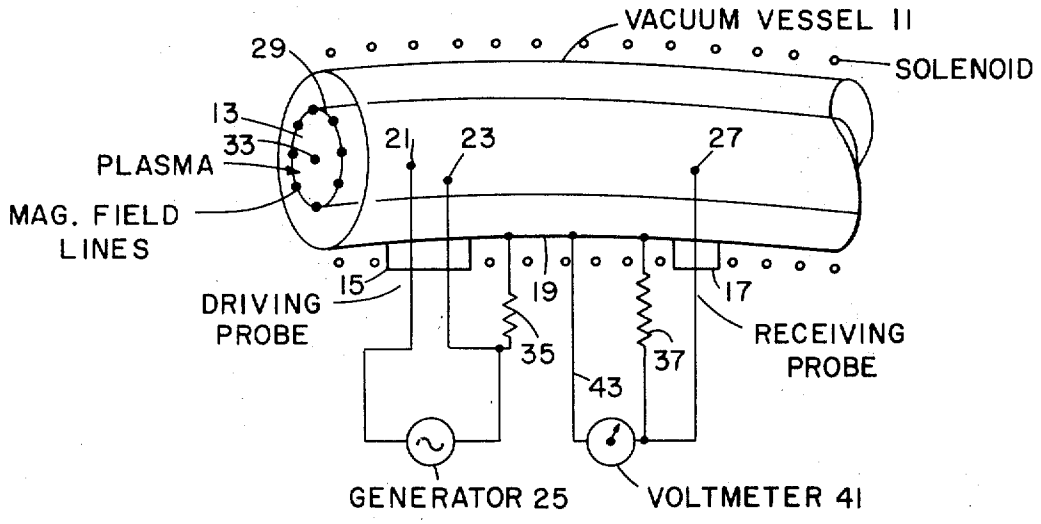
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DEVICE FOR DETERMINING THE SHAPE OF MAGNETIC SURFACES
IN TOROIDAL CONFIGURATIONS CONTAINING PLASMA
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DEVICE FOR DETERMINING THE SHAPE OF MAGNETIC SURFACES IN TOROIDAL CONFIGURATIONS CONTAINING PLASMA

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ABSTRACT OF THE DISCLOSURE

Method of surveying the shape and location of magnetic surfaces in a stellarator with an electrostatic acoustic oscillation mode that dominates ordinary sound waves associated with plasma particle motion along the magnetic surfaces.

BACKGROUND OF THE INVENTION

Field of invention

This invention relates to means for surveying the shape and location of magnetic surfaces in plasma research reactors for magnetically confining a plasma of ions and electrons in a toroidal configuration, and more particularly to means for determining the shape of plasma containing magnetic surfaces in a stellarator.

Description of prior art

In the field of plasma research reactors, a need exists for surveying the shape and location of toroidal magnetic surfaces. These surfaces, for example, are employed for confining a plasma away from the inside wall of an annular, endless, racetrack-shaped, toroidal, evacuated, cylindrical plasma research reactor of the stellarator type. An endless evacuated cylindrical stellarator having toroidal magnetic surfaces therein is described in U.S. Pats. 3,278,384; 3,088,894; 3,015,618; 3,012,955, and 3,002,912. As described in these patents, the magnetic surfaces must be shaped and located precisely to provide stable plasma confinement at high temperatures, densities, and currents; and precisely located and shaped conductors must be used for producing these magnetic surfaces. To this end, conventional axial and multipolar current carrying windings are used for producing specific axial and/or minimum B transverse magnetic fields (e.g., vacuum negative V'' cross fields). For example, as described in U.S. Pat. 3,278,384, the conductors produce vacuum magnetic fields having the property $d^2V/d\psi<0$ inside a bounded region, where V is the volume inside a magnetic surface that is labeled by the contained longitudinal magnetic flux ψ.

Heretofore, three major methods have been proposed or used to locate toroidal magnetic surfaces, such as those that are found in stellarators of the types described. According to the first method, an electron beam is injected in the direction of the magnetic field in the stelarator and by observing where the beam strikes a fluorescent screen or how many times the beam gets around the torus before it strikes the gun assembly or the vacuum wall, one can map the surfaces covered by a beam of particles with a specific velocity. By reversing the direction of the beam, one gets a partial correction for the effects of single-particle drifts and thus can estimate the position of the magnetic surfaces in the stellarator. In accordance with the second method, an obstacle is inserted into the plasma and by noting where it significantly affects the properties of the described system, one can acquire some information about the magnetic surfaces near the edge of the plasma. The third method injects thermal electrons at some point in the described system, and by observing the floating potential and current to a probe elsewhere, it is possible to map the magnetic surfaces quantitatively. However, none of these systems are useful when plasma is present. This is particularly true if the plasma is carrying currents.

SUMMARY OF THE INVENTION

This invention was made in the course of, or under a contract with the United States Atomic Energy Commission.

In accordance with this invention, it has been discovered that a new mode of oscillation can be used for determining the shape and location of the magnetic surfaces in a system where the field lines have curvature lying in these magnetic surfaces. This mode involves a sinusoidal standing pressure disturbance, as described in more detail by Winsor et al. in Physics of Fluids, volume 11, page 2448, which appeared in 1968, and in Princeton Plasma Physics Laboratory Report MATT–602 (1968). Also, this mode involves the period required for a sound wave to propagate around the torus divided by the square root of the Pfirsch-Schlüter factor $(1+8\pi^2/\iota^2)$. More particularly, one embodiment of this invention comprises an RF generator for oscillating the potential between two probes inserted into neighboring magnetic surfaces and a velocity-selective voltmeter to determine where a movable receiving probe detects the wave, thus providing means for generating a geodesic wave for determining the location and shape of the magnetic surfaces in the toroidal magnetically confined plasma in a stellarator. With the proper selection of components and frequencies, as described in more detail hereinafter, the desired mapping of the magnetic surfaces in stellarators is provided.

The above and other novel features and objects of this invention will become apparent from the following description when the same is read in connection with the accompanying drawing. It is to be expressely understood, however, that the drawing is not a definition of the invention but is for the purpose of illustration only.

BRIEF DESCRIPTION OF THE DRAWINGS

The figure is a partial three-dimensional view of apparatus for mapping magnetic surfaces containing plasma in a toroidal column in accordance with this invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

It is known that an electrical conductor having a short exposed end can be positioned in and out of a plasma column confined within the toroidal magnetic surface provided in a stellarator. Such a conductor may be used to bias the plasma potential. One such conductor for insertion into such a plasma column is described and shown in U.S. Pat. 3,171,788 to Gorman et al. FIG. 2 of that Gorman et al. patent illustrates a conductor of this type. The operation thereof is based on the fact that the movable conductor thereof is connected at one end to a suitable energy or potential source and is contained in a sealed body having bellows connected in sealing contact with a main stellarator tube. The conductor thus forms a probe, like a Langmuir probe, that can be moved into and out of the plasma column in the stellarator at right angles to the equilibrium axis thereof. Moreover, the movement and position of the probe are indicated on a suitable scale as shown in FIG. 3 of the cited U.S. Pat. 3,171,788 to Gorman et al. The invention hereinafter described utilizes a plurality of probes of the type described in this patent to Gorman et al., in which two first probes are connected respectively to a variable frequency oscillating energy

source, and another probe is connected to a voltmeter for measuring the plasma response. Also, the probes are variably inserted into a toroidal plasma column, such as a stellarator plasma that is magnetically confined in an endless evacuated tube, and oscillations are produced in the plasma which produce corresponding readings on the voltmeter that indicate the edge of the magnetic surfaces. Thus, by moving the probes carrying the oscillating potential signals and noting the varying voltmeter readings, the plasma containing magnetic surfaces are easily and accurately surveyed.

In order to explain how the apparatus of this invention performs the function of surveying the shape, and location of the magnetic surfaces, reference is made to the figure, which is a partial three-dimensional view of an evacuated vacuum vessel **11** having a plasma column **13** therein. Such a column is produced and magnetically confined, as is well known in the art, e.g., in a stellarator like the one described in the above referenced patents. Such a column is also produced in the well-known tokamak, levitron, spherator, and multipole devices for magnetically confining a plasma. In all of these devices, the field lines must have some geodesic curvature—that is, a component of the line curvature lies in a plane of the magnetic surface so that

$$\underset{\sim}{B}\times\underset{\sim}{\nabla}p.\underset{\sim}{\nabla}B^2$$

is not zero. By inserting in port **15** in wall **19** of vessel **11** two ordinary Langmuir probes **21** and **23**, such as described in the above-referenced Gorman et al. patent, and by connecting them to an AC source **25**, in accordance with this invention, an RF field of about 10 volts/cm. can be imposed between the probes **21** and **23**. By proper choice of the frequency, resonance of the plasma column in the geodesic resonance mode may be achieved. This resonance can be determined, for example, by first observing the frequency at which the plasma absorbs energy. Moreover, by then inserting a receiving third probe **27** into the plasma through port **17** to locations where the resonance frequency is observed in accordance with this invention, one can delimit the magnetic surface that has felt in the driving probe **21** with a sensitivity up to a gyration radius. Thus, this invention provides a system for mapping the real magnetic surfaces when plasma is present in column **13** in vacuum vessel **11**.

In operation, the resonant frequency of this geodesic wave is usually quite low and substantially independent of rotational transform. Also, the fluctuating electric field is large even for very small density variations. For example, with typical Model C stellarator parameters and at a resonant frequency of 45 kHz., a 1% density fluctuation will result in a 40 v./cm. electric field associated with the plasma flow cE/B across the field. In this regard, since B is not constant on the magnetic surface, a density accumulation occurs that in turn generates a current across the surface that modifies the electric field.

Experimentally, this above-described mode of this invention has two distinguishing characteristics. First, its frequency is quite low, and since ι is usually less than 2π, the geodesic wave of this invention is essentially independent of the rotational transform. For typical hydrogen discharges in a stellarator, $T=100$ ev., $\iota=2\pi/3$, $R=100$ cm., $\gamma=2$, and the frequency is 45 kHz. Second, its electric field is large. The formula relating the electric field to the pressure changes is $\partial\tilde{\phi}/\partial r\simeq(B_0R\omega/2c)p/p$ statvolts/cm.$=4000\ p/p$ v./cm. For a 30-kilogauss field produced by conventional solenoid axial windings a 10^{-3} relative density fluctuation produces observable electric fields of 4 v./cm. It is thought that this mode may help to explain some of the spontaneous or otherwise unexplained low-frequency oscillations observed in conventional toroidal plasma research reactors.

As described in the above-cited report, MATT–602, the new geodesic wave of this invention has been investigated for a general toroidal geometry by employing an ideal

electrostatic hydromagnetic model for studying small-amplitude perturbations about a static equilibrium. The results therefrom were then specifically applied to general axisymmetric geometries and to a Knorr model consisting of concentric nested magnetic surfaces with the result that this invention has been explained mathematically in detail.

In a practical embodiment, the plasma particles in column **13** are produced by any of a wide variety of well known means. For example, the plasma is advantageously produced in situ by conventional well known heating techniques and apparatus for injecting and heating low pressure gas particles in vessel **11**. For example, ohmic heating, ion cyclotron resonance heating, or laser heating may be used as is well known. Likewise, however, the plasma may be injected.

The RF energy source **25** is tuned to the resonant frequency, e.g., about 45 kHz. for typical Model C stellarator parameters for exciting a 40 v./cm. electric field and a 1% density fluctuation. To this end, probes **21** and **23** are selectively placed at different desired distances into column **13** in a direction at right angles to the axis **33** thereof, which direction is also at right angles to the outside of magnetic surface **29**, as well as its axis as shown in the figure. This causes geodesic standing waves on magnetic surface **29** and/or like adjacent magnetic surfaces concentric therewith (which are not shown for ease of explanation). Significantly and unexpectedly, the particular oscillations of this invention on different magnetic surfaces are not coupled with each other, whereby these oscillations can easily be detected by probe **27** and localized to the specific magnetic surface to indicate the location of that surface. To this end, one driving probe, e.g., probe **21**, and the receiving probe **27** are connected to the outside of wall **19** of vessel **11** through resistors **35** and **37**, and one side of voltmeter **41** is connected to the outside of wall **19** of vessel **11** through lead **43**. This meter **41** thus indicates the presence of the geodesic wave driven by driving probes **21** and **23** on the plasma in column **13**. Since the maximum signal occurs on magnetic surface **29** on which probe **21** is located, the shape and location of the magnetic surface **29** is determined by observing the positions of probe **27** for maximum indication on voltmeter **41**. Alternately, driving probe **23** could be replaced by a direct connection to the vessel wall **19**. Thus, the shape and location of each and every magnetic surface in vessel **11**, as well as the innermost and outermost magnetic surfaces in vessel **11**, can be determined, surveyed and easily accurately mapped at any location along vessel **11**.

The above described system of this invention is advantageous compared with the above-cited system of Gorman et al., since the latter is a DC system that causes DC plasma distortion eliminated by the described AC oscillations. Moreover, actual tests have shown that when the ends of the two driving probes **21** and **23** of this invention are located at magnetic surfaces separated by only a few gyration radii, that the plasma absorbs RF energy at the resonant frequency commensurate with the above-mentioned geodesic wave for detection by receiving probe **27**. Thereupon, this wave, which is detected by probe **27**, indicates the shape and location of the magnetic surfaces **29** one of which is shown in the figure, since the standing geodesic pressure disturbance thereof does not couple significantly from surface to surface. Thus, the shape and location of any or all of the plasma containing magnetic surfaces **29** in vessel **11** are accurately and easily surveyed with simple, inexpensive and trouble free equipment. In this regard, the wave period is that required for a sound wave to propagate around the torus divided by the square root of the Pfirsch-Schlüter factor $(1+8\pi^2/\iota^2)$, which is described by Johnson and von Goeler in Physics of Fluids, volume 12, page 255 (1969) and in Princeton Plasma Physics Laboratory Report MATT–605 (1968).

This invention has the advantage of providing the only known system for accurately surveying the shape and location of magnetic surfaces when plasma currents are large enough to affect the surfaces. This invention thus provides a system for determining the shape and location of a magnetically confined plasma column, such as the well known toroidal plasma columns found in stellarators, tokamaks, levitrons, spherators, and/or multipoles. Moreover, the system and apparatus of this invention not only are simple, efficient and easy to operate but also are accurate down to about a gyration radius.

What is claimed is:

1. In combination with a toroidal, evacuated container having an annular wall disposed along a longitudinally extending axis, and magnetic means for magnetically confining a toroidal column of plasma inside said container in a cylindrical, longitudinally extending, magnetic surface formed by axial magnetic field lines concentric with the axis of said evacuated toroidal container and spaced from the inside wall of said container, improved diagnostic means, comprising selectively movable, resonating wave-driving means extending into said container, energy source means for supplying oscillating energy to said driving means for producing resonance waves in said plasma along said magnetic surface, and receiving means for detecting said resonating waves along said surface for determining the shape and location of said surface relative to said axis and said wall of said container.

2. The invention of claim **1** in which said driving and receiving means comprise movable, electrically conducting probe means having resistive connections to the outside wall of said evacuated container, for producing and observing said resonance oscillation waves.

3. The invention of claim **1** in which said resonance waves oscillate at particular frequencies corresponding to particular standing geodesic pressure oscillations whose

frequency is different from sound going around the system in said plasma, whereby said resonance waves can be distinguished from other waves having the speed of sound in said plasma.

4. The invention of claim **1** in which said receiving means has a movable probe and a frequency-selective voltmeter connected thereto for determining the location where said geodesic wave driven by oscillating energy supplied to said driving means, said geodesic wave having maximum amplitude when said driving and receiving means intercept the edge of the same said magnetic surface.

5. The invention of claim **1** in which said driving and receiving means have probe means, and means for selectively moving said probe means into said plasma in said column at right angles to the axis thereof, for producing and detecting said resonance waves in a plurality of concentric magnetic surfaces in said evacuated container, whereby the shape and location of each and every concentric magnetic surface in said container can be surveyed and mapped, and the shape and location of the innermost and outermost of said magnetic surfaces in said container can be determined at various times, at various magnetic confining fields, and at various plasma densities and pressures with plasma confined by said magnetic surfaces in said container.

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3,171,788 3/1965 Gorman et al. ---------- 176—1

REUBEN EPSTEIN, Primary Examiner

U.S. Cl. X.R.

324—34