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Brayshaw

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[54] **METHOD AND APPARATUS FOR GENERATING PLASMA**

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Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 704,500, Jan. 12, 1968, abandoned, which is a continuation-in-part of Ser. No. 651,224, July 5, 1967, abandoned.

[52] **U.S. Cl.** **128/303.14**; 313/231.3; 315/111.2

[51] **Int. Cl.**[2] **A61B 17/32**; A61N 3/00

[58] **Field of Search** .... 128/303.1, 303.12–303.17, 128/395, 396, 404, 413, 414, 421, 422, 423; 219/121 P; 315/111.2; 313/231.3, 0.6; 230/43

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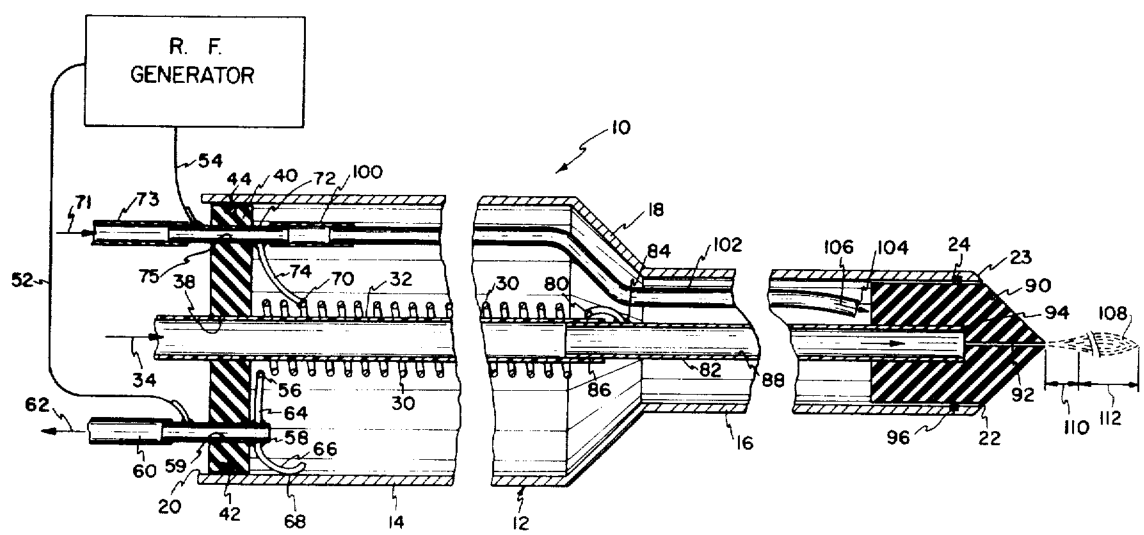
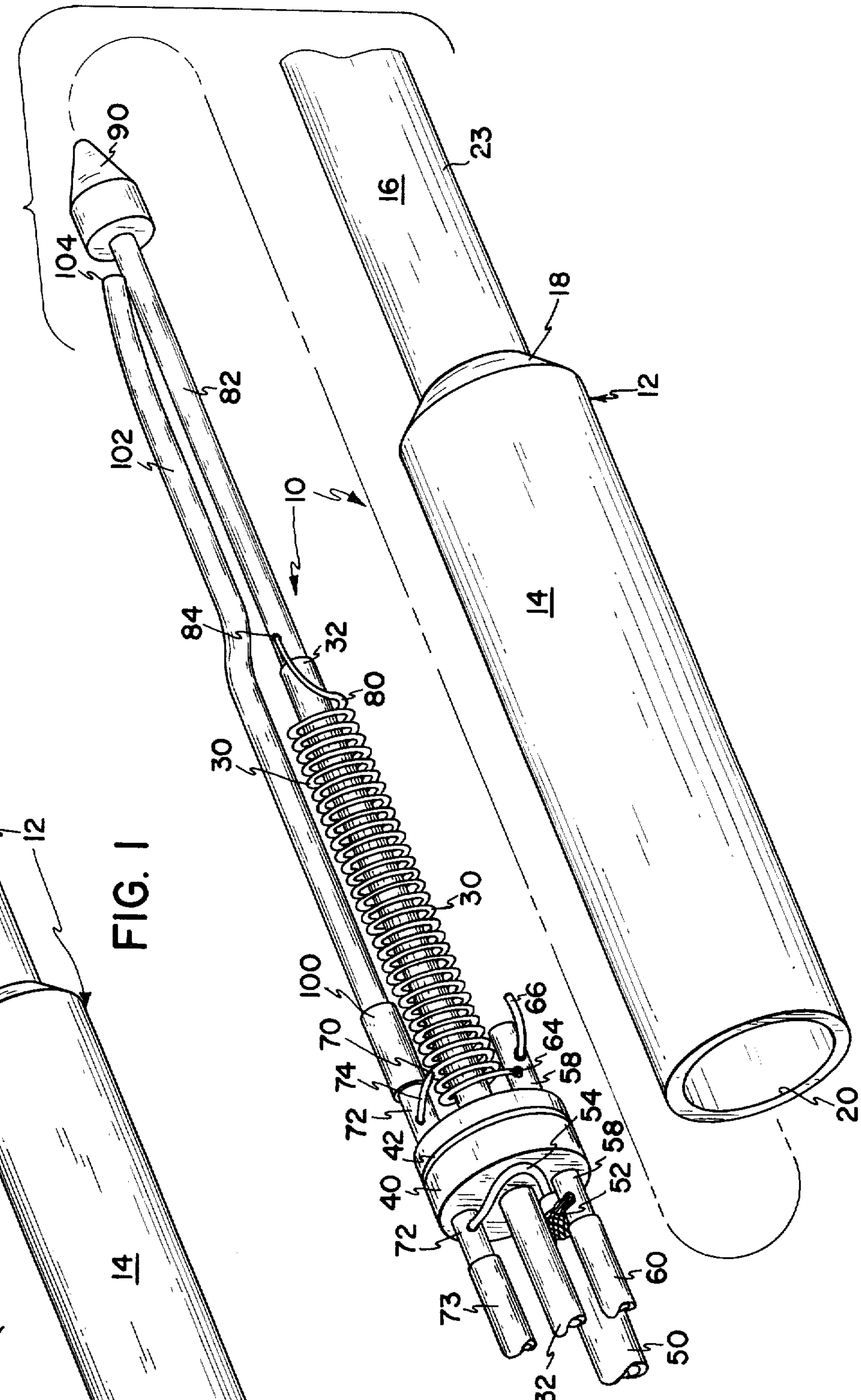
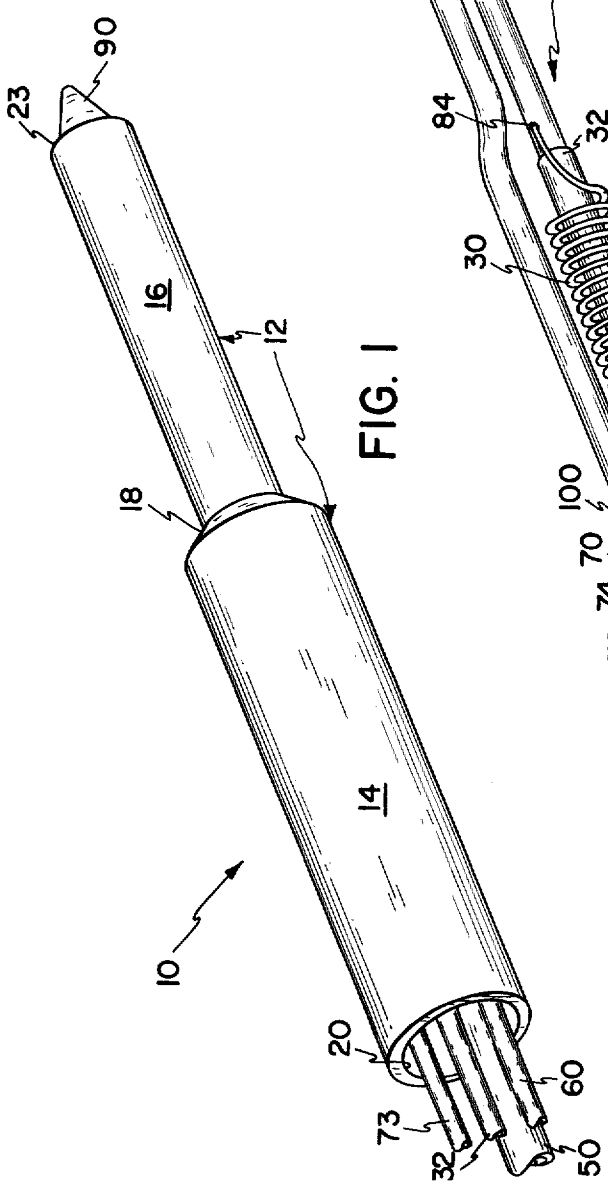
[57] **ABSTRACT**

Apparatus for producing an electric-field plasma is constructed with a hollow, electrically-conductive conduit connected in series with a radio frequency resonant circuit. The spatial relationship of the hollow conduit and the inductance of the resonant circuit is selected to avoid transformer action. The components of the generator (including the plasma) interact to effect a high Q under unloaded conditions and a low Q under loaded conditions. Flowable material, usually including a carrier gas, is displaced through the conduit while RF energy is applied to the resonant circuit. By proper adjustment of the process parameters, the gas may be excited to and maintained at preselected energization levels. Plasmas may be initiated by the application of RF energy alone without auxiliary initiation techniques. Plasmas generated at ambient pressures may optionally be either at close to thermal equilibrium or at substantial thermal nonequilibrium. Plasmas at thermal nonequilibrium may comprise noble gases (or other substances susceptible to excitation to a mestastable state) in a metastable state.

15 Claims, 5 Drawing Figures







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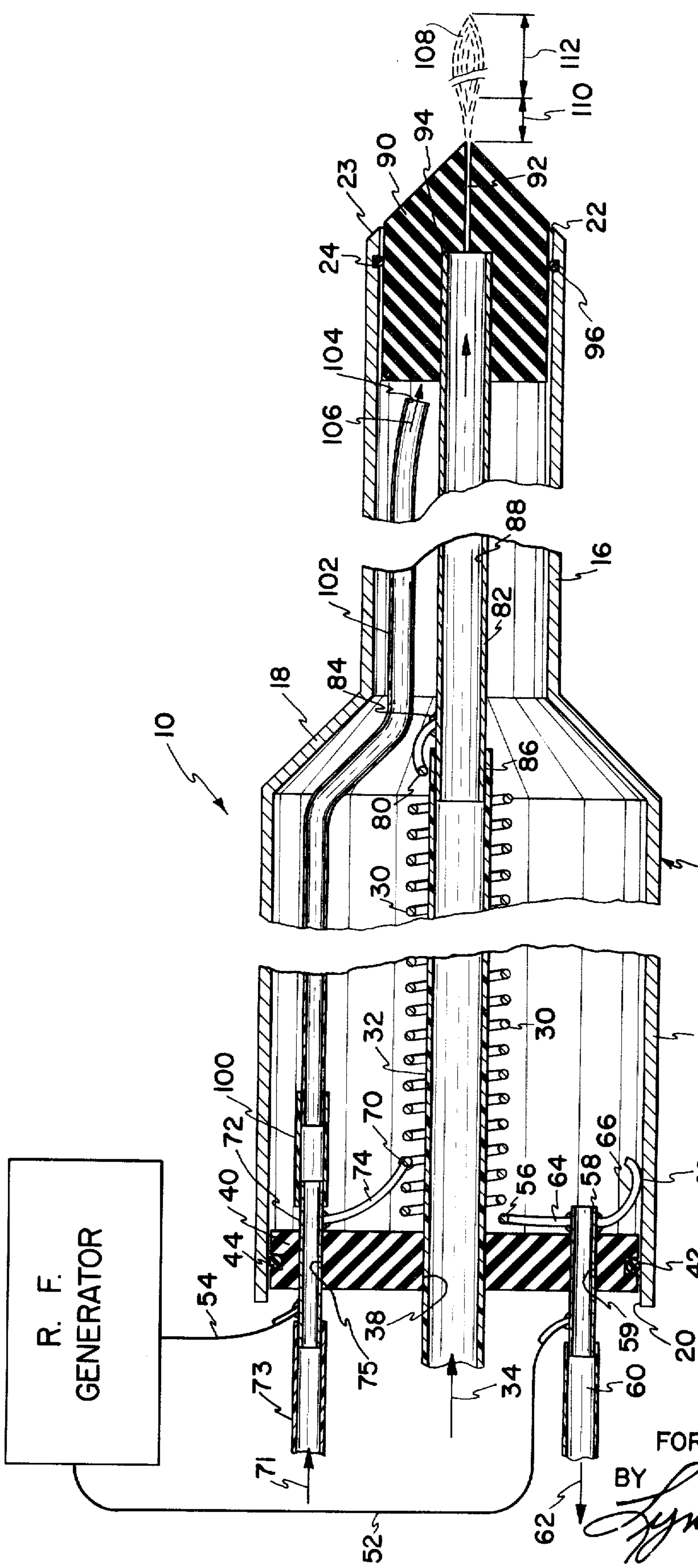

FIG. 3

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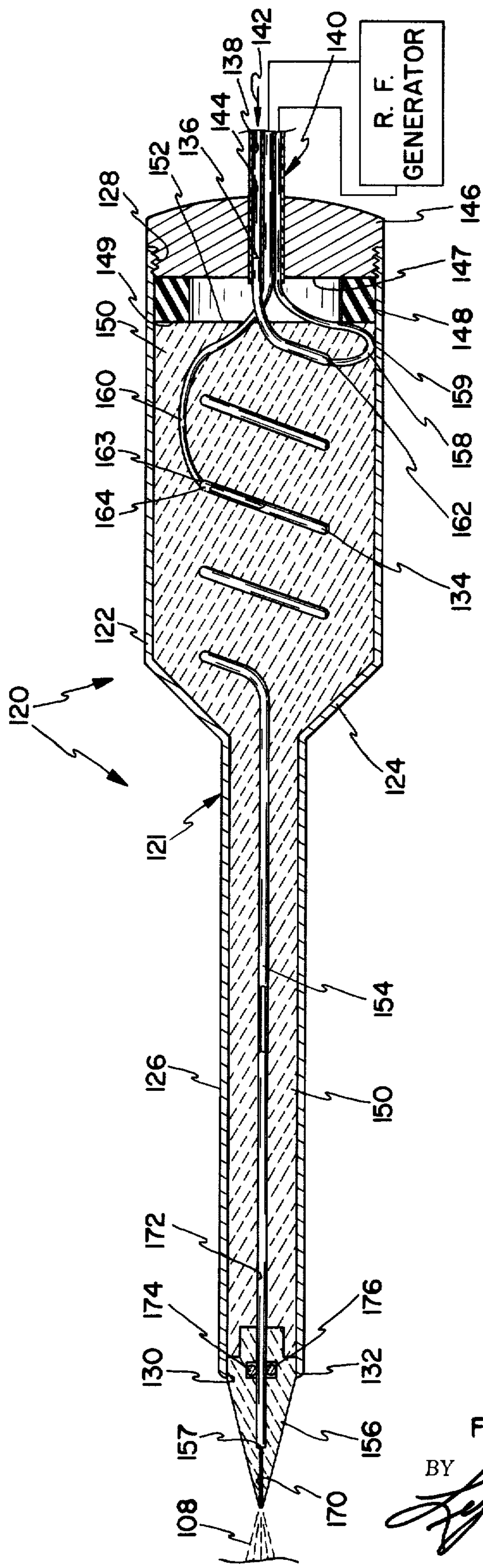

FIG. 4

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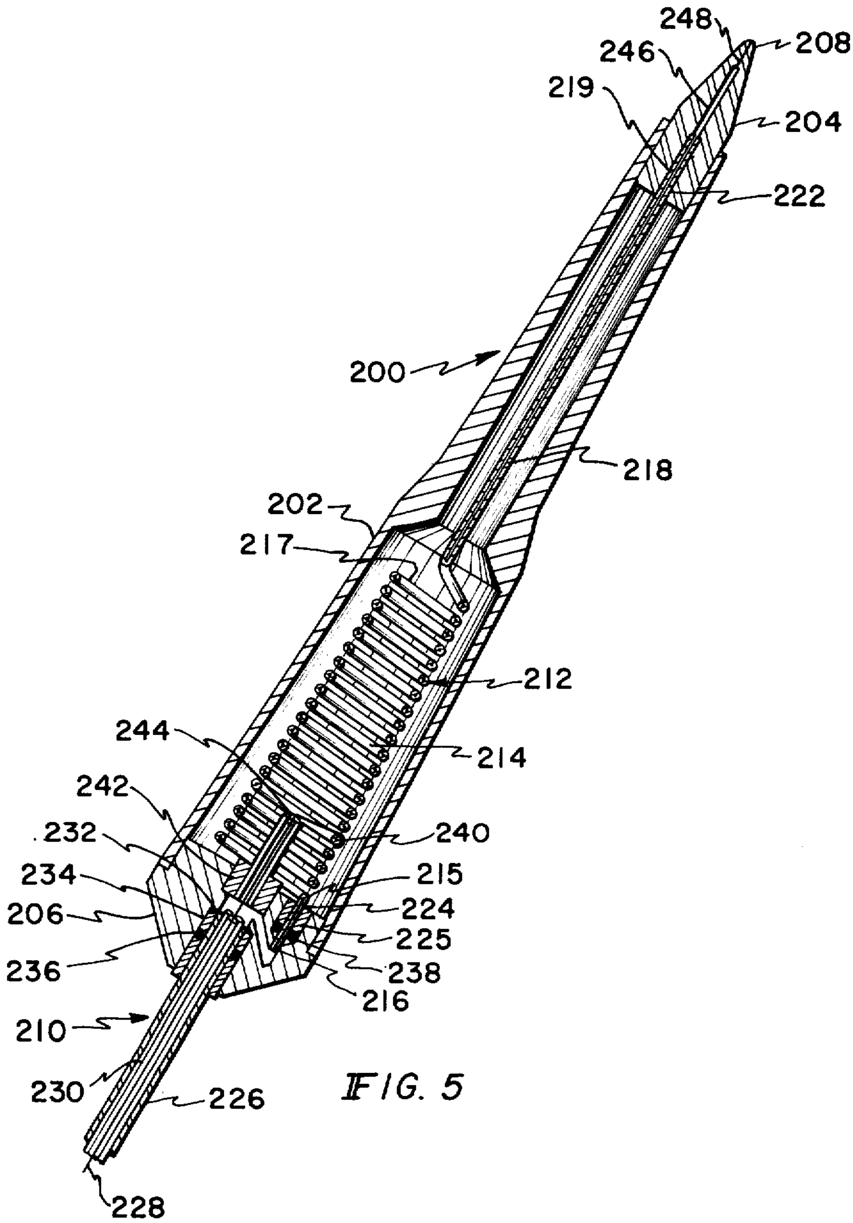

FIG. 5

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METHOD AND APPARATUS FOR GENERATING PLASMA

RELATED APPLICATIONS

This application is a continuation-in-part of commonly assigned, copending application Ser. No. **704,500,** filed Jan. **12, 1968,** now abandoned, which is a continuation-in-part of commonly assigned application Ser. No. **651,224,** filed July **5, 1967** (now abandoned).

BACKGROUND OF THE INVENTION

Field

This invention relates to electric-field plasmas and provides methods and apparatus for producing such plasmas. It is particularly directed to the production of "cold plasmas," (which may include gases in the "metastable" state) without the necessity for maintaining low pressure conditions, and to the self-initiation of plasmas.

State of the Art

Various methods for plasma generation are known. Of most interest, from the standpoint of this invention, are those which involve the release of electrical energy into a carrier gas, notably argon, helium, nitrogen (including air), and hydrogen. Such plasmas may be termed "electric-field plasmas" and are commonly classified as "arc," "glow discharge," or "corona discharge," depending upon the physical condition of the plasma and its appearance. When the electrical energy released into the carrier gas is alternating current (ac), any of the aforementioned classes of electric-field plasmas may exist with or without electrodes in contact with the carrier gas.

Glow discharge phenomena are well known. The most familiar applications of such phenomena are in lighting, e.g., in fluorescent, neon, sodium, and mercury lamps. Glow discharge plasmas are often described as cold plasmas because the energy density and wall-heating effect of such plasmas are very low. Such plasmas may also be regarded as being at thermal nonequilibrium because their gas temperatures are characteristically much lower than their "electron temperatures." The term electron temperature denotes a temperature (usually several thousand degrees) corresponding to the energy possessed by the electrons in a plasma. It is commonly understood that the operating conditions productive of cold plasmas are high voltage (**1–100**kV) and low pressure (usually below **10** torr). The term cold plasma, as used in the following specification and claims, is intended to include plasmas at thermal nonequilibrium which evidence a low wall-heating effect, whether or not such plasmas exhibit the appearance and other physical characteristics normally associated with the specific cold plasma and glow discharge phenomena heretofore recognized in the art. According to this invention, cold plasmas may be produced which possess a very high energy density, for example.

As used in this specification and in the appended claims, the term plasma is used in its broadest context and refers to an at least partially ionized gas, which may include molecules, atoms, ions, electrons, and free radicals, each moving with a velocity dependent upon its mass and its temperature. (A plasma is regarded as at thermal equilibrium only when the distribution of its particle velocities is such that the average energy of

each species is approximately the same.) The average energy of a particle (e.g., an electron) can be expressed as a temperature (e.g., electron temperature) according to the relationship $\frac{1}{2}mV^2 = (3/2)kT$, where m is the mass of the particle, V is the root-mean-square velocity of the particle, k is Boltzmann's constant, and T is the absolute temperature of the particle. The term plasma includes gases ionized to a very limited extent, e.g., **0.1** percent of its molecules, although it is often preferred to refer to such gases as being in an "energized" state. The term energized gas refers to any gas, whether ionized or not, which is storing energy, as a result of the application of electrical energy, in a form capable of subsequent release as heat and/or light. This term thus includes a gas which is ionized, disassociated, or in an "excited" state, including the "metastable" state. A gas is considered to be in an excited state when an electron of an inner orbital shell of a species (molecules, atoms, and/or ions) has absorbed a quantum of energy so that it is at a higher than its ground state energy level with respect to the nucleus; it is considered to be in the metastable state when an inner electron is excited to a level from which the return to ground state via electromagnetic emission is of extremely low probability. A species in the metastable state generally loses its excess energy either by imparting kinetic energy to its surroundings or by exciting other molecules, atoms or ions.

U.S. Pat. No. **3,424,533** discloses and claims an apparatus for spectrographic analysis which relies upon a radio frequency (RF) "discharge" to vaporize the sample. The apparatus disclosed includes an RF oscillator with a hollow induction coil of its output resonant circuit surrounding and electrically connected to a hollow conductor. The device is constructed such that there is transformer action between the induction coil and the hollow conductor. An atomized sample is introduced with a carrier gas through the induction coil to the central conductor, and the discharge originates at the opposite end of the conductor. The sample is "vaporized" by the plasma so it is apparent that the plasma produced is very hot.

A similar apparatus is disclosed in an article by Roddy, et al., "The Radio-Frequency Plasma Torch," Electronics World, February, **1961,** Vol. **65,** pp **29–31** and **117.** The apparatus of this article also includes a central conductor (which terminates as a torch tip) within the inductor of the output resonant circuit of a conventional tuned-plate, untuned-grid, RF oscillator. The plate circuit tap point on the inductor and the degree of feedback of the grid circuit are adjusted to obtain matched operation with an ignited flame. According to the article, operation of the torch takes place at relatively low pressures and low gas velocities, and it is necessary to provide a source of free electrons to initiate the plasma. An auxiliary electrode is used for this purpose. The torch tip is constructed of molybdenum and both the induction coil and the torch are of necessity water-cooled.

General Description of the Invention

The apparatus of this invention may be embodied in various forms and sizes, but in any event, comprises a radio frequency resonant circuit (preferably of the parallel-resonant type) with capacitive and inductive legs selected to effect a high Q at the resonant frequency of the circuit. The inductive leg may include a coil disposed about a gas inlet tube, but in such embodiments the tube is ordinarily constructed of dielectric material to avoid inductive coupling of RF energy to gas flowing through the tube. In any event, transformer action between the inductance of the resonant circuit and the gas inlet tube is avoided, either by proper shielding or by the spatial relationship of these components. The inductive leg is connected at one end to a source of high RF voltage, and at the other end to a reference potential of much lower magnitude, typically the chassis ground of the RF source.

The electrical parameters of the inductive and capacitive legs of the resonant circuit are selected such that under "no load" conditions (e.g., prior to the initiation of a plasma), its effective Q is very high, but under load conditions (when current is being drawn from the resonant circuit, e.g., when the plasma is coupled to ground, a workpiece, or the atmosphere) its effective Q drops very substantially. Accordingly, the inductance to capacitance ratio should be high, usually at least above **10** in a parallel-resonant circuit. In general, the effective Q of the resonant circuit under no-load conditions should exceed about **20.** Usually, the no-load Q will exceed **50,** the presently preferred values being between about **100** and about **300.** Under loaded conditions the effective Q should drop sufficiently to broaden the operational band width of the resonant circuit. Suitable loaded Q values are below about **20,** usually below about **15.** When the plasma is well grounded, the load effective Q value of the resonant circuit is often reduced to substantially below **10,** in some instances, below **2.**

The high potential end of the inductive leg of the parallel-resonant circuit is directly connected to a hollow, conductive conduit. The conduit is provided with an inlet for the introduction of displaceable, usually pneumatically-flowable (conveyable), materials and terminates in an outlet for the discharge of the displaceable material. The outlet is generally formed as a burner or torch tip designed and constructed for a specific application, such as cutting, heating or spraying. The term "pneumatically-flowable material" includes any carrier gas (with or without additional particulate, atomized or gaseous constituents) capable of being displaced through a hollow conduit. Although virtually any gas as well as liquids and solids may theoretically be energized by the methods and apparatus of this invention, the gases found most useful in the prior art for electric-field plasma applications are generally most useful in connection with similar applications of this invention for the same reasons. The conductive conduit is either shielded or isolated from the inductive components of the resonant circuit to avoid transformer interaction. Otherwise, it is not feasible to maintain the high Q values required for the apparatus of this invention.

In operation, when RF energy is first applied to the resonant circuit, the high effective Q of this circuit provides a substantial voltage buildup so that a potential is applied to the hollow conduit sufficiently above the reference potential to initiate a plasma in a carrier gas flowing through the conduit. Plasmas may readily be self-initiated in gases such as argon, helium, hydrogen and nitrogen (even in impure form such as air), in this fashion. By "self-initiated" is meant initiation solely by the application of electrical energy to the hollow, gas-carrying conduit; i.e., without the external aids conventionally employed to initiate a plasma.

Upon initiation of a plasma, the effective Q of the resonant circuit normally drops very substantially. An exception to this effect is sometimes observed when a plasma is initiated in a noble gas, such as argon. A metastable argon plasma, for example, can be maintained while drawing such small amounts of current from the resonant circuit that any decrease in potential at the conductive conduit (compared to the no-load potential) is undetectable on a conventional RF volt meter. The current flow from the resonant circuit (resulting in a substantial drop in the Q of the circuit) is increased by coupling such metastable plasmas to ground or a conductor, or by tuning the RF energy source to match more closely the resonant frequency of the resonant circuit.

The drop in effective Q which results from loading of the plasma (any condition resulting in current flow from the resonant circuit) is a very useful phenomenon from the standpoint of this invention. The lower Q permits greater energy flow into a plasma at a given power setting of the RF source, but even more important, the operational band width of the plasma generator is increased as the Q is decreased. Thus, the characteristics of the plasma may be altered appreciably by tuning the input frequency to the resonant circuit without extinguishing the plasma. In this fashion, the characteristics of a plasma may be selected with a broad spectrum of greater or lesser degrees of thermal nonequilibrium.

A notable characteristic of this invention is the capability of producing a plasma possessing many of the desirable properties of the art-recognized cold plasmas at ambient pressure conditions. Although the precise physical mechanism of this invention is not completely understood, and while applicant does not intend to be bound hereby, it appears that the more useful plasmas produced in accordance with this invention are at substantial thermal nonequilibrium. Moreover, this invention energizes noble gases, notably argon, to a metastable state at ambient pressures in a useful plasma column. Other gases, such as helium or vaporizied elements, such as mercury vapor may also be excited to a metastable state, but with more difficulty.

Although the wall heating effect of plasmas produced in accordance with this invention may be maintained at very low levels, their energy densities appear to be substantially higher than has been typical of cold plasmas. In any event, many plasmas of this invention appear to be exceptionally efficient in transferring energy (in the form of heat) to a workpiece. The plasmas produced in accordance with this invention have ideal properties for many applications, such as mineral processing, chemical production, surfical cutting and metal spraying; they may be sustained under widely varying degrees of attenuation, gas velocities, pressure conditions, and power levels, and the apparatus may be scaled to produce and sustain plasmas of widely varying volumes and energy levels. It is possible to energize many gases, notably nitrogen, to a highly ionized state with no substantial population of particles in a metastable state using the apparatus and procedures of this invention.

For surgical applications, plasma of metastable noble gas is preferred. In general, the plasma should be attenuated to a cross section which permits a narrow region of contact between the plasma and the tissue to be cut. A metastable argon plasma with a diameter between about **0.005** and about **0.015** inch is preferred. RF energy applied at between about **30** and about **200** (ideally between about **80** and about **100**) magahertz, between about **50** and about **300** volts, and between about **30** and about **300** watts to a scalpel relying upon a parallel-resonant circuit having a Q above about **20** (preferably above about **100**) produces a good metastable argon plasmas. RF energy applied to the resonant circuit at frequencies up to about **5** percent above its resonant frequency produces metastable argon plasmas ideal for surgical applications. In some instances, notably the treatment of brain lesions, it is desirable to supply RF energy to the resonant circuit of the scalpel at slightly (**1** or **2** percent) below its resonant frequency. Acceptable flow rates for the gas are generally below about **5**, preferably below about **2**, but rarely below about one-tenth cubic feet per hour

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, which illustrate what are presently regarded as the best modes for carrying out the invention:

FIG. **1** is a perspective view of a plasma torch constructed according to this invention;

FIG. **2**, an enlarged, exploded perspective view of the plasma torch of FIG. **1**;

FIG. **3**, a cross sectional view taken along the longitudinal center-line axis **3—3** of the plasma torch of FIG. **1**;

FIG. **4**, a longitudinal cross sectional view of an alternative plasma torch embodiment of this invention; and

FIG. **5**, a longitudinal cross sectional view of the apparatus of this invention embodied as a surgical scalpel.

DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

The plasma torch **10** illustrated by FIGS. **1** through **3** comprises a generally cylindrical conductive shield or casing, e.g., of aluminum, including a rear cylinder sleeve **14**, a tapered transitional section **18** and a forward cylindrical sleeve of reduced diameter. The shield **12** is provided with a rear opening **20**, a front opening **22** and a recess or groove **24** above the inside surface near its leading end **23**.

The shield **12** contains a radio frequency coil **30**, of copper or other conductive material, which surrounds a dielectric (plastic) gas inlet tube **32**. Gas may be displaced through the inlet tube **32** generally unidirectionally by pressure in the direction indicated by arrow **34** (FIG. **3**). The induction coil **30** has substantially no ionization effect upon the gas flowing through the inlet tube **32** and there is no transformer action between the coil **30** and the tube **32**. The gas inlet tube **32** could optionally be placed external the coil **30**, but it is located as shown as a matter of convenience. The tube **32** is desirably constructed of thermally-resistant material, such as teflon or nylon.

The gas inlet tube **32** enters the shield **12** through an aperture **38** centrally disposed in a dielectric plug **40**. The peripheral edge of the plug **40** contains a groove **42** adapted to receive a high-temperature resistant O-ring **44** to seal the plug against the shield so that the interior of the shield **12** is fluid-tight but also so that a suitable manually exerted force will pull the shield off from around the remainder of the torch **10**, as shown in FIG. **2**.

Radio frequency energy is directly conductively applied from an RF generator through a coaxial cable **50** (FIGS. **1** and **2**) to the torch head assembly. The ground lead **52** of the coaxial cable **50** is connected to the low potential or trailing end **56** of the coil **30** through a metal sleeve **58**, which passes through aperture **59** in plug **40**. The sleeve **58** also accommodates discharge of coolant from within the shield into a coolant outlet tube **60**, shown as being fabricated plastic material. The coolant effluent flows generally in the direction of arrow **62** to a suitable heat exchanger (not shown). A short electrical lead **64** connects the metal sleeve **58** to the low potential (as illustrated, the grounded) end **56** of the coil.

A resilient wire or spring **66** electrically connects the ground end **56** of the coil **30**, at the sleeve **58**, to the shield **12** (**68**, FIG. **3**).

The central coaxial cable lead **54** of the coaxial cable **50** is connected directly to the coil **30** a few turns forward of its ground end **56** at a tap **70** through a coolant influent metallic tube **72** and a short lead **74**. The coil **30** constitutes the inductive leg of a parallel-resonant circuit, as explained more fully hereinafter.

The exact turn of the coil at which the tap **70** is located is determined either experimentally or by mathematical calculations so as to match as closely as possible the impedance of the coaxil cable and to obtain a low standing wave ratio, preferably on the order of **1** to **1.5**, on the cable. The output impedance of the RF generator should also be adjusted to approximately match the impedance of the coaxial cable. When it is impractical to approximately match the input impedance of the resonant circuit with a coaxial cable, other expedients, such as conventional Pi circuits between the cable and the resonant circuit, may be used to improve the impedance match.

The hot end **80** of the coil **30** is directly connected, at **84**, to a hollow metal conduit **82**. The conduit **82** is of suitable diameter to accommodate easy coupling, as at **86**, to the gas inlet tube **32** and is provided with a hollow central bore **88** through which the gas to be excited, or any other pneumatically flowable meterial, is displaced.

The leading end **94** of the conduit **82** terminates at a tip or nozzle **90** of high temperature, ceramic material, such as boron nitride or aluminum oxide, having good thermal conductivity and good dielectric qualities. The gas-carrying conduit **82** should be made of conductive material, such as copper, having both good heat conducting and good electrical conducting characteristics.

The tip or nozzle **90**, in the illustrated embodiment, is machined or otherwise prepared to effect a fluid seal with a high-temperature resistant O-ring **96** when the interior part of the plasma torch is manually press-fit into assembled condition (FIG. **3**). The inside dimension and shape of the opening **92** of the tip **90** and the length and shape of the tip **90** itself are determined by the application to which the plasma discharge **108** is to be put and the desired power of the plasma to be generated. The illustrated tip **90** may be eliminated or replaced by other types of flow-restricting or attenuating nozzles or tips. The tip can be press-fit over the forward end **94** of the conduit **82** or otherwise suitably secured in position, as by use of a suitable bonding agent.

A cooling fluid may be delivered from a heat exchanger (not shown) in the direction indicated by arrow **71** through a coolant intake tube **73** and the coolant influent conductive tube **72**. Tube **72** passes through an aperture 77 in plug **40**. A coupling sleeve **100** and an influent delivery tube **102** may be provided as shown for the delivery of influent coolant at opening **104** to directly impinge on the tip **90**, as indicated by arrow **106**. The sleeve **100** and tube **102** are dispensed with in other embodiments.

As shown, the influent coolant first contacts the nozzle or tip **90**. Thereafter, the coolant flows front to rear generally in contact with the internal surface of the shield, the external surfaces of the electrode **82**, tubes **102** and **100**, and the gas inlet tube **32**, totally immersing the unductance coil **30** in the coolant. Cooling liquid then returns to the heat exchanger (not shown) through the serially disposed sleeve **58** and outlet tube **60**. Accordingly, the electrode tube, the ceramic tip or nozzle, the radio frequency coil, the gas inlet tube, the coolant influent and effluent tubes, including the radio frequency power connectors, and the cylindrical shield are all contacted by the coolant.

This shield **12**, which is shown at ground potential due to lead **66**, acts as one condenser plate and the conduit **82** and coil **30** act as a multiplicity of higher potential condenser plates. Capacitance is developed between the shield **12** and the conduit **82** and the shield **12** and each region of the coil **30** across the dielectric contained within the shield (in the illustrated instance the coo lant). The physical dimensions of the shield, the coil, and the conduit, the relative spacings thereof, and the properties of the dielectric help determine the capacitance in parallel with the inductive coil **30**.

Any coolant used must of course be selected on the basis of both its cooling properties and its electrical properties. An important aspect of this invention is that when cold plasmas are initiated and maintained, no special cooling is required so that the dielectric may be noncirculating air enclosed by the shield **12**.

During operation, the cooling solution is first caused to flow serially through the cooling inlet tubes **73, 72,** 100 and **102**, and circulate across the ceramic tip **90**, back along the metal electrode **82**, around the immersed radio frequency coil **30** and out the outlet tubes **58** and **60**. Gas, under pressure, is caused to flow into the gas inlet tube **32** as indicated by arrow **34**, through the hollow central bore **88** of the conduit **82** and out to the atmosphere through the orifice opening **92** in the ceramic tip **90**.

The plasma torch **120** illustrated by FIG. **4** comprises a generally cylindrical conductive shield or casing **121** integrally consisting of a rear cylindrical sleeve **122**, a tapered transitional section **124** and a forward cylindrical sleeve **126** of reduced diameter. The shield **121** is provided with a rear, internally threaded, opening **128** and a front opening **130** adjacent the leading end **132**.

The shield **121** envelopes in spaced relation a radio frequency hollow coil **134** terminating in a hollow conductor **154** and formed of tubular metal, such as brass. The hollow interior passage of the coil **134** and the conductor **154** are in fluid communication with the interior of a gas inlet tube **138**, comprising part of a coaxial cable **140**. Influent gas flowing in the direction of arrow **142** enters the coil **134** at the influent end **136** which is in fluid-tight relation with the tube **138**.

The coaxial cable **140** passes interior of the shield **121** through an aperture **144** centrally disposed in a peripherally threaded plug **146**, adapted to threadedly engage the rear opening of the shield **121** at **128**. The inside or forward face **147** of the plug **146** compressively engages an annular washer **148** of elastomeric or other suitable material.

The forward face **149** of the annular washer **148** compressively contacts the trailing edge **152** of a body of ceramic material **150**, cast to closely fit within the shield **121** and held in stationary position within the shield **121** by the force exerted by the compressed washer **148**. The coil **134** and the integral, forwardly-projecting electrode **154** are permanently embedded in the ceramic body **150**. When desired, the coil **134**, the electrode **154** and the ceramic body **150** can be removed from the shield **121** through the rear opening at **128**. One preferable dielectric ceramic material is boron nitride, although equivalent ceramic with a good high frequency electrical strength could be used.

Ceramic dielectrics are not always suitable, and in some cases elimination thereof results in improved operation. Ceramic materials tend to absorb power at high frequencies and are not, therefore, suitable dielectrics at such operating frequencies. Utilization of a dead air space in place of ceramic between the interior surface of the shield **121** and the spaced electrode **154** and the spaced coil **134** is effective, particularly when the operating frequency of the generator is on the order of 30 megacycles or more. The use of cooling fluids is generally required for applications in which the plasma exhibits a high wall-heating effect. In those instances, the plasma behaves more nearly as though it were in thermal equilibrium. Such plasmas are usually, but not necessarily, produced by the application of high power; e.g., on the order of **200** watts or more.

Radio frequency energy is coupled from an RF generator through the coaxial cable ground lead **158** and the "hot" cable lead **160**. The ground lead **158** is in turn conductively joined at **159** to the shield **121** and at **162** to the ground end of the coil **134**. The hot coaxial cable lead **160** is satisfactorily coupled at **163** to an intermediate turn **164**, illustrated as approximately one turn from ground potential. The exact placement of the connection of the lead **160** to the coil **134** is determined by the impedance of the coaxial cable. Of course, the coaxial cable may be replaced by any other suitable bundle of conductors, e.g. an open line cable.

The leading end **157** of the electrode **154** is in communication with a narrow passage **170** of the nozzle **156**, which is manually pressfit into the front opening **130** of the shield **121**. In this way, the tip **156** can be manually removed and replaced with a differently configurated nozzle for producing plasma of varying types and characteristics. The forward end portion of the electrode **154** fits within a close tolerance bore **172** opening toward the rear of the nozzle **156**. A high temperature-resistant O-ring **174**, situated in an annular groove **176** in the nozzle **156**, holds the nozzle tightly in place during use but permits the mentioned manual removal.

During operation, gas is caused to flow through inlet **136** into the hollow of the coil **134** and electrode **154**, as indicated by arrow **142**. The flow is preferably substantially laminar. The plasma gas at introduction into the coil is at ground potential, and with proper control, is excited to plasma only at the high voltage leading end **157** of the conduit **154**.

The plasma generator **200** illustrated by FIG. **5** is of presently preferred construction for use as a surgical scalpel. It is generally similar to the embodiment of FIG. 4 but is of more convenient shape for a surgical handpiece. Thus, the outer casing **202**, which may be of aluminum, among other conductive materials, is of generally tapered shape and is sealed at its opposite open ends by a press-fit tip **204** and a press-fit plug **206**, respectively. The tip **204** is of ceramic material and is configurated at its forward end as a nozzle **208**. The plug **206** has a central bore for accommodating a flexible supply cord **210**.

As in the case of the previously described embodiment (FIG. **4**), a continuous hollow metal conduit **212** is formed as an RF inductor coil **214**, terminating at its low potential end **215** as gas feed conduit **216** and at its high potential end **217** as a hollow conductor **218**. The conduit **218** functions as an electrode for the initiation of a plasma, as a supply passage for an excitable gas, and a high potential capacitor plate. The coil **214** is tapered to conform generally with the internal configuration of the outer casing or housing **202**, and it is supported as shown by its feed end **216** and by the leading end **219** of the electrode **218**. The leading end **219** of the electrode is inserted in a central bore **222** of the tip **204** in a press-fit relationship, and the low potential end **215** of the coil **214** is soldered **224** to a metal connector **225** mounted in the plug **206** to effect a fluid-tight seal.

The supply cord **210** comprises a coaxial cable with a grounded metal shield **226**, internal conductor **228**, and a bundle **230** of flexible gas supply tubes. The metal shield **226** is soldered **232** to a metal connector **234** so that the entire plug **206**, housing **202** and low potential end **215** of the coil **214** are at ground potential (or other convenient reference potential of the shield). O-rings **236, 238** may be used as previously described to effect fluid-tight seals within the plug **206** so that gas introduced through the supply tubes **230** can only enter the feed end **216** of the coil **214**. The central conductor **228** is connected at the appropriate tap point **240** on the coil, being brought through an insulated spacer **242** as shown. The spacer **242** is sealed, e.g., by a solder plug **244** to prevent gas leakage. Thus, according to this embodiment, the dielectric between the coil **214** and electrode **218**, respectively, and the housing **202** is either air or some other entrapped gas.

The tip **204** is machined with bores **246** and **248** of decreasing diameter following the terminus **219** of the electrode **218** to attenuate the gas stream before it exits the nozzle **208**. Of course, nozzles of varying shapes and sizes may be substituted, depending upon the characteristics desired for the plasma.

The invention will be better understood by reference to the drawings in connection with the following specific examples:

EXAMPLE I

A plasma generator was constructed as illustrated by FIG. **5**. When assembled, the resonant frequency of the parallel-resonant circuit comprised of the inductance coil and the capacitive elements in circuit therewith was **90** megahertz. The inductance of the circuit was determined by a Marconi, Model **TF1313A**, bridge to be about **0.6** microhenries, and the capacitance of the circuit was thus determined to be about **5** picofarads. Under loaded conditions, the Q of the plasma generator was determined to be above **140**. The hollow electrode was fitted with a nozzle having an orifice diameter of about **0.007** inches. One hundred ten watts of RF power was delivered to the tap of the coil at approximately **100** volts. The RF source was capable of being tuned to output frequencies ranging from about **80** to about **100** megahertz. Argon gas was displaced through the coil to exit the nozzle at a rate of about **1** cubic foot per hour.

a. With the RF source tuned to **90** megahertz, a plasma was initiated spontaneously within a fraction of a second after the power was turned on. The plasma was visible for about **1** inch beyond the terminus of the nozzle and had the blue-white color and general appearance typical of an argon plasma. The Q of the plasma generator under these conditions was determined to be below about **15**. Paper was readily ignited by the plasma, and copper wire about **0.030** in diameter was quickly melted upon contact by the plasma. An ozone odor was detectable in the vicinity of the plasma.

b. After the plasma was initiated, the RF source was tuned to **92** magahertz. The length of the plasma descreased by about half, and the plasma remained blue-white in color but emitted much less light. Pater could not be ignited by the plasma. Dielectric materials, such as plasites, rubber, cloth and paper, were apparently unaffected by being contacted with the plasma. Electrically conductive materials, such as metals and electrolytic solutions (e.g., isotonic solutions), were contacted by the plasma and received energy therefrom, as evidenced by heating or destruction of the contacted regions of the material.

The plasma was brought into contact with animal (both mouse and human) tissues by sweeping the plasma across an incision path. The tissue vaporized in a thin line to produce a substantially hemorrhage-free incision characterized by a complete absence of charred tissue. For surgical applications, nozzle orifices between **0.0050** and **0.0130** inches in diameter have been successfully used with this plasma generator.

c. Attempts were made to initiate a plasma with the RF source tuned at frequencies ranging from several megahertz above to several megahertz below resonant frequency (**90** Mhz). Spontaneous initiation of a plasma occurred at frequencies as high as **94** megahertz but would not occur at frequencies significantly below **88** megahertz.

d. After a plasma was initiated, the RF source was tuned from **90** megahertz to progressively higher frequencies and the nature of the plasma was observed. A cold plasma of the type described in (b) above was established at a frequency of about **92** Mh and was maintained up to a frequency of about **95** Mh, at which time the plasma extinguished. At all times until the plasma extinguised, it could be coupled to conductive material, such as tissue or metal; i.e., energy would be transferred into such material when it was contacted by the plasma.

e. After a plasma was initiated, the RF source was tuned from **90** megahertz to progressively lower frequencies, and the nature of the plasma was observed. A cold plasma capable of coupling to conductive materials was produced at frequencies only slightly below **90** megahertz, but at frequencies below about **88** Mh, the plasma lost its ability to couple to even good conductors, such as copper. The plasma grew progressively weaker in appearance as the source frequency was decreased until it extinguished at about **86** Mh.

EXAMPLE II

The plasma generator of Example II was operated in the same fashion as described in Example I except that the RF source was tuned to provide power at the resonant frequency of the generator (**90** Mhg). The power supplied to the generator was varied and the nature of the plasma was observed.

a. At a power setting of **500** watts, the plasma was visible to about **4** inches beyond the terminus of the nozzle. The plasma was blue-white for about **1** inch beyond the nozzle but the remainder of the plasma was dull orange. The Q of the plasma generator under these conditions was determined to be about **6.** The orange portion of the plasma was very hot (above **4500**°K) but could not be made to arc to ground. The diameter of the plasma flared out from the nozzle to more than **10** times the diameter of the orifice. When the plasma was applied to tissue, the tissue was charred and burned without producing a useful incision. The plasma behaved generally as a blowtorch.

b. The power setting was increased to **1500** watts. The plasma was visible for a length of about **6** inches and was entirely dull orange. Within **5** seconds, the hollow electrode melted in the vicinity of the nozzle.

c. At a power setting of **50** watts, the plasma was blue-white and was visible for approximately one-fourth inch beyond the nozzle. Paper could not be ignited by this plasma. When applied to tissue, the plasma produced an unacceptably wide, U-shaped incision at a rate too slow for practical surgery.

EXAMPLE III

The plasma generator of Example I was used successfully for microwelding and microcutting by tuning the RF source to about **94** Mh at about **500** watts, and by increasing the rate of argon gas flow to between about **5** and about **15** cfh. The plasma diameter tended to be smaller than the orifice of the nozzle and was blue-white in color. The plasma was visible for about ½ to about **1** inch in length. When the plasma was sustained in air, the Q of the generator was about **12.** When the plasma was brought into contact with a workpiece, the Q dropped to about **6.** When helium was substituted for argon, an orange plasma of much higher temperature was produced. The helium plasma, being hotter, is faster and even more effective for many cutting and heating applications.

EXAMPLE IV

A plasma generator (torch) was constructed generally as illustrated by FIGS. **1** through **3.** As assembled, the resonant frequency of the torch was about **74** Mh. The inductance of the parallel-resonant circuit of the torch was determined to be about **0.8** microhenries and the capacitance of this circuit was determined to be about **6** picofarads. A nozzle was selected with an orifice diameter of **0.030** inches. Argon was displaced through the generator at a rate of about **6** cubic feet per hour. Fifteen hundred watts of RF power was applied to the tap of the coil at approximately **500** volts. The unloaded Q of the apparatus was about **200,** but the Q dropped to about **13** upon initiation of a plasma.

a. With power supplied at resonant frequency, the visible length of the plasma was about **4** inches. The plasma was blue-white in appearance for about one-half inch beyond the tip of the nozzle, changing to orange-white in the core of the plasma beyond that point. The plasma color became a duller orange away from the core and toward the plasma boundary. The blue-white portion of the plasma could be made to arc to ground (evidencing the presence of RF energy) but the orange portion of the plasma could not be made to arc to ground and was apparently electrically neutral but at very high temperature.

b. With power supplied at about **75** MH, the visible plasma was entirely blue-white and was reduced to about **1** inch in length beyond the tip of the nozzle. As the frequency of the RF power was increased further, the length of the visible plasma was correspondingly reduced until the plasma ultimately extinguished at about **78** Mh. When the plasma was coupled into either conducting or semi-conducting material, the temperature of the plasma carrier gas was observed to increase appreciably.

c. With power supplied at about **73** Mh, the visible plasma decreased to about **1** inch and could not be made to couple into semi-conducting material. The plasma extinguished when the frequency of the power source was reduced further.

EXAMPLE V

The plasma generator of Example IV was operated at various frequencies of applied power, using a nozzle with a tip diameter of **0.020** inches and substituting first nitrogen and then helium for argon as the displaced gas. In each instance, the gas was displaced at a rate of **15** cfh (cubic feet per hour).

When nitrogen was used, the plasma was blue-white in color and appeared to contain some RF energy (evidenced by a propensity to arc to ground). At resonance (power supplied at about **74** Mh), the plasma was visible for about **2** inches beyond the tip of the nozzle. The visible length decreased to about one-half inch when power was supplied at **78** Mh and to about one-tenth inch when power was suppled at **70** Mh.

When helium was used, the plasma was orange in color and evidenced little or no RF energy. The visible plasma length at resonance was about **12** inches, decreasing to about **2** inches at **78** Mh and about one-half inch at **70** Mh supplied power, respectively.

Plasmas can also be sustained in other gases, such as ammonia, methane and propane, with the generator of this example by proper adjustment of flow rates and power levels.

EXAMPLE VI

A plasma generator similar to that of Examples IV and V was constructed, using circuit parameters which resulted in a resonant frequency of **100** Mh. The parallel-resonant circuit had an inductance of about **0.5** microhenries and capacitance of about **5** picofarads. Argon was displaced through the generator at about **15** cfh through a nozzle with a tip diameter of about **0.020** inches. Power was supplied at **1500** watts and **500** volts. A blue-white plasma was produced with a visible length of about **8** inches when power was supplied at **100** Mh. The visible length of the plasma decreased to about **2** inches when the frequency of the power was increased to **105** Mh and to one-half inch when power was supplied at **95** Mh.

I claim:

1. A method for performing surgery which comprises:

establishing and maintaining a cold plasma of a sufficiently small cross section to permit a narrow region of contact between the plasma and tissue; and applying said plasma to tissue to produce an incision.

2. A method according to claim **1**, wherein the plasma is produced by applying RF energy to a noble gas.

3. A method according to claim **2**, wherein the noble gas is Argon and sufficient RF energy is applied to said gas to excite it to a metastable state.

4. A method according to claim **2**, wherein the noble gas is displaced through a hollow electrode terminating in an effluent nozzle and RF energy is applied conductively to said electrode through a parallel-resonant circuit.

5. A method according to claim **4**, wherein RF energy is applied to said parallel-resonant circuit at a frequency close to, but different from, the resonant frequency of said circuit.

6. A method according to claim **5**, wherein RF energy is applied to said parallel-resonant circuit at a frequency up to about **5** percent higher than the resonant frequency of said circuit.

7. A method according to claim **6**, wherein the noble gas is Argon, the diameter of the plasma is between about **0.005** and about **0.015** inches, and the resonant frequency of the parallel-resonant circuit is between about **30** and about **200** megahertz.

8. A method according to claim **7**, wherein the resonant frequency of the parallel-resonant circuit is between about **80** and about **100** megahertz, and the flow rate of the Argon gas is below about **5** cubic feet per hour.

9. A method according to claim **8**, wherein the flow rate of the Argon gas is between about **1/10** and about **2** cubic feet per hour, the unloaded Q of the parallel-resonant circuit is above about **100**, and RF energy is applied to said circuit at between about **30** and about **300** watts and between about **50** and about **300** volts.

10. A method according to claim **1**, wherein the plasma is produced by applying electrical energy to a noble gas.

11. A method according to claim **10**, wherein the diameter of the plasma is adjusted to between about **0.005** and about **0.015** inches.

12. A method according to claim **10**, wherein the noble gas is Argon and said gas is excited to a metastable state by the application of electrical energy.

13. A method according to claim **12**, wherein the diameter of the plasma is adjusted to between about **0.005** and about **0.015** inches.

14. A method according to claim **13**, wherein the Argon is displaced through an effluent nozzle at a flow rate below about **5** cubic feet per hour.

15. A method according to claim **14**, wherein the flow rate of the Argon is held between about **1/10** and about **2** cubic feet per hour.

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