Sept. 16, 1969 G. L. CANN 3,467,885

METHOD AND APPARATUS FOR ELECTROMAGNETICALLY CONTAINING A PLASMA

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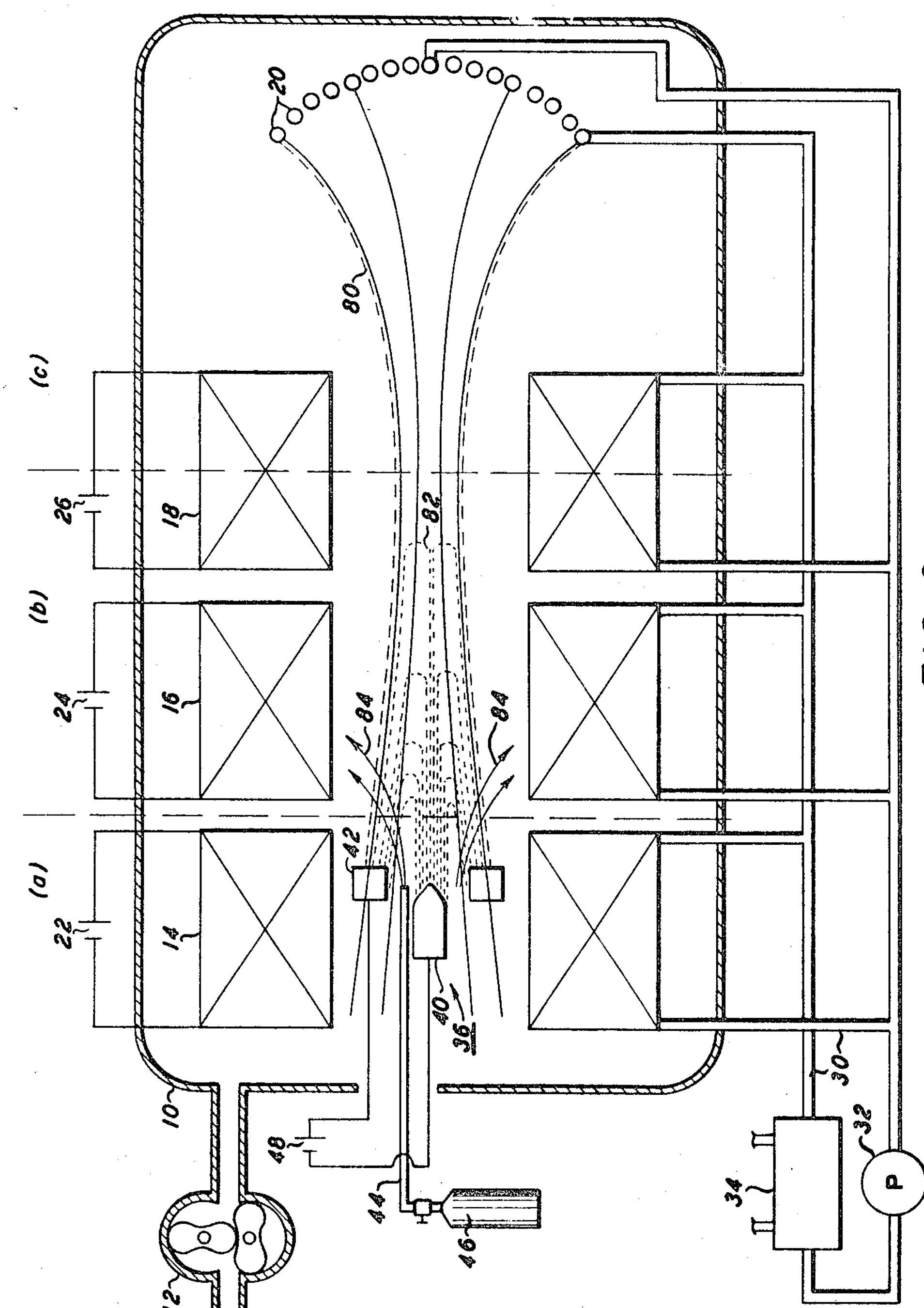

FIG. 1

INVENTOR
GORDON L. CANN

BY Joseph F. Rosenthal

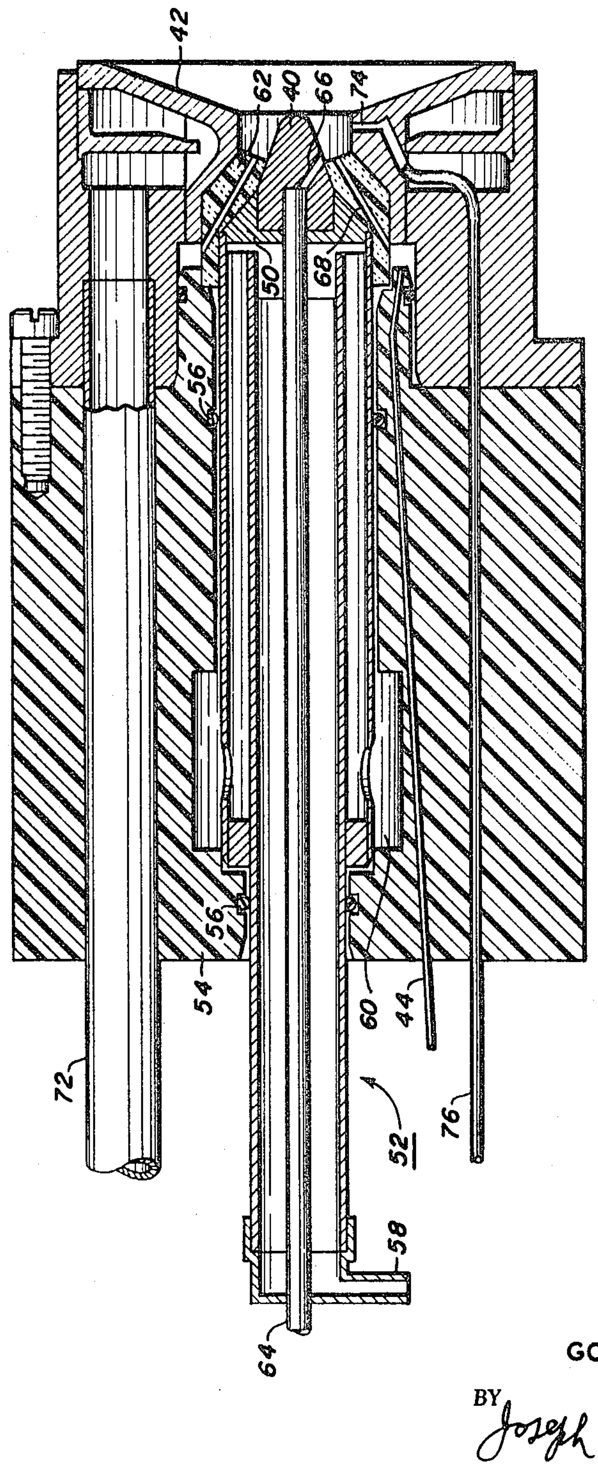

FIG. 2

INVENTOR.
GORDON L. CANN

BY Joseph F. Rosenthal

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METHOD AND APPARATUS FOR ELECTROMAGNETICALLY CONTAINING A PLASMA

Gordon L. Cann, Laguna Beach, Calif., assignor, by mesne assignments, to Xerox Corporation, a corporation of New York

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U.S. Cl. 315—111 2 Claims

ABSTRACT OF THE DISCLOSURE

A method and apparatus for plasma containment is disclosed in which a longitudinally continuous magnetic field symmetrical about an axis converges the plasma produced by a radial electric discharge at a single axial location to a remote pinch and allows it to diverge thereafter.

This application relates to methods and apparatus for plasma containment.

There are many situations where it is desirable to produce sustained high temperatures greatly in excess of the melting point of structural materials. These include the spectroscopic investigation of atomic structure, routine spectroscopic analysis, the study of chemical reactions, the generation of neutrons, and the study or utilization of thermonuclear reactions. Known or contemplated methods of producing extra high temperature involve generation of such temperatures in a body of plasma, which is a body of highly ionized electrically neutral gas having a very high electrical conductivity. The electrical properties of a plasma make it theoretically possible to effect containment by means of magnetic field rather than by physical contact with the walls of the container. The absence of such contact makes the containment possible at temperatures far above the melting points of all structural materials and without excessive heat losses to such containers. Many magnetic containment schemes have been proposed; some involve a transient or pulse type of operation while others are steady-state but require complex starting procedures. Prior methods involve the use of complex apparatus and have not been outstandingly successful in operation.

It is accordingly an object of the invention to provide a plasma containment and heating method which is simple, capable of steady-state operation, capable of small scale operation, requires no complex starting procedures, and is effective. It is a further object of the invention to provide a plasma containment and heating method which is electrostatic as well as magnetic in character and which makes use of Hall currents. It is still a further object of the invention to provide simple and effective apparatus for containing and heating the plasma. It is still a further object of the invention to provide a high temperature plasma jet. Further objectives will become apparent upon reading a description of the invention.

FIGURE 1 is a diagrammatic sectional view of apparatus according to the invention.

FIGURE 2 is a sectional view of the electrode assembly used in FIGURE 1.

Referring to FIGURE 1, there is shown an illustrative embodiment of the invention, including a chamber **10** which is evacuated by a vacuum pump **12** and which contains a set of coaxial magnet coils **14**, **16**, and **18**. A single long solenoid with appropriately proportioned windings can be used, but it is more convenient to use a set of individual coils as shown. Each coil **14** to **18** has an associated high current power supply **22**, **26** respectively. The coils are fluid cooled and each is provided with cooling tubes **30** through which water or other coolant is circulated by pump **32** which also circulates the coolant

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through a heat exchanger **34** to remove heat generated in the coils and also heat carried by or generated in the plasma. A cooling baffle **20** may also be provided as shown adjacent to magnet coils **18**. The resulting magnetic field is arbitrarily divided into three regions identified as (*a*), (*b*), and (*c*). In region (*a*) the magnetic field lines should be relatively parallel, but can converge or diverge slightly. In region (*b*), however, the field lines should converge so that the average axial magnetic field strength is a maximum at the downstream end of region (*b*). In region (*c*), the magnetic field lines should diverge. The junction of regions (*b*) and (*c*) can be referred to as magnetic "pinch." The illustrated magnetic field configuration can be termed an electromagnetic nozzle, since the processes occurring in a plasma confined therein are similar to those occurring to an ordinary gas in an axi-symmetric Laval nozzle.

Chamber **10** can also be located inside the magnet coil if it is constructed of non-magnetic material in order that the external coils may provide the necessary magnetic field within the chamber. An electrode assembly **36** is positioned axially within chamber **10** and facing to the right. Electrode assembly **36** is located within the longitudinally continuous field generated by coils **14** to **18** and more specifically is located in region (*a*) and illustratively within coil **14**. The electrode assembly includes a tapered or pointed cathode **40** surrounded by a concentric annular anode **42**. A gas supply channel **44** introduces a suitable gas such as hydrogen from a source **46** into the space between the cathode and anode, and a DC power supply **48** is connected between a cathode and anode. Conventional supporting means, not shown, will be included in chamber **10** to position and support electrode assembly **36**, magnet coils **14** to **18**, cooling baffle **20**, etc. and conventional electrical and fluid lead-throughs may be used to introduce the necessary electrical currents and gasses into an outer chamber **10** without breaking the vacuum therein.

A suitable electrode structure is shown in somewhat greater detail in FIGURE 2. Cathode **40** is constructed of tungsten, and like most structures in the figure, will normally be axially symmetric. It is mounted in a metal heat sink **50** which, in turn, is mounted at the end of a cathode support and cooling water conduit **52** which is sealed into phenolic support block **54** by sealing rings **56**. A cathode cooling water inlet **58** is shown at the back of conduit **52**. A cathode cooling water outlet will communicate with a cavity **60** in support block **54** that is out of the plane of the drawing and not shown. It will be understood that various other cooling water passages will not appear in the drawing for the same reason. A boron nitride insulator **62** is mounted on cathode conduit **52** and surrounds cathode **40** while leaving the tip portion exposed. Cathode **40** is bored to receive a hollow tubular pressure tap **64** located within the cathode water conduit **52**. Cathode **40** contains one or more small passages **66** which connect the pressure taps **64** to the exterior surface of the cathode **40** to the cathode insulator **62** which is itself provided with a gas passage, or preferably a plurality of circumferentially disposed passages **68** which communicate with the front face of the insulator and are connected to a feed tap **44** in support block **54**. Either passages **66** or **68** may be used to introduce a fluid to the space adjacent to the cathode, but it is generally preferable to introduce the fluid through passages **68** and to use passages **66** for measuring the pressure adjacent to cathode **40**.

A water cooled copper anode assembly **42** is mounted on the support block **54** and is insulated from cathode **40** by insulator **62**. The anode has a concave conical outer face and a cylindrical inner surface which joins the outer face along a sharp edge. Illustratively, the diameter of the inner surface is 1.5 cm. Anode **42** is connected to an electrically conductive water inlet conduit **72** and to an outlet conduit, not shown. It is also provided with one or more passages **74** which communicate with the inner surface of the anode and are connected to an anode pressure tap **76** which permits measurements of pressures adjacent to the anode. Other types of coaxial electrode assemblies may be used and it will be understood that the particular size, configuration, and materials described in FIGURE 2 are for illustrative purposes only. It is merely necessary that the central cathode tip be associated with a surrounding ring anode located axially adjacent to the cathode tip.

In operation, chamber **10** is evacuated, magnet coils **14** to **18** are energized, a gas is fed from source **46** through channel **44** to electrode assembly **36** and power supply **48** is energized to strike an electrical arc between cathode **40** and anode **42**. A plasma, i.e., positive ions and negative electrons, is thereby generated and fills the region to the right of electrode assembly **36**. Because of the magnetic field existing in the device, the plasma electrons are constrained to execute small diameter cyclotron oscillations about the magnetic lines of force. A magnetic field will be chosen in relation to the plasma pressure in accordance with conventional principles so that the electron orbital radius will be substantially less than the plasma column radius and so that the mean free path of the electrons will substantially exceed the electron orbital circumference, collision deflection, i.e., $2\pi\omega_e\tau_e$ is very large compared to unity, where ω_e is the angular cyclotron frequency for electrons and τ_e is the mean time between electron collisions. This condition is not difficult to achieve in a practical device because the effective collision cross section decreases at high plasma temperatures. Under this condition, as is known in the plasma art, the electric lines of force are essentially constrained to follow the magnetic lines of force. From a macroscopic point of view, a high temperature plasma in a magnetic field exhibits a high degree of electrical conductivity parallel to the magnetic lines of force, but a very low degree of conductivity perpendicular to the line of force. The reality of this effect can readily be demonstrated. In some cases, it is also preferred that $\omega_i\tau_i$ for the ions be small compared to unity so that the ion collision mean free path is large compared to the plasma radius. This condition is readily obtained in a practical plasma. Also, as high a vacuum as possible should be maintained in chamber **10** to minimize heat losses from the plasma.

Under the described conditions, a confined column of plasma **80** is formed in region (*b*) and can be visually observed through portholes in chamber **10**. The containment mechanism in region (*b*) can now be simply described. Electrons are confined to orbits about the magnetic lines of force and the ions and electrons are each urged outwards by the radial pressure gradient in the column. The constraining force on the ions is primarily the radial electric field rather than a force associated with the magnetic field. Considering a section taken normal to the axis of the device in region (*b*), it is obvious that the positive ions find themselves in an electrostatic potential well from which they are unable to escape unless they have an energy higher than the potential drop between the axis of the plasma and the outside thereof. This is in marked contrast to the prior schemes of plasma containment and has several favorable consequences. One of these is that the diameter of the containment device and the strength of the magnetic field need not be such as to provide ion orbital radii which are small in comparison to the device radius. The radial electric field exerts an outward force on the plasma electrons but they cannot move outward except by losing energy in collisions with plasma ions, neutral atoms, or other electrons. This is a useful effect since it serves to heat the plasma and particularly the ionic component. The interaction of the radial current flow with the longitudinal magnetic field also creates a rotating Hall current and a plasma rotation which tends to maintain the plasma column in rotation about its axis and to provide confining forces for the electrons because of the interaction between the circumferential Hall current and the axial magnetic field. The Hall current also generates a magnetic field which opposes that of magnets **14** to **18**.

The situation in region (*a*) in the vicinity of electrode assembly **36** is somewhat more complex. A diffuse arc is formed between the cathode tip and the anode ring and extends considerably downstream from the electrodes themselves. It is believed that the electrons produced at the cathode travel some distance along the axis of the device before diffusing outward as suggested in FIGURE 1. When all three spatial coordinates are considered, this picture must be substantially modified to account for the action of the magnetic field. The radial component of the current will interact with the longitudinal component of the magnetic field to produce strong confining Hall currents which circulate around the axis of the device. These currents arise in the absence of a circumferential electric field because of the $J_r x B_z$ interaction between the radial current density J_r and the longitudinal magnetic field B_z, x representing the conventional vector cross product. These Hall currents are in the same direction as those noted previously in discussing equilibrium in region (*b*) of the plasma column. The circumferential Hall currents will interact in a similar manner with the radial component of the magnetic field to produce an axial acceleration. Axial Hall current plasma acceleration is not considered beneficial in this invention and, therefore, the magnetic field lines in region (*a*) should be reasonably parallel.

There is also an ion current formed at the anode which travels longitudinally away from the anode before diffusing towards the center of the plasma column and returning to the cathode. It is believed that near the anode the ions carry the bulk of the current in the arc discharge because the plasma is not fully ionized and the ions are much more weakly coupled to the magnetic field than the electrons. Hence, the electromagnetic confining force on the plasma is largely independent of the strength of the applied magnetic field, provided it is large enough so that $\omega_e\tau_e\omega_i\tau_i$ is much greater than 1. This effect is enhanced by the mass injection or gas flow **84** which is supplied to the electrode assembly from gas source **46**. Some of this gas is ionized by the arc discharge or by heat conduction from the plasma and contributes to the plasma. Some of the gas is not ionized and escapes from the plasma column in the manner indicated in FIGURE 1. This gas flow provides several important functions. One important function is simply that of cooling the electrodes. The gaseous atoms also collide with the plasma ions and further decouple them from the magnetic field. The gas flow also serves other closely related important functions. In the absence of the gas flow the entire plasma column would be set into very rapid rotation by the electromagnetic torque and the resulting counter EMF between cathode and anode would then limit the flow of further current or energy into the system. On the other hand, the ion rotational frequency would approach the electron rotational frequency thus reducing the net Hall currents and the resulting stabilizing and containing effect in region (*b*). Finally, under these conditions, much of the plasma energy would be in the form of rotational kinetic energy rather than the desired thermal energy. The above mentioned gas flow carries off some of the angular momentum from the plasma column and this acts as a brake or counter-torque on the plasma column, particularly on the ions. This effect preserves the Hall current, thermalizes the ion kinetic energy, and permits the plasma column to absorb energy from the arc current. The torque acting on the plasma column is essentially the product of the magnetic field and the arc current. Assuming that the unionized gas reaches equilibrium with the plasma before escaping outward, the plasma angular velocity can be calculated as $Bi/\dot{m}$ where $\dot{m}$ represents the total gas freeput from the external source **46** and i is the arc current at the electrode assembly **36**. Accordingly, it is generally preferred to minimize the magnetic field B so that the "magnetic pressure" $B^2/2\mu_0$ (where μ_0 is the permeability of free space) is not excessively greater than the actual gas pressure. For small-scale experiments, as will be described hereafter, the plasma rotational velocity will be on the order of 1 million rotations a second. As noted previously, this macroscopic plasma rotation is believed to have a significant effect in stabilizing the operation of the device. Finally, the gas flow establishes a pressure gradient away from the electrode assembly which helps to reduce heat losses from the plasma to the electrodes.

A brief theoretical analysis of the invention will be given later on. The analysis is not as complete as has been made on certain other plasma containment invention, but the present invention is distinguished, among other things, from prior arc devices in that it is capable of successful operation on a normal laboratory scale and has in fact been so operated. Of course, the analysis will show that with this invention as with others, containment efficiency and plasma temperature tends to rise if equipment is constructed on a larger scale and operated at higher power.

In an experiment corresponding to FIGURE 1, three magnet coils were employed corresponding generally to coils **14**, **16**, and **18**. Each coil was 3¼" long by 3" inside diameter and wound in such a way that in coil **14** one gauss was produced in the center of an isolated coil for each ampere of exciting current and in coils **16** and **18** three gauss were produced for each ampere. The electrode assembly corresponded to that of FIGURE 2 and the internal diameter of the anode was 1.5 centimeters. Other types of coaxial electrode assemblies may be used. The face of coil **14** was spaced 3" from the adjacent face of coil **16** and the adjacent faces of coils **16** and **18** were spaced 1" apart. The face of anode **42** was recessed ¾ of an inch within coil **14**. A current of 2,410 amperes was applied to coil **14** and a current of 1,700 amperes to coils **16** and **18**. The arc current was 810 amperes and the arc voltage 105 volts. Hydrogen gas was introduced at the rate of 0.02 gram per second and the pressure in chamber **10** was .09 millimeter. Under these conditions a stable plasma column was obtained having a pressure of 30 millimeters as measured at cathode pressure tap **64**. The plasma column was essentially colorless with a sharply defined outer surface which was surrounded by a brilliant red globe believed due to atomic or molecular hydrogen.

It might be assumed that in an open-ended device of this character the plasma losses would be prohibitably high due to the flux from region (*b*) to region (*c*). Unexpectedly, however, both experiment and theoretical analysis indicate that this is not so and that the present invention has certain advantages. In this invention, the apparatus would be proportioned so that the arc current has all crossed from the anode sheet to the cathode jet entirely within regions (*a*) and (*b*). The plasma flow will be subsonic in regions (*a*) and (*b*) and become sonic at the pinch, or transition between region (*b*) and (*c*). Accordingly, a favorable relation can be established between the plasma pressure, the plasma mass flow rate, the area of the magnetic nozzle, and the power transfer to the gas. Much of the energy of the plasma escaping into region (*c*) can be recovered in cooling baffle **20** or the energy can be extracted in a magnetohydrodynamic electricity generator as described in connection with co-pending application entitled "Controlled Fusion Devices," Ser. No. 373,220, filed June 8, 1964, or the escaping plasma can be used for propulsive purposes in space applications.

The maximum attainable plasma temperature may be calculated as (MKS units).

$$T_{\text{max.}}=T_{\text{in.}}e^{a}$$

wherein:

$T_{\text{in.}}\approx$ionization temp.$\approx$20,000° K.

$$a=\frac{\pi(\gamma-1)}{4\gamma}\,\frac{M_a I}{|e|\dot{m}}\,(1-q^*)$$

γ=ratio of specific heats=5/3
M_a=mass of ion
$|e|$=charge of electron
I=current

In this equation, q^* is the percent of power radiated and is given by:

$$q^*=\frac{B^2R^2(1+\psi)}{3}\,\frac{\sigma\phi r}{p^2}$$

$$\psi=\frac{|e|\dot{m}}{M_a I}$$

$\dot{m}$=mass flow rate
B=magnetic field strength
R=radius of plasma column
σ=electrical conductivity
ϕ_r=bremsstrahlung radiation
p=pressure

$$\frac{\sigma\phi r}{p^2}203$$

Thus, in the present invention the temperature is strongly dependent on the current. The temperature equation also reflects the fact that the Hall currents essentially cancel the magnetic field in the hot high density core of the plasma column so that the cyclotron radiation losses, which are usually a major factor in plasma containment devices, are minimal compared to the bremsstrahlung losses.

A critical minimum length can be calculated for the combined length for regions (*a*) and (*b*).

$$L_{\text{min.}}=\frac{32\pi\gamma R^4B^2T_{\text{in.}}^{3/2}e^{3/2a}}{225(\gamma-1)\frac{(T^{3/2})}{\sigma}\dot{m}(1-q^*)}$$

$$=\frac{10^{-3}R^4B^2T_{\text{max.}}^{3/2}}{\dot{m}(1-q^*)}$$

This indicates that the length is essentially proportional to the square of the total magnetic flux in the plasma column and since the plasma column follows the field line there is no stringent requirement to have a strong magnetic field at the junction of regions (*b*) and (*c*) or to attempt to pinch the plasma column down to a very small diameter.

The power absorbed in the anode **42** can be calculated as:

$$P_a=\frac{25(\gamma-1)}{16\gamma}\left(\frac{|e|K}{\sigma k^2T}\right)\left(\frac{\frac{kT_{\text{in.}}e^{a/2}}{|e|}}{\frac{R^2B^2}{\dot{m}(1-q^*)}}\right)^2$$

where K=thermal conductivity (parallel to B). Thus, in the present invention the anode power dissipation does not rise as fast with increasing plasma temperature as might be expected. It is believed that this is because in the present invention much of the plasma heat energy is carried away from the electrodes by convection rather than into the electrodes by conduction.

Any gas or gasifiable material may be used to form the plasma, depending on the intended use of the plasma. Where neutron generation or power production is intended a hydrogenic gas will be used, particularly deuterium or tritium or mixtures thereof. Although a theory of operation has been proposed, the invention is not predicated on the validity of this theory since operability is a demonstrated fact. Furthermore, it appears likely that the theoretical mechanism of operation may vary under different operating conditions. Many variations may be made to a described embodiment without departing from the novel concept of the invention. Thus, complete symmetry about a liner axis is preferred, but departures from this symmetry can be tolerated and the "axis" itself can be curved since the discharge will follow the magnetic field whether straight or not. The magnetic coils can be other than solenoidal or cylindrical as by being wound on conical forms, and permanent magnets may be used within the limits of their technology. It is also possible to use an alternating magnetic field provided that the frequency f is high enough so that the period $1/f$ is small compared to the average residence time of an ion in the plasma column. This represents another mechanism for introducing energy into the plasma. Other variations in size, configuration, operating conditions and the like are encompassed by the invention as defined in the claims.

I claim:

1. The method of electromagnetically containing a body of high temperature plasma to which a macroscopic rotation about an axis is imparted in which the magnetic field, temperature, and plasma density are such that $2\pi\omega_e\tau_e$ is greater than 1 where ω_e is the cyclotron angular velocity for electrons and τ_e is a mean time between collisions for electrons comprising:

(a) producing a longitudinally continuous magnetic field substantially symmetrical about said axis such that the magnetic containment pressure is greater than but of the same order of magnitude as the plasma pressure,

(b) maintaining a radial electric discharge at a single axial location within said magnetic field substantially symmetrical about said axis and having a discharge radius less than the cyclotron radius for ions in said plasma, the outside of said discharge being positive with respect to the inside,

(c) supplying an ionizable gas to said discharge,

(d) converging the magnetic field lines of said axial magnetic field to a pinch downstream of and remote from said single axial discharge location, and

(e) diverging the magnetic field lines of said axial magnetic field downstream of said pinch.

2. A plasma containment apparatus for electromagnetically containing a body of high temperature plasma to which a macroscopic rotation about an axis is imparted in which the magnetic field, temperature, and plasma density within said apparatus is such that $2\pi\omega_e\tau_e$ is greater than 1 where ω_e is the cyclotron angular velocity for electrons and τ_e is the mean time between collisions for elecrons comprising:

(a) a chamber,

(b) means to evacuate said chamber,

(c) magnetic coil means to produce a longitudinally continuous magnetic field substantially symmetrical about said axis within said chamber, said magnetic field being of such magnitude that the magnetic containment pressure produced thereby is greater than but of the same order of magnitude as the plasma pressure, and said magnetic field means converging the lines of force of said magnetic field to a pinch and diverging said lines of force thereafter,

(d) a single plasma arc generator disposed within said magnetic field on said axis substantially symmetrical thereabout, upstream of and remote from said pinch, said generator comprising a central cathode electrode and an anode electrode encircling said cathode at a discharge radius less than the cyclotron radius for ions in said plasma, said generator including at least one passage terminating between said cathode and anode, the distance from said single plasma arc generator to said pinch being so related to the magnetic field strength that all current flowing between said cathode and said anode does so in the region between said arc generator and said pinch,

(e) gas supply means to introduce a plasma forming gas through said passage,

(f) power supply means to maintain an arc discharge between said anode and said cathode, and with said plasma arc generator constituting the sole means for maintaining an inwardly radial electric field within said plasma, and

(g) energy utilization means disposed substantially along said axis on the opposite side of said pinch from said single plasma arc generator.

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JAMES W. LAWRENCE, Primary Examiner

RAYMOND F. HOSSFELD, Assistant Examiner

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