Jan. 2, 1962 T. H. STIX 3,015,618

APPARATUS FOR HEATING A PLASMA

Filed June 30, 1958 2 Sheets-Sheet 1

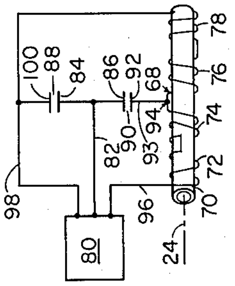

Fig. 2

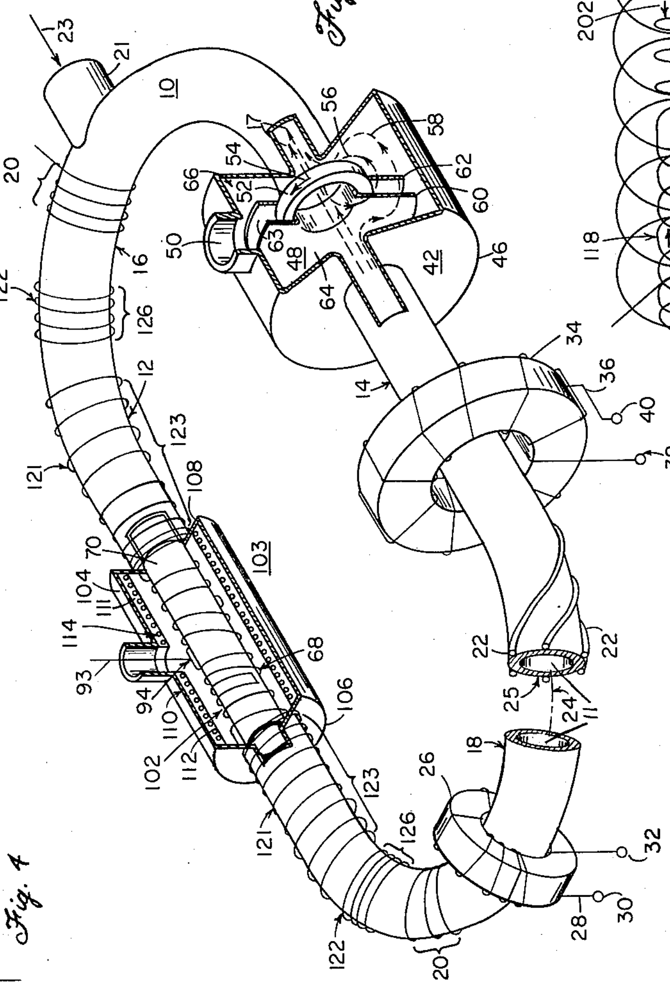

Fig. 1

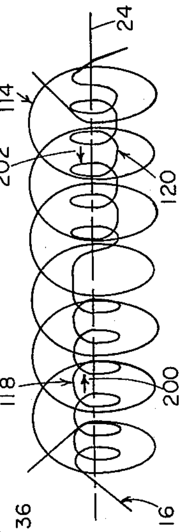

Fig. 3

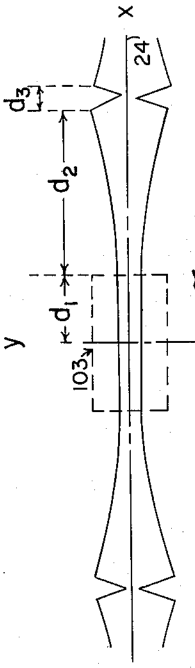

Fig. 4

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APPARATUS FOR HEATING A PLASMA

Filed June 30, 1958 2 Sheets-Sheet 2

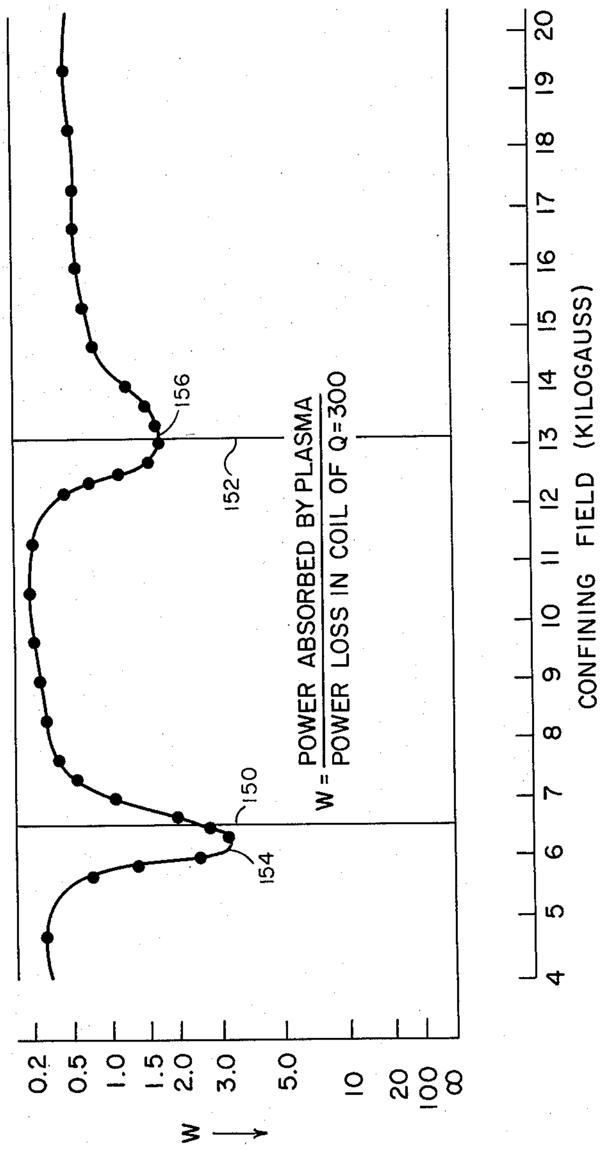

Fig. 5

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United States Patent Office

3,015,618
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3,015,618

APPARATUS FOR HEATING A PLASMA

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Filed June 30, 1958, Ser. No. 745,778
6 Claims. (Cl. 204—193.2)

This invention relates generally to a method and apparatus for transferring energy to a plasma immersed in a confining magnetic field and particularly to a method and apparatus for heating a plasma of low atomic number ions to high temperature by transfer of energy to plasma resonances.

Broadly, this invention involves method and apparatus for establishing a plasma confining magnetic field in an evacuated zone, establishing a plasma immersed in the field and transferring energy from a resonating field to a plasma resonance. A variation of this invention involves transferring energy from a resonating field to the plasma at the ion cyclotron frequency of the plasma ions. Another variation involves generating ion cyclotron waves in the plasma by a resonating field having a frequency below the ion cyclotron frequency of the plasma ions and thermalizing the energy in the waves.

In accordance with this invention, ion cyclotron motions and ion cyclotron waves are excited in a plasma of approximately cylindrical cross section immersed in a strong, axial magnetic field by a resonating section having an induction coil surrounding the plasma. The coil is made up of helical sections, and the azimuthal direction of current flow is caused to alternate every half wave length in the coil axial direction. The helical sections are connected electrically in a series parallel pattern, and their total inductance is resonated with a capacitor network by a radiofrequency voltage generator. Thus the current in the induction coil varries periodically with both time and distance along the direction of the plasma confining magnetic field. The radiofrequency current in the induction coil induces an electric field in the plasma. The frequency and wave length of the electric field are chosen close to a frequency and wave length of a resonance in the plasma so that it will be properly excited.

In the event an attempt is made to transfer energy to the plasma ion cyclotron resonance by a resonating magnetic field which does not have the necessary periodicity with distance, a space charge develops which precludes efficient energy transfer to the resonance. The space charge results from the different ion cyclotron frequencies of the ions and of the electrons of the plasma. Because of this difference, the electrons of the plasma cannot follow the ions as the ions are accelerated and the ions become separated from the electrons to produce the space charge. However, in accordance with this invention, the periodicity with distance of the resonating field permits electrons to flow along the lines of force and thereby cancel out the undesired ion space charge. The electrons in an adjacent sector of the resonating field having the required periodicity move toward the ions of the other sector separated from their plasma electrons.

An object of this invention is to provide method and apparatus for heating a plasma.

Another object of this invention is to provide method and apparatus for heating a plasma immersed in a confining magnetic field by exciting natural resonances in the plasma.

A further object of this invention is to provide method and apparatus for heating the plasma of a high temperature reactor in which the plasma is immersed in a confining magnetic field.

A first additional object of this invention is to provide

method and apparatus for heating a plasma immersed in a confining magnetic field by varying a resonating magnetic field periodically in time in a generating section of the confined plasma at a frequency approximately equal to the ion cyclotron frequency of the ions in the plasma.

A second additional object of this invention is to provide method and apparatus for generating waves in a plasma immersed in a confining magnetic field by varying a resonating magnetic field periodically in time in a generating section of the confined plasma at a frequency approximately equal to the frequency for which the plasma has a natural resonance such as the natural resonances of ion cyclotron waves and torsional and compressional hydromagnetic waves.

A third additional object of this invention is to provide method and apparatus for heating a plasma immersed in a confining magnetic field by causing thermalization of ion cycylotron motions and/or ion cyclotron waves through collisions of ions of different ratios of ion charge to ion mass.

A fourth additional object of this invention is to provide method and apparatus for heating a plasma immersed in a confining magnetic field by causing ion cyclotron waves to propagate into a thermalizing section wherein the plasma-confining magnetic field diminishes gradually in intensity along the lines of force and wherein thermalization of the ion cyclotron wave energy takes place.

A fifth additional object of this invention is to provide method and apparatus for heating a plasma immersed in a confining magnetic field and temporarily restrained in its movement along the lines of force of the confining magnetic field through the use of magnetic mirrors by varying a resonating magnetic field periodically in time in a generating section of the confined plasma at the frequency of a natural resonance in the plasma.

These and other objects of the invention will be understood through consideration of the following discussion and claims taken in conjunction with the drawings in which:

FIGURE 1 is a diagrammatic view, partially cut away, of a high temperature reactor of the stellarator class in accordance with this invention showing the electrical windings for both a resonating section and a thermalizing section.

FIGURE 2 is a schematic circuit diagram illustrating in simplified fashion the nature of the electrical windings of an embodiment of the present invention and the manner in which they are energized.

FIGURE 3 illustrates diagrammatically one manner of forming an electrical winding in accordance with this invention.

FIGURE 4 is a line drawing illustrating the manner in which the intensity of the confining magnetic field varies in different portions of a plasma heating device in accordance with this invention.

FIGURE 5 is a graph showing the variation of the plasma power absorption for two ion species, helium and hydrogen, as a function of the strength of the confining field for a particular exciting frequency.

A plasma is a gaseous state of matter in which some or all of the atoms are ionized and the total ion charge is neutralized by electrons. When two ions of a plasma comprising ions of low atomic number elements such as deuterium and/or tritium collide, there is a possibility that a high temperature reaction will occur. The value of the probability increases as the relative energy of the two ions increases. Such reactions result in an output of energy by the plasma. The output energy equals the external energy transferred to the plasma at a threshold plasma temperature and exceeds it above the threshold. In order that an appreciable number of reactions occur within a plasma, the relative energy of many colliding ions must be large. Energetic collisions of ions in a plasma occur when external energy transferred to the plasma has been randomized or thermalized among the ions thereof. The energy of a plasma embodied in the motion of its ions is randomized or thermalized when the ions move in a non-organized or non-cooperative manner. Wave or oscillation motion of ions in a plasma is termed a cooperative process. A plasma can have a great amount of stored energy without having a high temperature. A high temperature of a plasma results from a great amount of energy being in random motion of its electrons and ions.

Ions and electrons having a transverse component of motion across the lines of force of a magnetic field tend to gyrate about the lines of force. A plasma is immersed in a confining magnetic field when its ions and electrons, through their gyration about the lines of force, are temporarily localized.

The transverse gyration of an ion in a confining magnetic field is termed its "ion cyclotron motion." The frequency of an "ion cyclotron motion," $f_{\text{ion cyclotron}}$, is given by the expression

$$f_{\text{ion cyclotron}}=\frac{Z_i e B_0}{2\pi m_i c} \qquad (1)$$

where:

Z_i=atomic number of the ion
e=charge of an electron
B_0=flux density of the magnetic field
m_i=mass of the ion
c=velocity of light in vacuum

In accordance with this invention, it is possible to transfer energy with a high efficiency from a radiofrequency power source to a plasma immersed in a confining magnetic field by exciting certain resonances in the plasma. The resonances include ion cyclotron motions, ion cyclotron waves and torsional and compressional hydromagnetic waves. For a detailed discussion of the resonances, reference is made to the following articles and citations therein: "The Physics of Fully Ionized Gases," by L. Spitzer, Jr., chapter IV, Interscience Publishers, Inc., New York; and "Oscillations of a Cylindrical Plasma" by Thomas H. Stix, The Physical Review, volume 106, No. 6, pp. 1146–1150, June 15, 1957.

The term "ion cyclotron wave" refers to a natural oscillation or wave in a plasma which is immersed in a confining magnetic field, where the motion of the plasma ions taking part in the natural oscillation or wave is primarily transverse to the lines of force of the confining magnetic field, where the wave length (measured along a line of force) is relatively short, and where the frequency is slightly below the ion cyclotron frequency for the ions.

Ion cyclotron waves are excited in the plasma by a resonating field having frequencies slightly below the ion cyclotron frequency and relatively short wave lengths (wave length measured along a line of force). The short wave length is required because an undesirable ion space charge, which results from the wave motion, is thereby neutralized by electrons flowing along the lines of force. The inductive effect of this neutralizing electron current lowers the resonant frequency of the ion cyclotron wave below the ion cyclotron frequency and decreases the plasma heating effect of the ion cyclotron wave. The amount by which the resonant frequency is lowered becomes appreciable if the wave length is not short. For ion cyclotron motion, if the wave length is not short, a very similar inductive effect reduces the amount of heating of the ions which is achieved with a given induced electric field.

The characteristics of ion cyclotron waves are discussed at length in the Stix Physical Review article aforesaid. Ion cyclotron waves and torsional hydromagnetic waves correspond to the same root of a general dispersion relation, e.g., equation 10 of this article, whereas compressional hydromagnetic waves correspond to a different root. A dispersion relation for an oscillation or wave in a plasma gives the relationship between the frequency and wave length thereof. Ion cyclotron waves and torsional hydromagnetic waves have different sets of values of the parameters such as frequency, wave length, gas density and magnetic field strength. In principle, a torsional hydromagnetic wave may be converted in a continuous fashion into an ion cyclotron wave by gradual adjustments of these parameters. Herein, included in the meaning of the term "ion cyclotron wave" are those waves which can in this continuous fashion be, in principle, converted into ion cyclotron waves with properties and parameters as described in the referenced Stix article.

The ion cyclotron motions and the ion cyclotron waves are of especial interest for the heating of a plasma of a high temperature reactor. Radiofrequency energy in a resonating field is transferred into these plasma resonances in a generating section in accordance with this invention. The energy stored in the plasma resonances can, in accordance with this invention, be thermalized extremely rapidly into ion motions which are transverse to the magnetic lines of force with effectively random phases and amplitudes to heat the plasma.

The resonant frequency for ion cyclotron waves is given approximately by

$$f=f_{\text{ion cyclotron}}\sqrt{\frac{1}{1+\alpha/k^2}} \qquad (2)$$

where

$f_{\text{ion cyclotron}}$ is the same as in Equation 1 above,

$$\alpha/k^2=\frac{n_i\lambda^2 Z_i^2 e^2}{\pi m_i c^2}$$

n_i=number of ions per cc.,
λ=wave length of the resonating field,

the other symbols being the same as in Equation 1. Ions in a plasma confined by an approximately uniform magnetic field can be heated by exciting these resonances and causing the wave energy to thermalize. The ion energy gained is energy of transverse motion, so the heated ions can be temporarily confined to a limited spatial region through the use of magnetic mirrors. Magnetic-mirror ion confinement is produced when the ratio of the squares of the transverse and longitudinal ion velocities is relatively large. Magnetic mirrors are described at length in the Spitzer book aforesaid and in the co-pending application S.N. 443,447 of Richard F. Post.

The thermalization of energy of organized ion cyclotron motions may take place through the process of cyclotron damping, as described hereinafter, in approximately the time required for ion-ion collisions or the time required for ions to move along a line of force through the heating region whichever is shorter. The thermalization of ion cyclotron waves may also occur by cyclotron damping if the frequency of the oscillation is sufficiently close to the ion cyclotron frequency of plasma ions.

A brief description of the process termed "cyclotron damping" follows. Ions in a confining magnetic field move in a helical path. They spiral around a magnetic line of force with a frequency which is called their ion cyclotron frequency (Equation 1), and move in an unrestrained manner along the line of force. An ion may be accelerated by an electric field, and if an ion which has an oscillatory motion is accelerated by an oscillating electric field in such a manner that the oscillatory acceleration of the ion is in phase with the oscillatory velocity of the ion, the ion will gain energy. In this manner, an ion gains energy in the oscillatory electric field of a cyclotron, and similarly, an ion in a plasma can gain energy from an electric field which oscillates in the plasma with a frequency approximately equal to ion cyclotron frequency. If the electric field in the plasma also has a periodic spatial variation (distance measured along a line of force), an ion traveling along a line of force will "feel" the electric field at a different frequency than the electric field frequency because of Doppler effect (the apparent frequency variation which one notices when approaching and then leaving a musical tone producer, as when passing a ringing bell while riding on a train is due to the Doppler effect). Thus, even if the frequency of oscillation of the electric field in the plasma is not exactly equal to the ion cyclotron frequency for ions of the plasma, there will be some ions which travel through the oscillation along the lines of force with just such velocities that they will "feel" the electric field at their ion cyclotron frequency. For these ions, the acceleration due to the oscillating electric field will remain for a relatively long time (compared to other ions moving through the thermalizing section with different velocities) in phase with the oscillating component of the ion velocity. Such ions will gain large amounts of energy from the electric field. The energy gained will be energy of motion of the ions transverse to the lines of force of the confining magnetic field. If ions pass out of the region of acceleration, or if the ions suffer slight changes of velocity along the lines of force due to collisions with other ions, this transverse energy becomes partially thermalized in the sense that the resultant distribution of transverse energy and velocities will contain almost random phases and amplitudes. If the electric field is produced by an ion cyclotron wave, the absorption of energy from the wave by ions causes the wave to damp out with respect to either time or distance or with respect to both. The electric field may alternatively be simply the induced field of an induction coil. In either case, cyclotron damping is the absorption of energy from the electric field by those ions which pass through the electric field with just the proper velocities along the lines of force that they "feel" the electric field at their own ion cyclotron frequencies.

Thermalization of both ion cyclotron motions and ion cyclotron waves may also take place through collisions of charged particles of different mass. While ion-electron collisions transform the energy of organized plasma motion into random motion at a relatively slow rate, a faster thermalization occurs if the ion cyclotron motions or ion cyclotron waves are excited for one ion species in a plasma containing two or more species of ions such as deuterium and tritium. When the plasma contains a mixture of two or more ion species with different charge-to-mass ratios, the collective motion of the different ion species will be very different. The amplitude of collective motion will be much larger for the resonant ions, and thermalization will occur through collisions of resonant and non-resonant ions.

The excitation of a very short wave length resonance in a plasma by a correspondingly short wave length induction coil generally has a poor efficiency of transfer of radiofrequency power from the coil to the plasma. Yet the wave length for which the power transfer is efficient may be so long that thermalization of the wave energy will take place only very slowly in the plasma within the induction coil. In an embodiment of this invention, the wave length of the induction coil is such that the transfer is efficient. A thermalizing section is provided adjacent an end of the induction coil into which ion cyclotron waves are caused to propagate. In the thermalizing section there is a region of slowly decreasing magnetic field in the direction away from the induction coil. The decreasing field causes the wave length to become shorter and shorter and the frequency approaches the local ion cyclotron frequency. When the wave length is sufficiently short and the frequency is sufficiently close to the local ion cyclotron frequency, cyclotron damping begins to occur. Ions passing through the ion cyclotron wave in this region will pick up energy from the oscillation, and the wave amplitude damps out. Those ions which pick up energy or velocity increments by cyclotron damping have an axial velocity distribution, and the phases of their velocity increments will become incoherent or non-organized as these ions travel farther along axially. This phase mixing gives effective randomization of the ion motions and so there results a heating of the plasma.

This invention includes method and apparatus for: establishing a confining magnetic field which is unidirectional and approximately static in a zone which has been evacuated to a high vacuum; admitting a pure gas of low atomic number atoms into the zone; forming a plasma in the zone; establishing a resonating field in a generating section of the zone; and varying the resonating field at a frequency approximately equal to the ion cyclotron frequency of the ions in the plasma whereby the energy is transferred to the ions.

An aspect of this invention includes the apparatus and method where the resonating field in the generating section is caused to vary at a frequency approximately equal to the frequency at which the plasma has a natural resonance, such as the resonances of ion cyclotron waves and torsional and compressional hydromagnetic waves whereby such waves are generated and energy is transferred to the plasma.

In another aspect of this invention, the generating section is of a particular design, hereinafter called a periodic generating section. Within this section the intensity of the resonating field varies periodically with distance—measured along the lines of force of the confining magnetic field—and periodically with time. This distance periodicity is the same as that of the oscillatory motions induced in the plasma. The induced motions have preferentially a periodicity with a distance—measured along a line of force. Thereby energy is transferred to the plasma.

Still another aspect of this invention is apparatus and method for partial thermalization or randomization of ion cyclotron motions and/or ion cyclotron waves incorporating a plasma composition of ions with different ratios of ion charge (Z_ie) to ion mass (m_i) in which the waves and/or motions are induced at a frequency which is approximately equal to the ion cyclotron frequency of only one of the constituent ion types whereby the energy of the waves and/or motions is partially thermalized by collisions between resonant and non-resonant ions thereby heating the plasma.

A further aspect of this invention includes apparatus for the partial thermalization or randomization of ion cyclotron waves in which an ion cyclotron wave thermalizing section is established adjacent the generating section, and through this thermalizing section pass some or all of the lines of force of the confining magnetic field which have also passed through the generating section. In the thermalizing section, the confining magnetic field is caused to diminish gradually in intensity with increasing distance from the generating section. The ion cyclotron waves are propagated out of the generating section into the thermalizing section and therein undergo a change of character with increasing distance from the generating section, namely, their wave length decreases and the ratio of ion cyclotron wave frequency to the local ion cyclotron frequency approaches unity. Thereby in a portion of the thermalizing section, where the ratio is sufficiently close to unity, cyclotron damping occurs and the wave energy is partially thermalized.

In another aspect of the invention, a plasma is immersed in a main confining magnetic field in which the movement of its ions is temporarily restrained by magnetic mirrors. A magnetic mirror section is adjacent to the thermalizing section, and the magnetic field therein is caused to attain a value significantly higher than the lowest value of the flux density of the confining magnetic field in the generating or in the thermalizing section, the latter sections all as aforesaid.

With mirror sections near each end of a generating section, a plasma may be temporarily confined to the spatial region between the two mirror sections. With a mirror section near only one end of a generating section, or with mirror sections of unequal strength near the ends of a generating section (i.e., the peak confining magnetic field strength in the two mirror sections is of unequal strength), a plasma will diffuse or flow away from one end of the generating section faster than it diffuses or flows away from the other. Such an apparatus and method may be used to pump a gas from one spatial region to another and to separate ions of different charge-to-mass ratios. It may also be used in an ion propulsion rocket motor to impart momentum to the current carrying conductors which produce the magnetic mirror fields.

The excitation of particle and plasma resonances by transfer of energy to the plasma in accordance with this invention is applicable to purposes other than the heating of the plasma. One such use is the generation and detection of resonances such as torsional and compressional hydromagnetic waves and ion cyclotron waves and motions as a diagnostic technique. This yields information on those parameters of the plasma and its environment which affect the character of the resonances. Typical parameters would be the density distribution of the various ion species in the plasma, the electron and ion temperatures and the magnetic field strength. The waves may be detected through their magnetic and electric fields, and for detection, a magnetic pickup coil may be used which is in, out of, or surrounding the plasma.

The main problems involved in the development of a high temperature reactor to provide energy from self-sustaining nuclear reactions in a plasma relate to stable confinement of the plasma away from material objects, heating of the plasma to high temperature, and removal of impurities tending to contaminate the plasma. These problems and their solutions are interrelated. This invention relates generally to the confinement, heating and impurity problems and provides specifically a solution to the heating problem.

This invention is particularly suitable for heating a plasma of a high temperature reactor of the stellarator class described in co-pending applications of Lyman Spitzer, Jr., S.N. 688,089 and S.N. 705,071. It is, however, not limited to use in this class of reactor and may, for example, be utilized for heating the plasma of a reactor of the pyrotron class described in the referenced Post application.

A high temperature reactor of the stellarator class incorporates an endless, torus-like tube within which a fully ionized, high temperature plasma is confined. The plasma is confined within the tube by a static, unidirectional, magnetic field established by two different types of electrical windings on the tube. First there is a winding which establishes a strong, toroidal, magnetic field in the torus. Second, there is a winding which adds to the toroidal magnetic field a rotational transform and a radial variation thereof. Such an externally established magnetic field, having a rotational transform with a radial variation in a torus-like tube, can stably confine a plasma away from the tube wall. The tube is evacuated to a high vacuum, and a pure gas of reactive atoms of controlled composition is admitted therein. The gas is initially ionized to a plasma by a radiofrequency discharge or a high electric field pulse. Thereafter the ionized gas is raised to a high temperature by externally applied means.

At least one divertor is provided in the stellarator reactor tube for removing impurity ions from the plasma. Impurity ions comprise those ions which are close to the tube wall and are derived both from the plasma and by bombardment of the tube wall by energetic particles. The impurity ions are undesirable for a plasma because they are "cold," have a high atomic number or are reactants. In the divertor there is an electrical winding energized oppositely to the windings that produce the main confining magnetic field.

Hereinafter the injected gas atoms and ions of the plasma prior to their entering into reactions will be termed "reactive particles"; and after they have entered into reactions, the resultant particles and radiation will be termed "reactants."

The divertor winding bends outward the main confining magnetic field lines near the wall of the torus so that these field lines pass into an enlarged section of the torus. This section or divertor chamber has an annular, non-magnetic, conductive collector plate whose inner radius is at least as large as the minor radius of the torus. The magnetic lines of the main confining magnetic field, which are bent into the divertor chamber, pass through the collector plate and then reenter the reactor tube. The impurity ions (which are adjacent to the torus wall) follow the magnetic lines into the divertor and are prevented by the collector plate from reentering the reactor tube. They are removed from the divertor by a vacuum pump.

A neutron moderating means and coolant are placed near the outer wall of the stellarator tube to absorb energy released therein in the form of energetic particles and electromagnetic radiation.

Referring now to FIGURE 1, there is shown a torus-like, non-magnetic tube **10** defining an endless chamber **11**. It is formed of two equal length parallel sections **12** and **14** joined at their respective extremities by semi-circular sectors **16** and **18**. A radial tubular duct **21** into sector **16** serves both as an inlet for reactive gas atoms **23** from a reactive-gas source, not shown, and for evacuation of chamber **11** to a high vacuum, such as 10^{-6} millimeters of mercury, for example, by a vacuum pump means, not shown.

A toroidal magnetic field is established everywhere in the chamber **11** by an electrical winding **20** (a portion thereof being shown on each semicircular sector **16** and **18**) energized in a conventional manner by a direct voltage source, not shown. Electrical winding **20** is wound over tube **10** throughout its length except as later described. The lines of force produced by this winding are continuous around the torus. Helical windings **22** underlie winding **20** over a part of the length of tube **10**. They are preferably four or six in number and are evenly spaced about tube **10** as viewed at cross section **25**. Adjacent helical windings **22** are energized oppositely and impart to the axial field established by winding **20** a field component such that the resultant field is characterized by a rotational transform having a radial variation. The effect of the rotational transform is that each magnetic line established by windings **20** and **22** in cooperation, after it has made one traversal of the tube **10**, has a particular angular displacement instead of closing on itself. Because of the radial variation, this angular displacement increases as the distance of a field line from the magnetic axis **24** of tube **10**. The radial variation is a gradient of the aforesaid angular displacement with distance from the magnetic axis such that magnetic lines farther from the axis **24** of chamber **10** wind about the axis **24** in tighter and tighter helices.

An annular ferrite ring **26** is disposed about tube **10** at section **18** thereof. Electrical winding **28** is wound on ring **26**. A radiofrequency voltage appears along axis **24** of chamber **11** when winding **28** is energized at its terminals **30** and **32** by a radiofrequency voltage source, not shown. There occurs as a result thereof a radiofrequency discharge in the gas atoms **23** which ionizes them to a plasma.

A laminated iron annular ring **34** is disposed about straight section **14** of tube **10** for ohmic heating of the plasma in chamber **11**. Wound upon ring **34** is an electrical winding **36** which is energized at its terminals **38** and **40** by an audiofrequency voltage source, not shown. Laminated iron ring **34** and its energized winding **36** cause ohmic heating of the plasma by ohmic losses therein.

A divertor **42** is located in straight section **14** of tube

10 for removing impurity ions therefrom. It comprises a housing 46 defining chamber 48, in effect, an enlargement in the chamber 11. Chamber 48 is evacuated by a vacuum pump, not shown, through a port 50. Electrical winding 52 wound about tube 10 is electrically energized by a direct voltage source (such as the same voltage source used to energize winding 20) in the direction of arrow 54 and provides a magnetic field in chamber 48 which locally distorts the confining magnetic field represented by magnetic field lines 17. This causes the confining magnetic field lines near to the wall of tube 10 to be bent into chamber 48 as shown by typical magnetic field lines 56 and 58. Parallel, non-magnetic metallic impurity-ion-collector plates 60 and 62 form an enclosure 63 within which electrical winding 52 is disposed and divide chamber 48 into communicating subchambers 64 and 66. Magnetic field lines 56 and 58 thus enter subchamber 64, pass through collector plates 60 and 62, enter subchamber 66 and reenter tube 10 therefrom.

Generating section 103 for heating a plasma immersed in a confining magnetic field in accordance with this invention is located in straight section 12 of tube 10. Generally, it comprises a housing 104, an insulating tube 70 within the housing, and an induction coil 68 wound on the tube.

Referring now to FIGURE 2, which is a schematic diagram of a portion of an electrical circuit for the generating section 103 (FIGURE 1), there is shown electrical winding 68 wound on insulating tube 70. Winding 68 comprises winding sectors 72, 74, 76 and 78. Outer winding sectors 72 and 78 (with regard to the ends of tube 70) are wound in one direction about insulator tube 70, and inner winding sectors 74 and 76 are wound in the opposite direction about the tube axis, e.g., clockwise and counterclockwise viewed from one end of tube 70, respectively. Although an even number of winding sectors is shown, the number may be odd provided it is greater than one. Electrical winding 68 is energized by radiofrequency voltage generator 80 through high voltage conductor 82 connected between plates 84 and 86 of capacitors 88 and 90, respectively. Plate 92 of capacitor 90 is connected to juncture 94 of coil sectors 74 and 76 by conductor 93. Low voltage conductors 96 and 98 (e.g., at ground potential) connect radiofrequency voltage generator 80 to opposite ends of coil 68. Plate 100 of capacitor 88 is also connected to conductor 98. The capacitors 88 and 90 are selected so as to match the input impedance of coil 68 to the output impedance of radiofrequency generator 80. Thus, radiofrequency generator 80 causes coil 68 to produce a varying magnetic field (periodic both in time and distance) along the axis 24 of insulator tube 70.

Referring now to FIGURE 1, insulator tube 70 and electrical winding 68 are disposed within chamber 102 of generating section housing 104 and coaxial with straight section 12. Insulator tube 70 is sealed to the torus wall to insulate winding 68 from the plasma. However, winding 68 may otherwise be insulated from the plasma, e.g., as by using insulated wire for winding 68. Generating section housing 104 includes annular ring-like end plates 106 and 108 hermetically sealed to section 12 of tube 10. Additionally, housing 104 has an outer, cylindrical, non-magnetic wall 110 and an inner, cylindrical, non-magnetic wall 112 with an annular space 111 between them. Electrical winding 114 is the portion of winding 20 in generating section 103 and is disposed in the annular space 111 to establish, cooperatively with electrical windings 22, the plasma-confining magnetic field within insulator tube 70.

An alternative winding 116 to replace winding 68 is shown in FIGURE 3 disposed within winding 114. Alternative winding 116 comprises winding sections 118 and 120 wound about the axis of tube 70 in opposite directions. When winding 116 is energized by radiofrequency source 80, sections 118 and 120 produce oppositely directed magnetic fields along axis 24 of tube 10 as indicated by arrows 200 and 202, respectively.

In FIG. 1, a magnetic field gradient-producing winding 121 in thermalizing section 123 is shown wound on tube 10 adjacent each end of generating section 103. It comprises a plurality of turns with gradually increasing spacing between the turns, i.e., along the axis 24 of tube 10 away from the end of generating section 103. It causes the confining magnetic field in tube 10 to drop off approximately 20% in intensity over the length of thermalizing section 123. Winding 121 is part of magnetic-field-producing winding 20 and may be commonly energized.

In FIGURE 1 a mirror magnetic field winding 122 in mirror section 126 is shown wound on sections 16 and 18 of tube 10. Mirror winding 122 is part of winding 20 and may be commonly energized and produces high flux density over mirror section 126 as compared to the plasma confining field elsewhere in tube 10. Helical windings 22 underlie both magnetic-gradient producing winding 121 and mirror winding 122. However, in some embodiments of this invention, sufficient radial transform and radial variation thereof may be imparted to the field produced by coil 20 on other portions of the tube 10 and so helical windings 22 are not required on thermalizing section 123 and mirror section 126.

The reactor shown in FIGURE 1 is operated as follows: Tube 10 is evacuated via tube 21 and reactive gas atoms 23 are introduced into chamber 11. Axial confining magnetic field electrical winding 20 and cooperating parts thereof, 22, 114, 121, 122 and 52, are energized by a voltage means, not shown, approximately at the same time as the reactive atoms 23, e.g., deuterium, are introduced into chamber 11. Then, the reactive atoms are initially ionized to a plasma by a radio-frequency discharge produced by ferrite ring 26 as aforesaid. The ohmic heating ring 34 is used to bring the plasma to a state of almost complete ionization and to provide some heating of the plasma. The amount of ohmic heating needed is dependent upon the particular conditions of operation of the reactor such as pressure and temperature. Next, the plasma is heated by means of generating section 103.

In generating section 103, electrical winding 68 taken together with capacitors 88 and 90 comprises a resonant circuit energized by radiofrequency voltage source 80. Since sectors 72 and 76, and sectors 74 and 78 carry electric current in opposite directions about axis 24 of tube 70, respectively, the fields produced thereby are alternately 180° out of phase. That is, e.g., considering the fields at a particular instant, the fields produced by sectors 72 and 76 are to the right and the fields produced by sectors 74 and 78 are to the left.

For operation of an embodiment of this invention for transferring energy to a plasma through ion cyclotron motions, the frequency of the radiofrequency voltage produced by generator 80 is at the ion cyclotron frequency of plasma ions as given by Expression 1 above. During the operation of this embodiment, the electrical windings 121 and 122 are not energized. However, there are then provided in their respective locations, sectors of the main field winding 20.

In another mode of operation of this invention, radiofrequency generator 80 establishes a varying magnetic field in chamber 11 through winding 68. This field is at the resonant frequency for cyclotron waves or torsional hydromagnetic waves. In this mode of operation, electrical windings 121 and 122 of thermalizing section 123 and mirror section 126, respectively, are energized either at one or both ends of generating section 103.

FIGURE 4 is used to illustrate the effect on the plasma ions of the main confining magnetic field in the tube 70 produced by winding 114, the gradient magnetic field within winding 121, and the mirror field within winding 122. The block in FIGURE 4 represents generating section **103**. The position along the X axis measures the distance from the center of the generating section **103**. The position along the Y axis measures the reciprocal of the intensity of the confining magnetic field. The larger the Y-axis coordinate, the less is the magnetic intensity. An ion which moves in the X direction from the center of generating section **103**, e.g., at the intersection of X and Y axes, experiences a constant confining magnetic field force over the distance d_1 (while within the generating section), a gradually diminishing magnetic force over the distance d_2 (while within the thermalizing section), and an intensive magnetic force over the distance d_3 (while within the mirror section).

For heating the plasma, coil **68** is energized (by radiofrequency voltage source **80**) at a frequency appropriate for the generation of ion cyclotron or torsional hydromagnetic waves in tube **70** in a region of relatively high magnetic field strength. These ion cyclotron waves propagate along magnetic lines of force through the thermalizing section **123**. Here the intensity of the confining magnetic field is decreasing gradually with distance measured along a line of force from the generating section **103**, e.g., a 20% decrease in intensity from the generating section **103** to the mirror section **126**. This variation is produced by coil **121** having a greater and greater separation between turns away from the generating section **103**. As a result, the ion cyclotron wave wavelength gradually decreases. When the wave-length becomes sufficiently short, appreciable cyclotron damping occurs. The wave amplitudes decrease and the wave energy is transformed into energy of effectively random transverse ion motions, and so the ion cyclotron waves undergo thermalization through cyclotron damping.

FIGURE 5 presents experimental data on the absorption of energy by a plasma of helium and hydrogen ions from the induction coil **68**. The experiment was performed at Princeton University on a model of the stellarator. The frequency of the resonating field was 10.16 megacycles and its wave length was 9 inches. The abscissa of FIGURE 5 gives the strength of the confining magnetic field in kilogauss, and the ordinate W (on a non-linear scale increasing toward the abscissa) gives the ratio of the radiofrequency power absorbed by the plasma to the radiofrequency power that would have been ohmic loss if the figure of merit Q of the induction coil **68** were equal to 300. As the ohmic loss is the principal source of energy loss in power transfer, a value of W equal to 1 indicates a power-transfer efficiency of 50%, and higher values of W indicate higher power-transfer efficiencies. The vertical lines **150** and **152** indicate the values of the magnetic field for which the radio-frequency of generating section **103** is equal to the ion cyclotron frequency for hydrogen (approximately 6.6 kilogauss) and the doubly ionized helium (approximately 13.1 kilogauss), respectively.

The peaks **154** and **156** (near or at the ion cyclotron frequency values) shows that appreciable fractions of the radiofrequency power applied to coil **68** were absorbed by the plasma preferentially at and in the neighborhood of the ion cyclotron frequencies of hydrogen and helium, respectively.

While the invention has been disclosed with respect to certain preferred embodiments, 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.

I claim:

1. Apparatus for transferring energy to a plasma and heating the plasma, comprising a cylindrical torus-like tube defining a uniformly evacuated endless chamber, means for establishing a quasi-static plasma-confining magnetic field in said chamber, means establishing a plasma of ions and electrons immersed in said magnetic field, an induction coil around said tube having periodic oppositely directed windings, a resonating magnetic second field generating section operable with said coil to produce in said chamber ion accelerating second fields having a time and spatial periodicity along the lines of force of said confining magnetic field so as to excite hydromagnetic waves in said plasma, and means for thermalizing the energy in said hydromagnetic wave including means for establishing a magnetic field gradient in said confining magnetic field to heat said plasma by cyclotron damping.

2. Apparatus for transferring energy to a plasma and heating the plasma, comprising means for establishing a plasma-confining magnetic field in a uniformly evacuated zone, means for immersing a plasma of ions and electrons in said field, an induction coil around a portion of said field having periodic oppositely directed windings, means for energizing said coil to cause the direction of current flow to alternate periodically with distance in the coil axial direction, and to have a time periodicity to excite ion cyclotron motions and ion cyclotron waves in said plasma, and a thermalizing section having electrical winding means for producing a magnetic gradient in said confining magnetic field to cause the flux density of said confining field to decrease gradually over said thermalizing section whereby the energy in said ion cyclotron motions and ion cyclotron waves is thermalized.

3. Apparatus for transferring energy to a plasma and heating the plasma, comprising means for establishing a plasma-confining magnetic field in a uniformly evacuated zone, means for immersing a plasma in said field, an induction coil around a portion of said field having periodic oppositely directed series connected windings, means for energizing said coil to cause the direction of current flow to alternate periodically with distance, in the coil axial direction, and to have a time periodicity to excite ion cyclotron motions and ion cyclotron waves in said plasma, and mirror sections adjacent opposite ends of said coil having electrical winding means for locally increasing the flux density of said confining magnetic field to relatively high field strength to cause mirror confinement of said plasma.

4. Apparatus for transferring energy to a plasma and heating said plasma, comprising means for establishing a plasma-confining magnetic field in a uniformly evacuated zone, means for immersing a plasma in said field, an induction coil around a portion of said field having periodic oppositely directed windings, means for energizing said coil to cause the direction of current flow therein to alternate in the coil axial direction, and to have a time periodicity to excite ion cyclotron motions and ion cyclotron waves in said plasma, a thermalizing section including means for producing a magnetic gradient in said confining magnetic field to cause the flux density of said confining field to decrease gradually over said thermalizing section whereby the energy in said ion cyclotron motions and ion cyclotron waves is thermalized, and mirror sections adjacent opposite ends of said coil including means for locally increasing the flux density of said confining magnetic field to a relatively high field strength to cause mirror confinement of said plasma.

5. In a high temperature reactor of the type having a cylindrical tube defining a uniformly evacuated chamber, means for establishing in said chamber a unidirectional substantially static magnetic field, and means immersing a plasma of ions and electrons in said magnetic field, the improvement, comprising an induction coil encircling a portion of said tube and having periodic oppositely directed windings, a capacitor network having a radio-frequency source for energizing said coil to excite in said plasma electric fields having a time and spatial periodicity to excite ion cyclotron motions and ion cyclotron waves in said plasma, and a thermalizing section having windings around said tube with gradually decreasing spacing beginning adjacent said induction coil for thermalizing the energy in said motions and waves to heat said plasma to a high temperature.

6. A high temperature reactor, comprising a cylindrical torus-like tube defining an endless uniformly evacuated chamber, a first coil radially encircling said tube, said first coil extending axially around the entire length of said tube and having first and second windings, said first windings having gradually increasing spacing and forming a thermalizing section, said second windings having even spacing and forming a generating section connected in series with said thermalizing section, a second coil radially encircling said tube having helical third windings extending axially along only a portion of the length of said tube and being operable with said first coil to produce a unidirectional substantially static magnetic field with a rotational transform and radial variation, means for immersing a plasma of ions and electrons in said magnetic field, an induction third coil adjacent said second windings of said first coil and extending coaxially therewith to the place where the 1st windings of said first coil begin to gradually increase in spacing, said third coil having helical fourth windings oppositely directed to each other periodically with distance along the axis of said third coil and connected electrically in a series parallel pattern, and radio-frequency means having a capacitor network for energizing said third coil with a radio-frequency current alternating with a time periodicity so as to excite in said generating section ion cyclotron motions and ion cyclotron waves whose frequency is close to the frequency of said ion cyclotron motions whereby the energy excited in said ion cyclotron motions and ion cyclotron waves is thermalized in said thermalizing section.

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