United States Patent

[11] 3,571,734

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[21] Appl. No. 872,455
[22] Filed Nov. 21, 1969
[45] Patented Mar. 23, 1971
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[32] Priority Mar. 11, 1966
[33] France
[31] 53,205
Continuation of application Ser. No. 621,946, Apr. 9, 1969, now abandoned.

[54] **METHOD OF PRODUCTION, ACCELERATION AND INTERACTION OF CHARGED-PARTICLE BEAMS AND DEVICE FOR THE EXECUTION OF SAID METHOD**
13 Claims, 7 Drawing Figs.

[52] U.S. Cl. 328/233, 176/7, 313/63, 313/161, 313/231, 315/111
[51] Int. Cl. G21b 1/22, H01j 1/50, H05h 1/02
[50] Field of Search 313/63, 7, 161, 231; 315/111, 39

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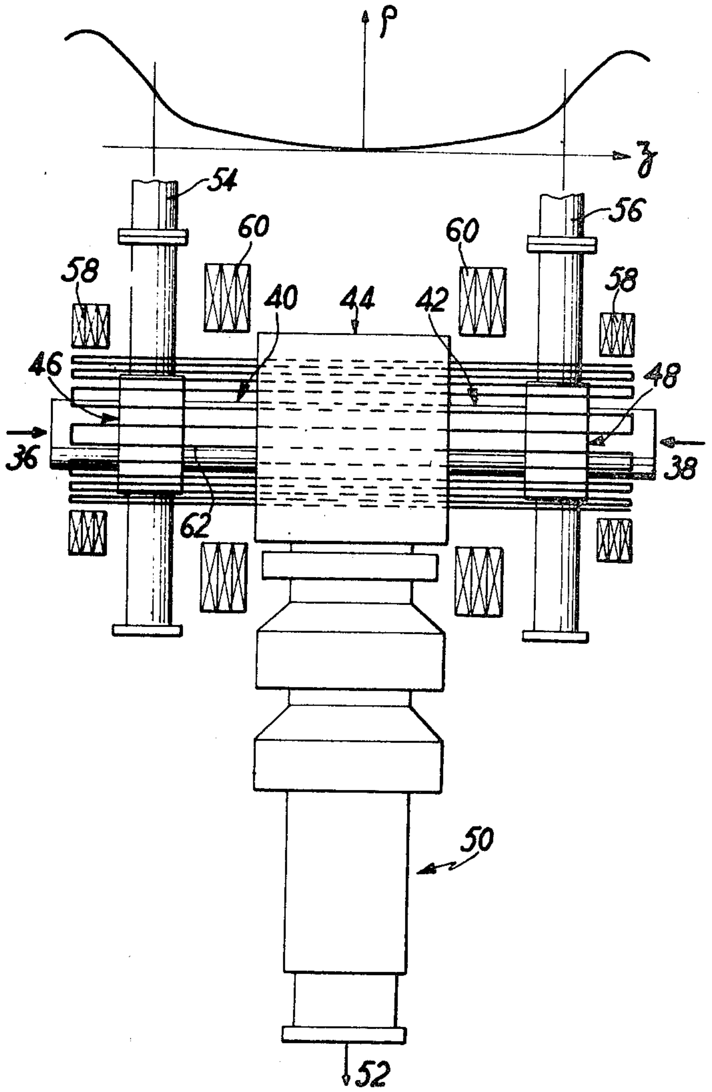
ABSTRACT: A method of accelerating particles of a nonionized or preionized ionizable gas parallel to an axis which consists in applying to said gas at least one high-frequency electromagnetic field having a frequency greater than 10^9 c/s, a so-called axial magnetic field having symmetry of revolution, a so-called radial magnetic field, said high frequency of the electromagnetic field being determined as a function of the amplitude of the axial magnetic field so that said electromagnetic field should yield energy to the ionized gas by cyclotron resonance, the ionized gas being then directed into a discharge space after having been subjected to the high-frequency field, and a device for the application of said method.



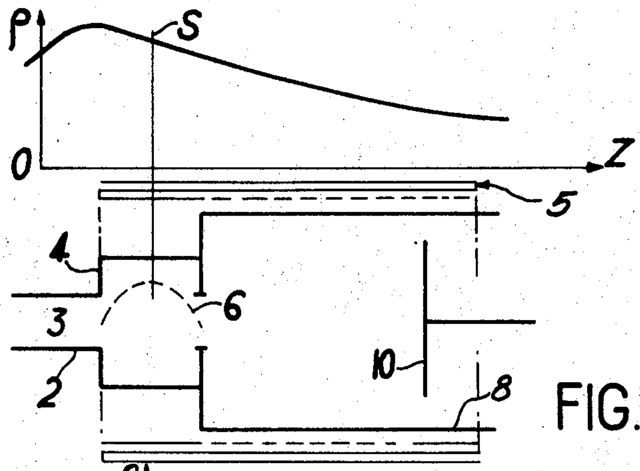


FIG.1

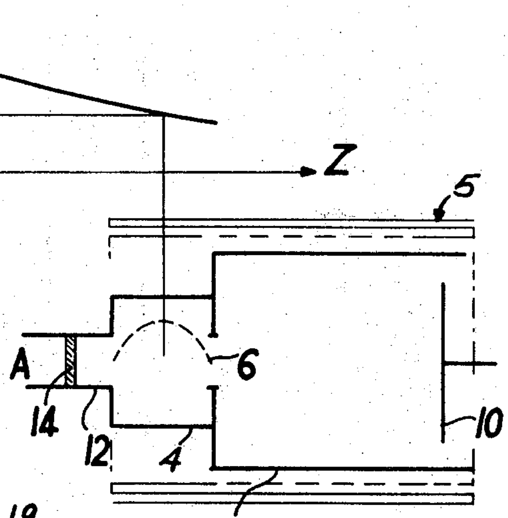


FIG.2

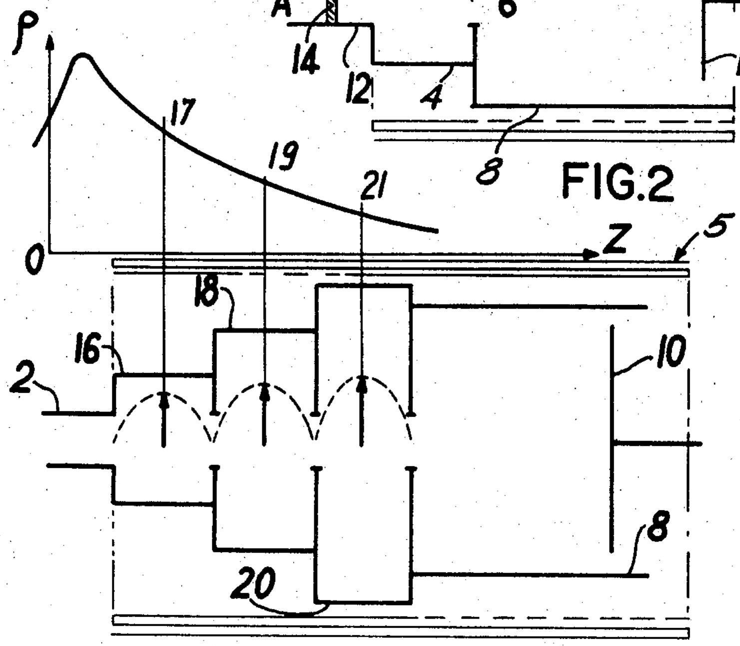


FIG. 3

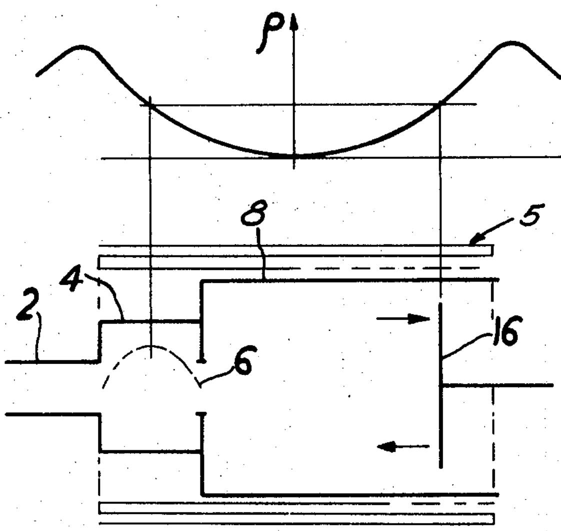
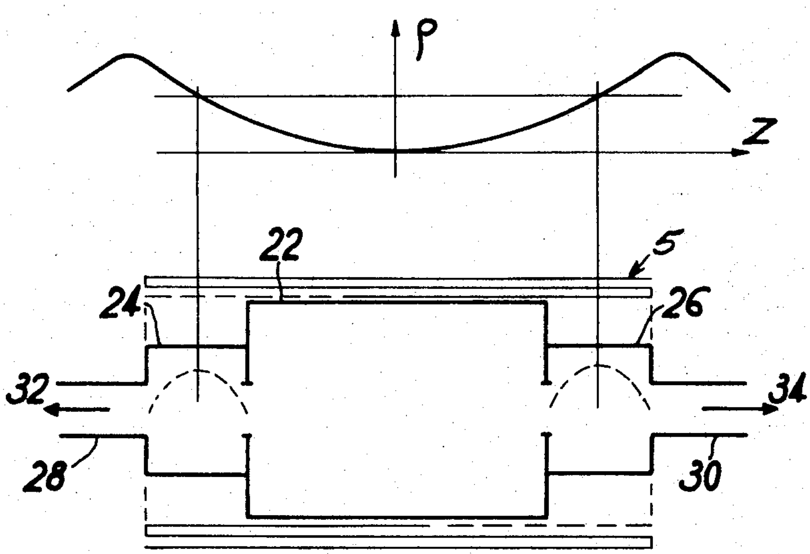


FIG. 4

FIG. 5



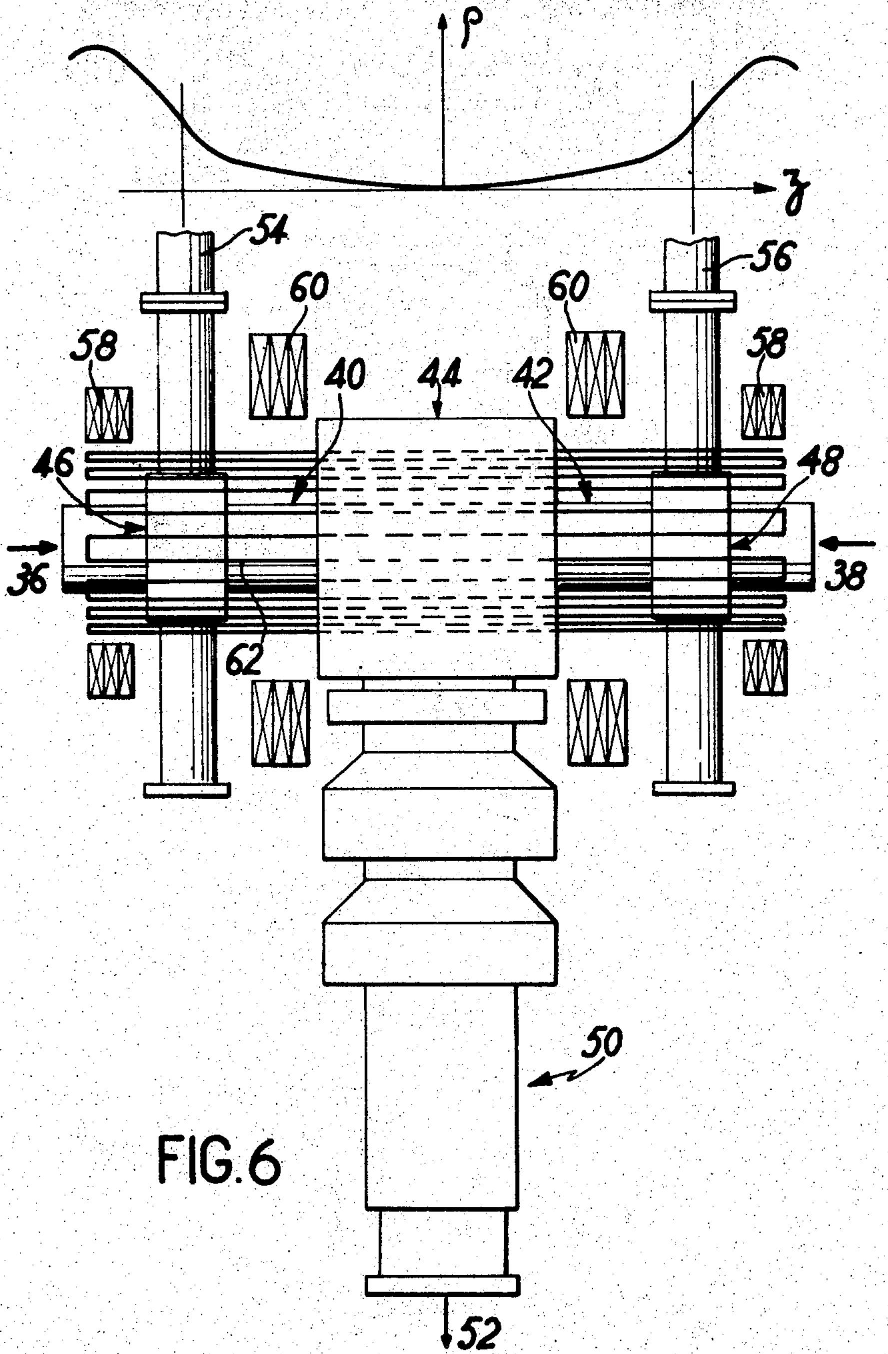
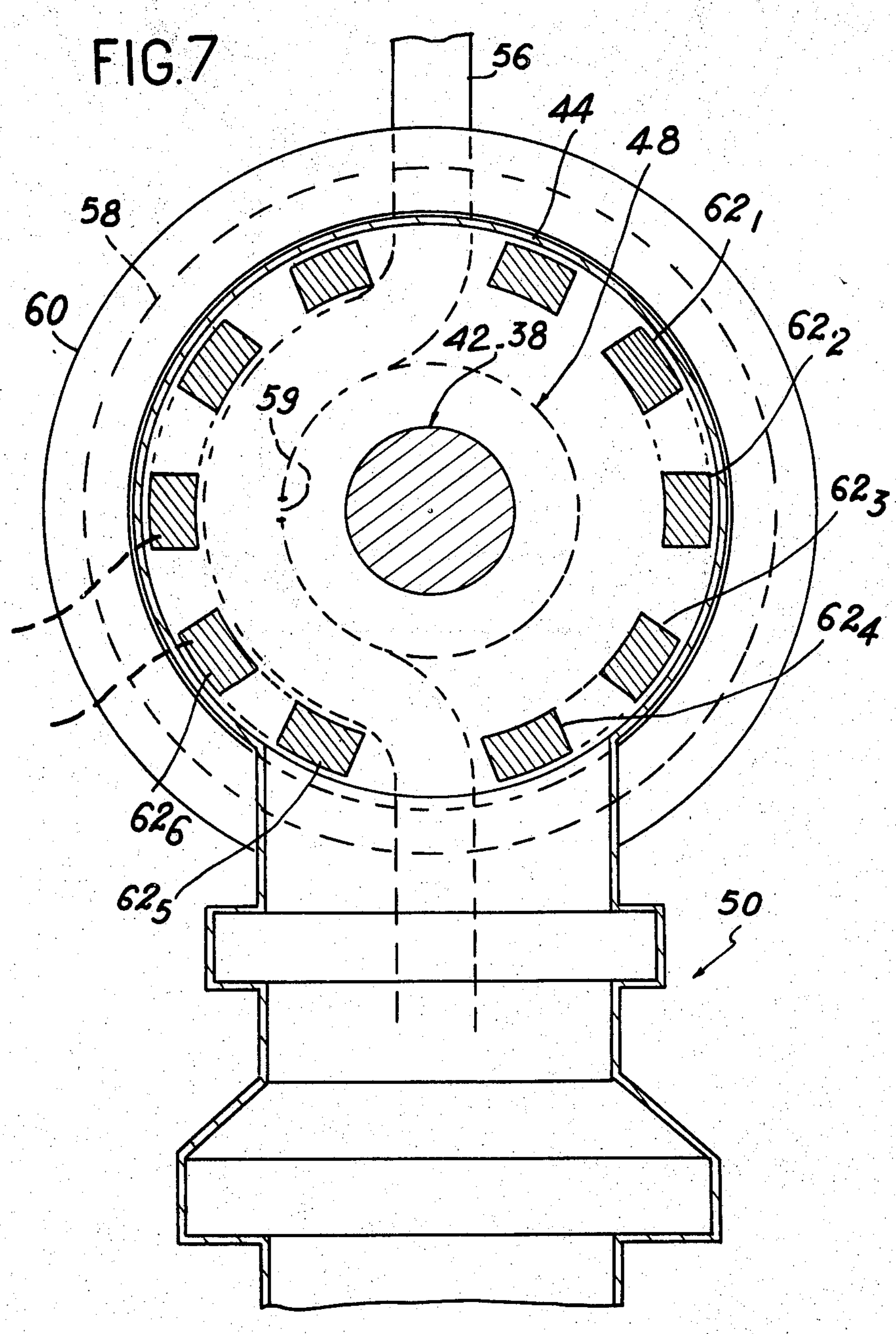


FIG. 6

FIG.7



METHOD OF PRODUCTION, ACCELERATION AND INTERACTION OF CHARGED-PARTICLE BEAMS AND DEVICE FOR THE EXECUTION OF SAID METHOD

This application is a continuation of Ser. No. 621,946 filed Apr. 9, 1967.

This invention is directed to a method of production, acceleration and confinement of an ionized gas, and further relates to devices for the practical application of said method.

This method makes it possible to initiate the accumulation and confinement of a plasma composed of high-temperature electrons and ions which can give rise to fusion reactions either as a result of the impact of a beam on a target or as a result of interaction of beams with or without thermalization of the beams.

In order to accelerate and confine a plasma, there have already been employed the simultaneous actions of a high-frequency electromagnetic field and a so-called axial magnetic field which is substantially parallel to the gradient of the electrical component of said high-frequency field. Under these conditions, each particle is subjected to a force having a component which is parallel to the above-mentioned gradient, the amplitude of said component being appreciable. In consequence, said particle moves towards a region in which the existing electric field is of either maximum or minimum intensity according as its cyclotron frequency (namely the natural rotational frequency of the particle in the magnetic field referred to) is higher than or lower than the frequency of the electromagnetic field.

The particles of a plasma which is thus accelerated have a high velocity in a direction at right angles to the axis and are oriented towards the exterior, thereby entailing a large orbital radius and substantial radial losses. It has already been proposed to reduce these losses by juxtaposing a multipolar radial field with the axial field, with the result that the total field increases in all directions starting from the zone of acceleration or of confinement of the plasma, and that the flux surfaces are concave. By the term "multipolar radial magnetic field" is meant a field having a minimum value in at least one central region of the type created by an even number of conductors placed in parallel relation and angularly spaced at uniform intervals over a cylindrical surface which is coaxial with the structure.

The invention proposes a method whereby a high-frequency electromagnetic field and a static magnetic field are applied simultaneously to an ionizable gas, whether nonionized or preionized, so as to permit the production, accumulation and confinement of a plasma composed of high-temperature electrons and ions.

The method according to the invention consists in applying to said gas at least one high-frequency electromagnetic field having a frequency greater than 10^9 c/s, a so-called axial magnetic field having symmetry of revolution and a gradient in the axial direction, and a so-called radial magnetic field having a minimum amplitude in at least one central region, said high frequency of the electromagnetic field being determined as a function of the amplitude of the axial magnetic field so that said electromagnetic field should yield energy to the ionized gas by cyclotron resonance in a region adjacent to that in which the electric component of the electromagnetic field is of maximum amplitude, the ionized gas being then directed into a discharge space after having been subjected to the high-frequency field.

The electric component of the electromagnetic field is perpendicular to the axis of the discharge space and its polarization is either linear or transversely circular. The axial field and the radial field are either continuous or pulsed.

The present applicants have found that, if the configuration of the axial magnetic field makes it possible to produce magnetic mirror effects at the ends of the accumulation space, there accordingly takes place an increase in the coupling between the particles and the magnetic field and a higher energy is consequently imparted thereto. By way of practical application of this finding, the method previously described has been completed by applying to the magnetic field along the axis of propagation of the beam a law of variation which increases symmetrically from a plane located in the vicinity of the center of the discharge space. A magnetic field of this nature creates magnetic mirror effects near the ends of the discharge space.

Finally, the results obtained are improved still further by applying the methods previously described to the acceleration of two intense beams towards each other, said beams having a common axis but opposite directions. In this case, the magnetic field again varies according to a symmetrically increasing law on each side of a plane located in the vicinity of the center of the discharge space and the axial magnetic field to which said beams are subjected creates magnetic mirror effects near the ends of the discharge space. There is thus obtained a particularly remarkable effect of confinement of charged particles. Moreover, at least two high-frequency electromagnetic fields which are symmetrical with each other yield energy to each of the beams.

The invention is also directed to a device for the execution of the method which has just been described. The device referred to comprises a source of nonionized or preionized ionizable gas, a discharge chamber of generally cylindrical shape connected to vacuum pumps, a unit for producing an axial magnetic field and preferably constituted by axial coils and a unit for producing a radial magnetic field formed by conductive rods substantially parallel to the axis and spaced around a coaxial cylindrical surface, one or a plurality of units each designed to apply a high-frequency electromagnetic field and inserted in a duct which serves to connect said source to the discharge chamber.

In accordance with a preferred alternative embodiment, the rods which produce the radial field are maintained in the superconducting state.

The unit employed for applying a high-frequency electromagnetic field to the charged particles is a cylindrical resonant cavity which oscillates to a TE_{mnp} mode and said field yields energy to said particles in a region close to that in which the amplitude of the electric component of the high-frequency field is of maximum value.

In certain cases, it is possible to employ as a unit for applying the high-frequency electromagnetic field either a transmission line or a device having a periodic structure.

It is possible to increase the quantity of energy yielded to the charged particles by applying to the beams three high-frequency electromagnetic fields respectively established with a view to fulfilling the condition of equality between the cyclotron frequencies or their harmonics and the frequencies of the electromagnetic fields.

It should be noted that it is preferable to utilize cavities which oscillate in the TE_{111} mode, wherein both the frequency and overvoltage in the absence of an ionized medium are related to the geometrical dimensions of the cavity.

The invention is also directed to an acceleration and confinement device having a structure which is asymmetrical in the case of the high-frequency electromagnetic field and symmetrical in the case of the axial magnetic field, with the result that magnetic mirror effects appear at the ends of the discharge space.

Finally, another embodiment which relates to a device for accelerating two intense beams towards each other, said beams having a common axis but being in opposite directions, and for confining the charged particles of said beams, is characterized in that said device is wholly symmetrical so far as both the high-frequency electromagnetic fields and the axial magnetic field are concerned.

Aside from these main arrangements, the invention is also concerned with a number of different secondary arrangements which will be mentioned hereinafter and which relate to forms of construction herein described of the device for the application of the method contemplated by the invention.

The radial magnetic field is intended to effect the focusing of accelerated or reflected plasma beams which are accordingly maintained at a distance away from the walls of the high-frequency cavity or cavities and of the discharge chamber. Said radial magnetic field also contributes to the radial stability of the plasma by virtue of the law of spatial distribution, and has the property of being zero along the axis, with the result that the confinement is not disturbed. It will be noted that such a field is of appreciable strength only in the lateral zones.

In order that the technical characteristics of the invention may be more readily understood, a number of forms of execution of the method which constitutes the primary aim of this invention will now be described, it being understood that these forms of execution are given solely by way of example without implying any limitation either in the modes of operation of the invention or in the potential applications thereof. Reference is made to the accompanying drawings, in which:

FIG. 1 is a diagram representing an asymmetrical accelerating structure as well as the curves of distribution of the axial magnetic field and of the high-frequency magnetic field;

FIG. 2 illustrates a particular form of execution of the structure of FIG. 1;

FIG. 3 is a diagram of the same type which illustrates an asymmetrical structure comprising a plurality of high-frequency cavities;

FIG. 4 is a diagram representing a structure which is asymmetrical in the case of the high-frequency field and asymmetrical in the case of the axial magnetic field;

FIG. 5 relates to an acceleration and confinement device having a completely symmetrical structure;

FIG. 6 illustrates a form of execution of a system having the structure which is shown in FIG. 5.

FIG. 7 is a sectional view from the left of the embodiment of FIG. 6 at right angles to axis of the enclosure and including the axis of the vacuum duct.

In the asymmetrical structure of FIG. 1, there is shown the duct 2 for the admission of ionizable gas which may be either nonionized or preionized, the cylindrical resonant cavity 4 at which said duct terminates and which oscillates in the TE_{mnp} mode, said resonant cavity being coupled by way of the opening 6 to the discharge or acceleration chamber 8 which comprises at its extremity a target 10.

There is shown in the same diagram as a function of the position along the axis of the structure (OZ) on the one hand the variations of the ratio ρ of the amplitude of the axial magnetic field to the amplitude corresponding to the resonance as well as, on the other hand, the high-frequency electric field.

The ratio ρ must be a monotonous and decreasing function of the abscissa Z. In order that the quantity of energy yielded by the high-frequency field to the charged particles should be of maximum value, steps are taken to ensure that the cyclotron resonance of the electrons takes place in a region which is close to the plane S of symmetry of the cavity 4 in which the amplitude of the high-frequency magnetic field is of maximum value. The asymmetrical structure of FIG. 1 also comprises a unit 5 for producing a radial magnetic field formed by conductive rods substantially parallel to the axis and spaced around a coaxial cylindrical surface.

The asymmetric structure of the device of FIG. 2 comprises a number of elements which are identical with those of FIG. 1 and are accordingly designated by the same reference numerals. This structure also comprises a unit 5 for producing a radial magnetic field. It will be noted in this example that the gas supply duct 2 is replaced by a wave waveguide 12 which serves to transmit a high-frequency traveling wave of the type TE_{11}. Said waveguide is divided into two compartments by means of an impervious dielectric window 14, with the result that the portion A of the waveguide can be at atmospheric pressure whilst the accelerator is exposed to vacuum. The high-frequency wave which propagates in the waveguide 12 as well as the high-frequency stationary field within the cavity, preferably has a circular polarization. In this case, the gas which is intended to form the plasma is introduced into the waveguide by means of a device which is not shown in the drawings.

An asymmetrical structure in which the energy is imparted to the beam by means of a plurality of stationary electromagnetic fields established in different cylindrical resonant cavities is illustrated in FIG. 3, in which elements which are identical with those of the structures of FIGS. 1 and 2 are again shown. In this case also, the same numerical symbols have been employed. This asymmetrical structure also comprises a unit 5 for producing a radial magnetic field. The essential difference between the structure of this example and the structure of FIG. 1 lies in the fact that the gas derived from the duct 2 passes successively through three cavities 16, 18 and 20 which are supplied with waves having different frequencies F_1, F_2, F_3 so determined that energy is yielded to the particles in regions adjacent to the planes of symmetry of said cavities, taking into account the amplitudes B_{z1}, B_{z2}, B_{z3} of the axial magnetic field in these planes.

The operation of accelerating devices of asymmetrical structure as shown in FIGS. 1, 2, 3 will now be explained.

The nonionized or preionized ionizable gas is introduced into the resonant cavity in which the stationary high-frequency field is produced and the combined action of the crossed fields, namely the axial magnetic field B_z and the high-frequency electric field E_{HF}, results in ionization or increased ionization by virtue of a cyclotron resonance phenomenon. The radial magnetic field effects the focusing of accelerated or reflected plasma beams which are accordingly maintained at a distance away from the walls of the high-frequency cavity or cavities and of the discharge chamber. Said radial magnetic field also contributes to the radial stability of the plasma by virtue of the law of spatial distribution and has the property of being zero along the axis with the result that the confinement is not disturbed. It will be noted that such a field is of appreciable strength only in the lateral zones.

Taking into account the gradient possessed by this high-frequency field and the axial magnetic field, the electrons are subjected to a unidirectional axial force which is directed towards the decreasing magnetic fields when they are subjected to the stationary high-frequency field in cavities in which overvoltages can be of a low order. These electrons then acquire a high radial velocity. In certain cases, they can become practically relativistic in a transverse plane.

In order that the energy corresponding to said radial velocity should be utilized, said velocity must accordingly be converted to an axial velocity. Furthermore, the energy is distributed between electrons and ions if the plasma is neutral so that the ratio of parallel energies of ions and electrons $W//i_{/} {}_{W/e}$ should be equal to the mass ratio Mi/me. However, whereas the energy corresponding to a radial velocity of the ions can be zero, the energy which corresponds to a radial velocity of the electrons remains high and can attain several tens or hundreds of KeV, this quantity of energy being a function of the power applied.

The cavities employed for the purpose of applying the high-frequency field to the ionized gas have a no-load overvoltage coefficient Q_o which is considerably higher than the load overvoltage coefficient Q_1 when they are traversed by the beam. Q_1 is a decreasing function of the conductivity of the plasma. The variation of the overvoltage coefficient results in a modification of its resonance frequency. Under these conditions, it is an advantage to ensure that the frequency of the electromagnetic energy source is controlled in dependence on the resonance frequency of the cavity by means of a special device.

The devices which have just been described operate in a satisfactory manner if two main conditions are complied with.

The axial magnetic field must have a high axial gradient, thereby facilitating the establishment of the cyclotron resonance.

Finally, the cyclotron frequency F_C of the electrons must be higher than the frequency of the electromagnetic wave in a portion of the cavity or cavities employed. As a result, the electric density of the accelerated plasma N_P can be higher than the cutoff value.

The devices of FIGS. 1, 2 and 3 are capable of operating only under acceleration conditions and the pressure developed therein can be of a very low order, thereby permitting of low particle flux having very high energy. In the case in which the gas supply duct terminates in a quartz tube and when the electron paths have extremely large Larmor radii, bombardment of the quartz tube gives rise to high secondary emission. Under these conditions, the plasma loses its neutral quality and the accelerator plays the part of an electrostatic generator. These special properties of the structures herein described can thus be turned to profitable account.

It is possible by means of these devices to initiate fusion reactions by beam-target interaction. For this purpose, the target is fabricated of titanium alloyed with tritium which has to be cooled. The number of reactions which can be obtained exceeds the number permitted by the utilization of neutron generators in which the source is a deuteron beam alone by reason of the fact that, by utilizing a plasma, any limitation due to the charge space is thereby removed.

The structure of FIG. 4 comprises only a single resonant cavity disposed on one side of the discharge chamber and is therefore asymmetrical in the case of the electromagnetic field whereas, on the contrary, the axial magnetic field has a law of variation which increases symmetrically from the midplane of the discharge chamber. This structure also comprises a unit 5 for producing a radial magnetic field.

Finally, FIG. 5 represents a structure which is completely symmetrical both from the point of view of the high-frequency field and from that of the axial magnetic field, and permits of confinement of the plasma within the discharge chamber 22. In this example, the nonionized or preionized ionizable gas is directed towards the resonant cavities 24 and 26 by means of ducts 28 and 30 which are connected to the gas sources 32—34 (not shown). This structure also comprises a unit 5 for producing a radial magnetic field.

It will be noted that the general indications given in connection with the operation of the devices shown in FIGS. 1 and 3 all relate to apparatus in which the method constituting the primary aim of the invention is utilized to full advantage.

The accelerating structure shown in FIG. 4 has a double role, namely that of injector in which it injects charged particles into the discharge space and that of reflector, and the axial magnetic field constitutes between the two magnetic mirrors a veritable "magnetic bottle." In order that the condition of operation referred to above should be possible, it is essential to ensure that the ratio of perpendicular velocities to parallel velocities of the electrons: $V_{\perp}/V_{\parallel}=R_V$ is considerably higher than 100. Under these conditions, the beam is reflected from the magnetic mirror in the vicinity of the target and a plasma can be accumulated as long as the collisions do not substantially reduce the ratio R_V and as long as this latter is comprised between limits such that the leakage flux at the magnetic mirror is smaller than the flux injected into the structure. It has been possible to check the validity of this condition by experiment.

The method according to the invention is of particular interest when use is made of a symmetrical structure as illustrated in FIG. 5 for the purpose of carrying said method into effect. In fact, the structures employed for applying the high-frequency field in this case are respectively located in both regions of the magnetic mirrors. Under these conditions, advantage is drawn from the fact that those particles whose ratio R_V has become small can still be utilized for the purpose of creating the plasma inasmuch as the energy yielded by the high-frequency field makes it possible to increase said ratio R_V once again to a value such that the magnetic mirrors are effective.

The efficiency of this device is limited by energy losses arising at frequencies in the vicinity of operating frequency but the highest losses are due to charge exchanges or to elementary processes. The losses last referred to are limited by reducing the residual pressure within the chamber.

The utilization of the device of FIG. 5 makes it possible to produce fusion reactions in two different ways.

The use of deuterium makes it possible to obtain D–D reactions. In the case in which the lifetime of the ions is shorter than the thermalization time, the effective cross sections of the reactions are those of the beam-beam interactions. In the contrary event, if the lifetime is longer, a thermalized plasma forms and the effective cross sections vary accordingly. A target formed of titanium alloyed with tritium and adapted to move or to rotate in order to prevent overheating can also be disposed in the accumulation zone, in which there takes place a multiple transfer of beams resulting from reflections. It is also possible to make use of granules of titanium or titanium alloyed with tritium; said granules fall freely into the plasma and constitute active microtargets.

FIGS. 6 and 7 illustrate a device for the practical application of the method according to the invention, the structure of this device being identical with the one illustrated in the diagram of FIG. 5. Two sources 36—38 (not shown) transmit nonionized or preionized ionizable gas into two quartz tubes 40—42 which terminate in a confinement chamber 44. Said chamber is connected by means of a duct 50 to vacuum pumps 52, not shown. These quartz tubes traverse oscillating cavities 46—48 which are supplied by way of waveguides 54—56. The complete structure is surrounded by pairs of axial coils 58—60 which create the axial magnetic field so as to produce magnetic mirror effects externally of the resonant cavities.

Finally, in order to reduce the radius of the particle paths, use is made of a device 62 for the production of a multipolar radial magnetic field constituted by parallel cylindrical series mounted conductive rods 62_1 to 62_6 (FIG. 7) which are angularly spaced in a uniform manner and designated by the name of Joffe rods.

In this embodiment, either a part of or all of the radial magnetic field conductors passes through the vacuum chamber. Said conductive rods can be in a superconducting state and are in that case disposed within protective cylindrical tubes which serve to convey the cooling liquid at a sufficiently low temperature in order that said liquid can be integrated if necessary in a cryogenic pumping system by condensation of titanium vapor.

We claim:

1. A method of acceleration of particles of an ionizable gas parallel to an axis, which consists in applying to said gas within at least one resonant structure a high-frequency electromagnetic field which is perpendicular to the direction of propagation, an axial magnetic field having symmetry of revolution and a gradient in the axial direction, and a radial magnetic field having a minimum amplitude in at least one central region, said high frequency of the electromagnetic field being determined as a function of the amplitude of the axial magnetic field so that said electromagnetic field should yield energy to the ionized gas by cyclotron resonance in a region adjacent to that in which the electric component of the electromagnetic field is of maximum amplitude, the beam constituted by the particles of ionized gas being then directed into a discharge space after having passed through at last one resonant structure.

2. A method of acceleration in accordance with claim 1, in which the radial magnetic field and the axial magnetic field are pulse modulated.

3. A method for acceleration in accordance with claim 1, in which the axial magnetic field varies along the axis of propagation of the beam according to a law of variation which decreases in a monotonous manner from the region of the resonant structure to the end of the discharge space.

4. A method of acceleration in accordance with claim 1, in which the axial magnetic field varies along the axis of propagation of the beam according to a law of variation which increases in a symmetrical manner starting from a plane located in the vicinity of the center of the discharge space and said field creates magnetic mirror effects near the ends of the discharge space.

5. A method of acceleration in accordance with claim 1 which consists in directing towards the beam formed by ionized particles of a gas a second beam which is also con-

stituted by the ionized particles of a gas and which has a common axis but is of opposite direction, in creating an axial magnetic field so as to produce magnetic mirror effects near the ends of the discharge space, said field being intended to vary according to a symmetrically increasing law on each side of a plane located in the vicinity of the center of the discharge space, and in applying to said second beam within at least one resonant structure a high-frequency electromagnetic field which is perpendicular to the direction of propagation.

6. An acceleration device which comprises an ionizable gas source, at least one discharge chamber having a generally cylindrical shape and connected to vacuum pumps, a unit for producing within said chamber an axial magnetic field and preferably constituted by axial coils and a unit for producing within said chamber a radial magnetic field formed by series mounted conductive rods substantially parallel to the axis of said chamber and coaxially spaced around a cylindrical surface of said chamber, one or a plurality of units each designed to apply within said chamber a high-frequency electromagnetic field and inserted in a duct which serves to connect said source to the discharge chamber.

7. An acceleration device in accordance with claim 6, in which the conductive rods which produce the radial magnetic field are maintained in the superconducting state.

8. An acceleration device in accordance with claim 6, in which the unit or units for applying a high-frequency field to the charged particles is at least one cylindrical resonant cavity which oscillates in a TE_{mnp} mode and said field yields energy to said particles in a region close to that in which the amplitude of the electric component of the high-frequency field is of maximum value.

9. An acceleration device in accordance with claim 6, in which the unit for applying the high-frequency field is a transmission line.

10. An acceleration device in accordance with claim 6, in which the unit which applies the high-frequency field to the charged particles is a cavity coupled to a circular section waveguide in which is propagated a traveling wave having transverse circular polarization, said waveguide comprising a dielectric window which is impervious to gases but transparent to electromagnetic energy.

11. An acceleration device in accordance with claim 6, in which the space for the application of high-frequency energy to the charged particles comprises a plurality of resonant cavities which oscillate in TE_{mnp} modes and the high-frequency fields yield energy to said particles respectively in regions adjacent to those in which the amplitude of the electric components of the high-frequency fields are of maximum value, said high frequencies being determined as a function of the amplitudes of the axial field in those regions in which energy yields take place.

12. A device, having a symmetrical structure, for accelerating two intense beams of particles towards each other, comprising two sources of ionizable gas each furnishing one of the intense beams of particles, a discharge chamber of generally cylindrical shape which is connected to vacuum pumps, a unit for producing within said chamber an axial magnetic field constituted by axial coils, said axial magnetic field having a plane of symmetry located in the vicinity of the center of the discharge chamber, a unit for producing within said chamber a radial magnetic field formed by series mounted conductive rods which are substantially parallel to the axis of said discharge chamber and coaxially spaced around a cylindrical surface of said chamber, at least one pair of resonant structures for the application of high-frequency electromagnetic fields and disposed in ducts which serve to connect said sources to the discharge chamber across the beams, said axial coils producing magnetic mirror effects in the areas where the structures providing said high-frequency fields are located, said rods producing said radial magnetic field extending up to said areas of the magnetic mirror effects.

13. An acceleration device comprising an ionizable gas source, a discharge chamber having a generally cylindrical shape with a long axis and connected to vacuum pumps, a unit for producing within said chamber an axial magnetic field constituted by axial coils, said axial magnetic field having a plane of symmetry located in the vicinity of the center of the discharge chamber, a unit for producing within said chamber a radial magnetic field comprising series mounted conductive rods substantially parallel to said axis and spaced coaxially around a cylindrical surface of said chamber and extending up to said ends of said chamber and at least one unit for applying a high-frequency electromagnetic field inserted.