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J. D. GOW ET AL

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ION MAGNETRON

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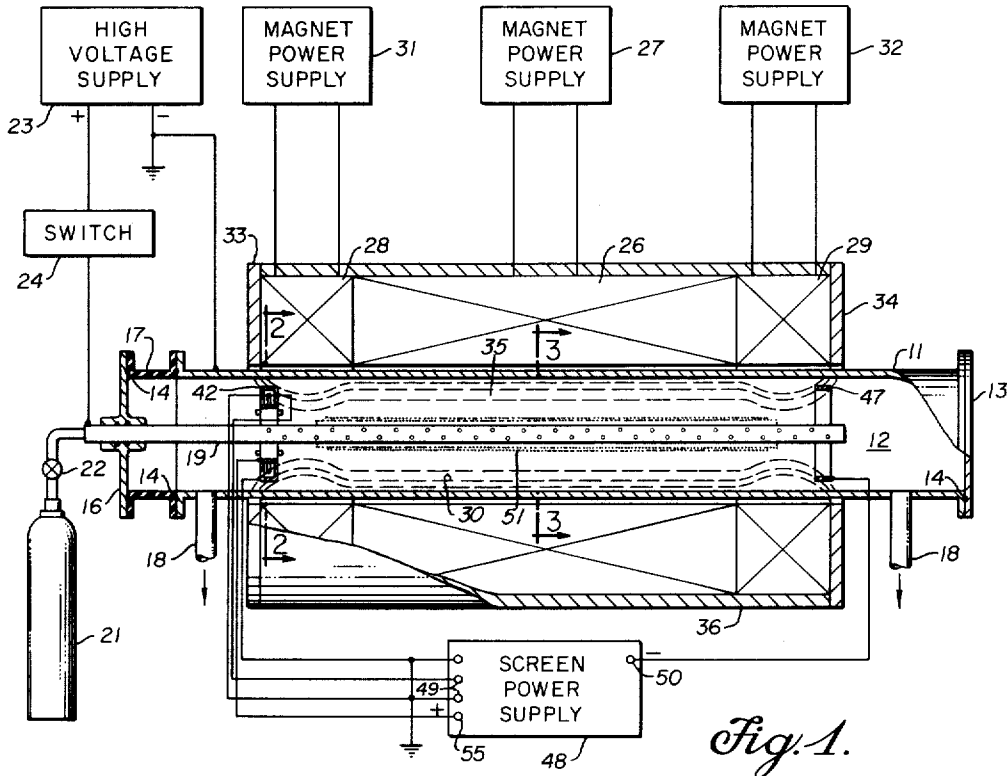


Fig. 1.

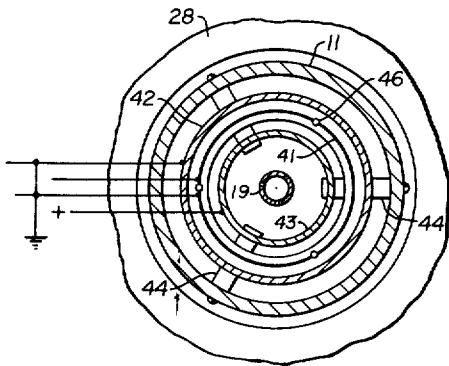


Fig. 2.

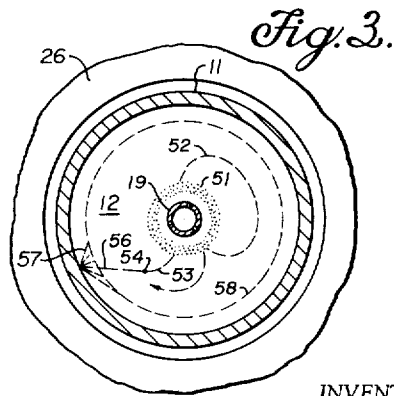


Fig. 3.

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1

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ION MAGNETRON

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The present invention relates to a containment and heating device for electrical plasma and more particularly to an improved ion magnetron usable as an ion source, neutron sources and for other purposes requiring the generation, containment and heating of an electrical plasma.

The ion magnetron is described in copending application Serial No. 758,633 entitled Ion Magnetron and filed September 2, 1958 by James D. Gow and John M. Wilcox and is further discussed in the text: Controlled Thermonuclear Reactions by Glasstone and Lovberg, D. Van Nostrand Co., Inc., New Jersey, 1960, pp. 435—437, such device being an advantageous containment means for an electrical plasma. In the ion magnetron, a plasma is generated having ions with very high energy or temperature. With a suitable "fuel" gas such as deuterium, nuclear interactions between ions can produce large quantities of high energy neutrons and high temperature ions may be extracted from the plasma and utilized externally.

As disclosed in the above-identified copending application the ion magnetron utilizes an axial magnetic field and a radial electric field to provide an annular crossed field region for ionizing, trapping and heating of gas particles. Neutral particles are injected from a central anode into the field region and ionized, the ionized particles being accelerated outwardly by the electric field, but normally being turned back to the central region in a cusped orbit by the magnet field. It has been found, however, that an encounter with a stray neutral particle may result in charge exchange whereby the ion becomes a neutral particle no longer deflected by magnetic field. Consequently, the new neutral particle strikes the outer shell or cathode of the ion magnetron and releases several other neutral particles into the field region. The release neutral particles cause still more charge exchanges with other circulating ions and a portion of the circulating ions may be lost. The operation of the machine may be greatly improved if the neutral particles released from the outer shell are kept out of the orbits of the circulating ions.

In the present invention a protective screen of electrons is established near the inside surface of the cylindrical shell of an ion magnetron. Neutral particles released from the shell wall are ionized while attempting to pass through the electron screen, the newly ionized particles being trapped by the magnetic field and removed from the machine by longitudinal drift along the magnetic field. The loss of the circulating ions which originate near the central part of the ion magnetron is reduced and the probability is enhanced that fusion collisions will occur within the trapping region.

It is, accordingly, an object of the present invention to improve the operation of an ion magnetron.

It is an object of this invention to provide a means for protecting an ionized plasma from contamination by neutral particles within a containment device of the class having cross electric and magnetic fields.

It is a further object of the present invention to form an electron screen for preventing neutral particles from entering the plasma trapping region of an ion magnetron.

It is another object of this invention to increase the high energy circulating ion current in an ion magnetron by preventing charge exchange with stray neutral particles.

2

It is still a further object of this invention to provide means for increasing the containment time of a plasma within an ion magnetron.

The invention both as to its organization and method of operation, together with further objects and advantages thereof, will best be understood by reference to the following specification taken in conjunction with accompanying drawings, of which:

FIGURE 1 is an axial section view of an ion magnetron embodying the invention;

FIGURE 2 is a cross section view taken at line 2—2 in FIG. 1 and showing further details of the structure; and

FIGURE 3 is a cross section view taken at line 3—3 in FIG. 1 and illustrating the effects of the invention on particles within the containment apparatus.

Referring now to the drawing and, more particularly, to FIG. 1 thereof, there is shown a cylindrical shell 11 of stainless steel or similar conductive material defining a plasma chamber 12 and constituting an outer electrode. A circular end plate 13 closes one end of the shell 11, the end plate being secured to a flange thereon with an annular metal gasket vacuum seal 14 therebetween. The plate 13 may be utilized as a window for extracting ions, or for other purposes, for example the plate may include transparent material and be used for observation of the plasma region. The opposite end of the shell 11 is closed by a centrally apertured circular second end plate 16, which plate is spaced from the shell 11 and electrically isolated therefrom by a flanged cylindrical insulator 17. Metal annular vacuum seals 14 are disposed between the end plate 16, insulator 17 and shell 11. A pump-out tubulation 18 is provided at each end of the shell 11 at the sidewall thereof for connection with vacuum pumping means whereby the chamber 12 may be evacuated to a low pressure.

A long narrow cylindrical central electrode 19 is disposed along the axis of the shell 11, the electrode extending through the central aperture in the second end plate 16 and being supported thereby. Owing to insulator 17, the central electrode is electrically isolated from the shell 11. If necessary, the opposite end of the central electrode 19 may be supported by the end plate 13 if similar insulation is also provided to isolate the plate 13 from the shell 11. The central electrode 19 is a hollow multiply perforated tube for the introduction of gaseous electrically neutral fuel into the chamber 12 and for establishing a radial electric field in the chamber 12 between the shell 11 and the inner electrode 19. In other embodiments, the central electrode 19 may be replaced by an ion beam or electron beam for the latter purpose and the fuel can be introduced in another way. However, in the device as shown here, the central electrode 19 projects outside the chamber 12 beyond the second end plate 16 where the gaseous fuel is supplied to the interior of the electrode from a gas supply 21 through a valve 22. The electric field between the shell 11 and the central electrode 19 is created by a potential from a high voltage supply 23 connected thereacross, the inner electrode 19 being positive relative to the shell. For practical considerations of safety and insulation, the shell 11 is generally placed at ground potential. A switch 24 is connected between the high voltage supply 23 and the central electrode 19 so that a pulsed voltage may be applied between the shell 11 and electrode 19. In some instances, it may be preferable to apply a direct current voltage with superimposed pulses.

The magnetic field is provided by three annular field coils disposed coaxially around the shell 11, a central magnet coil 26 being connected to a central magnet power supply 27 with a first and second mirror field coil 28 and 29 disposed at each end of the central magnet coil

3

26 and connected respectively to second and third magnet power supplies 31 and 32. Generally, the apparatus is operated so that the magnetic field of the mirror coils 28 and 29 is more intense than the field from the central magnetic coil 26, thereby creating a magnetic mirror at each end of the chamber 12. Typical magnetic field flux lines are indicated in FIG. 1 by dashed lines 30. The mirror effect is further enhanced by concentrating the magnetic field lines at each end of the chamber 12 by providing a first and second annular end cores 33 and 34 of a material with high magnetic permeability which cores are mounted coaxially on shell 11 adjacent the outer ends of coils 28 and 29. A cylindrical shell 36 of similar material is disposed about the coils 26, 28 and 29, a complete magnetic circuit being formed through the shell 36, first end core 33, chamber 12 and the second end core 34. Since the magnetic field is thus crossed with the electrical field, an annular plasma trapping region 35 is created between the shell 11 and the central electrode 19 and between the magnetic mirrors.

The apparatus as described to this point is essentially the basic ion magnetron and as previously discussed, is subject to some loss of plasma by charge exchange with neutral gas particles drifting from the wall of shell 11 towards the inner electrode 19. To minimize such loss, the present invention provides an annular electron sheath around the plasma trapping region and between the shell 11 and electrode 19.

Considering now the electron sheath forming means and with reference to both FIGS. 1 and 2, an annular filament 41 is disposed coaxially around the center electrode 19 near the inside surface of the shell 11 and near an end of the chamber 12 in the mirror field region, the filament being at the end of the shell closed by plate 16 in this instance. An annular shield 42 of channel shaped cross-section is symmetrically disposed around the filament 41 in spaced relation thereto. An annular accelerating electrode 43 is disposed in coaxial relationship with the filament 41 and radially inward therefrom. As shown in FIG. 2 in particular, a plurality of paired radially directed insulators 44 secure the shield 42 and accelerating electrode 43 to the shell 11. Filament insulators 46 support the filament 41.

Referring now again to FIG. 1, an annular reflector electrode 47 is disposed at the opposite end of the chamber 12 in coaxial relationship therein and in the same relative position in the second magnetic mirror field as is occupied by the filament 41 in the opposite mirror field. It is desirable that the filament 41 and reflector 47 have configurations and positions whereby each intercept the same magnetic flux lines. Thus, since the magnetic field in this embodiment is symmetrical about the central transverse plane of the apparatus, the filament 41 and reflector 47 have similar diameters. It should be understood, however, that this is not an essential condition in all embodiments, some of which may employ asymmetric magnetic fields.

A multi-tap power supply 48 provides operating potentials for the electron sheath producing elements described above. A pair of high current terminals 49 on supply 48 are connected to filament 41 to provide heating current thereto. One of the terminals 49 is connected to ground potential. To repel electrons a negative bias is applied to reflector 47 by connection with a negative terminal 50 on supply 48 and a positive terminal 55 thereof is connected with the accelerating electrode 43. Shield 42 is grounded.

Considering now the operation of the invention, it will be assumed that the screen power supply 48, and the magnet power supplies 27, 31 and 32 are energized. The high voltage supply 23 may be operated in either pulsed or steady state operation by suitable control of the switch 24. It will also be assumed that the chamber 12 has been evacuated and that a suitable gas such as deuterium has been introduced into the chamber 12 through the central

4

electrode 19 by opening the valve 22. The neutral gas emitted from the perforations in the central electrode drifts outwardly. With the switch 24 closed, a radial electric field is created between the shell 11 and the central electrode 19, the central electrode 19 being positive with respect to the shell 11. Thus positive ions will be attracted toward the negative liner 11 while electrons will form an annular layer 51 around the positive central electrode 19 as shown in FIG. 3. Breakdown occurs between the central electrode 19 and the shell 11, ionizing the gas. The ions and electrons tend to travel radially outwardly and inwardly respectively but are forced by the axial magnetic field to orbit around the central electrode in cusped paths. The ions, being heavier than the electrons, orbit in longer cusped paths (have a longer Larmor radius) than do the electrons and are relatively much more mobile across magnetic field lines than electrons. Electrons within a distance of one electron Larmor radius from the central electrode 19 easily strike the electrode 19 and are removed. The electron layer 51 therefore exists at a distance greater than one Larmor radius from the central electrode while an ion-electron plasma fills the trapping region 35 between the layer 51 and shell 11. Nearly the entire voltage drop between the central electrode 19 and shell 11 occurs across the electron layer 51, thus any neutral particle which is ionized by such layer 51 is immediately accelerated outwardly toward the shell 11. However, the axial magnetic field in the chamber 12 deflects the ion into a curved path along which the ion travels back into the electron zone again as shown in FIG. 3 by a typical cusped ion orbit 52. The ion will be again accelerated outwardly by the electric field of the layer 51 and will continually repeat this motion in a manner comparable to the electron orbits in a magnetron. In some operations, it is desirable that the ion remain in orbit long enough for a fusion reaction to take place where the gas used is one having a reasonable probability of fusing. In many instances, however, a charge exchange occurs between a high energy orbiting ion 53 and a stray neutral particle as at point 54, the ion taking an electron from the neutral particle, the former high energy ion then becoming a high energy neutral particle and the former low energy neutral particle becoming a low energy ion. Thus, a high energy ion has been exchanged for a low energy ion. The new neutral particle is no longer deflected by the magnetic field, following a straight path 56 until it impinges against the shell 11 with the possibility of knocking several more neutral particles 57 out into the chamber 12. The effect of such a charge exchange is a reduction of the probability of a fusion reaction and a lessening of plasma temperature and containment time. Thus the operation of the ion magnetron will be improved if there is a reduction of neutral particles in the region where the ions are orbiting.

The present invention was developed in order to prevent the above-described effect by screening the "secondary" neutral particles from the space where the ions are orbiting. An electron screen 58 is created near the inside surface of the shell wall 11 for ionizing any of the "secondary" neutral particles knocked out of the shell 11. The low energy ions so created are then removed by a process to be hereinafter described. Thus the neutral density in the space between the electron screen 58 and the electron layer 51 is considerably reduced. The orbiting ions are maintained for a much longer time than previously and the probability of a fusion collision between ions is greatly enhanced.

The circular filament 41 when heated is the source of the screen electrons. As shown in FIG. 1, electrons from the filament 41 move towards the center of the apparatus along the magnetic flux lines 30 which are intercepted by the filament. The filament electrons thus occupy an annular region of varying radius extending between the filament 41 at one end of the chamber 12 and the reflector electrode 47 at the other end forming a screen

58 coaxial with the inside surface of the shell 11 as shown in FIG. 3.

Electrons from the filament 41 can move in either direction along the magnetic field, either toward the reflector electrode 47 to form the screen 58 or toward the channel electrode 42. The electric field between the shield electrode 42 and the accelerating electrode 43 prevents the latter electron movement so that virtually all filament electrons are emitted into the screen 58. When an electron from the filament 41 reaches the reflector electrode 47, the negative potential thereon repels the electrons back toward the filament 41.

After particles traveling toward the electron screen 58 from the region of shell 11 are ionized in the screen, the particles are no longer free to move about except along the magnetic lines. The ions diffuse along the magnetic lines to the ends of the chamber 12 where the ions are attracted by the relatively negative charge of either reflector electrode 47 or the shield electrode 42. The ions are neutralized by contact with such electrodes and a large proportion are then removed through the adjacent vacuum pump-out connections 18.

In operation, considerable variation in the physical configuration and disposition of the electron screen producing electrodes is allowable without greatly altering the desired result, specifically the suppression of secondary ions. Similarly, variations in the applied potentials from the screen power supply 48 and the other operating parameters of the ion magnetron may be made without altering the basic operation of the device.

Thus while the invention has been disclosed with respect to a single 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 thus it is not intended to limit the invention except as defined in the following claims.

What is claimed is:

1. In combination with a plasma containment device of the class having a vacuum enclosure with a magnetic field therein and having spaced apart positive and negative electrodes for establishing an electrical field within said enclosure which electrical field is crossed with said magnetic field to provide a plasma trapping region, a means for preventing the movement of neutral gas particles into said trapping region from the region of one of said electrodes comprising a spaced apart electron emissive element and electron reflecting element disposed within said enclosure between said one electrode and said trapping region whereby an electron sheet is established therebetween, said electron sheet acting to ionize said neutral gas particles whereby said particles are constrained to drift along said magnetic field rather than into said trapping region.

2. In a plasma containment apparatus of the class having a vacuum envelope with a magnetic field therein which magnetic field is symmetrical about an axis passing through said envelope and having coaxial positive and negative electrodes centered on said axis and providing an electric field which is symmetrical about said axis and which is crossed with said magnetic field to provide an annular plasma trapping region, a means for preventing the movement of neutral gas particles into said trapping region from the region of one of said electrodes comprising an annular electron emitting element disposed within said envelope at a first end of said trapping region and centered on said axis, and an annular electron reflecting element disposed within said envelope at the second end of said trapping region and centered on said axis whereby an electron sheath is established around said trapping region to ionize said neutral gas particles whereby said particles are constrained to drift along said magnetic field.

3. In a plasma heating apparatus of the ion magnetron class having a cylindrical outer electrode and an inner electrode disposed coaxially therein providing a radial

electrical field and having means providing a longitudinal magnetic field within said electrodes to establish an annular crossed field plasma trapping region, the combination comprising an annular electron emissive element disposed coaxially within said outer electrode adjacent a first end thereof and radially outward from said plasma trapping region, an annular electron reflecting element disposed coaxially within said outer electrode adjacent the second end thereof and being radially outward from said plasma trapping region whereby an annular electron sheath is formed in said outer electrode which is coaxial with said annular plasma trapping region and radially outward therefrom.

4. A plasma heating apparatus as described in claim 3 and wherein said electron emissive element and said electron reflecting element are situated to intercept identical flux lines of said magnetic field.

5. In a plasma heating apparatus of the ion magnetron class having a cylindrical negative electrode and positive electrode disposed coaxially therein providing a radial electric field there-between and having means providing a longitudinal magnetic field within said negative electrode whereby a crossed field annular plasma trapping region is established between said electrodes, the combination comprising an annular filament disposed within a first end of said negative electrode in coaxial relationship therewith and spaced radially outward from said positive electrode, power supply means connected with said filament to provide for the emission of electrons therefrom, an annular conductor disposed within said negative electrode at the second end thereof and in coaxial relationship therewith, said annular conductor being spaced radially outward from said positive electrode, and a potential source connected to said conductor and applying a negative potential to said conductor relative to that of said filament whereby electrons emitted from said filament and traveling towards said conductor along said magnetic field are reflected back towards said filament to form an electron sheath around said plasma trapping region.

6. In a plasma heating apparatus as described in claim 5, the further combination of an annular shielding electrode of greater radius than said filament and disposed substantially concentrically therewith, and means applying a potential to said shield electrode which potential is at least as negative as that of said filament.

7. In a plasma heating apparatus as described in claim 5, the further combination of an annular accelerating electrode of lesser radius than said filament and disposed coaxially therewith in adjacent relationship thereto, and means applying a potential to said accelerating electrode which potential is positive with respect to that of said filament.

8. In a plasma containment and heating apparatus of the class having a long cylindrical coil providing a longitudinal magnetic field and having means at each end for intensifying said magnetic field to provide magnetic mirror fields thereat and having coaxial cylindrical electrodes disposed within said coil which electrodes are aligned along said magnetic field and provide a radial electric field within said coil, the further combination of an annular electron emissive filament disposed coaxially within said coil within a first of said magnetic mirror fields, said filament having a radius intermediate between that of said coaxial electrodes, an annular conductor disposed coaxially within said coil within the second of said magnetic mirror fields, said annular conductor having a radius intermediate between that of said coaxial electrodes, and means applying a negative electrical potential to said conductor whereby electrons emitted by said filament and traveling along said magnetic field are reflected by said conductor and form an annular sheath within said coil.

9. In a plasma generating and containment device of the class having a long cylindrical coil providing a longitudinal magnetic field therein and having means at each end for intensifying said magnetic field to provide mag-

7

netic mirror fields at the ends of said coil and having coaxial inner and outer cylindrical electrodes disposed longitudinally within said coil and means applying a negative potential to said outer electrode relative to said inner electrode to provide a radial electric field within said coil, the further combination of means for preventing the movement of neutral gas particles toward the region of said inner electrode, said means comprising an annular filament disposed between said outer and inner electrodes in coaxial relationship therewith and within the region of a first of said magnetic mirror fields, a power supply connected with said filament to provide for the emission of electrons therefrom, an annular conductor disposed between said outer and inner electrodes in coaxial rela-

8

tionship therewith and within the region of the second of said magnetic mirror fields, said annular conductor being situated to intercept the same magnetic flux lines as are intercepted by said filament, and means applying a negative potential to said annular conductor whereby electrons emitted by said filament and traveling along said magnetic flux lines are reflected toward said filament to establish an annular electron sheath between said inner and outer electrodes.

References Cited in the file of this patent

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2,961,558 Luce et al. ----- Nov. 22, 1960