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Shohet

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[54] **METHOD AND MEANS FOR MEASURING THE ANISOTROPY OF A PLASMA IN A MAGNETIC FIELD**

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[73] Assignee: **The United States of America as represented by the United States Atomic Energy Commission**

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[52] **U.S. Cl.** **250/366**, 250/362, 250/369, 250/526, 313/63

[51] **Int. Cl.** **G01j 39/18**, G01t 1/20

[58] **Field of Search** ..... 250/71.5 R, 83.3 R; 313/63

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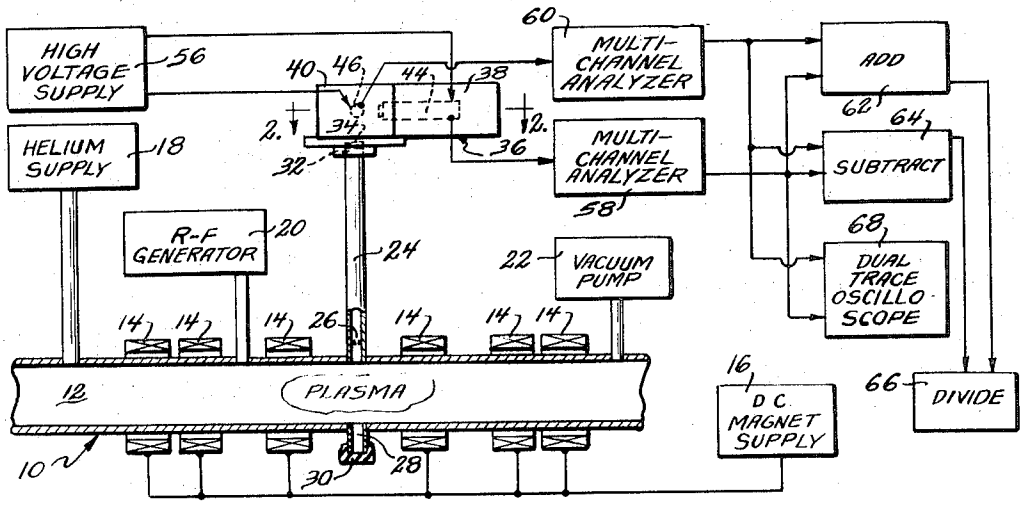
Primary Examiner—William F. Lindquist

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[57] **ABSTRACT**

Anisotropy is measured of a free-free-bremsstrahlung-radiation-generating plasma in a magnetic field by collimating the free-free bremsstrahlung radiation in a direction normal to the magnetic field and scattering the collimated free-free bremsstrahlung radiation to resolve the radiation into its vector components in a plane parallel to the electric field of the bremsstrahlung radiation. The scattered vector components are counted at particular energy levels in a direction parallel to the magnetic field and also normal to the magnetic field of the plasma to provide a measure of anisotropy of the plasma.

10 Claims, 6 Drawing Figures



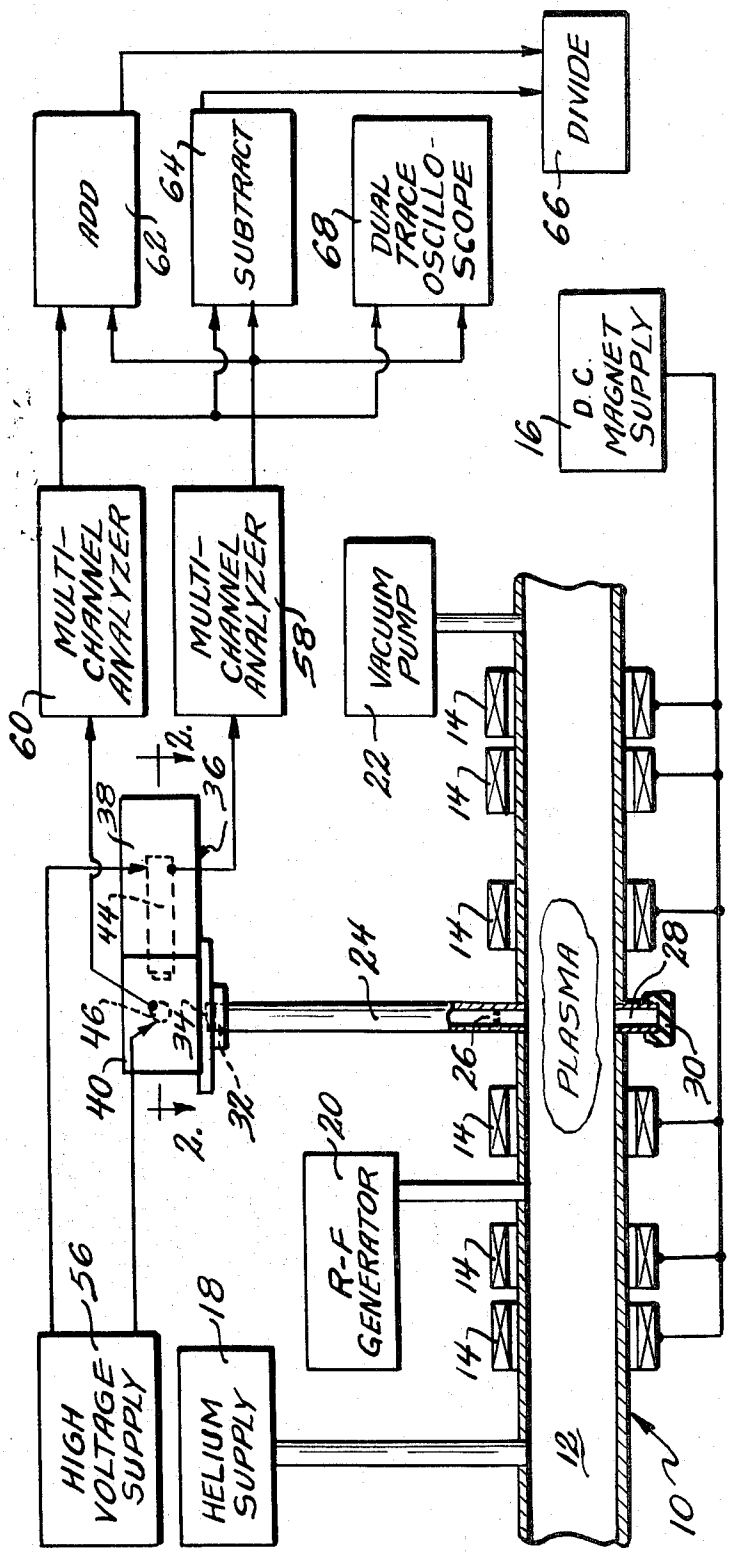

ADD
62
SUBTRACT
64
DUAL TRACE OSCILLO-SCOPE
68
DIVIDE
66
D.C. MAGNET SUPPLY
16
MULTI-CHANNEL ANALYZER
60
MULTI-CHANNEL ANALYZER
58
VACUUM PUMP
22
HIGH VOLTAGE SUPPLY
56
HELIUM SUPPLY
18
R-F GENERATOR
20
PLASMA
12
10
14
24
26
28
30
32
34
36
38
40
44
46
2.
12.

Fig — 1

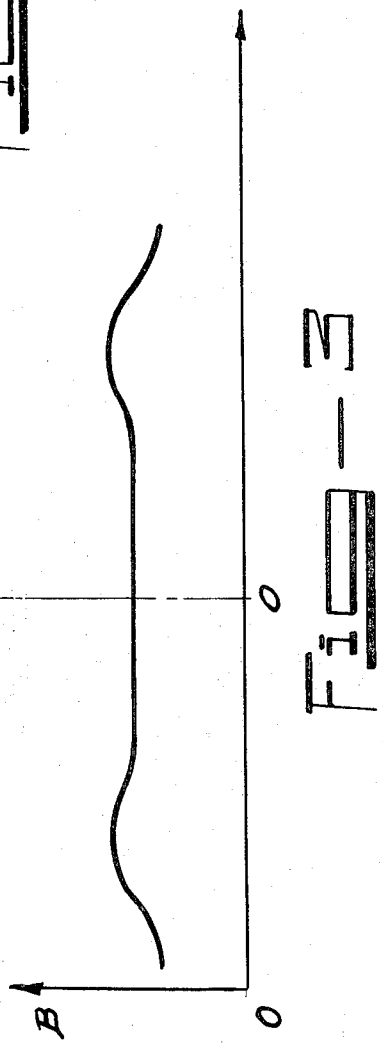

B
0
0

Fig — 2

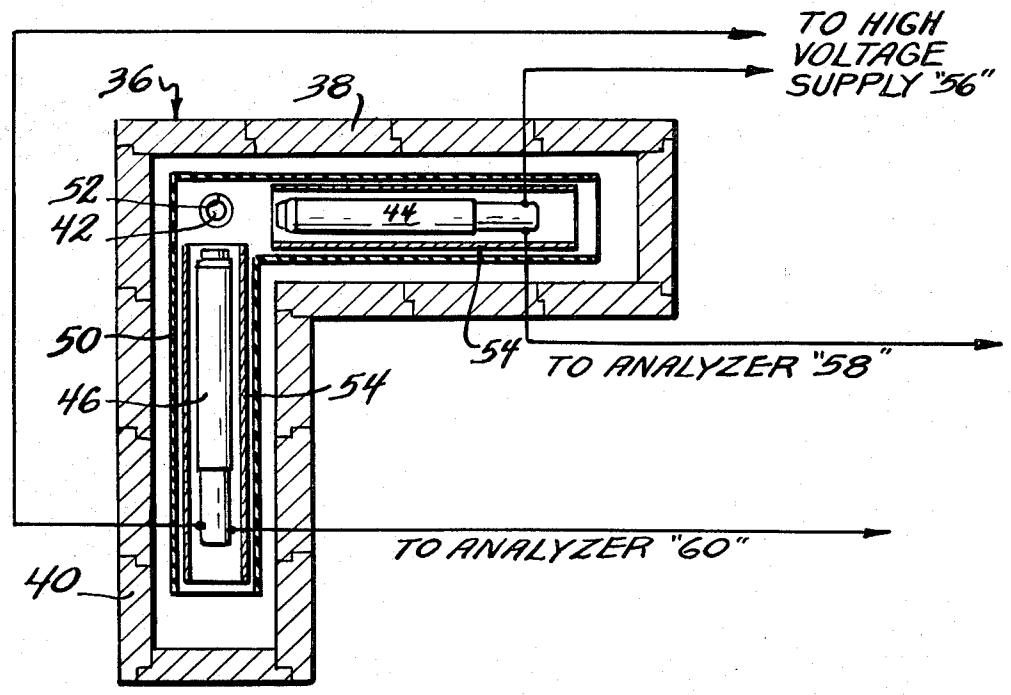

TO HIGH VOLTAGE SUPPLY "56"
36
38
52
42
44
50
46
54
54
TO ANALYZER "58"
TO ANALYZER "60"
40

Fig — 2

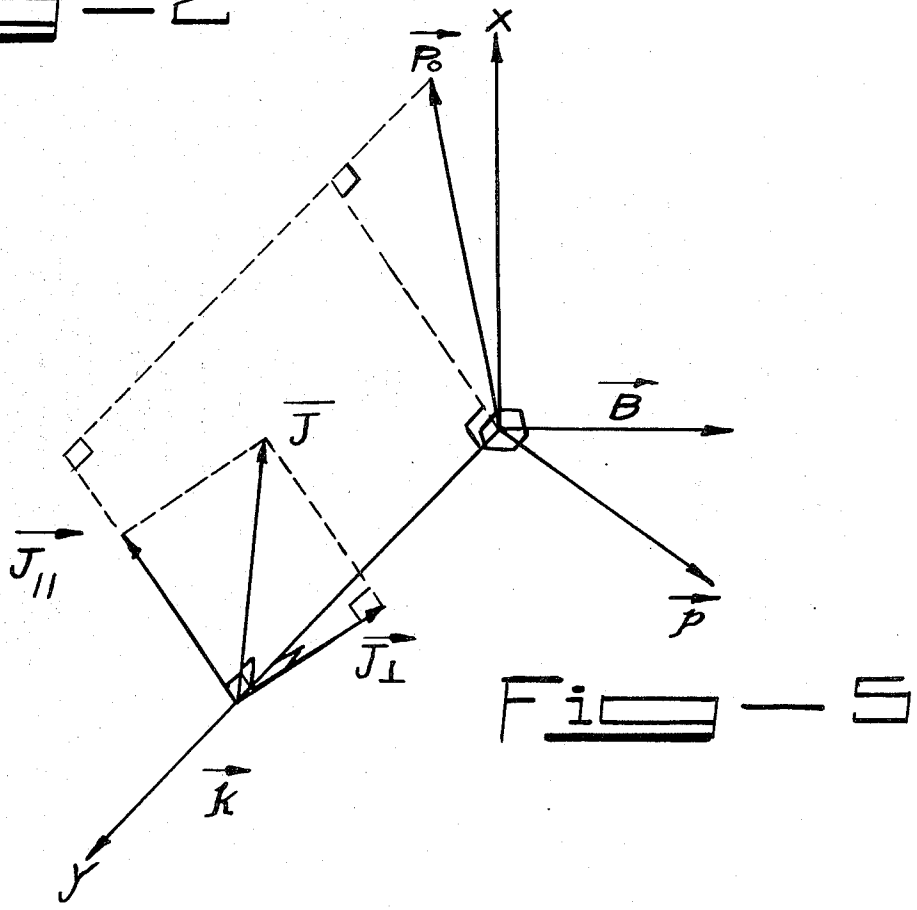
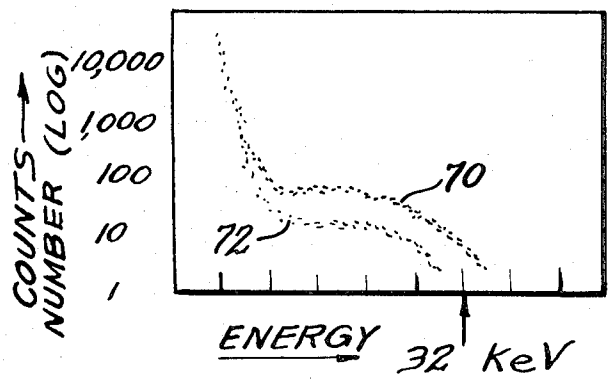

$\vec{P_o}$
X
$\vec{J}$
$\vec{B}$
$\vec{J_{11}}$
$\vec{J_1}$
$\vec{p}$
$\vec{k}$
Y

Fig — 5

Fig — 4


COUNTS NUMBER (LOG)
10,000
1,000
100
10
1
70
72
ENERGY
32 KeV

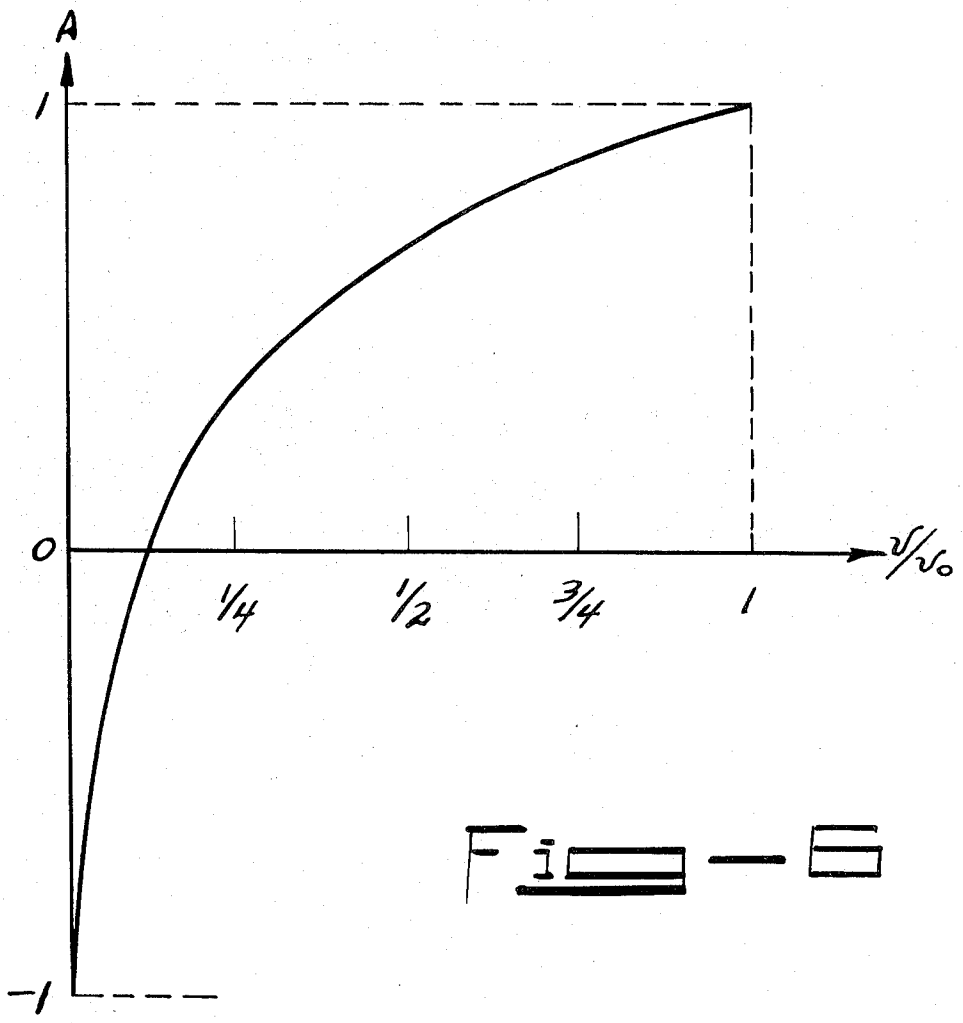

A
1
0
-1
1/4
1/2
3/4
1
V/V₀

Fig — 6

METHOD AND MEANS FOR MEASURING THE ANISOTROPY OF A PLASMA IN A MAGNETIC FIELD

CONTRACTUAL ORIGIN OF THE INVENTION

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

BACKGROUND OF THE INVENTION

The present invention relates to plasmas and more particularly to a method and means for determining anisotropy of a plasma in a magnetic field.

Thermonuclear power is an important potential source of power. Thermonuclear reactions are effected in high density plasmas in which the kinetic energy of the particles forming the plasma are at a high energy level. Magnetic fields are generally used to confine a plasma in which the particles forming the plasma are at a high energy level. An example of such an apparatus and tehcnique is a magnetic-mirror machine wherein an axial magnetic field is externally applied to a cylindrical tube to minimize the loss of charged particles from the ends of the tube. The external magnetic field is applied so that the field's strength is stronger at the ends of the tube than at the middle, and the stronger field acts as a magnetic mirror to reflect the particles back to the central weak field for confinement. The magnetic-mirror system not only confines the plasma but it also compresses the plasma, radially and axially, thereby increasing the temperature and density of the plasma.

In such thermonuclear machines, diagnostic tools and methods for measuring system parameters are extremely important. One desirable measurement for a plasma in a magnetic field is the determination of anisotropy. Anisotropy of a plasma is a measure of the velocity distribution of electrons in the plasma and therefore a measure of the kinetic energy of the particles forming the plasma. It has been further found in the present invention that anisotorpy is a measure of the impurity-gas pressure of the plasma and, in a magnetic-mirror machine, a measure of the mirror-ratio of the machine.

It is therefore an object of the present invention to provide an improved method and means for measuring the anisotropy of a plasma in a magnetic field wherein the plasma produces free-free bremsstrahlung radiation.

It is another object of the present invention to provide a method and means for measuring anisotropy of a plasma in a magnetic field wherein the plasma produces free-free bremsstrahlung radiation, which method and means are more sensitive than heretofore.

It is another object of the present invention to provide a method and means for measuring the anisotropy of a plasma in a magnetic field by measuring the polarization of free-free bremsstrahlung radiation produced by the plasma.

Other objects of the present invention will become more apparent as the detailed description proceeds.

In general, for the practice of the present invention, anisotropy of a plasma in a magnetic field is determined by measuring the degree of polarization of free-free bremsstrahlung radiation produced by the plasma.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of an apparatus for the practice of the present invention with a magnetic-mirror machine.

FIG. 2 is a horizontal section taken along lines 2—2 of FIG. 1.

FIG. 3 is an axial profile of the magnetic field of the apparatus of FIG. 1 about the center of the plasma chamber.

FIG. 4 is a logarithmic graphical plot of particle counts versus energy for the radiation vector components detected with the apparatus of FIG. 1.

FIG. 5 is a graphical coordinate representation of free-free bremsstahlung polarization from a particle deflected by a scattering center.

FIG. 6 is a graphical plot of photon frequency versus maximum photon frequency obtainable form an electron of predetermined momentum.

DESCRIPTION OF THE PREFERRED EMBODIMENT

For purposes of understanding, the present invention will be described as applied to a magnetic-mirror machine. It is to be understood that the present invention is not limited to such a plasma machine. It is applicable to any device wherein a plasma is formed in a magnetic field, which plasma produces free-free bremsstrahlung radiation.

In FIG. 1, a conventional magnetic-mirror machine **10** is shown in schematic form. The magnetic-mirror machine **10** comprises a stainless steel chamber **12** approximately 15 centimeters in diameter. Six magnetic-field coils **14** are disposed about the chamber **12** as shown along a length of approximately 1 meter to provide a magnetic field substantially parallel to the axis of the chamber **12** and having a profile about the center point of the chamber **12** as shown in FIG. **3**. A DC supply **16** is connected to the coils **14** to provide the currents through the coils necessary for establishment of the magnetic field in the chamber **12**. A helium source **18** is connected to the chamber **12** to provide a source of helium gas within the chamber **1**. An RF generator **20** in connected via waveguides to the interior of the cylindrical chamber **12** to provide, in cooperation with the magnetic field from magnet coils **14**, the heating and confinement necessary to form a plasma within the chamber **12** from the helium gas from source **18**. A vacuum pump **22** is also connected to the cylindrical chamber to maintain the chamber **12** in a partially evacuated condition. It will be appreciated that the structure described is a conventional magnetic-mirror machine which operates to form a plasma about the center point of the cylindrical chamber **12** by electron cyclotron resonant heating.

The plasma formed by the aforedescribed magnetic-mirror machine **10** produces free-free bremsstrahlung radiation within the interior of the cylindrical chamber **12**. For the practice of the present invention, a hollow collimating pipe **24**, of a material such as copper, is mounted to the cylindrical chamber **12** at the site of the plasma contained therein. The tube **24** is mounted normal with respect to the magnetic field from magnet coils **14** and is open at the end engaging the chamber **12** to provide access to the interior of the chamber **12** and permit partial evacuation of the tube **24**. A pinhole lens **26** is mounted within the evacuated collimating

tube 24 adjacent the cylindrical chamber 12. Diametrically opposite the collimating tube 24 a second short copper tube 28 is mounted on cylindrical chamber 12 in line with the collimating tube 24. The copper tube 28 is mounted so that one end thereof is provided with access to the interior of the cylindrical chamber 12. The other end of the tube 28 is sealed with a mylar window 30. A second mylar window 32 is mounted at the end 34 of collimating tube 24, remote from chamber 12, to effect a seal thereabout. The pinhole lens 26, collimating tube 24 and copper tube 28 cooperate to provide collimation of the free-free bremsstrahlung radiation from the plasma in cylindrical chamber 12 with minimal effect from wall-bremsstrahlung radiation or significant attenuation by air of the collimated free-free bremsstrahlung radiation.

A lead-brick radiation-shield housing 36 is built at the end of collimating tube 24 in an L-shape arrangement as shown in FIGS. 1–2. One arm 38 of the radiation shield 36 is formed substantially parallel to the axis of the chamber 12 and the magnetic field formed by magnet coils 14. The other arm 40 of the radiation shield 36 is formed normal to the arm 38 and hence normal to the axis of chamber 12 and the magnetic field formed by magnet coils 14. A low Z material 42 of generally cylindrical shape is mounted within the interior of the lead shield housing 36 to intercept the collimated free-free bremsstrahlung radiation passing through the collimating tube 24. The low Z material 42 intercepts the free-free bremsstrahlung radiation and effects Compton scattering thereof. A scintillation counter 4 is mounted within the arm 38 of lead-shielded housing 36 to detect from the low Z material 42 Compton scattered radiation having a direction parallel to the axis of the chamber 12 and the magnetic field formed by magnet coils 14. Another scintillation counter 46 is mounted with the arm 40 of lead-shielded housing 36 to detect from the low Z material 42 Compton scattered radiation which is normal to the axis of the chamber 12 and the magnetic field formed by magnet coils 14. The scintillation counters 44 and 46 are mounted within the lead-shielded housing 36 so that the radiation detected lies in a single plane substantially normal to the collimating tube 24 and hence the collimated free-free bremsstrahlung radiation therein. A cylindrical L-shaped magnetic shield 50 of soft-iron material is mounted within the lead-shielded housing 36 about the scintillation counters 44 and 46. The magnetic shield 50 has an aperture 52 cut therein to permit the passage therethrough of the collimated free-free bremsstrahlung radiation from the plasma in chamber 12. A pair of cylindrical magnetic shields 54 of high μ material are each mounted about an associated one of the scintillation counters 44 and 46.

A high voltqge supply 56 is connected to both scintillation counters 44 and 46 to provide the excitation high voltage therefor. The output of scintillation counter 44 is fed to the input of a multichannel analyzer 58 and the output of scintillation counter 46 is fed to the input of a multichannel analyzer 60. The outputs of multichannel analyzers 58 and 60 are fed to conventional add and subtract circuits 62 and 64. A conventional divide circuit 66 is connected to the outputs of the add and subtract circuits 62 and 84 to take the ratio thereof. A dual trace oscilloscope 68 is connected to simultaneously display the outputs of the multichannel analyzers 58 and 60.

In operation, the plasma within the cylindrical chamber 12 generates free-free bremsstrahlung radiation. The collimating tube 24 via the pinhole lens 26 collimates the free-free bremsstrahlung from the plasma at a point therein where the magnetic field generated by magnet coils 14 is at a relative constant value. The collimated free-free bremsstrahlung radiation travels up the collimating tube 24 to be incident upon the low Z material 42 which acts to scatter the free-free bremsstrahlung radiation. The Compton scattered radiation from the low Z material is detected by the scintillation detectors 44 and 46 in a plane normal to the collimated free-free bremsstrahlung radiation and parallel to the electric field of such free-free bremsstrahlung radiation. As previously stated, the scintillation detectors 44 and 46 detect the scattered bremsstrahlung radiation in a direction parallel to the magnetic field formed by magnet coils 14 and in a direction normal to the magnetic field formed by magnet coils 14. Thus, the scintillation counters 44 and 46 detect the vector components of the bremsstrahlung radiation incident upon the low Z material 42.

The mutlichannel analyzers 58 and 60 are energized for a predetermined time interval. During this inverval the multichannel analyzers 58 and 60 record the outputs of scintillation counters 44 and 46 and accumulate such outputs in storage according to the discrete energy levels thereof. The summed counts of each particular energy level for the predetermined time interval during which measurement is effected are extracted from the analyzers 58 and 60 and fed to the adding circuit 62 where the sum thereof for each particular energy level is obtained. Similarly, the particular energy level count is simultaneously fed to the subtract circuit 64 where the difference thereof is obtained. The divide circuit 66 then takes the ratio of the summed and subtracted particular energy count to give an output which is a measure of the degree of polarization at the particular energy level measured. This degree of polarization, A, may be expressed by the equation $A = (J_{11} - J_1)/(J_{11} + J_1)$, where A = the degree of polarization at the particular energy level measured, J_{11} = the number of counts at the particular energy level measured obtained during the time interval in a direction parallel to the magnetic field formed magnet coils 14 and J_1 is the number of counts at the particular energy level measured obtained during the time interval in a direction normal to the magnetic field formed by the magnet coils 14. The degree of polarization thus obtained for each particular energy level measured is a measure of anisotropy of the plasma formed in the cylindrical chamber 12, and is therefore reflective of the velocity distribution of the electrons in the plasma.

The dual trace oscilloscope 68 is connected to simultaneously display the outputs of the multichannel analyzers 58 and 60 in separate traces which are reflective of the particular energy levels and the total counts obtained therefor for the particular time interval that measurement has been taken. A display of such counts is shown in FIG. 4. The upper trace 70 in FIG. 4 reflects the counts obtained by the scintillation counter 44 and is the vector component which lies in a direction parallel to the magnetic field formed by magnet coils 14. The lower trace 72 reflects the counts obtained by scintillation counter 46 and is the vector component which lies in a direction normal to the magnetic field formed by magnet coils 14. From FIG. 4, it can be seen that

there is a greater vector component count whose direction is parallel to the magnetic field than the vector component count which is normal to magnetic field of the plasma. The anisotropy of the vector counts in FIG. 4 is approximately 4 to 1 which yields a polarization for the free-free bremsstrahlung radiation of 0.6.

The counts shown in FIG. 4 were obtained with the apparatus hereinbefore described with the collimating tube 24 being manufactured from copper and having a height above the cylindrical chamber 12 of approximately 210 centimeters. The low Z material 42 was a solid cylinder of beryllium mounted approximately 213 centimeters above the cylindrical chamber 12. The lead radiation shield 36 was manufactured from 2 inches thick lead bricks and the magnetic shield 50 was approximately 2 millimeters thick and the magnetic shield 54 approximately one-half inch thick. The plasma was produced in the helium gas from the helium source 18 at a pressure of approximately 7×10^{-4} Torr by means of electron cyclotron resonance heating from a 100 kilowatt pulsed microwave source 20 (360 2 microsecond pulses per second). The scintillation counters 44 and 46 were sodium-iodide scintillator-photomultiplied detectors and the counting was effected for 100 minute counts.

It was further found that the degree of polarization of the free-free bremsstrahlung radiation was a function of impurity-gas pressure. The normal base pressure of the apparatus of FIG. 1 was approximately 5×10^{-7} Torr. When the pumping rate was intentionally slowed down to produce a base pressure of 3×10^{-6} Torr, whereby the impurity concentration was increased, the polarization at the same operating pressure was decreased to approximately 0.3 along with a fourfold decrease in total radiation vector components detected because of the resultant increase in collision cross section. The relative shape of the plots shown in FIG. 4 remained the same however. The degree of polarization was also found to be a function of the mirror ratio of the apparatus shown in FIG. 1. The original mirror ratio was 1.10 to 1. When the mirror ratio was decreased to 1.02 to 1, the degree of polarization increased and the absolute vector components detected decreased, which decrease is reflective of the fact that the confinement time was lowered with the smallest value of mirror ratio.

Further appreciation of the present invention may be ottained by considering the quantum-mechanical non-relativistic theory of free-free bremsstrahlung polarization from a particle with a momentum $\vec{P}_o$ deflected by a fixed scattering center. The coordinate representation describing this relationship is illustrated in FIG. 5. The origin of the coordinate representation is at the scattering center. The magnetic field is in the z direction and $\vec{k}$, the propagation vector of the photon in the direction of observation, is in the y direction. $\vec{P}_o$ is the momentum vector of the electron before collision, and $\vec{p}$ is its momentum after the collision. The polarization vector $\vec{J}$ (parallel to the photon's electric field) is always perpendicular to $\vec{k}$. Thus for the directions shown, the polarization vector is in the x–z plane.

The degree of polarization, A, is given by

$$A = (J_{11} - J_1)/(J_{11} + J_1) = [(1 - 3D^2)\ 1n\ (1 + D/1 - D) + 6D] \times [(3 - D^2)\ 1n\ (1 + D/1 - D) + 2D]^{-1} \quad (1)$$

where $|p|/|p_o| = D$. The subscripts 11 and 1 refer to directions parallel and perpendicular to the plane of the incident momentum vector $\vec{p}_o$ and $\vec{k}$ (not to the direction of the magnetic field lines). A graph of this function is shown in FIG. 6 as a function of ν/ν_o, where ν is the photon frequency and ν_o is the highest photon frequency obtainable from an electron of momentum $\vec{p}_o$. The conditions under which the x rays are emitted in this system correspond to this high-frequency limit (that is, the photon energy is comparable to the electron energy). The degree of polarization should approach the value 1. Thus, in the y direction more photons are emitted with polarization in the x direction if the electron is incident in the x direction. For a plasma whose electron velocity distribution is anisotropic so that most of the electrons are in the x–y plane, J tends to be in the direction perpendicular to the magnetic field lines.

It will be appreciated that though the present invention has heretofore been illustrated using two scintillation counters 44 and 46, the present invention may be effected using a single scintillation counter. Where a single scintillation counter is used, the counts are first obtained for a perticular time interval in one of the desired directions (either parallel or normal to the magnetic field formed by the magnet coils 14). Then the scintillation counter is aligned in the same plane normal to its first direction to effect the count for a like time interval in the opposite direction (the other of either normal or parallel to the magnetic field formed by magnet coils 14). The counted results are then combined in a similar manner as for the simultaneous dual counting and the degree of polarization measured therefor. The degree of polarization as so measured is a measure of anisotropy of the plasma formed in the cylindrical chamber 12.

Persons skilled in the art will, of course, readily adapt the teachings of the present invention to embodiments and methods far different than those illustrated and described above. Accordingly, the scope of protection afforded the present invention should be limited only in accordance with the accompanying claims.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A method for measuring anisotropy of a plasma in a magnetic field which plasma produced free-free bremsstrahlung radiation comprising measuring the degree of polarization of said free-free bremsstrahlung radiation.

2. The method according to claim 1 wherein said free-free bremsstrahlung radiation polarization measurement comprises collimating said free-free bremsstrahlung radiation in a direction substantially normal to said magnetic field, scattering said free-free bremsstrahlung radiation to provide vector components thereof in a plane parallel to the electric field of said radiation, and measuring said vector components to provide a measure of anisotropy of said plasma.

3. The method according to claim 2 wherein said vector component measuring comprises detecting vector components parallel to said magnetic field and detecting vector components normal to said magnetic field, which detected components are a measure of anisotropy of said plasma.

4. The method according to claim 2 wherein said vector component measurement comprises counting over a predetermined interval the vector components at discrete energy levels of said free-free bremsstrahlung parallel to said magnetic field, counting over a like pre-

determined time interval the vector components at like discrete energy levels of said free-free bremsstrahlung normal to said magnetic field, and combining like-energy-level vector-component counts to provide a degree of polarization A for said free-free bremsstrahlung according to $A = (J_{11} - J_1/J_{11} + J_1)$, where J_{11} = number of vector component at a particular energy level parallel to said magnetic field, J_1 = number of vector component at said particular energy level of J_{11} normal to said magnetic field, which degree of polarization is a measure of anisotropy of said plasma.

5. The method according to claim **4** wherein said vector component counts are effected simultaneously over like time intervals.

6. An apparatus for measuring anisotropy of a plasma in a magnetic field which plasma generates free-free bremsstrahlung radiation comprising means for collimating said free-free bremsstrahlung radiation in a direction normal to said magnetic field, means intercepting said collimated free-free bremsstrahlung radiation to resolve said radiation into the vector components thereof, and means for measuring vector components mutually normal relative each other to provide a measure of anisotropy of said plasma.

7. The apparatus according to claim **6** wherein said collimating means comprise an evacuated first hollow member extending from said plasma in a direction essentially normal to said magnetic field and providing pinhole access to said plasma, and a second hollow member providing access to said plasma on the opposite side thereof relative said first hollow member and aligned with said first member.

8. The apparatus according to claim **6** wherein said vector-component resolving means comprise a scattering material positioned to intercept said collimated free-free bremsstrahlung radiation and resolve in a direction normal to the electric field of said radiation the vector components of said radiation.

9. The apparatus according to claim **8** wherein said vector component measuring means comprise scintillation-counter means positioned to detect from said scattering material said vector components parallel and normal to said magnetic field, means for summing during a predetermined time interval said vector-components having like energy levels and being parallel to said magnetic field, means for summing during a like predetermined time interval said vector components having like energy levels and being normal to said magnetic field, and means for combining said vector component summations according to $A = (J_{11} - J_1 J_{11} + J_1)$, where A = the degree of polarization of said free-free bremsstrahlung radiation, J_{11} = said vector component summation parallel to said magnetic field at a particular energy level, J_1 = said vector component summation normal to said magnetic field at a particular energy level, said degree of polarization being a measure of the anisotropy of said plasma.

10. The apparatus according to claim **6** wherein said collimating means, intercepting means and vector component measuring means comprise an evacuated hollow first member mounted normal to said magnetic field and providing pinhole access to said plasma at a constant value region of said magnetic field to collimate said free-free bremsstrahlung radiation, a hollow second member mounted on the opposing side of said plasma providing access thereto and aligned with said first member, a scattering material mounted to intercept said collimated free-free bremsstrahlung radiation and resolve said radiation into the vector components thereof in a plane parallel to the electric field of said bremsstrahlung radiation, scintillation-counter means positioned to detect from said scattering material said vector components parallel and normal to said magnetic field, summing means electrically connected to said scintillation counter means during a predetermined time interval to sum like-energy-vector-components parallel to said magnetic field and to sum like-energy-vector-components normal to said magnetic field, and means for combining said like-energy summed vector components according to $A = (J_{11} - J_1 J_{11} + J_1)$, where A = the degree of polarization of said free-free bremsstrahlung radiation level, J_{11} = said summed vector components at said particular energy level parallel to said magnetic field, J_1 = said summed vector components at said particular energy level normal to said magnetic field, said degree of polarization being a measure of the anisotropy of said plasma.

* * * * *