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3,674,634

PLASMA CONFINEMENT APPARATUS

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FIG.1.

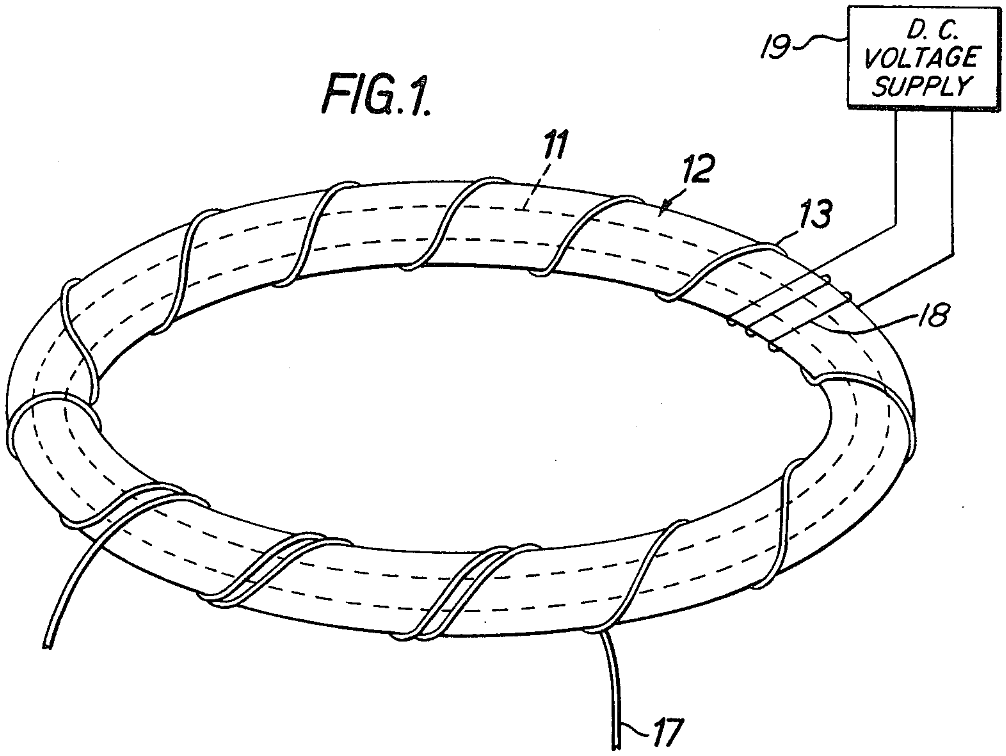
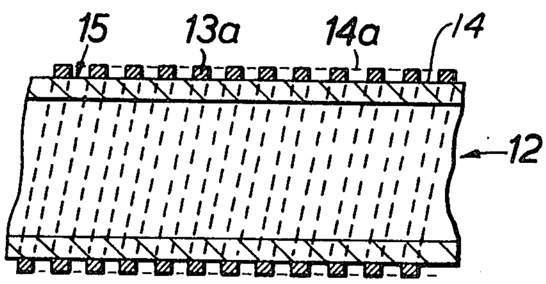


FIG.2.



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PLASMA CONFINEMENT APPARATUS

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U.S. Cl. 176—3 4 Claims

ABSTRACT OF THE DISCLOSURE

Plasma is principally confined in a toroidal configuration by a static magnetic field. For stabilising the plasma, a radiofrequency electromagnetic field moving faster than the ions in the plasma and of frequency in the region of 1 megahertz is applied. Power for generating the radiofrequency field is coupled into an endless path for conducting electromagnetic power, the path having a distributed inductance and capacitance such that it is a circuit which resonates at the frequency of the electromagnetic field.

Cross reference is made to British patent specification No. 830,252 to which United States Pat. specification No. 3,054,742 corresponds.

BACKGROUND OF THE INVENTION

The invention relates to plasma confinement apparatus.

For the generation of thermonuclear power, for example, it is necessary to device means for confining a hot plasma of thermonuclear fuel without the plasma coming into contact with material boundaries. For the attainment of economic thermonuclear power it is also necessary, inter alia, that the means for confining the hot plasma should not consume more power than can be secured from thermonuclear reactions in the contained plasma.

SUMMARY OF THE INVENTION

The invention provides a plasma confinement apparatus comprising a vessel for containing a gas at low pressure, means for forming in or introducing into the vessel a plasma, means for producing a static magnetic field tending to confine the plasma, means for producing a raido frequency electromagnetic field which moves relatively to the plasma faster than the ions in the plasma are moving, the frequency of the electromagnetic field being in the region of 1 megahertz, the said means for producing the radio frequency electromagnetic field including an electrical conductor forming an endless path for conducting electrical or electromagnetic power, which path has a distributed inductance and capacitance such that it is a circuit which resonates at the frequency of the electromagnetic field.

With a radio frequency electromagnetic field of frequency in the region of 1 megahertz, conductors used to localise the field may comprise subdivided electrically conducting wires within which volume currents flow.

Preferably the vessel is toroidal.

Preferably the electrical conductor forming the endless conducting path comprises a closed toroidal helix encompassing the vessel. Preferably the electrical conductor is formed by forming the vessel with an electrically insulating surface, depositing a thin layer of metal on the surface and cutting a groove or grooves through the metal layer, the groove or grooves following the required direction of the conducting path.

DESCRIPTION OF PREFERRED EMBODIMENT

A specific construction of apparatus embodying the invention will now be described by way of example and with reference to the accompanying drawings in which:

FIG. 1 is a diagrammatic illustration of part of the apparatus, and

FIG. 2 is a diagrammatic part sectional view of the apparatus.

In this example the plasma, illustrated at **11**, is contained within a torus **12**. The construction of such an apparatus and means for forming a plasma within the torus are described, for example, in U.S. Patent No. 3,054,742 the U.S. counterpart of British patent specification No. 830,252. Means for generating a static magnetic field has been shown diagramatically as winding **18** fed by a conventional D.C. supply **19**.

Economic considerations can enable one to define a minimal economic thermonuclear plasma and the following approximate parameters for such a minimal economic theronuclear plasma have been deduced:

Surface thermonuclear energy flux P_s: 250 watt/cm.^{2}
Thermonuclear power density P_v: 1 watt/cm.^{3}
Density n.: 5.3 10^{13} ions/cm.^{3}
Temperature T: 19.5 kev.
Pressure p: 3.3 atmospheres
Thermal energy density $3n$T: 0.5 joules/cm.^{3}
Volume V: 10^{10} cm.^{3}
Thermal Energy ϵ: 5.10^9 joules
Required energy confinement time: 1 second
Vacuum vessel radius R: 18 metres

These figures assume, for ease of the illustrative calculation, that the plasma is spherical with a radius r_p which is three quarters of the radius R of the surrounding vessel.

Confinement of such a plasma by radiation pressure alone would require an electric field strength of approximately 2.7×10^6 volts/cm. Fields of this strength might be obtained, although this has not yet been achieved.

However, if this electromagnet field were localised around the plasma by enclosing it within a resonant cavity, the dissipation of power in the cavity walls would exceed the thermonuclear power generated by the plasma in all practical cases.

These prohibitive RF losses are a consequence of the skin effect, and it is clear that totally different considerations apply once the frequency becomes so low that one can subdivide the conductors used to localise the RF field into thin wires, within which volume currents flow. This approach becomes possible around 1 mc./s., and the factors which affect RF losses in this waveband have to be considered. Since the skin depth in copper is still only around 0.1 mm. rigorous percautions have to be taken in order to approach the D.C. level of ohmic losses. In view of the necessarily heavy losses in the plasma at present laboratory temperatures, there has been little motivation to reduce the ohmic losses in the conductors. In consequence, existing circuits seldom have a quality factor Q exceeding 100. Whilst, on the scale of a small laboratory experiemnt is probable that the ohmic losses would remain dominant even if one reduced them to the D.C. level, on the scale of a reactor, however, radiation losses can become much more serious. A third source of loss is the power dissipated by currents induced in imperfect nearby conductors or dielectrics.

The importance of minimising all of these loss processes can be emphasised by considering the RF power required tho confine a minimal thermonuclear plasma by means of a 1 mc./s. circuit of Q=100. In the apparatus the volume occupied by the confining field is of the same order as the volume of the plasma, and the pressure balance condition requires their energy densities to be comparable. This requires a stored electromagnetic energy ϵ of order 5 10^9 joules, and the RF power dissipated is therefore $\epsilon\omega/Q\simeq3.10^{14}$ watts.

It is believed to be unlikely that this situation could be improved by the required factor (10^5) by increasing Q alone: thus the low frequency confinement of the present apparatus has to operate in conjunction with a static magnetic field. A further factor to be taken into consideration is that proposals to make use of an RF magnetic field to confine the plasma involve the use of a condenser bank to store the (necessarily equal) electrical energy in the circuit. At current prices, the cost of a long life condenser bank capable of storing 5 10^9 joules is of order £2 10^9, which gives a cost of £400/kw.(e) of output. This figure is unacceptable by nearly two orders of magnitude. Thus, the low frequency RF confinement system of this example has to meet the following requirements (i) the electrical energy has to be localised in the same region of space as the magnetic energy and not stored expensively elsewhere; (ii) a large fraction of the confinement has to be effected by a static magnetic field, and (iii) the Q of the circuit has to be raised by many orders of magnitude above those achieved in existing radio-frequency confinement systems.

To meet the first requirement, the circuit must be designed so that retardation effects are important and hence, since the vacuum wavelength at 1 mc./s. is much larger than reactor dimensions, it must take the form of a slow wave structure, wrapped around the plasma. The second requirement implies that the ion cyclotron frequency Ω_i in the static magnetic field would inevitably exceed 1 mc./s. This creates a geometric problem, since RF fields can freely propagate through a plasma along magnetic lines of force at frequencies w below Ω_i, and consequently exert no pressure on it. This geometric problem is solved in this example by employing a toroidal magnetic field topology. The third requirement involves special precautions to minimise both ohmic and radiative loss. Considering first radiative loss, it can be shown that when the number of terms N in the normal multipole expansion which is required to represent the radiation is large, and when the overall radius a of the antenna is small compared with the vacuum wavelength, very high radiation Q*s* can be obtained. For example, for $Wa/_c=0.15$, if

$$\begin{cases} N=2 \quad Q=300 \\ N=3 \quad Q=2\times10^4 \end{cases}$$

Thus, structures in which the RF currents have simple dipole or quadrupole representations have to be avoided.

For meeting this requirement the configuration of the conductor for localising the RF field in the apparatus of this example comprises a closed toroidal helix electrical conductor represented diagrammatically in FIG. 1 at **13**. This is a slow wave structure which permits RF power at any time of a discrete set of resonant frequencies to circulate repeatedly around the toroidal helix, until the power is dissipated by ohmic and/or radiation losses.

It can be shown that, under given geometrical conditions, there are relatively non-radiating resonant frequency modes in the toroidal helix in which the electromagnetic field is localised near the helix and, for a torus of minor radius approximately 1 meter, there exist such resonant modes at a minimum frequency of the order of 1 mc./s.

The field structure at these frequencies is ideally suited to plasma confinement, since both the electric and magnetic fields have minima on the circular axis of the torus and form a time-averaged minimum well in the electric and magnetic fields. It is believed that the toroidal helix arrangement of this example may have a Q as high as 10^5 at a frequency of 1 mc./s.

On this basis, the RF system of this example combined with (for example) a simple toroidal $1/R$ static magnetic field to provide the main confining force, can lead to a reactor having the following approximate parameters. It is assumed, as is optimum, that the surface flux is around the maximum permissible—say 1000 watts/cm.^{2}—and that the torus has an aspect ratio which is as large as is compatible with a reasonable minor helix radius—say 1 metre:

Gross thermonuclear output: 10^{10} watts
Minor radius of toroidal helix: 1 metre
Number of turns of toroidal helix: 750
Major radius: 25 metres
Power density: 30 watts/cm.^{3}
Plasma density: 3.6 10^{14} cm.$^{-3}$
Plasma pressure: 21 atmospheres

$$\text{RF power required } P_{RF}=5\ 10^8\,\frac{\omega}{Q}\,\frac{P_{RF}}{P}\,\frac{V_{RF}}{V}\text{ watts}$$

where P_{RF}/p is the ratio of the RF pressure to the plasma pressure and $^VRF/V$ is the ratio of the volume occupied by the RF field to that of the plasma. Estimates indicate a value of $P_{RF}\sim1.4\ 10^9$ watts and the required radio frequency pressure is around 1.6 atmospheres.

As mentioned above, it is important to reduce ohmic loss in conductor **13** as far as possible. One technique for this is illustrated in FIG. 2. The torus **12** comprises an electrically insulating shell **14**, on top of which is deposited a layer of metal **14***a* of the order of 1 millimetre thick. A helical groove **15** is cut through the metal layer to leave a helical conductor **13***a*.

A technique for coupling RF power into the closed helical conductor **13** is illustrated in FIG. 1. A separate conductor **17**, insulated from the helical conductor **13**, is wound around adjacent a few turns of the helical conductor **13**, thus providing a close electromagnetic coupling into conductor **13** for RF power fed into conductor **17**.

It will be appreciated that appropriate modification of part of the groove cutting described with reference to FIG. 2 may be employed to introduce the conductor **17** as part of the thin metal layer.

The invention is not restricted to the details of the foregoing example. For instance, other configurations of containment vessel and closed conductor may be devised within the requirements defined. One such other configuration envisaged for the conductor is that of a generalised tennis ball seam in which the closed loops along which the waves are guided lie on the surface of a sphere and have a number of symmetrically arranged lobes, giving rise to an approximately multipole field configuration within. This arrangement has the advantage over the toroidal helix of allowing a significantly more favourable surface to volume ratio (and hence lower minimum plasma pressure). A normal tennis ball seam would probably have an unacceptably low radiation Q, so a more convoluted configuration is required. A difficulty lies in the choice of the accompanying static magnetic field. A magnetic mirror field can be excluded: it is necessary to envisage a topologically toroidal field, for example that created by a straight current-bearing conductor passing through the centre, or that of a magnetohydrodynamic Hill vortex.

It should be further appreciated that, in the foregoing description, it is envisaged that the torus **12** carrying the toroidal winding **13**, **13***a* will, in practice, be supported within an outer torus through which cooling fluids, etc., flow. The calculations of radiative loss from the toroidal windings, assuming radiation in free space, are thus, of course, not directly applicable to the practical situation. However, the same considerations apply, except that one is concerned with loss of power to the outer torus, rather than with loss of power by radiation into free space.

The foregoing example has, effectively, subdivided electrically conducting wires for providing the endless toroidal conducting path. It is envisaged that the toroidal conducting path may, for example, be alternatively provided by a toroidal waveguide.

I claim:

1. A plasma confinement apparatus comprising a vessel for containing a gas at low pressure, means for producing a static magnetic field tending to confine the plasma, means for producing a radio frequency electromagnetic field which moves relatively to the plasma faster than the ions in the plasma are moving, the frequency of the electromagnetic field being in the region of 1 megahertz, the said means for producing the radio frequency electromagnetic field including an elongated electrical conductor wrapped around the plasma and forming an endless path for conducting electrical or electromagnetic power, which path has a distributed inductance and capacitance such that it is a circuit which resonates at the frequency of the electromagnetic field.

2. A plasma confinement apparatus as claimed in claim 1, in which the vessel is toroidal.

3. A plasma confinement apparatus as claimed in claim 1 or claim 2, in which the electrical conductor forming

the endless conducting path comprises a closed toroidal helix encompassing the vessel.

4. A plasma confinement apparatus, as claimed in claim 1 in which the electrical conductor comprises a thin layer of metal deposited on the surface of the vessel and provided with a groove or grooves through the metal layer, the groove or grooves following the required direction of the conducting path.

References Cited

UNITED STATES PATENTS

3,015,618	1/1962	Stix	176—3
3,156,621	11/1964	Josephson	176—3
3,219,534	11/1965	Furth	176—3

REUBEN EPSTEIN, Primary Examiner

U.S. Cl. X.R.

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