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BEAM PLASMA HIGH FREQUENCY WAVE GENERATING SYSTEM

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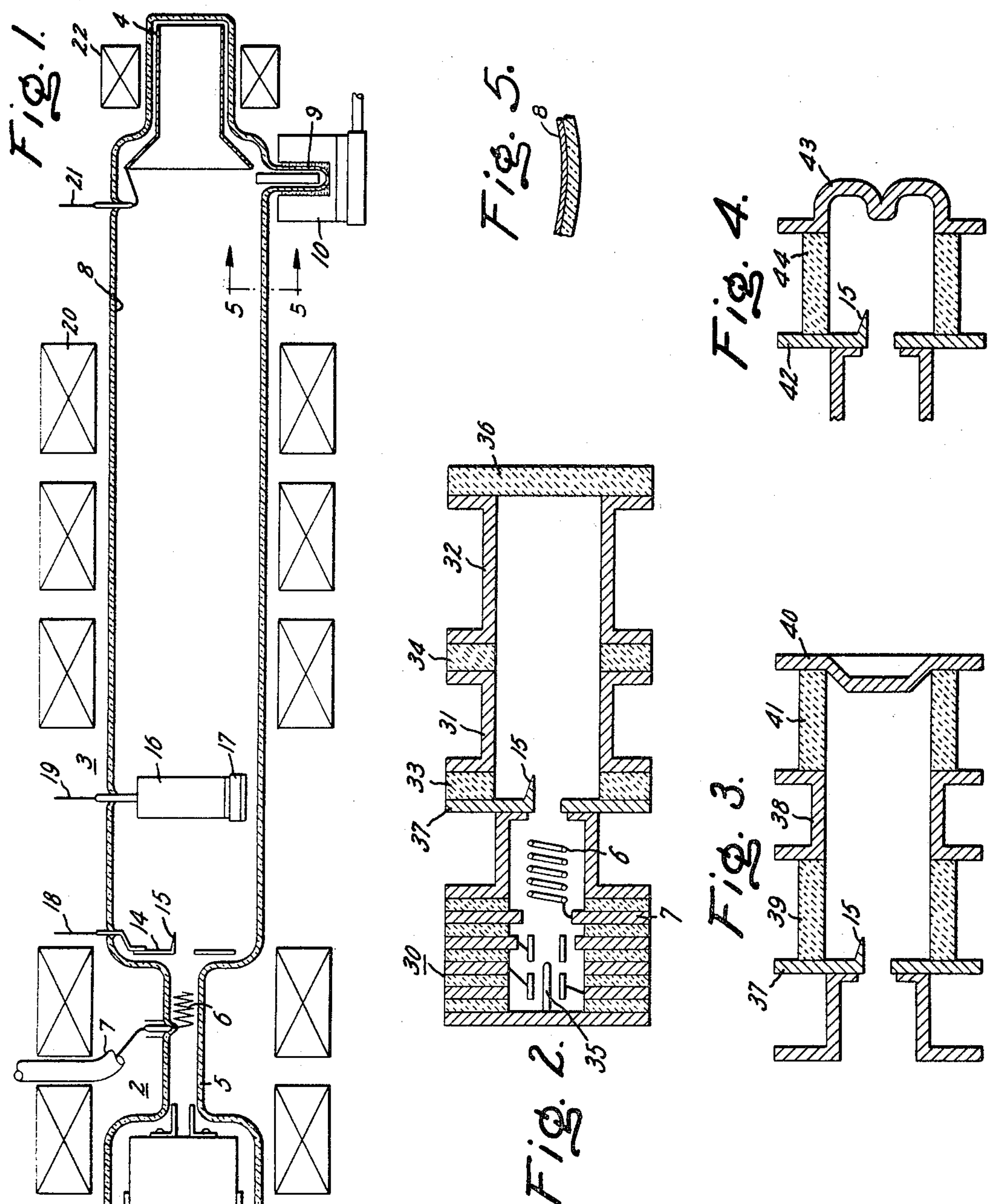

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BEAM PLASMA HIGH FREQUENCY WAVE GENERATING SYSTEM

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ABSTRACT OF THE DISCLOSURE

A system wherein a beam of density modulated electrons restricted to longitudinal motions traverses a plasma column having longitudinal and radial gradients. An interaction occurs between the beam and plasma in a section in the plasma column having a resonant frequency approximately equal to the driving frequency of the electron beam thereby permitting an electromagnetic wave to radiate out from the plasma.

Our invention relates to electromagnetic wave generating and translating apparatus and particularly to such apparatus using a resonant or near resonant plasma which interacts with an electron beam allowing an electromagnetic wave to radiate out of said plasma.

It has been suggested that if a space charge wave interacts with a fully ionized resonant or near resonant plasma, under certain conditions the fast wave component of the fast space charge wave may be amplified and radiated out of the plasma.

It has been demonstrated that the interaction of the slow wave space charge wave with magnetically confined nonresonant plasmas exhibits power gain. In these instances, the slow wave space charge wave is still contained within the plasma and to be useful must be converted to a fast space charge wave by an output coupler. These couplers are usually helices or cavities. For high power and very high frequency applications, the size and power handling capabilities of the coupler limits the efficiency of power transfer and frequency of utility.

It is a primary object of our invention to provide a new and improved electromagnetic wave generating and translating apparatus employing a density modulated electron beam which interacts with a plasma having a resonant frequency approximately equal to the beam driving frequency thereby allowing a fast wave to radiate directly out of the plasma and eliminating the need for output helices or cavities.

Another object of our invention is to provide a waveguide structure and integral output coupler associated with a beam-plasma interaction region which permits the electromagnetic wave radiating therefrom to be coupled directly to an output waveguide or external utilization device.

Briefly stated, in carrying out our invention, we inject a solid or hollow beam of density-modulated electrons into a magnetically compressed, plasma having both radial and longitudinal (axial) density gradients and having a resonance frequency section the same as the driving frequency of the electron beam to cause interaction and radiation of electromagnetic waves from the plasma. A waveguide structure may be incorporated therein which translates or couples such waves to an external utilization device. Examples of such external devices are horns, antennas or wave guides.

The novel features which we believe to be characteristic of our invention are set forth with particularity in the appended claims. The invention itself, however, may best be understood with reference to the following description taken in connection with the accompanying drawing in which:

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FIGURE 1 is a schematic longitudinal view of our electromagnetic wave generating and translating apparatus, and

FIGURE 2 is a schematic view of a portion of a device capable of operating in the millimeter wave region.

FIGURE 3 is a modification of the arrangement of FIGURE 2, and

FIGURE 4 illustrates a portion of an electromagnetic wave generator employing an arc discharge.

FIGURE 5 illustrates a cross-sectional view of the apparatus along line 5—5 of FIGURE 1.

The system of FIGURE 1 comprises an electron emitter region **1**, a traveling wave generating region **2**, a plasma tube **3**, and an output region **4**. The electron generating or emitting region may comprise a conventional Pierce electron gun, the details of which are well known, which supplies a beam of high speed electrons to a traveling wave region **2**.

The traveling wave region **2** comprises a narrowed portion **5** of the glass envelope of the tube which contains a helix **6**, preferably of tungsten wire, through which the direct current beam from the electron gun passes. High frequency potentials are supplied to the helix **6** over a coaxial input cable **7** from a conventional external oscillator (not shown). The frequency of these potentials may be, for example, of the order of 9000 gigacycles. As the electron beam traverses the helix **6**, the beam is modulated in a well-known fashion to produce a group of low velocity electrons and a group of high velocity electrons. The group of low velocity electrons is produced every negative half cycle of the modulating wave and the group of high velocity electrons is produced every alternate half cycle. The velocity modulated beam emerging from the helix **6** eventually converts to density modulation as the high velocity electrons catch up with the low velocity electrons, so that a density-modulated beam is introduced into plasma tube **3**.

Plasma tube **3** comprises an enlarged portion of the glass envelope of the entire tube which is coated with a conducting material such as, for example, silver paint **8**, to provide a conductive cylinder or circular waveguide. In order to interrupt circumferential currents generated by variations of the confining magnetic field produced by surrounding coils **20**, as well as to provide a means for viewing the characteristics of the discharge within plasma tube **3**, longitudinal slots are provided in the conductive coating on tube **3** in a well-known manner. However, when the confining magnetic field of coils **20** is operating on a steady state basis, circumferential currents will be nonexistent and hence the circular waveguide can be made of metal.

Attached to the right-hand end of the plasma tube **3** is an appendage **9** which contains a source of ionizable vapor for the tube **3**. The ionizable vapor may comprise, for example, mercury vapor, cesium vapor, or any other suitable gaseous medium. In the modification illustrated in FIGURE 1, the appendage **9** contains mercury whose vapor pressure within the tube **3** is controlled by a thermo-electric cooler **10**.

Located within the plasma tube **3** is a plasma generator of a well-known type and referred to as a Penning discharge or, alternatively, a Philips-ionization-gauge type discharge. The plasma generator consists of a cold cathode comprising a disc **14** of a suitable metal such as, for example, molybdenum, to which is attached a needle point **15**, which also may be of molybdenum, and which is displaced slightly from the center or axis of tube **3**. Spaced from the cathode **14** is an anode **16** in the form of a split metallic cylinder having the proper dimensions to develop propagation of the TM_{01} circular guide mode. A flash getter ribbon **17** is attached to anode cylinder **16** for conventional gettering purposes.

Arms (not shown) located on the outside of the anode cylinder **16** may be provided to suppress the formation of unwanted modes such as, for example, the TEM mode. Operating potentials are supplied to the cathode **14** by lead **18**, to anode **16** by lead **19** and to second cathode **4** by lead **21**.

Spaced on the opposite side of anode **16** from cathode **14** is a second cold cathode **4** in the form of a cylindrical horn.

Horn **4** is aligned along the axis of plasma tube **3** and is constructed of molybdenum, for example, which possesses a high secondary emission coefficient. So positioned, cathode **4** serves the following four functions:

(1) To supply ion induced secondary emission electrons for the Penning discharge;

(2) As an electron collector for the main electron beam from gun **1**;

(3) As a second terminating point for the plasma column;

(4) As a transition zone from the plasma to waveguide for the electromagnetic wave generated.

Surrounding horn **4** is a deflection magnet **22** which serves to deflect electrons and ions to the horn **4**.

Surrounding the entire tube configuration thus far described, is a magnetic structure comprising a plurality of Helmholtz coils **20**. Current is supplied to the coils **20** from an external circuit (not shown) of the conventional type which may comprise, for example, a capacitor bank and a spark gap which results in a critically damped magnetic wave having a short rise time or a direct current supply to generate a steady state magnetic field.

In the operation of our high frequency wave generator, the electron gun **1** injects an unmodulated beam into helix **6**, which is provided with high frequency potentials of the order of, for example, 9000 gigacycles. As electrons traverse helix **6**, they are velocity modulated to produce a group of slow electrons and a group of high velocity electrons, so that the velocity-modulated electron beam emerging from the helix eventually converts to density modulation as the fast electrons catch up with and pass the slow electrons. The density-modulated beam is passed through a magneticaly compressed plasma having radial and axial electron density gradients. The magnetic field established by coils **21** suppresses the radial movement of the electrons and allows longitudinal movement within tube **3**.

A fully ionized or nearly fully ionized plasma is produced by a single cold cathode Penning type discharge located within circular wave guide **3**. The plasma column is generated by an arrangement of electrodes in which needle point cathode **15** is displaced from the axis of circular waveguide **3** while extending parallel with that axis. Through the operation of anode **16** positioned between the cathode **14** and horn **4** and constructed to suppress the formation of undesired modes, a broad plasma column is produced extending from needle **15** to horn **4**. The initial column diameter is determined by needle cathode **15** and soon grows by diffusion to a diameter less than the diameter of anode **16**.

A radial cross-section of the plasma column will show a uniform and high level density of electrons across the center portion of the column, falling off to essentially zero density at the edges as electrons diffuse out of the column.

An axial cross-section will show that electron density is at a maximum at the cathode and does not go to zero at the horn.

One theory explaining the operation by which the density-modulated electron beam interacts with the plasma section having a resonant frequency matching the beam driving frequency (herein 9000 gigacycles as an example) to produce an electro-magnetic wave which is radiated to the waveguide formed by the coated cylinder **3**, is to consider the density modulated electrons as passing through a multiplicity of resonant sections in the plasma as it traverses the plasma column.

When the density modulated beam passes into a plasma section of proper length and electron density which resonates at the driving frequency of the beam, violent plasma oscillations are induced. Because the magnetic field established by coils **20** restricts radial motion of the electrons and allows longitudinal motion only plasma induced oscillations are longitudinal, acting like dipoles which radiate a fast TM_{01} wave out of the plasma and into the wave guide.

If the electron beam diameter is made nearly equal to the plasma column diameter, a cylindrical ring of oscillating dipoles will be formed within an annular section of the plasma column, which dipoles radiate a fast TM_{01} electromagnetic wave into the circular waveguide formed by the coating **8** on tube **3**.

For electromagnetic radiation out of the plasma to be most effective, the annular section and therefore the ring of dipoles should be located at the outer periphery of the plasma column with electron density decreasing from the center of the column radially outward. For the fast wave to escape the plasma, it is necessary that the plasma density (and therefore the plasma resonant frequency) of regions radially outward from the annular section to be less than the density of the plasma within the resonating plasma section, i.e., a decreasing plasma gradient. When this condition is not met, the fast wave is reflected back into the plasma.

The TM_{01} waves radiated out of the plasma and into the wave guide travel to the second cold cathode or horn **4** which constitutes a transition section for coupling the electromagnetic energy out to an external utilization device (not shown) and which may be for example a horn radiator or a waveguide.

In the operation of the generator to establish the plasma, a current pulse is supplied to anode **16** to initiate the generation of the plasma. This pulse may be obtained by discharging a conventional resistance capacitive network (not shown). At the same time, a rapidly rising current is supplied to magnet coils **20** to compress or delineate the plasma region creating a positive ion trap in that region. While neutral gas molecules will be present in tube **5**, such molecules are ionized by the electron beam and accelerated into the gun **1** while the free electrons are returned to tube **3** to enhance the Penning action.

In the modification of FIGURE 2, there is illustrated a tube structure capable of operating in the millimeter wave region. In this structure, a metal-ceramic tube structure is used rather than the glass structure of FIGURE 1. The electron emitter portion **30** and the helix **6** may be similar to those of the structure of FIGURE 1 or other conventional structures suitable for this purpose. The Penning arrangement is the same as that of FIGURE 1, the difference being that instead of using a glass cylinder 3, coated with a metallic conductor, a plurality of metallic cylinders **31, 32**, are employed being connected by ceramic members **33, 34**.

In FIGURE 2, the Penning discharge electrodes consist of needle cathode **15**, anode **31** and second cathode **32**; and for FIGURE 3 such electrodes comprise needle cathode **15**, anode **38** and second cathode **40**. Another feature of the electron emitter illustrated in FIGURE 2 comprises a bias pin **35** provided to produce and control the size of a hollow beam supplied to the slow wave structure **6**. The plasma generator arrangement is terminated at its right-hand end by ceramic member **36**, which permits the entire arrangement to be plugged into a conventional circular wave guide with radiation emanating from member **36**.

FIGURE 3 illustrates a modification of our high frequency electromagnetic wave generating system which permits side radiation of the electromagnetic wave. In this modification the first cathode **37** with needle cathode **15** of the Penning discharge structure corresponds to the similarly numbered elements of FIGURE 2. Anode **38** comprises a metal spinning spaced from cathode **37** by ceramic spacer **39**. The second Penning type cathode **40** is similarly spaced from anode **38** by the ceramic spacer **41**. In this modification, side radiation is encouraged whereas longitudinal travel of radiation is suppressed by proper choice of dimensions. The entire tube may be plugged into a rectangular wave guide which can transmit the dominant TE_{10} mode. One of the features of this particular modification is that member **40** not only serves as a second cathode for a Penning type discharge, but also functions as the anode of the electron gun (not illustrated in FIGURE 3 but which may comprise the structure of FIGURE 2).

In FIGURE 4, we have illustrated an additional modification in which the over-all length of the tube assembly is shortened by the use of an arc current rather than a Penning type discharge. In this modification, elements to the left of cathode **42** may be the same as those to the left of element **37** in FIGURES 2 and 3. Element **42** comprises the cathode member which is operative with anode member **43** to provide a high current arc in the region defined by members **42, 43** and a ceramic spacer **44**. Electromagnetic waves radiated to the side in this structure may be coupled directly to a wave guide as in the case of the structure in FIGURE 3.

In all of the arrangements illustrated, we have found that by providing a longitudinal magnetic field, coupling between the beam spaced charge waves entering the section of the plasma having the proper resonant frequency and the plasma section is achieved to excite electromagnetic waves within the plasma. The longitudinal magnetic field operates to compress the plasma which automatically provides a plasma density gradient across the plasma region.

While in the foregoing, we have discussed the use of mercury vapor for the plasma, any suitable gaseous medium, such as cesium, argon or similar gas may be employed.

While we have shown and described particular embodiments of our invention, it will, of course, be understood that we do not wish to be limited thereto, since various changes and modifications may be made without departing from the invention, and we contemplate by the appending claims to cover all such changes and modifications as fall within the true spirit and scope of our invention.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. A high frequency wave generator comprising

a circular enclosure;

plasma defining means including

- a needle-point cathode positioned at one end of said circular enclosure and displaced from and extending substantially parallel with the axis of said circular enclosure,
- an anode spaced apart from said cathode, and
- a source of ionizable vapor, said plasma defining means for establishing and magnetically delineating within said circular enclosure a plasma column having an axial density gradient which decreases from said needle-point cathode and a radial density gradient which decreases from the center of said plasma column;

electron beam means for injecting and density modulating a hollow electron beam into said plasma column adjacent said needle-point cathode, said electron beam means also providing said hollow electron beam with a predetermined driving frequency approximately equal to the resonating frequency of an annular section of said plasma column having the axial and radial density gradients;

said plasma defining means also providing a magnetic field which restricts the radial and permits the longitudinal motion of the electrons in said hollow electron beam wherein the interaction between said hollow electron beam and the plasma in said annular section establishes an annular section of resonating plasma and causes an electromagnetic wave to radiate from the resonating section; and

an output device for providing a transition section for the electromagnetic wave out of said circular enclosure.

2. The generator of claim **1** wherein said circular enclosure is a waveguide and said output device is an output horn positioned at the end of said waveguide opposite said cathode, said waveguide transmitting the electromagnetic wave to said output horn for external use.

3. The generator of claim **1** wherein said output device comprises a ceramic member terminating the end of said circular waveguide and wherein said circular enclosure is a plurality of metallic cylinders separated by a plurality of ceramic cylinder members, one of said metallic cylinders being said anode and another of said metallic cylinders being a second cathode.

4. The generator of claim **1** wherein said anode is a metal spinning and forms part of said circular enclosure, a second cathode terminates said circular enclosure at the end opposite said needle-point cathode, said anode, second cathode, and needle-point cathode being separated by a plurality of ceramic members.

5. The generator of claim **1** wherein said circular enclosure is comprised in part by said output device which is a ceramic member, said circular enclosure being terminated at the end opposite said needle point cathode by said anode.

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