Dec. 6, 1966 W. HERTZ 3,290,541

INDUCTIVE APPARATUS UTILIZING A MAGNETIC CUSP FIELD FOR ACCELERATING PLASMOIDS

Filed Dec. 18, 1964 3 Sheets-Sheet 1

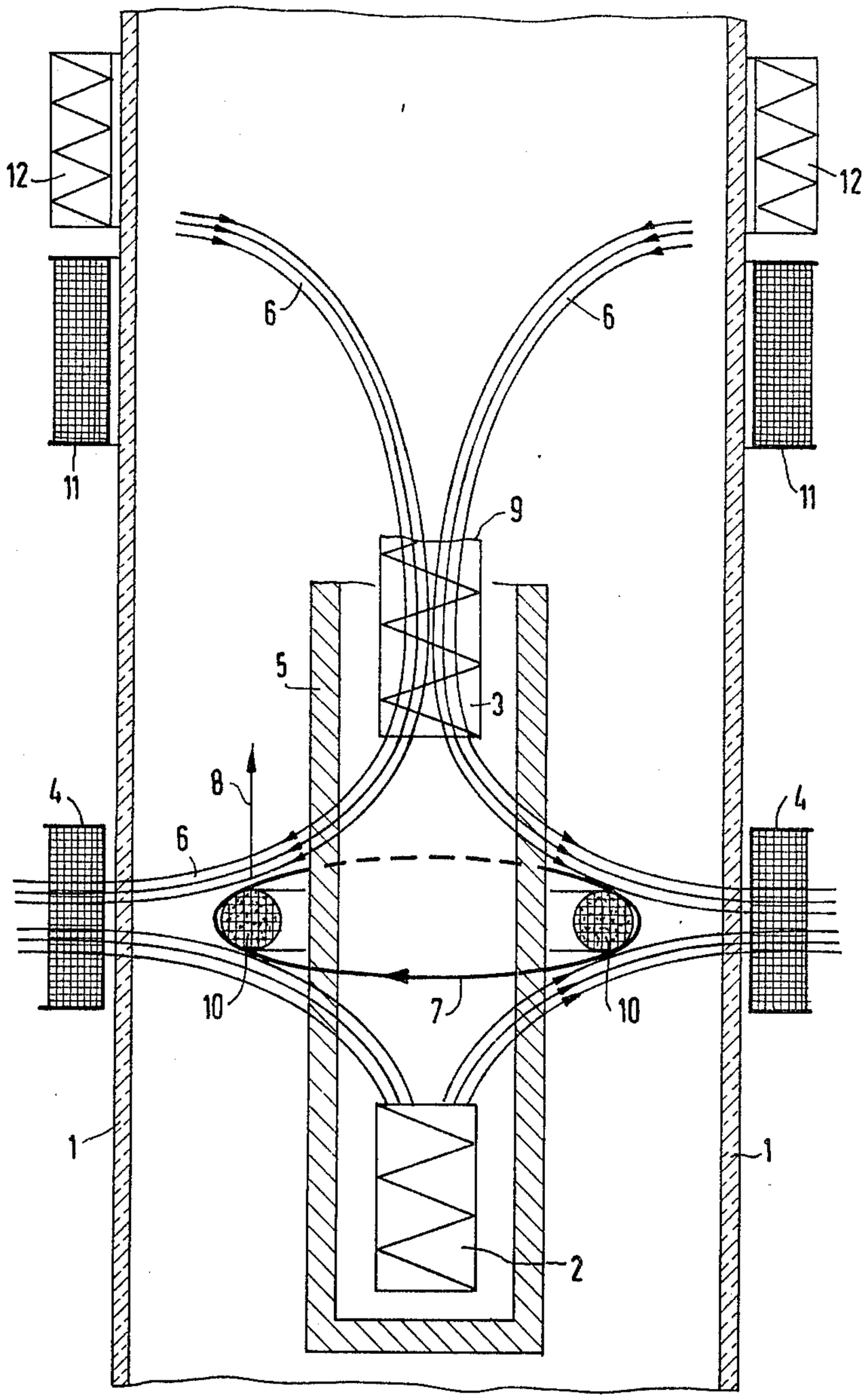


FIG. 1

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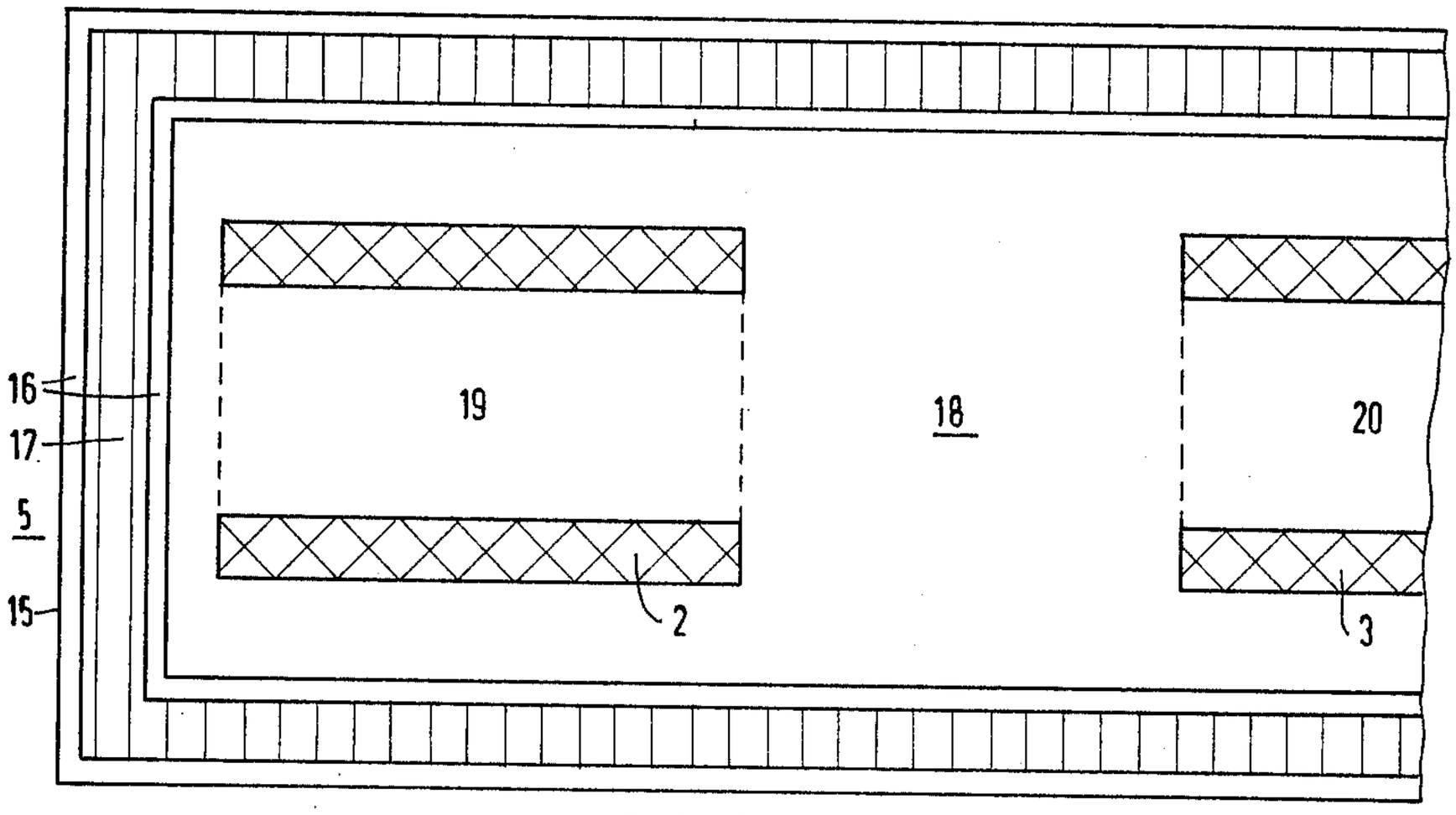


FIG. 2

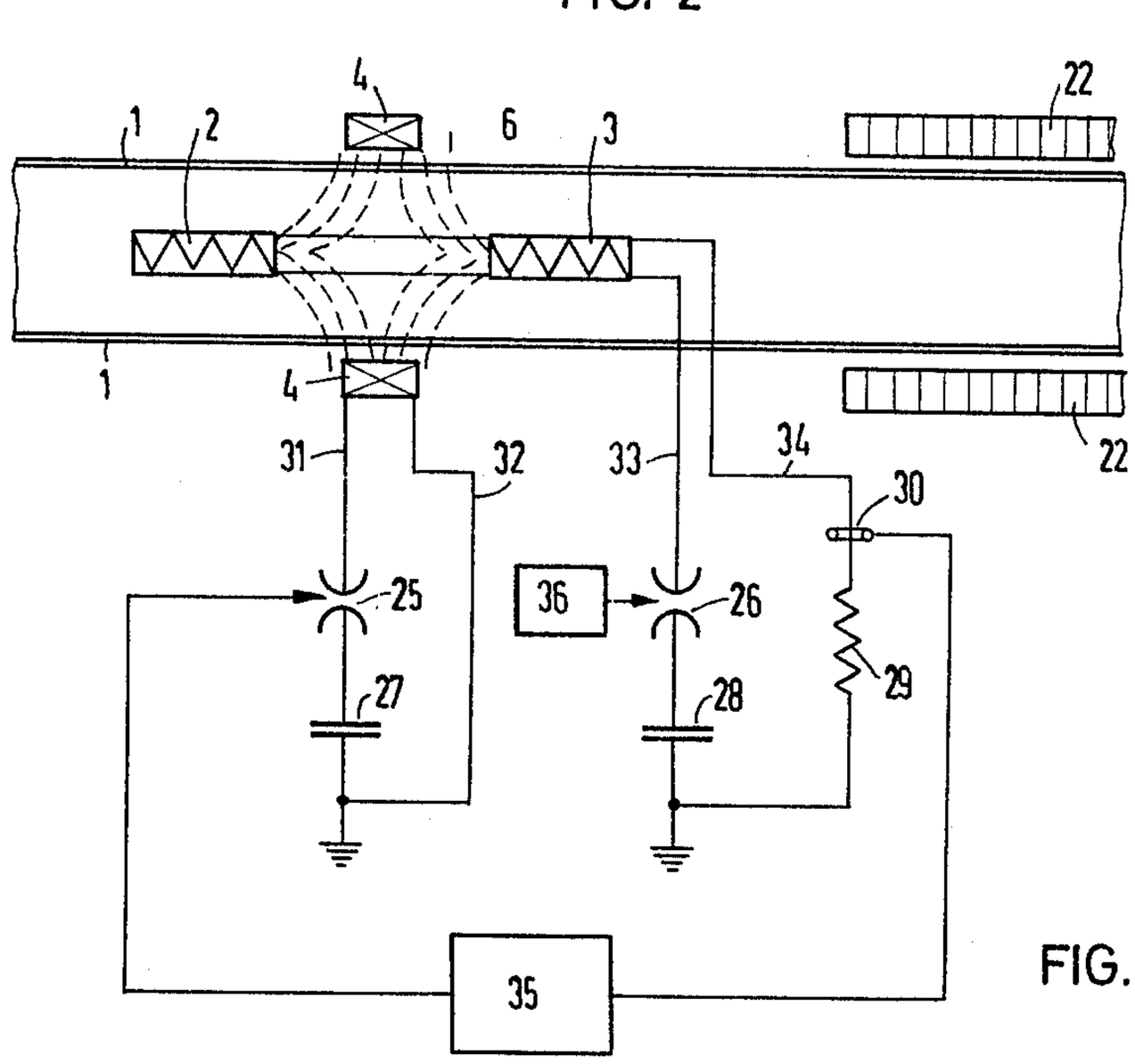


FIG. 3

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INDUCTIVE APPARATUS UTILIZING A MAGNETIC CUSP FIELD FOR ACCELERATING PLASMOIDS

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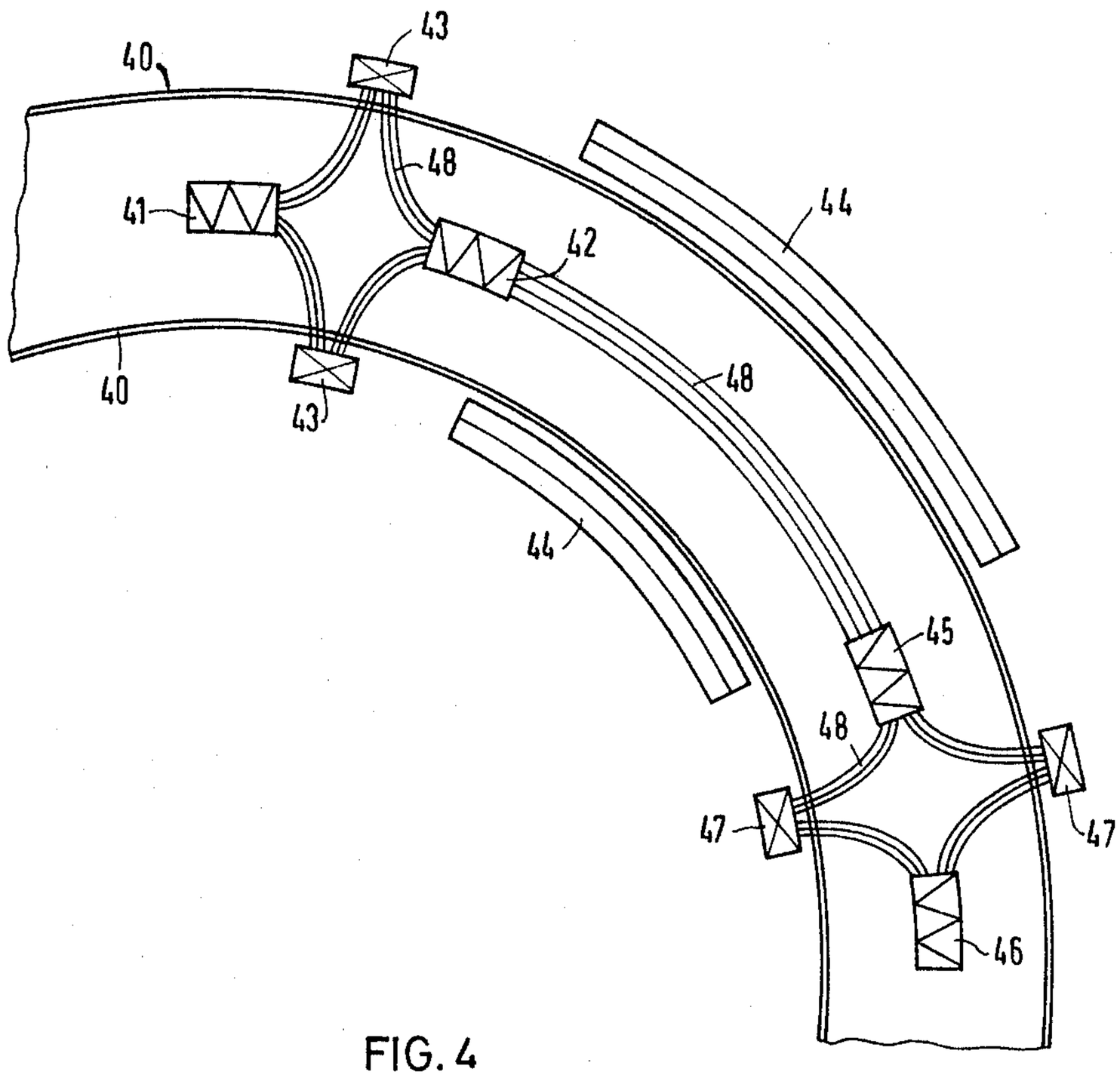


FIG. 4

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INDUCTIVE APPARATUS UTILIZING A MAGNETIC CUSP FIELD FOR ACCELERATING PLASMOIDS

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10 Claims. (Cl. 313—153)

My invention relates to electrodeless apparatus for producing and/or accelerating plasmoids in mutually intersecting electrical and magnetic fields.

Such apparatus is disclosed in the copending application Serial No. 349,996, filed March 6, 1964, and entitled "Electrodeless Apparatus for Producing or Accelerating Plasmoids." As described in the copending application, two field coils of mutually opposed winding sense are arranged in mutually spaced relation on an insulating tube so that a magnetic field having a radial component (cusp field) can be produced in the space between the two field coils. Mounted between the two field coils on the same insulating tube and in coaxial relation therewith is a low induction coil which when periodically excited by electric pulses, produces a resulting variable magnetic field which induces a circular electric field in the interior of the insulating tube. The latter electrical field produces a plasma and also produces within the plasma a ring path current in the radial magnetic field. This circulating current, conjointly with the magnetic field of the field coils, imposes an accelerating force (Lorentz force) upon the plasma with a force component in the direction of the tube axis.

It is an object of my invention to further improve this type of apparatus to more reliably and more completely achieve the desired generation and/or acceleration of the plasma. To this end, and in accordance with my invention, the two field coils are mounted symmetrically to the induction coil within a conducting shielding cylinder in coaxial relation to the cylinder and at a distance from each other.

The field coils may be excited pulsewise, periodically or permanently. The diameter of the field coils which produce the cusp field and their mutual distance are so chosen that a strongest possible radial field occurs in the vicinity of the inner wall of the additional insulating tube. The induction coil is placed around the insulating tube on the outside thereof, namely so that the middle of the induction coil is located in the middle plane between the two field coils. With a pulsewise or periodic electric excitation of the induction coil, its variable magnetic field induces in the interior of the insulating tube, but outside of the conducting shielding cylinder, a circular electrical field which generates the plasma and produces therein a circulating current (θ circuit). The current, conjointly with the magnetic field of the field coils, imposes upon the plasma an accelerating Lorentz force having a component in the axial direction of the apparatus.

The axial component of the magnetic field produced by the induction coil effects a compression of the plasma in the direction toward the peripheral surface of the conducting cylinder. The current-conducting plasma, however, compresses the magnetic field caught between the plasma and the conducting cylinder, this magnetic field being unable to penetrate into the conducting cylinder so that it acts in opposition to the motion of the plasma. In this manner, the plasma becomes crowded in an annular region between the shielding cylinder and the insulating tube. The ignition of the discharge is facilitated by the middle conductor, because the discharge reduces the inductivity of the above-mentioned θ circuit; and the inner conductor has a stabilizing effect upon the current-conducting ring of plasma. The performance remains unchanged if the conducting cylinder is surrounded by an insulating tube just fitting over the conducting cylinder, so that the plasma is located within an insulating hollow cylindrical space and consequently in a metal-free space.

The conducting cylinder arranged in the inner conductor of the insulating tube functions to prevent the ingress of rapidly variable magnetic fields, particularly the field of the induction coil. Since furthermore, according to the invention, the plasma is generated or accelerated outside of the volume of the field coils, there exists the possibility of inserting iron cores in the field coils for augmenting the cusp field.

When using normal coils with or without ferro-magnetic cores, insulation problems at the coils are avoided by the shielding of the variable fields. In unshielded coils, the rapidly variable field of the induction coil would induce very high electrical voltages which might cause breakdown.

The shielding cylinder or parts of this cylinder electrically insulated from each other, may be employed as an electrode for producing an electrical radial field, for example in order to generate a rotating plasmoid in conjuction with the axial magnetic field. Also applicable as field coils are coils of superconducting materials. These must be shielded from variable magnetic fields because otherwise the superconducting property may be impaired or eliminated. A conducting shielding cylinder may simultaneously serve as a component of the cryogenic device for maintaining the superconducting field coils at the required low temperature.

The force imposed upon the plasma is proportional to the vector product of the azimuthal current in the plasma times the radial magnetic field ($j_\theta \cdot B_r$). In order to make this force as large as possible, j_θ and B_r should be as large as feasible. The term j_θ depends upon the conductivity and upon the inductivity of the θ circuit. By applying a preionization, the conductivity is raised to a highest feasible value, and by the design of the apparatus, the inductivity of the θ circuit is kept at the practically attainable minimum. Further increase in the force imposed upon the plasma can be attained by increasing the cusp field. This may be achieved by the use of the aforementioned superconducting magnet coils.

The use of superconducting coils permits the production of a static cusp field. This is desirable if the apparatus is to be used for retarding a plasma in conjunction with the direct conversion of energy.

In order that the present invention may be readily carried into effect, it will now be described with reference to the accompanying drawings, wherein:

FIG. 1 is an axial section of the essential portion of an embodiment of the apparatus of the present invention;

FIG. 2 is a schematic view, partly in section of a portion of another embodiment of the apparatus equipped with superconducting coils;

FIG. 3 is a circuit diagram of the apparatus equipped with air-cored coils; and

FIG. 4 is a view, partly in section of a portion of still another embodiment of the apparatus.

In FIG. 1, the plasma is produced and confined in an insulating tube 1. The diameter of this tube may be 6 to 12 cm., for example. Mounted in the tube are two field coils 2 and 3 each having a diameter of 1 to 3 cm. The field coils 2 and 3 are axially spaced from each other a distance of 2 to 10 cm. The insulating tube 1 preferably consists of glass or quartz. The tube 1 is surrounded by an induction coil 4 which is positioned symmetrically to the radial center plane between the two field coils 2

and 3. The field coils are surrounded by a conducting shielding cylinder 5 comprising for example, brass.

As explained, the coils 2 and 3 may be iron-cored, air-cored or superconducting. They are wound in mutually opposed directions so as to produce between each other a magnetic field having a radial component (cusp field). The magnetic field lines are schematically indicated by 6. The induction coil 4 is energized by a rapidly increasing pulse or alternating current in the order of magnitude of 100 kiloamps, the rate of increase being 0.1 to 10 microseconds. The varying magnetic field produces a circular electrical field 7 in the interior of the insulating tube 1.

Assume that a neutral gas is confined in the tube 1. Under the operating conditions just described, the gas is ionized, and a circulating circular or ring current commences to flow in the plasma. A cross section through the circulating, circular or ring current is schematically indicated at 10. The Lorentz force resulting from the azimuthal ring current and the radial magnetic field drives the plasma in the direction of the tube axis and away from the acceleration center, this being schematically represented by an arrow 8. When the direction of the magnetic field or the current flow direction in the induction coil 4 is reversed, the direction of acceleration also reverses.

Toward the right of the illustration, the magnetic field lines 6 extend within the shielding cylinder. If desired, the flux may be prevented from leaving the shielding cylinder by ferromagnetic material. If the field lines 6 are permitted to leave the cylinder at 9, a second induction coil 11, as shown in FIG. 1, traversed by current in the opposed sense relative to the induction coil 4, may be used for imparting to the plasmoid an accelerated travel beyond the magnetic field lines. A guiding coil 12 may also be coaxially mounted on the insulating tube 1 at the exterior of said tube. With the aid of the guiding coil 12, an axial magnetic field may be produced which opposes any diffusion toward the wall of the insulating tube during the travel of the plasmoid. In the latter case, the flux of the field coil is not permitted to leave at 9, but is maintained in the insulating tube.

By employing ferromagnetic materials for the shielding cylinder or mounting such materials within the shielding cylinder, the magnetic flux of the field coils 2 and 3 may be so guided that it can leave the shielding cylinder only at a desired locality and enter into the surrounding space within the insulating tube 1.

If two or more coil assemblies are provided in sequence, an accelerated plasma can again be accelerated, retarded or reflected. Consequently, a plasmoid may thus be periodically moved back and forth between two such assemblies, thus obtaining a dynamic plasma confinement.

If the second induction coil 11 is mounted on the insulating tube 1 in a radial plane into which the flux of the field coil enters from the shielding cylinder, a largely field-free plasmoid may be ejected from the assembly. For this purpose, a current is passed through the second induction coil 11 when the plasma arrives at this coil, this current being opposed to the current produced by the first induction coil 4 in its flow direction. The plasmoid then moves additionally and with acceleration to the field lines leaving the one field coil and beyond these field lines. Without the second induction coil 11, the plasmoid would be decelerated by the field leaving the field coil.

As explained, a guiding coil 12 may be coaxially mounted on the insulating tube 1 in order to guide the plasmoid, generated and accelerated at the location of the first induction coil 4, along extended distances. The axial magnetic field of the guiding coil 12 impedes the diffusion of the plasma to the wall of the insulating tube 1. The guiding coil 12 is particularly applicable for passing the plasma in a circular path within a toroidal vessel.

FIG. 2 illustrates an embodiment of an apparatus utilizing superconducting field coils. In FIG. 2, as in FIG. 1, the two cusp-field coils are denoted by 2 and 3; the cryostat or shielding cylinder is denoted by 5. The coils 2 and 3 of FIG. 2 are located in liquid helium 18. Each of the field coils 2 and 3 consists either of copper, niobium stannate (Nb_3Sn) or other superconducting metal. The use of ferromagnetic material for the field coils 2 and 3 is avoided, and a magnet core is not necessary. Magnetizable cores are utilized in the inner spaces 19 and 20 of the respective field coils 2 and 3, only with normal conducting coils.

The liquid helium 18 is located in the cryostat 5 comprising vacuum spaces 16 of cylindrical shape which may be filled for example with liquid hydrogen 17. Typical numerical values for the superconducting coils 2 and 3 are a magnetic field strength of about 5 to 10 kilogauss and 10,000 to 20,000 turns in 6 to 8 layers of niobium-zirconium wire. The diameter of the wire may be 0.25 mm. The diameter of the coil assembly including the cryostat 5 is approximately 40 to 60 mm. The outer wall of the cryostat 5 simultaneously serves as a shield for high-frequency magnetic fields and may comprise, for example, brass.

The circuit of FIG. 3 utilizes air-cored coils for producing the cusp fields and the radial fields. When superconducting coils are utilized, the capacitor discharge circuit of FIG. 3 is replaced by a D.C. circuit. The electrical circuit for guiding coils 22 is not shown because it is identical with that of the cusp coils.

The embodiment of FIG. 3 includes the insulating tube 1, the field coils 2 and 3, the induction coil 4 and the field lines 6, as in FIG. 1. The guiding field coil 22 is wound on the outside of the insulating tube 1. The field coils 2 and 3 are connected to leads 33 and 34. The lead 33 is interrupted by a spark gap 26 which is ignited by an ignition device 36. A capacitor 28 is connected in series with the spark gap 26 in the lead 33. The capacitor 28 preferably has a capacitance of 40 μf. and is preferably rated for 40 kv. An ohmic resistor 29 is connected in the lead 34, which is grounded, as is the lead 33. The resistor 29 preferably has a resistance of 0.1 to 1.0 ohm. The magnitude of the resistance of the resistor 29 depends upon the required time constant of the circuit comprising the leads 33 and 34.

A Rogowski belt 30 is positioned around the lead 34. The Rogowski belt 30, which is a single turn coil, is connected through a time delay generator 35 to the ignition device for the spark gap of the field coil 4. The pulses provided by the Rogowski coil ignite a spark gap 25 which interrupts a lead 31 connected to the field coil 4. A capacitor 27 is connected in series with the spark gap 25 in the lead 31. The capacitor 27 preferably has a capacitance of 10 μf. and is preferably rated for 20 kv. The lead 31 and a return lead 32 of the field coil 4 are grounded.

FIG. 4 illustrates an embodiment of a toroidal plasma vessel of the invention which embodies the principles of FIG. 1. In FIG. 4, a toroidal vessel 40, for example, of glass, accommodates cusp-field coils 41, 42, 45 and 46, as well as induction coils 43 and 47 and a guiding coil 44. The magnetic field between each set of field coils is schematically indicated at 48. Aside from the toroidal arrangement, the design and performance of the system correspond to the one described with reference to FIG. 1.

While the invention has been described by means of specific examples and in specific embodiments, I do not wish to be limited thereto, for obvious modifications will occur to those skilled in the art without departing from the spirit and scope of the invention.

I claim:

1. Electrodeless apparatus for producing and accelerating plasmoids in an insulating tube having an axis and a periodically excited low-induction coil coaxially positioned around said insulating tube for producing an elec-

trical field in said insulating tube, comprising a shielding cylinder coaxially mounted in said insulating tube; and two field coils wound in opposite directions relative to each other coaxially mounted in axially spaced relation with each other in said shielding cylinder for producing a common magnetic cusp field, said low-induction coil being positioned in the common magnetic cusp field produced oy said field equidistantly from said field coils.

2. Electrodeless apparatus as claimed in claim 1, further comprising ferromagnetic material surrounding each of said field coils for concentrating magnetic flux leaving the shielding cylinder radially intermediate said field coils.

3. Electrodeless apparatus as claimed in claim 1, wherein each of said field coils is a superconducting coil.

4. Electrodeless apparatus for producing and accelerating plasmoids in an insulating tube having an axis and a periodically excited low-induction coil coaxially positioned around said insulating tube for producing an electrical field in said insulating tube, comprising

a shielding cylinder coaxially mounted in said insulating tube;

two field coils wound in opposite directions relative to each other coaxially mounted in axially spaced relation with each other in said shielding cylinder for producing a common magnetic cusp field, said low-induction coil being positioned in the common magnetic cusp field produced by said field equidistantly from said field coils; and

an additional low-induction coil coaxially positioned around said insulating tube in axially spaced relation from the first-mentioned low-induction coil and free of the magnetic field produced by said field coils for producing a plasmoid.

5. Electrodeless apparatus for producing and accelerating plasmoids in an insulating tube having an axis and a periodically excited low-induction coil coaxially positioned around said insulating tube for producing an electrical field in said insulating tube, comprising

a shielding cylinder coaxially mounted in said insulating tube;

two field coils wound in opposite directions relative to each other coaxially mounted in axially spaced relation with each other in said shielding cylinder for producing a common magnetic cusp field, said low-induction coil being positioned in the common magnetic cusp field produced by said field equidistantly from said field coils; and

additional low-induction coils coaxially positioned around said insulating tube in axially spaced relation from the first-mentioned low-induction coil and from each other.

6. Electrodeless apparatus for producing and accelerating plasmoids in an insulating tube having an axis and a periodically excited low-induction coil coaxially positioned around said insulating tube for producing an electrical field in said insulating tube, comprising

a shielding cylinder coaxially mounted in said insulating tube;

two field coils wound in opposite directions relative to each other coaxially mounted in axially spaced relation with each other in said shielding cylinder for producing a common magnetic cusp field, said low-induction coil being positioned in the common magnetic cusp field produced by said field equidistantly from said field coils; and

a guiding coil coaxially positioned around said insulating tube in axially spaced relation from said low-induction coil for guiding the plasma through the space between the shielding cylinder and the insulating tube.

7. Electrodeless apparatus for producing and accelerating plasmoids in an insulating tube having an axis and a periodically excited low-induction coil coaxially positioned around said insulating tube for producing an electrical field in said insulating tube, comprising

a shielding cylinder coaxially mounted in said insulating tube;

two field coils wound in opposite directions relative to each other coaxially mounted in axially spaced relation with each other in said shielding cylinder for producing a common magnetic cusp field, said low-induction coil being positioned in the common magnetic cusp field produced by said field equidistantly from said field coils;

an additional low-induction coil coaxially positioned around said insulating tube in axially spaced relation from the first-mentioned low-induction coil and free of the magnetic field produced by said field coils for producing a plasmoid; and

a guiding coil coaxially positioned around said insulating tube in axially spaced relation from said first-mentioned and additional low-induction coils for guiding the plasma through the space between the shielding cylinder and the insulating tube.

8. Electrodeless apparatus for producing and accelerating plasmoids in an insulating tube having an axis and a periodically excited low-induction coil coaxially positioned around said insulating tube for producing an electrical field in said insulating tube, comprising

a shielding cylinder coaxially mounted in said insulating tube;

two field coils wound in opposite directions relative to each other coaxially mounted in axially spaced relation with each other in said shielding cylinder for producing a common magnetic cusp field, said low-induction coil being positioned in the common magnetic cusp field produced by said field equidistantly from said field coils;

additional low-induction coils coaxially positioned around said insulating tube in axially spaced relation from the first-mentioned low-induction coil and from each other; and

a guiding coil coaxially positioned around said insulating tube in axially spaced relation from said first-mentioned and additional low-induction coils for guiding the plasma through the space between the shielding cylinder and the insulating tube.

9. Electrodeless apparatus for producing and accelerating plasmoids in an insulating tube of toroidal configuration having an axis and a periodically excited low-induction coil coaxially positioned around said insulating tube for producing an electrical field in said insulating tube, comprising

a shielding cylinder coaxially mounted in said insulating tube;

two field coils wound in opposite directions relative to each other coaxially mounted in axially spaced relation with each other in said shielding cylinder for producing a common magnetic cusp field, said low-induction coil being positioned in the common magnetic cusp field produced by said field equidistantly from said field coils; and

an additional low-induction coil coaxially positioned around said insulating tube in axially spaced relation from the first-mentioned low-induction coil and free of the magnetic field produced by said field coils for producing a plasmoid.

10. Electrodeless apparatus for producing and accelerating plasmoids in an insulating tube of toroidal configuration having an axis and a periodically excited low-induction coil coaxially positioned around said insulating tube for producing an electrical field in said insulating tube, comprising

a shielding cylinder coaxially mounted in said insulating tube;

two field coils wound in opposite directions relative to each other coaxially mounted in axially spaced relation with each other in said shielding cylinder for producing a common magnetic cusp field, said low-induction coil being positioned in the common mag-

netic cusp field produced by said field equidistantly from said field coils;

an additional low-induction coil coaxially positioned around said insulating tube in axially spaced relation from the first-mentioned low-induction coil and free of the magnetic field produced by said field coils for producing a plasmoid; and

a guiding coil coaxially positioned around said insulating tube in axially spaced relation from said first-mentioned and additional low-induction coils for guiding the plasma through the space between the shielding cylinder and the insulating tube.

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