high frequency. Each figure shows the successive positions of a single ion front. It also shows the successive positions and magnitudes of the monoenergetic neutron bunch produced by that ion front. In the embodiment of the invention shown in FIG. 2 the monoenergetic neutron beam is produced leaving from the forward or right-hand end of the target. Consequently, the ion front strikes the rear or left-hand end of the target with the leading edge of the ion front first and as the ion front passes through the thin target, the target is successively bombarded along its length by the incoming ions in such a manner that the point of intersection moves with constant velocity along the target. The ion velocity, the angle of the ion front and the angle of the linear target are all so chosen that the velocity of movement of the point of intersection of the ion beam and the target is identical with the velocity of the monoenergetic neutrons emitted in the forward direction along the target. Thus having adjusted the angular position of the target for the production of neutrons of the desired energy for the energy of the incoming ion beam, the sweep speed of the ion beam and the angles of deflection produced by the magnetic field are then adjusted so that the ion front has the proper angle with respect to the target. Thus the point of intersection of the ion beam and the target constitutes a small region in which an increasing number of neutrons is produced all having the same energy and all travelling in the forward direction along the target at the same velocity, whereby a bunch of neu-

trons is produced which leaves the target at the forward end thereof and enters the aperture in the collimator.

Referring now to FIGURE 3, the arrangement therein shown is similar to that shown in FIGURE 2 except that it is designed to bunch those neutrons which are produced along the backward direction of the inclined target. Consequently, first the forward end of the ion front strikes the forward end of the target and as successive parts of the ion front strike the target, the point of intersection between the ion front and the target moves back along the target with constant velocity. It will be noted that in the arrangement of FIGURE 3, the velocity of movement can be made as large as desired, since it tends to become infinite when the ion front has the same orientation as the target. Thus, a similar arrangement could be used for the production of an intensely bunched gamma ray beam wherein the velocity of the point of intersection between the ion beam and the target would have to move with the velocity of light.

The device shown in FIG. 4 is similar to those shown in FIGS. 2 and 3, except that the target is arranged perpendicular to the ion velocities.

In some cases the procedure in FIG. 1 can be simplified as illustrated in FIG. 5. In this case, no energy compensator is used in connection with the electric deflection, nor is the guiding magnetic field used. This method would be less accurate than the full method but would give sufficiently approximate results in some cases, especially in the early stages of development using these general principles. In this arrangement the ion front is not strictly monoenergetic, nor do the ions strike the target at precisely the same angle relative to the axis of the desired neutron beam. As a result, the bunched neutron beam is slightly inhomogeneous in energy and velocity but nevertheless would be suitable for certain cases, as, for example, the production of high energy neutrons (e.g. 14 m.e.v.) by bombarding tritium with low energy deuterons since in such cases most of the neutron energy comes from the reaction and not from the energy of the incoming deuterons.

FIGURE 6 illustrates a method of using beams of velocity-modulated ions in order to increase the line density of positive ions in the ion fronts approaching the target. The purpose of this additional process is to gain an additional factor in intensity of the neutron bunches in the final output beam. Since different ion velocities over a wide range would strike the linear target, it is necessary that the ions be guided in such a way that the angle of incidence at impact with the target compensates for the ion energy so that the neutrons produced in the proper direction along the target (and neutron beam) axis are monoenergetic. As shown in FIG. 6, the ion front 15 approaching the guiding magnet 14 is similar to the corresponding ion front 5 of FIG. 1, except that the ion front has been velocity modulated. As indicated by the velocity vectors in FIG. 6, the leading ions in the ion front have a velocity of only about 70% of the velocity of the trailing ions. The intermediate ions along the front have a continuous distribution of velocities between these two extremes. Thus as the ion front moves through the long drift tube its length steadily decreases, so that the line density of the ion front steadily increases. Unlike conventional methods for producing a bunched neutron beam, however, the ion beam itself need not be bunched but need only be enriched in this way. That is to say, although the ion density is increased, it is only increased within the vicinity of an extended line rather than within the vicinity of a point. This greatly reduces the space charge problem of a very intense ion pulse. As shown in FIG. 6, the ion-directing magnet 14 is so arranged that ions of different energy are deflected through different angles so that the ions of lesser energy strike the target at a direction closer to the trajectory of the emitted neutron beam 17.

FIG. 7 illustrates one embodiment of apparatus for producing a velocity-modulated ion beam suitable for use with the apparatus of FIG. 6. Referring thereto, negative ions 21 are injected into one end of an acceleration tube 22 which traverses a hollow electrode 23. The hollow electrode 23 is maintained at high positive potential by means of a high-voltage generator 24 having a high-voltage terminal 25 to which the hollow electrode 23 is connected by a transmission line 26 and an electron-acceleration tube 27. The anode 28 of the electron-acceleration tube 27 is connected directly to the high-voltage terminal 25 by the transmission line 26, and the cathode 29 thereof is connected to the hollow electrode 23. The positive potential of the hollow electrode 23 may be raised by controlling the potential of the grid in the electron-acceleration tube 27 to permit electrons to flow from the cathode 29 of the electron-acceleration tube 27 to the anode 28. For example, such electron flow may be permitted until the potential of the hollow electrode 23 is less than that of the high-voltage terminal 25 by an amount Δv .

In accordance with well-known principles of tandem acceleration, including one-stage, two-stage, and three-stage tandems, described, for example, in my co-pending application, Serial No. 844,711 stripping means (not shown) are provided within the hollow electrode 23 to convert the incoming particles 21 to positive ions after acceleration to the hollow electrode 23, the resultant positive ions then being further accelerated by the high positive potential on the hollow electrode 23. The ion beam may now be velocity-modulated in accordance with the disclosure of U.S. Patent No. 2,847-611, with particular reference to column 7 lines 20-33 thereof. In accordance with the teachings of said patent, enough electrons are permitted to flow through the electron-acceleration tube 27 as each ion pulse issues from the hollow electrode 23, so as not only to compensate for the loss of charge on the hollow electrode 23 due to the passage of ions therethrough, but also to increase the potential of the hollow electrode 23 in order to provide the desired velocity modulation. As is also shown in said patent, this arrangement may also be used to stabilize the voltage of the hollow electrode 23 so that highly monoenergetic ion pulses can be produced. By utilizing an insulating core transformer of the type disclosed in my co-pending application, Serial Number 154,937, as the high-voltage generator 24, not only may the potential of the hollow electrode 23 be controlled to a high degree, but also relatively large currents may be obtained for the production of high-current ion pulses as well as large-amplitude velocity modulation whereby very high ion densities may be obtained.

The deflector 13 of FIG. 7 serves the same purpose as the deflector 3 of FIG. 1. The horizontal scale of FIG. 6 is ten times larger than that of FIG. 7; that is to say, if FIG. 7 were drawn to the same horizontal scale as that of FIG. 6, the ion front 15 shown in FIG. 7 would be approximately ten times longer than shown in FIG. 7. Thus it can be seen that the velocity modulation results in substantial enrichment, or increase in ion density, of the ion front. In some cases, the drift tube (not shown) in which the ions travel between the deflector 13 of FIG. 7 and the magnet 14 of FIG. 6 will be more than 100 feet in length, and might be, for example, 600 feet in length.

Referring now to Fig. 8, therein is shown the use of a method for the bunching of monoenergetic charged particles from nuclear reactions. The ion front 35 is produced in the same manner as that used to produce the ion front 5 of FIG. 1 and the ion front 15 of FIGS. 6 and 7. However, the target 16 is positioned at a slight angle to the direction in which the charged particles to be bunched are emitted, and the various parameters are so chosen that the component along the target 16 of the velocity of the emitted charged particles to be bunched

is equal to the velocity of the point of intersection of the ion front 35 and the target 36. Thus the desired charged particles are emitted as a bunch 37 which may be further focused by a strong-focusing lens 40 of conventional design. Suitable radiation shielding 38 is provided; but, since charged particles can be focused by electric and magnetic fields, collimators of the type used with bunched neutron beams are not necessary.

Although the nature of the deflecting and guiding fields in the foregoing specification has been given as either electric or magnetic, in some cases it may be desirable to have a magnetic field where an electric field is mentioned or vice versa.

The invention may be used for a variety of purposes, including, for example, and not by way of limitation, the production of high temperatures and intense plasmas as well as thermonuclear processes.

It should be noted that, in permitting the use of a long target the invention makes use of a charged particle beam which is never brought to a very high current on the target. In conventional methods for the production of sharp monoenergetic neutrons pulses, it is necessary to bring the ion beam to the target at very high peak currents. In thus permitting the use of a long target and in eliminating any requirement that the ion current rise to a high value, the invention reduces the heat and radiation damage that might otherwise adversely affect the target.

Having thus described the principles of the invention together with several illustrative embodiments thereof, it is to be understood that although specific terms are employed, they are used in a generic and descriptive sense and not for purposes of limitation, the scope of the invention being set forth in the following claims.

I claim:

1. Apparatus for producing a bunched beam of monoenergetic neutrons comprising in combination: means for producing an ion beam; means for deflecting said ion beam so that after deflection the beam is divided into a series of ion fronts; means for directing said ion fronts onto a target; said target being so oriented that, as each ion front strikes the target, the point of impact moves along the target with a constant velocity equal to the velocity of the neutrons emitted by the target material in the direction in which said point of impact moves.

2. Apparatus for producing a bunched beam of neutrons comprising in combination means for producing an ion beam; means for deflecting said ion beam so that after deflection the beam is divided into a series of ion fronts; means for directing said ion fronts onto a target; means for producing an ion-deflecting field across the path of said ion fronts on their way to the target such that the ions emerging therefrom travel in mutually parallel paths; said target being so oriented that, as each ion front strikes the target, the point of impact moves along the target with a constant velocity equal to the velocity of the neutrons emitted by the target material in the direction in which said point of impact moves.

3. Apparatus for producing a bunched beam of neutrons comprising in combination means for producing an ion beam, means for directing said ion beam onto a target; an ion deflector including means for producing an ion-deflecting field across said ion beam and means

for varying said ion-deflecting field so as to deflect said beam so that it sweeps across said target; means for producing a region of controlled electric potential in the path of said ion beam, and means for varying said potential to compensate the energy variation introduced by said ion deflector; said target being so oriented that, as the ion beam strikes the target, the point of impact moves along the target with a constant velocity equal to the velocity of the neutrons emitted by the target material in the direction in which said point of impact moves.

4. Apparatus for producing a bunched beam of monoenergetic neutrons comprising in combination: means for producing an ion beam; means for directing said ion beam onto a target; means for deflecting said ion beam so that after deflection the beam is divided into a series of ion fronts; means for modulating the velocity of said ion beam so that the velocity of the ions in each ion front increases from the leading edge to the lagging edge; said target being so oriented that as each ion front strikes the target, the point of impact moves along the target with a constant velocity equal to the velocity of the neutrons emitted by the target material in the direction in which said point of impact moves; and means for modifying the direction of travel of the ions within each ion front so that the angle between the trajectory of ions arriving at the target and the direction in which said point of impact moves varies so as to counteract the effect upon the velocity of the neutrons emitted in said direction by the energy variation within each ion front.

5. Apparatus for producing a pulsed beam of gamma rays comprising in combination: means for producing a pulsed ion beam; means for deflecting said ion beam so that after deflection the beam is divided into a series of ion fronts; means for directing said ion fronts onto a target; said target being oriented at a slight angle to said ion fronts so that, as each ion front strikes the target, the point of impact moves along the target with the velocity of light in the direction of emission of the desired gamma rays from the target material.

6. Apparatus for producing a bunched beam of ions comprising in combination: means for producing a pulsed ion beam; means for deflecting said ion beam so that after deflection the beam is divided into a series of ion fronts; means for directing said ion front onto a target; said target being so oriented that, as each ion front strikes the target, the point of impact moves along the target with a constant velocity equal to the component, in the direction in which said point of impact moves, of the velocity of the ions emitted by the target material in the desired direction.

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RALPH G. NILSON, *Primary Examiner*.

A. R. BORCHELT, *Examiner*.