

Dec. 7, 1965

I. ALEXEFF ETAL

3,222,559

PRODUCTION OF COMPLETELY IONIZED PLASMA

Filed Dec. 11, 1964

2 Sheets-Sheet 1

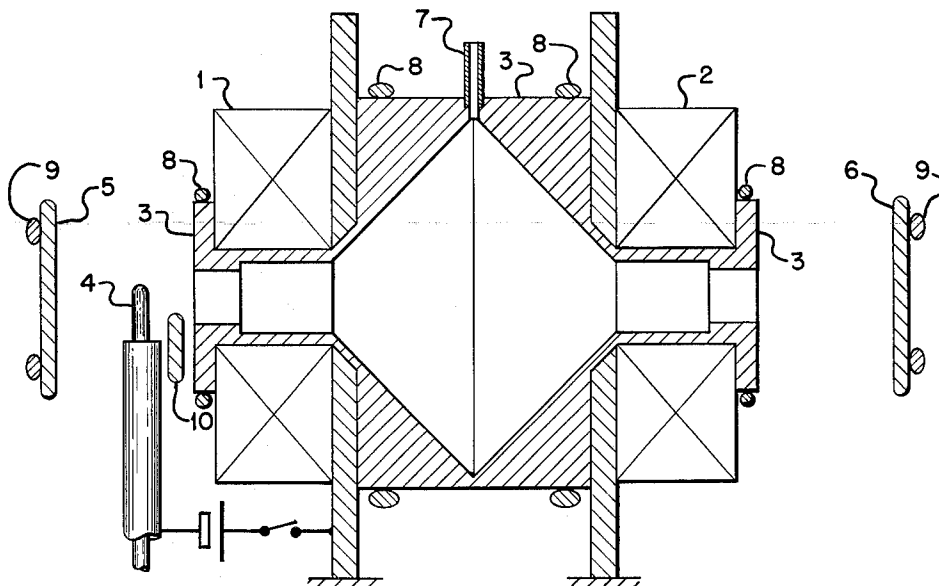


Fig 1.

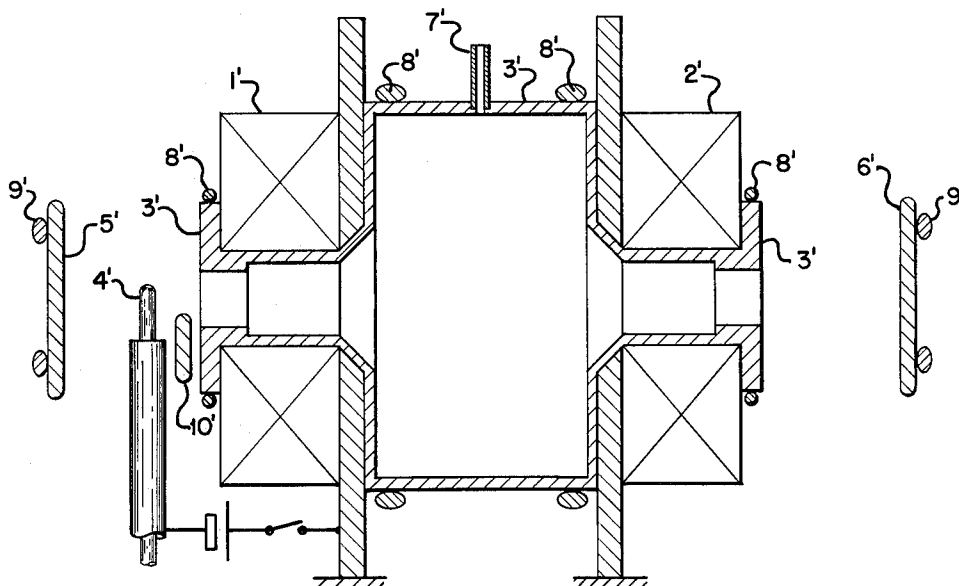


Fig 2.

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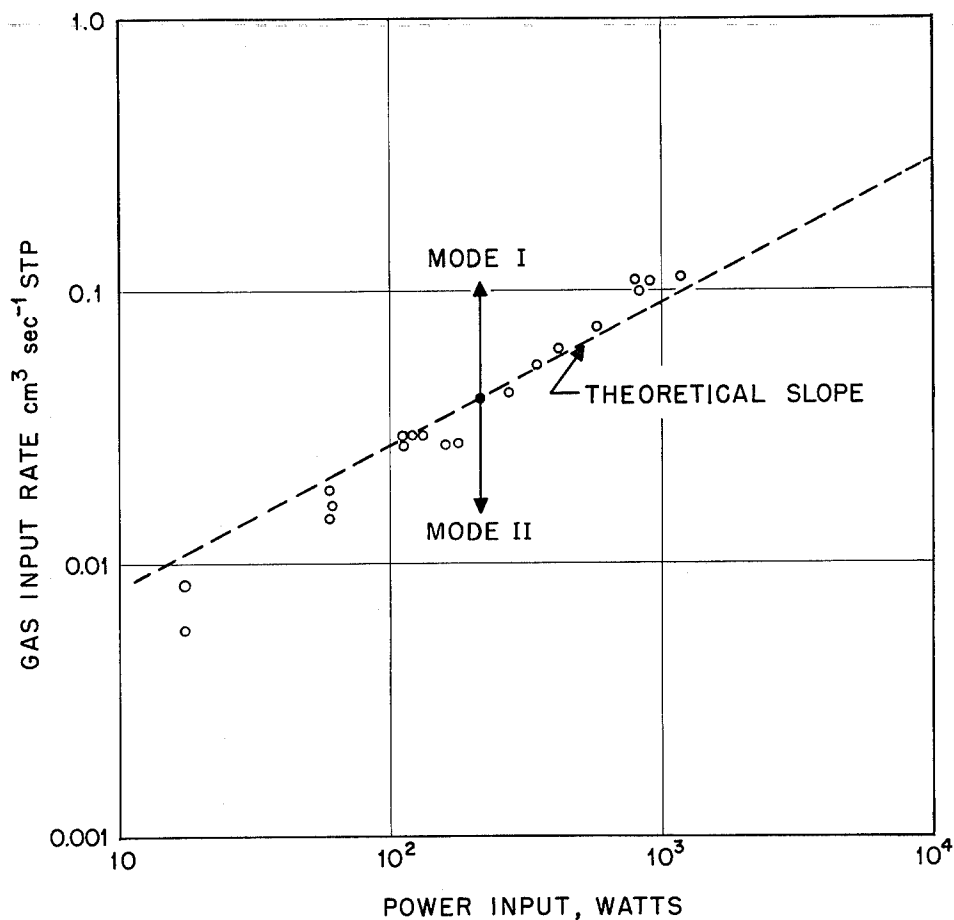


Fig 3.

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PRODUCTION OF COMPLETELY IONIZED PLASMA

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3 Claims. (Cl. 313-61)

This invention relates to a method and means for obtaining a neutral-free, energetic and magnetically confined, steady-state plasma for the heating of ions and as an environment for carrying out thermonuclear reactions.

One device for producing a high degree of ionization in a plasma is described in U.S. Patent No. 2,928,966, issued Mar. 15, 1960, entitled, "Arc Discharge and Method of Producing the Same." The arc discharge of that patent, referred to as a Mode II arc, is produced by passing electrons from a cathode through a hollow anode, maintaining a potential between the electrodes, and injecting gas into the anode at a rate to maintain the pressure in the anode of about 10^{-3} Torr while the pressure exterior to the anode is maintained at about 10^{-5} Torr. Thus, the arc is also referred to as a "pressure gradient" arc. The gas fed to the anode is greater than 90% ionized, and the ions produced within the arc are accelerated out of the arc with a substantial radial velocity component. The present invention is an improvement over the arc discharge of the above-mentioned patent.

In the above patent, the high degree of ionization occurred in the throat of one of the mirror coils; therefore, ions were rather easily lost to regions of lower magnetic field strength beyond the throat of the one mirror coil; the ions that were magnetically confined were moderately energetic, but not sufficiently energetic to produce any neutrons that could be measurably detected. Also, in the above patent it is not possible to achieve "burnout" of the neutral particles present in the background gas beyond the mirror throat.

Therefore, it is a primary object of the present invention to provide a method and means for obtaining a neutral-free, energetic and magnetically confined, steady-state plasma for the heating of ions and as an environment for carrying out thermonuclear reactions.

It is another object of the present invention to provide a method and means as in the preceding object for producing neutrons in substantial quantities.

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

FIG. 1 is a sectional view illustrating one embodiment of the present invention;

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

FIG. 3 is a graph showing the general relationship of input power and gas input for producing a plasma in the devices of FIG. 1 and FIG. 2.

The above objects have been accomplished in the present invention by increasing the volume of the anode of the prior patent and to center the anode between magnetic mirror coils. The cathode is in the same relative position as in the prior patent. Feed gas is admitted to the center of the anode, midway between the mirror coils. It has been determined that not only a neutral-free, steady-state plasma is provided in the operation of such a device, but also the ions created thereby are sufficiently energetic to produce a substantial quantity of neutrons.

Referring now to the drawings, FIG. 1 shows one em-

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bodiment in which the principles of the present invention may be carried out. In FIG. 1, the magnetic mirror coils 1, 2 are spaced about three inches apart and the throats thereof are $\frac{3}{8}$ inch in diameter. The space between the coils 1, 2 is occupied by an anode 3 having a double conical cavity. The effective plasma volume is defined by magnetic field lines which pass through the coil throats and is about ten cubic centimeters. Exterior and spaced $\frac{1}{2}$ inch from one coil throat is a cathode 4 aligned on the axis of the device. One electrically floating electron reflector 5 is spaced 1 inch beyond the cathode, and a second electrically floating electron reflector 6 is equally spaced exterior to the second coil throat. In addition, an electrically floating baffle 10 is provided between a portion of the cathode 4 and the end of anode 3 such that the electrons emitted from the cathode do not see the anode directly along field lines.

The entire unit of FIG. 1 is contained within a vacuum vessel, not shown, and this vessel is evacuated in a conventional manner. The mirror coils are energized in a conventional manner by means of a power source, not shown. Gas is admitted to the interior of the anode 3 from a gas source, not shown, and through the conduit 7 to the center of the anode, midway between the coils 1, 2. The anode 3 and the electron reflectors 5, 6 are cooled by means of cooling coils 8 and 9, respectively.

In the operation of the device of FIG. 1, the coils 1, 2 are energized to provide a mirror ratio of 1.5 to 1 with a magnetic field in the throats thereof of about 13,500 gauss, and at the midplane, a field of about 9000 gauss, for example. The vacuum vessel enclosing the device of FIG. 1 is evacuated to and maintained at a pressure of about 10^{-5} Torr, for example, and the gas feed, which may be deuterium, for example, is fed in through conduit 7 at a rate of about $\frac{1}{40}$ atmospheric cc./sec., for example, and with this feed rate the pressure within the anode chamber is about 10^{-3} Torr. The anode-to-cathode voltage is about 7 Kv., for example, and the current drawn from the supply is about 0.7 ampere. Using the above operating conditions, a plasma was obtained within the anode 3 that, by all observations, appeared to be completely ionized. Ion bombardment of the cathode provided sufficient electrons so that separate heating thereof was not required after establishment of the plasma.

Signals from R.F. probes and detection of ions escaping through a pin hole in the anode and impingement upon a detection plate demonstrated the presence of energetic ions, and an ion density of 4×10^{12} ions/cm.³ was determined as a result of the R.F. signal. Furthermore, the intensity of the R.F. signal and a neutron production of about 10^3 neutrons/sec. further attest to the energy of the ions.

The embodiment shown in FIG. 2 is very similar to that shown in FIG. 1 with the reference numerals being primed in FIG. 2 and referring to parts which correspond to those of the device of FIG. 1. The major difference in structure between FIG. 1 and FIG. 2 is that the anode of FIG. 2 is a cylindrical cavity. The effective plasma volume of the anode cavity of FIG. 2, as defined by the magnetic field lines, is the same as that of FIG. 1. The pressures and magnetic field strengths of FIG. 2 are the same as those used in FIG. 1. The optimum operating conditions for FIG. 2 are: cathode-anode potential of 8 Kv. (power supply drain of 0.8 ampere), and gas feed rate of $\frac{1}{40}$ atmospheric cc./sec. With the embodiment of FIG. 2, a neutron production of 3×10^5 neutrons/sec. was observed and the ion density is in the range of 10^{12} — 10^{14} ions/cm.³.

The device of FIG. 2 is not limited to a spacing of three inches between the mirror coils. For example, a spacing of about 22 inches has been used. In such a larger device, the magnetic field has a mirror ratio of about 2 to 1

and in the throats of the mirror coils it is about 50,000 gauss, and the magnetic field at the midplane is about 25,000 gauss, for example. The effective plasma volume of the larger device is about 500 cc. The gas feed rate in the larger device is about $\frac{1}{3}$ atmospheric cc./sec. to maintain the pressure in the anode cavity at about 10^{-3} Torr. The neutron production rate in the larger device is at least 50 times larger than that of the smaller device.

In all respects, the operation of the above-described devices is akin to that taking place within the small anode of the Mode II arc discharge of the above-mentioned patent. The pressure gradient occurs between the center of the anode, where the gas is fed, to the exterior volume at both ends of the anode. The apparent burnout condition occurs whenever the relationship of gas feed and input power falls below the line of FIG. 3. If the relationship is above the line, a standard or Mode I arc is observed, without burnout.

One difference between the present invention and the above-mentioned prior patent is the magnetic field configuration in the region of complete ionization. Formerly, the substantial ionization was conducted in the throat of a mirror coil; therefore, as pointed out above, ions were rather easily lost to regions of lower magnetic field strength and the ions beyond this mirror coil, although energetic, did not have sufficient energy to produce any measurable quantity of neutrons. On the other hand, by centering the anode between mirror coils and feeding gas into the center of the anode, midway between the coils, as in the present invention, a certain degree of containment of ions is achieved by the shape of the magnetic field. A study of the power dissipation in the device of FIG. 2 confirms this containment since only 10% of the power is dissipated on the end plates 5', 6', while the remaining power is dissipated equally in the two halves of the anode cavity. Also, by enlarging the anode as in the present invention to encompass not only the throats of the mirror coils, but the area between the coils, it is now possible to provide energetic ions that have considerably more energy than is possible by the above patented device, to provide better containment for the energetic ions, and to produce a substantial quantity of neutrons. As mentioned above, it is not possible to produce any measurable quantity of neutrons with the device of the above-mentioned patent.

The following procedures were used to determine the degrees of complete ionization, ion heating, electron heating, plasma density, and neutron emission in the devices of the present invention.

As an indication of complete ionization, hydrogen, deuterium, and helium discharges were dark in the operation of the device of FIG. 2. That is, spectral light of sufficient intensity to analyze by means of a spectroscope is not emitted from the working volume of the plasma. The apparatus in all other ways continued to function properly at burnout, drawing the full voltage and current from the power supply, keeping the filament incandescent by ion bombardment (filament heating power is turned off once the plasma is established), and emitting enormous quantities of radiation at approximately the ion plasma frequency.

Even though the ion temperature is not known quantitatively, there is considerable evidence for ion heating in the operation of the device of FIG. 2. The outer portion of the cavity wall was provided with a glass window with the center thereof intersecting with the magnetic midplane. After a plasma had been established and after a burnout operation of the device, there was a clean band down the center of the glass with deposits on both sides. The band appeared to be sand blasted. Analyses of the deposit on either side gave about 50% copper, some sputtered from the cavity wall, and 50% stainless steel from the coil enclosures which appear sputtered near the coil throats. The coil throat itself is lined with copper.

Electrostatic and magnetic analyses of ions near the

outer cavity wall of FIG. 2 identify the ions as deuterons with 20-25 Kev. energy. A velocity selector analyzer, such as described in U.S. Patent No. 3,096,438, issued July 2, 1963, whose sensitivity and aperture can be approximated, was used to look at the outer plasma in the device of FIG. 2. Two peaks were seen, one at 65-75 Kev. which indicated an ion density of about 10^{12} ions/cm.³, and a smaller peak at 20-25 Kev. which indicated an ion density of about 10^{11} ions/cm.³.

There is also evidence of electron heating in the operation of the device of FIG. 2 after burnout. The electron temperature is not known quantitatively, but X-ray images of the plasma and of the inside cavity walls have been made through 50 Kev. of absorber, which attests to the high energy of the electrons.

In plasma density measurements, two intense bands of radiation appear at ion plasma frequency and the bands are separated by approximately the ion cyclotron frequency, 7 mc. in the midplane. A traveling wave oscilloscope display measures the ion plasma frequency which indicates an ion density of about 4×10^{12} ions/cm.³. Radiation at the electron plasma frequency has not been studied; however, 10 kMc signals generated externally do not penetrate through the plasma, indicating that the electron density is probably higher than 10^{12} /cm.³.

Neutron emission in the operation of the device of FIG. 2 was first observed with a BF₃ counter and the source strength estimated to be about 10^5 reactions/sec. Nuclear track plates used to observe recoil protons from the fast neutrons stopped in the plate indicated: (1) that the BF₃ counter is indeed correct—there are neutrons and their source strength is about 10^5 reactions/sec.; (2) their energy is 2.5 Mev., that is, they come from the D—D reaction; (3) they do not come solely from the cathode, which is incandescent from deuteron bombardment, but appear to arise all along the length of the plasma column, outside the mirrors as well as between.

The above-discussed measurements were made in the device of FIG. 2 with the smaller dimensions, that is, with the three-inch spacing between the mirror coils. It should be understood that in the device of FIG. 2 with the larger dimensions, as described above, the neutron production rate is at least 50 times larger, that is, about 1.5×10^7 neutrons/sec. The larger device also provided complete ionization, and the ion heating, electron heating, and the plasma density were comparable to that provided by the smaller device of FIG. 2, as discussed above.

The above observations in the operation of the device of the present invention indicate that not only a burnout condition has been achieved, but that ions of rather high energy are present and that the neutral-free plasma can be magnetically confined so that a substantial neutron production rate is achieved. Thus, it should be evident that the devices of the present invention, as discussed above, provide an excellent environment for carrying out thermonuclear reactions. Also, the present devices provide an efficient neutron source. In addition, the plasma provided by the present devices may be used in combination with high energy ion injection to provide an even greater ion density.

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

What is claimed is:

1. A device for producing a substantially completely ionized, high energy plasma for producing neutrons, comprising an evacuated enclosure, a pair of annular magnetic mirror coils spaced apart a selected distance from 3 to 22 inches and axially aligned and being disposed within said enclosure, a cylindrical anode disposed between said mirror coils, said anode being provided with axial extensions extending into and beyond the throats of said coils, said anode defining an effective plasma containing volume as defined by the magnetic field lines of

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a selected value from 10 to 500 cc., an electron emissive cathode mounted exterior and in spaced relation from one coil throat and aligned on the axis of said coils, a first electron reflector spaced beyond the cathode, a second electron reflector spaced exterior and in spaced relation from the other coil throat, means for cooling said anode and said electron reflectors, means for energizing said cathode, means for energizing said magnetic mirror coils to provide a magnetic field in the mirror region of a selected value from 13,500 to 50,000 gauss and a magnetic field in the midplane between the coils of a selected value from 9000 to 25,000 gauss, and means for feeding gas at a controlled and selected rate into said cylindrical anode at the center thereof midway between said coils such as to maintain the pressure within said anode cavity at a higher vacuum pressure than the vacuum pressure within said enclosure, whereby a pressure gradient arc discharge is established and maintained within said anode cavity to produce a high energy, substantially completely ionized and magnetically confined plasma within said anode cavity, and high energy plasma effecting a neutron production rate of a selected value in the range from 10^3 to 1.5×10^7 neutrons per second.

2. The device as set forth in claim 1, wherein said enclosure is evacuated to a pressure of about 10^{-5} Torr,

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said mirror coils are spaced apart about 3 inches, said gas feed rate is about $\frac{1}{10}$ atmospheric cc./sec. to thereby maintain a pressure within said anode of about 10^{-3} Torr, said magnetic mirror coils providing a magnetic field in the mirror region of 13,500 gauss and a magnetic field in the midplane of 9000 gauss, said effective plasma containing volume being about 10 cc., and said neutron production rate being about 3×10^5 neutrons per second.

3. The device set forth in claim 1, wherein said enclosure is evacuated to a pressure of about 10^{-5} Torr, said mirror coils being spaced apart about 22 inches, said gas feed rate is about $\frac{1}{2}$ atmospheric cc./sec. to thereby maintain a pressure within said anode of about 10^{-3} Torr, said magnetic mirror coils providing a magnetic field in the mirror region of 50,000 gauss and a magnetic field in the midplane of 25,000 gauss, said effective plasma containing volume being about 500 cc., and said neutron production rate being about 1.5×10^7 neutrons/sec.

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