Feb. 4, 1969 D. R. SIMON ET AL 3,426,233

PLASMA STABILIZATION BY ROTATION OF ARC DISCHARGE TUBE

Filed Dec. 13, 1965 Sheet 1 of 3

FIG. 1

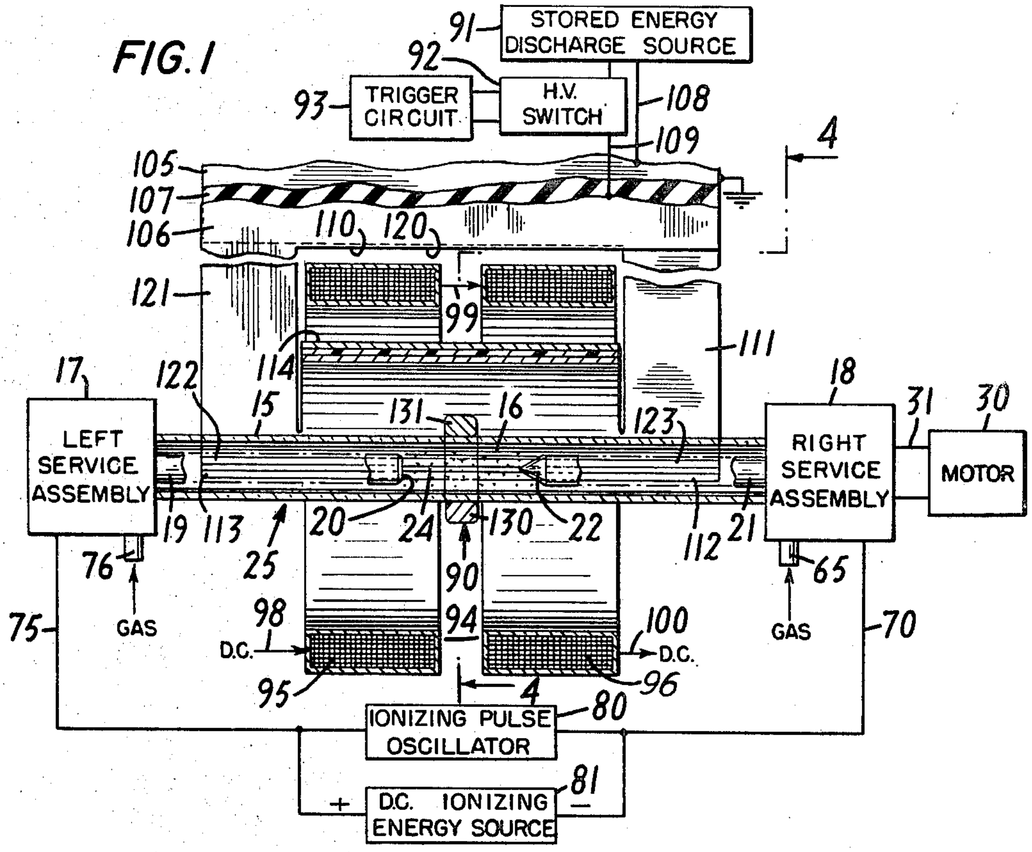
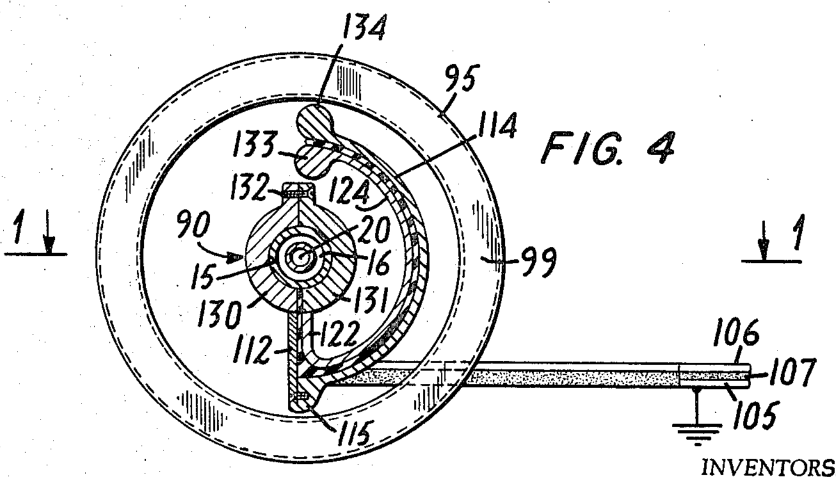


FIG. 4



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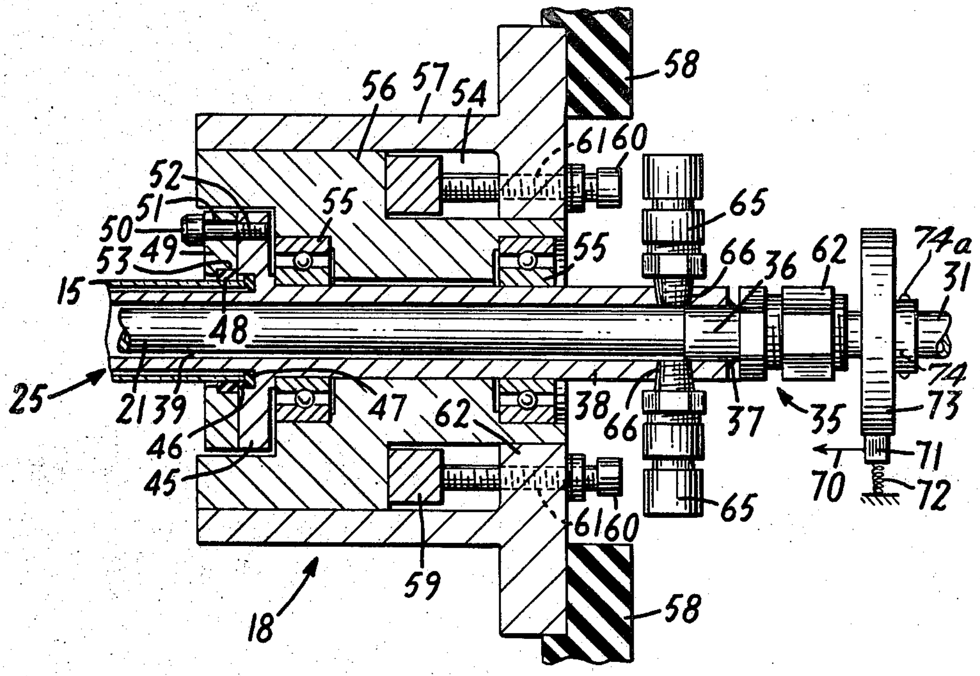

FIG. 3

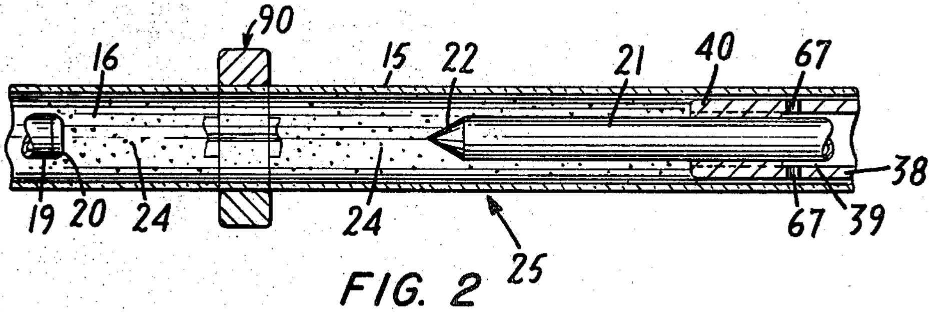

FIG. 2

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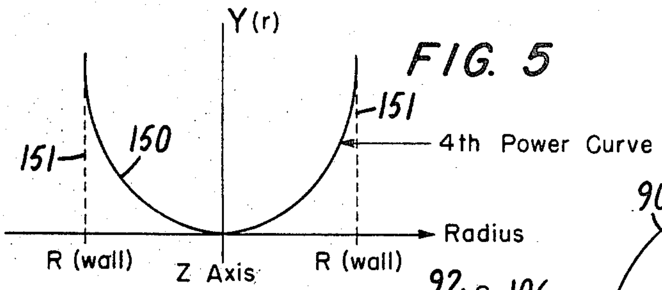

FIG. 5

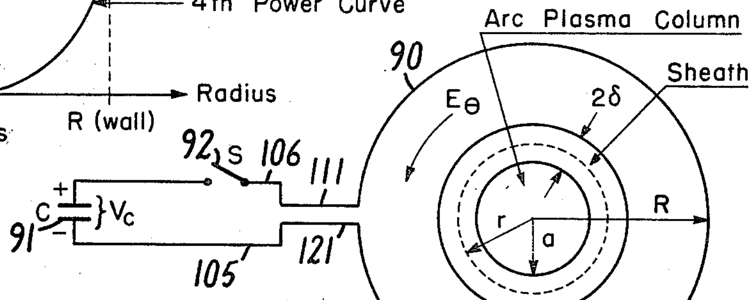

FIG. 6

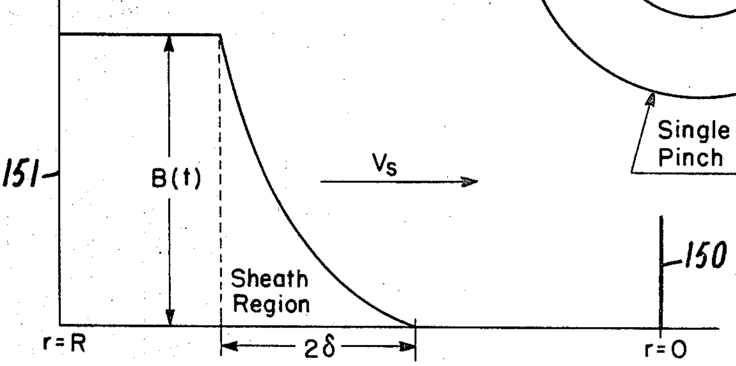

FIG. 7

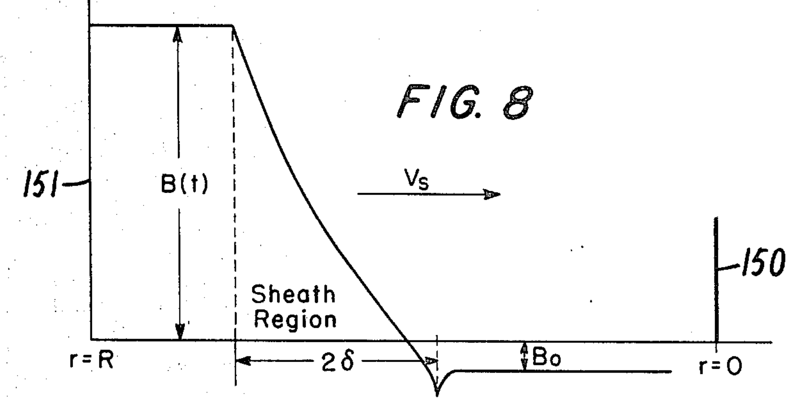

FIG. 8

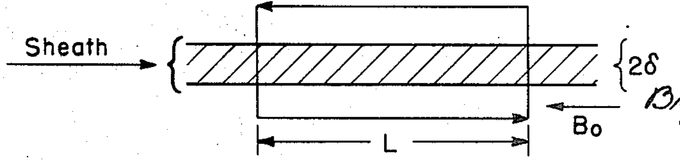

FIG. 9

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PLASMA STABILIZATION BY ROTATION OF ARC DISCHARGE TUBE

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U.S. Cl. 313—161 19 Claims
Int. Cl. H01j *1/50, 3/32, 29/76*

ABSTRACT OF THE DISCLOSURE

A gaseous medium with an initial density of at least 0.02 kilogram/meter^3 is pre-ionized to yield an electron density of at least 10^{16} electrons/cc. by the passage through the medium of an electric arc which is positionally stabilized by rotating the enclosure for the medium to rotate the medium. The pre-ionized medium is caused to emit soft X-rays and/or short ultraviolet by compression thereof by a transient axial magnetic field generated by a theta coil. The yield of radiation may be enhanced by the use of a supplemental D.C. axial magnetic field opposing the transient field.

This invention relates to methods and apparatus which employ a high density plasma to provide useful effects as, for example, an output of radiation in the form of X-rays or ultraviolet rays of short wavelength. In a more limited aspect, this invention relates to methods and apparatus wherein radiation is obtained from a high density plasma by subjecting it to a magnetic compression effect.

A well known way of creating a plasma is to develop in a gaseous medium between two spaced electrodes an electrical discharge which ionizes the medium. In devices such as fluorescent tubes wherein the discharge takes place through a gaseous medium which is of low density because it is under low pressure, the plasma column is stable in its position between the two electrodes. As, however, the density of the medium increases and the electrical discharge accordingly becomes an arc type discharge, the heat from the arc causes a buoyancy distortion in the path followed by the arc plasma column. That is, as exemplified by the usual arc developed between widely spaced electrodes in air under atmospheric pressure, the path of the arc varies with time in a random wavy manner so as to be characterized over its length by shifting perturbations or "kinks." In general, the higher the density of the medium in which the arc is produced, the more pronounced those perturbations become.

In accordance with one aspect of the invention, we have discovered that an arc plasma column in a high density gaseous medium may be stabilized in position by preliminarily imparting to the gaseous fluid a mechanically induced spin or rotation around the axis of spacing of the electrodes producing the arc. As later explained in detail, such spinning of the fluid stabilizes the position of the arc plasma column by a pressure gradient effect which varies directly with the density of the fluid so that, the higher such density, the greater the stabilizing influence of the spin on the column.

In accordance with another aspect of the invention, we subject a high density plasma to a magnetic compression effect to produce emanation from the plasma of high energy radiation such as soft X-rays or ultraviolet rays of short wavelength. The magnetic compression technique has been used heretofore in experimental devices aiming at the attainment of self-sustaining controlled nuclear fusion. In those prior art devices, however, the object has been to minimize emission of radiation from the magnetically "bottled" plasma in order the better to reach the critical temperature necessary for a nuclear fusion reaction to be initiated or to be self-sustaining. In contrast, in a system according to our invention, the emission of radiation from the magnetically compressed plasma is deliberately maximized. Further, in those prior art devices, the density of the gaseous medium has been on the order of 2×10^{-5} kilograms/meter^3 maximum, whereas in our system the density of the gaseous medium is at least 1000 times greater. Still, further, in the mentioned prior are devices, the time from start to finish of the dynamic reaction produced in the device has been on the order of 1000 microseconds or greater, whereas in our system the dynamic reaction which produces the desired radiation has a start to finish time of the order of one microsecond.

It is further in accordance with our invention to stabilize an arc plasma column in a high density gaseous medium by the mentioned pressure gradient effect and to then apply a magnetic compression to the stabilized column so as to cause emission of high energy radiation.

For a better understanding of the invention, reference is made to the following description of representative embodiments thereof and to the accompanying drawings wherein:

FIG. 1 is a plan view (partly schematic and partly in cross-section) of apparatus according to the invention; the cross-section being taken as indicated by the arrows **1**—**1** in FIG. 4;

FIG. 2 is an enlarged plan view (in cross section) of the central portion of the plasma tube of the FIG. 1 apparatus;

FIG. 3 is an enlarged front elevation view in cross section of the right service assembly of the apparatus of FIG. 1;

FIG. 4 is a side elevation in cross section of the FIG. 1 apparatus, the cross section being taken indicated by the arrows **4**—**4** in FIG. 1; and

FIGS. 5–9 inclusive are schematic diagrams explanatory of the mode of operation of the FIG. 1 apparatus.

Apparatus

Referring now to FIGS. 1 and 2, a hollow transparent quartz container cylinder **15** (of about 1" outer diameter and 36" length) is filled with a high density ionizable gaseous medium **16**, e.g., pure xenon at an absolute pressure of one atmosphere. At its left and right ends, cylinder **15** is supported by, respectively, a left service assembly **17** and a right service assembly **18**, The two assemblies are constructed to permit spinning of the cylinder about its own axis.

A thoriated tungsten electrode rod **19** (of which the center portion is shown broken away in FIG. 1) extends from unit **17** through the interior of cylinder **15** to a blunt termination forming an anode electrode **20** within the cylinder. Another thoriated tungsten electrode rod **21** (of which the center portion is broken away in FIG. 1) extends through the interior of the cylinder to a pointed termination **22** providing within the cylinder a cathode electrode spaced from anode **20** by an axial gap **24** disposed at a central position in the length of the container cylinder. The two electrode rods and the electrodes thereon are all coaxial with the axis of cylinder **15** and (as later described) are maintained by units **17** and **18** in rotatably fixed relation with cylinder **15** to spin therewith. The elements **15**, **16** and **19–24** together form a plasma tube designated generally by the reference numeral **25**.

Tube **25** is rotated by a motor **30** (e.g., an air motor or one of another type) of which the shaft is coupled to the tube by a conventional insulating sleeve coupling **31** (FIG. 1) connected to the right hand end of rod **21** at a point to the right of where rod **21** is shown rightwardly broken away in FIG. 3.

The service assembly **18** (FIG. 1) includes a standard tube fitting **35** comprised of a gland nut **62**, one or more ferrules (not shown) and a main body **36** through which the rod **21** passes. The body **36** of the fitting is received within and coupled by solder **37** to a stainless steel mounting tube **38** coaxial with rod **21** and containing a portion of that rod which extends from fitting end **36** through service assembly **18** and part way into the quartz cylinder **15** (FIG. 2). Except at its left-hand end **40** (which fits closely around rod **21** to provide a support therefor), the inner diameter of tube **38** is greater than the outer diameter of rod **21** to provide between the tube and rod an annular gas passage **39**. When nut **62** is tightened, fitting **35** provides both a torque coupling between elements **21** and **38** and a gas seal for the right hand end of passage **39**.

At the left-hand end of unit **18**, the mounting tube **38** is provided with an outwardly salient radial flange **45** in the left side of which is formed a leftward-facing annular groove **46** encircling the mounting tube proper. The right-hand end of quartz cylinder **15** is received in groove **46** to axially bear against a gasket ring **47** seated in the groove. Another gasket ring **48** encircles the right-hand end of the cylinder and is seated in an annular groove **53** formed in an annular coupling plate **49** in registration with and to the left of flange **45**. Plate **49** may be drawn towards flange **45** by the tightening of screws **50** (only one shown) passing through unthreaded holes **51** in the plate into threaded holes **52** in the flange.

The mounting tube **38** is journaled within a pair of high-speed radial thrust bearings **55** on the interior of and secured to a metal sleeve **56**. Sleeve **56** is received within and axially slidable in the bore **54** of a cylindrical metal housing **57** fastened to insulating members **58** which are in turn fastened to a support frame (not shown) for the described apparatus. The right-hand end of sleeve **56** is of reduced diameter and is contacted by angularly spaced conventional schematically shown swivel pads **59** on the forward ends of push-screws **60** passing through threaded holes **61** in an inwardly salient radial flange **62** formed at the right-hand end of housing **57** and fitting closely around the reduced-diameter right-hand end of sleeve **56** to provide a support therefor.

During preliminary adjustment of the apparatus, nut **62** is loosened to release tube **38** for axial movement relative to rod **21**, and the push-screws **60** are then turned to urge plate **59** leftward so as to force sleeve **56** in that direction. When so forced, the sleeve bears against the flange **45** of tube **38** to drive that flange and tube leftward to thereby cause gasket ring **47** to be axially squeezed between the flange and the right-hand end of quartz cylinder **15**. Thereafter, nut **62** is tightened to provide the mentioned gas seal at the right-hand end of passage **39** and to lock rod **21** and tube **38** together so that torque transmitted (FIG. 1) from motor **30** through sleeve coupling **31** to rod **21** is in turn transmitted (FIG. 3) from rod **21** to tube **38**.

Gasket ring **47** when axially squeezed provides a gas-tight end closure for the right-hand end of plasma tube **25**. After that gas-tight seal has been established, screws **50** are tightened to draw coupling plate **49** towards flange **45** and to thereby cause the gasket ring **48** to be radially squeezed between plate **49** and the outside of quartz cylinder **15**. Because of such radial squeezing, the cylinder is gripped firmly by the gasket ring to thereby be rotatably coupled through elements **49**, **50**, **45**, **38**, **37** and **36** to the cathode electrode rod **21**. In this manner, the cathode of the plasma tube **25** is locked for rotation with the container envelope thereof.

The gaseous medium **16** within the plasma tube may be introduced into or removed from the quartz container

15 through either one of a pair of "quick-disconnect" gas fittings **65** received in threadedly engaged relation in holes **66** in mounting tube **38**. Each fitting **65** provides an inlet to or an outlet from the annular gas passage **39** desired between the inside of tube **38** and the outside of the cathode rod **21**. Although that passage is closed at its left-hand end (see FIG. 2), radial holes **67** in the tube **38** permit flow of the gaseous medium through passage **39** in either direction between one of the fittings **65** and the central region of the plasma tube. The two fittings **65** balance each other relative to the axis of rotation of the plasma tube so as to minimize eccentricity in the mass rotated by the motor **30**.

An electrical connection is made to cathode **21** through a lead **70** (FIG. 3) terminating at a brush **71** biased by a spring **72** to bear against a slip ring or disc **73** encircling rod **21** to be in direct electrical contact therewith. Disc **73** has a collar **74** and is fixedly mounted on rod **21** by set screws **74*a*** passing through the collar.

The left service assembly **17** (FIG. 1) is not directly coupled to a motor but otherwise is similar to the right service assembly **18**. The unit **17** serves to provide a gas-tight enclosure for the left end of plasma tube **25** and to lock the quartz cylinder **15** to the anode rod **19** so that both elements rotate together. That is, the rotary motion imparted to quartz cylinder **15** by motor **30** is transmitted through that cylinder to the left-hand service unit and then through such unit to the anode **19** so that the anode rotates in angularly fixed relation with the container cylinder.

An electrical connection is made through unit **17** to anode **19** by way of a lead **75** coupled to a brush and slip ring arrangement (not shown) included in unit **17** and similar to the brush and slip ring (FIG. 3) of right assembly **18**. The gaseous medium **16** may be introduced into or removed from the interior of the plasma tube **25** by way of "quick-disconnect" gas fittings **76** (only one shown) provided by unit **17** and duplicating those of the right-hand unit **18**.

The leads **70** and **75** are connected to opposite terminals of an ionizing pulse oscillator **80** and of a D.C. ionizing energy source **81** in parallel with the oscillator. As later described in more detail, the components **80** and **81** are utilized sequentially to energize the electrodes of the plasma tube **25**.

The interelectrode gap **24** in the plasma tube is encircled by a single-turn theta compression coil **90** surrounding the quartz container cylinder of the tube. Coil **90** is adapted to be energized by a burst of high energy electric current from a stored energy discharge source **91**. Source **91** may be either a bank of selectively dischargeable storage capacitors or a high energy pulse storage network, the latter providing a more or less rectangular output pulse. The initiation of the discharge through the theta compression coil is controlled by a high voltage switch **92**. As shown (FIG. 1) switch **92** may be an exploding wire switch controlled by a manually actuated trigger circuit **93**. When switch **92** is closed, the resulting burst or surge of current through coil **90** develops in interelectrode gap **24** a transient axial magnetic field $B(t)$ of which the direction of the flux lines is positive, e.g., from left to right in FIG. 1.

As an optional feature of the FIG. 1 apparatus, the plasma tube **25** may be surrounded by a pair of D.C. magnet coils **95** and **96** coaxial with the plasma tube and each other and of substantially greater inner diameter than the outer diameter of the theta compression coil **90**. Coils **95** and **96** are adapted by flow of D.C. current through input lead **98**, coil-connecting lead **99** and output lead **100** to develop in interelectrode gap **24** an axial D.C. magnetic field B_0 of which the flux lines have a negative direction, e.g., are from right to left in FIG. 1 so as to be in opposition to the flux lines of the transient field $B(t)$. As shown, coil **95** and **96** are disposed on opposite axial sides of the theta compression coil **90** so as to be spaced apart by a radial "window" **94**. Such window permits radial escape to the exterior of coils **95** and **96** of radiation from plasma within cylinder **15** which is subjected to the transient axial magnetic field $B(t)$.

To minimize the inductance in the connection between the high energy discharge source **91** and the theta compression coil **90**, that connection is in the form of a flat plate transmission line comprised of spaced parallel lower and upper wide transmission plates **105** and **106** separated by an insulating layer **107** provided by, say, polytetrafluoroethylene sheeting. In practice, plates **105** and **106** extend all the way to source **91**. In FIG. 1, however, the rear portions of the plates have been shown broken away (for convenience of illustration) and are schematically represented in the drawing by the conductors **108**, **109**.

At their forward ends, plates **105** and **106** are electrically coupled to theta compression coil **90** by a curved shell structure which is specially shaped to fit inside the D.C. magnetic coils **95**, **96** while simultaneously providing a low-resistance, low-inductance connection to the compression coil. To describe that structure, forward of an edge **110**, the lower transmission plate **105** reduces in width to a flat right-hand arm **111** extending beyond edge **110** past D.C. magnet coil **96** to a front end slightly forward of the axis of the plasma tube **25**. At its front end, arm **111** is conductively joined with the lower portion of a vertical conductive strip **112** (FIG. 4) upstanding from the arm and extending axially from the right-hand edge of the arm to point **113**. Conductively joined to a section of strip **112** to the right of arm **111** is a semi-cylindrical conductor shell **114** of which the chord line is perpendicular to arm **111**. The undersides of the joints of arm **111** and shell **114** to strip **112** are rendered rounded by fairing **115** to thereby reduce corona leakage from those joints.

Upper transmission plate **106** is symmetrical with lower plate **105** in that the upper plate likewise reduces in width at a forward edge **120** to a flat left-hand arm **121** extending beyond that edge and past and to the left of coil **95** to a front end disposed slightly short of the axis of the plasma tube. The forward end of arm **120** is joined to a vertical conductive strip **122** parallel to and spaced from strip **112** and extending axially from the left-hand edge of arm **122** to the shown point **123**. Conductively joined to a section of strip **122** to the right of arm **121** is a semi-cylindrical shell **124** axially co-extensive with (and concentric with) and spaced radially inward of the previously described shell **114**. The joints of arm **121** and of shell **124** to the strip **122** are rounded off as shown (FIG. 4) to minimize corona leakage.

Theta compression coil **90** is in the form of a split ring comprised of semicircular halves **130** and **131** clamped together at the top by a screw **132** and separated at the bottom by a small space. The two ring halves **130** and **131** are conductively joined to axially central portions of the upper ends of, respectively, the strip **112** and the strip **122**. Insulating material (e.g., polytetrafluoroethylene sheeting) fills the spaces between the ring halves **130** and **131**, the vertical conductive strips **112**, **122** and the conductive shells **114**, **124**. The upper forward edges **133** and **134** of those shells are rounded as shown (FIG. 4) to minimize corona leakage from the salient upper end of the shell configuration.

Operation

The operation of the described system is initiated by actuating motor **30** to spin the plasma tube **25**. The full speed rate of spin should be at least 3×10^3 r.p.m. and preferably 10^4 r.p.m. or greater. The latter spin rate can be achieved without difficulty by the use of an appropriate motor.

When the plasma tube is so spun, the rotary motions of its container cylinder **15** and the electrodes therewithin are imparted to the contained gaseous medium **16**. In this manner, the gaseous fluid of the medium is caused to mechanically spin or rotate about the axis of rotation of the plasma tube at about the same spin rate as that characterizing the tube itself.

After tube **25** is spinning at full speed, the pulse oscillator **80** is actuated to strike an arc through the medium **16** in the gap **24** in cylinder **15** between the electrodes **20** and **22**. Oscillator device **80** may be, for example, a 40 kv. spark gap oscillator with an ascillation frequency of 2 mc. When the arc has been struck, it is maintained by the switching on of the D.C. voltage generator **81** of which exemplary operating parameters are: an open circuit output voltage of 320 volts or greater, and (depending on the circuit characteristics of the plasma tube) an output current of from 100 to 1,000 amperes productive of a voltage drop of from 30 to several hundred volts between electrodes **20** and **22**. Once the generator device **81** has assumed the load of maintaining the arc, the oscillator **80** is turned off.

The passage of the electric arc through the medium pre-ionizes that medium to create therein a column of plasma referred to herein as the arc plasma column. Because of the high current of the arc and the high density of the medium, the pre-ionization electron density n_e of the plasma is high, e.g., at least 10^{16}/cm.^{3} and preferably 5×10^{17}/cm.^{3} to 5×10^{18}/cm.^{3}. A pre-ionization electron density of at least 10^{16}/cm.^{3} is desirable in the described apparatus because the power in joules/m.^{2} radiated per unit surface area of radiating region is dependent on such electron density. The pre-ionization electron density of the plasma can be increased by increasing the pressure of the gaseous medium or by seeding it with particles in the gaseous phase of an easily ionizable chemical element. Limitations on increasing the electron density by increasing the pressure are (1) the electron density does not increase in proportion to the pressure, and (2) increased pressure results in a decreased mean free path for the electrons to thereby decrease the mean photon energy level of the emitted radiation.

The mechanical spinning of the plasma tube **25** and of the medium therein produces a corresponding mechanical spinning of the arc plasma column generated in the gap **24** between the electrodes **20** and **22**. Such spinning of the column has the following useful effect. The heat generated in the medium by the passage therethrough of the arc creates convection currents in the fluid medium, and those currents act over the length of the arc plasma column to tend to impart to it a buoyancy distortion. That is, if the arc plasma column were not spinning, the convection currents would produce over the length of the column local random radial displacements in the form of the perturbations or "kinks" similar to those observed in, for example, an arc produced in the atmosphere between widely spaced electrodes.

We have discovered, however, that, by mechanically spinning the arc plasma column, there is created a pressure gradient effect by which the column is stabilized in relation to the axis of spacing of the electrodes by which the column is produced. By virtue of such effect, the random radial perturbations of the column are eliminated or rendered inconsequential, and the column itself is caused to assume a stable position concentric with such axis. As later explained in more detail, the stabilization is directly proportional to the density of the medium and to, also, the square of the angular frequency of fluid rotation.

Besides being spun, the arc plasma column is subjected to the D.C. axial magnetic field B_0 generated by passage of D.C. current through coils **95** and **96**. Those coils may be energized either before or after establishment of the arc plasma column.

The pre-ionized, spin stabilized arc plasma column is then induced to emit radiation by subjecting it to a magnetic compression effect. The compression effect is produced by actuating trigger circuit **93** to "close" exploding wire switch **92** to cause the source **91** to discharge a burst of current through the theta compression coil **90**. An adequate strength discharge through the coil is provided when source **91** is pre-charged to a voltage value of from 120 kv. to 240 kv.

Because of the low inductance of the single turn of the theta compression coil and because, further, of the low inductance of the parallel plate transmission line **105, 106** and of the curved shell structure by which that line is connected to the compression coil, the LC system formed by source **91**, coil **90** and the coupling therebetween is characterized by a high ringing frequency, e.g., at least 300 kc. and preferably 500 kc. or greater. A high value of ringing frequency is desirable for reasons later explained.

The burst of current through coil **90** produces in gap **24** in cylinder **15** a transient axial magnetic field $B(t)$ opposed in direction to the D.C. field B_0. The $B(t)$ flux lines do not instantaneously penetrate to the radially interior region of gap **24** to there be admixed with the B_0 flux lines. Instead, the $B(t)$ field forms around the B_0 field a magnetic sheath which implodes at high velocity radially inwards towards the axis of the arc plasma column. The velocity of inward movement of the sheath is preferably on the order of 10^7/cm.-sec.

The imploding magnetic sheath compresses the plasma by exerting on the ions and electrons therein a magnetic pressure which drives the ions and electrons radially inward, and which causes both types of charged particles to be accelerated within the sheath. Because of their large difference in mass, the respective trajectories of the ions and of the electrons are quite different. The heavy mass ions are, relatively speaking, deflected very little by the magnetic pressure and, therefore, move radially inward with only an inconsequential component of motion in the angular or "theta" direction. The much lighter electrons are, on the other hand, vigorously deflected to describe sweeping arcs in the theta direction.

The difference in the ion and in the electron trajectories increases in the sheath region the mean ion-electron spacing to thereby create in the sheath a net space charge separation and a resulting radial electric field E_r within the sheath. During the early time of application of the compression effect, such radial field is strong enough to exceed in volts/meter the electric field E_θ which is induced in the angular or "theta" direction in the region within coil **90** by the changing magnetic field $B(t)$, and which is directed to oppose the flow of the discharge current through the compression coil **90**.

The radial electric field E_r serves to create across the thickness of the sheath a potential V_r which is equal to E_r multiplied by the sheath thickness and which accelerates electrons in the sheath to cause emission of radiation from the plasma in the sheath. The maximum photon energy level of the emitted radiation varies directly with V_r. Under the described conditions of operation, the value of V_r is, for a short period larger enough to produce radiation with a photon energy level of about one kev., e.g., soft X-rays. That the described apparatus is capable of realizing such result is due in an important degree to the use of a medium containing ions of a high mass number. To wit, a direct relationship exists between the mass number M of the ions in the medium and V_r in that (as later pointed out in more detail) the strength of the radial field E_r varies in direct proportion with M, and V_r varies in direct proportion with E_r. Hence, a high mass number M for the ions in the medium implements the emission of radiation of high photon energy level as, for example, soft X-rays.

As a matter of interest, the photon energy level of the emitted radiation is independent of the voltage to which source **91** has been pre-charged, but the power output in joules/meter^2 represented by that radiation is in direct proportion to that voltage. Such power output also varies directly as the 3/2 power of the pre-ionization electron density of the plasma, wherefore, in the described apparatus, a high pre-ionization electron density is provided, i.e., an electron density of 10^{16} electrons/cc. or greater.

A contributory factor to the power (in joules/meter^2) of the emitted radiation is the D.C. magnetic field B_0. While the use of that field is optional, its presence broadens the thickness of the magnetic sheath to thereby increase the volume of the region inside the sheath from which radiation is emitted. Thus, by using a B_0 field, the radiation output can be enhanced.

Both the strength of the radial sheath potential V_r and the character of the radiation vary as a function of the time t after onset of the discharge through the compression coil **90**. The potential V_r falls off rapidly with time so as to drop from, say 7×10^{17} volts at 10^{-10} seconds after onset to a value of, say, only 0.7 volt at 10^{-6} seconds after onset. With respect to the character of the radiation, during the first 10^{-8} seconds after onset, the sheath electron energy distribution cannot be properly characterized by a temperature but is more nearly monoenergetic, and the emitted radiation is probably predominantly from non-thermal electrons. After 10^{-8} seconds, the character of the radiation is believed to change so as to be, first, mostly Bremstrahlung emitted by thermal electrons and, thereafter, mostly residual recombination radiation and line radiation from multiply ionized ions. The entire burst of emitted radiation of interest is produced within a period of substantially less than 1 microsecond.

Because the major portion of the desired emitted radiation occurs within the first 10^{-8} seconds after onset, and because the photon flux of the emitted radiation varies directly with the discharge current passing in that period through the theta compression coil **90**, it is desirable to maximize the rate of rise within that period of the discharge current. This is done in the described apparatus by minimizing the inductance of the discharge system formed of source **91**, coil **90** and the coupling therebetween. Specifically, such inductance is made as small as practical by (1) using a compression coil of only a single turn and otherwise of low inductance, and (2) employing the described low-inductance coupling between the coil **90** and the source **91**. Alternative ways of expressing the low inductance of the discharge system are in terms of its ringing frequency and the width of the pass band provided for current from source **91** by coil **90** and its coupling to source **91**, both the ringing frequency and the width of such pass band varying inversely with the system inductance. For the purpose of producing a copious photon flux output, we have found that, as a practical matter, the ringing frequency of the discharge system should be at least 300 kc. (and, preferably, 500 kc. or more) and, correspondingly, the width of the described pass band (as measured between zero and the half current point) should be at least 300 kc. (and, preferably, 500 kc. or more).

QUANTITATIVE ASPECTS OF OPERATION

The following is a simplified explanation in quantitative terms of the manner in which the described apparatus is believed to operate. While such explanation is deemed to conform with reasonable accuracy to what actually occurs, the phenomena and mechanisms by which the apparatus is caused to emit radiation may, in fact, be more complicated than the explanation suggests. Accordingly, we do not wish or intend to be limited or bound in respect to our invention by the explanation given herein of its believed mode of operation.

I. Spin stabilization

As previously described, the arc plasma column is stabilized by mechanically spinning the pre-ionized fluid of the medium **16** about the axis for the column. The stabilizing provided by the spinning can be adduced mathematically from the following equations of motion of individual ions and electrons in a frame of reference rotating with the fluid velocity.

The Hamiltonian for axisymmetric motion in cylindrical coordinates r and θ is:

$$H=\frac{p_r^2}{2m}+\frac{p_\theta^2}{2mr^2}+Y(r)$$

where p is the momentum, m is the particle mass and Y is the potential energy of the particle. The equation for $\dot{p}_r$ is then:

$$\dot{p}_r=-\frac{\delta H}{\delta_r}=\frac{p_\theta^2}{mr^3}-\frac{\delta Y}{\delta r}$$

but

$$\frac{\delta Y}{\delta r}\approx 0 \text{ and:}$$

$$F_r=\frac{p_\theta^2}{mr^3}=\frac{m^2r^4\dot{\theta}^2}{mr^3}=mr\dot{\theta}=mr^3w^2$$

where F_r is the radial force on the particle and w is the angular frequency of fluid rotation. Since the force F_r can be written as $\delta Y/\delta_r$ we can plot Y(r) vs. r and we obtain the curve **150** shown in FIG. 5 wherein the Z axis is the axis of spin of the plasma tube **25**, and the dotted lines **151** indicate the inner wall surface of the container cylinder **15**. In FIG. 5 the ordinate and abscissa are, respectively, the value of Y(r) and the radial distance r from the Z axis. Curve **150** shows that Y(r) varies as the 4th power of r. As demonstrated by curve **150**, the pressure gradient caused by spinning of the medium serves to produce a potential energy "well."

If we assume a conservative system, the sum of the kinetic energy and potential energy of a given particle is constant. When, as in FIG. 5, $\delta^2 Y/\delta_r^2$ for the article is positive at the equilibrium position (the bottom of the potential energy well), a displacement of the particle in either direction increases its potential energy and hence decreases its kinetic energy. Hence, each particle (and, also, the column as a whole) is in static equilibrium (zero kinetic energy) and cannot climb out of the well without external help.

As indicated by the foregoing equations, the magnitude of the stabilizing effect is directly proportional to the density of the fluid medium and, also, to the square of the angular frequency of fluid rotation.

II. Dynamic sheath effects

In the following analysis, the properties of the magnetic sheath are reviewed and are then related to the properties of the plasma compressed by the sheath.

(1) Sheath velocity.—FIG. 6 shows schematically the theta compression coil **90** and associated components and, also, the arc plasma column and sheath.

Referring to FIG. 6, at the onset of an idealized theta compression, the flow of current through coil **90** is opposed by an induced voltage E_θ which is the only voltage present at that instant. The voltage on the capacitor (V_c) must at all times be equal to the voltage drop around the coil **90** if the switch **92**, transmission line **105**, **106** and coupling **111**, **121** (and associated unshown coupling components) have no inductance. Thus,

$$2\pi RE_\theta(R)=V_c=\pi R^2\frac{dB(t)}{dt} \tag{1}$$

or

$$E_{\max}=\frac{V_c}{2\pi R} \tag{2}$$

where B(t) is the magnetic flux density associated with the current in the load coil **90**. If B(t) is assumed constant in amplitude and direction but varies as a sinusoidal function of time (i.e., is instantaneously equal to B sin ω t) then:

$$2\pi rE(r)=\pi r^2\frac{dB}{dt} \tag{3}$$

and

$$E(r)=\frac{r}{2}\frac{dB}{dt}=\frac{r}{R}\left(\frac{V_c}{2\pi R}\right)=\frac{r}{R}E_{\max} \tag{4}$$

When a pre-ionized medium is present within coil **90**, the discharge therethrough causes the formation of a sheath of thickness 2δ where $\delta=(r-a)$, and:

$$B=0 \text{ where } 0<r<a$$
$$B=\text{Uniform where } a+2\delta<r<R$$

The application of Faraday's law results in:

$$\oint E\cdot d1=-\frac{d\Phi}{dt}=-\frac{dt}{d}[B(t)\pi(r^2-a^2)] \tag{5}$$

Hence, at r:

$$2\pi rE_\theta=\pi(r^2-a^2)\frac{dB}{dt}-2\pi aB(t)\frac{da}{dt} \tag{6}$$

or

$$E=\frac{(r^2-a^2)}{2r}\frac{dB}{dt}-\frac{a}{r}B(t)\frac{da}{dt} \tag{7}$$

However, the amplitude of

$$\frac{dB}{dt}=\omega B$$

wherefore:

$$E_\theta=\frac{r}{2}\left(1-\frac{a^2}{r^2}\right)\omega B-\frac{a}{r}B(t)\frac{da}{dt} \tag{8a}$$

But da/dt is the sheath implosion velocity (v_s). From FIG. 6, we see that $(r-a)$ equals δ. If the sheath is thin, r can be approximated as:

$$r\cong\frac{r+a}{2}$$

and we obtain the approximation

$$E_\theta\cong\frac{r}{2}(2r)\delta\frac{1}{r^2}\omega B-v_sB(t) \tag{8b}$$

or

$$E\theta=\delta\omega B+v_sB(t) \tag{9}$$

in rationalized M.K.S. units.

In a typical case of interest, the first term is less than one part in a thousand of the second term, and a good approximation of Equation 9 is

$$E_\theta=v_sB(t)\frac{\text{volts}}{\text{meter}} \tag{10}$$

The upper limit of v_s can be determined by imposing Equation 4 where E_θ is the vacuum value at r. The expression for the sheath velocity is then:

$$E_\theta(r)=\frac{r}{R}\frac{V_c}{2\pi R}=v_sB(t) \tag{11a}$$

or

$$v_s=\frac{rV_c}{2\pi R^2B(t)} \tag{11b}$$

FIGS. 7 and 8 illustrate the plasma sheath parameters and the magnetic field which are shown in the drawings both without (FIG. 7) and with (FIG. 8) the bias field B_0.

As indicated by FIGS. 7 and 8, the sheath travels with velocity v_s in the r direction corresponding to the inward radial direction. In FIG. 7, the magnetic field in the Z direction (axial) is reduced from its driving value $B(t)$ to zero over the sheath thickness 2δ. The essential property of such a sheath is that the electrons in the plasma feel an induced electric field E_θ as they are overtaken by the sheath, and, accordingly, they are accelerated in the θ direction which is transverse to the direction of propagation of the sheath. The reverse field B_0 in FIG. 8 provides a mechanism for creating a thicker sheath than would normally occur in its absence.

(2) Sheath thickness.—From the previous considerations the sheath thickness can be deduced as follows.

Referring to FIG. 9, by Ampere's law:

$$(B(t)+B_0)L=\mu_0 en_e v_\theta^2 \delta L \tag{12a}$$

or

$$B(t)+B_0=2\mu_0 en_e v_\theta \tag{12b}$$

where

$$v_\theta=\frac{e}{M}E_\theta\frac{\delta}{v_s}$$

and n_e is the electron density and:

$$(B(t)+B_0)=2\mu_0 en\delta\frac{e}{M}E_\theta\frac{\delta}{v_s} \tag{13}$$

Substituting into Equation 13 Equation 10 and noting that

$$\mu_0=\frac{c^2}{\epsilon_0}$$

we obtain:

$$\frac{B(t)+B_0}{B(t)}=\frac{2e^2n_e\delta^2}{\epsilon_0 mC^2}=\frac{2\omega_p\delta^2}{C^2} \tag{14}$$

where ω_p is the plasma frequency. Hence from (14) we obtain:

$$\delta=\frac{C}{\omega_p}\left(\frac{B(t)+B_0}{B(t)}\right)^{1/2}\text{ meters} \tag{15}$$

If $B_0 \gg B(t)$ there is an appreciable enhancement of the photon flux of the emitted radiation, the enhancement being a condition which occurs in time near $t=0$ on the first quarter cycle of the discharge.

(3) Radial electric field.—In the previous discussion the effects of the ion population have not been considered. The effect of the ions is twofold. First, the massive ions by their inertia balance the magnetic pressure $B^2/2\mu_0$ driving the sheath. That is, the advancing sheath is like a massive piston which projects the ions and electrons inward with a velocity $2v_s$ (relative to the laboratory frame of reference) and, concomitantly sweeps them up. Momentum balance then requires:

$$\frac{B(t)^2}{2\mu_0}=nv_s(2Mv_s)=2_nMv_s^2 \tag{16}$$

The second effect of the ions is the generation of a net space charge in the sheath which gives rise to the electrostatic field E_r in the radial direction. That field is generated because there is a large difference in the trajectory of the electrons and the ions in the sheath due to the difference in masses. The ions are essentially not deflected by the magnetic field and therefore move in the radial direction. The electrons, however, describe sweeping arcs in the θ direction. The resulting charge separation produces the electric field E_r which can be expressed as:

$$E_r=\frac{2M}{e}\frac{v_s^2}{\delta} \tag{17}$$

or

$$E_r=\frac{2M}{e\delta}\left(\frac{E_\theta}{B}\right)^2\frac{\text{volts}}{\text{meter}} \tag{18}$$

From (18) the voltage drop across the sheath is:

$$V_r\equiv\delta E_r=\frac{2M}{e}\left(\frac{E_\theta}{B}\right)^2\text{ volts} \tag{19}$$

An order of magnitude estimate of E_θ/B can be obtained by a simple argument which yields:

$$V_r\cong\frac{2M}{e}\left(\frac{r}{2t}\right)^3\text{ volts} \tag{20}$$

If we assume an ion mass number of ~130 (cesium or xenon) and an arc column radius of 1 cm., then:

$$V_r=7\times10^{-13}t^{-2}\text{ volts} \tag{21}$$

Under the assumed condition, V_r varies with time t in accordance with the following tabulation:

t sec.:	V_r volts
10^{-10}	7×10^7
10^{-9}	7×10^5
10^{-8}	7×10^3
10^{-7}	7×10
10^{-6}	0.7

(22)

From tabulation 22, we see that the sheath voltage is sufficiently high to accelerate electrons to ~1 kev. during the first 10^{-8} seconds after closure of the switch **92** in FIG. 6.

(4) Photon energy level.—Referring to Equation 20, the voltage V_r sets the maximum photon energy level of the emitted radiation in the sense that, if an electron is accelerated through that full voltage, the resulting radiation will have the highest photon energy level attainable under the given operating conditions. In practice, the maximum photon energy level is not attained for every electron accelerated by V_r because a substantial percentage of the accelerated electrons undergo a collision before being accelerated through the full voltage V_r. Thus, the attained mean photon energy is less than the maximum attainable photon energy level. At the same time, with other conditions being kept constant, the mean photon energy level increases with an increase in the maximum photon energy level.

Equation 20 further indicates that the voltage V_r varies directly with the mass number M of the ions in the compressed plasma. Hence, increasing the mass number of those ions increases the maximum attainable photon energy level of the emitted radiation and, also (with other conditions being kept constant), its mean photon energy level.

The latter level is a partial function of the mean free path of the electrons accelerated by V_r. If the pressure of the medium is low so that the mean free path is long (e.g., substantially greater than the sheath thickness), then the mean photon energy level approaches the maximum photon energy level. If, on the other hand, the mean free path is short (e.g., substantially less than the sheath thickness), then the mean photon energy level is lowered relative to the maximum photon energy level.

Thus, while the maximum photon energy level is set by the mass number M of the ions in the medium, the mean photon energy level can be progressively reduced from the maximum attainable value by increasing the pressure of the medium.

By utilizing a medium of high mass number (e.g., pure xenon) and of low pressure (e.g., 100 microns Hg), it is feasible with the described apparatus to produce hard X-rays. Of more interest, however, it is the production of radiation in the wavelength region embracing soft X-rays and ultraviolet rays of short wavelength because it has been difficult heretofore to artificially produce radiation in that wavelength region. We have found that radiation in such preferred region can readily be provided with the described apparatus when operating in the described manner by appropriate selection in combination of a suitably high mass number M for the medium and of a suitable value for the pressure of the medium. Thus, for example, when the plasma tube is charged with pure xenon (for which M is about 130) at a pressure of about one atmosphere absolute, the described apparatus is adapted to produce radiation having a mean photon energy level such that the emitted radiation contains a usefully large percentage of soft X-rays of about 1 kev.

The product of the mass number M of the medium and of its pressure is the density of the medium. For the reasons just set out, there is a correlation between the density of the medium and the suitability thereof to act as a source of radiation in the mentioned preferred wave-length region. That is, in order to produce radiation containing a usefully large percentage of soft X-rays or of ultraviolet rays of short wavelength, the density of the medium should be in the range from 0.02 kg./meter^3 to 2.0 kg./meter^3.

(5) Photon flux output.—With the described apparatus, a radiated power value on the order of several hundred joules is obtainable. For a given mean photon energy level, the radiated power varies directly with the emitted photon flux of which the value is dependent on the following factors.

First, because all or most of the energy represented by the photon flux is derived from the compression field $B(t)$ and because the strength of $B(t)$ varies with the voltage V_c to which source **91** has been precharged, increasing V_c increases the photon flux.

Second, the photon flux output varies directly as the 3/2 power of the electron density characterizing the plasma. A high electron density is realizable as follows: The field B_0 tends to increase the electron density of the arc plasma column by inhibiting diffusion of electrons out of the column. Further, the electron density of the column can be enriched by seeding the parent gaseous medium with particles in the gaseous phase of a chemical element having a low ionizing potential, e.g., cesium. While the seeding particles have little effect on M and thus upon the maximum or mean photon energy of the emitted radiation, the particles do, upon ionization, act as donors of electrons to the plasma to increase its electron density and, accordingly, the emitted photon flux.

Still further, the electron density can be increased by increasing the pressure of the medium. The last-named mode of increasing electron density is, however, limited in effectiveness by the considerations that, (a) the electron density does not increase in direct proportion with the pressure, (b) an increase in pressure results in a decrease in means photon energy level relative to the maximum attainable photon energy level.

Third, besides increasing the electron density, the field B_0 increases the photon flux by increasing the thickness of the sheath (see FIG. 8) to thereby increase the volume of the region of the plasma from which radiation is emitted.

Fourth, the greater part of the radiation is, as described, emitted in the first 10^{-8} seconds after onset of the discharge pulse through compression coil **90**. Hence, the photon flux output is increased by maximizing in that short period between t equals zero and t equals 10^{-8} the conditions which implement the production of a large flux. Specifically, in the described apparatus the field $B(t)$ produced within that period is maximized in strength by minimizing the inductance of the discharge system comprised of source **91**, coil **90** and the coupling therebetween (i.e., maximizing the ringing frequency of such system). Moreover, that the plasma will have a high electron density in that period is assured by ionizing the medium to have a high electron density before the compression field $B(t)$ is applied. That is, by passing of the arc between the electrodes **20** and **22** for a suitably long interval before onset of the compression field, the medium **16** within interelectrode gap **24** is pre-ionized to present a plasma of high electron density to the compression field when generated. As stated, the pre-ionization electron density produced in the described apparatus is at least 10^{16} electrons/cc. and preferably is larger, i.e., 5×10^{17} electrons/cc. to 5×10^{18} electrons/cc.

Composition and properties of the medium

Although medium **16** has been described above as being composed of pure xenon, the medium is not necessarily limited to such composition. Alternatively, the medium may be composed of a pure monatomic gas other than xenon (e.g., krypton, radon), a mixture of monatomic gases, metallic vapors (e.g., cesium vapor, mercury vapor), or a mixture of one or more monatomic gases and one or more metallic vapors. While diatomic or other molecular gases are not necessarily wholly unsuitable for use as or in the medium, they have the disadvantage that much of the energy of the arc is absorbed in effecting molecular dissociation and is, therefore, not available for producing a high electron density in the plasma.

The appropriate pressure for the medium depends upon its composition and upon the spectral energy content required for the radiation from a medium of that composition. In general, however, the pressure of the medium is greater by a factor of at least 10^3 than that utilized in prior art experimental pinch devices aiming at the attainment of a self-sustaining nuclear fusion reaction.

As mentioned, heretofore, the medium may be in the form of a parent gas seeded with a material which is in the gaseous or vapor phase, and which is more easily ionizable than the parent gas. Preferably, the parent gas is, as described above, a pure monatomic gas or a mixture of monatomic gases. The seeding material is preferably one of the alkali metals (e.g., potassium, sodium, etc.) because they are the most easily ionized of all the chemical elements. Cesium is particularly suitable as a seeding material because of its very low ionizing potential.

Seeding may be accomplished by vaporizing the seeding material into the parent gas and by heating the resulting mixture so as to maintain the vapor pressure of the seeding material at a significant value. Usually the concentration of seeding material in the medium is too low to have a substantial effect on its mass number M (which, therefore, is effectively determined entirely by the composition of the parent gas). Even at such low concentration, however, the seeding material may enhance considerably the electron density of the plasma generated in the medium.

The above-described embodiments being exemplary only, it is to be understood that additions thereto, modifications thereof and omissions therefrom can be made without departing from the spirit of the invention, and that, therefore, the invention comprehends embodiments differing in form and/or detail from those specifically disclosed. Accordingly, the invention is not to be considered as limited save as is consonant with the recitals of the following claims.

We claim:

1. The method of producing radiation comprising, passing externally generated electric current through electrodes spaced apart in a gaseous medium having an initial density of at least 0.02 kilogram/meter^3 and through the interelectrode gap in said medium so as to pre-ionize said medium to an electron-density of at least 10^{16} electrons/cc. by generating in said gap a plasma column in the form of an electric thermal arc, and thereafter compressing said pre-ionized medium by a magnetic field so as to induce emission from said medium of radiation within the wavelength interval of the electromagnetic spectrum occupied by soft X-rays and ultra-violet rays.

2. The method as in claim **1** in which said medium is comprised of a monatomic gas.

3. The method as in claim **2** in which said monatomic gas is xenon.

4. The method as in claim **1** in which said medium is comprised of a parent gas seeded with ionizable particles in the gaseous phase.

5. The method as in claim **4** in which said particles are more easily ionized than said parent gas.

6. The method as in claim **1** in which said magnetic field is developed by flow of electric current in the theta direction relative to an axis through said medium.

7. The method as in claim **1** in which said compression field acts in opposition in said medium to a supplemental static magnetic field previously applied to said medium.

8. The method comprising, introducing an ionizable gaseous medium into a rotatable enclosure therefor, generating an electrical discharge within said enclosed gaseous medium to produce a body of plasma therein, and rotating said enclosure to impart to said enclosed medium a mechanical rotation around an axis of rotation for said enclosure to positionally stabilize said body of plasma relative to said axis, said body of plasma being urged by a pressure gradient effect derived from said rotation of said medium to stay in coaxial relation with said axis.

9. The method comprising, introducing a gaseous medium into a container therefor, energizing spaced electrodes within said container to produce an arc plasma column in said medium between said electrodes, and spinning said container and electrodes around the axis of spacing of said electrodes to positionally stabilize said column relative to said axis.

10. The method comprising, pre-ionizing a gaseous medium to produce a plasma column therein, imparting to said pre-ionized medium a mechanical rotation around an axis for said column to positionally stabilize said column relative to said axis, and compressing said stabilized plasma column by a magnetic field so as to induce emission of radiation from said medium.

11. The method as in claim **10** in which said medium has an initial density of at least 0.02 kilogram/meter^3.

12. Apparatus comprising, container means for a gaseous medium, first and second electrode means spaced along an axis in said container means and responsive to energization to develop an arc plasma column in said medium, and means to rotate said container means and electrode means around said axis so as to positionally stabilize said column relative to said axis.

13. Radiation-generating apparatus comprising, container means for a gaseous medium, first and second electrode means spaced along an axis in said container means and responsive to energization to develop an arc plasma column in said medium, means to rotate said container means and electrode means around said axis so as to positionally stabilize said column relative to said axis, and means to compress said column by a magnetic field productive of emission of radiation from plasma in said column.

14. Apparatus as in claim **13** in which said compressing means is comprised of a single turn theta compressing coil.

15. Apparatus as in claim **13** further comprising means to apply to said stabilized column a supplemental magnetic field opposing said compression field.

16. Radiation-generating apparatus comprising, container means for a gaseous medium and characterized by a central axis, anode and cathode electrodes spaced in said container means along and coaxial with said axis and responsive to energization to develop an arc plasma column in said medium between said electrodes, means to mechanically rotate said container means and electrodes around said axis so as to positionally stabilize said column relative to said axis, and a theta compression coil disposed axially between said electrodes and around said container means, said coil being responsive to a discharge therethrough of electrical energy to apply to said stabilized column a magnetic compression field by which the plasma in said column is induced to emit radiation.

17. Radiation generating apparatus comprising; container means filled with a gaseous medium having an initial density of at least 0.02 kilogram/meter^3, first and second electrode means spaced from each other in said container means by an interelectrode gap provided in said medium, electrical energy source means coupled in circuit with said two electrode means and said interelectrode gap to produce in said gap a plasma column which is in the form of an electric arc and which pre-ionizes said medium, and means to compress said pre-ionized medium by a magnetic field so as to induce emission from said medium of radiation within the wavelength interval of the electromagnetic spectrum occupied by soft X-rays and ultraviolet rays.

18. The method as in claim **8** in which said body of plasma is urged by said pressure gradient effect and magnetic field to stay out of contact with the inside of said enclosure.

19. A system comprising, a rotatable enclosure for a gaseous medium, means to introduce said medium into said enclosure, ionizing means to produce in such enclosed medium a body of plasma, and means to rotate said enclosure around an axis of rotation therefor to impart to said enclosed medium a mechanical rotation so as to produce in said medium and relative to said axis a radial pressure gradient for which the direction of increasing pressure is the radially outward direction, and which positionally stabilizes said body of plasma by urging such body to stay in coaxial relation with said axis, said means coacting with a source of magnetic flux to further urge said body of plasma to stay out of contact with the inside of said enclosure.

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