Aug. 9, 1966 W. R. BAKER ET AL 3,265,583

APPARATUS FOR PRODUCING AND PURIFYING PLASMA

Filed April 14, 1964 2 Sheets-Sheet 1

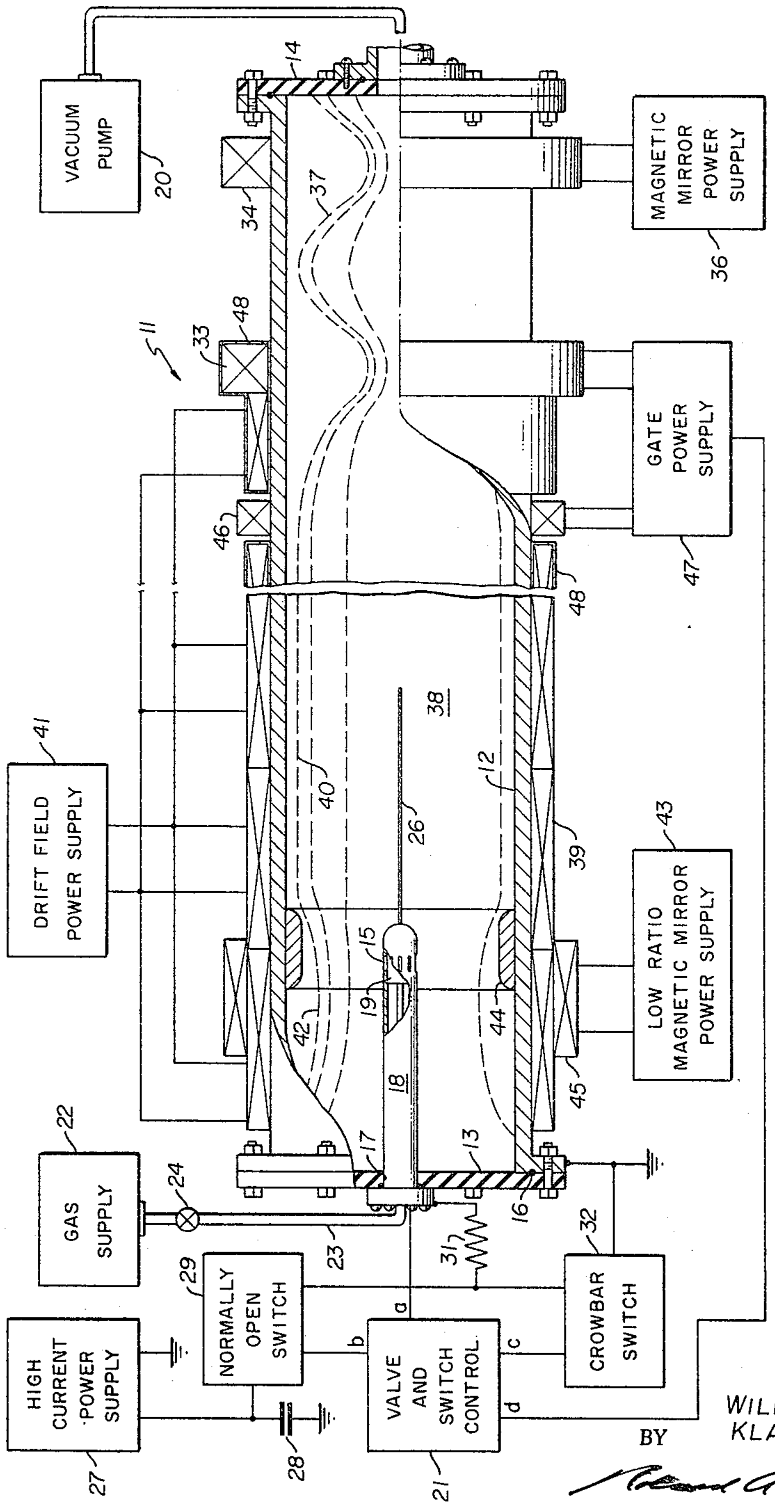

Fig. 1.

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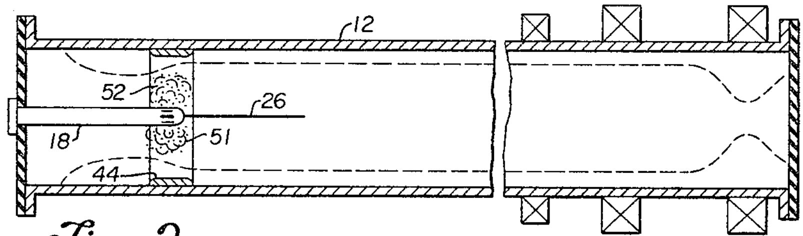


Fig. 2.

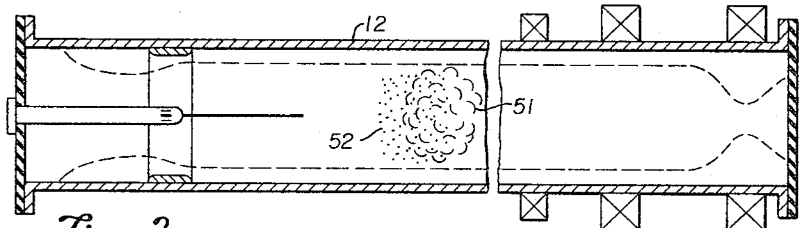


Fig. 3.

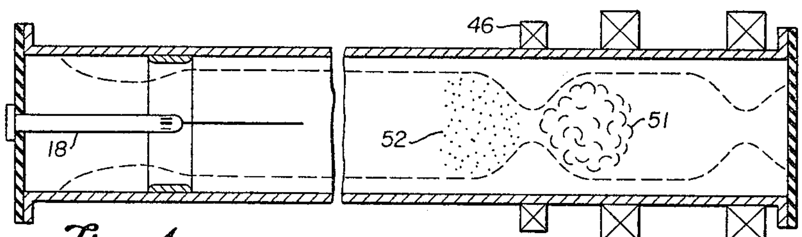


Fig. 4.

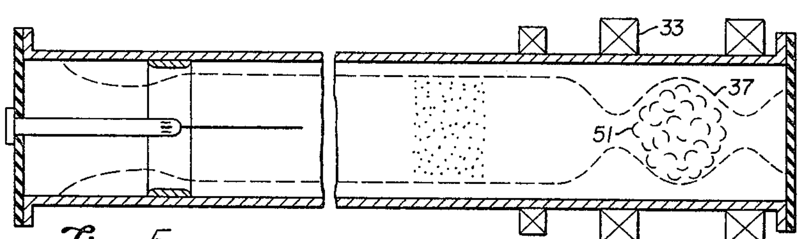
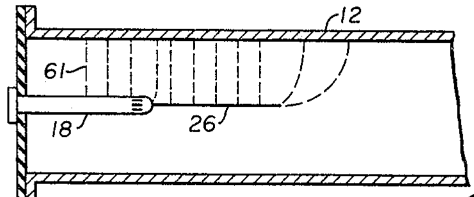


Fig. 5.

Fig. 6.



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APPARATUS FOR PRODUCING AND PURIFYING PLASMA

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The present invention relates generally to magnetohydrodynamic plasma devices and more particularly to a device for generating, containing and heating an ion-electron plasma of high purity.

The maximum degree of heating, and consequently the number of nuclear reactions, that may be obtained in a plasma heating device is severely limited if even small quantities of impurities are present. Thus, various devices have been developed in which the generation and maintenance of more pure plasma has been a major objective, the apparatus described in U.S. Patent No. 3,104,345 and in copending U.S. Application Serial No. 177,140 filed March 2, 1962 by William R. Baker, now Patent 3,156,623, dated November 10, 1964, being examples.

Most impurities enter a plasma during the formation of the plasma and immediately after the plasma is produced as at such times the plasma is proximal to various electrodes associated with producing the plasma. The energetic plasma particles bombard the electrodes and release impurities therefrom.

The prior devices intended to produce pure plasma control only the initial conditions under which the plasma is produced. The present invention also provides control over the initial conditions, but in addition provides a means for removing impurities which enter a plasma soon after it is produced but before it has left the vicinity of the electrodes so that higher degree of final plasma purity is obtainable.

In the present invention, the plasma is produced between a conductive cylinder and a short axial electrode disposed at one end thereof. An axially directed magnetic field and a radially directed electric field are provided between the electrode and the cylinder and the combined fields cause charged particles to rotate around the center electrode in cycloidal orbits. Considering now the means by which initial purity is maximized, it will be observed that for each particular ratio of magnetic to electric field, the size of the orbit of every charged particle of a given mass will be equal. Heavier particles have orbits with a larger radius than the orbits of lighter particles. Plasmas are generally comprised of very light elements such as isotopes of hydrogen, for instance. Therefore, if the spacing between the electrode and the encircling cylinder is slightly larger than the orbital radius of the heaviest desired particle in the plasma, all heavier particles, which are considered to be impurities, will strike the encircling cylinder and thus be removed from the plasma.

The purity of the plasma is further maintained by control of still another condition. The electrode projects a short distance into one end of the tube. The portions of the electric field lines near the tip of the axial electrode are parallel with the magnetic field lines, thus permitting plasma particles to accelerate along the electric field lines without restraint by the magnetic field. In previous apparatus such particles strike the electrode and release contaminants into the plasma. In the present invention, the above process is minimized by eliminating the electric field when the plasma is adjacent the tip of the axial electrode, this being effected by use of a novel axial electrode configuration and by control of the electric field power supply.

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The initial purity of the plasma is relatively high owing to the means described above. However, in spite of such means, some impurities subsequently enter the plasma as a result of electrode bombardment. Such impurities are removed from the plasma in the present invention by producing the plasma at one end of the long conductive cylinder and then drifting the plasma in a cluster or cloud toward the final containment and heating region at the opposite end of the tube. The energy imparted to the plasma particles during plasma creation is generally much higher than that of the subsequent contamination particles. Therefore, as the plasma progresses along the tube, the contaminating particles tend to lag behind the plasma cloud and are separated therefrom. After separation, a magnetic barrier field is rapidly produced between the plasma cloud and the impurities to prevent the impurities from following the plasma into the plasma containment magnetic field.

It is an object of the present invention to provide a more efficient means for producing and maintaining a highly pure plasma.

It is an object of the invention to provide a magnetohydrodynamic device characterized by intense plasma heating whereby a greater rate of nuclear interactions may be obtained.

It is an object of the invention to provide means for avoiding contamination during the generation of a plasma.

It is another object of the invention to provide a means for separating out plasma contaminants prior to injection of the plasma into a trapping region.

It is another object of the present invention to provide a means for controlling the electric field configuration adjacent the electrodes of a plasma generator so that the production of contaminants is minimized.

It is another object of the present invention to produce a purified plasma by providing a suitable combination of electric and magnetic fields between a spaced pair of electrodes so that orbiting plasma particles may pass therebetween while heavy impurity particles which have a larger orbital radius are removed from the plasma.

It is another object of the present invention to provide a means for removing impurities from a plasma by utilizing differences in the drift times between two distant points for the plasma and the impurities.

The invention will be better understood by reference to the following specification together with the accompanying drawings of which:

FIGURE 1 is a broken-out view taken at right angles to the axis of a magnetohydrodynamic device embodying the present invention,

FIGURES 2 to 5 are simplified views of the invention showing the position of the plasma during progressive stages of the operation, and

FIGURE 6 is a simplified view of the plasma generating electrodes in the invention with an indication of the electric field configuration therebetween.

Referring now to FIGURE 1, there is shown a plasma device **11** which is formed in part by a long, electrically conductive cylindrical tube **12** with a length at least ten times greater than the diameter. The ends of the tube **12** are closed by insulative discs **13** and **14**, which are bolted and sealed, for example, by O-rings **16** so that all gasses can be evacuated from the tube **12**. Gasses are removed by a vacuum pump **20** communicated to the interior of the tube **12** through the disc **14**. The opposite disc **13** is provided with a central aperture **17** through which an axial electrode **18** extends for a short distance into the tube **12** along the axis of the tube. A plurality of openings **15** are distributed around the circumference of the axal electrode **18** near the inner end thereof and a rapidly opening gas valve **19** is disposed within the electrode 18 to control the release of gas from the openings. Thus gas released by the valve 19 may readily diffuse into the space within the tube 12 through openings 15. The rapidly opening valve 19 releases a measured quantity of gas in a sudden burst or puff in response to an electrical control signal, the valve being of the quick opening type described in U.S. Patents, 3,021,272 or 3,096,269. In the present invention, each valve control signal is provided by a central valve and switch control 21. A gas such as deuterium or tritium is provided from a gas supply 22 through a gas line 23 to the valve 19. A conventional shutoff gas valve 24 is also generally included in the gas line 23.

A conductive rod-shaped electric field shaping element 26 is affixed to the inner end of the axial electrode 18 and projects therefrom along the axis of the tube 12 toward the insulative disc 14. The end of the element 26 is rounded to avoid field emission and the diameter of the element is approximately ten percent of the electrode 18 diameter. The length of the field shaping element 26 and the axial electrode 18 combined is generally less than ten percent of the total length of the tube 12. Because of the small diameter of the element 26, many charged particles which are accelerated toward the element by the electrical field will miss it, thus avoiding release of impurities therefrom. The function of the element 26 in controlling the electric field is further discussed hereinafter.

To form a plasma, an axially directed magnetic field and a radial electric field are established between the electrode 18 and the tube 12 to effect the ionization of the gas released by valve 19. Power for producing the electric field is provided by a conventional high voltage and current power supply 27, shown in block form. Since power supplies generally have a high output impedance, a sudden large surge of current cannot be produced as is required for the present invention. Therefore, the high voltage supply 27 is used to charge a capacitor bank 28 over a relatively long time period. After being charged, the capacitor bank 28 is suddenly discharged by closing a normally open switch 29, usually an ignitron which, when closed, connects one side of the capacitor bank 28 to the axial electrode 18 through a low ohmage damping resistor 31, the purpose of which will be discussed later in detail. The tube 12 is grounded as is the opposite side of capacitor bank 28.

After burn out, defined as complete ionization of the gas in the tube 12, the electric field is removed as rapidly as possible by closing a normally open crowbar switch 32 connected from ground to the juncture of the damping resistor 31 and the normally open switch 29. The timing of the closing of crowbar switch 32 provides for complete removal of the electric field before the plasma passes the end of the field shaping element 26. The crowbar switch 32, also generally an ignitron, thus provides a short circuit across the capacitor bank 28, but oscillatory current reversal in the power circuitry is prevented by the critical damping resistor 31. Such resistor 31 generally will have a resistance of less than one ohm, the value being found by taking twice the square root of the net circuit inductance divided by the total capacitance of capacitor 28.

(Resistance of resistor 31

$$=2\sqrt{\text{net circuit inductance/capacitance of bank 28}})$$

There are three main sections of the magnetic field in tube 12, a first being a magnetic mirror field 37 for containing and heating the purified plasma. Such field is produced by a pair of annular spaced apart field coils 33 and 34 disposed coaxially around the tube 12 at the end opposite the axial electrode 18. A magnetic mirror power supply 36 provides electrical power to the coil 34. The coil 33 is energized by a gate power supply 47 in the same phase as coil 34 so that a conventional magnetic mirror field is created within the tube 12 shaped as indicated by dashed lines 37.

A second magnetic field 38 is provided by a plurality of drift field coils 39 disposed coaxially along nearly the entire length of the tube 12 except for the end portion where the magnetic mirror coils 33 and 34 are disposed. A drift field power supply 41 provides excitation for the coils 39 to form an axially directed magnetic field 40 within the control region of tube 12 essentially as indicated by dashed lines. As part of the drift field 40, a low ratio magnetic mirror 42 from a low ratio mirror coil 45 is provided at the region of the gas openings 15 near the end of axial electrode 18. When energized from a power supply 43 the resultant mirror field 42 is five to ten percent more intense than the remainder of the drift field 40. The purpose of such low ratio mirror 42 is to impel the plasma toward the magnetic mirror containment field 37. The drift field 40 guides the plasma from the region of the axial electrode 18 toward the containment field 37. While the low ratio mirror supply 43 is indicated as having a steady state output current, it is equally feasible as a variation to operate supply 43 in a pulse mode controlled by a signal from control 21.

To aid in maintaining plasma purity, a spacer ring 44 is disposed coaxially against the inside wall of the tube 12 around the gas opening 15 so that such inside wall, with the spacer ring, conforms approximately to the shape of the low ratio mirror 42. The ring 44 prevents plasma from reaching the outermost magnetic flux of the low ratio mirror 42 which flux intersects the wall of the tube 12 at the start of the drift field 38 region. Thus such plasma cannot subsequently release impurities by striking the tube 12 wall. Such spacer ring 44 also determines the size of the gap within which the plasma is produced. As previously discussed, impurities are heavier than the plasma particles, and have a larger orbit around the center electrode 18 than the plasma particles. Owing to the size of the gap, only the lighter plasma particles can orbit without striking the spacer ring 44. Thus the heavy impurities are removed.

A third magnetic field is provided in a pulsed manner to aid in separating the purified plasma from impurities. An annular gate coil 46, disposed around the tube 12 near the plasma entrance end of the magnetic containment field 37, is connected to the gate power supply 47 which provides a pulse of current to the coil. The gate coil 46 has relatively low inductance compared to the mirror field coil 33 so that a magnetic field is very rapidly created in the gate coil 46 while the magnetic field of coil 33 builds up much more slowly. The time at which the gate power supply 47 is actuated is related to the opening of the fast gas valve 19 by an appropriately delayed signal from the valve and switch control 21 such that high purity plasma is trapped in the mirror containment field region 37 and later arriving impurities are rejected by buildup of the intervening pulsed field of coil 46. Since, in moving along tube 12, the impurity particles lag behind the plasma, gate supply 47 is pulsed on after the plasma passes the region encircled by the gate coil 46, but before the impurities have arrived at such region. The gate magnetic field of coil 46 reflects the late arriving impurities back toward the region of the axial electrode 13 while the purified plasma passes on into the containment mirror field 37. Thus the gate coil 46 provides a pulsed magnetic field which rapidly rises and decays. However, during the gate pulse the mirror field of the coil 33 has time to build up and take over the function of containing the plasma.

It is possible to combine the functions of the gate coil 46 and the mirror coil 33 into that of a single coil if such single coil and the associated power supply are adapted to provide a magnetic field which is very rapidly pulsed on and remains on. However the use of both the gate coil 46 and the field coil 33 significantly lowers the cost of construction.

The presence of a rapidly pulsed gate field from coil **46** requires that the adjacent containment field coil **33** and nearby drift field coils **39** each be shielded by an outer conductive cover **48** formed of a material such as copper sheet. Such covers **48** prevent a rapidly expanding pulsed magnetic field from the gate coil **46** from inducing unduly high and possibly damaging currents in the adjacent coils **33** and **39**. A rapidly changing magnetic field cannot penetrate through the copper shields **48**, but the more slowly changing magnetic fields of the field coil **33** and the steady state fields from the drift coils **39** are not affected appreciably by such shields. The shields **48** must each be discontinuous so as not to constitute a shorted turn.

Considering now the operation of the invention, assume first that the containment magnetic mirror coil **34**, the drift magnetic coils **39**, and the low ratio magnetic mirror coil **45** are all actuated. The gate power supply **47** is not initially energized. The switch control **21** provides an "*a*" output signal to open the valve **19** and release gas through the apertures **15** of axial electrode **18**. It is necessary that the gas not be allowed to diffuse along any substantial portion of the tube **12**, but rather that the gas be ionized immediately so that a well defined body of plasma is created. Thus the switch **29** is closed by a "*b*" signal from the switch control **21** nearly simultaneously with the release of gas from the valve **19** so that an electric field is already established between the axial electrode and the tube **12** by the time the gas has diffused sufficiently that a discharge can form. The gas, therefore, can function as its own switch by diffusing out to the wall of tube **12** and providing a current path between the tube **12** and electrode **18**. Utilizing such effect, switch **29** may be eliminated in some instances.

Referring now to FIGURE 2 in conjunction with FIGURE 1, there is shown a simplified diagrammatic view of salient elements of the invention in which the initial configuration of the plasma cloud is shown. The plasma **51** in FIGURE 2 and the subsequent FIGURES 3 to 5 is indicated by short curved lines while impurities **52** are indicated by dots. The plasma **51** is created between the axial electrode **18** and the tube **12** and, as described previously, impurities are filtered out by the orbital spacing between the ring **44** and axial electrode **18**. The low ratio magnetic mirror **42** causes plasma **51** and the impurities **52** to drift toward the opposite end of the tube **12** owing to the well known repulsive force exerted by a magnetic mirror. As soon as burn-out (complete ionization) occurs and before the plasma **51** has reached the end of the field shaping element **26**, the "crowbar" switch **32** (FIGURE 1) is closed to remove the electric field as previously described. Such prompt removal of the electric field prevents, to some extent, charged particles from being accelerated at the field element **26** and releasing impurities therefrom.

Referring now to FIGURE 3 in conjunction with FIGURE 1, the plasma cloud **51** then progresses along the tube **22** beyond the axial electrode **18**, the plasma being guided by the magnetic drift field **38** previously described. During this movement along tube **12** the plasma impurities **52** tend to lag behind the plasma cloud **51**.

Referring now to FIGURE 4 in conjunction with FIGURE 1, the plasma cloud **51** subsequently passes through the gate coil **46**, which is then energized as controlled by a signal "*d*" from valve and switch control **21** so that the impurities **52** are prevented from following the plasma cloud **51** and are accelerated back toward the axial electrode **18**. The containment function is subsequently assumed by the mirror field from the field coil **33**, as shown in FIGURE 5. After the plasma **51** is in the containment field **37**, various further heating means, well known in the art, may be employed to cause nuclear interactions such as fusion of the plasma particles for example.

Referring now to FIGURE 6, the configuration of electric field **61** between the field shaking element **26** of electrode **18** and the tube **12** is shown to clarify the action of element **26** with respect to preventing impingement of plasma particles on electrode **18**. The electric field **61** extends radially between the tube **12** and the element **26**, therefore the electric field is transverse to the axial magnetic field in tube **12**. Without the field element **26**, the electric field in the region near the end of the axial element **18** would tend to be parallel to the magnetic field lines, since field lines emerge from a surface at a right angle. The disadvantage of having the electric field directed parallel to the magnetic field is that charged particles can accelerate along the electric field lines without restraint by the magnetic field. Accelerated particles would thus strike the end of the electrode **18** and impurities would be released into the plasma. However, with the field element **26**, the axial component in the electric field is largely avoided. Before the plasma body reaches the free end of the element **26**, the electric field has been removed by the closing of the "crowbar" switch **32**, thus the electric field at the end of the element **26** does not exist when the plasma body is adjacent thereto. If the element **26** were not provided, the plasma would be within a zone having parallel electric and magnetic field lines before the "crowbar" switch **32** could function. The small diameter of the element **26** causes the particles which are accelerated toward the element to miss it, thus avoiding release of impurities.

Accordingly, means are employed in the present invention to avoid contamination of the plasma at the time it is formed with further means being provided to remove impurities which unavoidably get into the plasma after it is formed and before it can be removed from the vicinity of the electrodes. The resultant plasma is thus relatively quite free of impurities and therefore may be heated to higher temperature.

While the invention has been disclosed with respect to a particular embodiment, it will be apparent to those skilled in the art that numerous variations and modifications may be made within the spirit and scope of the invention and it is not intended to limit the invention except as defined in the following claims.

What is claimed is:

1. In apparatus for producing and containing a very pure magnetohydrodynamic plasma, the combination comprising a pair of spaced apart coaxial field coils producing a first magnetic field having a plasma containment configuration, said first field being symmetrical about a linear axis, a pair of spaced apart electrodes disposed in proximity to said axis at a position remote from said first magnetic field whereby a plasma drift space is provided therebetween, means for maintaining a vacuum in the region of said first field and said electrodes and the drift space therebetween, means providing a second magnetic field in the region of said electrodes and said drift space, said second field being directed substantially parallel to said axis and being of greatest intensity in the region of said electrodes, means for admitting gas to the region between said electrodes, an electrical power supply connected across said electrodes, a third magnetic field generating means situated between said first field and said drift space, and a pulsed power supply coupled to said third field means to energize said third field means after said plasma has passed therethrough and prior to the arrival of trailing impurities thereat.

2. Apparatus for producing and containing a very pure magnetohydrodynamic plasma as described in claim **1** wherein said third field generating means comprises an annular coil disposed coaxially with respect to said first field coils and spaced apart therefrom a distance which is small relative to the distance of said electrodes therefrom.

3. A magnetohydrodynamic device for creating a purified plasma, comprising, in combination, a long hermetically sealed tube having a length substantially greater than the diameter thereof and having a first end and a second end, means for evacuating said tube, a hollow electrode extending a small distance along the axis of said tube at said first end thereof, said electrode having at least one gas aperture at the inner end thereof, a rapidly opening gas valve disposed within said electrode for release of gas through said aperture, a gas source connected to said valve, a first high current power supply connected between said tube and said electrode, a pair of annular magnetic mirror coils disposed coaxially on said tube at said second end thereof, a second power supply connected to said mirror coils, a drift field coil disposed coaxially on said tube to provide an axially aligned magnetic field in the region thereof between said electrode and said pair of magnetic mirror coils, said drift field having a highest intensity in the region between said first end of said tube and said apertures in said electrode, a gate coil disposed coaxially on said tube between said pair of magnetic mirror coils and said electrode, and a pulse power supply connected to said gate coil.

4. A magnetohydrodynamic device as described in claim 3, comprising the further combination of a valve and switch control providing for sequential operation of said valve and said pulse power supply whereby said gate coil is energized immediately after the passage of said plasma therethrough and prior to passage of plasma impurities therethrough.

5. A magnetohydrodynamic apparatus for creating and purifying a plasma, comprising, in combination, a long gas tight tube having a first end and a second end, a vacuum pump communicated with said tube, an electrode disposed at said first end of said tube and extending for a short distance along the axis thereof with a first end facing said second end of said tube, a rapidly opening gas valve disposed at the first end of said electrode for releasing a burst of gas to produce said plasma, a thin conductive rod affixed at one end to said first end of said electrode and aligned along the axis of said tube, means impelling said plasma toward said second end of said tube, a pair of magnetic mirror field coils disposed coaxially with respect to said tube at the second end thereof, at least one drift field coil disposed coaxially with respect to said tube and providing an axially aligned magnetic field therein, a coil disposed coaxially with respect to said tube between said electrode and said pair of mirror field coils, and a pulse power supply connected to said gate coil whereby impurities which follow said plasma along said tube may be stopped from entering said mirror field.

6. A magnetohydrodynamic apparatus as described in claim 5, wherein the inside wall of said tube is constricted in the region of the first end of said electrode and has a configuration substantially following the curvature of said drift field in the region adjacent said electrode.

7. In a magnetohydrodynamic device for creating substantially pure plasma, the combination comprising a long hermetically sealed tube having a first end and a second end, a vacuum pump coupled to said tube, an electrode disposed at said first end of said tube along the axis thereof and having an inner end projecting toward said second end of said tube, a relatively thin conductive rod secured to the inner end of said electrode and projecting therefrom toward the second end of said tube along the axis thereof, means producing an axially directed magnetic field within said tube, a power supply connected between said tube and said center electrode to produce an electric field from said rod and said electrode to said tube, means for impelling said plasma from said first end of said tube toward said second end of said tube, means releasing a burst of gas in said first end of said tube to form a plasma thereat, a control circuit for disconnecting said power supply to eliminate said electric field a timed interval after operation of said gas release means whereby said electric field is absent when said plasma passes the free end of said rod, means producing a magnetic plasma containment field at the second end of said tube, and a rapidly closing gate means of a type impervious to the passage of charged particles, said gate means being disposed along said tube between said electrode and said plasma containment field and being operative an interval after operation of said gas release means whereby impurities which follow said plasma along said tube are prevented from entering said containment field.

8. In a magnetohydrodynamic device for creating a pure charged particle plasma, the combination comprising a long conductive tube having first and second ends, an insulative closure at said first end of said tube, an electrode having one end affixed to the center of said closure and having an apertured inner end which projects along the axis of said tube toward said second end thereof, said electrode being short relative to said tube, a plasma containment magnetic field producing means disposed at said second end of said tube, means emitting a burst of gas through said apertured end of said electrode, a plasma drift field producing means disposed between said first end of said tube and said containment field means, means providing a low intensity magnetic mirror in said first field in the region between said inner end of said electrode and said closure, a high voltage power supply connected between said tube and said electrode, the voltage output of said power supply having a value whereby the heaviest of said charged plasma particles are guided in orbits having a maximum radius slightly less than the spacing between said electrode and said tube, a rod secured to said apertured end of said electrode and projected axially therefrom toward said second end of said tube, means de-activating said power supply when said plasma particles approach the end of said rod, and a pulsed gate magnetic field generating coil disposed coaxially with respect to said tube between said containment magnetic field and said electrode.

9. A magnetohydrodynamic device as described in claim 8, further characterized in that said means de-activating said power supply comprises a valve and power supply timing circuit, said timing circuit being of the type producing time related output signals, a first of said output signals causing said gas emitting means to be activated, followed in time by a second of said signals initiating operation of said power supply de-activating means.

10. A magnetohydrodynamic device as described in claim 8, further characterized in that said means de-activating said power supply is a normally open switch connected across the output of said power supply, and wherein a low ohmage damping resistor is connected between said power supply and said electrode.

11. In a magnetohydrodynamic device for producing a purified plasma of energetic particles, the combination comprising a long conductive cylinder, an axial electrode disposed within one end of said cylinder and having a first end facing the opposite end of said cylinder, the radial distance between said electrode and said cylinder slightly exceeding the orbital radius of said particles therebetween, means for releasing gas from said electrode to produce said plasma, means providing a magnetic field axially through said cylinder, means impelling said plasma toward said opposite end of said cylinder along said magnetic field, a plasma containment means at said opposite end of said cylinder, a conductive axially disposed rod affixed at a first end to said first end of said electrode and having a second end directed toward said opposite end of said cylinder, a high voltage power supply connected from said electrode to said cylinder, and means de-energizing said power supply when said plasma is adjacent said second end of said rod.

12. In a magnetohydrodynamic device for producing a purified plasma of charged particles the combination comprising a long evacuated conductive cylinder, an axial electrode disposed within said cylinder at one end thereof and radially separated therefrom by a gap of predetermined radial depth, means producing a radial electric field between said cylinder and said electrode, means producing an axially directed magnetic field through said tube,

means releasing a gas into the gap between said cylinder and said electrode to produce said plasma, said predetermined radial depth of said gap being greater than the orbital radius of the heaviest of said plasma particles and less than the orbital radius of particles heavier than said plasma particles, a narrow conductive rod disposed on the axis of said cylinder and attached to said electrode, and means inactivating said radial electric field means when said plasma approaches the end of said rod.

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REUBEN EPSTEIN, *Primary Examiner.*