

Jan. 9, 1968

J. W. FLOWERS ETAL

3,363,130

FREQUENCY TUNING OF AN ENERGETIC ARC DISCHARGE BY VARYING
THE DIAMETER OF THE CYLINDRICAL HOLLOW ARC

Filed Oct. 23, 1965

2 Sheets-Sheet 1

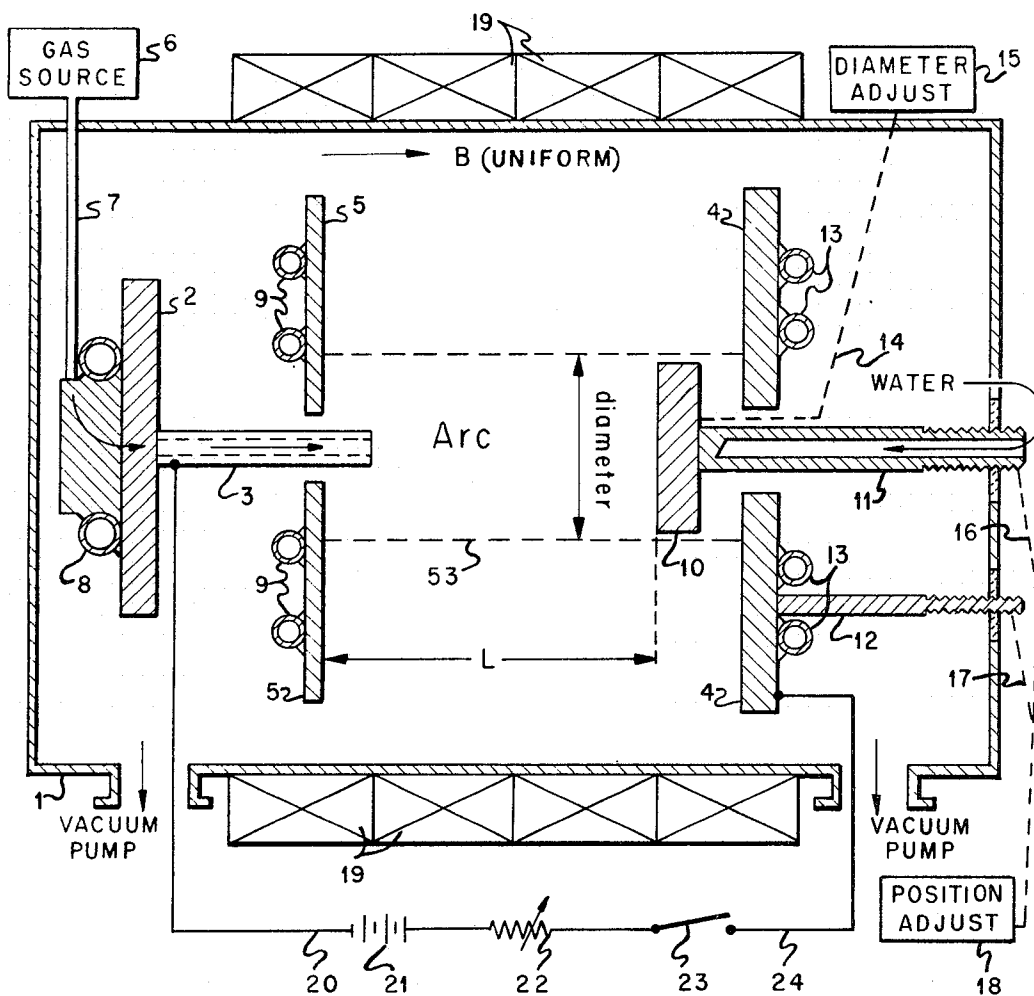


Fig. 1

INVENTORS.

John W. Flowers

BY William A. Dunnill

Roland G. Anderson

ATTORNEY.

Jan. 9, 1968

J. W. FLOWERS ET AL.

3,363,130

FREQUENCY TUNING OF AN ENERGETIC ARC DISCHARGE BY VARYING
THE DIAMETER OF THE CYLINDRICAL HOLLOW ARC

Filed Oct. 23, 1965

2 Sheets-Sheet 2

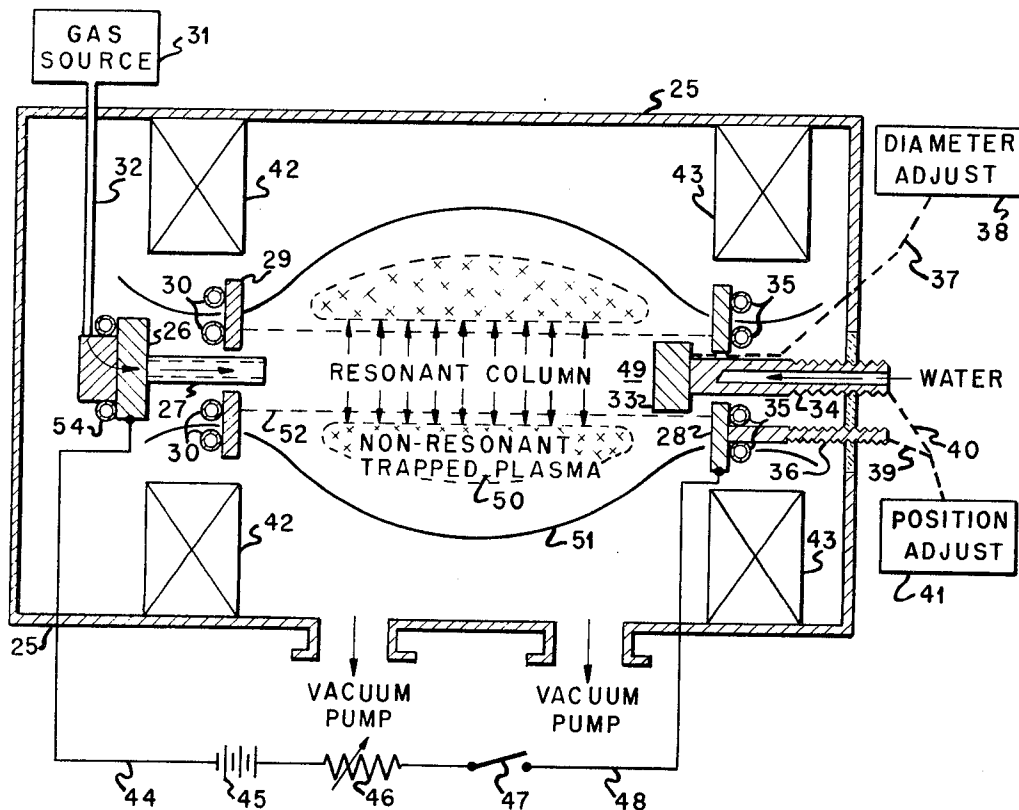


Fig. 2

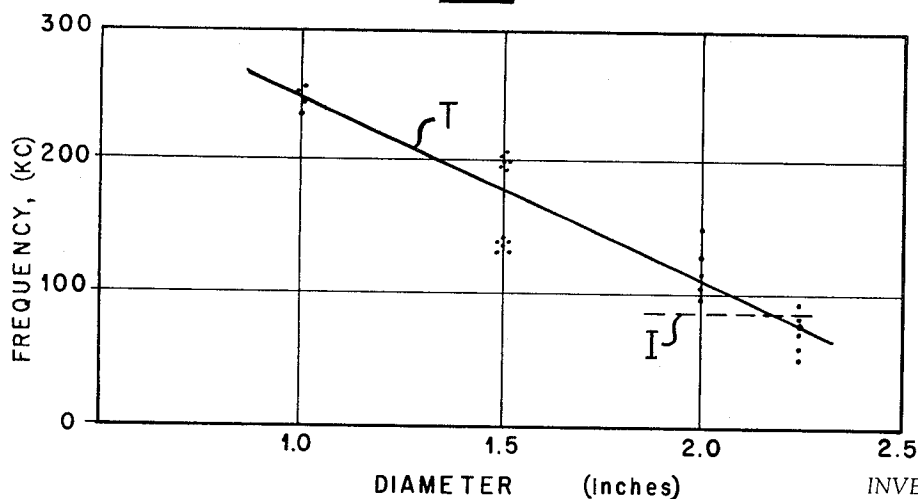


Fig. 3

INVENTORS

John W. Flowers

BY William A. Dunnill

Robert A. Gundersen

ATTORNEY.

1

3,363,130

FREQUENCY TUNING OF AN ENERGETIC ARC DISCHARGE BY VARYING THE DIAMETER OF THE CYLINDRICAL HOLLOW ARC**John W. Flowers, Gainesville, Fla., and William A. Dunnill, Tullahoma, Tenn., assignors to the United States of America as represented by the United States Atomic Energy Commission**

Filed Oct. 23, 1965, Ser. No. 504,276

4 Claims. (Cl. 313-161)

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

The present invention relates to a system and method for tuning an arc discharge by adjusting the frequency spectrum to provide strong oscillations in the region of a useful frequency or a critical frequency whereby energetic ions can have their energies enhanced and be resonantly diffused from the tuned arc outside of which the resonances disappear rapidly and thermal equilibrium proceeds.

Certain intense arc discharges such as cylindrical discharges of high temperature plasma are known to contain intense oscillations at frequencies covering a very broad spectrum from kilocycle per second regions to kilo-mega cycles per second regions. In general, of most concern in the operation of such discharges has been the manifestation of the unstable nature of the plasma of these discharges. Thus, according to usual considerations there exists a need for some means and method to avoid the instability caused by the intense oscillations in such discharges, thereby providing an arc discharge which is substantially more energetic and stable.

In contrast, it is the object of the present invention to provide a means and method for operating a cylindrical arc discharge device including a method for controlling the discharge to thus produce very intense arc oscillations at a useful frequency.

This and other objects and advantages of the present invention will become apparent upon a consideration of the following detailed description and the accompanying drawings, wherein:

FIG. 1 is a sectional view of an arc discharge device illustrating one embodiment of the present invention;

FIG. 2 is a sectional view of another embodiment of the present invention; and

FIG. 3 is a graph illustrating the relationship between the frequency in the discharge and diameter of the reflector electrode in the device of FIG. 1.

The above object has been accomplished in the present invention by providing means to adjust the size of the reflector electrode in an arc discharge device, thus varying the size of, or diameter of, the cylindrical arc discharge. It was discovered that it is possible to tune the arc discharge by this method and that the frequency spectrum can thus be adjusted to provide strong oscillations in the region of a useful frequency or a critical frequency. It has been determined that the dominant frequencies in the low frequency spectrum are influenced by pressure, current, and magnetic field. However, the strong frequencies which appear in the operation of such a device are somewhat erratic and unpredictable in frequency position with the variations of these parameters. Variations in the arc length are useful in providing some adjustment of the frequency spectrum for lower values of magnetic field, 400 gauss for example, but at higher magnetic fields (1000-3000 gauss) the variations in arc length only provide for marginal adjustment of the frequency spectrum. However, with variation of the arc diameter, the frequency behavior is consistent; that is, as the arc diameter is increased, the dominant frequency, which appears in the

2

spectrum, decreases. Thus, adjustment of the arc diameter provides a means and method for easily and accurately tuning the arc discharge such that it is possible to attain a dominant frequency equal to the ion cyclotron frequency of the gas used which provides for optimum operation of the arc discharge. It should be noted that no oscillations in the tunable frequency range are observable when the reflector electrode is removed from the system, when the reflector is shorted to the anode regardless of the size of the reflector, when no magnetic field is on, or when the system pressure is above about 10^{-3} mm. Hg.

With reference to the drawings, FIG. 1 shows one embodiment of the present invention for accomplishing the above object. In FIG. 1, a vacuum chamber 1 is provided with two openings, as shown, which are connected to respective vacuum pumps, not shown, for evacuating the chamber. A plurality of magnetic field coils 19 are provided which encompass the chamber 1 to provide a magnetic field whose direction is shown by the arrow B. These coils 19 are energized by means, not shown, in a conventional manner to provide a magnetic field of a selected value in the range from 1000-3000 gauss.

Mounted within the chamber 1 are a hollow tungsten cathode 3 supported by a cathode holder 2, an anode 4 provided with a centrally disposed aperture, a water cooled reflector electrode 10 whose diameter is adjustable, a shield member 5 encompassing the cathode 3, and cooling lines 8, 9 and 13 for cooling the cathode holder 2, shield member 5 and the anode 4, respectively. Gas from a gas source 6 supplies feed gas to the hollow cathode 3 by means of a gas feed tube 7 and through a gas feed tube, not shown, in the cathode holder 2. The feed gas may be argon, nitrogen, deuterium, or hydrogen, for example.

The diameter of the reflecting electrode 10 is adjustable by means of a mechanical coupling 14 coupled thereto which is actuated by a diameter adjust means 15 in any convenient manner. The diameter of the electrode 10 may be varied from about $\frac{1}{2}$ inch up to $2\frac{1}{2}$ inches, for example.

The reflector electrode 10 is supported by a movable, water cooled support member 11, and the anode 4 is supported by a movable support member 12. Members 11 and 12 are coupled by mechanical couplings 16 and 17 to a position adjust member 18, such that the electrode 10 and anode 4 are movable as a unit to thereby vary the distance "L" between the electrode 10 and shield member 5, when such is desired. For example, the arc electrodes may be moved for ease of starting the arc discharge at the start of operation of the device, and then moved after initiation of the discharge to any desired position. Also, in some cases the distance "L" may be varied to obtain optimum operation of the discharge and for additional arc tuning when lower magnetic fields are employed.

The cathode 3 is connected to a battery 21 by a lead 20, and the battery 21 is also connected to the anode 4 by a variable resistor 22, a manual switch 23, and a lead 24.

In operation of the device of FIG. 1, the chamber 1 is evacuated to a selected pressure in the range from 5×10^{-4} - 4.2×10^{-5} mm. Hg, the magnetic field coils 19 are energized to provide a magnetic field having a uniform flux density of a selected value in the range from 1000-3000 gauss, feed gas is fed from the gas source 6 to the interior of hollow cathode 3, and an arc discharge 53 is established between the cathode 3 and anode 4, the diameter of such discharge being determined by the diameter of the reflector electrode 10. It should be noted that variations in the vacuum pressure in the chamber 1 are not critical to the operation of the device and variations in pressure within the above-mentioned range have little effect as far as arc tuning is concerned. The discharge is

initiated by closing the switch 23 and moving the electrode 10 and anode 4 as a unit by the means 18 to a position close to the cathode 3 until the discharge is initiated and then these members are moved away from the cathode 3 to a desired arc operating position. The distance "L" during arc operation may be from $1\frac{1}{16}$ inches to $9\frac{1}{16}$ inches, for example. Water is circulated through the tubings 8, 9, and 13 and within the electrode 10 support member 11 for cooling the various members associated therewith during arc operation.

During a typical operation of the arc discharge of FIG. 1, using argon gas as the feed gas, setting the magnetic field strength at about 2500 gauss, with an arc discharge voltage of about 400 volts and a current of about 10 amperes, and varying the diameter of the reflector electrode 10, a series of frequency measurements were made of the arc by means of an electrostatic probe placed near the arc and a panoramic spectrum analyzer, model SPA-3. The essential results of such measurements are shown in FIG. 3. As can be seen in FIG. 3, as the arc diameter is increased by increasing the diameter of electrode 10 by the means 14 and 15, the dominant frequency, which appears in the spectrum, decreases. Thus, it can be seen that the dominant frequency of the arc discharge, as represented by the line "T" in FIG. 3, is a direct function of the diameter of the discharge as determined by the diameter of the electrode 10. The ion cyclotron frequency for argon at 2500 gauss approximately 90 kc. and is represented by the dashed line I in FIG. 3. It is possible to thereby attain a frequency in the arc discharge which is equal to the ion cyclotron frequency of the gas used to operate the discharge. When a strong arc oscillation is made to occur in the same region as the ion cyclotron frequency by adjustment of arc diameter, this resonant condition has been evidenced by an intense erosion of the copper reflector electrode 10 and extreme copper sputtering and copper plating of the entire vacuum chamber. Thus, from such evidence it should be apparent that the ions from such a resonant operation of the arc discharge are very energetic with temperatures which have been greatly increased above the very high ion temperatures of the arc discharge from which they originate.

The use of the above-described tuning process for tuning an arc discharge into a resonant condition with the ion cyclotron frequency of the gas used for every energetic arc ion sources. This is particularly true for ion sources of high ion current such as might be used for space propulsion. Also, such high temperature ion sources, as discussed above, can be used as a thermonuclear injection method. Such a use is shown in FIG. 2, which will now be described.

The device of FIG. 2 is structurally similar to that of FIG. 1 except magnetic mirror coils are used to provide a magnetic "bottle" field configuration 51 instead of the uniform field configuration of FIG. 1, and the anode-cathode spacing is about five feet, for example. In FIG. 2, a vacuum chamber 25 is provided with suitable openings for connection with vacuum pumps, not shown, for evacuating the chamber. Mounted within chamber 25 are a hollow cathode 27 provided with a cathode holder 26, an anode 28, a shield member 29 encompassing the cathode 27, a reflecting electrode 33 whose diameter can be adjusted by the means 37 and 38, and magnetic mirror coils 42 and 43 for providing a magnetic mirror field. Cathode holder 26 is cooled by water cooling tube 54, shield member 29 is cooled by water cooling tubes 30, and the anode 28 is cooled by water cooling tubes 35. The reflecting electrode 33 is supported by a movable water cooled member 34 and the anode 28 is supported by a movable member 36. Members 34 and 36 can be moved as a unit by means of a unit 41 coupled to these members by couplings 39 and 40.

Gas, which may be argon for example, from a gas source 31 is fed to the interior of the hollow cathode 27 through a feed tube 32 and through a channel, not shown,

in cathode holder 26. A battery 45 is connected by a lead 44 to the cathode holder 26, and by a variable resistor 46, a manual switch 47, and a lead 48 to the anode 28.

The operation of the device of FIG. 2 is similar to the operation of FIG. 1, described above, in that the arc discharge 52 can be tuned by varying the diameter of the reflector electrode 33 such that the dominant frequency thereof can be made equal to the ion cyclotron frequency of the feed gas used in the operation of the device to thus create a resonant column 49 of energetic ions.

The general mechanisms of the processes which occur in the operation of the device of FIG. 2 are as follows: In the magnetic field, ions gyrate in a perpendicular plane with the well known fundamental cyclotron frequency and its harmonics. The plasma column 52 oscillates unrelated in general to the ion cyclotron frequency. There are many modes of oscillation with varying degrees of coupling and with all the complications of coupled oscillators. Nevertheless, the gross features of relative importance are a motor-like rotation of the plasma cylinder with harmonics of rotation and a longitudinal vibration or oscillation along the column length which is harmonically related. Relatively large electric fields occur in the plasma for conditions of resonance. Thus, when the tuned frequencies become harmonically related to the otherwise independent ion cyclotron frequencies, further resonance proceeds with the ions. The ions then cease to drift in their more usual manner in crossed electric and magnetic fields, and instead, they are then accelerated in spiral paths as in a cyclotron. Both diffusion rate and energy content then become maximized. Since the diffusion rate becomes maximized at resonance, the ability to adjust the frequency by the diameter control means, as discussed above, to achieve the resonance condition provides the fundamental control. Thus, with careful control, large quantities of energetic ions can have their energies enhanced and be resonantly diffused from a tuned arc ion source outside of which the resonances disappear rapidly to thus form a non-resonant trapped plasma 50, as in FIG. 2, and thermal equilibrium proceeds.

It should be noted that the feed gas for use in the devices of FIG. 1 and FIG. 2 may be other than argon, as set forth above. For example, nitrogen, deuterium, or hydrogen may also be used, if desired. The device of FIG. 1, when nitrogen feed gas was used in the operation thereof, shows that the dominant frequencies can be adjusted to well below the cyclotron frequency of the gas used, such that there is a wide range of possible frequency adjustments possible with the adjustments of the diameter of the reflector electrode.

It should be noted that the means for adjusting the diameter of the arc discharge cylinder, as described above, is not limited to the means set forth above. For example, the diameter of the hollow arc discharge may be adjusted by providing a hollow, gas fed cathode which is axially displaced and movable to different axial positions to provide an adjustable diameter plasma cylinder in the same manner as set forth in the application of John W. Flow-ers, Ser. No. 367,266, filed May 13, 1964, now Patent No. 3,268,758, issued Aug. 23, 1966, if such is desired.

This invention has been described by way of illustration rather than limitation and it should be apparent that it is equally applicable in fields other than those described.

What is claimed is:

1. A method for tuning an arc discharge comprising the steps of initiating said discharge within an evacuated enclosure and within a magnetic field between a hollow, gas-fed cathode and an annular anode with an axially disposed reflector electrode disposed between said anode and said cathode to form said discharge in the shape of a cylindrical plasma, and adjusting the diameter of said cylindrical discharge by adjusting the diameter of said reflector electrode, whereby the dominant frequency in the frequency spectrum of said discharge can be adjusted to

5

progressively lower and higher values as a function of the diameter of said cylindrical arc discharge.

2. The method set forth in claim 1, wherein said magnetic field is uniform and of a selected value in the range from 1000-3000 gauss.

3. The method set forth in claim 1, wherein argon gas is fed to said hollow cathode, and said magnetic field is provided by a pair of magnetic mirror coils.

4. The method set forth in claim 3, wherein the diameter of said reflector electrode is adjusted to adjust the diameter of said cylindrical arc discharge until the harmonics of rotation of said plasma cylinder and the longitudinal oscillation along the length of said plasma cylinder are harmonically related to the ion cyclotron frequency of the feed gas, whereby both diffusion rate and ion energy content become maximized and the reasonably

6

diffused ions from the thus tuned arc discharge rapidly lose their resonances and are magnetically trapped by said magnetic mirror field where thermal equilibrium can proceed.

References Cited

UNITED STATES PATENTS

2,928,966	3/1960	Neidigh	313—230 X
2,945,972	7/1960	Blue et al.	313—63
2,956,224	10/1960	Heil	315—111 X
3,222,559	12/1965	Alexeff et al.	313—230 X
3,268,758	8/1966	Flowers	313—231

JAMES W. LAWRENCE, *Primary Examiner*.

15 S. A. SCHNEEBERGER, *Assistant Examiner*.