

Dec. 24, 1968

R. B. HALL ET AL
PARTICLE ACCELERATOR

3,418,206

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2 Sheets-Sheet 1

Fig. 1.

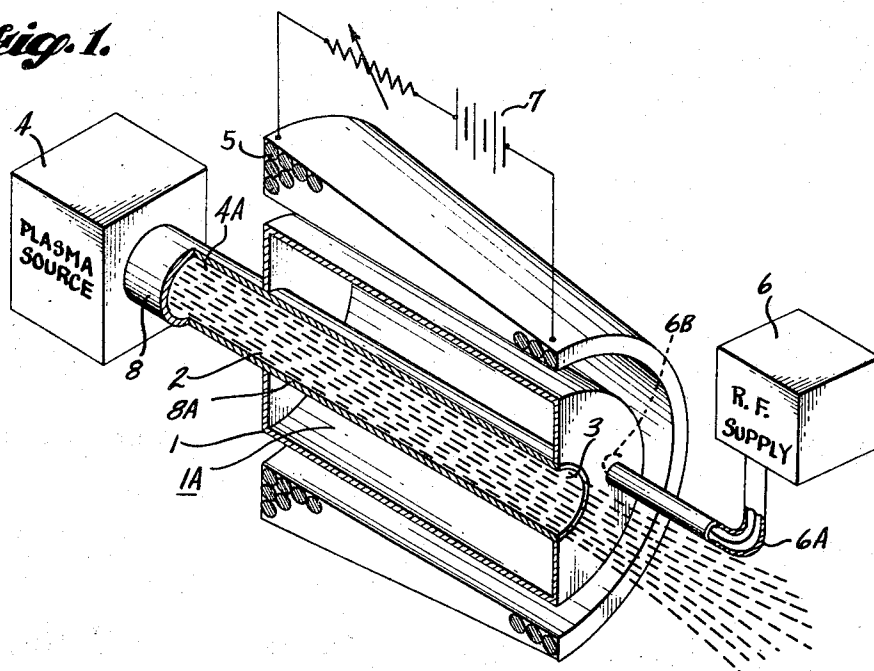


Fig. 2.

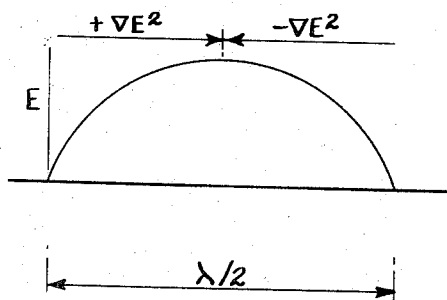
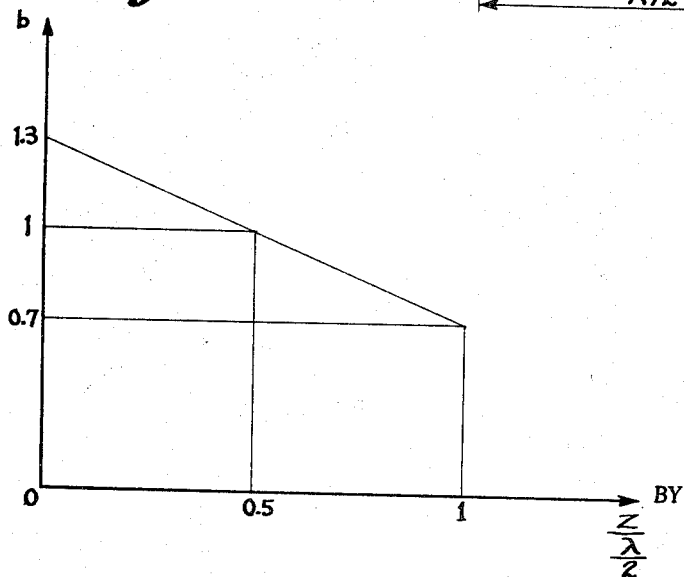


Fig. 3.



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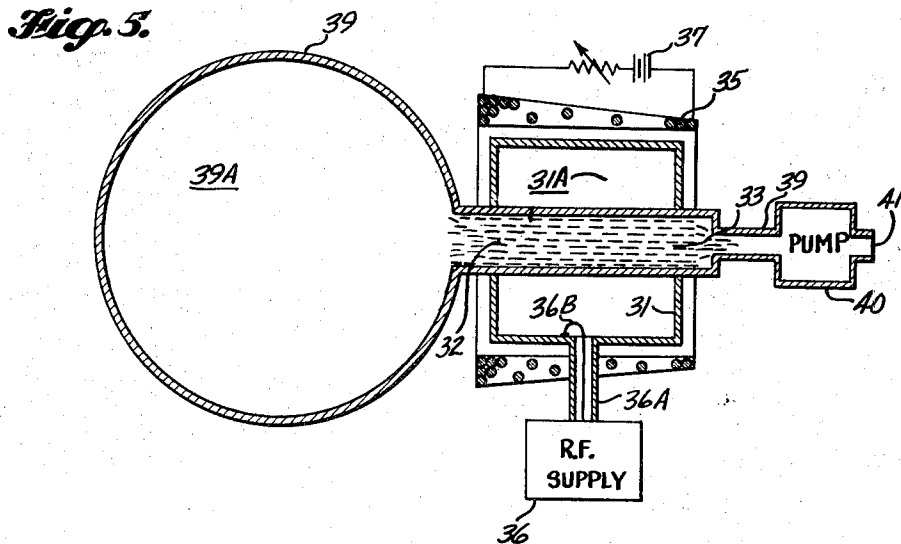
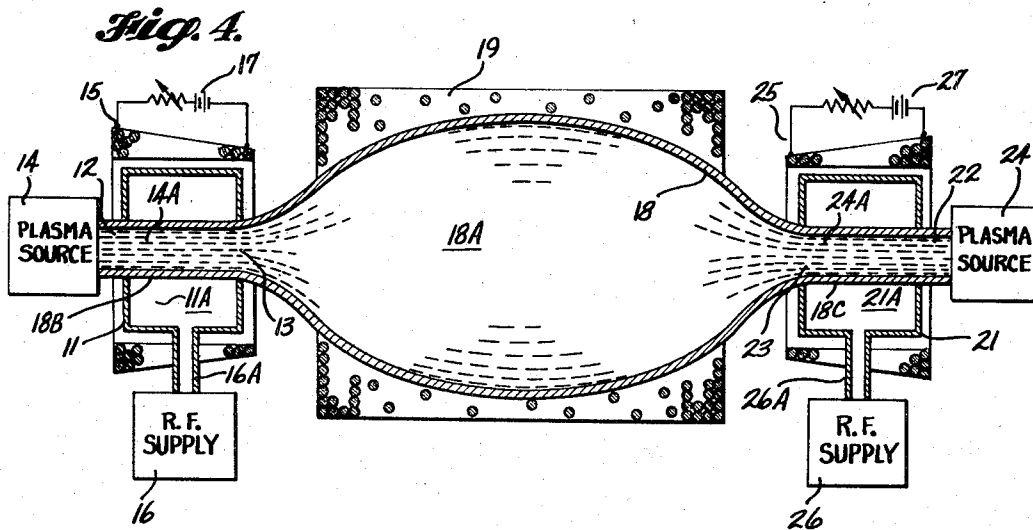
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2 Sheets-Sheet 2



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PARTICLE ACCELERATOR

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ABSTRACT OF THE DISCLOSURE

A high energy particle accelerator is described which makes use of a radio frequency cavity disposed within a longitudinal magnetic field extending between opposite openings in the ends of the cavity. The magnetic field is established with a field gradient existing within the cavity being of such a magnitude that at one point in the cavity the frequency of the RF signals applied to the cavity will correspond to the cyclotron frequency of the particles for the magnetic field at that point. The magnetic field strength is established to be greater than and less than the field strength at said point at respective locations on opposite sides of said point with the arrangement being such that charged particles entering the apparatus will be highly accelerated. An improved evacuation apparatus is disclosed making use of the described particle accelerator to remove particles from a container. In a further embodiment of the invention a pair of the particle accelerators are illustrated in combination with a magnetic bottle for generating high temperatures.

The present invention relates in general to particle accelerators and more particularly to an improved accelerator which makes use of magnetic fields and electromagnetic radiation to accelerate charged particles in a manner such that the apparatus is adapted for various uses and in particular for use in propulsion systems, vacuum creating systems, and high temperature fusion systems.

It is well known at the present time that charged particles such as electrons and ions when subjected to an appropriate electric field will be accelerated and consequently their energy increased. This phenomenon in combination with the effect of a magnetic field upon charged particles has made possible various types of particle accelerators as for example the cyclotron, synchrotron and accelerators of other types. Such equipment has generally been relatively bulky and heavy and therefore not particularly well suited for use in propulsion systems wherein the discharge of the accelerated particles can serve to provide an opposite thrust to the source of particles. With the growing importance of the field of study frequently referred to as plasma physics a need has also arisen for compact particle accelerators which can be used to increase the energy of a plasma composed of charged particles.

It is therefore an object of the present invention to provide an improved apparatus for increasing the velocity of electrically charged particles and consequently their energy.

It is another object of the present invention to provide an improved particle accelerator which can be used as a propulsion system by increasing the discharge velocity of charged particles at the expense of magnetic and electric fields in a manner such that the source of the particles is accelerated in a direction opposite to the direction of discharge of the particles.

It is a further object of the present invention to provide an improved compact particle accelerator making use of simplified and rugged components.

Another object of the present invention is to provide an evacuation apparatus which makes use of an improved particle accelerator to substantially completely remove a

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gas from a container in a manner such that a high vacuum is produced within the container.

In accordance with the teachings of the present invention a suitable gas or plasma of charged particles is subjected to a magnetic field and simultaneously to an alternating electric field which is perpendicular to the axis of the magnetic field and has a field gradient parallel to the magnetic field. A radio frequency cavity having oppositely disposed openings is preferably utilized with the magnetic field extending between the two openings and having a magnetic field gradient established therebetween of a particular magnitude such that charged particles at a given point intermediate the two openings will have a cyclotron frequency corresponding to the frequency of RF signals applied to the cavity. With the magnetic field gradient between one of the openings and the point at which the cyclotron frequency of the charged particles is equal to the frequency of the applied RF electromagnetic energy being greater than the field strength at said point and with the field gradient decreasing between said point and the other opening, it is found that charged particles entering the cavity are continuously accelerated within the cavity and hence are discharged at a velocity substantially greater than their entrance velocity. The source of the particles can either be a plasma of charged particles or a natural gas which ionizes at the interior of the cavity in the presence of the electric field.

By using an enclosed source of a neutral gas as the source of particles to be accelerated it is found that the enclosed source will be effectively evacuated as a result of the continued acceleration and discharge of the gas by the accelerator. Thus an improved evacuation system is provided which can be readily used in combination with conventional pumping devices.

In accordance with further teachings of the present invention a pair of improved particle accelerators are diametrically opposed so that each simultaneously accelerates charged particles into the interior of a "magnetic bottle" which serves to apply compressional force to the high energy particles in the interior thereof. Suitable reflecting magnetic mirrors are positioned adjacent the two entrances to the magnetic field and therefore as a result of the high energy imparted to the particles by the accelerators and the presence of the compressional magnetic forces extremely high temperatures are generated leading to an improved high temperature system useful in fusion experiments.

The above as well as additional advantages and objects of the present invention will be more clearly understood from the following description when read with reference to the accompanying drawings wherein,

FIGURE 1 is an orthographic projection of one embodiment of the present invention which includes a high frequency resonant cavity having a steady magnetic field maintained therein;

FIGURE 2 is a diagram of electric field intensity within the cavity of FIGURE 1 as established by a suitable RF signal source;

FIGURE 3 is a graph showing one suitable variation in the ratio of the cyclotron frequency to electromagnetic signal frequency with respect to location inside the cavity and as established by the apparatus of FIGURE 1;

FIGURE 4 is a schematic illustration of a system which includes a pair of improved particle accelerators in combination with a suitable magnetic "bottle" for generating high temperatures required in fusion experiments; and

FIGURE 5 is a schematic illustration showing in cross section an improved evacuation system utilizing the improved particle accelerator.

Referring now to the drawings and in particular to FIGURE 1 there is illustrated a cylindrical radio frequency

(RF) cavity resonator 1 which may be made of copper or other suitable material and advantageously silver plated on the interior. The resonator is provided with openings 2 and 3 disposed in the opposite ends thereof and each coaxial with the center longitudinal axis of the cavity. A source of particles to be accelerated shown for purpose of illustration as a plasma source 4 is coupled with the interior of the cavity by the conduit 8 which passes through the opening 2. The section 8A of conduit 8 within the cavity is preferably made of quartz or of suitable glass to allow passage of RF energy therethrough. The plasma source 4 is adapted to inject a plasma of charged particles illustrated generally at 4a into the interior of the cavity 1 in a direction indicated as being generally parallel to the central longitudinal axis thereof. The plasma may include both positively and negatively charged particles. If only particles of one polarity of charge are used then an external neutralizing circuit may be used to prevent a build-up of charge on the apparatus. It should be noted that the particles would actually traverse complex paths in the cavity and therefore the paths indicated in the drawings are only used as an illustration to show that the particles do have an acceleration component causing them to be accelerated from one end of the cavity to the other.

A magnetic field is maintained parallel to the central longitudinal axis of the cavity and for purpose of illustration a series of windings 5 energized by a suitable DC power source 7 is shown as providing the magnetic field. As described hereinafter, the field established by the helix or winding 5 exhibits a longitudinal field gradient and therefore for purpose of illustration the number of windings is shown as being greater near one end of the cavity 1A defined by the resonator than near the other end thereof. A similar field can be obtained using a plurality of windings connected in series circuit along and about the cavity with the separate windings having shunt resistors of different values connected in parallel therewith so that the desired magnetic field gradient (described hereinafter) is achieved.

High frequency electromagnetic signals are introduced into the interior of the resonator 1 from an RF signal source 6 shown schematically as being coupled with the interior of the cavity by means of the coaxial cable 6a having the terminating loop 6b secured to the interior of the cavity 1. It should be understood that the manner of coupling of the RF signal source to the cavity 1A can be accomplished in various ways well known in the art including the use of a conventional waveguide and therefore a coaxial cable terminated on the interior of the resonator is shown only for the purpose of illustrating that the signals generated by the source 6 are applied to the interior of the cavity 1. The electromagnetic signal energy is applied to the interior of the cavity 1 in the TE mode in the example illustrated in FIGURE 1. The resulting electromagnetic field within the cavity 1 thus has an electric field E which is polarized in the transverse plane of the cavity and exhibits a field gradient along the central longitudinal axis of the cavity 1A.

It is well known that the gradient of a scalar quantity $E(x, y, z)$ is a vector with components $\partial E/\partial x$, $\partial E/\partial y$, $\partial E/\partial z$, respectively, on three orthogonal axes Ox, Oy, Oz. As discussed with more particularity hereinafter, the gradient of the electric field $E(x, y, z)$ is defined as ∇E . The mean force $\bar{F}$, expressed in dynes, for the duration of one period of an electromagnetic field acting on a charged particle introduced into the interior of a cavity, as for example an electron, of a plasma which is confined to or near the vicinity of the longitudinal axis of the cavity and for a uniform magnetic field is given by the relation:

$$\bar{F} = -\frac{e^2 \nabla E^2}{4m\omega^2(1-b^2)} \quad (1)$$

in which $b=f_e/f$; e is the charge of the particle, for the electron equal to 4.8025×10^{-10} electrostatic CGS units,

m the mass of the particle which for an electron is equal to $9.1076 \times 10^{-28}g$, ω the radian frequency of the electromagnetic field which is related to the frequency f of the latter by the relation $\omega=2\pi f$, f_e is the cyclotron frequency of the particle submitted to the action of the magnetic field B, and E represents the amplitude in volts per cm. of the electric component of the electromagnetic field.

The cyclotron frequency f_e for the particles of mass m and charge e in a magnetic field B is:

$$f_e = \frac{eB}{2\pi mc} \quad (2)$$

where c is the velocity of electromagnetic radiation in vacuum.

The cavity 1 is preferably of a length corresponding to one-half the wavelength of the electromagnetic signals applied thereto by the source 6 and in the example illustrated is resonant in the mode TE_{111} . FIGURE 2 shows the variation of electric field along the axis of the cavity to illustrate the field gradient within the cavity 1 when the length of the cavity corresponds to one-half the wavelength of the applied RF signals. It will be seen in FIGURE 2 that the field strength corresponds generally to a sine wave, starting at zero adjacent to the opening 2, increasing to its maximum in the central transverse plane of the cavity, and then decreasing to zero adjacent the exit opening 3. The sense of the variation in amplitude of the electric field along the central longitudinal axis determines the sense of the gradient ∇E and thus of the gradient of the square of the amplitude in Equation 1. This gradient is in the left to right direction for the first half of the cavity 1A of FIGURE 1 between the opening 2 and the transverse symmetry plane, and is in the opposite direction for the second half of the cavity corresponding to the space between the transverse plane of symmetry and the exit opening 3. This is indicated by the notations $+\nabla E^2$ and $-\nabla E^2$ above the curve of FIGURE 2.

From Equation 1 it will be seen that in the case of a uniform magnetic field such that b is greater than unity throughout the length of the cavity and in the presence of an electric field having a gradient such as that producing the curve illustrated in FIGURE 2, the mean force $\bar{F}$ acting on a charged particle such as an electron which enters the cavity 1 through the entrance opening 2 would cause the particle to be accelerated up to the transverse symmetry plane. Since the sense of the electric field gradient reverses after the particle passes the central plane of symmetry it will be seen that the particle would be decelerated between the central plane of symmetry and the exit opening 3. Therefore the particle would leave the cavity through the opening 3 with a velocity approximately equal to the velocity with which the particle entered the cavity. If the ratio of f_e/f were less than unity throughout the length of the cavity, $\bar{F}$ would be negative for the first half of the cavity so that particles entering opening 2 would be either reflected or decelerated in the first half of the cavity and accelerated in the second half so that again the entrance and exit velocities would be approximately the same. To maintain the force $\bar{F}$ of the proper algebraic sense to cause constant acceleration of the particles from the opening 2 to the opening 3, it has been ascertained that the amplitude of the factor b can be varied along the central longitudinal axis of the cavity. The specific variation desired in the ratio of the cyclotron frequency of the particles to the frequency of the applied electromagnetic field is discussed in greater detail hereinafter.

An analysis of the forces acting upon a charged particle which is close to the central longitudinal axis of the cavity and positioned immediately adjacent the transverse plane of symmetry will be advantageous at this point. The system is designed so that in a transverse plane which for the example shown is the central transverse plane, corresponding to the plane of symmetry, the intensity of the

magnetic field in that plane and the frequency of the applied signals are such that the cyclotron frequency f_c is equal to the frequency f of the electromagnetic field applied to the cavity. The electric field intensity as well as the magnetic field intensity are such that each of the two quantities varies along the longitudinal or z axis of the cavity. To reflect the effect of such variations in electric field and magnetic field in the force exerted on a particle in the cavity, the following equations are utilized:

$F_1 = F_\omega + F_b$ in which:

$$F_\omega = -\frac{e^2}{4m\omega^2} \frac{\partial}{\partial z} \left(\frac{E^2}{1-b^2} \right) \text{ and } F_b = -\frac{(KE)}{B} \frac{\partial B}{\partial z} \quad (3)$$

The force F_1 is the sum of two forces, F_ω due to the electromagnetic field of radian frequency ω ; and F_b due to the motion of the particles at the cyclotron frequency in the magnetic field B . In these equations z represents the distance of a point on the central longitudinal axis from the plane of the opening 2 in the left end of the resonator with the positive direction corresponding to the direction from opening 2 toward opening 3. (KE) represents that part of the kinetic energy which is at the cyclotronic frequency.

If the electromagnetic field is intense, the ratio α of the amplitudes of forces F_b and F_ω can be approximated by the equation:

$$\alpha = \frac{F_b}{F_\omega} = \frac{(1+b^2) \frac{db}{dz}}{2 \left[kb(1-b^2) \coth kz + b^2 \frac{db}{dz} \right]} \quad (4)$$

in which k is the wave number equal to $2\pi/\lambda$ or in the example illustrated $k=\pi/L$ where L is the length of the resonator.

The value of the cyclotron frequency ω_c which is equal to $2\pi f_c$ is proportional to the static magnetic field B , and the variable $b=f_c/f$ is therefore related to the field B . Consequently, the ratio $\alpha=F_b/F_\omega$ depends on the variation of the intensity of the static magnetic field B with respect to z . In order to give a numerical value to α and, consequently, to maintain a constant sense for the force F_1 , a magnetic field gradient providing a variation in the ratio b with respect to location along the central axis (z) defined by an equation $b=f(z)$ is chosen. One such equation is:

$$b = b_0 + \frac{z}{\lambda} 2(1-b_0) \quad (5)$$

in which b_0 represents the value of b measured at the point of entrance of the particles corresponding in the present example to the point at which the magnetic field has maximum value. λ is the wavelength expressed in cm. of the electromagnetic signal which is generally in the order of one to thirty cm.

The curve in FIGURE 3 is one example of the variation of b with respect to distance from the plane of maximum magnetic field intensity (the left end of the cavity in the embodiment of FIGURE 1) which produces the desired result. In FIGURE 3 the value of b is represented on the ordinate with the abscissa being in units of

$$\frac{z}{\lambda}$$

(z being distance from the opening 2). In the example of FIGURE 3 b_0 is equal to 1.3. According to this curve, b is equal to one in the transverse symmetry plane of cavity 1A. Consequently, the intensity of the static magnetic field in this plane is such that the cyclotron frequency of the particles (such as electrons) is equal to the frequency of the electromagnetic field. Moreover, the slope of the curve shows that there is a gradient of the magnetic field

B along the axis of the cavity 1A and such gradient maintains a constant sense. The intensity of the magnetic field will be seen to be of a first intensity in a first region adjacent opening 2 and to the left of the plane of symmetry; of a second intensity less than said first intensity in a second region corresponding to the plane of symmetry in which the intensity establishes the cyclotronic frequency f_c ; and of a still lower third intensity in the third region adjacent said exit opening 3.

The gradient of the static magnetic field illustrated in FIGURE 3 serves to maintain the direction of the force F_1 constant and therefore particles entering the cavity through the opening 2 are constantly subjected to an appropriate accelerating force. Each particle of mass m in the equations previously set forth (as for example the mass of an electron) is therefore subjected to the force F_1 . As a result of the constant acceleration of the charged particles of mass m it will be seen that a space charge of such particles will exist between the openings 2 and 3. In the case where the particles of mass m are electrons, any ions in the plasma will be accelerated through the cavity as a result of and under the influence of the space charge caused by the preferential acceleration of the electrons by the field. It will be seen from Equation 1 that the accelerating force which acts on particles in the field is inversely proportional to the mass of the particles and therefore electrons are more rapidly accelerated than are ions. The ions however are entrained and accelerated by the space charge associated with the electrons and hence will be subjected to a force which is in the same sense as is the force F_1 . The intensity of the static magnetic field in the central plane can be adjusted to provide therein a cyclotron frequency of f_c for the ions together with a corresponding lower frequency electromagnetic field so that the ions can be directly accelerated.

From the above it will be seen that by providing a magnetic field having a first intensity in a transverse plane of the cavity corresponding to a field strength such that the cyclotron frequency of particles in that plane is equal to the frequency of the applied electromagnetic field and with the gradient of the magnetic field being such that the field strength on opposite sides of said plane is respectively greater and less than said first intensity, particles are continuously accelerated throughout the length of the cavity. As set forth above, the source of particles 4 can be any of a number well known in the art and adapted to apply a plasma to the cavity 1A. A neutral gas which ionizes at the interior of the cavity 1 in the presence of the intense electric field therein can also serve as the source of particles. In each case particles are ejected from the opening 3 with a velocity which is greater than the entrance velocity thereof. As a result of the increased velocity of the particles it will be seen that an oppositely directed reaction force will be applied to the walls of the cavity and hence a propulsion system is provided. It has been found that when the strength of the applied electromagnetic energy is in the order of 200 kilowatts a thrust in the order of .02 Newton is obtained.

Referring now to FIGURE 4 there is illustrated a system which includes two improved particle accelerators in combination with a suitable "magnetic bottle" to provide a high temperature fusion apparatus. The first plasma or particle accelerator will be seen to include a cavity resonator 11 having inlet and outlet openings 12 and 13 positioned in opposite ends thereof and located coaxially with respect to the central longitudinal axis of the cavity. A first plasma or particle source 14 is adapted to supply a first plasma 14a to the interior of the resonant cavity 11A by being connected with the entrance opening 12. The winding shown generally at 15 provides the required coaxial magnetic field along the central longitudinal axis of the cavity 11. A radio frequency supply 16 is coupled to the interior of the cavity 11 by the waveguide illustrated generally at 16A. For purpose of illustration a source of DC potential illustrated as a battery

17 will be seen to be connected through a variable impedance element to the winding 15.

The exit opening 13 of the first plasma accelerator will be seen to be directly communicating with the interior of a chamber 18A provided by the enclosure member 18 which is shown for purpose of illustration as having an elliptical cross section. The member 18 preferably communicates directly with the plasma source 14 with the section 18B thereof which is inside cavity 11A preferably being made of quartz or other suitable material which permits the passage of RF energy therethrough and also to permit evacuation of the system. The flux required for applying magnetic pressure to the particles introduced into the chamber 18A can be provided by a number of systems well known at the present time. For example pairs of straight conductors forming the sides of a right circular cylinder and referred to as a cusped arrangement having current passed in opposite directions through adjacent conductors will provide the required confining magnetic field. For purpose of illustration in FIGURE 4 an elongated generally cylindrical winding 19 which is suitably energized by a power supply (not shown) provides the requisite field commonly referred to in the art as a "magnetic bottle" or cylinder.

At the right end of the chamber 18 it will be seen that a second plasma accelerating apparatus substantially identical to the apparatus shown at the left end thereof is provided. This second accelerator includes: a second resonator 21 defining a cavity 21A having entrance and exit openings 22 and 23; a second plasma source 24 providing the plasma 24A; a second electromagnet 25; RF supply 26 coupled to the interior of cavity 21 by the waveguide 26A; and a second DC power supply 27. The cavities 11A and 21A are each one half wavelength long and resonant at the frequency of the RF sources 16 and 26 with the electromagnets 15 and 25 providing the fields previously described. The section 18C of the member 18 within cavity 21A is preferably quartz. The two particle accelerating systems will thus be seen to be oppositely directed for simultaneously applying accelerated particles to the interior of chamber 18A. As is well known in the art, the winding 19 serves to apply magnetic pressure to the moving charged particles but also the ends thereof act as magnetic mirrors to prevent the escape of charged particles from the chamber 18A. Further details of the apparatus for applying pressure to the charged particles introduced in the cavity 18A are not included herewith since any of a number of the various types of apparatus well known in the art are suitable for use in the system of FIGURE 4. It is of importance to note, however, that the ultimate temperature achieved in the fusion apparatus is increased as the entrance energy (or velocity) of the plasma particles is increased and therefore through the use of the two plasma accelerators a very high temperature can be achieved. Thus a simplified and effective high temperature apparatus is provided which is well suited for laboratory use. It is of course obvious that a single accelerator together with an appropriate magnetic pressure system can be provided.

Since the simplified particle accelerating apparatus of FIGURE 1 serves to continuously receive low energy particles and discharge the same at an increased velocity it has been found that the apparatus is suitable for use for evacuating an enclosed chamber such as for example a chamber having a gas therein. Thus in the embodiment of the invention illustrated in FIGURE 5 it will be seen that a container 39 defines an enclosed chamber 39A which is substantially spherical in shape and is coupled with the entrance opening 32 of a resonator 31 defining a cavity 31A. The exit opening 33 of the cavity is coupled by means of the enclosed conduit 39 with the intake port of a conventional evacuation pump 40 having a discharge opening 41. A magnetic field is provided parallel to the central longitudinal axis of the resonator 31 by the electromagnet 35 shown for purpose of illustration as being ener-

gized by a suitable battery 37. The magnetic field provided parallel to the central longitudinal axis of the resonator 31 exhibits the field gradient requirements set forth in connection with the embodiment of the invention illustrated in FIGURE 1. It will also be seen in FIGURE 5 that a source of RF energy 36 is coupled by means of the coaxial cable 36A which terminates at 36B in the interior of the RF cavity 31 so that an RF field will be established in the interior of the cavity 31. The length of the resonator 31 is preferably chosen to be equal to one half the wavelength of the RF signals applied to the interior thereof by the supply 36. The intensity of the magnetic field in the central transverse plane of the cavity 31 as established by the electromagnet 35 is such that the cyclotron frequency of the ionized gas particles in that plane is equal to the frequency of the signals provided by the radio frequency supply 36. As a result of the magnetic field gradient from left to right down the central longitudinal axis of the resonator 31 and the electromagnetic field inside the cavity 31A neutral gas particles entering the cavity opening 32 will be ionized and then continuously accelerated from left to right down the resonator 31. The pump 40 serves to initially create a low pressure to start the movement of the gas from the chamber 39A into the interior of the cavity 31A and then serves to continuously remove the particles discharged through opening 33. As a result of the operation of the apparatus in FIGURE 5 an extremely high vacuum is created within the chamber 39.

There has thus been disclosed an improved compact particle accelerator and systems having various uses including those of a propulsion system, an evacuation device, and as an apparatus for use in combination with a magnetic confinement system to provide a high temperature apparatus. Those modifications and changes which will be obvious to a person skilled in the art from the above description and accompanying drawings of illustrative embodiments are intended to be encompassed by the following claims.

What is claimed is:

1. A particle accelerating apparatus comprising in combination: means defining a radio frequency cavity having a particle entrance opening and a particle exit opening; signal input means adapted to apply electromagnetic signals of frequency f to said cavity to establish an electric field gradient ∇E between said openings wherein the gradient is positive in a first section and negative in a second section; and magnetic field means establishing a magnetic field in said cavity having an intensity gradient between said openings which maintains the ratio f_c/f greater than 1 where ∇E is positive and less than one where ∇E is negative with f_c being the cyclotron frequency established by said magnetic field for particles of mass m and charge e which are to be accelerated.

2. A particle accelerating apparatus in accordance with claim 1 wherein said cavity is of a length equal to an integral multiple of one half the wavelength of signals at said frequency f and wherein said magnetic field means provides a magnetic field of an intensity such that said ratio f_c/f is equal to one at a point between said openings in said cavity.

3. A particle accelerator comprising in combination: means defining a radio frequency cavity resonant at a frequency f and having first and second opposed openings therein adapted to permit particles to pass therethrough; means establishing a magnetic field in said cavity extending in a direction from said first to said second opening and having an intensity gradient between said openings and with the intensity of said field in a first region in said cavity establishing a cyclotron frequency of f_c which is equal to said frequency f for particles of mass m and charge e ; and means for applying electromagnetic signals of said frequency f to said cavity, the length of the cavity and said frequency f being such that an electric field is

established perpendicular to said direction and having a positive gradient in a first region of said cavity and a negative gradient in a second region of said cavity.

4. A particle accelerator in accordance with claim 3 wherein the length of said cavity is equal to one half the wavelength of said signals at said frequency f .

5. A particle accelerator in accordance with claim 3 wherein the intensity of said magnetic field in a second region between said first opening and said first region is greater than the intensity in said first region and the intensity of said magnetic field in a third region between said first region and said second opening is less than the intensity in said first region.

6. A particle accelerator in accordance with claim 5 wherein the length of said cavity is equal to one half the wavelength of signals at said frequency f .

7. A particle accelerating system comprising in combination: means defining a radio frequency cavity having first and second openings therein; means establishing a magnetic field extending in a first direction from said first opening to said second opening and having a gradient such that the intensity of said magnetic field is greater in said first opening than in said second opening and the intensity at a point intermediate said two openings establishes a cyclotron frequency f_c for particles of mass m and charge e ; means for applying electromagnetic signals at said frequency f_c to said cavity, the length of the cavity and said frequency f being such that an electric field is established perpendicular to said first direction and having a positive gradient in a first portion of the cavity and a negative gradient in a second portion of the cavity; and means for injecting particles of said mass m and charge e through said first opening into said cavity.

8. A particle accelerator in accordance with claim 7 wherein said cavity is of a length equal to one half the wavelength of said signals at frequency f_c and wherein said signals are applied to said cavity in a TE mode.

9. A particle accelerator in accordance with claim 7 wherein said last named means includes a plasma source, and conduit means coupling said source with said cavity and extending between said first and second openings.

10. A particle accelerator comprising in combination: a cavity resonator having a first opening for receiving particles to be accelerated and a second opening for discharging particles; means establishing a magnetic field in said resonator with the direction thereof extending between said openings, said magnetic field being of a first intensity in a first region within said resonator adjacent said first opening, of a second intensity less than said first intensity in a second region within said resonator, and of a third intensity less than said second intensity in a third region adjacent said second opening; and means establishing electromagnetic signals within said resonator with the electric field component thereof being transverse to a line extending between said openings and having a positive electric field gradient between said first and second regions and a negative field gradient between said second and third regions.

11. A particle accelerator in accordance with claim 10 wherein said second intensity is equal to B where B is proportional to $fm c/e$, where f =the frequency of said signals, m =the mass of a particle to be accelerated, c =the velocity of an electromagnetic wave in vacuum, and e =the electric charge of a particle to be accelerated.

12. A particle accelerator in accordance with claim 10 wherein said cavity resonator is resonant at a frequency f and wherein the length of said cavity resonator is equal to one half the wavelength of electromagnetic signals at said frequency f .

13. A particle accelerator in accordance with claim 11 wherein said cavity resonator is of a length equal to one half the wavelength of electromagnetic signals at said frequency f .

14. A particle accelerator in accordance with claim 10 wherein said magnetic field has a constant gradient between said openings.

15. A particle accelerator in accordance with claim 10 and including particle conduit means extending between said openings in said cavity composed of a material adapted to permit the passage of radio frequency energy through the walls thereof.

16. An evacuation system comprising in combination: means defining a radio frequency cavity having first and second openings at opposite ends thereof; means for applying electromagnetic signals to said cavity at a frequency f , the length of the cavity and said frequency f being such that an electric field is established perpendicular to a direction extending from said first to said second opening with the field having a positive gradient in a first portion of the cavity and a negative gradient in a second portion of the cavity; means establishing a magnetic field between said openings in said cavity with the intensity of said field decreasing with increasing distance from said first opening and of a magnitude at a point intermediate said two openings such that a cyclotron frequency equal to said f is established for particles of mass m and charge e ; means defining a chamber to be evacuated having an opening therein coupled with said first opening of said cavity; and pressure reduction means coupled with said second opening of said cavity.

17. A system in accordance with claim 16 wherein said cavity is of a length corresponding to one half the wavelength of a signal at said frequency f .

18. An apparatus for accelerating and confining charged particles comprising in combination: means defining a first radio frequency cavity having first and second aligned openings therein; a source of particles to be accelerated; means defining an enclosed chamber; conduit means extending from said source through said first and second openings and coupled with said chamber to permit passage of particles from said source through said cavity to said chamber; first magnetic field means disposed about said chamber adapted to provide a confining magnetic field therein; second magnetic field means adapted to provide a magnetic field extending between said openings having a first intensity at a point intermediate said openings to establish a cyclotron frequency of f for particles of mass m and charge e and further being of a second intensity greater than said first intensity adjacent said first opening and of a third intensity less than said first intensity adjacent said second opening; and means applying electromagnetic signals at said frequency f to said cavity, the length of the cavity and said frequency f being such that an electric field is established perpendicular to a direction extending from said first to said second opening with the field having a positive gradient in a first portion of the cavity and a negative gradient in a second portion of the cavity.

19. An apparatus in accordance with claim 17 wherein the length of said cavity is equal to one half the wavelength of signals at said frequency f .

References Cited

UNITED STATES PATENTS

2,817,045	12/1957	Goldstein et al.	315—39
3,151,259	12/1964	Gloersen et al.	313—63
3,179,838	4/1965	Adler	315—3
3,221,212	11/1965	Gorowitz et al.	313—231 X
3,257,579	6/1966	Delcroix et al.	313—63 X

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