April 17, 1962 J. S. LUCE 3,030,543

METHOD AND APPARATUS FOR TRAPPING IONS IN A MAGNETIC FIELD

Filed April 15, 1958 2 Sheets-Sheet 1

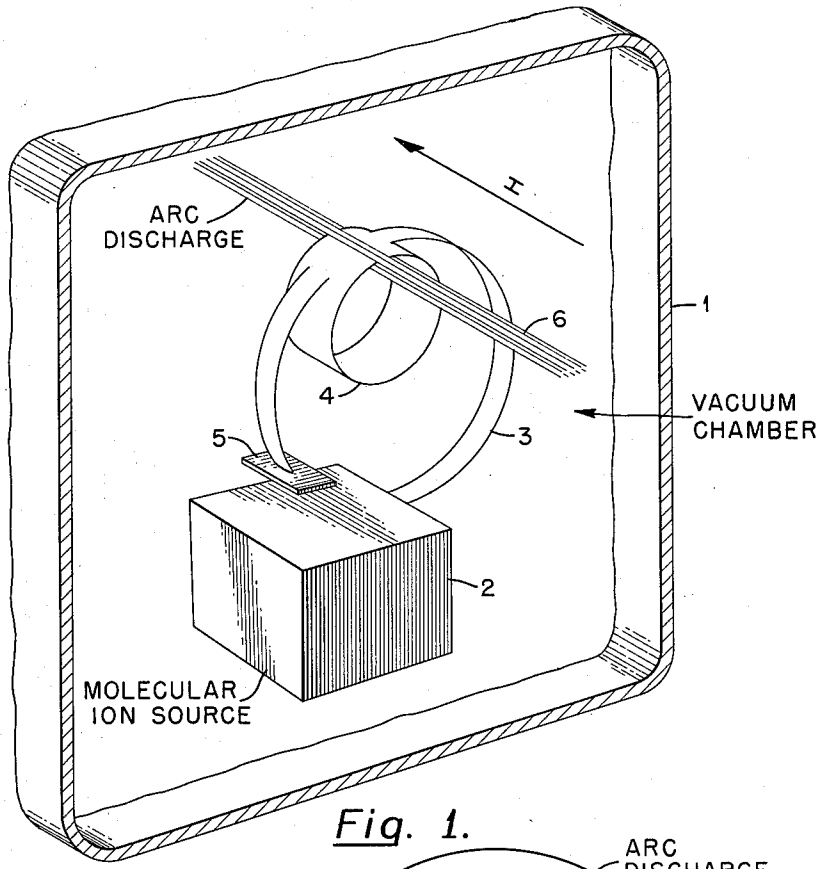


Fig. 1.

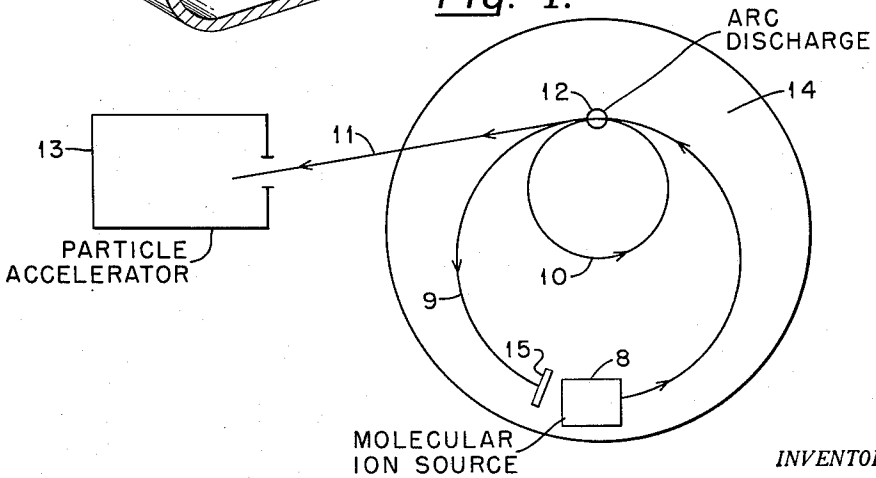


Fig. 2.

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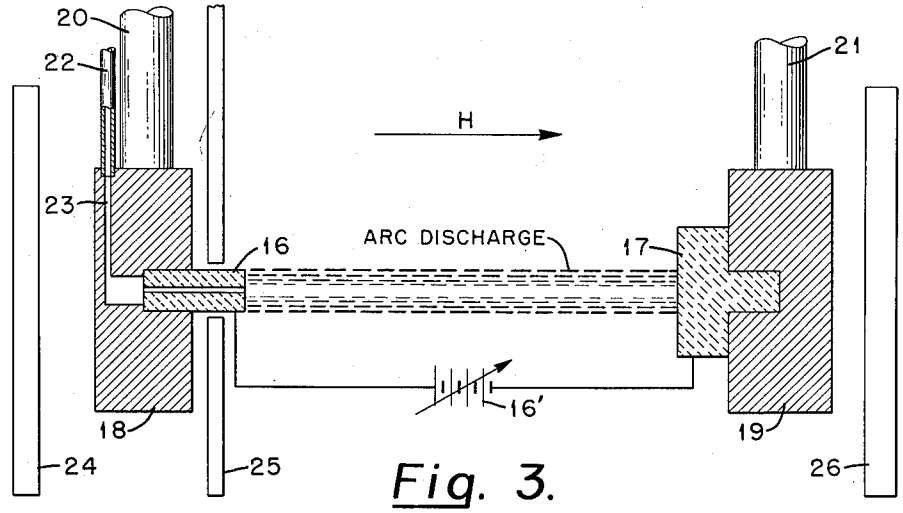


Fig. 3.

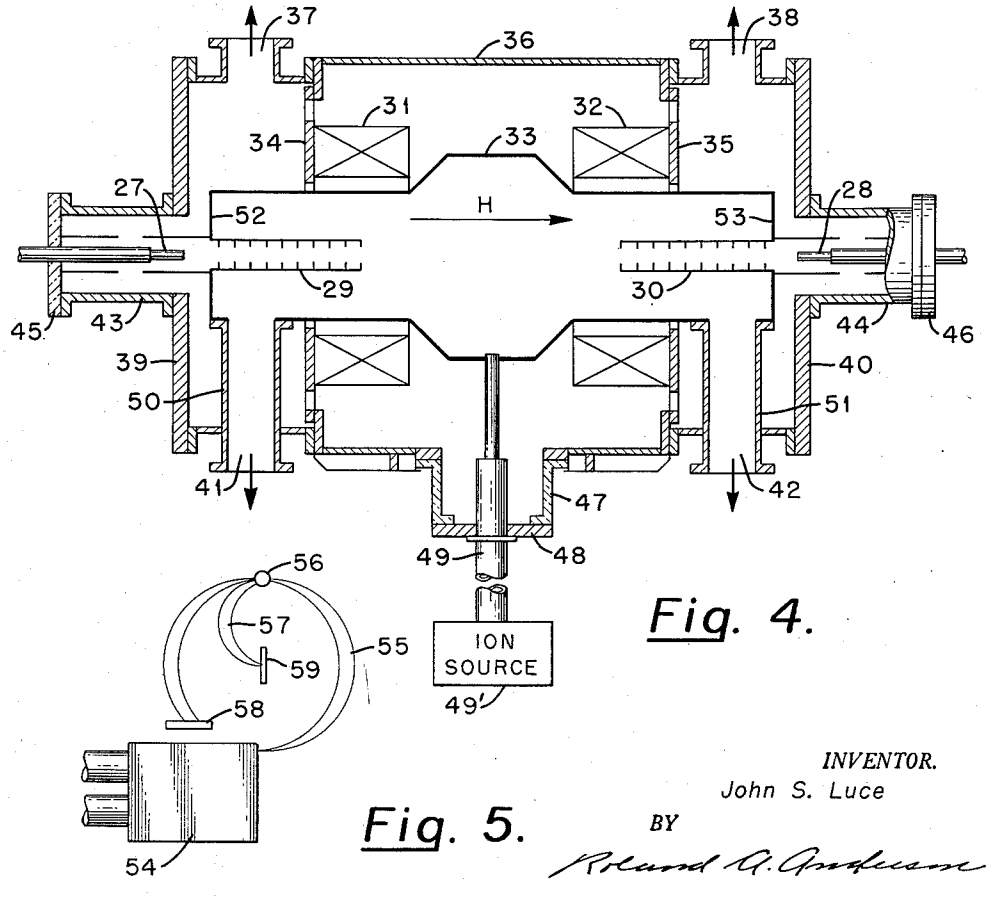


Fig. 4.

Fig. 5.

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METHOD AND APPARATUS FOR TRAPPING IONS IN A MAGNETIC FIELD

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7 Claims. (Cl. 313—161)

This invention relates to a novel method of and apparatus for trapping ions in a magnetic field utilizing dissociation and/or ionization of molecular ions and trapping the ions as a result of a change of charge-to-mass ratio, and especially to a method of forming a plasma by trapping ions.

It is known that the sun produces energy by thermonuclear reactions which proceed at exceedingly high temperatures. Most of these reactions and all of the proposed controlled thermonuclear reactions in the laboratory depend upon collisions between nuclei to liberate energy. It can be shown that extremely high temperatures must be reached to attain useful thermonuclear power, but at those temperatures the energy loss due to radiation is also great. Deuterium releases energy at a relatively low temperature and emits relatively little radiation and so it is a suitable thermonuclear fuel. Confinement of the fuel at such temperatures with present materials is not feasible, so that it has been proposed to confine the fuel in a leak-proof "magnetic bottle"—a strong magnetic field. The fuel must be ionized, injected into the field, confined within the field, and heated to thermonuclear temperatures.

Deuterium ions can be generated in mass spectrometer ion sources and in larger quantities in ion sources such as those used in the "calutron" or the electromagnetic mass separator developed for uranium isotope separation. A suitable high current source of ions up to 50 ma. may be provided by the apparatus set forth on page 18 of Nucleonics, volume 9(3), or by apparatus set forth on page 394 of Rev. Sci. Instr., vol. 24, (1953), or by that described by Von Ardenne, "Tabellen der Elektronenphysik, Ionenphysik and Ubermikroskopie," VEB Deutscher Verlag der Wissenschaften, Berlin, 1956 (Duo-Plasmatron). From such sources ions may be accelerated into a magnetic field by application of an accelerating potential to an electrode adjacent the source ion exit slit in the conventional manner. The "magnetic bottle" may comprise a cylindrical vacuum chamber inside a solenoid magnet coil so wound as to produce a longitudinal magnetic field with the greatest strength near the respective ends, the lines of force near the coil axis being gathered in at the ends in the form of a sausage, forming magnetic "mirrors" at the ends. Torroidal geometries for magnetic fields may also be employed.

If charged particles are accelerated into such a magnetic field at right angles thereto, they will be bent into a circular path by the field, traverse 360°, return to the point of entry and thus be lost by striking the walls or other structure. In order to "trap" particles within the field, various means for altering the ion trajectory by changing the magnetic field strength with time have been evolved. Continuous injection of ions cannot be achieved with this "pulsing" method, but only short bursts can be injected at a time.

The present inventor has discovered a novel method of and means for injecting and trapping a continuous ion beam within a magnetic field without pulsing the field. In accordance with this invention, molecular ions are generated in an ion source, formed into a beam and accelerated into a strong containing magnetic field at right angles thereto. At a point in the beam path before it

travels 360°, either on or off the axis of the magnetic field, the molecular ions are physically dissociated into atomic ions and atomic neutrals. The atomic ions, having a reduced mass-to-charge ratio, will assume a new, smaller-radius trajectory, will spiral in toward the axis of the field, and will continue to rotate in a tight ring in the center of the field. The neutrals will pass out of the discharge region unbent by the field, while the molecular ions will continue along their old path and be removed by striking a target or the source. The central region of the containing magnetic field will build up to a plasma of high-energy ions. With a suitable magnetic containing geometry, a high-density arc discharge serves to dissociate the ions and also furnishes electrons for the plasma. Other possibilities for dissociation include pinch discharges, R. F. energy, beams of neutrals, shock waves, ultraviolet radiation and electric fields.

It is, therefore, a primary object of this invention to provide an improved method of trapping atomic ions within a strong magnetic field.

Another principal object of this invention is to form a high temperature plasma by providing a circulating beam of ions inside a confining magnetic field.

A secondary object of this invention is to provide means for generating a beam of energetic neutral particles.

These and other objects and advantages of this invention will be apparent from a consideration of the following detailed specifications and the accompanying drawings wherein:

FIG. 1 is a schematic drawing illustrating trapping of ions in a magnetic field.

FIG. 2 is similar to FIG. 1 and shows in addition the paths of particles resulting from dissociation within the magnetic field.

FIG. 3 illustrates a device for producing a high intensity arc.

FIG. 4 is a schematic showing of an injection system with a containing magnetic geometry of the mirror type.

FIG. 5 is schematic showing of a device for measuring or collecting the dissociated ions.

In FIG. 1, reference numeral **1** designates in cross section the wall of a vacuum chamber which is provided with a containing magnetic field whose direction is designated by the arrow H. The magnetic field H may be provided by a pair of magnets (not shown) mounted externally of the vacuum chamber. A molecular ion source **2**, such as the ion source of a calutron or a mass spectrometer, is provided with an accelerating electrode to inject a molecular ion beam **3** into the evacuated chamber. The ion source is normally positioned outside of the vacuum chamber, but is shown on the inside of FIG. 1 for ease of illustration only. Due to the presence of the magnetic field H, the beam follows a curved trajectory. A high intensity arc discharge **6** is established parallel to the magnetic field H by electrodes, not shown. The beam **3** is arranged to pass through the discharge **6** in a plane normal thereto. The intense arc discharge dissociates and/or ionizes the molecular ions in beam **3** into atomic ions and neutrals by the collisions and the portion of the molecular ions that are not dissociated and ionized will continue in their circular path until they reach a collector **5** or the source **2**. The atomic ions which were dissociated from the molecular ions will have a Larmor radius smaller than that of the original molecular ions since their mass-to-charge ratio is reduced and will be formed into a ring-like beam **4**.

In operation, the simplest case to consider is D_2^+ particle. Referring to the drawing, the beam **3** could be D_2^+ particles injected by the source **2** and, due to the presence of the magnetic field, follows a curved trajectory. The D_2^+ particle may collide with another particle or an elec-

tron from the arc discharge resulting in the formation of atomic particles according to the equations:

$$D_2^+ \rightarrow D^+ + D^0$$

or

$$D_2^+ \rightarrow D^+ + D^+ + e$$

The resultant atomic particles (D^+), having a mass and energy one-half that of the D_2^+ particle, describe a circle, which is indicated by the beam 4, with a radius one-half that of the D_2^+ particle. Should H_3^+ particles be employed instead of the D_2^+ particles, the resultant radius of the atomic particles would be one-third that of the original molecular ion radius.

In addition to its primary use for trapping ions, my invention is useful in that it provides a means of generating a beam of energetic neutrals. Many of the collisions cause dissociation without ionization:

$$D_2^+ \rightarrow D^+ + D^0$$

or

$$H_3^+ \rightarrow H^+ + H_2^0$$

Under these conditions the energetic neutrals are free to move across the magnetic field until an ionizing collision occurs. In the case of H_3^+ there are probably more neutrals than ions. These energetic neutrals may be useful in a particle accelerator as shown in FIG. 2, wherein reference numeral 8 designates a source of molecular ions which are ejected as a beam 9 in the evacuated space 14 in the presence of a uniform magnetic field which is normal to the face of the drawing. When this beam 9 passes through an arc discharge 12, which is also normal to the face of the drawing, the molecular ion beam dissociates and the atomic ions are trapped in the magnetic field and form a beam 10. The portion of the molecular ions that do not dissociate continue to travel in the same trajectory and will reach the collector 15 where they are absorbed. Some energetic neutrals are created in the arc discharge and will travel in a straight line beam 11. These energetic neutrals may be used in a particle accelerator 13, injected into a controlled thermonuclear device, or utilized in any other device in which a source of energetic neutrals are required, as in studying the effects of various neutrals on different materials.

Referring now to FIG. 3, there is shown one device for obtaining a high intensity carbon arc. In FIG. 3, carbon cathode 16 is mounted in a water cooled jacket 18 which is supplied with cooling water through conduit 20. Carbon anode 17 is mounted in a water cooled bracket 19 which is fed cooling water by a conduit 21. Cathode 16 is provided with electrical insulating shields 24, 25 and anode 17 is provided with an insulating shield 26. Hollow cathode 16 is connected by a conduit 23 to a tube 22 which is connected to a source of gas supply. The structure of FIG. 3 is enclosed in a vacuum chamber, such as chamber 1 of FIG. 1, and a pair of magnets, not shown, are provided, one adjacent each of the shields 24 and 26 to provide a containing magnetic field whose direction is represented by the arrow H. One of the magnets is located just to the left of shield 24, and the other magnet is located just to the right of shield 26. The anode and cathode are connected by a variable source of supply 16' which is used to help initiate and maintain an arc discharge and to vary the intensity of the arc. Gas is fed through the tube 22, conduit 23 to the hollow cathode 16. When a voltage is applied across the anode and cathode an arc is struck, after which the gas feed to the cathode is stopped. There are various means for helping to initiate an arc other than the use of a gas fed cathode. Such other means include heating the cathode and anode electrodes to outgas said electrodes, providing a movable auxiliary electrode adjacent the cathode and applying a R.F. voltage across said auxiliary electrode and cathode until an arc is struck and then removing said auxiliary electrode, and by making the position of the anode adjustable with respect to the cathode until an arc is struck and then varying the relative position of the anode and cathode to a desired operating position.

Referring now to FIG. 4, a device is shown in which high energy ions are injected into a chamber normal to a containing magnetic field and high intensity arc, for forming a plasma by trapping ions. The device of FIG. 4 comprises an outer cylindrical shell 36 with joining end walls 39 and 40. End wall 39 has a circular opening to which a tubular member 43 is affixed. Member 43 has an end closure member 45 in which the cathode 27 is fixedly mounted. End wall 40 has a circular opening to which is affixed a tubular member 44. Member 44 has an end closure 46 in which the anode 28 is fixedly mounted. Outer shell 36 is provided with a circular opening to which is attached a tubular member 47 which in turn has affixed thereto an end closure member 48. Fixedly mounted in said member 48 is a member 49 through which ions are injected from an external ion source 49' and then through an opening in liner 33 and into the path of the arc formed between the anode and cathode electrodes. The arc formed between said electrodes is substantially enclosed in an inner chamber formed by liner 33 and end walls 52, 53. The walls 52 and 53 have circular openings in axial alignment with the anode and cathode. Surrounding the cathode 27 and anode 28 are suitable tubular baffles 29 and 30, respectively, which extend through the openings in said walls 52 and 53, respectively. Liner 33 has a pair of circular openings in alignment with a pair of circular openings in outer shell 36. The aligned openings are joined by insulating bushings 50 and 51, respectively. The inner chamber, formed by liner 33 and walls 52, 53, is connected to a vacuum through openings 41 and 42 of bushings 50 and 51, respectively. Outer shell 36 also has a pair of additional openings 37 and 38 connected to a vacuum, said openings being connected to an outer chamber located between the shell 36 and inner liner 33. A circular magnetic mirror coil 31 is disposed around the outside of inner liner 33 between the ion source tube 49 and bushing 50, and is mounted on a perforated member 34. Another circular magnetic mirror coil 32 is disposed around the outside of inner liner 33 between ion source tube 49 and bushing 51, and is mounted on a perforated member 35.

In operation of the device set forth in FIG. 4, a high intensity arc discharge is initiated between the cathode and anode electrodes by means such as set forth in the operation of FIG. 3 above. The inside and outside chambers are evacuated and for a suitable operation of the system the pressure of the inside chamber is maintained at approximately 10^{-7} mm. Hg, while the outside chamber pressure is maintained at approximately 10^{-6} mm. Hg, for example. The mirror coils 31 and 32 have an inside diameter of 17 inches and a spacing between the inner faces of the coils of 18½ inches. With these dimensions, a cylinder can be inscribed whose rims just touch the inner edge of the coils and the volume of such a cylinder is then equal to 6.9×10^4 cm.^{3}. The plasma which is formed by dissociation of the high current ions as they pass through the high intensity arc is confined and trapped within the said inscribed volume by the magnetic field H. The gas used for the ion source input is deuterium and the injection voltage is approximately 300 kev. A suitable high current source of ions may be provided by apparatus such as set forth in any of the devices set forth in the aforementioned publications. Dissociation of the molecular ion beam is not limited to that effected by the arc discharge. There are other possibilities for dissociation, as set forth above. The device of FIG. 4 will produce a trapped beam of atomic ions, and a beam of energetic neutrals, in the same manner as set forth in the operation of FIG. 2 above. The molecular ions that are not dissociated will return and be lost or collected at the source of these ions. The

neutral beam will pass out of the system and can be used for the same purpose as the neutral beam of FIG. 2.

Referring now to FIG. 5, the system of FIG. 1 is shown as adapted to a device for collecting or measuring the current of dissociated ions. Ion source **54** injects a stream of molecular ions **55** into a containing magnetic field normal to the drawing. The stream of ions **55** pass through arc discharge **56** where a portion of the molecular ions are dissociated and ionized and form a beam **57** of atomic ions which are collected by a collector **59**. The molecular ions which were not dissociated continue in their same path and are collected by a collector **58**.

In describing my invention, I have referred primarily to deuterium. A better radius-ratio of the trapped atomic ions to the molecular ions is achieved with HOH^+, CH_4^+ and other complex molecules than when D_2^+ is used, however. D^+ resulting from dissociation of CD_4, for example, would have a radius only 10 percent of the molecular radius of CD_4.

In addition to its primary usefulness in the forming of a plasma and for generating a beam of energetic neutrals, the present invention also finds utility in creation of a circulating beam of ions as an experimental tool for research purposes.

This invention has been described by way of illustration rather than limitation and it should be apparent that the invention is equally applicable in fields other than those described.

What is claimed is:

1. In the method of establishing an energetic carbon arc discharge between widely spaced electrodes axially oriented within the central zone of a container evacuated to a selected pressure and permeated by a containing magnetic field parallel to the axis of said electrodes, the improvement comprising the method of utilizing said discharge to establish within said central zone a body of trapped atomic ions comprising the steps of: generating molecular ions outside said zone, accelerating said molecular ions into said field in a direction normal thereto such that said molecular ions follow a curved path toward said discharge and said zone, said discharge dissociating and ionizing said molecular ions after less than 360 degrees of travel in said path into atomic ions and atomic neutrals, removing said atomic neutrals from the region of said discharage in a straight line path tangent to said curved path, and trapping said atomic ions within said magnetic field, whereby said atomic ions move into said central zone from the points of dissociation.

2. The method set forth in claim 1, wherein said molecular ions are deuterium.

3. In the method of establishing an energetic carbon arc discharge between widely spaced electrodes axially oriented within the central zone of a container evacuated to a selected pressure and permeated by a containing magnetic field parallel to the axis of said electrodes, the improvement comprising the method of utilizing said discharge to generate a beam of energetic neutrals comprising the steps of: generating molecular ions outside said zone, accelerating said ions into said field in a direction normal thereto such that said molecular ions follow a curved path toward said discharge and said zone, said discharge dissociating and ionizing said molecular ions after less than 360 degrees of travel in said path into atomic ions and atomic neutrals, and removing said atomic neutrals in a straight line path tangent to said curved path from the points of dissociation.

4. In a container which is evacuated to a selected pressure, which is permeated by a containing magnetic field oriented in a selected direction, and in which an energetic carbon arc discharge has been established between widely spaced electrodes, the discharge being parallel to the direction of said magnetic field, the improvement comprising means for generating and injecting a plurality of energetic, molecular ions in the form of a beam into said field in a direction normal to said field, said beam of molecular ions having a circular trajectory within said field and being directed into the path of said arc discharge, said discharge dissociating and ionizing said molecular beam into atomic ions and atomic neutrals, said atomic ions being trapped by said magnetic field in a circular trajectory smaller than the trajectory of said molecular ions, and said atomic neutrals being ejected in a straight line beam from the point of dissociation.

5. The improvement set forth in claim 4, wherein there is provided beam utilization means disposed in the path of said beam of neutrals.

6. The improvement set forth in claim 4, wherein said molecular ions are deuterium.

7. A magnetic mirror device for trapping a plasma of atomic ions and creating a beam of atomic neutrals comprising a container, said container including an inner chamber and an outer chamber, means for evacuating said chambers to selected pressures, means for establishing a containing magnetic field oriented in a predetermined direction within said inner chamber, said last named means including magnetic mirror coils which provide magnetic mirror fields with a uniform field between said mirror fields, means for establishing an elongated, high intensity, carbon arc discharge within said inner chamber, said discharge having a path parallel to the direction of said magnetic field, means for generating and injecting a plurality of energetic molecular ions in the form of a beam into said uniform field in a direction normal thereto and into the path of said discharge, said discharge dissociating and ionizing said beam into atomic ions and atomic neutrals, said atomic neutrals being ejected in a straight line beam from the point of dissociation, and said atomic ions being trapped by said magnetic field in a circular trajectory smaller than the trajectory of the molecular ions.

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